National Cooperative Highway Research Program

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Task 2.3 Synthesis Report
Review of Key Climate Impacts to the Highway System and Current Adaptation Practices and Methodologies

Climate Change and the Highway System: Impacts and Adaptation Approaches

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1.0 Introduction

Over the last decade, a growing number of highway agencies from around the world have come to realize that climate change will likely impact the highway system and that the time to anticipate, plan for, and adapt to expected changes is now. Many of these pioneering agencies have undertaken studies to characterize the risk climate change poses to their assets and operations: some have even begun to incorporate adaptation into planning and project development. One of the key challenges for such agencies is staying on top of the latest practices and methodologies in this nascent yet burgeoning field. New ideas and approaches are constantly being developed, and keeping abreast of the latest developments can be challenging, especially given that much of the material is in the form of unpublished “grey” literature. This report attempts to bring all of the disparate literature on climate change threats and methodologies for dealing with them into one place. After reading this document, one should come away with a strong sense of the state of the highway adaptation practice as of the fall of 2010.

The substance of the report begins with Chapter Two, which sets the stage for later sections by providing a conceptual model that defines the highway system and identifies key components for adaptation planning. Chapter Three then provides an overview of how the highway system might change in the future given demographic and technological development. This is followed by a brief discussion of national climate change projections and a synopsis of the current literature on how those projections are likely to impact the highway system. Chapter Four describes current practices and methodologies for dealing with those impacts as determined from an extensive international literature review and interviews with agency officials. Appendices are provided which give more detail on some of the more technical approaches identified in the literature review.

2.0 Conceptual Model of the Highway System

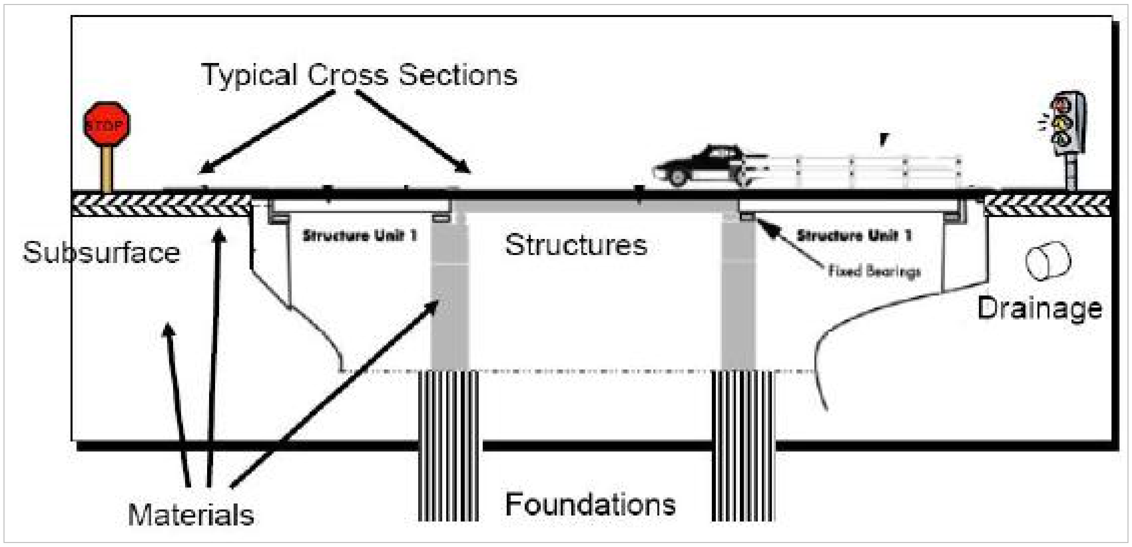
Prior to examining the probable impacts of climate change factors on highways (and opportunities for potential adaptation strategies), it is important to define what is meant by the highway system. A conceptual framework of the system will help guide future research tasks, as well as possibly lead to a way of organizing the research results so as to be most useful to transportation practitioners. The idea of a highway-related conceptual framework for climate adaptation is not new. This approach was used in the writing of the resource paper for TRB Special Report 290 in which the conceptual framework shown in Figure 2-1 was used to target potential components of road infrastructure design that could be affected by changes in environmental conditions (National Research Council, 2003). This conceptualization was the basis for a matrix that then indicated expected changes in environmental conditions and the influence on the design of the road network.

Although the concept shown in Figure 2-1 will be useful for this research, it clearly needs to be expanded to include more than just a road segment and more than an interest in design since most of the highway system that will serve the next few generations is already built (and showing its age), and network level land use patterns largely set. For example, the intermodal connections that the road network serves are an integral part of the transportation system that helps sustain our society and a more “network-oriented” concept of the highway system is essential for conceptualizing this. One also needs to look beyond the road right-of-way in recognition of the fact that state DOTs are often involved in a range of activities (such as emergency response and environmental mitigation) that could be affected by changes in environmental conditions.

Perhaps most importantly, the range of state DOT activities that will be affected by such changes should be defined in a systematic and comprehensive way. We are not interested in just road design, but instead the transportation services essential for sustaining our society as we consider the full range of activities that constitute what a state DOT and other transportation agencies do to develop and manage a road network, including operational support and intermodal facilities.

For purposes of this report, three different frameworks are presented representing three scales of roadway design and operation. The first is shown in Figure 2-1 and represents a typical road segment. From the perspective of change in local environmental conditions due to changes in climate or weather, this representation is perhaps the most useful. However, as noted above, a much broader picture of the potential impacts of climate change on transportation services and agencies is needed. The second framework presented in this section expands the road segment to a corridor perspective, one that includes beyond the right-of-way concerns, such as wetland mitigation issues and emergency response. The third framework presents a network perspective, which expands the perspective even further to include system continuity of an already overtaxed and aging system as reflected in operations and maintenance policies, and from a physical network perspective the connections between the road network and other components of the transportation system, such as intermodal terminals and stations.

Figure 2-1: Assets of a Typical Road Segment [Meyer, 2008]



Source: National Research Council, 2003.

2.1 A “Typical” Road Segment[1]

There are several components and design issues that are common to most transportation facilities, including roads and highways, rail lines, runways, and transit facilities. There are five key components to the design of a typical road segment—subsurface/foundation conditions, materials specifications, structures, typical cross sections, and drainage/erosion. Each is discussed in the following paragraphs.

2.1.1 Subsurface Conditions

The stability of a built structure depends upon the soils on which it is built. Geotechnical engineers focus their attention on the properties of different soil types and their behavior given different design loadings (see, for example, Budhu, 2000 and Coduto, 1999). The expected behavior of soils influences directly the design of foundations and support structures for the infrastructure itself. Various stresses act upon soil, including geostatic, horizontal and shear stresses, as well as stress associated with the weight of structures built on the soil. The design of foundations for transportation facilities reflect the soil conditions, water table, dead weight of the structure, and forces that add to the dynamic loads being placed on the structure (Reese et al, 2006).

One of the important factors for subsurface design is the degree of saturation and expected soil behavior under saturated conditions. Changes in pore water pressure can have significant effects on the shear strength of soils, and in fact it is a change in soil shear strength that has caused many failures in ground slopes (e.g., mud slides). A good example of how subsurface conditions can affect design is the behavior of different soils under seismic forces and the resulting effects on built structures. The shifting or liquefaction of soils during a seismic event creates significant risks of

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[1] The following section relies on an upcoming article in the ASCE *Journal of Transportation Engineering*, Meyer, M. and B. Weigel, “Climate Change and Transportation Engineering: Preparing for a Sustainable Future,” forthcoming.

unstable soil conditions, and thus the destabilization of structures built on top of the soils. Seismic codes have been enacted in many regions of the world focused in particular on dealing with the changing characteristics of foundation conditions during such extreme events (National Research Council, 2003).

2.1.2 Materials Specifications

Transportation structures are constructed of materials selected for their performance under design loads and environmental conditions. Much of the original research in transportation during the 1940's and 1950's focused on improving the ability of materials to withstand the loads associated with transportation use while still remaining resilient in response to changes in environmental conditions. Transportation research engineers continue to improve the physical properties of both asphalt and concrete pavements. Pavements, as a transportation facility component, affect facility performance at a considerably large spatial scale and their performance can change dramatically given changing conditions, such as heavier vehicles, higher traffic volumes, more dramatic freeze-thaw cycles, or subgrade soil dynamics (saturation, erosion, etc.).

Construction materials have a significant influence on the design and performance of bridges as well. Steel, concrete, or timber bridges must each handle the dead weight and dynamic loads they will be subject to, and thus the strength and resiliency of the bridge materials become of paramount concern to the bridge engineer. In addition to the changing conditions mentioned above, the strength and protection of materials used in the design might have to be enhanced to account for expected wind loads, increased moisture or humidity (that could accelerate corrosion), and (for bridges located in coastal regions) more violent storm surges.

2.1.3 Cross Sections and Standard Dimensions

Given the complexity of designing a transportation facility, and of all the subcomponents that it consists of, engineers often identify typical sections that are applicable to much of a given design corridor. A typical longitudinal cross section for the road shown in Figure 1-1, for example, would show the depth of subgrade, pavement materials and thickness, width of lanes and shoulders, slopes of the paved surface, expected design of the area outside the paved surface, and other appurtenances that might be found in a uniform section of the road. As noted above, the type of pavement and design of the subgrade would reflect the environmental conditions found along the alignment. The slope of paved surface would be determined not only by the physical forces from the vehicles using the facility (e.g. superelevation), but also by the need to remove water from the paved surface. In areas where one would expect substantial precipitation, the slope of pavement might be slightly higher to remove water to the side of the road as soon as possible. Cross sections would also be developed for areas where designs would be different from the typical section, such as locations for culverts, special drainage needs, bridges, and other structures that would be close to the side of the road.

The design of each of the key components of the cross section usually reflects design standards that have been adopted by the owner of the facility, such as a transportation agency. Thus, one can often find design manuals with standards for lane and shoulder widths, transverse slopes, radii for road curvature, dimensions of barriers, merge and exit areas, culverts, drainage grates, signing, and pavement markings. Most of these standards are based on field or laboratory studies, many of which occurred decades earlier.

Design criteria are also associated with such things as the vertical clearance over waterways and other roads. For example, the U.S. Coast Guard establishes vertical clearance guidelines for bridges over waterways, with the vertical clearance dimensions depending on the type of navigation occurring on the river. One of the lessons learned from Hurricane Katrina was that the probabilistic vertical clearance designed into of many Gulf Coast bridges over water channels was too low to withstand the actual storm surge that went over the bridge deck and floated the decks off of their supports. The bridges have been rebuilt with a higher clearance over the water surface along with improved fasteners to the bridge piers.

2.1.4 Drainage and Erosion

Water is one of the most challenging factors to design for in transportation engineering. As noted above, saturated or near saturated soils can be a critical consideration in the design of a facility's substructure and foundations. In addition, runoff from impermeable surfaces such as bridge decks or road surfaces must be handled in a way that redirects water flows away from the facility itself, but which does not harm the surrounding environment. Standard designs for drainage systems, open channels, pipes, and culverts reflect the expected runoff or water flow that will occur given assumed magnitudes of storms. Something as simple as the design of a culvert entrance would be affected by the assumed surge of water that would flow through it with due consideration for consequences of exceedances and construction costs vs. failure risks.

For drainage considerations relating to highways, the AASHTO *Model Drainage Manual* (AASHTO, 2004b) provides the most accepted guidance.

2.1.5 Structures

In the context of this paper, structures will primarily refer to bridges. Consistent with the previous discussion on how engineers account for different physical forces when developing a design, civil engineering has a long history of research and practical experience with understanding how such forces act upon buildings and bridges (see Ellingwood et al, 2005 for an overview of how building codes have evolved over time in response to new types and degrees of structural loading). The engineering design process is based on understanding the likely loads or forces that will be applied to the structure (note the practice of assigning a factor that represents how important the bridge is) and developing a design that provides a level of resistance to these forces that will exceed expected loads. The current approach toward bridge design is to consider the inherent uncertainty in expected loads and resistance factors that a bridge will be exposed to, and thus probabilistic methods are used to incorporate such uncertainty. The primary focus of such an approach is to increase the reliability of the structure over its lifespan while considering the economic costs of failure vs. construction / rehab cost. AASHTO's most recent bridge design manual, the *LFRD Bridge Design Specifications* (AASHTO, 2004a) incorporates risk into the calculations of bridge design parameters, although the economic costs of failure are not totally considered.

Bridges over water present a special challenge to bridge engineers. According to AASHTO's *LFRD Bridge Design Specifications*, waterway crossings should be studied with respect to the following factors:

- Increases in flood water surface elevations caused by the bridge
- Changes in flood flow patterns and velocities in the channel and on the floodplain
- Location of hydraulic controls affecting flow under the structure or long-term stream stability
- Clearances between the flood water elevations and low sections of the superstructure to allow passage of ice and debris
- Need for protection of bridge foundations and stream channel bed and banks
- Evaluations of capital costs and flood hazards associated with the candidate bridge alternatives through risk assessment or risk analysis procedures.

As can be seen in this list, the assumed behavior of the water body below the bridge significantly affects how the design of the bridge proceeds.

The design of bridges in coastal areas has received renewed attention given the experience with Hurricane Katrina. According to a recent position paper of the Federal Highway Administration (FHWA, 2005), "in the coastal environment, design practice assumes that flood events would essentially behave in a manner similar to a riverine environment. However, bridge failure mechanisms associated with recent storm events have resulted in a reevaluation of these assumptions. The result is a need to differentiate how FHWA considers the state-of-practice to hydraulically design bridges in the coastal environment." As noted in the paper, the hurricane damage to the Gulf Coast bridges resulted primarily from the combination of storm surge and wave crests. However, most state DOT's assume a riverine environment when designing bridges, which assumes a 50-year storm event (this approach is codified in state drainage manuals, AASHTO drainage guidance, and in FHWA Floodplain regulations). The result of this assumed frequency of storm is that designs do not consider the effect of wave actions on the bridge. In other words, according to their own regulations and design guidelines, state DOTs can consider a storm surge, but not additional wave actions. As noted by the FHWA, "state DOTs find themselves in the position that their own regulations and guidelines do not permit them to consider alternative bridge design frequency criteria." The FHWA recommended that a 100-year design frequency be used for interstate, major structures and critical bridges that would consider a combination of wave and surge effects, as well as the likelihood of pressure scour during an overtopping event (water levels going over the structure). The consideration of a super flood frequency surge and wave action (that is, the 500-year design frequency) was also suggested. It was also recommended that risk and cost assessments be conducted. Note that the marginal costs of additional safety factors must also be kept in mind.

Long-span bridges, especially over water, present a special challenge in two respects. First, very long bridges have to account for wind forces, which can be quite substantial in areas where the topography results in a "canyon effect," that is, high hills or cliffs that concentrate and thus make more powerful the winds striking the bridge. For suspension or cable-stayed bridges, these wind forces must be accounted for in the design strength of the support structure and in the level of deflection or flexibility designed into the bridge itself (Simiu and Scanlan, 1996). For long-span bridges, engineers conduct wind tunnel tests of different sections of a proposed design to assess section behavior under varying wind conditions.

Second, columns or piers that are located in water are subject to scour, that is, the erosion of the river or stream bed near the column foundation. The majority of bridge failures in the United States are the result of scour (AASHTO, 2004a) in that the flow of water currents at the column base can erode the stability of the column foundation. The FHWA requires that bridge owners evaluate bridges for potential scour associated with the 100-year event (known as the base flood) and to check scour effects for the 500-year event (known as the superflood). If floods or storm surges were expected to occur more frequently or channel flows were to become more turbulent, one would potentially have to rethink the design of such foundations (Sturm, 2001).

The above description of the different components of a typical roadway segment does not cover all of the different considerations that would enter into the design thought process of the engineer. However, it does illustrate the important influence of standards and guidelines in the design process in response to expected environmental factors. In addition, the discussion suggests some of the design categories in response to changes in these environmental conditions, and in particular those related to climate change, and their implications as to how engineers should design a transportation facility. How this relates to likely climate change impacts on the highway system will be discussed later.

2.2 A Corridor Perspective

The potential impacts of changing environmental conditions due to climate change on a typical road segment would of course accumulate over a corridor and throughout the network where similar circumstances exist. Thus, if subsurfaces are affected because of changes in soil moisture in one location, there is a strong possibility that this effect will be found in many other parts of a network, or certainly within a corridor (where similar soil conditions could be expected). Figure 2-2 illustrates other types of concerns that might be found within a road corridor over and above those related to specific design components. Most of these concerns relate to either maintenance practices or environmental mitigation and/or avoidance strategies.

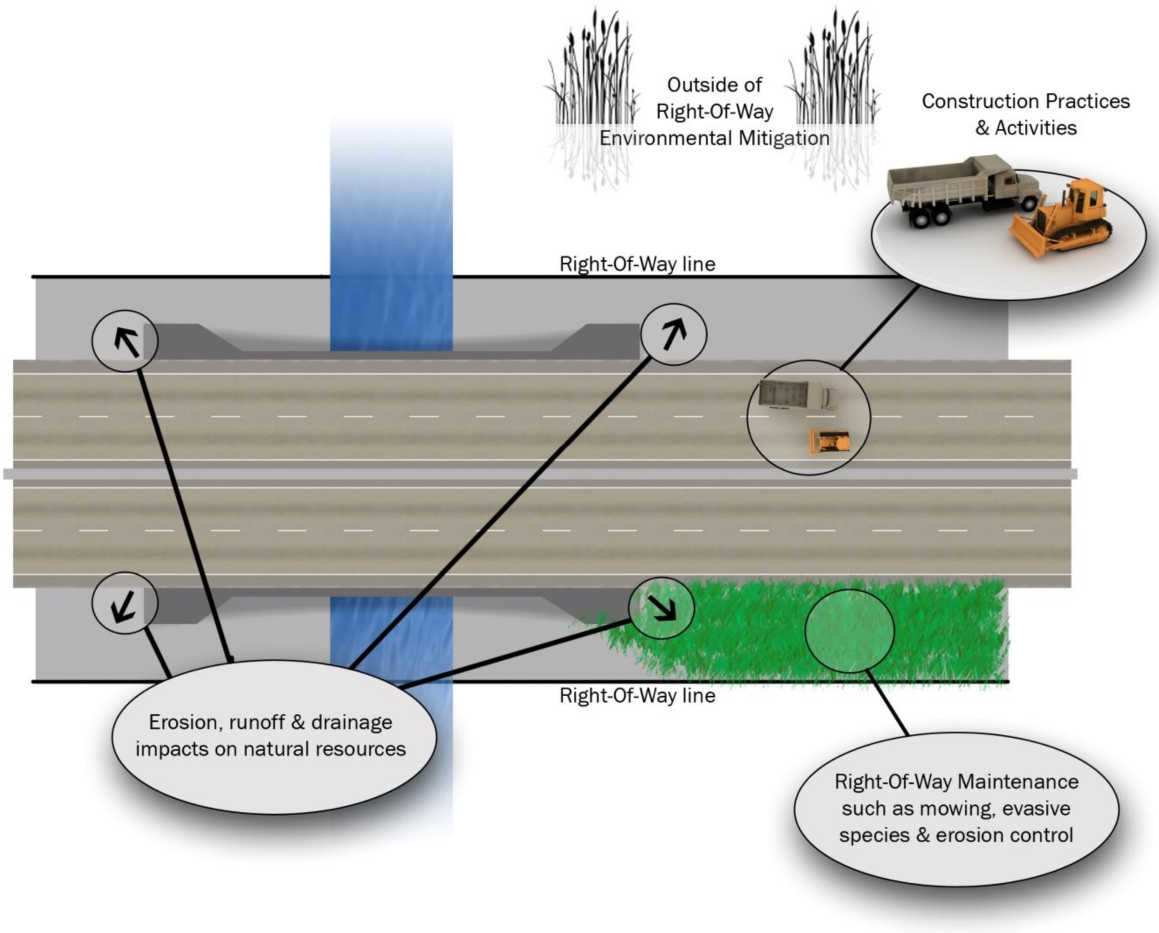
2.2.1 Outside-of-Right-of-Way Environmental Mitigation

Many transportation agencies have developed environmental mitigation programs that focus on replacement assets outside of a corridor’s right-of-way. An example of this includes the concept of wetland banking for wetlands that are disturbed as part of a construction process. With changing environmental conditions due to long-term climate change, the ability to develop ecologically sound and functionally replicating ecological mitigation strategies could be seriously hindered. The State of Washington DOT is currently taking into account projected sea level rise when identifying wetland mitigation sites as many of the previous wetland mitigation sites have been located in estuaries that are likely to be impacted by sea level rise.

2.2.2 Erosion, Drainage and Runoff Impacts

Changes in precipitation, both overall levels and rainfall intensities, are considered one of the major changes likely to be experienced in the future. The design implications of these changes to such things as culverts and road-related drainage systems were discussed in the previous section. The impact noted here is the likelihood of increased runoff and erosion impacts on surrounding land uses and ecological resources. Increased runoff, with higher volumes and perhaps higher intensities, could have significant impacts on nearby water bodies, such as streams and rivers. Such a possibility might require new means of handling erosion and runoff, primarily by reducing volumes or diverting flows away from sensitive areas.

Figure 2-2: Corridor-Level Impacts of Changing Local Environmental Conditions



2.2.3 Right-of-Way Maintenance

Studies overseas have identified changing right-of-way maintenance operations as one of the potentially important impacts of changes in climate on transportation agency practices. These impacts could relate to changes in growing season (and thus more or less mowing), invasive species infestation, snow removal, and flooding caused by backed up drainage systems. Synergistic effects of climate change such as unseasonable freezing rain on trees already weakened by increased predation from invasive species could contribute to widespread power outages and road closures in the wake of storm events. It will be difficult to predict a specific point in time when such issues might become a serious concern to a transportation agency. More likely, changes in maintenance practices will be phased in as “emergencies” become more “routine”, and it becomes apparent that current approaches are no longer meeting the needs of the highway system.

2.2.4 Construction Practices and Activities

Changes in temperature and precipitation and the corresponding need to utilize different construction materials could affect construction practice. In addition, a lengthening or shortening of the construction season could also influence a transportation agency’s construction program. Transportation agency adaptation plans from overseas identify an increasing frequency of more intense storms as affecting construction costs and scheduling, as well as the need to provide improved training to construction workers who might have to work more often in inclement weather.

2.3 A Network Perspective

The final perspective on potential climate change impacts on the highway system relate to the overall management of the highway network, including building and protecting the agency’s assets as well as developing system management strategies for expected disruptions (see Figure 2-3).

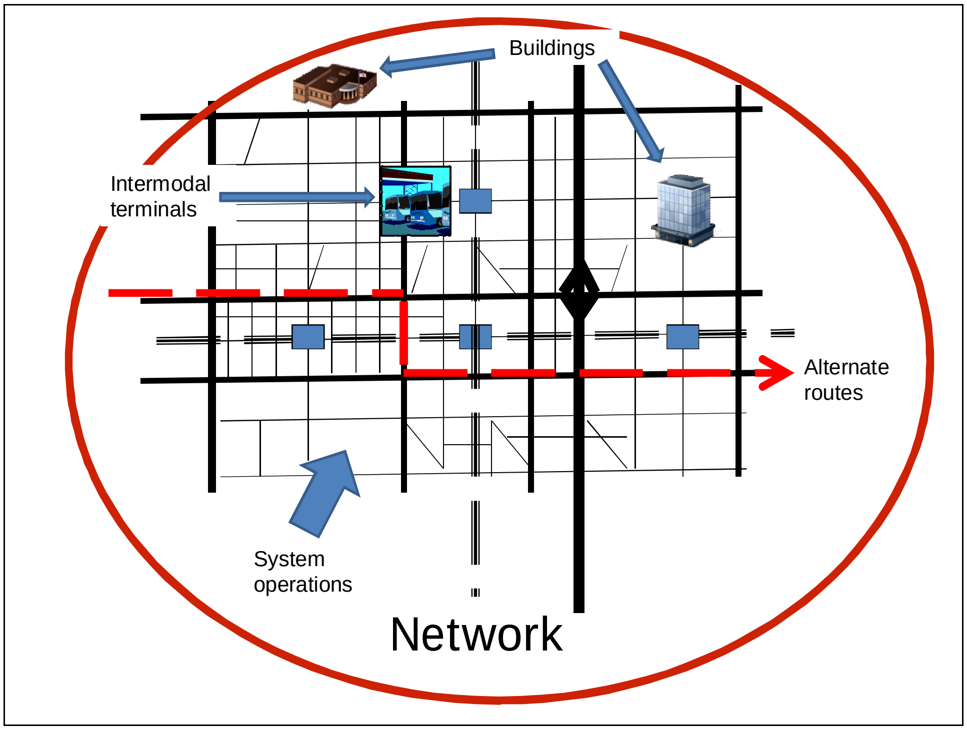
2.3.1 Alternate Routes and Corresponding System Operations Strategies

One of the likely characteristics of future weather conditions is more intense storms (or extreme events as they are called in the literature) and a corresponding disruption to the highway network. The impacts of Hurricane Katrina on all aspects of the region’s transportation network, including highways, transit facilities/services, airports, ports, and freight terminals have been well documented. Responses to events such as this will require strategic and coordinated response plans to deal with not only the immediate aftermath, but also help speed the recovery process. In metropolitan areas, in particular, where traffic management centers have been established to coordinate and guide traffic flows, it is likely that such centers will be used more frequently to respond to weather-related events and that improved emergency response systems including 511 Traveler Information systems be developed and deployed as part of an overall “Adaptive Management” strategy..

2.3.2 Intermodal Connections

Although this project is focused on the “highway system,” in reality today’s transportation system consists of interconnections among different modes serving a variety of purposes. Examples of such interconnections include intermodal passenger and freight terminals, park and ride lots, access roads to freight intermodal facilities, and pedestrian/bicycle facilities connecting to transportation stations or terminals. Even though a transportation agency might not have jurisdiction over intermodal facilities, it makes sense for someone to view the facility and the access to the facility as one part of a larger system. Strategies to protect road access should be combined with strategies to protect the facility itself and maintain vital transportation services in this “just in time delivery” economy.

Figure 2-3: Network-Level Impacts of Changing Local Environmental Conditions



2.3.3 Location Engineering (where to put the facility to begin with)

Designs for new or relocated transportation facilities always include location studies to determine where to build the facility. Such efforts are often associated with much broader environmental impact analyses that examine a range of alternative alignments and design characteristics. Location studies themselves often do not have specific design criteria associated with where facilities will be located, although factors such as right-of-way width, roadway curve radii, and vertical slope limitations for different types of facilities will constrain designs to certain design footprints. In addition, as part of environmental analyses, a fatal flaw analysis often identifies areas or sites so environmentally sensitive that the designer will stay clear of these locations. The important question with respect to transportation facility location studies is how areas that might be susceptible to climate change effects, such as coastal or low-lying areas might be evaluated for suitability.

2.3.4 Building and Protecting Agency Assets

Transportation agencies are often owners of a substantial number of buildings, shelters, and other physical assets used by employees in the day-to-day operations of the agency. Although such assets are not often considered in most adaptation studies, which tend to focus on the transportation network itself, agency managers will have to deal with managing such assets with changing local environmental conditions. This could mean strategies ranging from enhanced protection from wider temperature ranges to protection from inundation. It is likely that as climate and weather conditions change, the building industry will change with it, including the use of innovative materials to better handle new loads and stresses on the structures. So, in such cases, these changes will be incorporated into building and materials specifications. However, especially in the case of state transportation agencies, which have buildings spread out over an entire state, the need to be cognizant of changing local environmental conditions and their potential impact on the agency's assets could be an important concern to future managers.

2.4 Summary

This section has presented a multi-level perspective on potential impacts of climate change on the "built" and "yet to be built" highway system. Each level examines a particular scale of application, and in many ways can be viewed as adding a more complex and strategic management role. For example, many of the design changes that might be necessary at the typical road segment level can be incorporated into design standards and agency standard operating procedures. However, dealing with system-wide operations strategies or a more comprehensive management of an agency's physical assets would imply a higher level of management involvement to deal with an already built, increasingly congested, and aging system.

The following sections identify in more detail some of the changes in climate that could affect the highway system and potential strategies in response. The next section then presents the results of a literature review and telephone survey of adaptation practice.

3.0 Review of Key Climate Impacts to the Highway System

The future functionality, operations, and look of the highway system in the U.S. will be impacted by many factors including demographic shifts, changes in land use patterns, new technology, and, of course, climate change. This section examines some of the important factors driving the future of the nation's highway system, with special focus on changes in climate that could affect how we plan, design, construct, operate and maintain that system.

3.1 The Future Highway System: Demographic and Technological Drivers

The U.S. highway system serves a primary role in moving people and goods throughout the country, and as the U.S. population grows, so will the need for transportation. By mid-century, the U.S. population is expected to grow by more than 40 percent over 2008 estimates, reaching a total population of more than 439 million people. Maybe more importantly from the perspective of potential impacts to the highway system is where this increased population will be located.

Population growth is expected to be very high on both coasts, in the southeast and in the southwest, two regions that are anticipated to experience some of the most severe impacts of climate change in the coming decades. Of course the extent to which the highway system is impacted depends not only on the number of people, but also how they are distributed throughout the region.

There is still considerable debate over how development will occur in the coming decades. Housing developments over the past couple decades have predominantly been in low-density suburban areas. However, as the composition of population changes, many reports point to trends in housing development that suggest a turn to more compact urban development. Transportation infrastructure is already in place for urban development, while low-density developments typically require transportation infrastructure to be built to connect these areas, often a high-cost strategy. Regardless of how land use patterns develop in the coming decades, there is little debate that the nation is going to grow and that the highway system will need to accommodate such growth.

The demographic and technology changes that will likely affect the future performance of the nation's highway system were described in detail in the Task 1.2 report, *Technical Memorandum Review of Climate Drivers and Key Climate Impacts to the Highway System*, and thus will not be repeated here. However, the Task 1.2 report did summarize its findings as follows:

- Message 1: The U.S. population will continue to grow with most of this growth occurring in urban areas, and in parts of the country expecting notable changes in climate.
- Message 2: The composition of this population will be very different than it is today, with more diverse populations and more elderly individuals in the nation's population mix.
- Message 3: Significant levels of housing and corresponding development will be necessary to provide places to live and work for this population, with much of this development likely to occur in areas subject to changing environmental conditions.
- Message 4: Increasing population growth will create new demands for transportation infrastructure and services, once again in areas that are vulnerable to changing climate conditions.

- Message 5: The nation's highway system will be facing increasing demands for reconstruction and rehabilitation over the next 40 years (to 2050), which provides an opportunity to incorporate climate adaptation strategies into such efforts, if appropriate.
- Message 6: New vehicle, fuel and system management technologies will likely be more widely used in 2050 than they are today, but the net effect of such technologies will be to make travel easier and more environmentally benign. This along with increasing travel demand will result in higher levels of vehicle miles traveled.

3.2 Potential Climate Impacts to the Highway System

By 2050, the highway system in the U.S. will likely look very different than it does now. Existing highways will be rehabilitated and reconstructed, new links in the National Highway System will expand its spatial reach, potential changes in vehicle fuels might necessitate extensive new supporting infrastructure, and solutions to urban congestion could change how many highways function. And, of course, environmental considerations such as climate change could be beginning to create significant challenges for transportation agencies.

This research analyzed a wide range of possible changes in climate. These included a high, middle and low GHG emissions scenario. The high scenario (A1FI from the IPCC Special Report on Emissions Scenarios (SRES); Nakićenovic et al., 2000), assumes very high rates of growth in global income, moderate population growth, and very high fossil fuel use. The middle scenario (A1B) has the same economic and population assumptions as the A1FI scenario, but assumes more use of low carbon emitting power sources and clean technologies. Finally, the low scenario (B1) has the same population growth as the other two, but assumes a more service oriented economy and much more use of low carbon emitting power sources and clean technologies. (Note that by about the second half of this century, even the low scenario would likely exceed the 2°C target for limiting climate change that has been widely agreed to by many nations including the United States.)

Climate sensitivity is how much average global temperatures will rise with a doubling of carbon dioxide (CO_2) levels in the atmosphere. It is a measure of how sensitive the Earth's climate is to a change in greenhouse gas concentrations. Three climate sensitivities: 1.5, 3.0, and 4.5°C were selected to capture a wide range of potential responses of the Earth's climate to increased greenhouse gas concentrations. Finally, 10 climate models were used to best simulate the current U.S. climate (see the Task 2.4 report for a more detailed discussion of these models). These models gave a wide range of projected changes in climate, particularly at the regional scale.

Table 3.1 shows the projections of temperature and precipitation changes that were developed during this research. The projections of change in temperature and precipitation in the table are an estimate of *average* change for the mainland United States. As discussed below, specific results will vary by location. Readers should not use these results to estimate impacts in specific locations.

3.2.1 Key Projection Results

There are many aspects of climate change that will be important for the U.S. transportation system. Some major changes for the nation as a whole are that temperatures will rise, minimum temperatures are projected to increase more than maximum temperatures, sea level will continue to rise and most likely the rate of rise will accelerate, precipitation levels on average will increase, precipitation intensity will increase, and intensity of the strongest hurricanes is projected to increase. These and other climate change consequences are briefly discussed below (see the Task 2.4 Technical Memorandum for more detailed maps and regional projections).

Temperature

Increasing greenhouse gas emissions are projected to increase temperatures across the United States (see Figure 3-1). On average, temperatures are projected to increase 1.6°C (about 3°F) by 2050 relative to current climate (about 2010).[2] While all regions in the United States are projected to have a significant increase in temperature, the amounts will vary by location and season. In general, areas farther inland will warm more than areas near the coast. That is because oceans warm more slowly than land and the relatively cooler oceans will moderate the warming over land near the oceans. In addition, northern areas will warm more than southern areas. Snow and ice reflect sunlight and lead to cooler temperatures, whereas exposed land absorbs sunlight which allows for a more rapid increase in temperatures. As snow and ice become less frequent from higher temperatures, less land is covered by snow and ice, resulting in more warming. This amplifies warming in northern (higher latitude) areas. The models tend to show summer temperatures increasing more than winter temperatures, particularly in northern areas. This is mainly due to projected increases in winter precipitation, but limited change or decreases in summer precipitation. Generally, increased precipitation means more clouds and less warming, while less precipitation means fewer clouds and more warming.

Since average temperatures will increase, so will daily high temperatures. However, daily low temperatures are in general projected to rise faster than daily high temperatures (Meehl et al., 2007).

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[2] Changes in temperature in precipitation are based on MAGICC/SCENGEN's estimation of climate in 2050 compared to the model's estimation of climate in 2010, not compared to observed conditions.

Table 3.1: Key Climate Change Drivers Relevant for Transportation Systems, 2040-2060 Relative to Current Climate (ca. 2010)[3]

	Climatic/ Weather Change	Intensity of Impact	Regions of the United States
Temperature	Change in temperature	Models project an average increase in temperature for the continental United States of 1.6°C (2.9°F) from 2010 to 2050 (range is from 0.3 to 3.8°C (0.5 to 6.9°F).	Temperature is projected to increase over entire United States, but relative increases will be higher in the north and in inland areas.
	Change in range of maximum and minimum temperatures	On average, minimum temperatures are projected to increase more than maximum temperatures.	This will happen across the United States.
Precipitation	Overall changes in precipitation levels	On average, U.S. precipitation is projected to increase 2.3% from 2010 to 2050, but model results vary widely, ranging from –11 to +10%.	The Midwest and Northeast are likely to see increased precipitation, while the Southwest is projected to face a decrease in precipitation.
	Precipitation changes by season	On average, U.S. precipitation is projected to increase 2.4% in the winter from 2010 to 2050, but model results vary widely, ranging from –10 to +15%. Summer precipitation is projected to decrease 1.6%, with model results ranging from +15 to –21%.	Northern areas are more likely to face increased winter precipitation. All areas are likely to see a decrease or no change in summer precipitation, although increases in some areas are possible.
	Increased intense precipitation and other changes in storm intensity (except hurricanes).	The most intense storms will likely increase. The increase in intensity is projected to be 7%/°C (4%/°F).	The increases will likely be greater in northern than southern areas.
Sea level rise	Sea level rise	Sea level is projected to rise 0.5-2 feet by 2050; the most likely increase is about 10 inches; 100-year and 500-year storm expected flood heights would increase accordingly.	Need to account for local subsidence or uplift. Examples of such rates are (negative is uplift offsetting sea level rise, positive I> that is > 3 is subsidence ; all measures in mm/yr): San Francisco: 0.21; Los Angeles: -0.97; Grand Isle, LA: 7.44; Charleston, SC: 1.35; Boston, MA: 0.83.
Hurricanes	Increased hurricane intensity	The total number of hurricanes could decrease. The intensity of the strongest storms (Categories 4 and 5) are projected to increase.	The Gulf Coast and Atlantic Coast along southern states. Storm tracks could move northward in the Atlantic.

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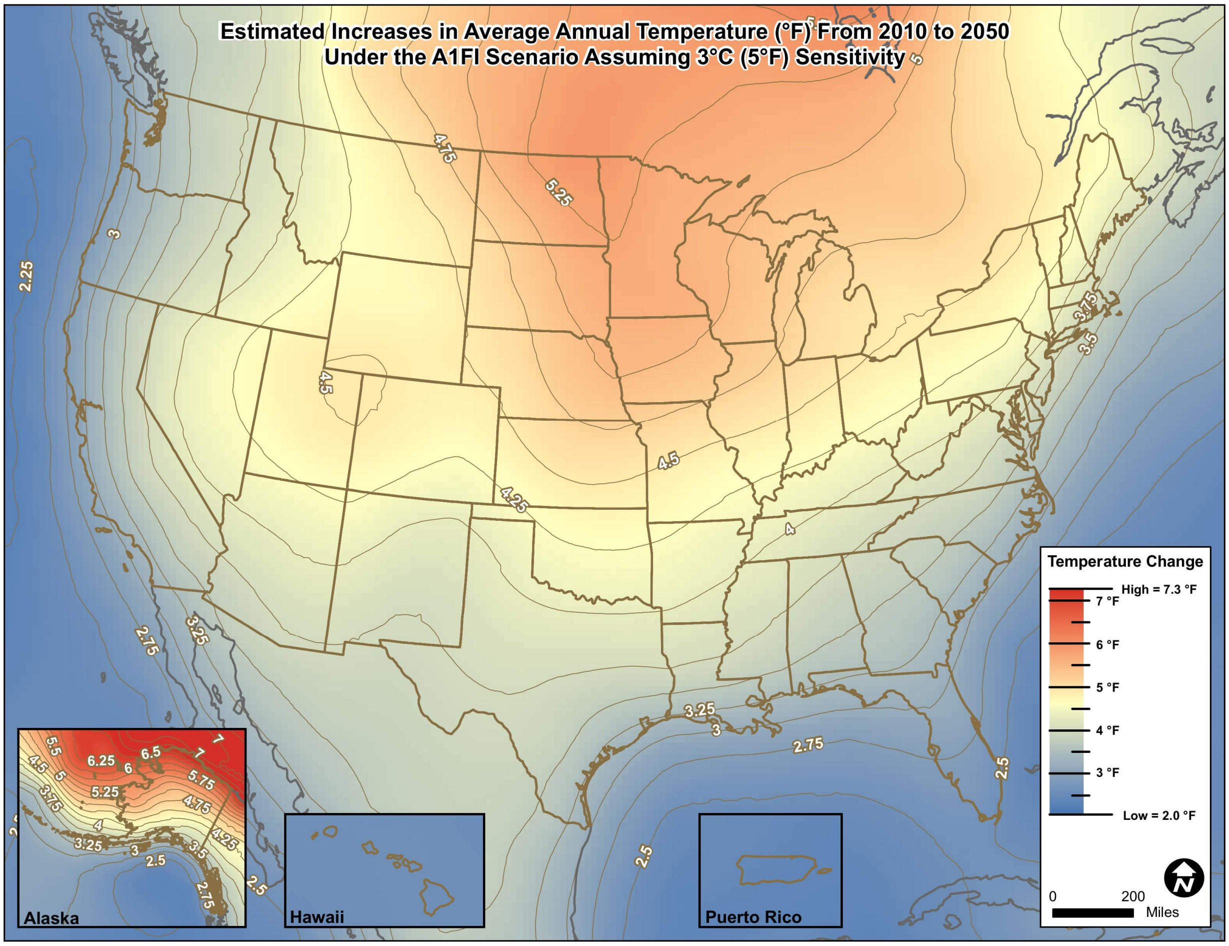
[3] The changes in temperature and precipitation are calculated using MAGICC/SCENGEN, are for 2050 relative to 2010 as simulated by M/S.

Figure 3-1: Estimated Increases in Average Annual Temperature (°F) From 2010 to 2050 Under the A1FI Scenario Assuming 3°C (5°F) Sensitivity



Note:This figure presents change in temperature across the United States. It is based on output from MAGICC/SCENGEN, which reports data in 2.5° grid boxes. Each grid box is approximately 150 miles across and contains an average change in temperature for the entire grid box. The data are interpolated and smoothed to make them more presentable. Since the data are smoothed, transitions between different changes in temperature should not be taken as being exact model output. Note that this map is only intended to provide a broad-brush overview of potential changes: see the Task 2.4 Technical Memorandum for more detailed maps useful for referencing data on particular regions and locations.

It is also likely that there will be longer periods of extreme heat in summer. For example, there will be more days exceeding 90°F (32°C) (Karl et al., 2009). It is possible that high pressure systems will become more intense, making heat waves hotter and last longer. During heat waves, it is also possible that maximum temperatures will increase more than minimum temperatures.

Higher temperatures will have a number of important consequences that will affect transportation. Among them:

- More precipitation will fall as rain instead of snow. With warmer temperatures, the period during which precipitation falls as snow will decrease, with more time in the fall and spring during which precipitation will fall as rain.

- Snowpacks will generally become thinner and cover a smaller spatial extent because the time of year during which precipitation falls as snow will decrease. However, as noted below, winter precipitation may increase in many areas. How the combination of a shorter season and more intense winter precipitation nets out in terms of total snowpack is currently uncertain. Generally, snowpacks in the western United States have been decreasing (Mote et al., 2005). Lower latitude and lower elevation areas are more likely to see a reduction in snowpack.
- Higher temperatures already are and will continue to cause snowpack to melt off earlier in the year. This will likely make peak runoff (and flooding) from snowmelt happen earlier in the year.
- Extreme cold temperatures will moderate. There will most likely be fewer days below freezing and deep freezes will not be as cold.
- The total number of days with frost is projected to decrease (Tebaldi et al., 2006), although freeze/thaw cycles could increase in some areas such as in the north (Karl et al., 2009).

Precipitation

Generally, precipitation over the United States is projected to increase. This is because as the atmosphere warms, it can hold more water vapor and more water vapor causes more precipitation. The models on average project precipitation over the United States to increase 2% from current conditions (approximately 2010) by 2050 (see Figure 3-2).

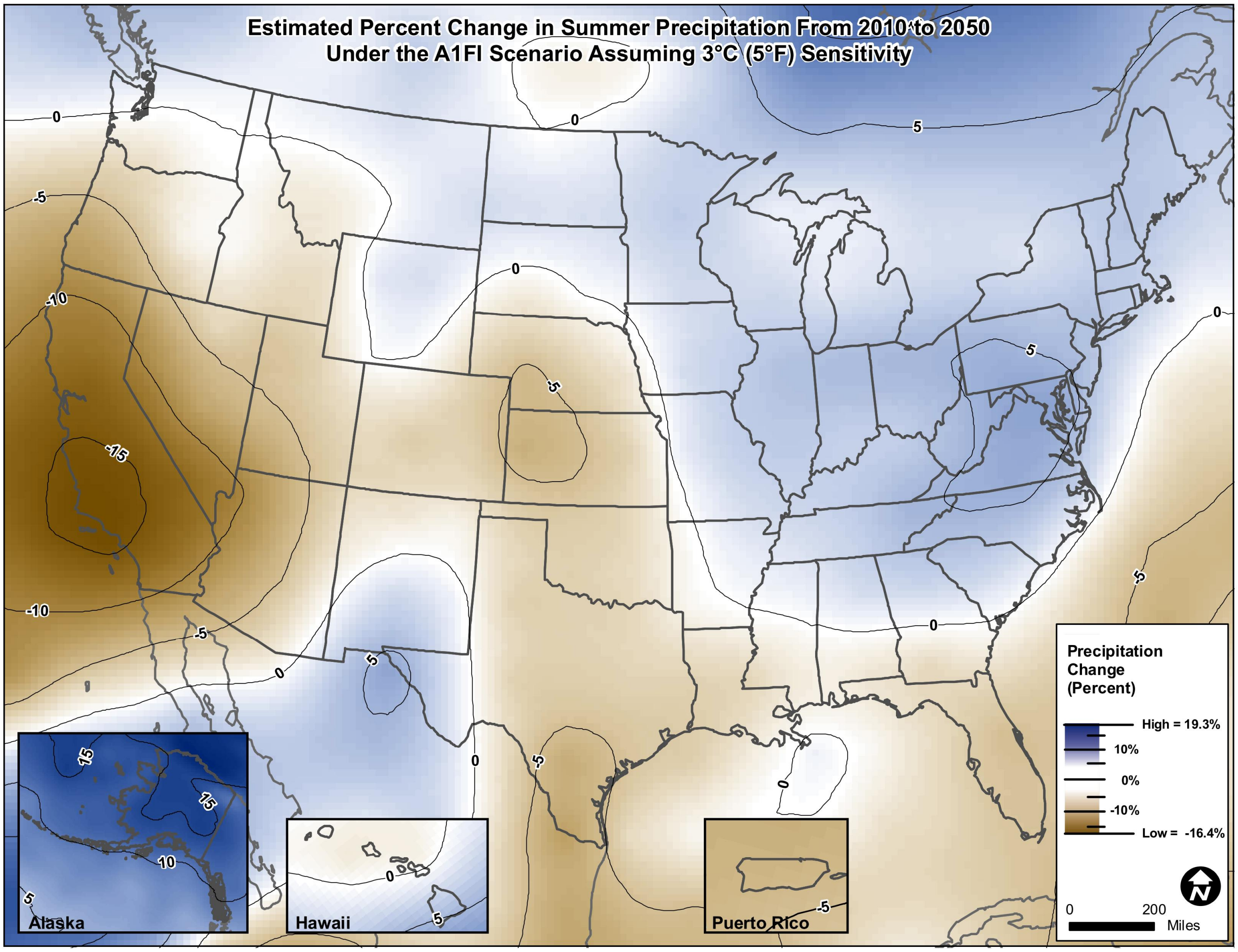
As with temperatures, how precipitation changes on average will vary by season and location. Unlike temperature, precipitation is projected to decrease in some areas and increase in others. In general, winter precipitation is projected to increase, while summer precipitation is projected to either not change or decrease (Solomon et al., 2007). It is possible, but not certain, that there could be an increase in summer precipitation along the East Coast.

The winter precipitation increase is likely to be more pronounced in northern areas than in southern parts of the United States. This is partly the result of the jet stream being projected to move northward steering storm systems in this direction. The IPCC projects a decrease in winter precipitation in the southwestern United States. The increase in winter precipitation in the north and spring runoff could lead to increased flooding when the snowpack melts. The Midwest and Northeast are projected to have the largest increases in runoff in the United States.

While the models tend to project a decrease or no change in summer precipitation, this result should be interpreted with caution. Convective precipitation such as thunderstorms is an important component of summer precipitation. These storms form on a small spatial scale and the climate models have difficulty simulating such events. Thus, one cannot rule out increases in such events, which could increase summer runoff at least in some locations.

However, increased drought in the summer is also quite possible because of higher temperatures, fewer days with precipitation, and summer precipitation either being reduced or not changing much in many locations. Changes in year-to-year variability are uncertain, but interannual variability can increase.

Figure 3-2: Estimated Percent Change in Precipitation From 2010 to 2050 Under the A1FI Scenario Assuming 3°C (5°F) Sensitivity



Note:This figure presents change in precipitation across the United States. It is based on output from MAGICC/SCENGEN, which reports data in 2.5° grid boxes. Each grid box is approximately 150 miles across and contains an average change in precipitation for the entire grid box. The data are interpolated and smoothed to make them more presentable. Since the data are smoothed, transitions between different changes in precipitation should not be taken as being exact model output. Note that this map is only intended to provide a broad-brush overview of potential changes: see the Task 2.4 Technical Memorandum for more detailed maps useful for referencing data on particular regions and locations.

The intensity of precipitation events is already increasing as a result of higher temperatures and is very likely to increase more with continued warming. This is the result of the atmosphere holding more water vapor with higher temperatures. Precipitation observations show that small precipitation events have increased only slightly, but larger events have increased at a faster rate.

While total precipitation is projected to increase a few percent by 2050, the intensity of precipitation is projected to increase by a greater percentage. The number of days with precipitation is projected to decrease, meaning those days that have precipitation will have more precipitation per day. Precipitation intensity is projected to increase 7% for every degree Celsius increase (approximately 4% for each degree Fahrenheit increase; Trenberth et al., 2003). So, with a projected 1.6°C projected increase in average temperature by 2050 relative to 2010, average precipitation intensity would increase by about 11%. The increase in precipitation intensity is projected to be greatest in the Midwest and Northeast (Karl et al., 2009). More intense rain events could increase local stream flow, flooding, erosion of hillsides through mudslides, or dislodging of boulders, while more intense snow events can also lead to more peak runoff.

Sea Level

Global sea levels have been increasing because of higher temperatures. The higher temperatures cause oceans to expand. In addition, they cause melting of glaciers, which further raises sea levels. Sea levels rose about 1.5 to 2 mm per year over the 20th century, but since the early 1990s have been rising 3 mm per year.

Projections of future sea level rise vary widely. The IPCC projected that sea level will rise 0.2 to 0.6 m (6 inches to 2 feet) by 2100 relative to 1990. But this projection only partially accounted for potentially significant melting of major ice sheets in Greenland and West Antarctica. Each ice sheet contains enough water to raise sea levels 7 m (23 ft), but it would take centuries to millennia for that amount of sea level rise to happen even with destabilizing of these ice sheets. Nonetheless, several studies published since the IPCC report estimate that sea level could rise 1.5 to 2 m (5 to 6.5 ft) by 2100 (Rahmstorf, 2006; Pfeffer et al., 2008). Pfeffer et al. (2008) conclude that the most likely rate of sea level rise by 2100 is 0.8 m (2.6 ft) relative to 1990. Using MAGICC, we estimated that a scenario yielding a 0.8 meter sea level rise by 2100 would have 25 cm (10 inches) of sea level rise by 2050 relative to 1990.

The sea level that is realized at any coastal location is affected by local subsidence and uplift. Some U.S. coastal areas, particularly near the Mississippi River, are subsiding. That makes “relative sea level rise” greater than “eustatic” sea level rise (i.e., the projections discussed above). Parts of Louisiana, for example, are subsiding at a rate of almost 1 m (3 ft) per century. On the other hand, some coastal areas of the United States are rising (uplift), making realized sea level change less than the global average.

Continued and accelerated sea level rise will have a number of important consequences, including:

- Inundation of low-lying coastal areas.
- More coastal erosion from the combined effects of higher sea levels and more intense storms.
- Higher storm surges from the combined effects of higher sea levels and more intense hurricanes (see below).
- In Alaska, coastal erosion is resulting from storm activity and wave action eroding shorelines once protected by shore-fast sea ice.
- Loss of coastal habitats such as wetlands.
- Encroachment of saltwater on freshwater sources and ecosystem.

Hurricanes and Other Extreme Events

While the total number of hurricanes may not change or could even decrease, the intensity of the most powerful hurricanes (Categories 4 and 5) is projected to increase (Bender et al., 2010). Increased hurricane intensity will result in higher wind speeds, which will cause more destruction on land and will increase the height of storm surges. As noted above, this will be in addition to higher sea levels. Higher storm surges would flood more unprotected coastal areas. In addition, more intense hurricanes will increase total precipitation from hurricanes, which will affect flooding in low-lying areas (Knutson and Tuleya, 2008). Coastal erosion could also increase.

Climate change has been linked with an increase in forest fires in the western United States (Westerling et al., 2006). Such fires are likely to increase in the future in the West. In addition, forests have become more susceptible to insect outbreaks (e.g., Kurz et al., 2008). Fire and forests weakened by insects or drought can present risks to travel.

Hotter summers, combined with a decrease or even no change in precipitation, can result in reduced river and lake levels and increased drought. This could adversely affect inland navigation. Drought can also cause more cracking of soils.

3.3 Impacts on Highway Infrastructure and Operations

In this section, we first review the range of climate impacts on infrastructure and operation/ maintenance activities that may require adaptation. These are identified in Table 3.2 and discussed in further detail in the following sub-sections. We then discuss the impact of climate changes on ecological conditions; planning, design and construction; and ecological mitigation. Finally, we provide an introduction to the implications that adapting to these changes will have for planning, design, and construction.

Table 3.2: Summary Table of Climate Impacts on Highway System

	Climatic/ Weather Change	Impact to Infrastructure	Impact to Operations/ Maintenance
Temperature	Change in extreme maximum temperature	• premature deterioration of infrastructure; • damage to roads from buckling and rutting; • bridges subject to extra stresses through thermal expansion and increased movement.	• safety concerns for highway workers limiting construction activities; • thermal expansion of bridge joints, adversely affecting bridge operations and increasing maintenance costs; • vehicle overheating and increased risk of tire bow-outs; • rising transportation costs (increase need for refrigeration); • materials and load restrictions can limit transportation operations; • closure of roads because of increased wildfires
	Change in range of maximum and minimum temperatures	• fewer days with snow and ice on roadways; • reduced frost heave and road damage; • structures will freeze later and thaw earlier with shorter freeze season lengths • increased freeze-thaw conditions creating frost heaves and potholes on road and bridge surfaces; • permafrost thawing leads to increased slope instability, landslides and shoreline erosion damaging roads and bridges due to foundation settlement (bridges and large culverts are particularly sensitive to movement caused by thawing permafrost); • hotter summers in Alaska lead to increased glacial melting and longer periods of high stream flows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments.	• decrease in frozen precipitation would improve mobility and safety of travel through reduced winter hazards, reduce snow and ice removal costs, decrease need for winter road maintenance, result in less pollution from road salt, and decrease corrosion of infrastructure and vehicles; • longer road construction season in colder locations. • vehicle load restrictions in place on roads to minimize structural damage due to subsidence and the loss of bearing capacity during spring thaw period (restrictions likely to expand in areas with shorter winters but longer thaw seasons); • roadways built on permafrost likely to be damaged due to lateral spreading and settlement of road embankments; • shorter season for ice roads.

Table 3.2: Summary Table of Climate Impacts on Highway System (continued)

	Climatic/ Weather Change	Impact to Infrastructure	Impact to Operations/ Maintenance
Precipitation	Greater changes in precipitation levels	• if more precipitation falls as rain rather than snow in winter and spring, there will be an increased risk of landslides, slope failures, and floods from the runoff, causing road washouts and closures as well as the need for road repair and reconstruction; • increasing precipitation could lead to soil moisture levels becoming too high (structural integrity of roads, bridges, and tunnels could be compromised leading to accelerated deterioration); • less rain available to dilute surface salt may cause steel reinforcing in concrete structures to corrode; • road embankments at risk of subsidence/heave	• Regions with more precipitation could see increased weather-related accidents, delays, and traffic disruptions (loss of life and property, increased safety risks, increased risks of hazardous cargo accidents); • closure of roadways and underground tunnels due to flooding and mudslides in areas deforested by wildfires; • increased wildfires during droughts could threaten roads directly, or cause road closures due to fire threat or reduced visibility
	Increased intense precipitation, other change in storm intensity (except hurricanes)	• heavy winter rain with accompanying mudslides can damage roads (washouts and undercutting) which could lead to permanent road closures; • heavy precipitation and increased runoff are likely to cause significant flood damage to tunnels, culverts, roads in or near flood zones, and coastal highways; • bridges are more prone to extreme wind events and scouring from higher stream runoff; • bridges, signs, overhead cables, tall structures at risk from increased wind speeds	• the number of road closures due to flooding and washouts will rise; • severe erosion at road construction project sites as heavy rain events take place more frequently; • road construction activities will be disrupted; • increase in weather-related highway accidents, delays, and traffic disruptions; • increase in landslides, closures or major disruptions of roads, emergency evacuations and travel delays; • increased wind speeds could result in loss of visibility from drifting snow, loss of vehicle stability/maneuverability, lane obstruction (debris), and treatment chemical dispersion; • lightning/electrical disturbance could disrupt transportation electronic infrastructure and signaling, pose risk to personnel, and delay maintenance activity

Table 3.2: Summary Table of Climate Impacts on Highway System (continued)

	Climatic/ Weather Change	Impact to Infrastructure	Impact to Operations/ Maintenance
Sea level rise	Sea level rise	• higher sea levels and storm surges will erode coastal road base and undermine bridge supports; • temporary and permanent flooding of roads and tunnels due to rising sea levels; • encroachment of saltwater leading to accelerated degradation of tunnels (reduced life expectancy, increased maintenance costs and potential for structural failure during extreme events); • loss of coastal wetlands and barrier islands will lead to further coastal erosion due to the loss of natural protection from wave action	• coastal road flooding and damage resulting from sea-level rise and storm surge; • underground tunnels and other low-lying infrastructure will experience more frequent and severe flooding; • increase in number of road accidents, evacuation route delays, and stranded motorists.
Hurricanes	Increased hurricane intensity	• stronger hurricanes with longer periods of intense precipitation, higher wind speeds, and higher storm surge and waves are projected to increase; • increased infrastructure damage and failure (highway and bridge decks being displaced)	• more frequent flooding of coastal roads; • more transportation interruptions (storm debris on roads can damage infrastructure and interrupt travel and shipments of goods); • more coastal evacuations

3.3.1 Temperature Changes

Change in Extreme Maximum Temperature

The literature points to a likely increase in very hot days and heat waves. As discussed in section 3.2, heat extremes and heat waves will continue to become more intense, longer lasting, and more frequent in most regions during the 21st century (NRC, 2008). Increasing periods of extreme heat will place additional stress on infrastructure, reducing service life and increasing maintenance needs.

Extreme maximum temperature and prolonged duration of heat waves are expected to lead to premature deterioration of infrastructure. Temperature increases have the potential to affect and reduce the life of asphalt road pavements through softening and traffic-related rutting (Karl et al., 2009; CNRA, 2009; Field et al., 2007; CSIRO, 2007; Maine DOT, 2009). Extreme heat can also stress the steel in bridges through thermal expansion and movement of bridge joints and paved surfaces (Karl et al., 2009; CSIRO, 2007; New York City Panel on Climate Change, 2009).

The increase in very hot days and extended heat waves are expected to impact highway operations and maintenance in several ways. The first is the probable limit on construction activities and the number of hours road crews can work due to health and safety concerns for highway workers (Karl et al., 2009; Peterson et al., 2008). The increase in extreme heat could also lead to load restrictions on roads. Pavement damage and buckling will disrupt vehicle movements (Karl et al., 2009). Extreme heat could disrupt vehicle operations because of overheating and increased risk of tire blow-outs in heavily loaded vehicles (Karl et al., 2009; Peterson et al., 2008). Higher temperatures could lead to an increased need for refrigerated freight movement, and thus result indirectly in higher transportation costs (Karl et al., 2009; CNRA, 2009).

A secondary impact of extreme and extended periods of heat, when combined with reduced precipitation, is the projected increased risk of wildfires, especially in the Southwest region. Fire poses a risk to infrastructure and travelers, and can necessitate road closures (Karl et al., 2009).

Change in the Range of Maximum and Minimum Temperatures

Changes in the projected range of temperatures, including seasonal changes in average temperatures, can also impact highway systems. The increase in range of temperatures will likely benefit highways in some ways, while increasing risks in others.

Warmer winters will likely lead to less snow and ice on roadways, and incidence of frost heave and road damage caused by snow and ice in southern locations is likely to decline. However, in some regions warmer winters could also increase the freeze-thaw conditions that create frost heaves and potholes on road and bridge surfaces; particularly in northern locations that previously experienced below-freezing temperatures throughout much of the winter. They may lead to an increase in freeze-thaw conditions in northern states, creating frost heaves and potholes on road and bridge surfaces that increase maintenance costs: repairing such damage is already estimated to cost hundreds of millions of dollars in the U.S. annually (Peterson et al., 2008).

In Alaska, warmer temperatures will likely adversely affect infrastructure for surface transportation. Permafrost thaw in Alaska will damage road infrastructure due to foundation settlement and is the most widespread impact (Larsen et al., 2008). Permafrost thaw will also reduce surface load-bearing capacity and potentially trigger landslides that could block highways.

Roadways built on permafrost already have been damaged as the permafrost has begun to melt and ground settlement has occurred leading to costly repairs for damaged roads. Dealing with thaw settlement problems already claims a significant portion of highway maintenance dollars in Alaska (Karl et al., 2009). A study in Manitoba, Canada, projects the degradation of permafrost beneath road embankments will accelerate because of warmer air temperatures. The symptoms of permafrost degradation on road embankments are lateral spreading and settlement of road embankments. This can create sharp dips in road surfaces which require extensive patching every year and lead to dangerous conditions for motorists (Alfaro et al., 2009).

In Southern Canada, studies suggest that rutting and cracking of pavement will be exacerbated by climate change and that maintenance, rehabilitation, or reconstruction of roadways will be required earlier in the design life (Mills et al., 2009). Similarly, simulations for pavement in Alberta and Ontario show that temperature increases will have a negative impact on the pavement performance in the Canadian environment. As temperature increases, accelerated pavement deterioration due to traffic loads on a warmer pavement was expected and observed. An increase in temperature would facilitate rutting because the pavement is softer. Pavement movement due to loads on a softer pavement would also result in increased cracking. Overall temperature changes significantly affected the level of pavement distress for the international roughness index (IRI), longitudinal cracking, alligator cracking, AC deformation, and total deformation (Smith et al., 2008).

The effects of changing temperatures are particularly apparent in the Arctic. Warming winter temperatures, especially in the high northern latitudes of Alaska, could cause the upper layer of permafrost to thaw. Over much of Alaska, the land is generally more accessible in winter, when the ground is frozen and ice roads and bridges formed by frozen rivers are available (NRC, 2008; Karl et al., 2009). Winter warming would therefore shorten the ice road season and affect access and mobility to northern regions. Thawing permafrost could also damage highways as a result of road base instability, increased slope instability, landslides and shoreline erosion. Permafrost melt could damage roads and bridges directly through foundation settlement (bridges and large culverts are particularly sensitive to movement caused by thawing permafrost) or indirectly through landslides and rockfalls. In addition, hotter, summers in Alaska and other mountainous western locations lead to increased glacial melting and longer periods of high stream flows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments.

The change in range of maximum and minimum temperatures will likely produce both positive and negative impacts on highway operations/maintenance. In many northern states, warmer winters will bring about reductions in snow and ice removal costs, lessen adverse environmental impacts from the use of salt and chemicals on roads and bridges, extend the construction season, and improve the mobility and safety of passenger and freight travel through reduced winter hazards (Karl et al., 2009).

On the other hand, warmer winter temperatures could also have negative impacts on highway operations and maintenance. Greater vehicle load restrictions may be required to minimize damage to roadways when they begin to subside and lose bearing capacity during the spring thaw period. With the expected earlier onset of seasonal warming, the period of springtime load restrictions might be reduced in some areas, but it is likely to expand in others with shorter winters but longer thaw seasons (Peterson et al., 2008).

In the far north, the season for ice roads will likely be compressed. Temporary ice roads and bridges are commonly used in many parts of Alaska for access to northern communities. Rising temperatures have already shortened the season during which these critical facilities can be used (Karl et al., 2009; Peterson et al., 2008; Field et al., 2007).

The indirect effects of changing temperatures on travel behavior are also a consideration. For example, tourism-related traffic is projected to increase in Maine because of the longer summer season and as more people seek to escape increasingly hot summers in other parts of the country (Maine DOT, 2009). Conversely, southern destinations (Florida, the desert Southwest) could see decreased summertime tourism.

3.3.2 Precipitation Changes

Changes in Overall Precipitation

As discussed in section 3.2, changes in precipitation – of both rain and snow - will vary widely across the various regions in the U.S. These changes are expected to impact highways in several ways, depending on the specific regional precipitation levels and geographic conditions.

In areas with increased precipitation, there is greater risk of short and long term flooding (e.g. more spring floods in the upper Midwest). In other areas more precipitation may fall as rain rather than snow in winter and spring, increasing the risk of landslides, slope failures, and floods from the runoff which can cause road washouts and closures. In addition, northern areas are projected to have wetter winters, exacerbating spring river flooding. In other areas the increase in precipitation could lead to higher soil moisture levels affecting the structural integrity of roads, bridges, and tunnels and leading to accelerated deterioration.

If soil moisture levels become too high, the structural integrity of roads, bridges, and tunnels, which in some cases are already under age-related stress and in need of repair, could be compromised. Standing water can also have adverse impacts on the road base. (Karl et al., 2009; Smith et al., 2008) Overall, the increased risk of landslides, slope failures, and floods from runoff will lead to greater road repair and reconstruction needs (Karl et al., 2009).

Some regions of the country will experience decreased precipitation. Where there is less precipitation, there may not be enough runoff to dilute surface salt causing steel reinforcing in concrete structures to corrode. In some regions, drought is expected to be an increasing problem.

Changes in rain, snowfall, and seasonal flooding can affect safety and maintenance operations on roads. More precipitation increases weather-related accidents, delays, and traffic disruptions and, consequently, increases loss of life and property and safety risks such as hazardous cargo accidents) (Koetse and Rietvelda, 2009). In New York City and other urban areas, precipitation-related impacts may include increased street flooding and associated delays, and an increase in risk of low-elevation transportation flooding and water damage (New York City Panel on Climate Change, 2009). Increases in road washouts and landslides and mudslides that damage roads are expected.

Climate models tend to show wetter winters but drier summers. Dry summers or droughts can lead to increased wildfires which could threaten roads and other transportation infrastructure directly, or cause road closures due to reduced visibility. Areas with both wetter winters and drier summers may be particularly at risk, as wetter winters may promote increased springtime vegetation growth, in turn providing more fuel for summer wildfires. There is also increased susceptibility to mudslides in areas deforested by wildfires, particularly if wintertime precipitation increases (Karl et al., 2009).

Increased Intense Precipitation

Heavier rainfall downpours and more intense storms is very likely to continue to become more frequent in widespread areas of the United States (NRC, 2008). This intense precipitation has immediate effects on highways, and could cause changes to the ecological system that ultimately affect highway infrastructure and operations/maintenance.

The increase in intense precipitation could have major impacts on infrastructure. In areas with heavy winter rain, mudslides and rockslides can damage roads from washouts and undercutting and lead to permanent road closures. For example, winter rain has caused yearly washouts of Highway 1 in California (Peterson et al., 2008). Heavy precipitation and increased runoff during winter months are likely to increase the flood damage to tunnels, culverts, and coastal highways (CNRA, 2009). The combination of a generally drier climate in the southwest in the future, which will increase the chance of drought and wildfires, with more frequent extreme downpours (and occasionally wet winters), is likely to cause more mud- and landslides that can disrupt major roadways. In California, the debris impacts generated by intense precipitation are well known; as these events become more intense the state will incur even greater costs for more frequent repair. (CNRA, 2009) An Australian study found that in Victoria the projected increase in the frequency and intensity of extreme rainfall events has the potential to cause significant flood damage to roads - especially tunnel infrastructure - due to acceleration in the degradation of materials, structures and foundations of transport infrastructure from increased ground movement, changes in groundwater affecting the chemical structure of foundations and fatigue of structures from extreme storm events (CSIRO, 2007). Bridges are more prone to extreme wind events and scouring from higher stream runoff, and bridges, signs, overhead cables, tall structures face increased risk from greater wind speeds.

Generally, intense precipitation and increased runoff during winter months are likely to increase the flood damage to tunnels, culverts, and coastal highways. The combination of a generally drier climate in the future in the southwest, which will increase the chance of drought and wildfires, and the occasional extreme downpour, is likely to cause more mud- and landslides where topography favors such conditions which can disrupt travel on major roadways(CNRA, 2009). The number of road closures due to flooding and washouts will likely rise, as will the potential for extreme incidents of erosion at project sites as more rain falls in heavy rain events (Maine DOT, 2009).

In Victoria, Australia the projected increase in the frequency and intensity of extreme rainfall events has the potential to cause significant flood damage to roads, especially tunnel infrastructure. Acceleration in the degradation of materials, structures and foundations of transport infrastructure may occur through increased ground movement, changes in groundwater affecting the chemical structure of foundations and fatigue of structures from extreme storm events. Bridges are prone to extreme wind events while coastal roads are at risk when storm surges combine with sea level rise (CSIRO, 2007).

The increase in heavy precipitation will inevitably cause increases in weather-related accidents, delays, and traffic disruptions in a network already challenged by increasing congestion. There will be potential flooding of evacuation routes and construction activities will be more frequently disrupted (Karl et al., 2009).

3.3.3 Sea Level Rise

Sea levels will continue to rise in the 21st century as a result of thermal expansion and the possible loss of mass from ice sheets (NRC, 2008), as discussed in section 3.2. Infrastructure in coastal areas is expected to be heavily impacted by rising sea levels, often compounded by regional subsidence (the sinking of a land mass due to compaction of sediments or tectonic forces). Coastal highways are at risk from the combination of rising sea levels along with increased heightened coastal flooding potential from tropical and non-tropical storms (Oregon Coastal Management Program, 2009). Most coastal DOTs interviewed as part of this project, including Oregon, Washington, California, Florida, Massachusetts, and North Carolina, all cite the impacts associated with sea level rise as being the primary vulnerability their state is exposed to. Massachusetts is currently in the process of modeling what sea level rise means to the future of the state's transportation system. Note that storm surge risks related to hurricanes will be discussed in more detail in the next section.

In many coastal states, the greatest impacts and largest projected damages to highway infrastructure will come from sea level rise (CNRA, 2009). Sea level rise will also increase the risk of coastal flooding and damage to transportation infrastructure: the same storm surge will now have more elevation because of higher sea levels. Sea level rise is likely to contribute to more frequent storm-related flooding of roads in coastal floodplains. An estimated 60,000 miles of coastal highway are already exposed to periodic flooding from coastal storms and high waves (Karl et al., 2009). Along with the temporary and permanent flooding of roads and tunnels, rising sea levels and storm surges will likely cause erosion of coastal road bases and bridge supports.

In addition to more frequent and severe flooding, underground tunnels and other low-lying infrastructure may also experience encroachment of saltwater, which can lead to accelerated degradation of infrastructure. This can reduce the structure's life expectancy, increase maintenance costs as well as the potential for structural failure during extreme events (Peterson et al., 2008; CSIRO, 2007; New York City Panel on Climate Change, 2009). Underground tunnels and other low-lying infrastructure will experience more frequent and severe flooding. Higher sea levels and storm surges may also erode the road base and undermine bridge supports. The loss of coastal wetlands and barrier islands will lead to further coastal erosion due to the loss of natural protection from wave action (Karl et al., 2009).

Studies from a number of coastal states indicate thousands of miles of major roadway are at risk of flooding and erosion as climate change and land subsidence combine to produce a relative sea-level rise (Savonis et al., 2008; Maine DOT, 2009; Heberger, 2009). As coastal roads are flooded more frequently and for longer periods of time, road closures may become longer and the cost of repair may rise. These affected roads may need to be protected by raising or rerouting the road (Heberger, 2009). The significance of the vulnerability of coastal roads is compounded by the fact that many coastal highways serve as evacuation routes during hurricanes and other coastal storms. These routes could become seriously compromised and lead to evacuation route delays and stranded motorists because of rising sea levels (Karl et al., 2009).

3.3.4 Increased Hurricane Intensity

Hurricanes are projected to increase in intensities, with larger peak wind speeds and more intense precipitation (NRC, 2008; Peterson et al., 2008). The number of category 4 and 5 hurricanes is projected to increase, while the number of less powerful hurricanes is projected to decrease (Bender, 2010). Three aspects of hurricanes are relevant to transportation: precipitation, winds, and wind-induced storm surge. Stronger hurricanes have longer periods of intense precipitation, higher wind speeds (damage increases exponentially with wind speed), and higher storm surge and waves (Karl et al., 2009). Increased intensity of strong hurricanes could lead to more evacuations, infrastructure damage and failure, and transportation interruptions in transportation service (Karl et al., 2009). The prospect of an increasing number of higher category hurricanes has serious implications for the highway system.

Road infrastructure for passenger and freight services are likely to face increased flooding by strong hurricanes (Karl et al., 2009). Prolonged inundation can lead to long-term weakening of roadways. A study of pavements submerged longer than three days during Hurricane Katrina (some were submerged several weeks) found that asphalt concrete pavements and subgrades suffered a permanent strength loss equivalent to two inches of pavement (Gaspard et al., 2007).

With an increase in future hurricane intensity, there will also be more damage to roadway infrastructure. Roads and bridges can be damaged during hurricanes by wave battering (from water driven inland by storm surge) and high winds. Concrete bridge decks weighing many tons can literally be blown off during hurricanes, as seen during Hurricanes Katrina and Rita. The widespread damage to highways from these hurricanes illustrated the powerful effects of these intense tropical storms. Damage to signs, lighting fixtures, and supports also is a product of hurricanes force winds.

More intense storms will leave behind greater volumes of debris on roads, which causes road closures and disruptions until it can be cleared (Karl et al., 2009). Damage to the highway networks caused by the storms increases the challenge for system operations and emergency management. In addition, there will be more frequent and potentially more extensive emergency evacuations, placing further strain on highways. At the same time, sea level rise may render existing evacuation routes less useable in future storms.

3.3.5 Climate Impact to Ecological Conditions

As noted in section 2.0, in addition to the direct effects of climate changes on highways, climate change will likely affect ecological dynamics in ways that will have implications for transportation systems. Highway infrastructure interacts with ecosystems in a number of different ways. Highway construction can destroy ecosystems by displacing natural environments, such as wetlands. Roads can act as a barrier, restricting the movement of flora and fauna and fragmenting ecosystems, and changing the natural flow of water across their right-of-way. Vehicles can also be a hazard to wildlife, killing or injuring animals as they attempt to cross roads. Roads can also be a local source of pollution and damage water bodies, as with the materials that run off roads with rainfall. Transportation professionals have worked for years with resource agencies and ecologists to understand these interactions and develop strategies to reduce or mitigate the negative effects of highways on ecosystems – and to identify opportunities to restore and strengthen compromised environments.

However, climate change will present new challenges to ecological protection and restoration, by affecting the assumptions of ecological conditions under which a road system is built and designed. Some of the changes to ecosystem processes that will likely be relevant for transportation are identified in the Global Climate Change Impacts in the United States (Karl et al., 2009) and include:

- Large-scale shifts in the ranges of species and the timing of the seasons and animal migration
- Increases in fires, insect pests, disease pathogens, and invasive weed species
- Deserts and drylands becoming hotter and drier, feeding a self reinforcing cycle of invasive plants, fire, and erosion
- Coastal and near-shore ecosystems, already under multiple stresses, will be made more vulnerable by ocean acidification
- Potential contractions of the habitats of some mountain species and coldwater fish.

Changing climatic conditions can affect the nature and severity of the ecological impacts of a road and can also change the effectiveness of mitigation measures that have been put in place to reduce ecological harm. For example:

- Coastal Ecosystems: As sea levels rise, coastal ecosystems will migrate inland. Coastal highways can serve as a barrier to this migration, especially where the road is armored against rising sea levels. As a result, coastal ecosystems will be squeezed between retreating shores and immobile highway right-of-ways, in some cases eventually disappearing. (Some states, such as Massachusetts and Rhode Island, prohibit shoreline armoring along the shores of some estuaries so that ecosystems can migrate inland, and several states limit armoring along ocean shores).
- Runoff: Changes in precipitation patterns will affect the magnitude and ecological impact of storm water runoff. More intense precipitation events in areas of high impervious cover could result in runoff spikes that can cause increased erosion in streambeds and, in warm weather, thermal shock to water bodies from the sudden infusion of pavement-heated runoff. It may also result in pollutant loading spikes, particularly if rainfall events become less frequent. On the other hand, decreased use of snow and ice chemicals in wintertime will reduce the harmful effects of these chemicals on water bodies.
- Wildlife Movement: Roads can act as barriers to wildlife movement and migration, either by preventing movement (e.g., walls and fences) or by increasing the risk of injury and mortality while crossing roadways. As climate changes, species may need to relocate to areas that have appropriate climatic conditions and resources. Facilitating wildlife movement under climate change can be achieved through mitigation measures that have already been developed. For example, warning signage for motorists and wildlife passageways ("critter crossings") have been developed to make road crossings more

manageable for wildlife, often after detailed studies of local animal movements; the locations for these crossings may need to be adjusted to accommodate future animal movement patterns. Similarly, the design and placement of culverts, which is critical for maintaining aquatic habitats in streams and waterways that cross highway right-of-way, may also not be optimized for future precipitation and hydrologic patterns. Culverts may need to be redesigned to accommodate new precipitation regimes and to allow fish to pass unimpeded. In places like Oregon, where salmon and other fish are an integral part of the state's ecosystem, bridge alternatives looking at building bridges wider and higher to allow for greater fish passages are being considered.

- Roadside Vegetation: Current practices for maintaining or controlling roadside vegetation for a given region may not be well adapted to future climates. For instance, current roadside vegetation may not persist or may be more prone to fire under drier climate conditions.
- Invasive Species: Invasive species - non-indigenous species - will become much more difficult to control, as changing climate conditions render the "native" species less suited for a given region. In some cases, native species may become more vulnerable both to current and novel invasive species.
- Wetland Mitigation/Restoration: Replacing wetlands destroyed by highway project construction is an accepted part of project mitigation. Recent studies have shown that replacement wetlands often do not function as well as "natural" wetlands. This may be exacerbated by a changing climate, which would require designing wetlands that function in both the current and future climates.

3.3.6 Climate Impact to Planning, Design and Construction

The literature summarized above lays out the range of effects climate change is expected to have on transportation infrastructure, operations and maintenance. The impact of climate drivers on the condition and performance of transportation systems underscores the importance of considering climate in all phases of transportation decision making: in long range planning, and in design and construction phases.

When designing new infrastructure, there will be a need to switch from designing with standards developed for historic climate trends to designing for future (and uncertain) climate projections – transportation infrastructure is sufficiently long-lived that it will not be prudent to base plans on historic averages. Other possible changes to the design phase include the need for a broader systems approach and risk management procedures to incorporate climate change into decision making and defining appropriate design characteristics (Meyer, 2008). This long range perspective needs to be balanced with monitoring for near-term changes that may require more immediate design adjustments. For example in Lithuania, the need to monitor air temperature has been identified in order to track changes in the depth of frozen ground, which affects the selection of the thickness of the road pavement structure (Jukneviciute and Laurinavicius, 2008).

In addition to the direct effects on transportation infrastructure and services, climate change will catalyze changes in the environmental, demographic, and economic conditions within which transportation agencies conduct their work. In the long run, these broader changes may have very significant secondary impacts on the transportation sector that will need to be examined as part of the planning process. For example, changes in population centers induced by shifts in weather conditions will affect travel demand. As regions of agricultural production shift freight flows may likewise change. The effect on waterborne traffic on the Columbia River system is one example; this system will be particularly vulnerable to potential declines in Northwest agricultural production. Grain – primarily wheat – accounts for more than one-half the tonnage carried on the Columbia River segments in Oregon. Because these products comprise such a large share of inland waterway traffic, declines in production could be detrimental to the viability of barge traffic on the Columbia River system (USACE, 2006).

A growing number of transportation agencies have begun incorporating climate change considerations into their planning and design. A survey of state DOTs, conducted for the FHWA in 2008, found that 13 state DOTs had some kind of action or activity underway regarding adaptation, 15 had discussions on the issue taking place, and another 24 had no action or activity related to adaptation at all (FHWA, 2008). For instance, California has begun requiring state agencies to plan for sea level rise, shifting precipitation, and extreme weather events; and is developing a statewide information strategy to support infrastructure vulnerability assessment. As part of this effort, California has formed the Coastal and Ocean Climate Action Team, whose task it is to ensure the state's ability to adapt to climate change impacts on coastal resources. Alaska, which is already experiencing climate impacts, has set up a state-level Adaptation Advisory Group, which includes a Public Infrastructure Technical Working Group, and the state Department of Transportation and Public Facilities (DOTPF) is actively involved in community relocation and seeking enhanced data collection and collaboration across agencies (Ritter, 2009).

Most state DOTs, as well as the FHWA, regard development of an infrastructure inventory and vulnerability assessment as one of the first steps that will be needed in developing a comprehensive approach to adaptation. For example, Oregon has already taken strategic planning steps in that direction, documenting existing knowledge about climate change impacts and summarizing data that can lead to the development of a full vulnerability assessment of transportation infrastructure. That risk and vulnerability assessment will be critical to identifying the highest priorities for protection and the most critical areas for further study (Cambridge Systematics, 2010).

3.4 Summary

This section has described some of the major changes in climate that are expected to occur in the United States over the next 50 to 100 years. Importantly, this section emphasizes that such changes will be felt differently across the nation. In some cases, sea level rise will likely be of greatest concern, while in others temperature change or changing levels of precipitation will be of most interest. Table 3.1 best summarizes the expected changes in the key climate factors that will be of concern to transportation officials. It is likely, however, that how transportation agencies respond to these concerns will vary from one locale to another. The next section provides some indication of this by reviewing some of the leading transportation-related adaptation studies in the world.

4.0 Current Adaptation Practices and Methodologies

4.1 Overview

Based on an extensive review of the literature and on the results of a targeted telephone survey, there is a wide range of experiences dealing with climate change and adaptation strategies in the U.S and the world. This section reviews current adaptation practices and methodologies by presenting (1) the institutional context for these efforts, (2) the frameworks developed by various agencies to guide their adaptation work, (3) the climate data they used, (4) their vulnerability / risk assessment methodologies, (5) the adaptation strategies they identified, and (6) what they have implemented thus far. The report maintains a distinction between domestic and international approaches for each of the above categories to help readers better compare and contrast them.

4.2 Institutional Context for Adaptation

4.2.1 Domestic Perspectives

Overview

At the federal level, FHWA has assumed a leadership position on adaptation. The agency began its involvement by hosting a Peer Workshop on Adaptation in December of 2008 that involved MPO and state DOT officials interested in climate adaptation. The workshop concluded by calling for a national adaptation strategy and for FHWA and other federal agencies to provide relevant and actionable guidance, research, and policy documents on the topic. Over the past year, FHWA has followed through by releasing a literature review, high-level climate data by U.S. regions, and a preliminary conceptual model to assess the vulnerability of transportation infrastructure to climate change. Much of this work is reviewed in this report.

At the US state and local government levels, many jurisdictions have begun to broadly address climate change by developing Climate Action Plans as a framework to meet the challenge. These Climate Change Plans evaluate potential impacts and recommend policies to tackle climate change. These plans often also identify adaptation as one of the key components for addressing climate change. However, in most Climate Action Plans, adaptation takes a back seat to emission reductions. As a result, there are fewer examples where governments have taken the next step to develop and implement adaptation strategies in general – and this is especially true with regard to transportation infrastructure-focused strategies. For most agencies, adaptation planning is at the stage of identifying the major climate drivers, risks and vulnerabilities, and high-level adaptation strategies; but they are not yet at the implementation stage. Nonetheless, there are some leaders in adaptation strategies who have taken a more focused look at transportation infrastructure. In the US, leaders are Alaska, California, Maryland, Massachusetts, New York City, and King County, WA. It is interesting to note that all of the US leaders in adaptation are in coastal locations, presumably in response to the clear risks presented by sea level rise.

At this point in time, although many US governmental agencies have developed adaptation plans at some level, actual implementation for the transportation sector is very much at the conceptual and planning stage. Many agencies have begun to study the issue, some have identified ways to incorporate adaptation into their processes, and a few have actually begun to implement these recommendations. There are very few examples of agencies actually making changes to transportation projects to address adaptation concerns.

In the US, DOTs are rarely the leaders of statewide or local adaptation efforts. In most cases, the state or local environmental agency takes the lead on multi-sector adaptation planning, with transportation agencies participating as stakeholders for transportation infrastructure. This suggests that transportation adaptation will have a strong flavor of interagency coordination. Yet DOTs will need to be active participants in developing adaptation plans for transportation networks; other agencies cannot effectively inventory vulnerabilities, conduct risk assessments, and develop viable adaptation strategies for the systems that DOTs understand and control.

State Adaptation Planning

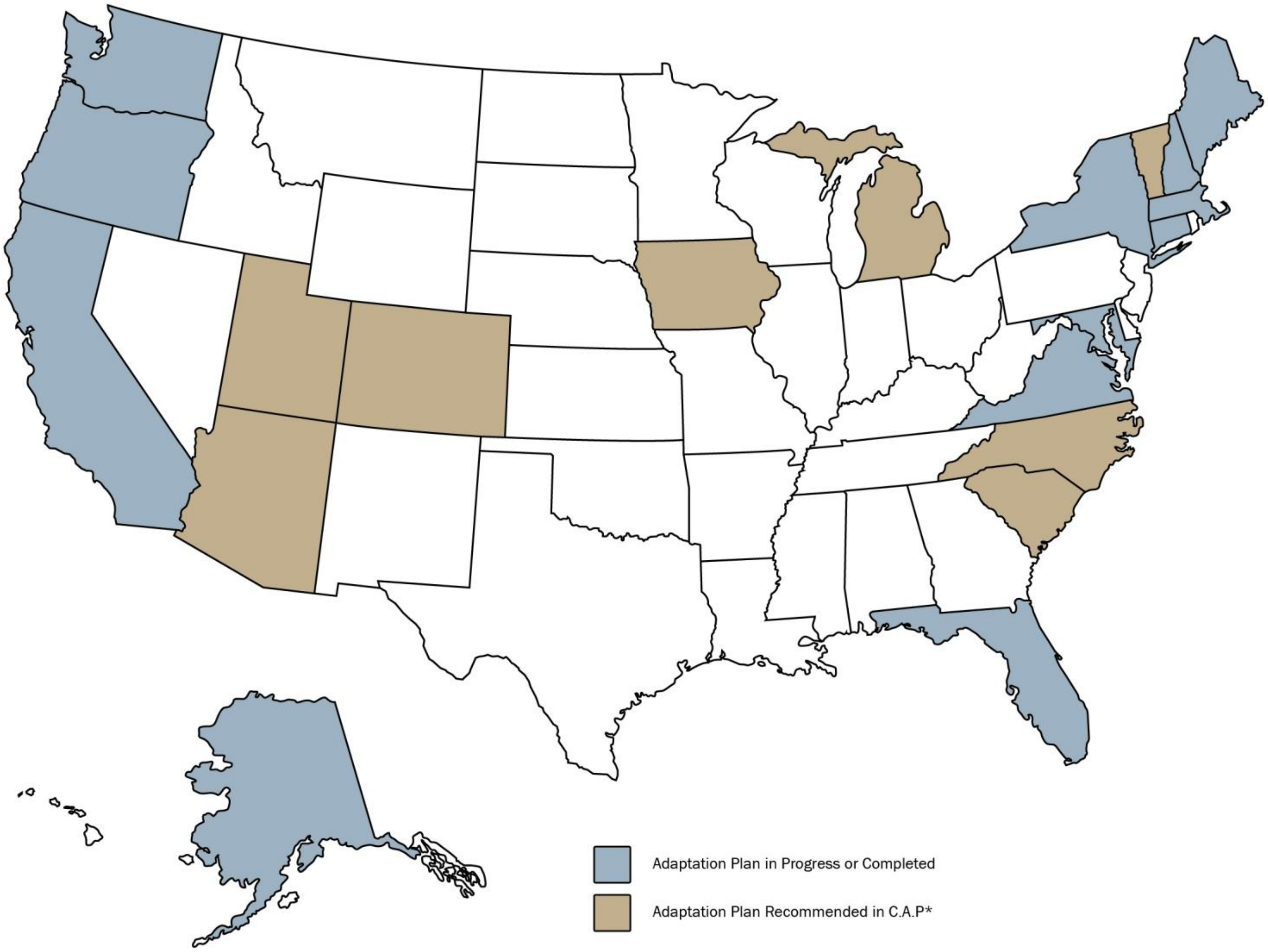
Twelve states have developed or are developing some kind of climate adaptation plan, and in another eight states an adaptation plan was recommended in the state Climate Action Plan (CAP) (see Figure 4-1). In most cases, these adaptation plans are an outgrowth of climate action planning that is primarily focused on mitigation (reducing emissions).

Typically, these climate action plans are led by the governor's office, or by the state Department of Natural Resources. In many states, the Governor issued an Executive Order that established a State Commission or Sub-Cabinet to develop a State Climate Change Plan. These states formed multi-stakeholder working groups to broadly address climate change impacts to the human and natural environments, with transportation as one of many components being addressed by these working groups.

These statewide climate change workgroups have generally followed a framework that looks at climate change impacts, assesses the vulnerability of human and natural environments, and formulates policy or adaptation strategies. Examples include the Florida Energy and Climate Change Action Plan, Alaska Climate Change Strategy, California Climate Adaptation Strategy, and Maryland Climate Action Plan.

For instance, the Alaska Climate Sub-Cabinet organization chart (Figure 4-2) shows how the adaptation advisory group is just one part of the climate action planning cabinet, and transportation is in turn just one part of adaptation planning (combined with public infrastructure, in part reflecting the dual transportation and public facilities role of the Alaska DOT&PF).

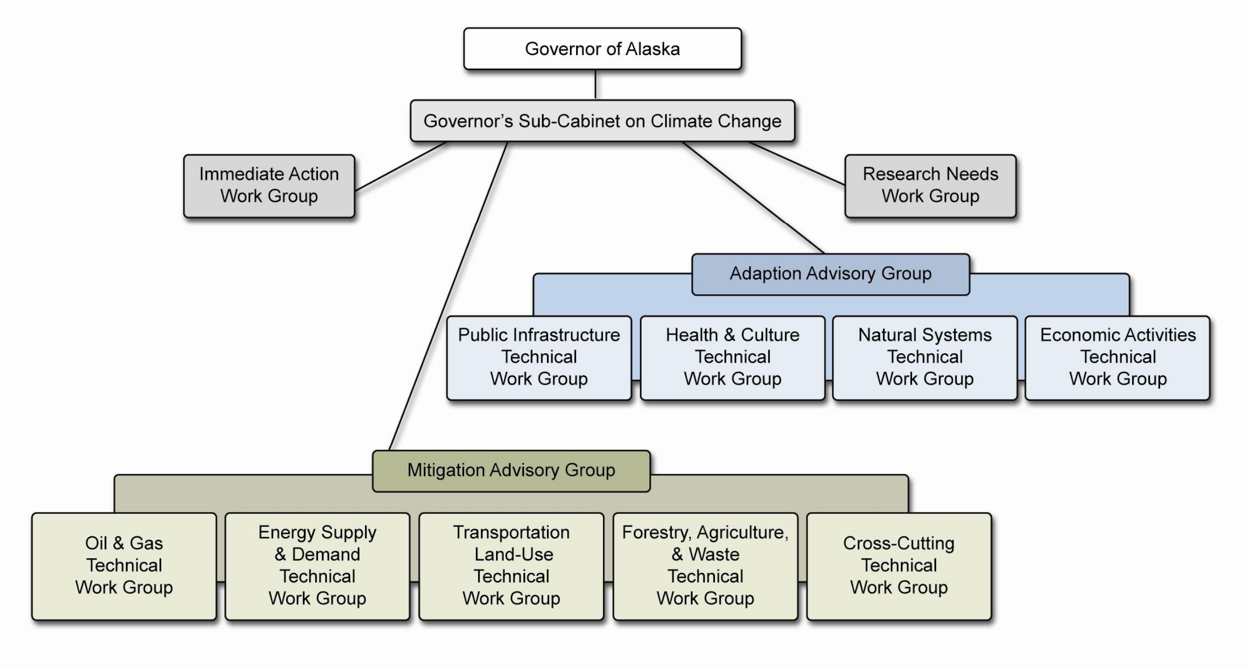
Figure 4-1: Status of State Adaptation Plans



Source: "State Adaptation Plans," Pew Climate Center, http://www.pewclimate.org/what_s_being_done/in_the_states/adaptation_map.cfm

In an example of an alternate structure, in Maryland the Department of the Environment chaired the Commission on Climate Change, which includes members representing legislative leadership and State agencies. The Maryland Department of Transportation is but one of many State agencies on the Commission, which includes a host of agencies such as the Emergency Management Agency, the Department of Business and Economic Development, Department of Planning, Department of Agriculture, Department of Housing and Community Development, the University System of Maryland, the Public Service Commission, and the Maryland Energy Administration – virtually every major state agency. Three Technical Working Groups were established to address specific issues for the Commission: the Scientific & Technical Working Group, the Greenhouse Gas and Carbon Mitigation Working Group, and the Adaptation and Response Working Group. Many of the same state agencies in the Commission were also part of the Technical Working Groups.

Figure 4-2: Strategic Approach to Climate Change, Alaska



Source: Alaska's Climate Change Strategy: Addressing Impacts in Alaska. Page 1-3

In other states, adaptation planning has become a full-fledged activity separate from mitigation. In California, for instance, the Climate Change Adaptation Strategy was initiated through a separate Executive Order (S-13-08) to begin a statewide, ongoing, and committed process of adapting to a changing climate for all state agencies.

With this growing importance, several states have initiated regular reporting requirements on adaptation planning. California, for instance, requires a biennial science assessment report on climate impacts and adaptation. King County, WA and Maryland both require annual reports detailing each agency's (including the transportation agency's) activities in addressing the climate plan, including the adaptation component, and plans for the coming year.

States have shown a willingness to partner with universities and NGOs to assist in developing these adaptation plans. Typically, states draw upon their state university system for support in adaptation planning (the University of Maryland and the University of Alaska for those two states, respectively) but there can be other combinations, such as New York's partnership with Columbia University. Also, the nonprofit Center for Climate Strategies (CCS), which provided much of the support to states in developing CAPs, has also provided support in developing adaptation plans.

The adaptation plans developed from these statewide efforts are almost always multi-sector plans, not transportation plans. Nor is transportation always a priority – issues may rise to the forefront. The Pennsylvania Climate Impact Assessment Report, for instance, fails to address transportation at all. Colorado's Climate Action Plan, for instance, lists 15 adaptation recommendations – of which 14 were related to water resources, which is a pressing concern for that state with the expected decrease in precipitation and snowpack. Utah, similarly, focused almost entirely on water resources.

Regional Adaptation Planning

At the regional level, some Metropolitan Planning Organizations (MPOs) have also started to undertake adaptation planning. One notable example is the Houston-Galveston Area Council's (H-GAC) efforts. In 2007, H-GAC formed the Foresight Panel on Environmental Effects to assess possible climate change impacts in the Houston region. In 2008, the Panel produced the Foresight Panel on Environmental Effects Report that highlighted its findings. The report, piggybacking off of data from the FHWA's Gulf Coast Study, outlines projected climate changes for the Houston metro area and their impacts on infrastructure, public facilities, ecosystems, and public health. A GIS-based study of sea level rise and flooding scenarios helped to illustrate vulnerable infrastructure and facilities. A number of adaption recommendations for the region were also offered. For highways, these included using alternative paving products for higher temperatures and consideration of adaptation in long term transportation planning (including exploring adaptation implications of different mode choices).

Local Adaptation Planning

At the local level, adaptation planning generally also follows climate action planning focused on mitigation. Some of the same characteristics observed at the state level can be seen at the local level. For instance, King County, Washington, developed its *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments* in conjunction with its Climate Plan. The County formed an interdepartmental climate change adaptation team, partnering with the Climate Impacts Group at the University of Washington for scientific expertise. Each year, the Executive Action Group is required to produce a report that provides updates on the County's climate planning.

In New York City, the climate adaptation effort grew directly out of the release of the report *PlaNYC: A Greener, Greater New York*, which recommended the formation of an inter-governmental task force, a plan to protect communities at high risk from climate impacts, and an overall adaptation planning process. The following year, Mayor Bloomberg formed a Climate Change Adaptation Task Force to address infrastructure vulnerabilities, and also a New York City Panel on Climate Change (which includes university representation) to function as a Technical Advisory Committee on developing city-specific climate change projections and assist in new infrastructure standards. New York requires annual performance reports on established indicators. The Port Authority of New York and New Jersey has also been very active in addressing climate adaptation, by implementing guidance to consider the impacts of climate change, raising the flood plain elevation, and even implementing some strategies in projects.

In both Seattle and New York, the task of coordinating adaptation planning has been assigned to the city sustainability office – the Office of Long-Term Planning and Sustainability in New York, and the Office of Sustainability and Environment in Seattle. In New York, in fact, the office was established specifically for this purpose.

Other approaches can be seen at the local level, as well. For example, the City of Punta Gorda, Florida, inserted an adaptation component into the city comprehensive plan as well as its Comprehensive Conservation and Management Plan in 2008. It has already adopted comprehensive plan language to address the impacts of sea level rise, and seeks strategies to combat its effects on the shoreline of the City. Punta Gorda developed its adaptation plan in partnership with the U.S. EPA, as part of EPA's Climate Ready Estuaries program.

Early Action
It is clear from the state of the practice that some states and localities have recognized an urgency to certain aspects of climate change adaptation. Alaska, for instance, is already experiencing infrastructure impacts from climate change, and in response set up an Immediate Action Work Group to deal with responses that the state must implement right away. These are focused on known threats to communities caused by coastal erosion (due to the loss of protective sea ice), thawing permafrost, flooding, and fires. Actions already taken have included relocating airports in communities vulnerable to coastal erosion and funding to address permafrost thawing under highways.

Most often, however, specific studies have been commissioned to address sea level rise. This reflects both the relative certainty of sea level rise as compared to other climate impacts, and the potentially devastating effect it can have on infrastructure in general, as well as transportation facilities and network connectivity.

California
The Executive Order that required a statewide Climate Adaptation Study also required the preparation of a California Sea Level Rise Assessment Report. In conjunction with this, the state requested the NAS to assemble a panel to assess sea level rise impacts on California to inform these state planning efforts. The *Vulnerability of Transportation Systems to Sea Level Rise: Preliminary Assessment* has already been released.

Maryland
Long before beginning Climate Action Planning, Maryland produced *A Sea Level Rise Strategy for the State of Maryland* (2000).

New York
The New York State Sea Level Rise Task Force was created in 2007 by the New York State Legislature, to assess impacts to the state's coastlines from rising seas and recommend protective and adaptive measures. The task force held its first meeting on June 27, 2008; its report is due to the Legislature by January 1, 2011. The task force is composed of state agencies – including NYSDOT - local governments, not-for-profit groups and private citizens appointed by the members of the Legislature.[4]

Virginia
The Climate Action Plan calls for a separate Sea Level Rise Strategy to be developed by 2011.

4.2.2 International Perspectives

Eleven adaptation studies from four countries (United Kingdom, Australia, Canada, and Norway) were reviewed. These countries were chosen because they are considered leaders in climate change adaptation practice and they have extensive literature available in English. We do not claim that

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[4] http://www.dec.ny.gov/energy/45202.html

this literature list is exhaustive as there are many gaps in adaptation practice and linguistic barriers also hamper this research. Nonetheless, we feel the literature reviewed does provide a good cross-section of the current state of practice internationally.

Before discussing the specific studies, it is useful to have an understanding of the different contexts in which the various plans were created. For three of the countries studied (United Kingdom, Australia, and Canada) a brief summary of the national perspective overarching these plans is provided.

The Climate Change Act 2008 made the UK the first country in the world to have a legally binding long-term framework to cut carbon emissions. The Act also created a framework for building the UK's ability to adapt to climate change. The Climate Change Act created a new approach to managing and responding to climate change in the UK, by:

- Setting ambitious, legally binding targets
- Taking actions to help meet those targets
- Strengthening the institutional framework
- Enhancing the UK’s ability to adapt to the impact of climate change
- Establishing clear and regular accountability to the UK Parliament and to the devolved legislatures.[5]

Key provisions of the Act specific to adaption are:

- A requirement for the Government to report at least every five years on the risks to the UK of climate change, and to publish a program setting out how these will be addressed. The Act also introduces powers for Government to require public bodies and statutory undertakers to carry out their own risk assessment and make plans to address those risks.
- An Adaptation Sub-Committee of the Committee on Climate Change, providing advice to, and scrutiny of, the Government's adaptation work.

These efforts are managed by Department for Environment, Food, and Rural Affairs (Defra). Energy policy and mitigation are managed by the Department of Energy and Climate Change, which was created in October 2008 to bring together energy policy, which had been part of the Department for Business, Enterprise, and Regulatory Reform, and climate change mitigation policy, which had been part of the Defra. An additional tool in the UK’s adaptation arsenal is the UK Climate Impacts Programme (UKCIP). This advisory service set up by the government focuses on making complex scientific information understandable and useful to organizations so that they can make decisions on adapting to climate change (UKCIP).

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[5] http://www.decc.gov.uk/en/content/cms/legislation/cc_act_08/cc_act_08.aspx accessed 11/9/10

UKCIP undertakes the following activities:

- Provides a range of tools to help others understand the possible impacts of climate change, including a set of scenarios that show how our climate might change at a regional and national level.
- Offers advice on adaptation
- Assists with research.[6]

In Australia, mitigation and adaption are managed under the same government agency – the Department of Climate Change and Energy Efficiency. The Government's climate change policy rests on three actions:

- Mitigation – to reduce Australia's greenhouse gas emissions
- Adaptation – to adapt to the climate change we cannot avoid
- Global solution – to help shape a collective international response[7]

Australia is spending up to $126 million on its Climate Change Adaptation Program, which helps citizens understand and mange the risks associated with climate change as well as help them take advantage of possible opportunities. Government activities include funding up to $20 million over four years to establish a national climate change adaption research facility, offering grant programs to local governments and professionals, and conducting national vulnerability assessments.[8] The Government believes it has an important capacity building and reform rule. This includes providing information to businesses and communities so they can adapt, setting the right conditions for businesses and communities to adapt, and ensuring that their own programs and assets are adapting. However, the Government recognizes that the roles of the Commonwealth, State, Territory, and local governments are different, and "in many cases impacts of climate change are most effectively managed by a single State, Territory or Local Government. In other cases a combined response by several governments or tiers of governments will be required. In cases where a number of governments must act, or where national leadership by the Commonwealth is required, COAG may be the appropriate body through which to act. Local Governments will be key actors in adapting to the local impacts of climate change and the engagement of Local Government will be a critical part of any national reform agenda."[9]

In Canada, climate change does not appear to be the jurisdiction of a single agency. Climate change activities can be found on Environment Canada and Natural Resources Canada's websites, and the

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[6] http://www.defra.gov.uk/environment/climate/adaptation/ukcip.htm accessed 11/9/10

[7] http://www.climatechange.gov.au/en/government.aspx accessed 11/9/10

[8] http://www.climatechange.gov.au/government/initiatives/climate-change-adaptation-program.aspx

[9] http://www.climatechange.gov.au/en/government/~/media/publications/adaptation/190210-dcc-positionpaper.ashx

Government of Canada also has a website devoted to climate change. On its website, it describes the following four investments it has made to help Canadians adapt to climate change and its impacts:

- Developing a pilot alert and response system to protect the health of Canadians from infectious disease;
- Assessing key vulnerabilities and health impacts related to climate change in Northern/ Inuit populations;
- Improving predictions of climate changes in Canada; and
- Disseminating management tools for adaptation and supporting the development and implementation of regional adaptation programs.[10]

In addition, Natural Resources Canada through its Climate Change Impacts and Adaptation Division has funded more than 300 impacts and adaptation research projects, which have emphasized local decision-maker participation in addressing climate change impacts and adaptation. Future activities of the Division are facilitating regional adaptation planning and decision-making through the Regional Adaptation Collaboratives Program, which will equip decision-makers with the information and advice that they need to make policy, operational, and management changes that respond to regional opportunities and threats from a changing climate, and by providing adaptation tools, such as guidelines, methods and approaches, to help people incorporate information about a changing climate in decision-making.[11]

4.3 Overview of Adaptation Frameworks

4.3.1 Domestic Perspectives

At the federal level, FHWA has taken the lead in developing an adaptation framework applicable to state highways agencies and MPOs. A draft of the FHWA conceptual model has been completed and will be finalized after being piloted with three to four state transportation departments or MPOs. The overall process is illustrated in Figure 4-3.

There are three primary components of the model as illustrated by the blue highlights in the graphic: (1) inventory of assets, (2) climate information, and (3) a risk assessment. The asset inventory phase consists of developing a comprehensive inventory of all the components of an agency's transportation system and their importance for given priorities such as emergency response and people and goods movement. Those assets that are considered more important are the first to be evaluated for climate risks. In the climate information phase, agencies are instructed to gather data on the likelihood and magnitude of future climate changes. Risk assessments are then performed on those climate drivers found to have either a (1) high likelihood and high magnitude, (2) a high likelihood but low magnitude, or (3) a low likelihood but high magnitude of impact. These climate drivers of concern are then related to important infrastructure assets and the vulnerabilities and risks identified. Where risks are high, adaptation options are to be explored;

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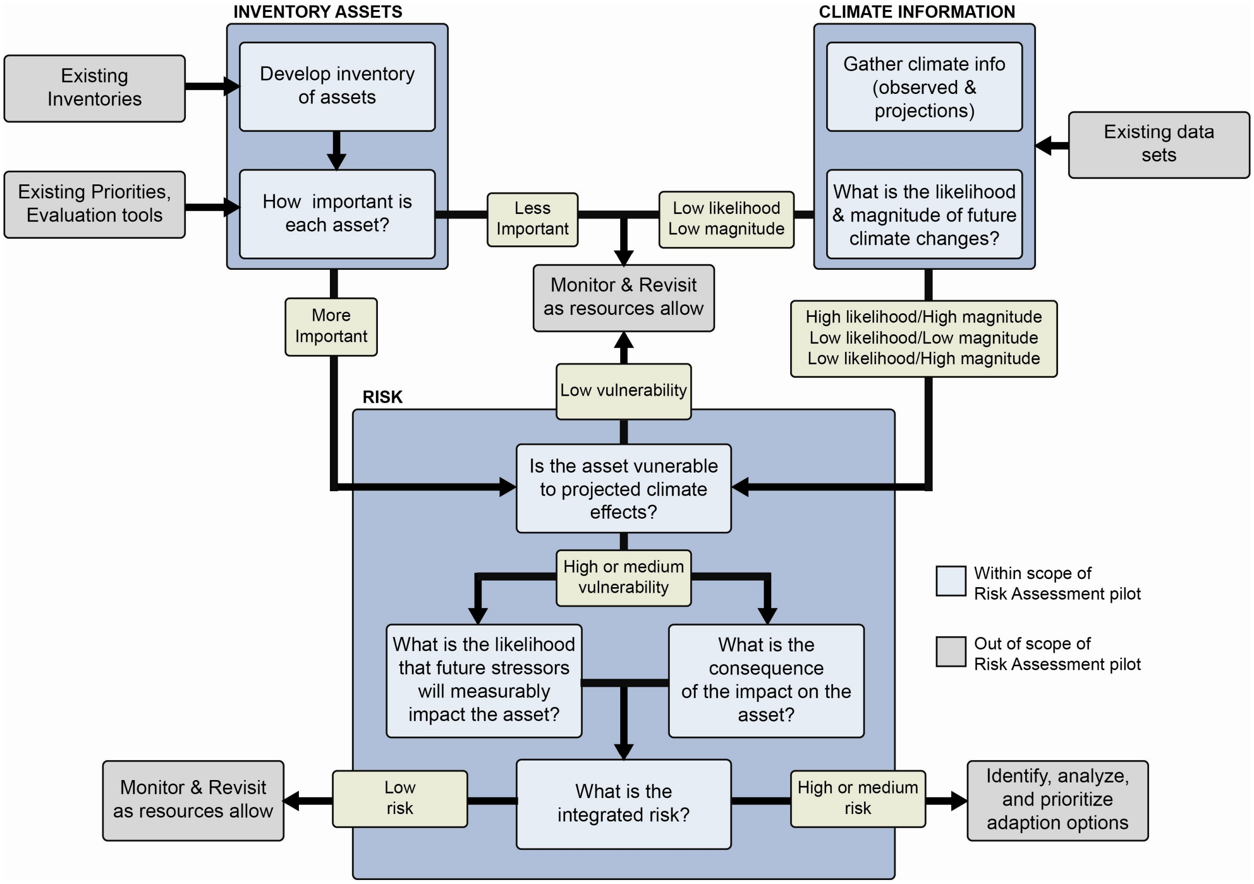
[10] http://www.climatechange.gc.ca/default.asp?lang=En&n=E2553C74-1 accessed 11/9/10

[11] http://adaptation.nrcan.gc.ca/whaquo_e.php accessed 11/9/10

where low, monitoring of conditions is to be implemented and the situation reassessed from time to time as resources allow.

Figure 4-3: Draft FHWA Adaptation Model



Source: FHWA, http://www.fhwa.dot.gov/hep/climate/conceptual_model62410.htm

The extent of domestic adaptation planning at the state and local levels varies: some States have identified the need to integrate adaptation strategies into State agencies' plans, while New York City has developed a comprehensive risk management process. Some States have identified adaptation strategies to include with long range transportation plans, while others are in the beginning stages of policy development. For example, the Climate Change Adaptation Advisory Committee is just getting underway in Massachusetts.

Most studies and plans identified the same general approach to adaptation planning: develop or gather climate projections, inventory assets to identify and prioritize at risk areas (risk and vulnerability assessment), set preparedness goals, develop an adaptation strategy and action plan that meets those goals, and implement and monitor that plan. At this point, most of the specific adaptation strategies recommended are more at a planning level. There is general recognition that climate change adaptation plans should be developed as part of a risk management process, and also recognition that adaptation is likely to be a dynamic, iterative process.

Several states have also included a role for education in their adaptation planning. For instance, the Oregon Climate Change Integration Group includes education, outreach, and research as part of its climate planning. Florida recommended developing required training provisions to educate professionals in relevant fields (such as architecture, engineering, and construction management) on the need to incorporate adaptation to climate change, as a basis for establishing design criteria for new infrastructure; these training provisions could even be made a condition for licensing.

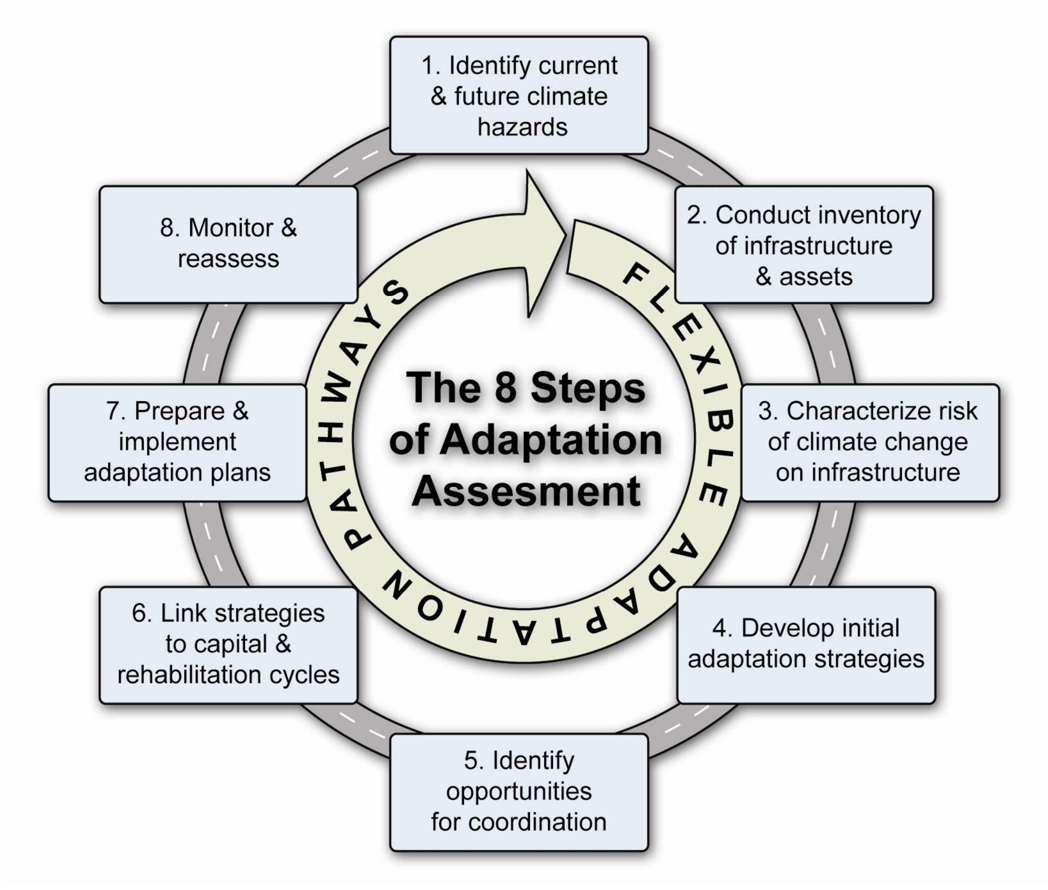
One of the most sophisticated looks at an overall framework for developing and implementing adaptation policy can be found in the New York Panel on Climate Change (NPCC) *Adaption Assessment Guidebook* (AAG). Although developed for New York City, it is designed to be a framework that can be used in any urban area, with region-specific adjustments related to climate risk information, critical infrastructure, and protection levels. It is intended to be general enough to be useful for a range of jurisdictions and infrastructure sectors, yet specific enough to serve as a template for developing and implementing a sector's adaptation efforts.

The *Adaption Assessment Guidebook* includes an 8-step process to inventory at-risk infrastructure and develop adaptation strategies to address risks (Figure 4-4). These steps are designed to be incorporated into risk management, maintenance and operations, and capital planning processes of agencies.

- Identify current and future climate hazards.
- Conduct inventory of infrastructure and assets.
- Characterize risk of climate change on infrastructure.
- Develop initial adaptation strategies.
- Identify opportunities for coordination.
- Link strategies to capital and rehabilitation cycles.
- Prepare and implement adaptation plans.
- Monitor and reassess.

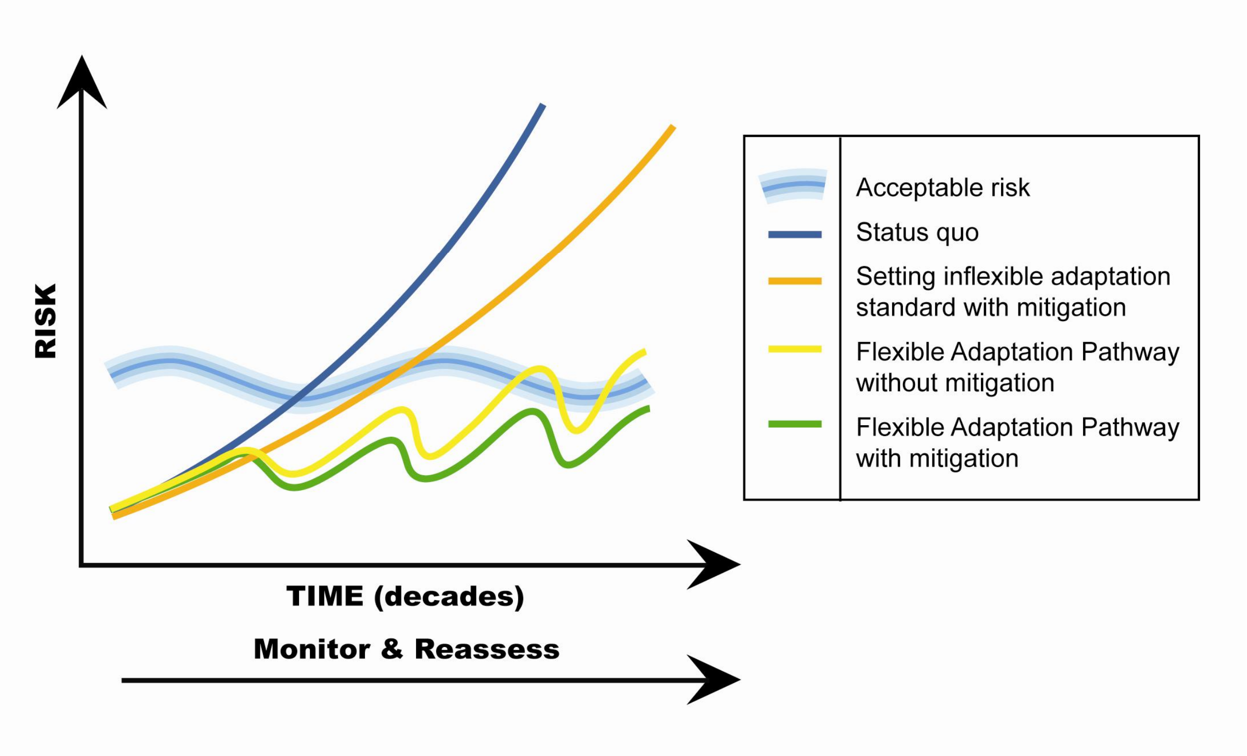
The NPCC also describes the importance of Flexible Adaptation Pathways (FAP), a dynamic approach to developing effective climate change adaptation strategies (Figure 4-5). Adaptation strategies developed under FAP are not fixed and can evolve through time as climate risk assessment, evaluation of adaptation strategies, and monitoring continue. The development of FAP is likely to be more effective and less costly than more permanent, inflexible approaches. The concept would be to embed Flexible Adaptation Pathways in the operations and planning of the agencies and organizations that manage the critical infrastructure of the city

Figure 4-4: New York City Process for Adaptation Planning



Source: New York City Panel on Climate Change, Adaptation Assessment Guidebook -.Appendix B, 2009.

Figure 4-5: Adaptive Adaptation Pathways, New York City



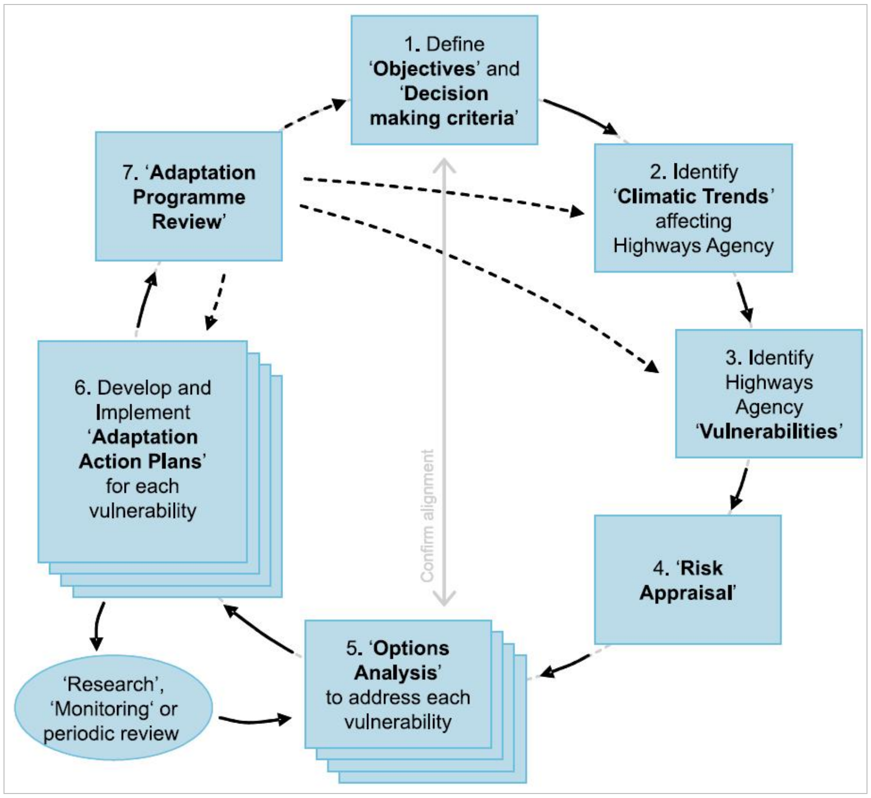
Source: New York City Panel on Climate Change, Adaptation Assessment Guidebook -.Appendix B, 2009

4.3.2 International Perspectives

Similar to the US experience, most of the international studies reviewed have the same general approach to adaptation planning: develop or gather climate projections, establish how those climate changes will impact assets, determine the severity of the impact, and develop recommendations to address the high-risk impacts.

Perhaps the most fully-developed adaptation framework is that described in England's Highway Agency's *Climate Change Adaptation Strategy, Volume 1.* The Highway Agency Adaptation Strategy Model (HAASM), which is the focus of the *Climate Change Adaptation Strategy, Volume 1,* is a seven-step process for developing a climate change program. It provides a method for prioritizing risk and identifies staff members responsible for different climate change adaptation program development efforts. The other international reports reviewed do not provide such an inclusive look at climate change adaptation. Figure 4-6 provides a graphic overview of the HAASM (more detailed discussion of the HAASM is provided in Section 4.5.2).

Figure 4-6: Highways Agency Adaptation Strategy Model (HAASM)



Source: Highways Agency of the U.K., 2008.

The Australian Government's *Climate Change Impacts & Risk Management: A Guide for Businesses and Government* proposes a process for organizations to follow as they investigate the risks of climate change. It asks users of the Guide to "identify those activities and assets that are at risk from a changing climate." The workshop-based process has participants "1. consider (based on their professional knowledge) which activities and assets of the organization are sensitive to climate change; and 2. form a judgment as to whether climate change is a significant source of risk to the assets and activities relative to other sources of risk (p. 18)." The first step in the workshop-based process begins before the workshop. It calls for all participants in the climate change risk management exercise to understand the context in which the evaluation will be occurring. Establishing the context consists of five parts:

- Defining how the climate will be assumed to change in the future.
- Defining the scope of the assessment including activities to be covered, geographic boundaries and the time horizon.
- Determining whose views need to be taken into account, who can contribute to the analysis and who needs to know its outcomes.
- Defining how risks will be evaluated by clarifying the objectives and success criteria for the organization and establishing scales for measuring consequences, likelihoods and risk priorities.

- Creating a framework that will assist in identifying risks by breaking down the organization's concerns into a number of areas of focus and relating them to the climate scenarios. (p. 26)
- At the workshop, time is spent on three tasks: identifying the risks, analyzing the risks, and evaluating the risks.

The Guide recognizes that for some issues there may be need for more detailed analysis (for reasons of needing to better understand the climate change itself, needing to better understand the impact of climate change on operations, or to better understand and evaluate the treatment options). The Guide provides a brief overview of the above issues, but because the issues affecting individual organizations will be different it cannot go into great detail. The Guide concludes with information about how to prepare and plan for a climate change risk management workshop.

Two of the reports reviewed, *Scottish Road Network Landslide Study: Implementation* and *The Road Well Traveled: Implications of Climate Change for Pavement Infrastructure in Southern Canada*, followed more technical procedures for evaluating impacts. This is because these studies were less concerned with setting up organizational protocols of risk management and more interested in testing climate change impacts on the landscape and infrastructure.

The *Scottish Road Network Landslide Study: Implementation* report is focused on assessing and ranking the hazards presented by debris flow. "The hazard assessment process involves the GIS-based spatial determination of zones of susceptibility which are then related to the trunk road network by means of plausible flow paths to determine specific hazard locations. The approach taken, using a GIS-based assessment, enabled large volumes of data to be analyzed relatively quickly and was able to rapidly deliver a scientifically-sound platform for the assessment. This desk-based approach to hazard assessment was then supplemented by site-specific inspections, including site walkovers, to give a hazard score for each site of interest. The subsequent hazard ranking process involved the development of exposure scores predicated primarily upon the risk to life and limb, but also taking some account of the socioeconomic impact of debris flow events. Finally, these scores were combined with the hazard scores to give site-specific scores for hazard ranking from which a listing of high hazard ranking sites in Scotland was produced (p. 6)." The full explanation of their methodology can be found in Technical Appendix 7.1.

The Road Well Traveled: Implications of Climate Change for Pavement Infrastructure in Southern Canada used two different methodologies to test the impact of different climate change related variables on pavement performance. The first set of case studies "examined deterioration-relevant climate indicators that are routinely applied or referenced in the management of pavement infrastructure (p. vii)." The second set of case studies used the United States NCHRP/AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG). A series of analyses were conducted to test (1) the influence of climate and climate change alone, (2) influence of structure type and baseline traffic volume, and (3) combined influence of traffic growth and climate change. The study does not raise significant concern over the impacts of climate change on pavement performance. However, it does worry that secondary and tertiary roads (with weak pavement structures and excessive traffic loads) will experience more impacts associated with climate change (p. 68). A full description of their methodology is provided in Technical Appendix 7.2.

4.4 Climate Modeling / Data

4.4.1 Domestic Practices

Given that climate projections are produced by complex global climate models, well out of the experience base of DOTs, where are they turning for future climate projections? Two approaches are used by states and localities attempting to identify their climate future:

- One is to use available reports and data on large-scale climate changes, primarily based on IPCC data, and now, on data from FHWA. This is the simplest approach, requiring no new analysis by individual DOTs.
- The other is to commission new modeling and data gathering efforts focused on developing climate projections specific to the region or locality being studied. This involves either new global climate model runs, or employing downscaling techniques to existing model runs.

These are discussed in turn below. In the climate literature, 2100 is generally used as the benchmark end-year for analyses for a variety of reasons, but in part because possible futures resulting from different emissions scenarios do not begin to diverge significantly until the latter half of the century; in that sense 2100 provides a more useful benchmark for policy comparisons. For adaptation assessments, however, earlier time horizons such as 2050 are useful as well because it is within the lifetime of infrastructure planned today, and is not so far outside planning horizons. The adaptation practices in the US today generally test a range of benchmark years, with 2050 and 2100 the most common range (as used, for instance, in California's plan and in H-GAC's plan). The New York City Adaptation Plan, on the other hand, used 2020, 2050, and 2080 as benchmarks, even though relatively small changes would be expected by 2020. The Oregon Rogue River basin report used 2040 and 2080, reflecting a middle ground approach.

Using Existing Data

Localities using existing data have traditionally utilized IPCC regional projections for North America, or information from the U.S. National Climate Assessment. For instance, King County used IPCC 2007 and the U.S. National Assessment for national and regional projections. All of the adaptation plans related to Florida – the state plan, The City of Punta Gorda Adaptation Plan, and even the state oceans and coastal resources plan – made use of IPCC findings and data.

In the spring of 2010, FHWA made accessing climate data much easier for transportation agencies. As part of their adaptation efforts, they compiled standardized climate projections for the entire country and posted them on their website.[12] Climate variables projected include sea level rise and changes in mean temperatures and precipitation by season through the end of the century. For presentation purposes, the US is divided into nine regions and the data presented for each of them. Some datasets showing intraregional differences are also provided. The FHWA website will likely become the go-to source on existing high-level climate data for US transportation agencies.

Where more localized data is available, localities have shown themselves willing to find and use it. H-GAC used the climate change scenario from the U.S. Department of Transportation's Impacts of

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[12] http://www.fhwa.dot.gov/hep/climate/climate_effects/effects00.cfm.

Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I ("the Gulf Coast Study") as the basis for its adaptation assessment.

In most cases, the data sources above were used in a relatively qualitative way; to identify general categories of risk rather than for numerical analyses of vulnerability. Although these do not represent a technically sophisticated approach, using these existing analyses provides sufficient data for agencies just beginning to address adaptation. At this stage, when specific adaptations are being considered only in the most general form, these existing assessments may be enough to guide agencies in understanding the nature of the climate impacts they will face in the future – the main climatological factors that will change and the range of sea level rise expected globally. However, to develop detailed adaptation strategies, more precise information is often desired– and that can be provided by working with climate modelers.

Specialized Climate Modeling

The leading adaptation plans included sophisticated downscaling and modeling to get projections specific to their region. These adaptation leaders generally tap into modeling expertise available in their local community. For instance, the NYC assessment was a joint effort with researchers from the Columbia University Earth Institute Center and the NASA Goddard Institute for Space Studies. In Alaska, the state partnership included researchers from the University of Alaska. In California, research was done with the Scripps Institute of Oceanography at UC San Diego (as well as other universities in the California system) via the California Energy Commission's Public Interest Energy Research Program (PIER).

All of the modeling efforts identified were based on emissions scenarios from the 2007 IPCC assessment, consistent with practice in the climate modeling community. Most used several emission scenarios to capture a range of possible futures. For instance, New York used the A2, A1B, and B1 scenarios; California used A2 and B1. Although spanning a range of emissions, the scenarios chosen generally reflect "middle of the road" assumptions on future energy use, in which there is some balanced mix of fossil fuel and renewable sources.[13] This in part reflected the availability of model runs; more model runs are available for these scenarios (because GCM runs are so complex, time-consuming, and expensive, researchers generally rely on the data from previous model runs rather than re-running the GCMs for each new analysis).

In addition, these modeling efforts developed regional climate projections by downscaling the results from global climate models. This was done through statistical analyses that related the coarse outputs from GCMs (in which a grid box might be 100-200 miles across) to finer-scale datasets using observed climate data so as to account for local climatic influences such as elevation and proximity to water bodies.

More detail on these three modeling efforts is provided below.

California

California sponsored climate change research to support its planning through the PIER program. The California Scenarios Project examined future projections for changes in average temperatures,

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[13] http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/

precipitation patterns, sea-level rise, and extreme events, as well as resulting impacts on particularly climate-sensitive sectors. For the Scenarios Project, California-specific projections were developed by downscaling global climate models to produce regional and small-scale projections that are useful for impacts studies. This process is used to provide higher resolution results than are initially generated by the relatively coarse resolution global or national climate model outputs. A set of six global climate models were then run using two emissions scenarios. These emissions scenarios are part of a family of common scenarios used by the Intergovernmental Panel on Climate Change (IPCC) in its 2007 assessment. The scenarios signify plausible pathways of how global emissions may change as a result of economic, technological, and population shifts over the 21st century. One scenario depicts a higher-emissions scenario (A2), the other a lower-emissions scenario (B1).14

Alaska

For the Alaska Climate Change Strategy, the Scenarios Network for Alaska Planning (SNAP), a collaborative organization linking the University of Alaska, state, federal, and local agencies, and NGOs, developed fine-scale projections of future climate for Alaska based on downscaled global models used by the IPCC in its Fourth Assessment Report (2007). To conduct the downscaling procedure, SNAP investigators compared model output for past years to actual climate data for the same time period, and analyzed how well each model predicted monthly mean values for three different climate variables (surface air temperature, precipitation, and sea level air pressure) over four overlapping northern regions (Alaska, Greenland, latitude 60-90°N, and latitude 20-90°N) for the period from 1958–2000 (Walsh et al. 2008). They noted that models that performed well in one northern region tended also to perform well in others. The SNAP climate projections then relied on output from the five models that provided the most accurate overall results.[15] Results were scaled down to match local conditions using data from Alaskan weather stations and various analytical tools. In the long run, additional linked models connecting climate data to variables such as transportation and construction parameters, hydrologic shifts, or optimal conditions for tourism, recreation, hunting, and fishing will improve the connections between SNAP climate data and landscape changes of concern to Alaskans (Walsh et al. 2008).

New York City

Sixteen GCMs used for IPCC 2007 that had data available for the A2, A1B, and B1 emissions scenarios were used to generate the New York climate projections. The projections were downscaled to the New York City region by applying the projected changes from the relevant gridbox to observed climate data. In addition, because there has been controversy over the IPCC 2007 sea level rise predictions, which did not include melting of the Greenland and Antarctic ice sheets, the New York scenarios included an additional sea level rise scenario that corresponded to more rapid ice melt was developed.

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[14] The A2 scenario represents a more competitive world that lacks cooperation in development and portrays a future in which economic growth is uneven, leading to a growing income gap between developed and developing parts of the world, while the B1 scenario denotes a future that reflects a high level of environmental and social consciousness combined with global cooperation for sustainable development.

[15] www.snap.uaf.edu

4.4.2 International Practices

Seven of the 11 international reports included information about the climate change models used. The level of detail on the discussion varied. Some reports simply stated what models were used and other provided a more detailed discussion about why a particular model was used or chosen. Table 4.1 summarizes the models used; the spatial resolutions and temporal windows used are listed if that information is available.

Table 4.1: International Adaptation Studies and Characteristics

County	Study	Model(s)	Spatial Resolution	Temporal Window
England	Climate Change Adaptation Strategy, Volume 1	UK Climate Impacts Programme 2002 Report (UKCIP (2002)) Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (2007a)	n/a	n/a
Scotland	Scottish Road Network Climate Change Study	HadRM3 HadRM2	25km 50 km	1961-1990 2071-2100
Australia	Infrastructure and Climate Change Risk Assessment for Victoria	CSIRO's CCAM (Mark 2) CSIRO's CCAM (Mark 3)	50km	2030 2070
Australia	Climate Change Impacts & Risk Management: A Guide for Business and Government	CSIRO scenarios	n/a	n/a
Canada	Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure	Canadian Regional Climate Model	n/a	n/a
Canada	The Road Well Traveled: Implications of Climate Change for Pavement Infrastructure in Southern Canada	A2x emission experiment from the Canadian Centre for Climate Modeling and Analysis Coupled Global Climate Model 2 (CGCM2A2x) B21 experiment run through the Hadley Climate Model 3 (HadCMB21)	n/a	2050s
Norway	"Climate and Transport" – R&D Programme for Adaptation of Norwegian Roads to Climate Change	Norwegian Meteorological Institute, based on the results of the RegClim project	n/a	n/a

4.5 Vulnerability and Risk Assessment

4.5.1 Domestic Practices

The approaches to risk assessment found in this review showed a common understanding of the basic components needed to conduct a successful risk and vulnerability assessment – identification of climate drivers, identification of critical infrastructure, an assessment of the risks those climate drivers present to the critical infrastructure, and a prioritization of the resulting vulnerabilities based on level of risk and criticality of infrastructure (in fact, since many Climate Action Plans were facilitated by the Center for Climate Strategies, it is not surprising that similar frameworks would be seen).

In most cases, the frameworks described above have been used to conduct initial, high-level risk assessments that qualitatively answer the basic questions of what kinds of infrastructure are at risk to those climate drivers, and what sorts of impacts could be expected. Fewer have performed quantitative assessments of these risks and vulnerabilities, and fewer yet have performed asset inventories to identify the vulnerability of individual facilities. Most agencies approach risk assessment as an iterative process, in which overall risk is scoped first, followed by more detailed studies as warranted. At this point, the general state of practice is still at the scoping level, but in the next few years many more agencies will begin to dive deeper into the details and specifics of implementation.

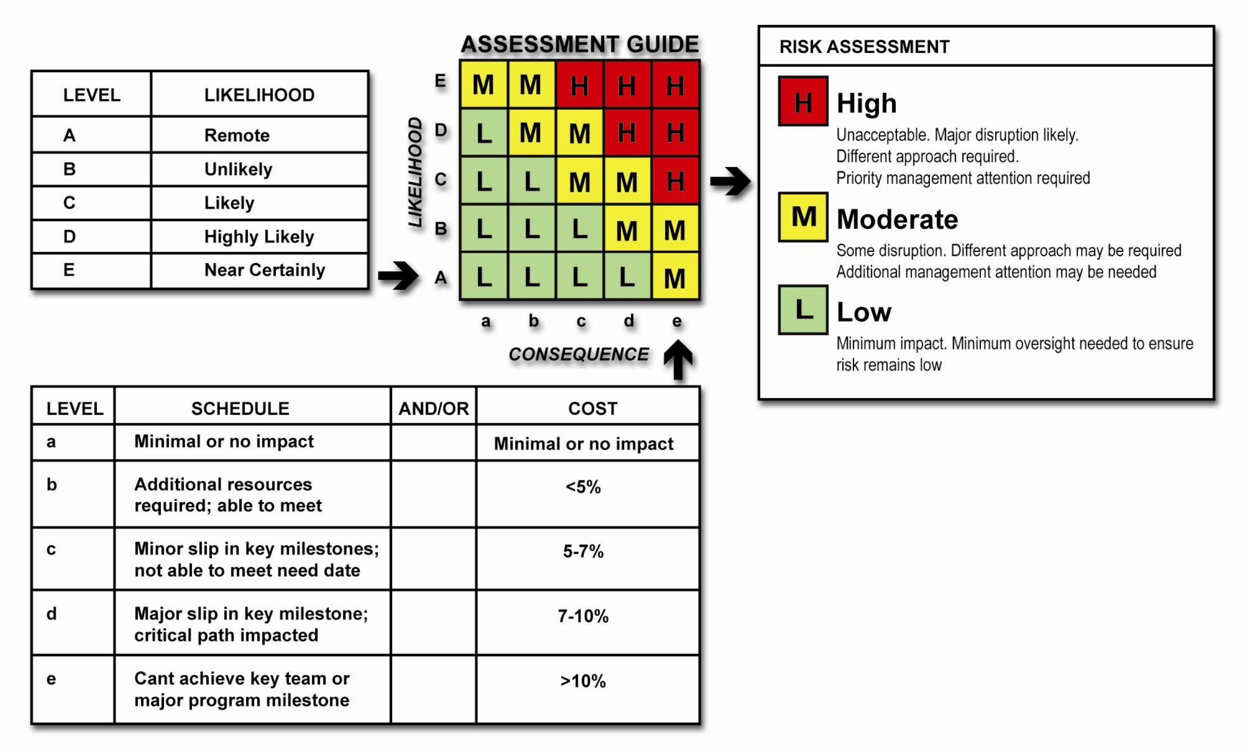
The sections below describe some of the tools currently found in domestic adaptation plans, discuss the nature of these high-level risk assessments, and, finally, look at some of the more comprehensive risk assessment that is starting to take place.

Tools and Frameworks for Risk Assessment

At the federal level, FHWA's pilot conceptual model (see Figure 4-7) incorporates a qualitative risk assessment component. The risk analysis is to be conducted on assets of high importance and to consider only those changing climate variables where there is either (1) a high likelihood and high magnitude of impact, (2) a high likelihood but low magnitude of impact, or (3) a low likelihood but high magnitude of impact. The vulnerability of each important asset is then to be evaluated based on how it has responded to historical changes in the climate variable in question and to associated extreme weather events. The costs of any repair or service disruptions are to be noted and a determination made as to the capacity of the particular asset to withstand the projected future changes in the climate stressor. From here, important assets that history indicates have a medium or high vulnerability to projected climate changes are carried forward for further risk analysis. Low vulnerability assets are to be noted and marked for future monitoring.

An integrated risk assessment is then performed on the vulnerable assets. The assessment considers the likelihood of impacts and their consequences. These two factors are related to each other using the matrix in Figure 4-7 and their intersection determines the risk level facing the asset. Adaptation options are then to be considered for high or medium risk assets while low risk assets are given lower priority for the time being.

Figure 4-7: Qualitative Risk Assessment Example, FHWA



LEVEL	LIKELIHOOD
A	Remote
B	Unlikely
C	Likely
D	Highly Likely
E	Near Certainly

ASSESSMENT GUIDE

LIKELIHOOD	a	b	c	d	e
E	M	M	H	H	H
D	L	M	M	H	H
C	L	L	M	M	H
B	L	L	L	M	M
A	L	L	L	L	M

CONSEQUENCE

LEVEL	SCHEDULE	AND/OR	COST
a	Minimal or no impact		Minimal or no impact
b	Additional resources required; able to meet		<5%
c	Minor slip in key milestones; not able to meet need date		5-7%
d	Major slip in key milestone; critical path impacted		7-10%
e	Cant achieve key team or major program milestone		>10%

RISK ASSESSMENT

H High
Unacceptable. Major disruption likely.
Different approach required.
Priority management attention required

M Moderate
Some disruption. Different approach may be required
Additional management attention may be needed

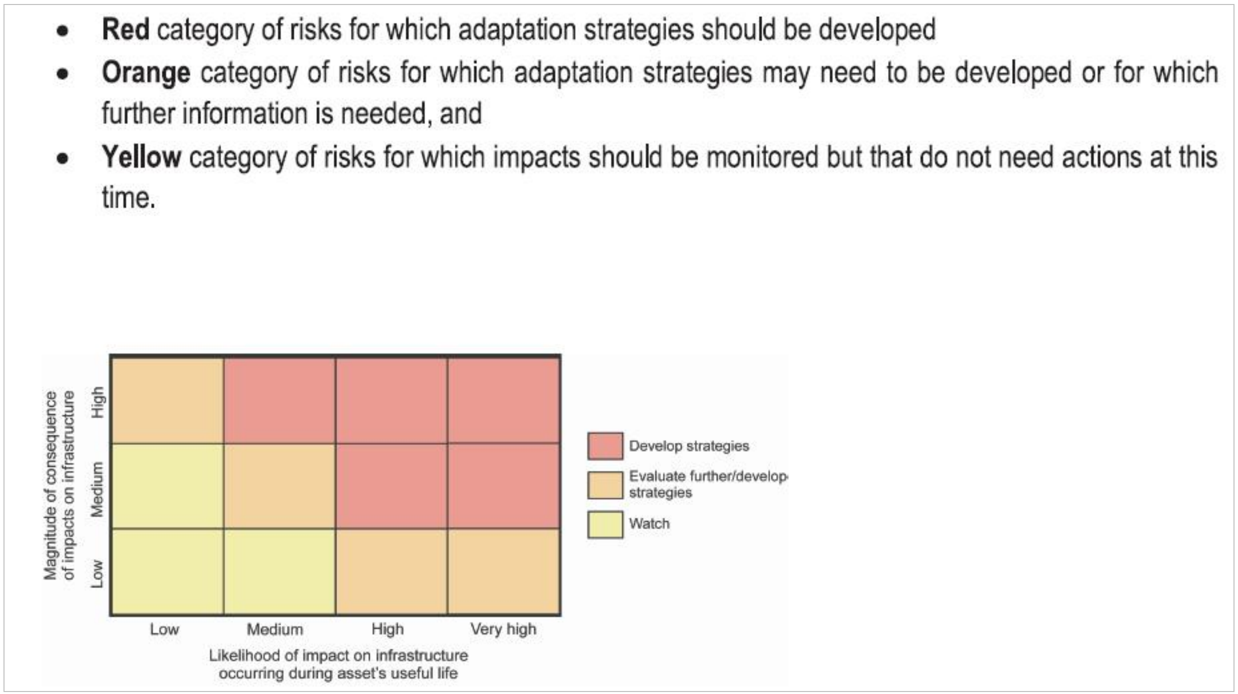
L Low
Minimum impact. Minimum oversight needed to ensure risk remains low

Source: FHWA, http://www.fhwa.dot.gov/hep/climate/conceptual_model62410.htm

Several of the other adaptation plans evaluated for this literature review illustrate some of the tools and processes for risk assessment that have been developed by various states and localities. Both King County, WA and New York City provided tools primarily meant to assist staff in their own agencies in structuring risk and vulnerability assessments, but also designed to be generic enough to be used by other localities. For instance, King County's *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments* provides a checklist and recommendations for conducting vulnerability and risk assessments. Other agencies have already made use of these tools – most notably, *A Framework for Climate Change Adaptation in Hawaii* was based directly on the King County guidelines.

The New York City NPCC *Adaption Assessment Guidebook* also contains tools to help stakeholders. For instance, like King County, this guide provides Infrastructure Questionnaires (IQ), which are sector specific questionnaires to guide the assessment process and create an inventory of infrastructure at risk to climate change impacts. It also provides a Risk Matrix (RM), a tool to help categorize and prioritize the risk assessment findings by facility, based on the probability of the climate hazard, likelihood of impact, and magnitude of consequence (see Figure 4-8).

Figure 4-8: Characterizing Risk, New York City



- **Red** category of risks for which adaptation strategies should be developed
- **Orange** category of risks for which adaptation strategies may need to be developed or for which further information is needed, and
- **Yellow** category of risks for which impacts should be monitored but that do not need actions at this time.

Magnitude of consequence of impacts on infrastructure	Low	Medium	High	Very high
High	🟧	🟥	🟥	🟥
Medium	🟨	🟧	🟥	🟥
Low	🟨	🟨	🟧	🟧

Likelihood of impact on infrastructure occurring during asset's useful life

🟥 Develop strategies
🟧 Evaluate further/develop strategies
🟨 Watch

Source: City of New York

The approach taken by the city of Punta Gorda, Florida, represents an advanced approach for a small city (no doubt in part because of its participation in EPA's Climate Ready Estuaries Program, which provided additional technical support). For the plan, critical facilities of all types were identified. For transportation, this consisted of a list of all bridges in the City; no other transportation facilities were singled out as critical facilities. Infrastructure costs, based on estimates prepared for a previous FEMA disaster preparedness plan, were used to estimate losses from storm flooding (based on the facilities location in flood zones). To assess risk and vulnerability of critical infrastructure to various climate effects, rather than conduct a quantitative engineering analysis of the infrastructure, the City turned to a stakeholder and public involvement approach. At a series of public meetings, stakeholders and the public engaged in exercises to identify and prioritize areas of vulnerability, and to recommend preferred adaptation strategies.

High-Level Risk Assessments

Most actual risk assessments for transportation infrastructure to date have been fairly qualitative. The frameworks described above have been used to conduct initial, high-level risk assessments that identify the major climate drivers most likely to impact a given agencies' infrastructure, the types of infrastructure most vulnerable, and discuss the kinds of impacts that might be expected.

These risk assessments have primarily focused on the water-related impacts discussed in the literature: sea level rise, flooding, intense tropical storms, intense precipitation. Threats to evacuation routes have also been assessed in many coastal locations. Fewer have focused on temperature itself as a major issue for highway systems, although some have included air quality and heat island concerns. For instance, the vulnerabilities identified by Hawaii to transportation include threats to transportation infrastructure (evacuation routes) due to sea level rise and storm flooding; weakening of infrastructure due to repetitive and prolonged stress (dams, roads, bridges, tunnels, storm drains); and submersion of vital transportation infrastructure due to sea level rise and flooding. Alaska, of course, identified a unique set of vulnerabilities that do not exist in the other 49 states, particularly infrastructure damage from permafrost thaw and severe coastal erosion from lack of sea ice armoring.

Quantifying risks and vulnerabilities is most often seen around the risk of sea level rise or flooding. These parameters are both more pressing and somewhat easier to identify for most agencies due to the (relative) simplicity of comparing infrastructure elevation to sea level rise scenarios. For instance, California's *Preliminary Transportation Assessment* identified the number of miles of highway that would be inundated by a 55 inch sea level rise, by county and road.

Asset Inventories

Few agencies have gone to the point of systematically inventorying their assets to identify how each transportation link or facility will be affected by climate change. Nonetheless, as states have finished the initial round of adaptation planning, some have begun the process of identifying vulnerabilities to their transportation infrastructure in a more comprehensive manner. For instance, California and Maryland DOTs are in the process of conducting in-depth assessments of the vulnerability of their road systems (assessments are due to be completed this year; a preliminary assessment for California has already been released, as described above). Washington State DOT is also conducting a vulnerability assessment of WSDOT-owned infrastructure.[16]

Maryland provides an illustrative example of a state implementing the systems needed for a more detailed risk inventory. It is one of the first states to begin systematically inventorying the vulnerability of its transportation assets to climate change, beginning with vulnerability to sea level rise. Sea level rise is an initial priority for Maryland's adaptation plan because of that state's particular vulnerability: it has more than 4000 miles of coastline, much of it low-lying land on the Chesapeake Bay at risk to inundation (in fact, in the past century several islands in the Bay disappeared under the rising water levels). As a result, the Maryland adaptation plan recommended the integration of coastal erosion, coastal storm, and sea level rise impacts into existing state and local policies and programs.

To that end, the state has pursued several initiatives in partnership with universities, NGOs, and NOAA. For instance, the Coast-Smart Communities Initiative provided funding and technical support to towns in coastal counties to prepare for sea level rise, coastal erosion, and storm inundation. More concretely, the state has developed a high-resolution LIDAR dataset to allow development of sea level rise inundation models along its coastlines. This dataset has been made available to the public as the Maryland Coastal Atlas[17], including maps of SLR vulnerability areas (viewable with the Coastal Atlas Shoreline mapping tool). State-wide Sea Level Rise Vulnerability Maps have been created for 14 coastal counties, depicting lands at potential risk (see example figure below). These maps show lands (i.e., 0 to 2 feet, 2 to 5 feet, and 5 to 10 feet) above mean sea level. The use of LIDAR data allowed the Maryland Coastal Atlas to map sea level rise with more

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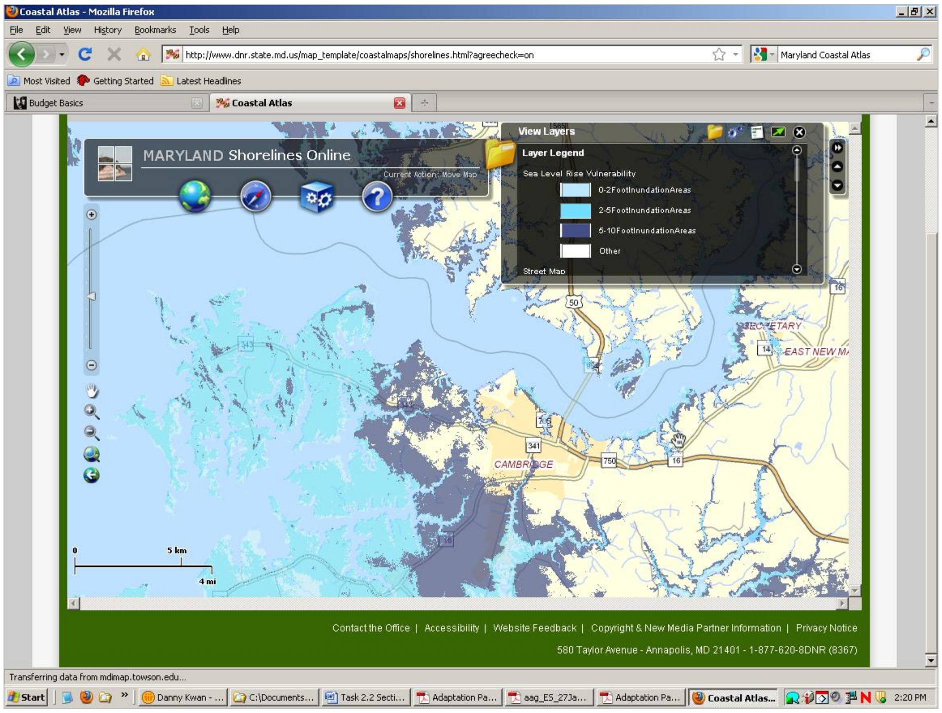
[16] WSDOT, 2009: Sustainable Transportation Workplan Development and Implementation, August 19.

[17] http://www.dnr.state.md.us/ccp/coastalatlas/index.asp

precision than was found in two previous reports on Mid-Atlantic sea level rise by the U.S. Climate Change Science Program[18] or USDOT[19], making it the most advanced sea level rise resource for the mid-Atlantic region. Not all locations possess this data and can do analyses at this resolution: the US CCSP reports that it may be some time before the rest of the mid-Atlantic region has comparable LIDAR elevation data that are suitable for detailed assessments of submeter increments of sea-level rise (see Figures 4-9 and 4-10).

One potential use of the mapping tool is to identify coastal areas subject to coastal flooding from storm inundation and sea level rise for long-range planning, floodplain management, and emergency management. Using this dataset, the Maryland State Highway Administration is currently building a new shoreline dataset as a polygon for GIS mapping to determine which assets are located within the zone of inundation. This data will eventually be compiled into an overall MDOT assessment of Maryland's critical transportation facilities and the system's vulnerability to projected sea-level rise and extreme weather damage.

Figure 4-9: Shoreline Mapping in Maryland for Risk Assessment



Source: Maryland Coastal Atlas Shoreline mapping tool

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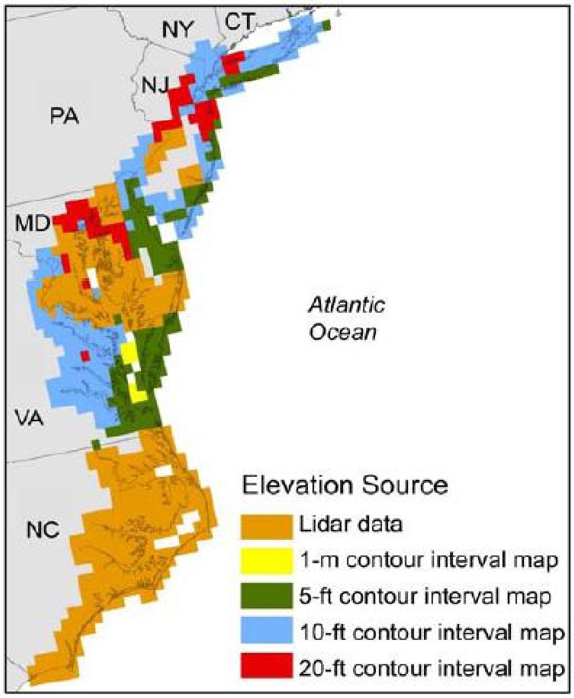
[18] U.S. Climate Change Science Program, 2009: Synthesis and Assessment Product 4.1 - Coastal Sensitivity to Sea Level Rise: A Focus on the Mid-Atlantic Region.

[19] USDOT, 2008: The Potential Impacts of Global Sea Level Rise on Transportation Infrastructure, Phase 1 - Final Report: the District of Columbia, Maryland, North Carolina and Virginia. Center for Climate Change and Environmental Forecasting.

Figure 4-10: Tidal Surge in Maryland for Risk Assessment



Source: U.S. Climate Change Science Program; Synthesis and Assessment Product 4.1 - Coastal Sensitivity to Sea Level Rise: A Focus on the Mid-Atlantic Region, January 2009. Page 125

4.5.2 International Practices

Similar as in the US, much of the international experience with identifying vulnerabilities is qualitative. Even the most sophisticated approach – the Highways Agency HAASM model – relies on professional judgment to determine how climate change will impact agency activities. To determine the severity of the impact, people need to consider the uncertainty of the impact, the rate of climate change, the extent of disruption, and the severity of the disruption. This is also the premise behind *Climate Change Impacts & Risk Management: A Guide for Business and Government*, which advocates a workshop-based approach to determine and evaluate climate change risks. The qualitative nature of these approaches should not be considered a flaw. In fact, it is a strength as it forces participants to think about climate change and how it impacts their organizations. In addition, because downscaling climate change data to the site level is fraught with uncertainty, conducting quantitative analysis with it has the potential of creating a false sense of precision.

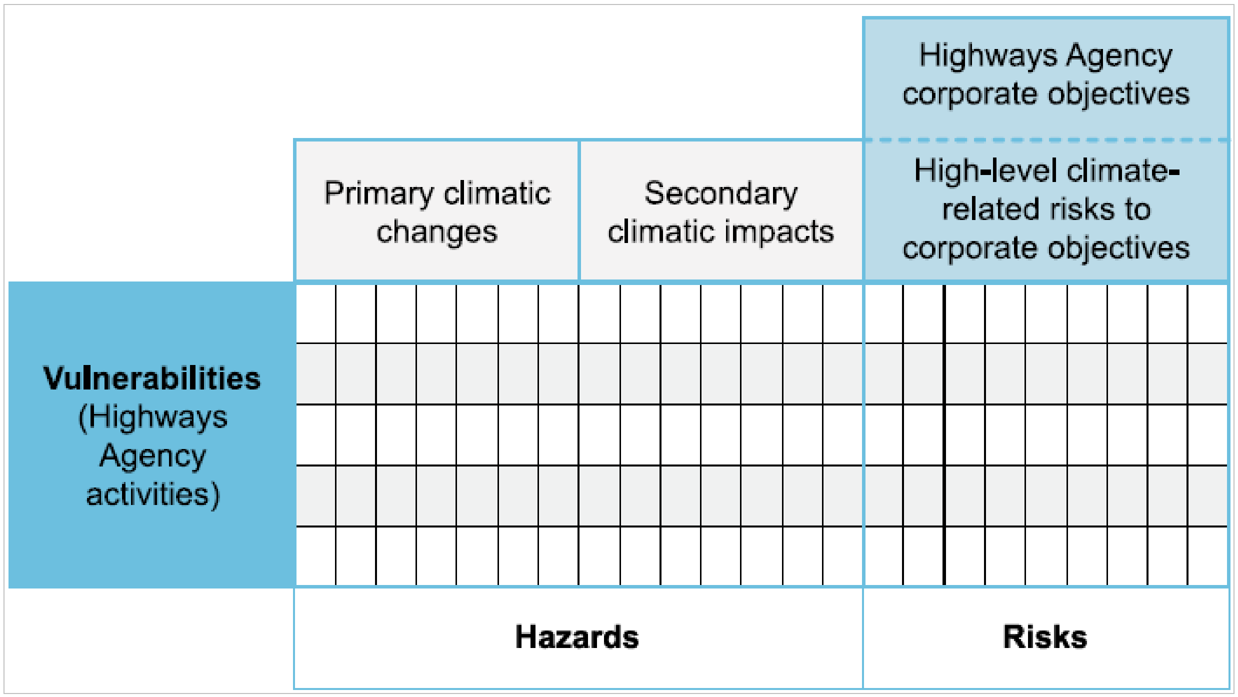
Not many reports mentioned potential benefits of projected climate change. Of the ones that did, possible reduction in winter maintenance activities was often cited in northern climates. In Australia, a possible benefit cited was decreased corrosion rates of steel and concrete, including reinforced concrete, as a result of reduced annual rainfall or a decrease in available moisture (a combination of less rain and increased evaporation rates). The most frequently mentioned vulnerabilities include insufficient drainage capacity, landside risks, flooding, accelerated degradation of materials, and rutting, The UK's HAASM model is one of the best examples of incorporating risk into its analysis. This seven-stage process includes:

Stage 1: Define Objectives and Decision-Making Criteria
The first step of the HAASM is to define the objectives and decision making criteria so that the model is aligned with the agency's mission. The Objective is "to enable the Highways Agency to systematically develop and implement its responses to the challenges of climate change in support of the delivery of its corporate objectives (p. 5)." The decision making criteria for selecting adaptation actions are in "accord with the Highway Agency's sustainability requirements and provide the optimum balance between minimum whole life-cost, certainty of risk, and residual risk (p. 5)."

Stage 2: Identify Climate Trends That Affect the Highways Agency
The second stage categorizes possible climate changes hazards into primary and secondary impacts based on their impacts on the Highways Agency's activities. The possible climate changes form the bases for identifying vulnerabilities in Stage 3.

Stage 3: Identify Highways Agency Vulnerabilities
Vulnerabilities are the Highways Agency activities that could be affected – positively or negatively – by climate change. They represent the ways the Agency may need to change its current practices in the future. The vulnerabilities are documented in a vulnerability schedule, which considers how climate change impacts could affect the delivery of the Highways Agency's corporate objectives. The vulnerability schedule format is shown in Figure 4-11.

Figure 4-11: Vulnerability Schedule



Source: Highways Agency of the U.K., 2008

Stage 4: Risk Appraisal

Stage 4 "scores" the climate change associated risks to the vulnerabilities so that the Highways Agency can focus its climate change adaptation efforts to those activities that are most at risk. Four primary criteria are used in the risk appraisal: uncertainty, rate of climate change, extent of disruption, and severity of disruption. Table 4.2 summarizes the criteria.

The Highways Agency employs a methodical way of scoring vulnerabilities. Each vulnerability receives a high, medium, or low ranking for each of the primary risk appraisal criteria (the ranking standards are described in Tables 4.3 to 4.6) and the rankings are converted to numbers (3,2,1 respectively).

Rather than create a single, composite score, the HAASM develops five scores reflecting different reasons for taking action. The formulae for each prioritization criteria are given in Table 4.7.

Stage 5: Options Analysis to Address Vulnerabilities

Stage 5 establishes a preferred option for managing the risk associated with each of the vulnerabilities identified in Stage 3 and prioritized in Stage 4. In some cases, the preferred option will be apparent, while others may require more detailed analysis. To determine the best option, the HAASM recommends that feasible options are considered, expected outcomes are determined, and costs and benefits are estimated. "The key requirement is for experts to consider carefully the sustainable options they consider have the potential to offer the minimum whole-life-cost, minimum risk and greatest certainty of outcome (Highways Agency of the U.K., 2008)."

Stage 6: Develop and Implement Adaptation Action Plans

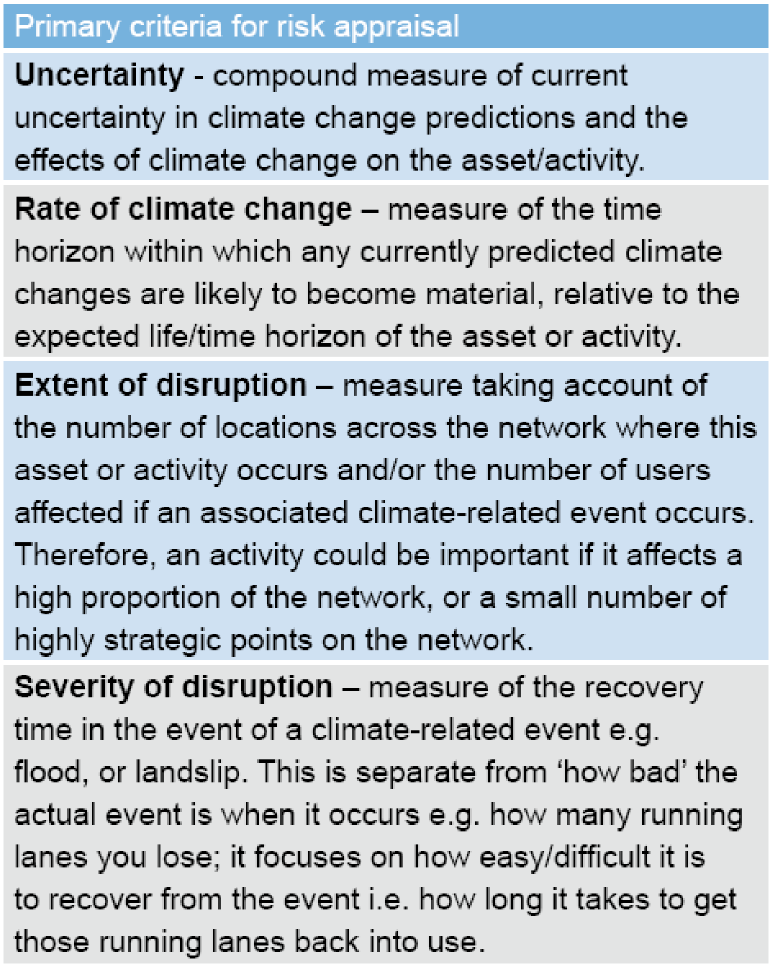
In Stage 6, detailed adaptation plans for each preferred option are developed. "Wherever possible, the adaptation action plans will define the steps necessary to modify existing Highways Agency Standards, Specifications and other operating procedures, rather than lead to the development of new requirements. In some cases, they may determine that no immediate action is necessary, but instead a trigger for future review (Highways Agency of the U.K., 2008)."

Stage 7: Adaptation Programme Review

Stage 7 draws key information from the adaptation action plans into an overall adaptation program. The Climate Change Programme Manger is responsible implementation and oversight of the program and preparing an annual Climate Change Adaptation Progress Report. As part of Stage 7, it is expected that four feedback loops are completed. The model recommends that the following stages be revisited and information revised as needed based on the findings

- Stage 1, revisiting the HAASM objective and decision-making criteria in the light of changes to Highways Agency corporate objectives or Department of Transportation requirements.
- Stage 2, reassessing the climatic trends affecting the Highways Agency in the light of new scientific understanding and / or published literature.
- Stage 3, ensuring any new areas of vulnerability are identified.
- Stage 6, ongoing review of progress of each of the adaptation action plans.

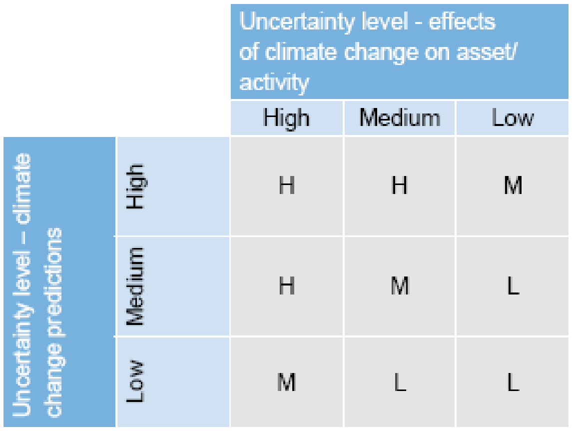
Table 4.2: Primary Criteria for Risk Appraisal



Primary criteria for risk appraisal
Uncertainty - compound measure of current uncertainty in climate change predictions and the effects of climate change on the asset/activity.
Rate of climate change – measure of the time horizon within which any currently predicted climate changes are likely to become material, relative to the expected life/time horizon of the asset or activity.
Extent of disruption – measure taking account of the number of locations across the network where this asset or activity occurs and/or the number of users affected if an associated climate-related event occurs. Therefore, an activity could be important if it affects a high proportion of the network, or a small number of highly strategic points on the network.
Severity of disruption – measure of the recovery time in the event of a climate-related event e.g. flood, or landslip. This is separate from 'how bad' the actual event is when it occurs e.g. how many running lanes you lose; it focuses on how easy/difficult it is to recover from the event i.e. how long it takes to get those running lanes back into use.

Source: Highways Agency of the U.K., 2008

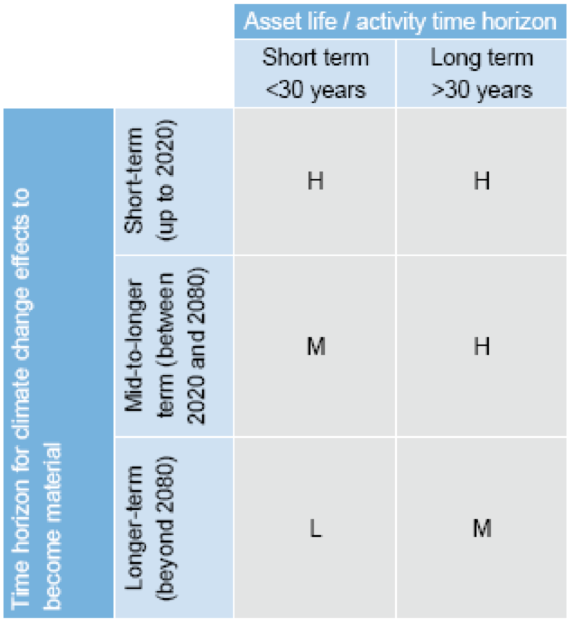
Table 4-3: Matrix for Determining the Uncertainty Level Criterion



		Uncertainty level - effects of climate change on asset/ activity		
		High	Medium	Low
Uncertainty level – climate change predictions	High	H	H	M
	Medium	H	M	L
	Low	M	L	L

Source: Highways Agency of the U.K., 2008

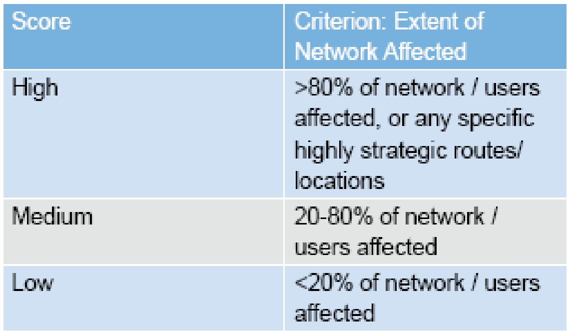
Table 4-4: Matrix for Determining the Rate of Climate Change Criterion



		Asset life / activity time horizon	
		Short term <30 years	Long term >30 years
Time horizon for climate change effects to become material	Short-term (up to 2020)	H	H
	Mid-to-longer term (between 2020 and 2080)	M	H
	Longer-term (beyond 2080)	L	M

Source: Highways Agency of the U.K., 2008

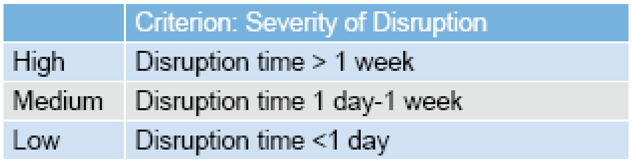
Table 4-5: Determining the Extent of Network Affected Criterion



Score	Criterion: Extent of Network Affected
High	>80% of network / users affected, or any specific highly strategic routes/ locations
Medium	20-80% of network / users affected
Low	<20% of network / users affected

Source: Highways Agency of the U.K., 2008

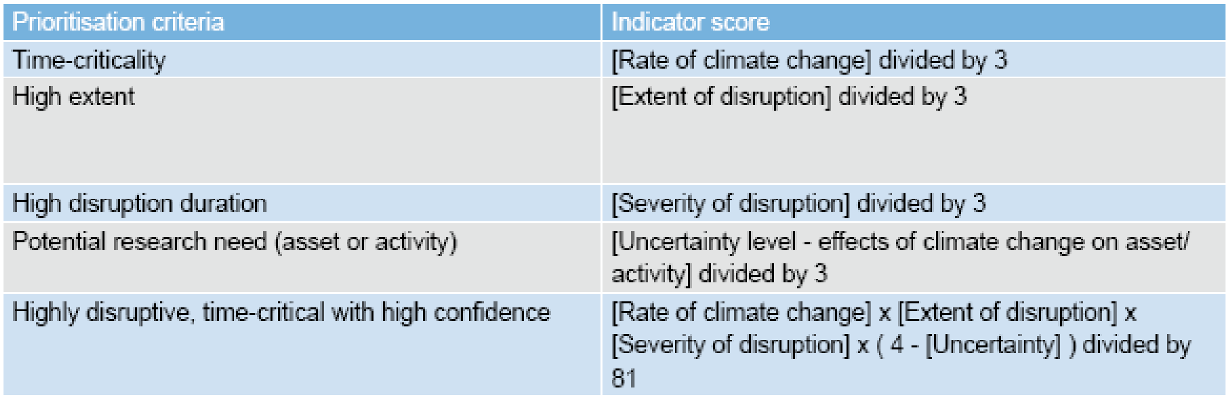
Table 4-6: Determining the Severity of Disruption Criterion



	Criterion: Severity of Disruption
High	Disruption time > 1 week
Medium	Disruption time 1 day-1 week
Low	Disruption time <1 day

Source: Highways Agency of the U.K., 2008

Table 4-7: Formulae for Prioritization Criteria



Prioritisation criteria	Indicator score
Time-criticality	[Rate of climate change] divided by 3
High extent	[Extent of disruption] divided by 3
High disruption duration	[Severity of disruption] divided by 3
Potential research need (asset or activity)	[Uncertainty level - effects of climate change on asset/ activity] divided by 3
Highly disruptive, time-critical with high confidence	[Rate of climate change] x [Extent of disruption] x [Severity of disruption] x (4 - [Uncertainty]) divided by 81

Source: Highways Agency of the U.K., 2008

Australia's *Climate Change Impacts & Risk Management: A Guide for Business and Government* recommends that risk identification, analysis, and evaluation be conducted by risk element, that is, discrete elements or areas facing the organization. This can provide focus to the discussion and help workshop participants more efficiently look at the risks. The recommended workshop process is

- Step 1: Brainstorm risks associated with the element until the main issues are felt to have been exposed.
- Step 2: Taking each risk in turn:
  - Identify any existing controls (features of the environment, natural and manmade structures and mechanisms, procedures and other factors) that are already in place and tend to mitigate the risk;
  - Describe the consequences the risk would have if it was to arise, given the controls, and in each of the scenarios under consideration;
  - Describe the likelihood of suffering that level of consequence, again given the controls, in each of the scenarios under consideration;
  - Assign an initial priority in each scenario based on the likelihood and consequence of the risk; and
  - Where two or more scenarios are being considered, consider adjusting the priority in recognition that some scenarios are less likely to occur than others.
- Step 3: Return to step 1 for the next key element (p. 24).

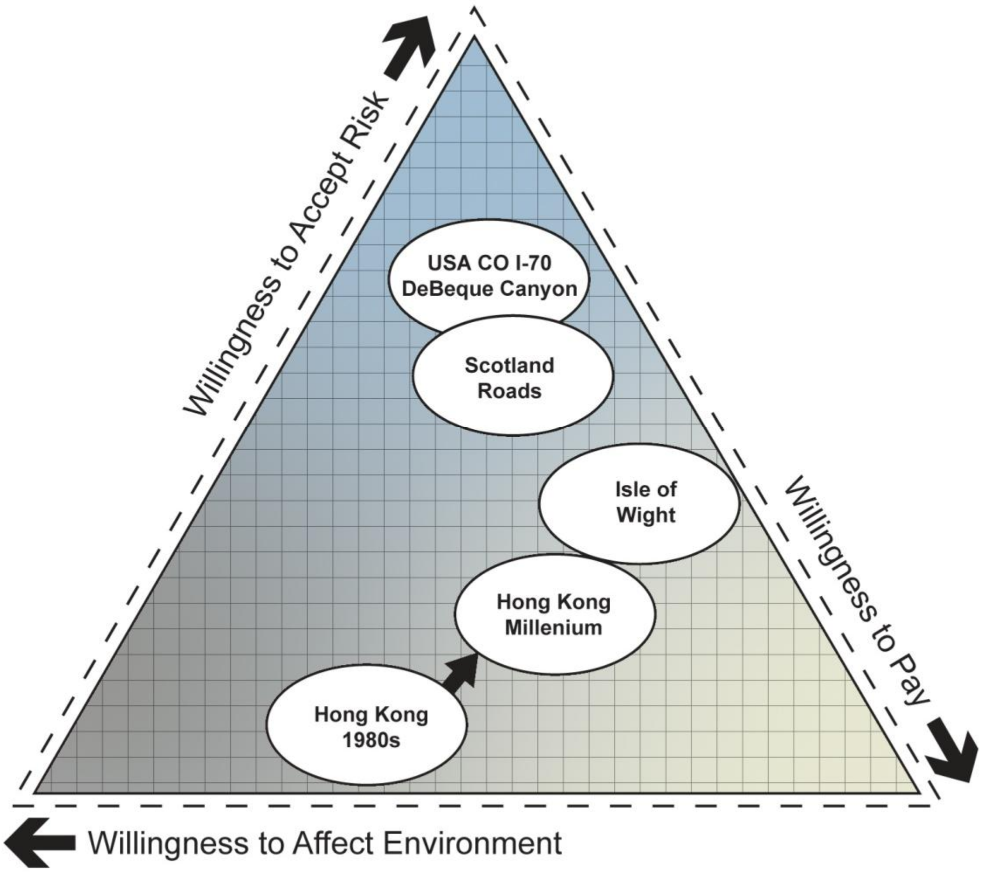
After the workshop, the identified risks must be treated. This is when the most cost-effective actions needed to address the risks are determined. The Guide provides six principles (gleaned from climate change adaptation processes) for treating climate change risk. They are:

- Achieve balance between climate and non-climate risks.

- Manage priority climate change risks.
- Use adaptive management.
- Look for win-win or no-regrets treatment options.
- Avoid adaptation constraining decisions.
- Review your treatment strategy (p. 51).

A final thought when considering risk and adaptation strategies is presented in the Willingness Diagram (Figure 4-12). This figure shows the tradeoffs between willingness to accept (or tolerate) risk, willingness (and/or ability) to pay, and willingness to alter the environment in the pursuit of lower risk. How a managing agency views each one of these factors will influence where a particular project falls in the triangle. Individual projects (not described in this report but included to illustrate the concept) appear as white bubbles showing their status with respect to the metrics. At present, when it comes to roadway infrastructure, projects tend to fall at the upper point of the triangle – a high willingness to accept risk and a low willingness to pay. This may be partly driven by the fact that the risks seem low and there are low cost, incremental approaches available.

Figure 4-12: Willingness Diagram for Risk Assessment



Source: Scottish Road Network Landslide Study: Implementation (p. 44)

4.6 Adaptation Strategies Identified

4.6.1 Domestic Strategies

Numerous adaptation strategies have been identified as a result of these risk assessments. As with adaptation planning in general, at this stage most plans identify adaptation strategies at a high level – a planning level, rather than an implementation level. For instance, agencies might identify the need to update design standards for the new climate future, but not specify which standards or what the new standards should be.

In general, adaptation strategies can be split into several categories:

- Incorporate Into Planning. Numerous adaptation plans recognize the general need to incorporate the changing climate into long-range planning. Florida's Climate Action Plan, for instance, recommends that FDOT should update the Florida Transportation Plan to develop long range goals, objectives, and strategies for adapting to potential impacts from climate change. Likewise, California proposes to incorporate climate change vulnerability assessment planning tools, policies, and strategies into existing transportation and investment decisions (e.g. Regional planning, programming, project planning).[20] Similarly, Oregon's *Framework for Addressing Rapid Climate Change* recommended that state agencies integrate climate change preparation into existing sustainability plans, agency risk management plans, or other long-range plans. Maryland also recommends integration of adaptation strategies into local comprehensive plans and implementing codes and ordinances; as well as integration of adaptation strategies into state plans and underlying management and regulatory programs. Some provide more specific recommendations on what these long range planning considerations might be. Punta Gorda recommends constraining locations for certain high risk infrastructure. H-GAC, for instance, recommends considering the appropriateness of different modes of transportation given climate change impacts and the increased costs to maintain and operate each mode, and suggests considering a longer term view of infrastructure needs over the next 50-100 years (in terms of maintenance, construction, and rehabilitation costs). Nor is this limited to long-range transportation planning; the City of Punta Gorda is incorporating climate change into its comprehensive plans. King County, WA is among the most advanced in this respect. There, climate change is incorporated into planning documents such as the Transportation Needs Report and Six Year CIP.
- Improve Design Standards. A number of plans list changes to design standards as a needed strategy to adapt to climate change – but at this stage few provide specifics. California, for instance, recommends developing transportation design and engineering standards to minimize climate change risks to vulnerable transportation infrastructure. For instance, both H-GAC and the City of Punta Gorda recommended using paver blocks (which

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[20] http://www.dot.ca.gov/hq/tpp/offices/orip/Updated_Climate_Change/climate_change.html

act as a form of permeable pavement) for parking lots to address stormwater runoff and the urban heat island effect (which will be exacerbated by global warming). Among those that do get to a greater level of detail, Maine DOT recommends upgrading design standards from Q50 to Q100 to build in resiliency in the face of extreme weather events. Again, King County is in the forefront here, and is already incorporating climate change considerations into the project designs of bridges and culverts being rebuilt.

- Retrofit Infrastructure. Many plans also show an awareness of the need to integrate planning policy into the decision to retrofit, rather than approaching the issue from a purely engineering perspective. For instance, the Maryland plan identifies several engineering strategies for retrofitting coastal infrastructure to protect against sea level rise, such as structural bulkheads, seawalls, or revetments. However, it also notes that larger decisions on whether to protect, relocate, or abandon infrastructure need to be made as well. In another example, to address flooding risks Washington State DOT's strategies focus on restoring natural processes. This includes limiting shoreline armoring, restoring shorelines, and targeted removal of dikes.
- Maintenance. Fewer strategies have been developed for maintenance procedures, although some of the design changes suggested are meant to reduce future maintenance costs. The Maine DOT is currently conducting a pipe and culvert vulnerability assessment, and the Maine DOT Bridge Maintenance Division completed a scour report. Based on this information, the DOT is preparing bridge-specific scour plans.[21] The Rogue River Basin, Oregon, plan recommends expanding road upgrading and maintenance such as the installation of larger culverts and regular culvert clean outs to prevent wash outs during major storms and floods.
- Operations. Although it is to be expected that transportation operations will need to change to respond to climate change – road weather programs, to name an obvious example - very few plans address operations at this point. Primarily, operations are included in terms of strategies dealing with evacuation planning. California, for instance, recommends incorporating climate change impact considerations into disaster preparedness planning for all transportation modes. The City of Punta Gorda, FL, provides a similar recommendation. In a different approach to the issue, the Rogue River Basin, Oregon, plan suggests linking public transportation systems as much as possible to facilitate movement of people and equipment in emergency situations.

Overall, it appears that most strategies identified have not yet been taken to the engineering level. This is consistent with the general state of practice of adaptation planning in the US; given that most agencies have only started adaptation planning in the last few years, it will take some time to bring these strategies to the implementation level. It is also likely that as this happens, maintenance and operations will receive more study.

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[21] Climate Change and Transportation in Maine

As a result, some adaptation strategies included in these plans are really process recommendations to further adaptation planning. For example, Florida identifies research as an immediate adaptation action. Alaska recommends creating a coordinated and accessible statewide system for key data collection, analysis, and monitoring. Some governments have also identified the need for training and establishing criteria so agencies can better integrate climate change impacts into their planning efforts. King County, WA is a good example of this. The Climate Plan identified the need for training and educating the Road Services Division staff on expected changes in climate, how these changes potentially affect the facilities they manage and identify adaptation solutions to address near and long-term impacts.

Finally, some plans show an additional focus on the need for monitoring to assess how the climate is actually changing and whether adopted adaptation strategies will therefore need to be modified. For instance, New York City's risk-based approach to adaptation, "Flexible Adaptation Pathways," is an iterative process that recognizes the multiple dimensions of climate hazards, impacts, adaptations, economic development, and other social factors. This iterative process is predicated on the establishment of climate change monitoring programs that can provide feedback to the process to allow for changing "pathways."

The adaptation strategies under study by King County, WA's Road Services Division provides an illustrative example of the range of adaptation strategies an individual transportation agency might consider:

- Replacing or rehabilitating bridges in order to improve floodwaters conveyance and to avoid scour during high flows.
- Using pervious pavement and other low impact development methodologies to manage stormwater through reduced runoff and on-site flow control.
- Modifying existing seawalls to avoid failures in transportation facilities.
- Evaluating roadways to minimize their vulnerability to potential risk from landslides, erosion, or other failures triggers.
- Developing new strategies to effectively respond to increasingly intense storms, including providing alternative transportation access.
- Managing construction and operations to minimize effects of seasonal weather extremes.
- Identifying opportunities to incorporate habitat improvements that buffer the effects of climate change on ecosystem health into project designs.

4.6.2 International Strategies

Of the international reports reviewed, only three provided strategies for dealing with climate change impacts to roadway networks. And in most cases, the strategies were general calls for additional research in design and maintenance practices. As *The Road Well Traveled: Implications of Climate Change for Pavement Infrastructure in Southern Canada* put it, "The key adaptation issues will surround not how to deal with potential impacts, but rather when to modify current design and maintenance practices," and the report recommends that study results should be discussed in the engineering community to move from exploratory research to practical guidance. (p. 65)

The Canadian Council of Professional Engineers' report, *Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure*, which looked at the impacts of climate change on four types of infrastructure, classified its conclusions into seven themes and five recommendations – none of which call for far-reaching design approaches or solutions.

Themes

- Some infrastructure components have high engineering vulnerability to climate change.
- Improved tools are required to guide professional judgment.
- Infrastructure data gaps are an engineering vulnerability.
- Improvement is needed for climate data and climate change projections used for engineering vulnerability assessment and design of infrastructure.
- Improvements are needed in design approaches.
- Climate change is one factor that diminishes resiliency.
- Engineering vulnerability assessment requires multi-disciplinary teams.

Recommendations

- Revise and update the Engineering Vulnerability Assessment Protocol.
- Conduct additional work to further characterize the vulnerability of Canadian public infrastructure to climate change.
- Develop an electronic database of infrastructure vulnerability assessment results.
- Assess the need for changes to standard engineering practices to account for adaptation to climate change.
- Initiate an education and outreach program to share results of this assessment with practitioners and decision-makers.

An important point made in the report is that many of the potential impacts of climate change can be alleviated through improved system preservation activities and that climate change is only one factor that diminishes resiliency. "In recent years, concerns have been raised in Canada about the present levels of maintenance and future needs for infrastructure. … Climate change is likely to intensify the engineering vulnerability if current levels of maintenance continue. Properly maintained infrastructure enables the infrastructure and its components to function as designed, which includes accounting for changing climate events (p. 68)."

The Scottish Road Network Climate Change Study also emphasizes this point in its discussion of the impacts of predicted climate change factors on the road network. The impact of heat on roadway rutting is frequently mentioned as a climate change concern. However, the report observes that "most rutting problems on the trunk road network are the result of pavement failure due to the volume of heavy goods vehicles (p. 62)." Impacts of roadway flooding due to increase amounts or intensity of rainfall is also an often-mentioned climate change concern. But, as the report notes, "the most common cause of flooding in areas where drainage is present is due to detritus washing into the system, resulting in partial or complete blockage (p. 65).” The report posits that “The effective maintenance of watercourses and ditches is essential to the operation of culverts and it is recommended that measures to target areas where known problems exist through preemptive clearing of detritus in advance of predicted heavy rainfall should be considered by all maintaining authorities (p. 68).” It also recommends, given the expected changes in rainfall, that the design storm be amended from a return period of between 1 in 100 years to 1 in 200 years (p. 67).”

The Scottish Road Network Climate Change Study was the only report that discussed the impact of a lengthened growing season on the roadway network. It notes that in recent years it has been necessary to cut roadside grasses three times a year, up from two cuts a year. At most locations, landscape maintenance requires traffic management, which impacts the traveling public. To offset the potential effects of a longer growing season, “it is recommended that slow-growing elements are used where appropriate, in order to minimize the extent of cyclic maintenance required (p. 63-64).”

The report also notes that many roadway risks associated with severe weather, which is predicated to increase under climate change scenarios, cannot be completely eliminated through design, but should be addressed through ongoing road user education. These include conditions that result in poorer skidding resistance (such as heavy rains, roadway flooding, and winter conditions); reduced visibility due to fog; and unexpected forces being applied to vehicles in high wind conditions. The report suggests that “ongoing road user education is an essential component in raising the awareness of the need to modify behavior during severe weather events. It is also considered that the provision of relevant information to road users in respect of such events would assist in encouraging modified behavior (p. 76).” In fact, the only condition in which large-scale adaptation strategies are suggested relates to coastal flooding situations and even then it proposes other approaches – including user education - first. “Areas at risk may then be addressed through a combination of warning signage, edge strengthening, or introducing sea-defenses. In extreme cases, consideration could be given to whether re-routing is appropriate. It is also recommended that any new projects proposed in low-lying areas should be reviewed with respect to these risk factors, to enable appropriate decisions to be taken at the design stage (p. 75).”

4.7 Implementation

4.7.1 Domestic Examples

Despite the progress described above, very few locations have moved beyond studies and recommendations and consciously begun implementing adaptations to climate change for transportation infrastructure and operations. One notable exception is Louisiana who, after the damage with Hurricane Katrina, drafted a plan to address the threat of sea level rise and enhanced storm surges. The plan called for elevating several roadways in the coastal region and some projects are underway (e.g. state route 1A to Port Fourchon). Also, all bridge projects in the coastal area require relative sea level rise and surge studies to determine if and how designs should be altered.

Another example comes from the Port Authority of New York and New Jersey. In response to increased flooding, the Port Authority raised the floodgates at the top of stairways leading to station platforms at the PATH Hoboken Station to account for sea level rise and sealed all gates that were below the one hundred year floodplain. The Washington DOT has taken an interesting project approach to adaptation by advancing the construction of pontoons to restore the SR 520 bridge over Lake Washington in the event of a catastrophic failure. This project anticipates the failure of this bridge in the event of an extreme storm event and therefore is proactively addressing the issue by constructing and storing the pontoons which are the foundation of the floating bridge and can take several years to construct.

Two places that have begun to implement adaptation actions in the U.S. on a jurisdiction-wide basis are King County, WA, and Alaska. These are discussed below.

King County, WA

King County has begun implementation of its 2007 Climate Plan. As part of that process, the Interdepartmental Climate Team produces annual Climate Reports describing progress towards the goals of the Climate Plan. According to these annual reports, the transportation-related measures that have been accomplished include:

- Institutional capacity building. King County has initiated educational efforts to facilitate the sharing of information among staff on the projected impacts of climate change.
- Design. In 2009, the county continued to assess and plan for impacts that events caused by climate change could have on its assets and infrastructure. Examples include analyzing the impacts that rising sea level would have on road infrastructure, and incorporating projected changes in the Department of Transportation’s infrastructure design. The county is choosing pavement materials that are more resilient to heat.
- Construction and retrofitting. Actions already underway by King County Road Services Division include evaluation of higher flows on bridge and culvert design as well as seawall modifications. The Road Services Division is currently rebuilding over 57 bridges and 40 culverts to improve steamflows and endure the most significant impacts of climate change.

Alaska

The Alaska Department of Transportation and Public Facilities is in an unusual position in that its program includes non-transportation public facilities, giving it a wider jurisdiction than most DOTs. Among its most immediate concerns are six communities that are in jeopardy of accelerated coastal erosion from winter storms, due to lack of protective sea ice. Three of those communities have already begun to develop relocation plans. As a result, much of its adaptation activities focus on shoreline protection and relocation. One airport whose runway was directly threatened by coastal erosion has already been relocated. A partially completed USACE project is underway to armor the shoreline of one of the communities as well. In addition, ADOT & PF has dedicated $10 million in funding to combat permafrost thawing under highways, and is also actively working on drainage improvements and evacuation routes and shelters. [22]

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[22] Coffey, Michael, 2010: Arctic Civil Infrastructure and Adaptation to Climate Change; and Arroyo, Vicki, 2010: An Update From Our Laboratories of Democracy, AASHTO Climate Change Symposium.

4.7.2 International Examples

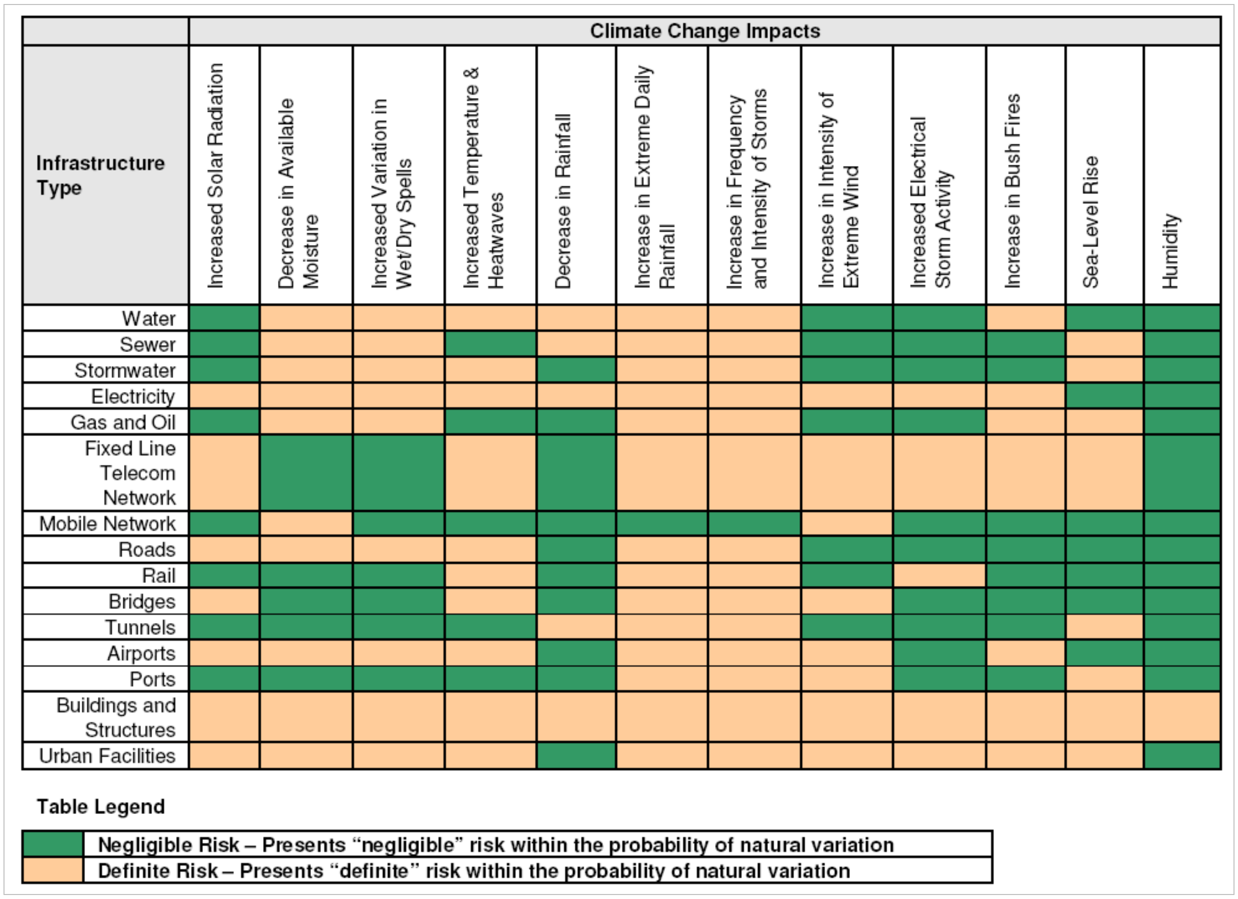
Similar to the U.S. experience, the literature review revealed few examples of infrastructure projects being changed or modified due to climate change. This is partly driven by the reports reviewed; many of them focused on procedures and protocols rather than identifying or documenting specific adaptation action plans. However, based on the findings in the reports, there are additional reasons why there may not be many examples of projects being modified.

First, in many cases climate change impacts on roadways have been found to be moderate, especially when compared to the needs other public infrastructure. Figure 4-13 is a table from the Infrastructure and Climate Change Risk Assessment for Victoria report. It indicates that there are six types of infrastructure that will be more impacted by climate change factors than roadways (buildings and structures, urban facilities, electricity, airports, the fixed line telecommunications network, and water) and three affected by the same number of factors (sewer, stormwater, and gas and oil).

Second, roads have comparatively shorter life spans than other infrastructure so less adaptation measures are needed in the near term. Also, “usually roads can be more readily repaired following a disruption.” (*Adapting to Climate Change: Canada’s First National Engineering Vulnerability Assessment of Public Infrastructure* p. 50)

However, while not part of this review, it is important to note that Canada’s Confederation Bridge, a 13 km bridge between Borden, Prince Edward Island and Cape Tormentine, New Brunswick, is an example of a completed project that took climate change into account during the planning and design phase. The bridge, which replaced an existing ferry connection, consists of a high-level two-lane road structure built on piers over the entire crossing of the Northumberland Strait. It provides a navigation channel for ocean-going vessels with vertical clearance of about 50 meters. During the planning and design process, which was begun in 1985, sea-level rise was recognized as a concern. So that vertical clearance could be maintained into the future, the bridge was built one meter higher than was currently required to accommodate sea-level rise over its hundred-year lifespan. The bridge opened to traffic in 1997.

Figure 4-13: Exposure and Risk Assessment Example, Victoria, Australia



	Climate Change Impacts											
Infrastructure Type	Increased Solar Radiation	Decrease in Available Moisture	Increased Variation in Wet/Dry Spells	Increased Temperature & Heatwaves	Decrease in Rainfall	Increase in Extreme Daily Rainfall	Increase in Frequency and Intensity of Storms	Increase in Intensity of Extreme Wind	Increased Electrical Storm Activity	Increase in Bush Fires	Sea-Level Rise	Humidity
Water	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟩	🟩
Sewer	🟩	🟧	🟧	🟩	🟧	🟧	🟧	🟩	🟩	🟩	🟧	🟩
Stormwater	🟩	🟧	🟧	🟧	🟩	🟧	🟧	🟩	🟩	🟩	🟧	🟩
Electricity	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩
Gas and Oil	🟩	🟧	🟧	🟩	🟩	🟧	🟧	🟩	🟩	🟧	🟧	🟩
Fixed Line Telecom Network	🟧	🟩	🟩	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟩
Mobile Network	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩
Roads	🟧	🟧	🟧	🟧	🟩	🟧	🟧	🟩	🟩	🟩	🟩	🟩
Rail	🟩	🟩	🟩	🟧	🟩	🟧	🟧	🟩	🟧	🟩	🟩	🟩
Bridges	🟧	🟩	🟩	🟧	🟩	🟧	🟧	🟧	🟩	🟩	🟩	🟩
Tunnels	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟩	🟩	🟩	🟧	🟩
Airports	🟧	🟧	🟧	🟧	🟩	🟧	🟧	🟧	🟩	🟧	🟩	🟩
Ports	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟩	🟩	🟧	🟩
Buildings and Structures	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Urban Facilities	🟧	🟧	🟧	🟧	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟩

Table Legend

🟩	**Negligible Risk – Presents “negligible” risk within the probability of natural variation**
🟧	**Definite Risk – Presents “definite” risk within the probability of natural variation**

Source: Infrastructure and Climate Change Risk Assessment for Victoria p. 17

5.0 Conclusions

The climate change adaptation field is in its infancy and continues to evolve rapidly. New approaches and techniques for assessing the threats it poses are constantly being offered. This report has attempted to describe the state of the practice as it stands in the fall of 2010. Overarching conclusions include:

- There is a growing consensus amongst academic researchers and highway agencies that climate change is a threat to many aspects of the highway system which warrants spending resources to investigate the specific risks it poses. Still, the majority of US highway agencies remain unaware (or dismissive) of the potential threats and have yet to take any adaptation actions.
- The lack of engineering relevant and spatially precise climate data and the uncertainty surrounding those data remain obstacles and will likely remain so for the foreseeable future despite the best efforts of climate modelers. This should not, however, be an excuse for inaction. Some governments, such as New York City, realize the data shortcomings issue and have put forth alternative approaches (e.g. flexible adaptation pathways) to enable prudent decision making in light of the uncertainty.
- Leadership is critical. Strong national mandates to consider adaptation and provide relevant data greatly encourage adaptation activities. That said, they need not be a prerequisite. Absent mandates, strong state or local leadership by individuals concerned about climate changes can also spur action as is the case in most US examples. Visible on-the-ground changes, as in Alaska, can also focus attention on the topic.
- Most agencies that are concerned about adaptation begin by conducting a risk assessment of existing assets. Most of these risk assessments remain largely qualitative and based on professional judgment. This will likely remain the case until more probabilistic climate projections become available.
- Both domestically and internationally, limited action has been taken on the ground thus far to build climate resiliency into the transportation system. Indeed, with some notable exceptions, much adaptation work remains at a planning or risk assessment level and has yet to be incorporated into the design of individual projects. This is likely to change in the near future as the risk assessment studies progress and the global economy picks up providing more resources for adaptation.
- Some risk assessments to date have shown the highway system to have only modest vulnerabilities to climate change. Others have indicated enough cause for concern to recommend action be taken. Whether an agency chooses to take adaptation action depends on their fiscal and political capacity to effect change and their level of tolerance for risk. It is quite possible that separate agencies, facing the same risks, might choose very different courses of action, especially absent any set of national or industry standards.
- Risks to the highway system due to sea level rise and increased precipitation amounts/intensity appear to be the biggest cause for concern and amongst the first priorities for action.

Future phases of this project will take note of these observations and build off of them to generate new techniques for ensuring highway system resiliency as we enter a new period of climate uncertainty.

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7.0 Technical Appendices

7.1 Scottish Road Network Landslides Study: Implementation

SCOTTISH ROAD NETWORK LANDSLIDES STUDY:
IMPLEMENTATION

SCOTTISH ROAD NETWORK LANDSLIDES STUDY:
IMPLEMENTATION

Editors
M G Winter (Transport Research Laboratory),
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Transport Scotland, Edinburgh 2008

Cover Photograph (© Perthshire Picture Agency, PPA: www.ppapix.co.uk):

The A85 in Glen Ogle blocked by two debris flows on 18 August 2004. RAF and Royal Navy helicopters are pictured airlifting some of the 57 occupants from the 20 trapped vehicles to safety.

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MINISTERIAL FOREWORD

The implications of landslides on the operation of the road network and thus on the economy of Scotland were brought into sharp focus in August 2004, when significant rainfall led to serious events on roads in the north and west of Scotland.

Improving communications, enhancing the country’s transport infrastructure and supporting a stable economy are vital elements of the work of the Scottish Government and Transport Scotland. For these reasons the importance of advancing our understanding of landslides in Scotland was immediately recognised.

The Scottish Road Network Landslides Study, a programme of detailed research, began immediately after the events of 2004 and continues today. The study sets a benchmark in terms of the assessment of such large areas at relatively large scale.

The results documented here provide us with a comprehensive picture of the future risk of landslides in Scotland and the evidence that we require to properly plan for and manage that risk, reducing as far as possible the impact on our roads and road users.

This study has been delivered primarily by experts from Scotland’s geotechnical community. They have drawn on their own international experience, and that of others, and experience from other disciplines, as appropriate. They have used technology in innovative ways to achieve the objectives of the study. The body of work produced places Scotland amongst other leading nations involved in the study of landslides and landslide management. I would like to thank all of those involved.

A number of the recommendations made in this study have already been taken on board and activities are underway in key locations to manage the exposure of road users to landslide hazards.

I believe that continued investment in this study, its recommendations and the associated study of the broader implications of climate change on the road network will ensure that Scotland is well placed to deal effectively with landslide events in the future.

Stewart Stevenson
Minister for Transport, Infrastructure and Climate Change

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Scotland TranServ: Scotland TranServ is the operating company responsible to Transport Scotland for the management and maintenance of the Trunk Road Network in North West Scotland. Scotland TranServ is a joint venture which brings together the expertise of two of the UK's leading providers of management and maintenance services of roads and bridges, namely the Balfour Beatty Group and the Mouchel Group, who both have wide ranging experience of working for Transport Scotland.

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EXECUTIVE SUMMARY

In August 2004 Scotland experienced rainfall substantially in excess of the norm. The rainfall was both intense and long lasting and as a result a large number of landslides, in the form of debris flows, were experienced in the hills of Scotland. A small number of these intersected the trunk (strategic) road network, notably the A83 between Glen Kinglas and to the north of Cairndow (9 August), the A9 to the north of Dunkeld (11 August), and the A85 at Glen Ogle (18 August).

The most dramatic events occurred at Glen Ogle, where 57 people had to be airlifted to safety when they became trapped between two major debris flows (see cover picture). It was, perhaps, fortuitous that there were no major injuries to those involved. However, the real impacts of the August events were economic and social, in particular the severance of access to and from relatively remote communities.

The need to acknowledge such natural processes and act accordingly was recognised by Transport Scotland and an initial landslides study was commissioned alongside a second study on climate change. The landslides study comprises two parts. The initial study collated and presented the background information and developed the plan for the second part. The second part of the landslides study presents the proposed means of debris flow management on the trunk road network and is documented in this report.

The overall purpose of the landslides study is to ensure that Transport Scotland has systematically assessed and ranked the hazards posed by debris flows and has in place a management and mitigation strategy for the Scottish trunk road network. The purpose of the ranking system is to allow the future effects of debris flow events to be appropriately managed and mitigated as budgets permit, thus ensuring that the exposure of road users to the consequences of future debris flows is minimised.

It is important to recognise that it is not possible to prevent landslide events from occurring and some may occur in such close proximity as to affect the operation of the trunk road network.

The work undertaken and set out in this report is therefore targeted at developing the evidence base for allocating resources to reduce the exposure of road users to landslide hazards and/or to reduce the physical hazard. Notwithstanding this, the latter actions involve higher cost solutions and are likely to be applied only in rare cases.

CONCLUSIONS AND RECOMMENDATIONS

The landslide events of August 2004 had a substantial effect on the operation of Scottish trunk road network and led to wide-ranging media and political interest. The nature of these events broadly conformed to the relatively fast-moving, shallow debris flow-type of landslide with which this report primarily deals. There have since been other debris flows of a similar nature including, for example, those that affected the A9 in 2006 and the A83 in 2007, as well as a wide range of similar occurrences that affected the local road network. In general the events detailed in this report confirm that landslides typically occur in Scotland in two seasons, namely:

- Summer: July and August.
- Winter: November to January (with events sometimes occurring in October).

The work reported here forms a component of Transport Scotland's response to the August 2004 events and builds upon the earlier report (Winter *et al*., 2005) which described the background and objectives behind the work presented in this report. The findings from the work have already been widely presented on both nationally and internationally.

Consideration of the socio-economic aspects of landslide risk illustrates the diverse approaches taken by different societies and cultures. These considerations support the principle that the landscape itself has both a social and an environmental value and that a drive towards risk mitigation and/or reduction is only one part of the wider picture.

Notwithstanding this, the core of the work addressed by this report is the assessment and ranking of hazards presented by debris flows.

The hazard assessment process involves the GIS-based spatial determination of zones of susceptibility which are then related to the trunk road network by means of plausible flow paths to determine specific hazard locations. The approach taken, using a GIS-based assessment, enabled large volumes of data to be analysed relatively quickly and was able to rapidly deliver a scientifically-sound platform for the assessment. This desk-based approach to hazard assessment was then supplemented by site-specific inspections, including site walkovers, to give a hazard score for each site of interest.

The subsequent hazard ranking process involved the development of exposure scores predicated primarily upon the risk to life and limb, but also taking some account of the socio-economic impact of debris flow events.

Finally, these scores were combined with the hazard scores to give site-specific scores for hazard ranking from which a listing of high hazard ranking sites in Scotland was produced.

An approach to the management and mitigation of debris flow hazards has also been developed. Two approaches are described:

- Exposure reduction, which involves for example education, warning, signing and road closure.
- Hazard reduction, which includes engineering measures that protect the road, reduce the opportunity for debris flow to occur, or involve realignment of the road.

Most of the recommendations (see Section 10.2) are based upon the reduction of the exposure of the road users to debris flow hazards as a reaction to events and utilise lower cost and less environmentally intrusive approaches rather than the typically high cost, environmentally intrusive approach of specific hazard reduction. Exposure reduction is predicated upon the simple and easily-remembered, three-part management tool, Detection-Notification-Action (DNA).

Weather and climate are clearly key influences upon the triggering of debris flows in Scotland and climate change models generally indicate that such events may become more frequent and/or more intense in the future. In the longer term the ability to forecast of debris flow from rainfall data is clearly desirable in order to allow, at least, the Detection and Notification aspects of the DNA process to be carried out in advance of events.

In support of this a variety of international approaches to the back analysis and forecast of landslide events resulting from rainfall have been researched and described. Back analysis of the rainfall associated with a selection of Scottish debris flow events has enabled a tentative debris flow trigger threshold, in terms of rainfall intensity-duration, to be proposed. This threshold, however, needs to be further validated against observations in the future and it is estimated that at least five years of data will be required prior to implementing such a system. Work is currently in progress to develop the dataset and validate the threshold. During the development period a system will also need to be put in place to allow 'real-time' capture and analysis of data to enable forecasting.

The work presented in this report gives Transport Scotland the means to apply appropriate management measures to the sites of highest risk on the trunk road network. Specific recommendations to achieve this and to further develop and improve the management process are given in the following section.

The main recommendations relate to:
- A series of management actions predicated towards exposure reduction.
- Opportunities for physical hazard reduction on new works and rehabilitation schemes.
- The vital role of the development of rainfall-monitoring systems and interpretative techniques to enable proactive warning of debris flows to be brought into play in future years.
- The value of studying the ongoing effects of climate change on the prevalence of debris flows, of carrying out an evaluation of the economic effects of debris flow events, and working with Forestry Commission in order to ensure that best practices are adopted in terms of forestry harvesting and hill slope stability.
- The need for a continuing site inspection programme to validate all four priorities of sites on the network, and the role of re-assessment and re-inspection at some time in the future.
- Consideration of actions relating to rock slope surveys.
- The need for separate assessment of scree-slope sections in Glen Coe and on Skye.

1 INTRODUCTION

by M G Winter, F Macgregor and L Shackman

In August 2004 Scotland experienced rainfall substantially in excess of the norm. Some areas of Scotland received more than 300% of the 30-year average August rainfall[1], while in Perth & Kinross figures of the order of between 250% and 300% were typical. Although the percentage of the monthly average rainfall that fell during August was lower in the west, parts of Stirling and Argyll & Bute still received between 200% and 250% of the monthly average[2].

The rainfall was both intense and long lasting and as a result a large number of landslides, in the form of debris flows, were experienced in the hills of Scotland. A small number of these intersected the trunk (strategic) road network, notably the A83 between Glen Kinglas and to the north of Cairndow (9 August), the A9 to the north of Dunkeld (11 August), and the A85 at Glen Ogle (18 August).

The most dramatic events occurred at Glen Ogle, where 57 people had to be airlifted to safety when they became trapped between two major debris flows (see cover picture). It was, perhaps, fortuitous that there were no major injuries to those involved. However, the real impacts of the August events were economic and social, in particular the severance of access to and from relatively remote communities.

While the overall rainfall levels for August were relatively high, the storm rainfall associated with these events was particularly significant. A retrospective analysis of rainfall radar data was undertaken by SEPA for Callander, some 20km distant from Glen Ogle. The analysis indicated that approximately 85mm of rain fell in the storm event and that 48mm of that rain fell in just 20 minutes, reaching a peak intensity of 147mm/hour.

The need to acknowledge such natural processes and act accordingly was recognised by Transport Scotland and an initial landslides study (designated at the outset as Study 1, Part 1) was commissioned alongside a second study on climate change. This latter study was designed to identify the potential impacts and consequent necessary actions in the light of anticipated climate change and is not considered further in this report, although it is important to note that action has been taken to ensure that the two studies are complementary (Galbraith *et al*., 2005a; 2005b).

The landslides study comprises two parts (Part 1 and Part 2). The initial study (Winter *et al*., 2005a; 2005b) collated and presented the background information and developed the plan for the second part. The second part of the landslides study presents the proposed means of debris flow management on the trunk road network and is documented in this report.

The overall purpose of the landslides study is to ensure that Transport Scotland has systematically assessed and ranked the hazards posed by debris flows and has in place a management and mitigation strategy for the Scottish trunk road network. The purpose of the ranking system is to allow the future effects of debris flow events to be appropriately managed and mitigated as budgets permit, thus ensuring that the exposure of road users to the consequences of future debris flows is minimised.

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[1] The 30-year average August rainfall in Scotland varies between 67mm on the east coast and 150mm in the west of Scotland (Anon, 1989).

[2] Source: http://www.metoffice.com/climate/uk/2004/august/maps.html.

It is important to recognise that it is not possible to prevent landslide events from occurring and some may occur in such close proximity as to affect the operation of the trunk road network.

The work undertaken and set out in this report is therefore targeted at developing the evidence base for allocating resources to reduce the exposure of road users to landslide hazards and/or to reduce the physical hazard. Notwithstanding this, the latter actions involve higher cost solutions and are likely to be applied only in rare cases.

Since the events of August 2004 a number of other events have affected the trunk road network. Examples include incidents on the A9 to the north of Inverness in 2006 and on the A83 at the Rest and be Thankful in 2007. Such events should not be seen as isolated occurrences and planning to take account of further such episodes in the future should be regarded as sound management practice.

The sections contained in this report are briefly described in the following paragraphs.

The different types of landslides that can occur are described in Section 2, including the debris flow-type landslides with which this report is mainly concerned. The events of August 2004, that led to the work reported here being commissioned, are described in some detail and some other events that have occurred since that date are briefly described. The main times of year during which such events occur in Scotland are also indicated.

The response to the 2004 events is detailed in Section 3 and the initial work that was undertaken in the immediate aftermath is described in the context of the two Transport Scotland reports produced (Winter *et al*., 2005a; 2005b). This section goes on to describe the background and intentions behind the work presented in later sections of this report. The key dissemination activities that have been undertaken in order to raise awareness of landslides and their consequences are listed along with the main target audience, generally the membership of relevant professions, the public and politicians. Such activities promote the work undertaken both nationally and internationally in support of Transport Scotland's approach to professional excellence. Section 3 also explores landslide risk issues in a socio-economic context using international examples.

The first key objective of the work commissioned was to assess and rank debris flow hazards. Section 4 describes the methodology used to undertake this pan-Scotland, GIS-based, assessment of debris flow hazards (further details are given in Appendix A). The results from this are also presented in summary form in Section 4. This assessment presents information, essentially on debris flow susceptibility, in the form of a virtual map that can be viewed in three dimensions with the addition of a suitable digital elevation model (DEM).

The interpretation of the GIS-based assessment was then achieved by examination of this, and other, imagery to evaluate plausible flow paths from zones of susceptibility to the road. Sections of road alignments subject to hazards were thus able to be determined. The process undertaken and the results obtained are presented in Section 5. At this point initial hazard scores were assigned to each site at which a hazard had been determined (the detailed results are presented in Appendix B).

The work presented in the sections described above is, however, purely desk-based. To complete the hazard assessment site-specific inspections, including site-walkovers, formed an essential concluding part of the process. The methodology for this process is described in Section 6 and the results of the site inspections carried out during 2007 are reported in Appendix C. The outputs from the site inspections were then used to modify the hazard scores assigned in Section 5.

The hazard scores were then further modified by the use of scores related to the exposure of road users to debris flow hazards and the socio-economic impact of the events to give a hazard ranking. This hazard ranking is considered to be an analogue for risk. This whole process is described in Section 7 and final hazard scores, exposure scores and hazard ranking scores are presented in Appendix D. Also included is a listing of high hazard ranking sites in Scotland.

The second key objective of the work presented herein was to develop an approach to the management and mitigation of such debris flow hazards. Section 8 describes risk reduction techniques for sites of high and very high hazard. Two approaches are described:

- Exposure reduction which includes education, warning, signing and road closure for example.
- Hazard reduction which includes engineering measures that protect the road, reduce the opportunity for debris flow to occur, or involve realignment of the road.

Most of the recommendations are based upon the reduction of exposure as a reaction to events, using lower cost and more environmentally acceptable approaches rather than the generally high cost, environmentally intrusive approach of specific hazard reduction. A review of international approaches to the signing of landslides in a road environment is presented in Appendix E, while Appendix F presents the draft content of a proposed educational leaflet for road users which is intended to be made available online initially and possibly at key locations on the network at a later date.

In the longer term it is proposed that the approach to exposure reduction should use proactive techniques and Section 9 describes climatic influences on landslides, including the potential impacts of climate change on both the prevalence and intensity of debris flow in Scotland. Methods for forecasting landsides from rainfall data are described and a series of international case studies is presented in Appendix G. Progress towards the development of a rainfall trigger threshold for debris flow in Scotland is set out and a tentative threshold described in terms of rainfall intensity-duration is included (the background and detail to this work is given in Appendix H). It is anticipated that the development of adequate data and confidence in its application to forecast landslides from such rainfall thresholds in Scotland will take some significant time.

Section 10 draws conclusions from the work presented and makes recommendations for action at a number of different levels including aspects relating to the design, construction, operation and maintenance of the trunk road network. Recommendations for work to further develop the understanding of debris flow events in Scotland and the management of their effects form part of Section 10.

2 LANDSLIDE EVENTS

by M G Winter, A P Heald, J A Parsons, D Spence, F Macgregor and L Shackman

2.1 LANDSLIDES AND DEBRIS FLOW

In recent times, extreme rainfall in Scotland has led to events that have been described in the media under the generic term ‘landslide’. The major events of August 2004 intersected with the A83, A9 and A85 trunk roads (see Section 2.2).

While these recent happenings have been of both high magnitude (in terms of the amount of material moved) and severe (in terms of their impact on the trunk road network and the exposure of its users) it is important to understand that they are by no means unique. Similar events have also been observed in recent years at Invermoriston, intersecting the A887, and at Stromeferry, intersecting the A890 local road (e.g. Nettleton *et al*., 2005a). Other events have been observed, at various times, at A83 Rest and be Thankful, A9 Slochd, A95 Craigellachie and A84 Strathyre, for example.

The word ‘landslide’ covers a range of types of gravitational mass movement. Many systems have been proposed for the classification of landslides, however, the most commonly adopted systems are those of Varnes (1978) and Hutchinson (1988).

The International Geotechnical Societies’ UNESCO Working Party on World Landslide Inventory (WP/WLI) was formed for the International decade for Natural Disaster Reduction (1990 to 2000). The WP/WLI (1990) report ‘A Suggested Method for Reporting a Landslide’ uses Varnes’ (1978) classification and reports that it is the most widely used. The World Road Association (PIARC) report ‘Landslides: Techniques for Evaluating Hazard’ (Escario *et al*., 1997) also presents a classification based on Varnes.

Figure 2.1 presents the five kinematically distinct types of landslide identified by Varnes (1978), as follows (after Escario *et al*., 1997):

a) *Falls:* A fall starts with the detachment of soil or rock from a steep slope along a surface on which little or no shear displacement takes place. The material then descends largely by falling, bouncing or rolling.

b) *Topples:* A topple is the forward rotation, out of the slope, of a mass of soil and rock about a point or axis below the centre of gravity of the displaced mass.

c) *Slides:* A slide is the downslope movement of a soil or rock mass occurring dominantly on the surface of rupture or relatively thin zones of intense shear strain.

d) *Flows:* A flow is a spatially continuous movement in which shear surfaces are short lived, closely spaced and usually not preserved after the event. The distribution of velocities in the displacing mass resembles that in a viscous fluid.

e) *Spreads:* A spread is an extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material. The rupture surface is not a surface of intense shear. Spreads may result from liquefaction or flow (and extrusion) of the softer material.

However, Varnes (1978) also presented a sixth mode of movement, ‘Complex Failures’. These are failures in which one of the five types of movement is followed by another type (or even types). For such cases the name of the initial type of movement should be followed by an 'en dash' and then the next type of movement: e.g. rock fall-debris flow (WP/WLI, 1990).

The EPOCH (1993) project (The Temporal Occurrence and Forecasting of Landslides in the European Community) produced a European classification based on Varnes (1978). For the purpose of this work Varnes' (1978) classification has been adopted with amendments from Cruden and Varnes (1996). This approach is consistent with the UNESCO Working Party on World Landslide Inventory (WP/WLI, 1990; 1991; 1993).

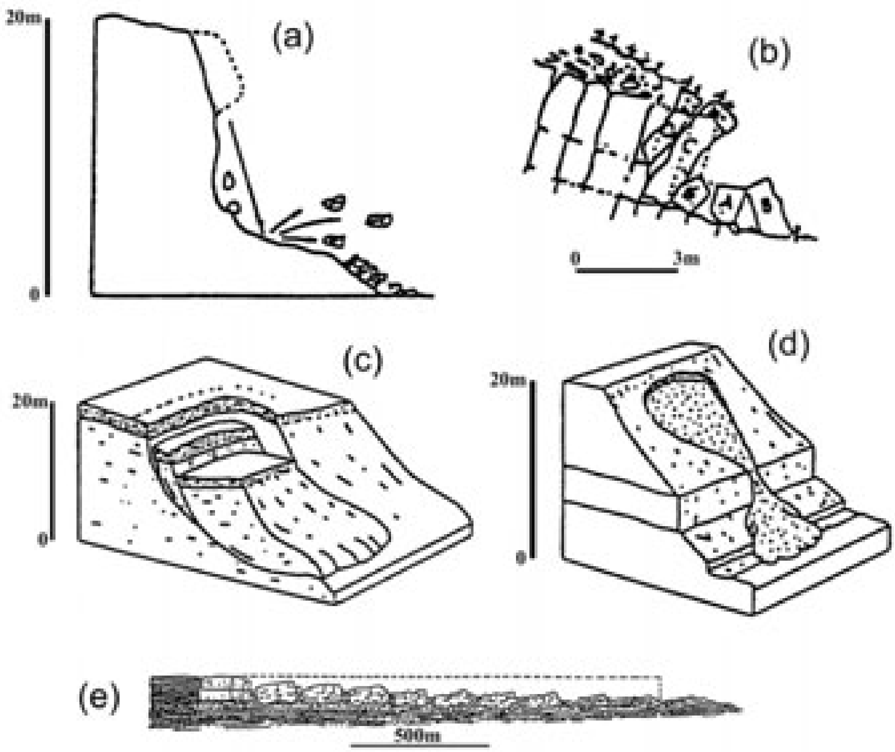

Figure 2.1 – Types of landslide: (a) falls, (b) topples, (c) slides, (d) flows, and (e) spreads (after Escario *et al.*, 1997).

The recently observed landslide events have been typical of flow-type landslides. The influence of substantial flows of water, the stripping of superficial deposits, and the speed with which debris has both flowed and been deposited have all been apparent. In many cases the initial trigger appears to have been the displacement of relatively small amounts of material, often into a stream channel. This has added a substantial debris charge to already high and potentially damaging water flows. The combination of water with high sediment loadings then has substantial erosive power. In other cases highly saturated materials have slumped rapidly downslope in a manner not dissimilar to that illustrated in Figure 2.1(d).

Such events are typically described as 'debris flows' and are distinguished from most other types of landslides involving shear by the dynamic, as opposed to broadly static, nature of the failure mechanisms. This is an important distinction and not simply an academic nicety. Failure to make such a distinction can very easily lead to inappropriate approaches being proposed and inappropriate data being collected.

Flows are largely dynamic in their trigger mechanisms and are generally characterised by rapid erosion and movement with high proportions of either water or air acting as a lubricant for the solid material that generally comprises the bulk of their mass (Pierson & Costa, 1987 and as discussed further by Winter *et al*., 2005d). Stürzstrom, debris avalanches and grain flows are generally air-lubricated slides and are beyond the scope of the work of this study. Similarly normal and hyperconcentrated streamflow are typical of flooding, showing some similarity to the August 2004 events in Boscastle in south-west England, and are not considered further herein.

The remaining categorisations of debris flow and earth flow are the flow types with which we are concerned here and for simplicity are for now referred to simply as debris flows. These sediment-water flow features are broadly characteristic of the debris flow types experienced in Scotland in recent years.

Debris flows occur, in the main, because of the character of natural slopes, the deposits of which they are comprised, and the amount and duration of rainfall (and consequent infiltration) to which they are subject. The fact that they impact on any road network is, irrespective of the consequences, a matter of coincidence. Debris flows affecting the trunk road network do not have as their cause its construction or management, except in unusual circumstances. However, some aspects of the built environment, including a road network, may contribute to the outcomes of such events.

At this point it is important to note that debris flows are neither a recent phenomenon nor an uncommon occurrence. The first church in the Falkland Islands, for example, was wrecked in 1886 when a "*river of liquid peat … roared down from the hills*" (Winchester, 1985). Closer to home, a cloud burst in 1744 resulted in the flow and associated erosion of the gulley below the summit of Arthur's Seat known today as the Gutted Haddie (McAdam, 1993).

It is, however, clear that the August 2004 events in Scotland had the potential to cause injury and even death. Fortunately, such potential was not on the same scale as the reality that is experienced elsewhere in the world on a regular basis, such as following the Kashmir (Pakistan) earthquake in October 2005 and the catastrophic landslide in The Philippines in February 2006.

2.2 EVENTS OF AUGUST 2004

2.2.1 Introduction

The rainfall experienced in Scotland in August 2004 was substantially in excess of the norm. Some areas of Scotland received more than 300% of the 30-year average August rainfall, while in the Perth & Kinross area figures of the order of between 250% and 300% were typical. Although the percentage rainfall during August reduced to the west, parts of Stirling and Argyll & Bute still received between 200% and 250% of the monthly average[3]. Subsequent analysis of radar data indicated that at Callander, some 20km distant from the events at the A85 (see Section 2.2.4), 85mm of rain fell during a four hour period on 18 August. Some 48mm fell in just 20 minutes and the storm reached a peak intensity of 147mm/hour. The 30-year average rainfall for August in Scotland varies between 67mm on the east coast and 150mm in the west of Scotland (Anon, 1989).

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[3] Source: http://www.metoffice.com/climate/uk/2004/august/maps.html.

The rainfall was both intense and long lasting and a large number of landslides, in the form of debris flows, were experienced in the hills of Scotland. A small number of these intersected the trunk, or strategic, road network, notably the A83 between Glen Kinglas and to the north of Cairndow (9 August), the A9 to the north of Dunkeld (11 August), and the A85 at Glen Ogle (18 August). These locations are illustrated in Figure 2.2.

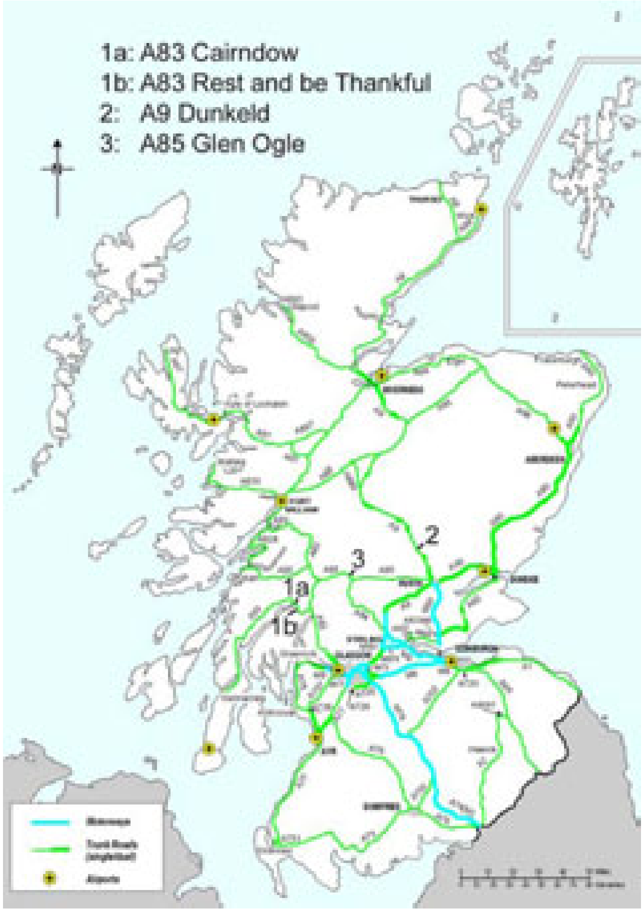

Figure 2.2 – Map showing the trunk road network, including motorways, in Scotland. The locations of the three main debris flow event groups that affected the trunk road network (1, 2, 3) in Scotland in August 2004 are shown as are areas in which the local Highland road network was affected by debris flows in August 2004, December 2004 and October 2006.

While there were no major injuries to those affected, 57 people had to be airlifted to safety when they became trapped between the two main debris flows at Glen Ogle. However, the real impacts of the events were economic and social, in particular the effects of the severance of access to relatively remote communities. The A85, carrying up to 5,600 vehicles per day (all vehicles two-way, 24 hour AADF – Annual Average Daily Flow), was closed for four days. The A83, which carries around 5,000 vehicles per day, was closed for slightly over a day and the A9, carrying 13,500 vehicles per day, was closed for two days prior to reopening, initially with single-lane working under convoy. The disruption experienced by local and tourist traffic, as well as to goods vehicles, was substantial.

The traffic flow figures are for the most highly-trafficked month of the year for each of the roads, either July or August. Minimum flows occur in either January or February and are roughly half those of the maxima. The figures reflect the importance of tourism and related seasonal industries to Scotland's economy.

This section provides an overview of the events of August 2004, based upon that of Winter *et al*. (2006a).

2.2.2 A83 Glen Kinglas/Cairndow – 9 August

The A83 in Argyll & Bute was blocked at two locations in Glen Kinglas, 0.5km and 2.5km from the junction with the A815, and at a point approximately 1km north of Cairndow. In addition to causing the road to be closed for slightly over a day, the debris flow at Cairndow (Figure 2.3) also had a substantial effect on a residential property immediately upslope from the road (Figure 2.4). Numerous smaller debris flows were also observed on the hill slopes either side of Glen Kinglas.

Figure 2.3 – Debris fan containing boulders (estimated up to 9 tonnes) at A83 Cairndow.

The A83 is a single-carriageway route and in Glen Kinglas lies at approximately 100m AOD, at the toe of the steep undulating slopes of Binnein an Fhidhleir and Stob Coire Creagach, which extend some 700m to 800m above the road. The slopes are generally vegetated with grass, bracken and occasional heather cover with a few forested areas on the lower slopes adjacent to the road. Rock outcrops locally on the slopes, but mainly on the higher ground. The slope is frequently incised with watercourses. These are culverted below the road and into Kinglas Water, located a short distance to the south of the A83.

In early August 2004 the hillsides were in a saturated condition following a relatively wet spell during the preceding weeks. This was followed by a relatively short period of exceptionally heavy rainfall.

Typically the flows commenced in the steep upper reaches of the slopes at around 500m AOD (Figure 2.5). At the head of each a shallow scarp, less than 1.5m, was observed. The waterlogged material is assumed to have flowed into existing water courses providing a more erosive sediment charge, resulting in erosion up to between 10m and 15m either side of the channels. Deposition occurred at the toe of the slope where the gradient slackens.

Figure 2.4 – Debris flow above the A83 to the west of Cairndow showing the effects on a roadside cottage and the trunk road immediately downslope from the cottage.

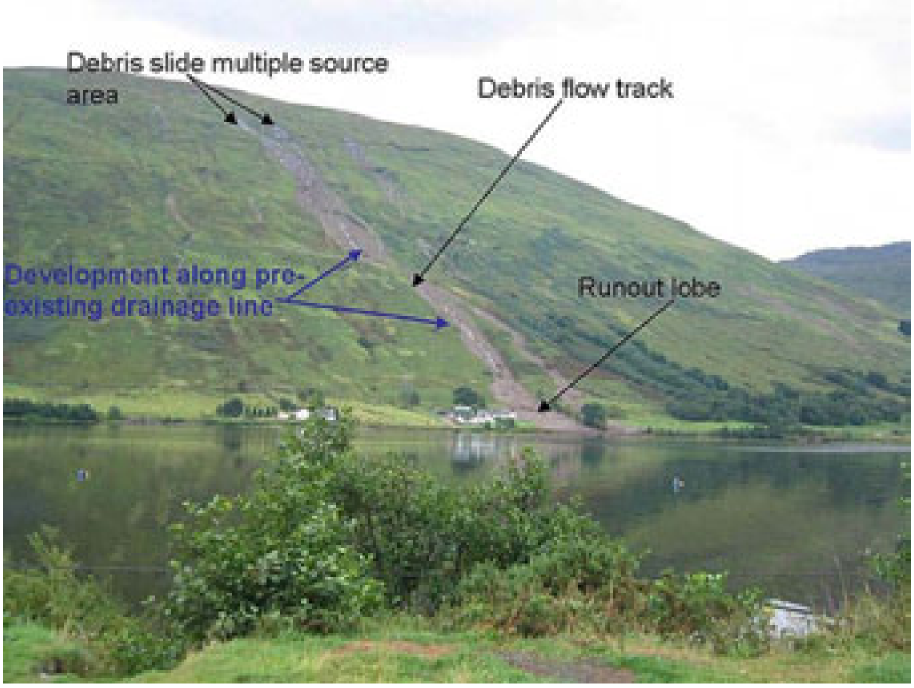

Figure 2.5 – Upland debris slide and flow development at Cairndow on the A83. (Courtesy and © copyright of Halcrow.)

Several hundred tonnes of material are estimated to have blocked the road at the two locations in Glen Kinglas with possibly two to three times this amount at the Cairndow slide. The debris blocking the road comprised very silty sand and gravel with frequent cobbles and boulders, the largest of which was estimated to weigh nine tonnes (Figure 2.3). Smaller boulders remained within the watercourses, although none was considered to be a further threat to the road.

2.2.3 A9 North of Dunkeld – 11 August

The heavy rain that triggered the A83 events continued for three more days over much of Scotland and precipitated further debris flows, three of which affected the A9 just to the north of the Jubilee Bridge near Dunkeld in Perth & Kinross.

At this location the A9 is single-carriageway and passes at the foot of a steep slope on its eastern side. The River Tay is a short distance to the west. The old A9, now a minor local road (C502), traverses the hillside above the trunk road. The upper part of the slope between these two roads is wooded, whereas the lower part is vegetated by broom with few trees. The lower part of the slope was steepened at the time of construction of the present trunk road, to a gradient close to 1 in 2 (vertical to horizontal) whereas the upper part is slightly less steep, steepening again at the top to form the bench on which the old A9 was constructed. Above the old A9 the wooded hillside continues to rise for approximately 250m in elevation.

The upper part of the slope is notable for the presence of a superficial layer of yellow fine sand that is both slightly denser and lighter in colour than the underlying uniformly graded fine sand. This denser material is absent from the lower part of the slope and it seems likely that material of this nature was removed when the lower part of the slope was steepened to accommodate the A9 trunk road.

It is clear that, as a result of the exceptional rainfall, a large amount of surface water runoff descended the slope above the old A9, both along the course of existing streams and on the open hillside between. When it reached the old road, the drainage system was unable to contain or disperse such large volumes of water. The surface runoff travelled along the old road, spilling over the edge onto the slope below in a number of places, as illustrated in Figure 2.6 and effectively concentrating the flows at these locations.

In at least five major locations and a number of minor locations, this overspill of water caused failure of the outer edge of the old A9 road (Figure 2.7). In two such locations (the central and northern flows, see Figure 2.6) the flow of water, charged with debris from these failures brought with it trees from the upper part of the slope. A deposition zone, approximately 20m wide at the central flow, corresponded with this stage of the event, which resulted in the flooding and trees on the A9 that were first observed and reported by trunk road users.

Following the first stage, the power of the flood increased and it entered an erosive phase in which gullies, some 3m to 4m deep and up to 6m wide, were scoured. These gullies stretched from the top of the cut slope (or above) to the A9 trunk road verge. Once the vegetation was stripped and the underlying fine sand was mobilised, it flowed freely down the slope and onto the trunk road. The erosion gullies did not extend into the upper part of the slope due to the slightly lesser gradient and the presence of the more erosion resistant layer of the lighter yellow fine sand (Figure 2.8).

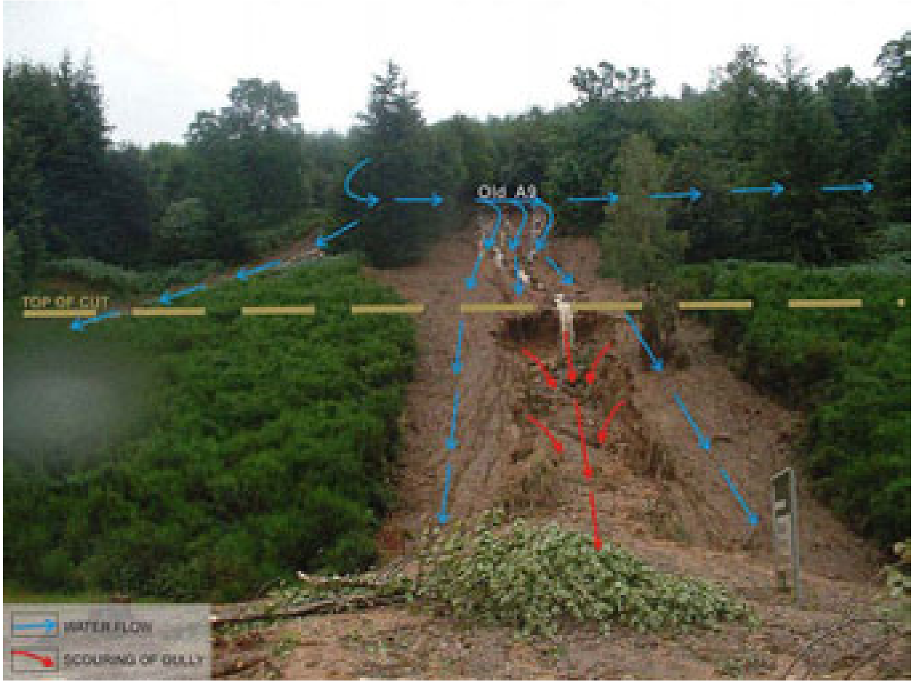

Figure 2.6 – Influence of old road on debris flow at A9 Dunkeld. The central flow is shown and the northern flow can also be seen on the left of the picture. Photograph dated 11 August 2004. (Courtesy of Alan Mackenzie, BEAR.)

Figure 2.7 – Instability at the downslope edge of the old A9 above the central debris flow. Photograph dated 12 August 2004. (Note that the brown pipe running horizontally across the backscarp is a telecommunications duct.)

The southern flow (see Figure 2.9), differed only in detail from the central and northern flows. A low point and a change in crossfall of the old A9 caused a large amount of the water flowing along the road to spill onto the upper part of the slope. The ground immediately below the old A9 did not fail, because of either the presence of more mature trees in this area and/or an unknown detail change in the road construction. The water then appears to have flowed down the slope to the top of the cut slope, where a deep gully was eroded. This was similar in form to, but rather wider and deeper than, the central and northern gullies, and deposited a large amount of sand on the trunk road (Figure 2.9). The top of this southern gully is marked by exposed rocks, both within the gully and at surface immediately above. It thus seems likely that the extension of this gully was limited by the presence of bedrock or boulders.

Figure 2.8 – The top of the central erosion gully at the top of the cut slope. The overhang of the denser yellow fine sand is clearly visible and it appeared that this material was better able to shed the water and debris. Photograph dated 12 August 2004.

Figure 2.9 – The southerly debris flow at the A9 north of Dunkeld. The flow has formed its own channel by erosion. Photograph dated 12 August 2004. (Courtesy of Alan Mackenzie, BEAR.)

Both forest roads and minor roads can act either to retard or to concentrate the downslope flow of water and thus aid its penetration into the slope below. Such a mechanism has been a factor in a number of previous events such as the washout that blocked the A83 Rest and be Thankful in the vicinity of Roadman's Cottage in 1999. However, in the A9 Slochd failure of July 2002 it was the presence of the trunk road that contributed to the failure of the old road below (now used as a cycle path) and consequently to the failure of the A9 itself by undercutting. The presence of forest tracks was also identified as a contributory factor in the debris flow which occurred at the A887 Invermoriston in August 1997 (Winter *et al*., 2005a; 2005b; Nettleton *et al*., 2005a).

An brief account of the repair work undertaken to the drainage systems at and immediately below the old A9 (C502) is given by Fossett *et al*. (2006)

2.2.4 A85 Glen Ogle – 18 August

Following the A83 and A9 incidents, the rainfall in the area decreased for several days but on 18 August a short but exceptionally intense rainstorm occurred in west Stirlingshire and triggered two debris flows that blocked the A85 in Glen Ogle north of Lochearnhead. The southerly slip occurred first and, as advice was being offered to motorists by Trunk Road Operating Company staff, a second landslide occurred to the north of the first. Some 20 vehicles were trapped between the two debris flows, and 57 occupants were airlifted to safety by RAF and Royal Navy helicopters (Figure 2.10).

Figure 2.10 – Fifty-seven occupants of the 20 vehicles that were trapped between the two debris flows in Glen Ogle were airlifted to safety. (© Perthshire Picture Agency: www.ppapix.co.uk.)

The A85 trunk road through Glen Ogle is a relatively narrow single carriageway and climbs north-westward from Lochearnhead, at an elevation of approximately 100m AOD, to a pass at the head of the glen at around 290m AOD before descending into Glen Dochart to the north. From Glen Ogle Farm (approximately 1.2km from Lochearnhead) northwards, the road climbs up the eastern flank of the valley to the top of the pass; it is along this section that the most significant flows occurred.

The hillside above the road rises some 400m at approximately 1 in 2. It is covered with bracken and heather with isolated boulders and areas of crags. Below the road the gradient of the slope decreases rapidly to the Glen Ogle Burn. The two slips followed steep streams that descend this hillside and are culverted beneath the road. The southerly stream descends through an area covered by heather and bracken while the northerly stream descends a partially rocky area of the hillside.

As a result of the exceptional rainfall, and possibly because of the additive of the high level of antecedent rainfall, the soils in the upper catchments to the streams became saturated, triggering slides into the headwaters of both streams. The culverts rapidly became blocked and debris spilled across the road (Figure 2.10) and down the slope beyond (Figure 2.11). Most of the debris came to rest on the slope below the road but a small proportion reached the Glen Ogle Burn. This burn was also in spate at the time and rapidly removed the debris that reached it.

Figure 2.11 – View of the northern A85 Glen Ogle debris flow two days after the event, showing the sharp bend in the channel just above road level.

2.2.4.1 Northern Flow

Both terrestrial and helicopter-based examinations of the northern flow (Figure 2.11) undertaken two days after the events indicated two independent sources. To the north is an arcuate scar from which a shallow translational slip broke away. The turf and upper soil travelled over the surface of the vegetation below and entered the upper part of the stream gully. However, scarring indicates that instability occurred independently at the very top of the gully. It is not known which instability occurred first although both slides appear to have generated only a relatively small amount of debris. The debris was, however, channelled into and down the steeply inclined bed of the stream and scoured the gully, removing turf and soil. It is likely that the volume of water and debris increased further down the gully and that the consequent damage was increased in areas closer to the road.

In the middle and lower parts of the flow, large and small boulders and trees were mobilised in addition to soil and turf. In that locality the schistose bedrock is generally encountered at shallow depths and scouring appears not to have been deep but rather to have spread laterally. However, it appears that bedrock was loosened in places in the area of a small waterfall a short distance above the road. The dominant component of the debris comprised fine particles but many cobbles and boulders were also in evidence. Several boulders of up to 10 tonnes were deposited on the road and one boulder, estimated at 90 tonnes, was deposited some 10m above the road. From eyewitness accounts it would appear that the debris reached the road in pulses. These were most likely associated with the temporary damming of the stream by debris or by new areas of instability in the stream banks. Similar observations were made regarding the August 1997 debris flow which affected the A887 at Invermoriston (Winter *et al*., 2005b; Nettleton *et al*., 2005a).

The west-flowing stream channel then takes a sharp, right-angled turn to the south approximately 10m before it reaches the road due to a bluff of rock. This outcrop steers the stream channel into a course that runs sub-parallel to the road before the stream makes another sharp, right-angled turn to the west to pass under the road by means of a high arched culvert and descends the lower slopes to the Glen Ogle Burn.

On the afternoon of 18 August the initial part of the debris flow followed the course of the stream. However, at some point the culvert became blocked with boulders up to 2m in size and fallen trees, causing the water and debris to flow over the road, largely destroying the parapet of the culvert. As the energy of the debris flow increased, it reached a point where some or all of it failed to negotiate the first corner and it swept over the rock bluff and crossed the road some 40m to 50m to the north of the culvert. An unoccupied Trunk Road Operating Company vehicle that had been parked in the lee of the spur was swept over the edge of the road and for some distance downslope before it came to rest against a tree (Figure 2.12). A wide debris fan was left on the slope between the road and Glen Ogle Burn (Figures 2.12 and 2.13).

2.2.4.2 Southern Flow

The failure in the southerly stream was less extensive than that in the northern, the erosion scar being both narrower and less deep. This may have been due to the flow having less momentum than the northerly flow as this stream appears to be less continuously steep. Much of the material was coarser than that from the northern slip, being predominantly cobble-sized (see Figure 2.10). Otherwise, the general mechanism appears to have been similar, although in this case there is no major bend in the stream. The culvert is smaller and rapidly became blocked and debris spilled across the road causing damage to the outer face of the culvert and the outer edge of the road.

Figure 2.12 – A85 Glen Ogle showing the Trunk Road Operating Company vehicle that was swept away by the northern debris flow.

Figure 2.13 – The debris fan formed by the northern debris flow in Glen Ogle viewed from the A85 trunk road, looking towards Glen Ogle Burn and down the valley towards Lochearnhead.

2.3 OTHER EVENTS

There has been a number of landslide – including debris flow – events in Scotland since August 2004. Relatively minor events affected the road network, albeit not always the trunk road network, at the A832 near Kinlochewe in December 2004, on the A82 approximately 1.5 miles north of the Corran Ferry junction in January 2005 (details of this event are rather sketchy but it was most likely a small rockfall), on the A82 at Letterfinlay on 7 January 2005 and on the A814 in January 2006. Other events affecting the local road network in Highland in August, October and December 2004, September 2005 and October 2006 as described in Section 2.3.1. The events of October 2006 also affected the trunk road network as did later events in December of that year – primarily on the A82 at Letterfinlay and on the A9 north of Inverness at Berriedale, Helmsdale and Portgower.

However, perhaps the most serious single event to affect the trunk road network since August 2004 is that which occurred at approximately 0330 hours on Sunday 28 October 2007 on the eastern approach to the Rest and be Thankful. The event intersected the trunk road at approximate National Grid Reference (NGR) NN 23600 07000.

Figure 2.14 illustrates the event and the surrounding hillside; the photograph is taken from the opposite side of Glen Croe and evidence of numerous past events can be clearly seen. Figure 2.15 illustrates the event in more detail and it is clear that the system of mass movement comprises two discrete but related events.

Figure 2.14 – View of the hillside above and below the approach from the east to the Rest and be Thankful (from NGR NN 23160 06559 on the opposite side of Glen Croe). Not only can the event dated 28 October 2007 be clearly seen but evidence of numerous past events can be seen on the surrounding hillside.

A detailed site walkover revealed that the flow above the road commenced with a relatively small slide (or slides) into an existing drainage channel. This then triggered the movement of a large amount of marginally stable material in and around the stream channel which was deposited at road level. The Operating Company (Scotland TranServ) estimated that around 400 tonnes of material were deposited at road level. This material blocked the open drain which runs carries water along the road to a series of culverts beneath. While the material from above the road had limited impact upon the slopes below the road, water diverted from the drain was channelled across and over the edge of the road causing some significant undercutting of the slope below and associated deposition further down the hill as can be seen in Figure 2.15.

While not necessarily germane to the events reported here, it was observed that the culvert at this location was of a small size (around 400mm) and most likely of only marginal adequacy for water flows let alone for effectively carrying debris. In addition it is clear that the culvert does not follow a straight path, a feature that would reduce its capacity and increase the potential for blocking. Additionally, this means that water has been flowing from the culvert at an angle to the hillside of considerably less than ninety degrees. This is the most likely cause of the erosion observed in Figure 2.15 below the main road and to the left of the recent scar. The issues relating to this particular stretch of road are discussed further in Section 8.

Figure 2.15 – View of the debris flows above and below the A83 on the approach to the Rest and be Thankful (from NGR NN 23160 06559 on the opposite side of Glen Croe). The head scar is at approximately 370m AOD, the A83 at 240m AOD and the old road at 180m AOD.

2.3.1 Landslides in the Highlands

2.3.1.1 Background

In the Scottish Highlands, the combination of hard metamorphic and igneous rocks, glacially steepened valley slopes and high rainfall is ideal for generating debris flows and slides.

The bulk of the Highlands falls into the physiographic regions of 'Western Plateaux and Foothills', 'Dissected Central Mountains' and 'Eastern Mountains Plateaux' (Sissons, 1976), all of these regions being characterised by steep valley sides (>30^o) and a mantle of varying thickness of granular morainic material and weathered rock. Several major geological structures also traverse the region, for example, the Great Glen Fault, and the existence of these features tends to increase the availability of shattered rock material.

In terms of levels of precipitation that may provoke a landslide event, the average annual rainfall in some Highland areas can exceed 4,000mm, occurring either in short bursts (summer convective storms) or in persistent medium to heavy falls (mainly autumn/winter).

Landslides affecting the road network in some way occur somewhere in the Highlands almost annually. Many affect only minor routes with little disruption to traffic. They are usually small-scale events and are cleared within a short space of time. However, some significant landslides have, as reported earlier in this section, have affected main trunk routes giving rise to severe disruption to traffic, as, generally speaking, there are few available diversion routes.

2.3.1.2 Landslide Types and Locations

Landslides of various types occur throughout the Highlands. These may include rotational slips, mainly in the soils associated with the Mesozoic rocks of Skye and east Sutherland (see Figure 2.16), mass movement of boulder fields (see Figure 2.17) and – by far the most common variety – debris flows/slides. Events of this latter variety have occurred on a number of occasions within the period 2004 to 2006.

Figure 2-16 – Part of a rotational slip at Flodigarry, Skye.

Figure 2.17 – Road at Duntulm, Skye being moved by mass movement of boulder field, accelerated by erosion at toe

Many of the landslides affecting roads occur in the western, more mountainous areas of the Highlands, the most noted locality being the A890 at the Stromeferry Bypass which has been known to be affected by landslides on several occasions in the course of a year. The less mountainous eastern areas are however not immune to landslide events, with several incidents having occurred within recent years. This is probably the Highland Council's most problematic road with regard to debris flow activity. It continues to be the subject of ongoing study by consultants and a rigorous programme of inspection and maintenance on the part of the Council. The problems and issues relating to this locality have been discussed elsewhere (Nettleton *et al*., 2005a; 2005b).

Although the majority of the roads affected by slides and debris flows in the Highlands are B, C and unclassified routes, many of these are nevertheless locally very significant, in some cases being the only access routes to remote communities.

Recent landslides affecting the local road network in the Highlands have most notably occurred during August and December of 2004 and in October 2006. The slide in December 2004 at Glenelg was the largest in extent and volume of material. The August 2004 events were concentrated in Easter Ross and the Black Isle but are not discussed further herein. The approximate location of these events are illustrated in Figure 2.18.

Shiel Bridge to Glenelg Road, December 2004: On 6 December 2004, following a sustained period of heavy rainfall, a debris flow occurred on the C46 road between Shiel Bridge and Glenelg at Cnoc Fhionn in the Lochalsh area. Approximately 1,500m^3 of material was brought down and the route was disrupted for two days (Figures 2.19 and 2.20).

Whilst many of the smaller landslides, and particularly debris flows, may have been exacerbated by factors such as poor roadside drainage, blocked field drains and other anthropogenic factors, the larger scale events, such as the Shiel Bridge to Glenelg slide, seem to be largely natural in origination.

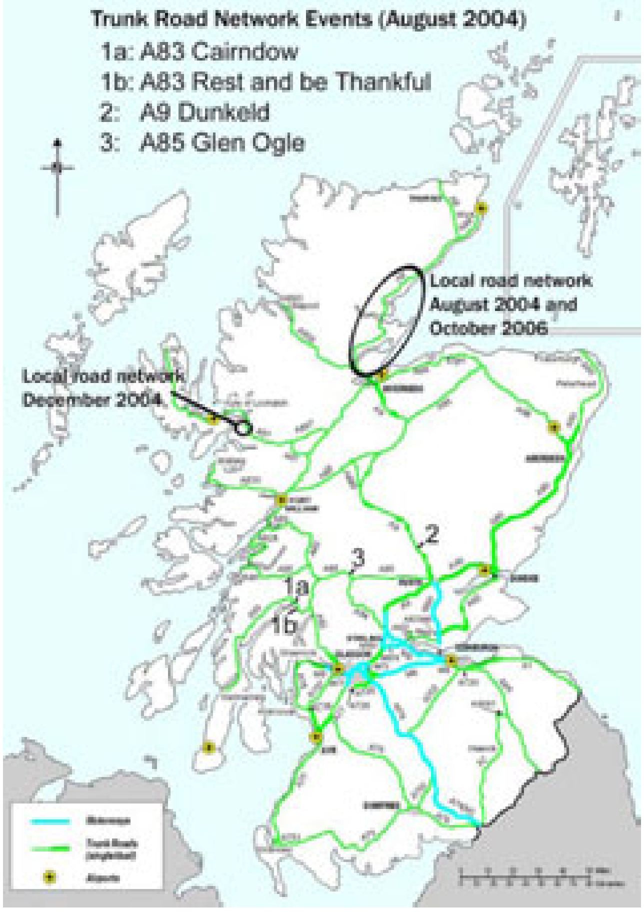

Figure 2.18 – Map showing the trunk road network, including motorways, in Scotland. The locations of the debris flows on the local Highland road network are shown. The numbers 1a, 1b, 2 and 3 refer to the locations described in Figure 2.2.

Figure 2.19 – Head of slip near source at Glenelg.

Although not a principal transport route, the road is however of very high importance locally, being the only overland link between the communities of Arnisdale, Glen Beag, Glenelg and the outside world.

Figure 2.20 – Debris causing road closure at Glenelg.

The local geology has led to the formation of a step-like hillside topography (Figure 2.21) and Figure 2.22 shows distinct linear features which have acted as accumulation zones for water. This has led to a potential for slippage over the entire hillside.

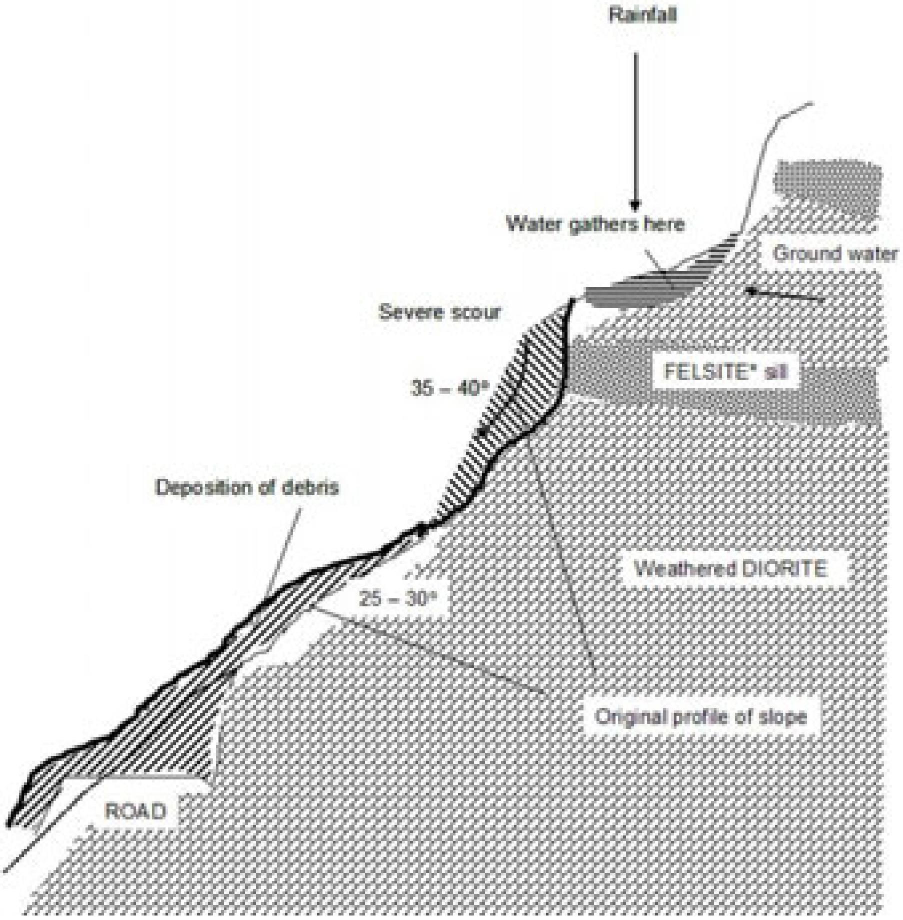

Figure 2.21 – Glenelg Landslip, likely failure mechanism.

Figure 2.22 – Slips on hillside above and below road at Glenelg.

Easter Ross and Sutherland, October 2006: A number of local roads and properties in localities between Dingwall and Helmsdale were affected by flooding and landslides on 25 and 26 October 2006.

Torboll (north of Dornoch), October 2006: A combination of toe erosion and a cascade of water down a steep slope on the road led to complete collapse of the natural slope below the unclassified road between The Mound and Bonar Bridge at Torboll (to the north of Dornoch). Part of the already-narrow carriageway was undermined (Figure 2.23) and subsequently progressively collapsed, with the safety barrier being left suspended (Figure 2.24).

Figure 2.23 – Landslide at Torboll, 26 October 2006.

Quebec Bridge – (south of Tain), October 2006: Drainage system problems, which have caused difficulties previously in this locality, led in this instance to a massive amount of water being channelled down the roadway, causing erosion and slippage and major damage to the bridge structure (Figure 2.25).

Figure 2.24 – Torboll, showing ongoing erosion, 14 February 2007.

Figure 2.25 – Landslide at Quebec Bridge, October 2006.

B9176 Struie road at New Bridge (north of Alness), October 2006: Two debris flow slides on the uphill side of the road at New Bridge on the B9176 Struie road in Easter Ross deposited large amounts of debris on the carriageway on 26 October 2006 (Figure 2.26). The water and debris continued to flow over the road causing significant erosion and deposition of material on the downhill side also (Figure 2.27). Blocked agricultural drains above the slope on the uphill side were thought to have been a main contributing factor. Major repair and reconstruction work was necessary, especially on the downhill side, but in addition small debris-retaining gabion structures were constructed on the uphill side to attempt to contain any reoccurrence (Figure 2.28).

Figure 2.26 – Struie slide at south end.

Figure 2.27 – Erosion and deposition below road, Struie.

Figure 2.28 – Gabion debris trap, Struie.

A862 Ardullie (north of Dingwall), October 2006: A minor slip occurred above the road (Figure 2.29) at Ardullie, just west of the Cromarty Bridge, depositing material on the road and causing erosion of the downhill (seaward) slope (Figure 2.30). A void appeared adjacent to the seaward side retaining wall indicating that the downhill embankment slope had been subject to movement.

Figure 2.29 – Ardullie slip above road.

Figure 2.30 – Erosion on downhill side, Ardullie.

2.4 SEASONALITY

Observation indicates that, within the recent past, debris flow activity in Scotland has occurred largely in the periods July to August and November to January, with the latter season occasionally stretching to October and February. There is, of course, no certainty that such a pattern will be continued in the future, even though eastern parts of Scotland do receive their highest levels of rainfall in August. Additionally, climate change models indicate that rainfall levels will increase in the winter but decrease during the summer months and that intense storm events will increase in number. These factors, therefore, may change both the frequency and the annual pattern of debris flow events.

In recent years debris flow events do appear to have had an increasing effect on the Scottish trunk and local road network, together with the Scottish rail network. At face value this suggests that such events have become more common. Such a conclusion would however be somewhat speculative as comprehensive, detailed records are not generally available for events that do not impact upon man’s activities. What does appear clear from simple observation is that a large number of debris flows are initiated on the Scottish hills. However, only a relatively small number turn into major events that impact upon road networks or other forms of infrastructure. This implies that in order to manage the impacts of debris flows it is necessary to understand the preparatory factors (that make a slope vulnerable to debris flows), the trigger factors (that lead to initiation of flows) and any propagation and/or magnifying factors. This theme is developed further in Section 4.

A number of debris flows have historically occurred in the month of August. One example is an event that intersected the A887 at Invermoriston in 1997.

Debris flow events have also been observed at other times of the year. They have affected both the A890 and the railway at Stromeferry in January 1999, October 2000 and October 2001. The January 1999 and October 2000 events were characterised by the mobilisation of material from a pre-existent landslide which slipped into a gully thus providing the source material for the debris flow event. The October 2001 event was propagated from a gully that had been infilled with silt, gravel and cobble fractions. In each case disruption to the road and railway was experienced (Nettleton *et al*., 2005a).

Logging or deforestation can have a dramatic effect on the drainage patterns of a slope, reducing root moisture uptake and removing the physical restraints on downslope water flow (for example), as well as disrupting root systems that help to reinforce to slope. Such effects were especially noted as factors in the triggering of a translational landslide (not a debris flow) at Loch Shira adjacent to the A83 trunk road near Inverary in January 1994.

3 RESPONSE TO THE 2004 EVENTS

by M G Winter, F Macgregor and L Shackman

The need to act in response to the events of August 2004 was recognised by Scottish Ministers. As an objective, Transport Scotland decided that a system should be put in place for assessing hazards posed by debris flows. It was also recognised that such a system must be capable of ranking the hazards in terms of their potential relative effects on road users. In that way the future effects of debris flow events would be able to be managed and mitigated as appropriate and as budgets permitted, thus ensuring that the exposure of road users to the consequences of future debris flows would be minimised but with the acknowledgement that the prevention of such events is not possible.

As a first step towards that overall objective, the initial landslides study was set in motion by the Minister for Transport to address the following activities:

- Considering the options for undertaking a detailed review of side slopes adjacent to the trunk road network and recommending a course of action.
- Outlining possible mitigation measures and management strategies that might be adopted.
- Undertaking an initial review to identify obvious areas that have the greatest potential for similar events in the future.

This initial study[4] was reported in both a comprehensive Technical Report (Winter *et al*., 2005a) and in summary form (Winter *et al*., 2005b), the latter being intended to inform a wider audience of Transport Scotland's actions since the events of August 2004 and planned for the future. The Technical Report was divided into a number of sections, each of which introduced one or more of the key issues that were to be addressed in order to move the work forward towards implementation. These were as follows:

- Section 1 introduced landslides in Scotland and the background to the inception of the study (Winter *et al*., 2005c).
- Section 2 gave the background to the study as a whole. It described the different types of landslide, focusing on debris flows, and illustrated the recent history of debris flows in Scotland. It also dealt with climatic issues and those issues which relate to third party ownership of land from which landslides may originate (Winter *et al*., 2005d).
- Section 3 examined sources of relevant information, including previous literature and available data sets from sources such as the Scottish Executive and the British Geological Survey (McMillan *et al*., 2005).
- Section 4 dealt with the classification and type of debris and other types of flows. It explained how rapid landslides develop from their causes and the underlying soil failure mechanisms, through the mechanics of their downslope propagation and, finally, to their run-out at the base of the slope (Nettleton *et al*., 2005b).
- Section 5 examined the relevance of key factors in debris flow initiation and propagation that have been identified from past events, including the events of August 2004. These were considered in terms of factors affecting the likelihood of debris flow occurrence, including the effects of run-out, and factors affecting the exposure of road users to debris flows (Heald and Parsons, 2005).

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[4] A second, parallel, study on climate change (Galbraith *et al*., 2005a; 2005b) identified the potential impacts and associated actions in the light of UKCIP02 (http://www.ukcip.org.uk/). That study did not consider landslides, but contained data which helped to inform views on the potential impacts of climate change reported in Section 10.2.

- Section 6 described the proposed assessment methodology in terms of hazard assessment and the approach to the second part of the study, reported herein, and also detailed the hazard assessment and exposure factors forming the core of the methodology for the detailed assessment (Winter *et al*., 2005e).
- Section 7 identified areas of high hazard that, based upon collective experience, were considered to have the greatest potential for similar debris flow events in the future and set out opportunities for early actions (Winter *et al*., 2005f).
- Section 8 described management and mitigation options, particularly focusing upon the sequential approach to management of Detection, Notification and Action (DNA) that was promulgated by the Editors of the Technical Report at a workshop held at the start of the project. This approach is set out in terms of a response to both precursor conditions, such as intense rainfall, and also to the management of future debris flow events (Sloan *et al*., 2005).
- Section 9 presented a summary of the report and made recommendations for the way forward (Winter *et al*., 2005g).

The findings and recommendations of the Technical Report were used to produce the plan for the second part of the study as reported here. This develops a system to allow a detailed review of the network to be undertaken to identify the locations of greatest hazard, for those hazards to be ranked and for appropriate mitigation and/or management measures then to be selected.

A consistent, repeatable and reproducible system was configured as it was anticipated that a variety of consultants would be involved in the data gathering, analysis and interpretation process. Consultants often have preferred approaches which are different, but nonetheless valid, when operating independently. Should such independent operation occur, this would render any comparison between individual consultant's results and recommendations unworkable for the purpose of, for example, allocating funds on a priority basis across the network. It was thus apparent at the outset that a system that produced consistent and comparable results was required.

It was thus recognised at an early stage of the development of the work that the input of a wide range of experts and stakeholders would be required in order for the studies to be completed successfully. A facilitated Project Workshop was held on 28 September 2004, exactly one month after the events at Glen Ogle, in order to capture the knowledge vested with individual experts who formed a Working Group. Focused discussion sessions at the Project Workshop led to task-assigned activities which eventually formed the chapters of the Technical Report, this being launched along with the Summary Report at a public seminar at The Royal Museum in Edinburgh on 14 June 2005.

3.1 IMMEDIATE ACTIONS

As part of the Project Workshop a series of areas of high perceived hazard was identified. The identification of these areas was intended to serve the joint functions of assisting prioritisation of areas for action during this second part of the study whilst providing, in parallel, a shortlist of sites appropriate for validating the debris flow hazard model in its development phase.

The sites identified (in the order in which they were suggested at the Workshop, but not in any order of perceived hazard or hazard ranking) are set out as follows:

- A83 Ardgarten to Loch Shira (29km).

- A84 South of Strathyre (8km).
- A85 Glen Ogle (6km).
- A87 Glen Shiel (18km, plus a possible further 17km).
- A82 Fort Augustus to Lochend (29km, plus a possible further 9km).
- A835 Ullapool to Braemore Junction (16km).
- A9 Dunkeld to Drumochter (22km).
- A95 Craigellachie (1km).
- A86 Spean Bridge (5.5km).
- A87 (Skye) Gleann Torra-mhichaig to South of Raasay ferry (1.5km).

Collectively, the above correspond to a total length of 162km.

A number of shorter-term actions were also instigated following the events of August 2004. A significant programme of clearing vegetation and rocks from, and adjacent to, ditches, gullies, catchpits and culverts was undertaken and some new ditches were added at the crest of slopes to limit water ingress.

On a related theme the national drainage standards have since been updated and enhanced and these are used for the design of all construction and maintenance operations. The new standards upgrade the design storms used in determining the various required capacities (e.g. from a 1 in 2 year return period to 1 in 5 years).

With regard to the specific areas of high hazard identified in the report the following works have been progressed:

- A83 between Ardgarten and Loch Shira (29km). Culvert realignment and renewal works were completed in 2005 including upgrading of Ardgarten Culvert to provide increased capacity. A further phase of boulder stabilisation and repair/improvement to cascades has also been undertaken at Rest and be Thankful. Installation of Rain gauges is being progressed in conjunction with SEPA and the Met Office.
- A85 in Glen Ogle (6km). A Scheme is currently at design stage to improve the road alignment and reduce the potential impact of landslides.
- A87 in Glen Shiel (18km, plus a further 17km either end of Glen Shiel). Numerous small rock falls which have been blocking culverts and ditches have been cleared in addition to routine maintenance activities.
- A82 between Fort Augustus and Lochend (29km, plus a further 9km to the south). No additional work done other than routine maintenance as the presence of a rock face along the length of the trunk road makes improvements difficult at reasonable cost.
- A835 between Ullapool and Braemore Junction (16km). Ditching and vegetation clearance has been undertaken in addition to general routine maintenance.
- A9 between Dunkeld and Drumochter (22km). Drainage improvements imminent at the site of the Dunkeld landslip. The local authority are also working at this location to minimise the hazard. In addition extensive re-ditching works have been undertaken along this length of the A9 during 2005.
- A95 in the Craigellachie area (1km). Top of slope ditching has been undertaken but further works are required to address short term problems. It is likely that improvements will require carriageway reconstruction.
- A86 around Spean Bridge (5.5km). Extensive ditch clearance works and improvements to drainage and cross road culverts have been undertaken during 2005.

- A87 (Skye) between Gleann Torra-mhichaig and South of the Raasay ferry (5.5km). Ditching to the top of the cutting slope has been undertaken to arrest minor rock slips.

3.2 DEVELOPMENT OF FUTURE MANAGEMENT OPTIONS

The initial stage of the work may be divided into four elements and can be summarised as follows:

- Development of a debris flow hazard and exposure assessment system to provide a hazard ranking of 'at-risk' areas of the road network.
- Undertaking a computer-based GIS assessment as a first stage in the hazard assessment process.
- Undertaking site-specific hazard and exposure assessments of areas identified by the GIS as being of higher hazard.
- Identification and development of appropriate management processes for each category of hazard ranking.

Figure 3.1 presents a flowchart of the work undertaken. The initial stage of the process was to develop the methodology for the assessment of hazard and exposure to provide a hazard ranking, together with the selection of an appropriate management approach. The second stage was to test the methodology and apply it more widely to the trunk road network.

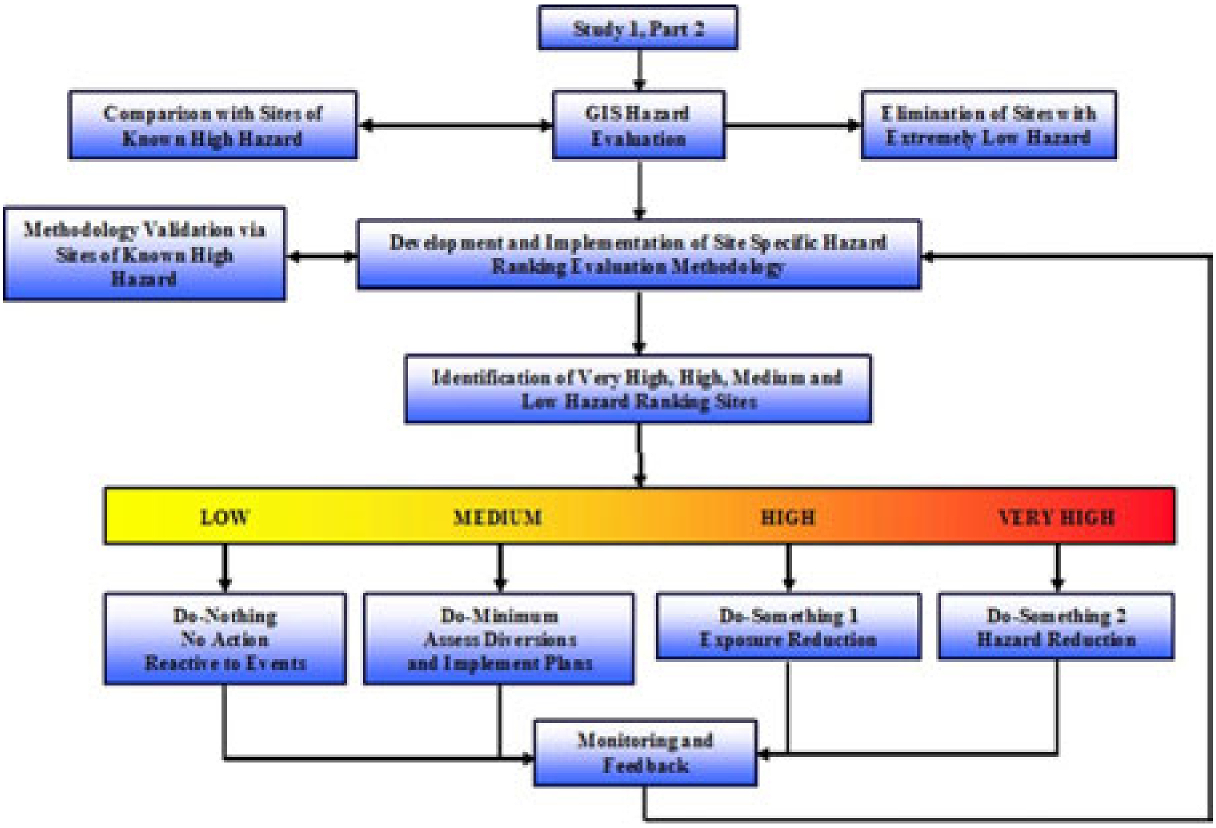

Figure 3.1 – Outline flowchart of the current study.

A **GIS-based assessment** was used as a first stage in the hazard assessment process. This enabled site-specific assessments to be targeted in order to obtain better value from such relatively resource-intensive activities. It also allowed the elimination of large areas of the network having minimal hazard (see Sections 4 and 5).

It is particularly important to note that the **site-specific assessment**, described in Sections 6 and 7, was not a simple ‘drive-by’ survey; it comprised a highly specialised detailed site examination using an overall consistent approach. Prior to undertaking any site surveys the system for consistently describing and identifying hazards and the associated exposure was established. Some of the factors that needed to be incorporated into such a system, such as slope angle and the broad nature of the geology, were already incorporated into the GIS assessment. Other, more detailed, factors such as the effects of forestation were incorporated into the site-based survey. The site-specific assessments were predicated upon the principle that the hazard assessment derived from the interpretation of the GIS-based assessment should be changed only on the basis of information that had not been previously taken into account. Once a hazard assessment was been completed it was combined with an assessment of the exposure of the road user to that hazard to give a hazard ranking. This in turn allowed an appropriate management option to be selected from the range of options developed.

There are a number of outline options which could be applied to the management of debris flows depending upon the level of hazard ranking pertaining at any given site. These are addressed in the following paragraphs.

The **‘Do-Nothing’** approach is intended to be applied to sites of low hazard ranking for which substantial expenditure is inappropriate. For such sites, whilst it is not possible to eliminate the chance of a debris flow event affecting such areas, it is seen as unlikely, largely unforeseeable and/or the exposure is less serious than at other locations where resources might be better expended.

The **‘Do-Minimum’** option, with the potential to mitigate the impacts of debris flows to some extent, involves simply ensuring that forward plans are in place to ensure that diversion routes are available and may be exploited in an expedient and well-organised manner. Diversion route maps and contingency plans are currently held for many areas of the trunk road network. Whilst it is not possible to eliminate the chance of a debris flow event affecting such areas any occurrence is seen as unlikely and largely unforeseeable. Any residual exposure cannot readily be quantified and is unlikely to justify the commitment of additional resources which might be better expended at other locations.

‘Do-Something 1’ is the first management option where site-specific action is contemplated. Such action is essentially exposure reduction by managing the access to the network and/or actions of road-users at times when events occur or precursor rainfall has indicated a high likelihood of debris flows occurring.

‘Do-Something 2’ involves more major works in order to achieve hazard reduction (as opposed to exposure reduction in the ‘Do-Something 1’ case). The approaches involved here entail physical measures such as the protection of the road, reduction of the opportunity for a debris flow to occur or realignment of the road away from the area of high hazard. Such options need to be considered in the context of the policy governing Transport Scotland’s overall trunk road maintenance and construction programme. In general, these are likely to be of high cost, necessitating their restriction to the very few areas of highest hazard ranking.

For all trunk road routes, irrespective of the particular type of risk or incident that might force a closure (landslide, flood, road traffic accident, etc), diversion routes are in place and these have been agreed in advance with the relevant local authority and with the police. In all of the cases described above, in the event of a landslide incident closing the road such diversionary routes will be used.

The approach to and specific methods of exposure and hazard reduction are specifically addressed in Section 8.

Clearly, and as illustrated in Figure 3.1, M**onitoring and Feedback** is fundamental to the success of the system and key to deriving best value from the arrangements proposed. The system developed operates actively and lessons learned from future debris flow events, whether they occur in areas of high or very high hazard ranking or not, will produce valuable data which needs to be taken into account in adjusting the parameters that form the cornerstone of the assessment methodology.

In parallel with this there exists a need to ensure that actions identified by the existing Rock Slope Hazard Index system (as developed in the early 1990s: McMillan & Matheson 1997) are carried out on a priority budget basis. Such actions will include both maintenance works and re-inspection activities. While the rock slope system and the proposed debris flow system have very different structures, great efforts have been made to ensure that the critical exposure evaluation and the output categories are capable of being mutually compatible.

3.3 DISSEMINATION

Dissemination activities include a wide range of presentations to a wide range of audiences, both specialist and otherwise. A range of publications has been published in technical journals (Winter *et al.*, 2006a) and in international conference proceedings aimed at disseminating the work undertaken in the UK (Winter *et al.*, 2006b; 2007a), the USA (Winter *et al.*, 2007b; 2007c) and Hong Kong (Winter *et al.*, In Press). This is a continuing process and further technical papers are in preparation including ones intended to be delivered at international conferences in Asia and Europe.

More than 40 separate dissemination activities have been undertaken to date; Table 3.1 lists the key activities.

Table 3.1 – Key dissemination activities.

Activity	Audience, Location and Date
Project Workshop	Project participants, North Queensferry, September 2004
Cover picture for the *Quarterly Journal of Engineering Geology and Hydrogeology*	Profession, all four journal issues in 2005
International Conference on Land Risk Management (attendance and awareness raising), part-funded by Royal Academy of Engineering	Profession, Vancouver (Canada), June 2005
Report to Royal Academy of Engineering on visit to Canada (see above)	Profession, 2005
Study Technical Report	Profession, June 2005
Study Summary Report	Public and politicians, June 2005
Launch Seminar for Technical and Summary Reports	Profession, Edinburgh, June 2005
Paper in *Proceedings of International Conference on Landslides and Avalanches: ICFL 2005*	Profession, Norway, 2005

Table 3.1 (continued) – Key dissemination activities.

Activity	**Audience, Location and Date**
Interview on BBC Radio Scotland (Good Morning Scotland) on anniversary of Glen Ogle events	Public, 18 August 2005
Article in *TRL News*	Profession, October 2005
Book review of Technical Report in *Engineering Geology* journal	Profession, 2005
Article in *Surveyor* magazine	Profession, November 2005
Presentation to *Seminar on Landslides and Sediment Control – Implications of Climate Change for the Design and Management of Forestry*	Forestry Commission, Dunkeld, December 2005
Article in *Surveyor* magazine	Profession, February 2006
Paper in *Quarterly Journal of Engineering Geology and Hydrogeology*	Profession, 2006
Presentation to Scottish Universities Geotechnical Network – *Landslides Masterclass*	Profession, Dundee, April 2006
Presentation to Central Scotland Regional Group of the Geological Society	Profession, May 2006
Presentation to Ground Engineering Magazine *Seminar on Slope Engineering*	Profession, London, July 2006
Article in *Surveyor* magazine	Profession, July 2006
Presentation to Climate Impact Forecasting for Slopes (*CLIFFS*) network seminar	Profession, Kingston-upon-Thames, July 2006
Paper in *Proceedings of Engineering Geology for Tomorrow's Cities: Proceedings, 10th International Association of Engineering Geology Congress*	Profession, Nottingham, September 2006
Presentations to *RoadEXPO 2006*	Profession, Edinburgh, October 2006
Consultation on Scottish Executive's State of Scottish Soils	Government Organisations, 2006
Article posted on *CLIFFS* website	Profession, 2007
Leaflet drafted for Transport Scotland on Scottish Roads and Landslides	Public, 2007
Presentation to HR Wallingford	Profession, Oxfordshire, March 2007
Presentation to TRL (*Landslides Masterclass*)	Profession, Berkshire, May 2007
Presentation at IAT National Conference	Profession, Telford, May 2007
Paper in *Proceedings of International Conference on Landslides and Climate Change: Challenges and Solutions*	Profession, Isle of Wight, May 2007
Presentation at Climate Change and the Roads Seminar	Profession, Nottingham, June 2007
Two papers in *Proceedings of First North American Landslides Conference: Landslides and Society – Integrated Science, Engineering, Management and Mitigation*	Profession, Vail (Colorado, USA), June 2007
Presentation to *SCOTS Training Module II* – Design and Construction	Profession, Hamilton, September 2007
Presentation to Northern Ireland Geotechnical Group *Earthworks Seminar*	Profession, Belfast, September 2007
Paper in *Proceedings of the International Forum on Landslide Disaster Management*	Profession, Hong Kong, December 2007
Presentation to Hong Kong Regional Group of the Geological Society	Profession, Hong Kong, December 2007
Presentation to public *CLIFFS* network seminar	Profession, Loughborough, February 2007
Presentation to Royal Meteorological Society	Profession, Norwich, March 2007
Presentation to EGU Session on *The role of plants on slope stability and the impacts of climate change and land-use change on landslides* (co-convened by lead editor)	Profession, Vienna (Austria), April 2008
Paper accepted for the *Proceedings of 10th International Conference the Application of Advanced Technologies* in Transportation	Profession, Athens (Greece), May 2008
Papers submitted to the *First World Landslide Forum*	Profession, Tokyo (Japan), November 2008

Other relevant publications that expressly relate to or refer to the work include (Nettleton *et al*., 2005a; Winter *et al*., 2006c; 2007d; 2007e).

3.4 RISK ISSUES IN CONTEXT

The affirmation that we live in a 'risk-averse society' is becoming a common viewpoint and implies that the willingness to accept, or to tolerate, risk is low. In many spheres of life such a statement may well be accurate, but it remains relatively meaningless unless it is viewed in a broader context. Such a context includes the willingness (and/or ability) of society (as an individual, a corporation, an organisation, or as a sector of government) to pay for risk reduction measures and the willingness to alter the environment in order to accommodate such measures.

The United States of America is often cited as a definitive example of a risk averse society. However, the evidence does not always support this assertion. Interstate 70, the main east-west route through Colorado, traverses the toe of the DeBeque Canyon landslide (Figure 3.2). During the last reactivation of the landslide in April 1998, the road heaved 4.3m and shifted 3m laterally towards the nearby river (White *et al*., 2007). The landslide continues to move forewarning of possibly future rockslides from above and heaving of the road associated with rotational failure. The Colorado Department of Transportation (CODoT) have undertaken a series of remediation measures as described by White *et al*. (2007) and commissioned a long term monitoring system. The overall approach seems to be that the movements described above are at an acceptable level and can be managed on an emergency works basis as and when they happen.

Figure 3.2 – DeBeque Canyon landslide showing Interstate 70 passing over the toe.

The example of DeBeque Canyon, cited above, implies a high level of willingness to accept risk and an associated low level of willingness to pay, possibly driven by an unwillingness to affect the environment. There also may be higher levels of risk elsewhere which may take priority. Provided that the willingness to accept risk, to pay and to affect the environment can be consistently described at a conceptual level then the approaches in different parts of the world and in different situations may be straightforwardly and graphically compared to gain a deeper understanding of the drivers for the approach to risk mitigation.

This has been achieved by means of the ternary 'Willingness (ternary) Diagram' (Winter *et al*., In Press) (Figure 3.3). The Willingness Diagram inter-relates three parameters, thus constraining any one of the three in terms of the levels assigned to the other two, the implicit assumption being that there is a fixed amount of 'willingness' to share between the following parameters:

1. Willingness to accept (or tolerate) risk.
2. Willingness (and/or ability) to pay.
3. Willingness to alter the environment in the pursuit of lower risk.

The example of DeBeque Canyon, cited above, implies a high level of willingness to accept risk and an associated low level of willingness to pay, possibly driven by an unwillingness to affect the environment and, potentially, higher levels of risk elsewhere which may take priority.

The situation in Hong Kong, where life has been valued at a high, but nevertheless realistic, level and the willingness to accept risk is relatively low, provides and interesting counterpoint. In the 1980s the willingness to affect the environment was also at a relatively high level with hard engineering solutions often dominating the scene (e.g. Figure 3.4). In the latter part of the 1990s and beyond there was an apparent shift in the approach in Hong Kong and the willingness to affect the environment was much reduced leading to softer vegetative solutions where appropriate. This change in approach may have been associated with an increase in the willingness to accept risk as some of the design solutions used may be less robust. There may also have been an associated increase in the willingness to pay, if only in terms of an increase in the long-term maintenance expenditure required for such soft solutions.

Figure 3.3 – The Willingness Diagram showing the different approaches to landslide risk in respect of the Scottish main road network, the Undercliff at Ventnor, I-70 DeBeque Canyon and in Hong Kong.

Figure 3.4 – A shotcrete slope in Kowloon, Hong Kong SAR.

In the Isle of Wight, the willingness to accept risk is also low and the willingness to pay is high, despite the fact that the risks are generally to property rather than to life and limb. At the same time the willingness to affect the environment is low and these factors drive the use of the generally discrete and 'invisible' solutions that are implemented.

In respect of Scotland's roads the both the willingness to affect the environment and the willingness to pay are relatively low, and management solutions are thus favoured over intrusive engineering solutions. With this comes an acceptance that a certain level of risk must be accepted and that these risks are generally significantly less than those posed in other situations – by road traffic accidents, for example.

In terms of the Scottish environment some of the key drivers for the willingness (or indeed unwillingness) to accept risk are social, economic and environmental and often include components of all three. Roads in Scotland provide vital communication links to residents of remote communities from both the social and economic viewpoint and the effects of the severance of the communities from services and markets for goods is highly undesirable.

An example of the adverse impacts that severance may have on communities may be drawn from Jamaica. In this case (Figure 3.5) a landslide has occurred on the B1 route in the Blue Mountains in Jamaica effectively severing the local coffee production industry from the most direct route to markets accessed from the island's north coast.

Figure 3.5 – Landslide on the B1 road at Section in Portland Parish, Jamaica.

The landscape has both a social and an environmental value, but what is often forgotten is that, for Scotland, its economic value is substantial as it attracts much business in the form of tourism, especially important to many of the remote communities potentially affected by landslides. The height of the tourist season does also coincide with the summer landslides season of July and August and thus, in parallel with the need to maintain access, detrimental effects on tourism from negative publicity are unwelcome to all involved parties, including both politicians and the public. At the same time adverse visual impacts on the landscape by large defence/remediation structures (e.g. debris basins, overshoots, shelters, etc.) are seen as undesirable and, as a result, the underlying philosophy of any remediation must be to preserve the natural landscape as much as is possible insofar as this is what tourists come to enjoy.

The avoidance of adverse impacts on other valuable natural resources is also a key issue. Examples of such adverse affects might include measeres that result in the alteration of the hydrogeological regime of protected peat bogs and activities which may add silt to protected/valuable salmon fishing/spawning rivers.

4 GIS-BASED ASSESSMENT

by M Harrison, A Gibson, A Forster, D Entwisle and G Wildman

4.1 INTRODUCTION

This section describes the development of the GIS-based assessment tool for debris flow hazard assessment in respect of the entire Scottish road network and illustrates the data and results from this process.

In order to ensure that a comprehensive knowledge of debris flows, the road network and the interaction between these two entities was fully captured within the work being undertaken a working group was formed. This group comprised the authors of this section, who were tasked with producing the actual assessment, the editors of this report and other specific individuals with relevant experience (see acknowledgements).

A series of four meetings were held to consider the following issues:
Meeting 1: The specification for the work.
Meeting 2: The available data sets and their relevance to the task in hand.
Meeting 3: The scorings and weightings to be assigned to each data set.
Meeting 4: Fine-tuning of the results from scorings and weightings in the light of the group's knowledge and experience.

The process of knowledge capture and input used in this work was akin to the process that is used to capture information and develop rules for knowledge-based systems (e.g. Winter and Matheson, 1992). This approach forms a vital part of any knowledge and rule-based interpretation of data.

The methodology developed is based on assessing the propensity for debris flow formation. In order to establish the hazard to sites on the road network, further interpretation of the outputs is required in order to establish the likelihood of any given area that exhibits a propensity to debris flow formation producing a flow that might intersect the road (see Section 5).

GIS-based imagery relevant to the local road network was distributed to the individual Local Authorities for further action in the context of their particular needs.

4.2 BACKGROUND

4.2.1 Causal Factors for Debris Flow in Scotland

Winter *et al*. (2005a, p30, 31, 58), describing the findings of the initial study, identified 86 different factors that contribute to the debris flow hazard to the Scottish Roads network. Each of these factors is valid, and could be individually considered for inclusion in a system that seeks to model debris flow potential. However, for the purposes of this study it was important to use datasets that possessed reasonably consistent coverage across the whole country and for which some form of quality could be assured and for which availability could be guaranteed.

In effect this meant that many ‘point’ datasets, such as borehole records and site investigations could not be included within the analysis. However, many of the properties recorded as ‘point’ data are to some extent, described by spatially continuous datasets; for instance, data on permeability, grain size, and cohesion are intrinsically linked to polygons of different lithologies described by a geological map.

4.2.2 Data Sources

The working group identified three relevant data sources that were available for the entire study area:

1. BGS DiGMap: GIS layers of geology at 1:50 000 scale showing bedrock and superficial deposits (supplied by BGS). Each polygon of the geological map is attributed with a code that describes the litho-stratigraphic unit to which the rock type belongs. That is, each polygon is labelled with a code that describes the polygon in terms of the type and age of the rock.
2. NEXTMap Britain: a digital terrain model derived from the INTERMAP Digital Terrain Model product. NEXTMap is a high-resolution elevation model of Great Britain. It was generated from a 2005 airborne survey in Scotland where the time it takes for a signal to be sent down to the ground and bounce back was measured. This was calibrated with a GPS on board the plane to give the height of the ground surface, accurate to 0.5 m.
   The initial NEXTMap product was a digital surface model that represented the height of the surface of the ground. This dataset contains all ‘cultural’ features such as buildings and wooded areas. The second product from INTERMAP is a digital terrain model, which is the same product but with the cultural features removed. The algorithms that have been employed to remove these features are in the most part very effective. However, some areas of woodland are still shown by areas of raised elevation. Although this can cause localised error in the data, the NEXTMap digital terrain model is a very accurate and high-resolution dataset, and it provides continuous coverage for all of Scotland.
3. CEH (Centre of Ecology and Hydrology) land use data: CEH Landcover 2000 is a digital map that gives a comprehensive picture of the UK Broad Habitats (LCM 2000). Sixteen Target classes (Level-1) and 27 subclasses (Level-2) allowed construction of the Broad Habitats. The subclasses are described in greater detail in Level-3. It was mapped by analysing satellite spectral reflectance data on a grid of approximately 25 m square pixels. Ground survey assessed the spectral characteristics of the Broad Habitats and an automated system selected the most likely class for each pixel in a remotely sensed image. Accuracy was checked against ground survey and other information. The minimum mappable unit is about half a hectare. Data is available as digital outlines of the level 2 subclasses, which are treated as ‘objects’ in ArcView.

At an early stage of the research, it was proposed that rainfall data was also included. However, the working group concluded that, as intense rainfall could occur anywhere within the geographical study area, it was not necessary to include this as a separate factor. Therefore, Meteorological Office rainfall data have not been utilised at this stage.

The research described by this report considered how best to integrate aspects from the three data sources described above to provide a reasonable model for debris flow hazards affecting the Scottish road network. This has mainly been carried out through an iterative process of attributing or manipulating each dataset to represent as many of the factors described by Winter *et. Al*. (2005a). Thus, expertise in the geology of Scotland has been applied to

DiGMap to change the standard attribution of polygons (age and type of rock) to numerical codes that estimate bedrock permeability and the degree to which source material for debris flows can be formed.

4.3 DEBRIS FLOW POTENTIAL ASSESSMENT

The working party concluded in the initial study that five main components should be considered when determining the hazard potential of debris flows affecting the road network:

1. Availability of debris material.
2. Hydrogeological conditions.
3. Land Use.
4. Proximity of Stream Channels.
5. Slope Angle.

It was considered that information regarding each of these could be usefully retrieved from the datasets described in Section 4.2. The interpreted data could then be combined to produce a working model of debris flow hazard that could be validated by comparison with scenarios taken from accounts of investigated debris flows.

The possibility of seismic acceleration as a causal factor was raised at a working group meeting. After discussion it was thought unlikely to be a significant factor in the generation of debris flows that could impact significantly of the trunk road network as the ground accelerations developed by anticipated earthquakes were an order of magnitude less than those typically generated by heavy construction plant. However, further research into this subject may be useful at a later stage to properly consider the implications of a major seismic event.

4.3.1 Availability of Debris Material

For a debris flow to occur, there must be an available source of material, usually granular, often with a very wide particle size range in such a state that it would easily be mobilised by the action of a fluid (usually water). Thus the material that has the highest potential for debris flow activity is likely to be non-cohesive, with significant particle granularity. Material that is cohesive due to high clay content or inter-granular cement would be difficult to mobilise.

4.3.1.1 Analytical Method

On this basis, the lithologies represented by polygons in DiGMap were interpreted against a scale that indicated the degree to which the bedrock or superficial unit at surface would provide non-cohesive granular material as a source of debris. The ROCK_D (BGS Rock Description code) attribute of each polygon was re-interpreted by asking the following two questions:
‘Is this material capable of being mobilised by water into a debris flow in its fresh, unweathered state?’
Or
‘Is this material likely to have a weathered regolith or covering of head that could be mobilised by water to form a debris flow?’

Each ROCK_D description has been assigned a number on a scale of 1 to 10 to give an indication of its potential to supply the material, from within its outcrop, that would be capable of generating a debris flow. The judgement is based on the indicated grain size distribution or its assumed probable grain size distribution (for superficial material) or the likely 'block size' distribution of near-surface material/regolith (bedrock materials) as inferred by expert judgment. Table A.1 (Appendix A) shows the criteria used to assign each of the 4200 BGS codes identified. These are based upon the general principles outlined by Terzaghi (1955a, 1955b) and updated in BS8002:1994, BGS geologists' knowledge of each lithology and guidance from the working group.

In consultation with the working group, these were adjusted to account for the significance given to chemical weathering of certain rock types and the lower likelihood of the generation of clays by chemical weathering in some lithologies in Scotland. The interpreted codes were stored within the BGS Scottish Debris Flow Attribution Database (BGS SDABD).

4.3.1.2 Analytical Method – 'Accumulation Zone' Supplementary Dataset

It was recognised by the working group that in many locations, BGS data did not record the presence of peat or other deposits that may form sources of debris flow material. This was a function of the age of the BGS data used and the mapping methods historically employed by BGS mapping teams. In previous decades, priority was given to recording the presence of bedrock materials – superficial materials were considered ubiquitous and not mapped. To counter this, the working group recommended that a method be sought that could identify areas where deposits of non-cohesive material could collect and form source areas for debris flows.

The NEXTMap digital elevation model was analysed, using GIS to identify those areas where material was likely to accumulate. The analytical method used, highlighted those areas where changes in the shape (morphology) of the ground meant, that a flow of water would be slowed, and any material held in the water flow might be deposited. The two types of slope are identified by the method are:

1. Convergent slopes – where horizontal bends in the ground mean that flows come together to form 'sinks', (Figure 4.1). This is termed a change in horizontal or 'plan curvature'.
2. Slope bases – where the relief of the ground changes quickly from a steep gradient to a shallow gradient, (Figure 4.2). This is termed a change in vertical or 'profile curvature'

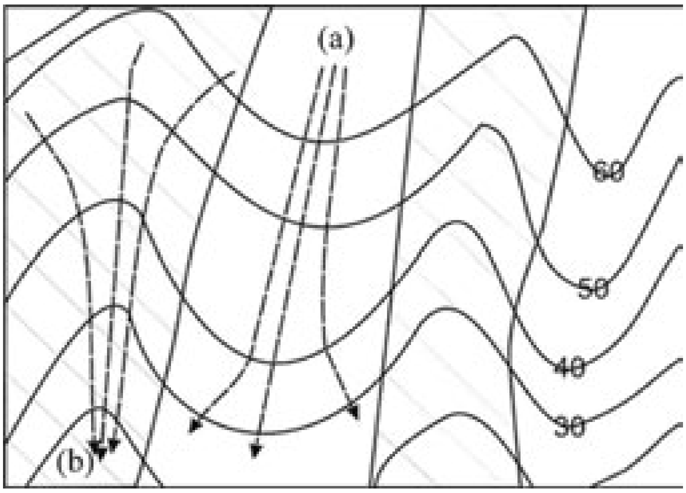

Figure 4.1 – Diagram showing how material flows away from (a) higher, convex (divergent) ground (b) and towards lower, concave (convergent) ground (after Shary, 2002).

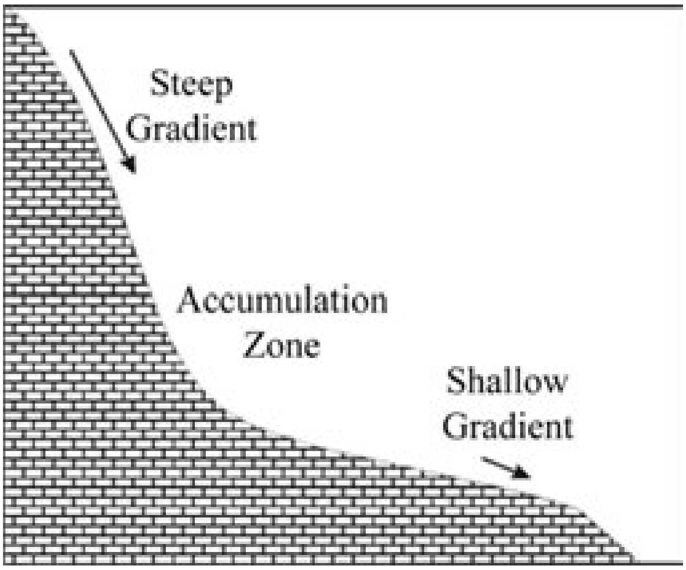

Figure 4.2 – Diagram to show where accumulation might be expected in an area of relief change, where slope gradient changes from steep to shallow (after Shary, 2002).

Characterisation of plan curvature and profile curvature were analysed together, to identify zones where the ground surface is 'convergent', where a flow of water would decelerate and deposition can occur (Figure 4.3). Likewise, the analysis can identify 'divergent' ground, where a flow of water would accelerate and erosion would occur.

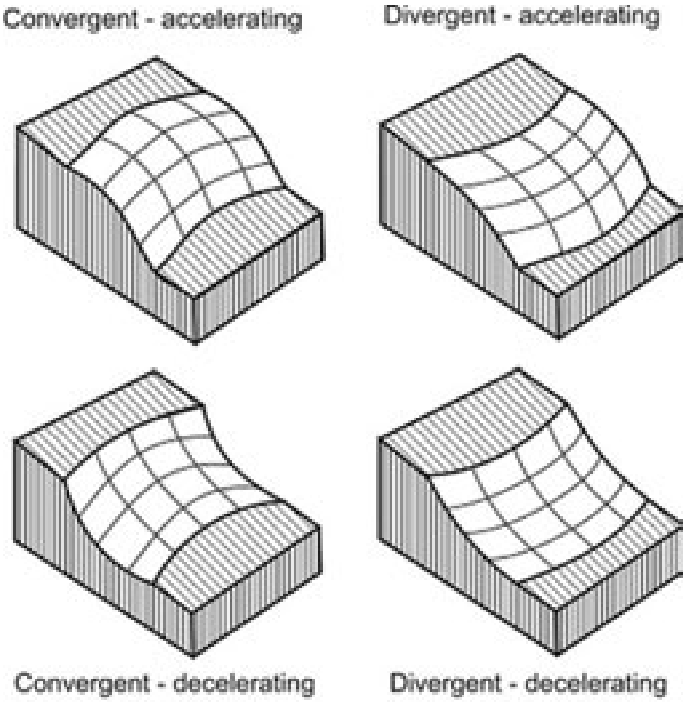

Figure 4.3 – Landform classification based upon a combination of horizontal curvature and vertical curvature (Troeh, 1964, Shary, 2002).

4.3.1.3 Method to Calculate the 'Accumulation Zone' Supplementary Dataset

Although a number of methods are available to perform this analysis, experience in other BGS projects has shown the K-Accumulation model by Shary (2002) works well and is flexible to different types of terrain. The method can be given by the algorithm:

$$K_{accum} = (Meancurve)^2 - ((Plancurve - (Profilcurve\ ) \times 0.5)^2 \tag{4.1}$$

Where:

K_{accum} is a value indicating the shape of the ground, positive values indicate areas of accumulation.

Meancurve, Plancurve and Profilecurve are all numbers that mathematically describe the shape of the ground, calculated from the 25 m pixel NEXTMap DEM using ArcGIS.

- *Meancurve* is the average normal section. Positive values highlight a broadly convex slope, negative values describe broadly concave landforms.
- *Plancurve* is the rate of change of horizontal curvature. Positive values highlight a divergent slope, negative values a convergent slope (Figure 4.4).
- *Profilecurve* is the rate of change of vertical curvature or slope. Positive values indicate convex slope, negative values indicate concave profiles (Figure 4.4).

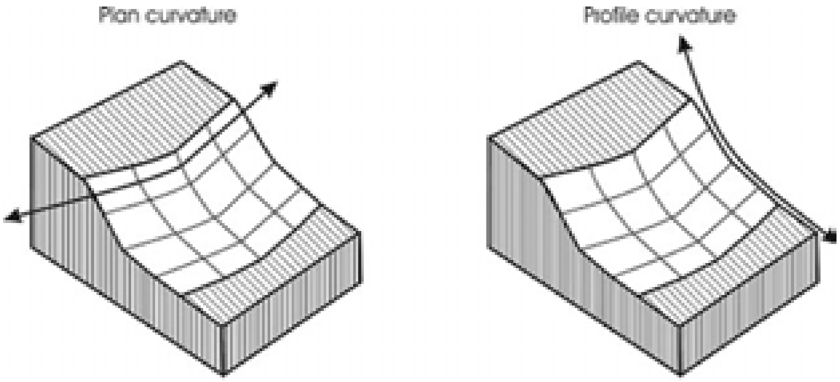

Figure 4.4 – Visual representation of plan curvature and profile curvature.

The output from the algorithm is a number rating (K_{accum}) that indicates the likelihood that material will be deposited, as a result deceleration of a flow. Although previous use of the method by BGS was to estimate areas where head may accumulate in the south of England, it has been possible to adapt the method to indicate areas where material may accumulate in the Scottish Highlands. This was carried out by an iterative process whereby the original formula was applied to known areas and a visual assessment made, comparing the estimated area of material deposition with local knowledge of areas of deposition. Where the estimated area of deposition was incorrect (for instance on cliffs or in stream channels), the score given by the formula was discounted. After a number of iterations, it was decided that those areas likely to be depositional zones had a values in the range 0 – 1. Table A.2 (Appendix A) shows the result of this analysis, with suggested values to be used in the overall debris flow algorithm.

4.3.1.4 Results

Figure 4.5 shows the availability of debris material scoring for two areas – Glen Ogle and Inverness – as examples. These same examples will be followed for each of the stages in the report. The diagrams show that the generally more granular, alluvial or glacial materials in the base of the valley in Glen Ogle and more widely distributed in Inverness, have higher scores and therefore greater influence on the result in this part of the methodology. In this analysis these materials are regarded a potential sources areas for landslide debris.

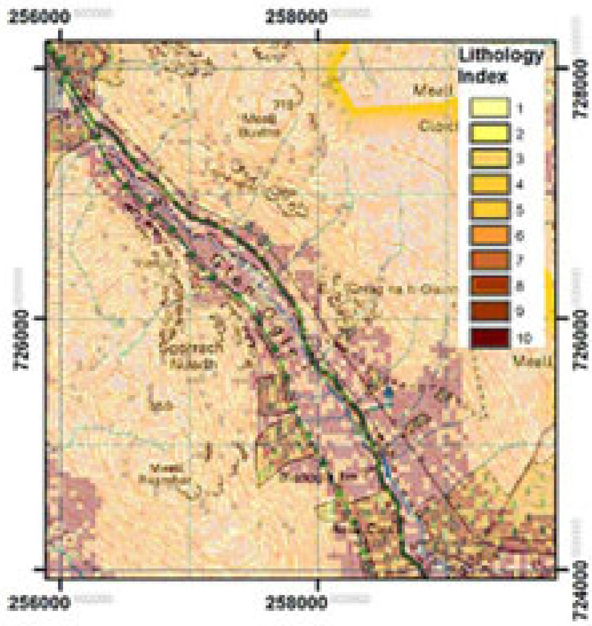

Figure 4.5 – Availability of debris material. Excerpts from the GIS showing the variation in availability of debris material scoring for two areas; (left) Glen Ogle and (right) Inverness. The legend in the diagram refers to this as lithology index, reflecting the scoring of the source material. (OS Data © Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

4.3.2 Water Conditions

Two aspects of water conditions are relevant to the generation of debris flows.

1. The ability of water, as rainfall or overland flow to infiltrate a potentially mobile deposit (permeability of the deposit).
    - This has been taken into account in the scoring for *Availability of Debris Material* (Section 4.3.1), which combines judgements on grain-size and permeability.
2. The ability of water to remain within the deposit to an extent where pore water pressures can build to a level where the shear strength is sufficiently reduced to initiate failure (permeability of the underlying material).
    - A factor was required that would take account of the permeability of the underlying bedrock, this is considered in this section.

The substrate beneath potentially mobile deposits may exert either a positive (destabilising) or a negative (stabilising) input to debris flow generation. A positive input will be generated where the substrate is impermeable. In such a case, infiltration through the surface material is impeded, leading to a build up of pore-water pressures, a lowering of effective shear strength and increasing the likelihood of a ground failure. Most bedrock materials may be locally expected to be relatively impermeable with regard to the timescale of a high intensity rainfall event.

A negative (stabilising) input to debris flow potential is generated where the substrate is permeable. If a debris flow moves over permeable ground it may be slowed by under-drainage – (water draining from the moving mass into the substrate) with a consequent increase in shear strength. It is unlikely that this mechanism will have a significant effect except where the debris flow has flowed onto shallow, very permeable slopes and has spread out to allow under drainage over a large area (as seen in the lowest part of some debris flows). The permeability of a rock type will be a function of grain size distribution for superficial materials and discontinuity spacing and dilation for bedrock materials. For superficial materials, coarse, clean gravels will be the most permeable and clay the least permeable. Consideration of the permeability of bedrock in Scotland needs to consider the possibility that in most places, relatively impermeable bedrock lies beneath a potentially permeable and mobile regolith. However, depending upon specific rock type, discontinuities in the bedrock may have been developed and dilated by thermal, physical and chemical weathering. At depth, most bedrock lithologies in the study area are likely to be interlocked and unlikely to be incorporated in a debris flow.

It should be borne in mind that, in many locations, there will often be a pre-existing drainage system that will have a significant impact upon the nature and distribution of pore-water pressures. Although such systems are likely to be a significant control on debris flow potential, there is no proven method available at this time that can be used to digitally analyse this using existing data. It was considered by the working group that this may be an avenue for further investigation at another stage of the research.

4.3.2.1 Analytical Method

Lithologies represented in DiGMap were interpreted on a scale that indicated the relative permeability of substrate materials. The ROCK_D (BGS Rock Description code) attribute of each polygon was interpreted by asking the following question:
'What is the permeability of this rock type?'

Each ROCK_D description has been assigned a number on a scale of 1 to 10 to give an indication of its permeability within its outcrop. The judgement is based on the indicated grain size distribution or its assumed grain size distribution (superficial material), consolidation/cementation and discontinuities. Table A.3 (Appendix A) shows the criteria used to assign each code.

4.3.2.2 Results

Figure 4.6 shows the result of these assessments in the two example areas. High values represent areas of low permeability hence a higher likelihood of contributing to debris flow formation.

4.3.3 Vegetation and Land Cover

Vegetation may have three beneficial effects in maintaining slope stability:
1. Intercepting rainfall to reduce infiltration into the ground
2. Removing soil moisture
3. Reinforcement of the ground by a root network.

The amount by which particular vegetation improves the stability of a slope will vary with the type of vegetation. Trees are likely to be more beneficial than shrubs, which would be better than grass.

Other land uses are likely to have adverse influence on slope instability, for instance, bare soil or cultivated (bare) ground would be prone to debris flow, as it is often unbound and in a loose condition. Urban or rural development may also be detrimental to stability due to the possibility of the inappropriate disposal of surface water, or leaking services that may feed water into a susceptible slope leading to high antecedent water level prior to a high magnitude event or a focusing of a high magnitude event such as to initiate debris flow activity.

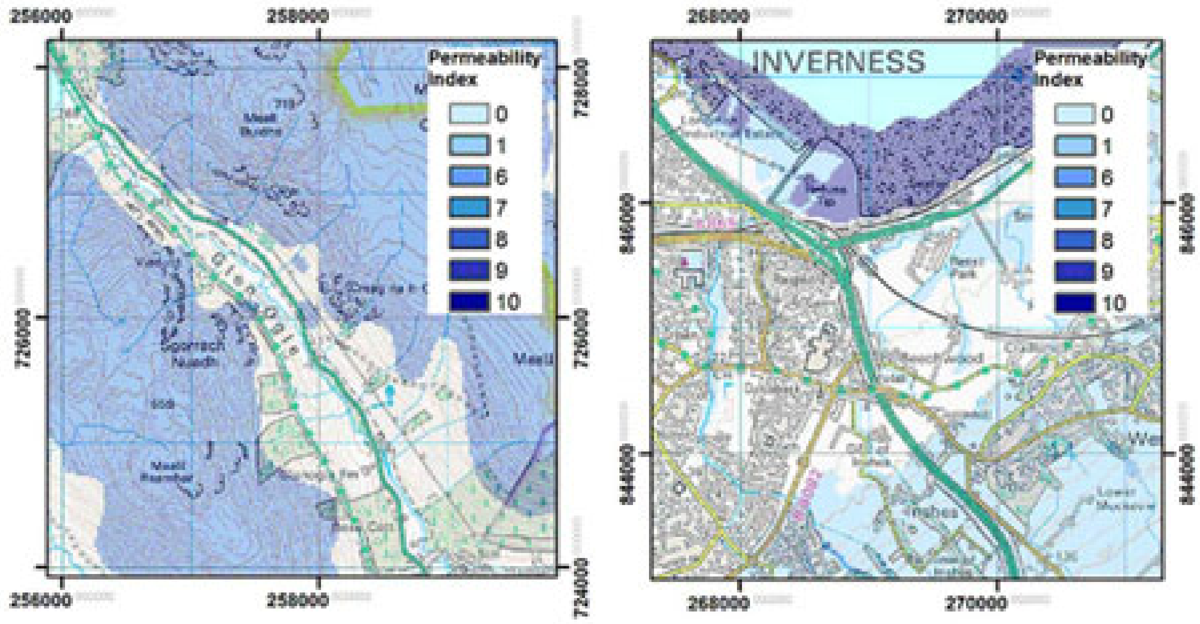

Figure 4.6 – Excerpts from the GIS showing the variation in water conditions (permeability) for two areas; (left) Glen Ogle and (right) Inverness. (OS Data © Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

4.3.3.1 Analytical Method

Expert judgement has been used to assign appropriate scores for the land use categories in the CEH land use dataset (Table A.4 of Appendix A) by asking the following question:
'What is the likely effect of this landcover upon debris flow potential at a site?'

The judgement was based upon the assumptions described above and on guidance from the working group. Each cover type was given a rating between 0.7 and 1.2 to indicate by how much the vegetation may improve stability. The lowest value is for woodland and the highest value for annual crops where the ground is regularly disturbed producing an open structure with little root strengthening. Other land use and vegetation cover have intermediate values.

4.3.3.2 Results

Figure 4.7 shows the result of these assessments in the two example areas. As can be seen in the Inverness area, the built environment gives a high stabilising factor, whereas in the Glen Ogle example, the vegetation would have a more limited affect on stabilisation.

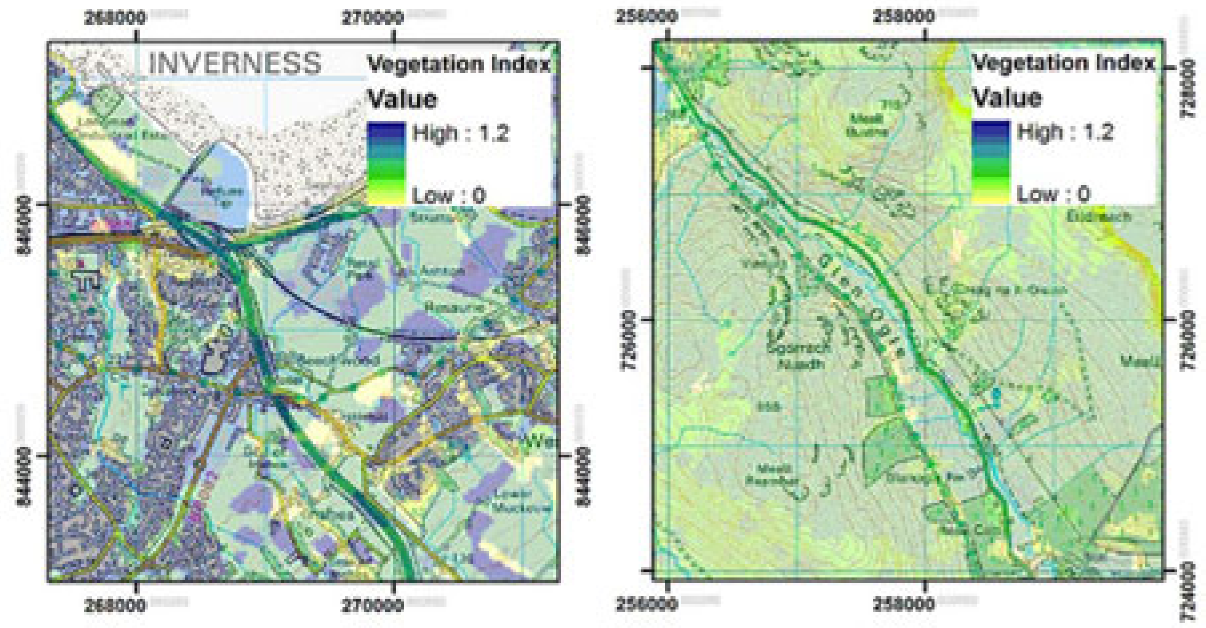

Figure 4.7 – Excerpts from the GIS showing the variation in Vegetation conditions from satellite data for two areas; (left) Glen Ogle and (right) Inverness. (OS Data © Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

4.3.3.3 Peat

Peat was initially considered separately, as it may fail in slides and bog bursts in certain environments. When it fails it may form a source of water and material to debris flows and may be part of the initial slide or, if part way down slope, may add impetus to the flow. A method of combining peat and slope that identified areas of peat above roads with slope of greater than 5° was discussed. However, the stability of peat involves many complex factors, some listed below, and a proper understanding of peat behaviour would require field assessment. As peat could not be suitably assessed using available national datasets, it was decided that this was a specialist issue and would not be pursued in detail during this project.
Some factors affecting the stability of peat:

- Peat layer overlies a relatively impermeable material.
- A convex slope or break of slope at its head.
- Proximity to local drainage including seeps, flushes and subsurface flow.
- Connection between surface drainage and the base of the peat.

As a primer to the peat assessment, BGS have used the NEXTMap data to calculate flat areas (that could contain peat) that lie above the trunk road network, with a connecting slope.

The first step was to locate areas of steep and flat ground (Figure 4.8). For the purpose of this exercise, steep ground over which peat could move was assessed as anywhere that had a slope greater than 5 degrees. Flat ground, where peat materials may form was identified as anywhere with a slope less than 2 degrees.

This was performed on a slope model for Scotland, derived from NEXTMap Digital Terrain Models (DTM), resampled to a 50m cell size. ESRI's Spatial Analysis extension was used to create two grids: one for steep ground and one for flat ground.

The steep and flat grids were converted to shapefiles, resulting in polygons representing instances of steep and flat ground. In some cases these polygons were quite large in size, so they were broken up into smaller polygons for analysis. This was achieved by intersecting the polygons by the trunk road and a catchment dataset calculated from the underlying DTM.

It was decided that only flat areas within a 3km buffer from the roads should be included for analysis, to reduce the data volumes. The intersected layers for steep and flat areas were both clipped to a 3km buffer of the trunk road network.

The polygons representing steep ground for the area around Glen Ogle are shown below.

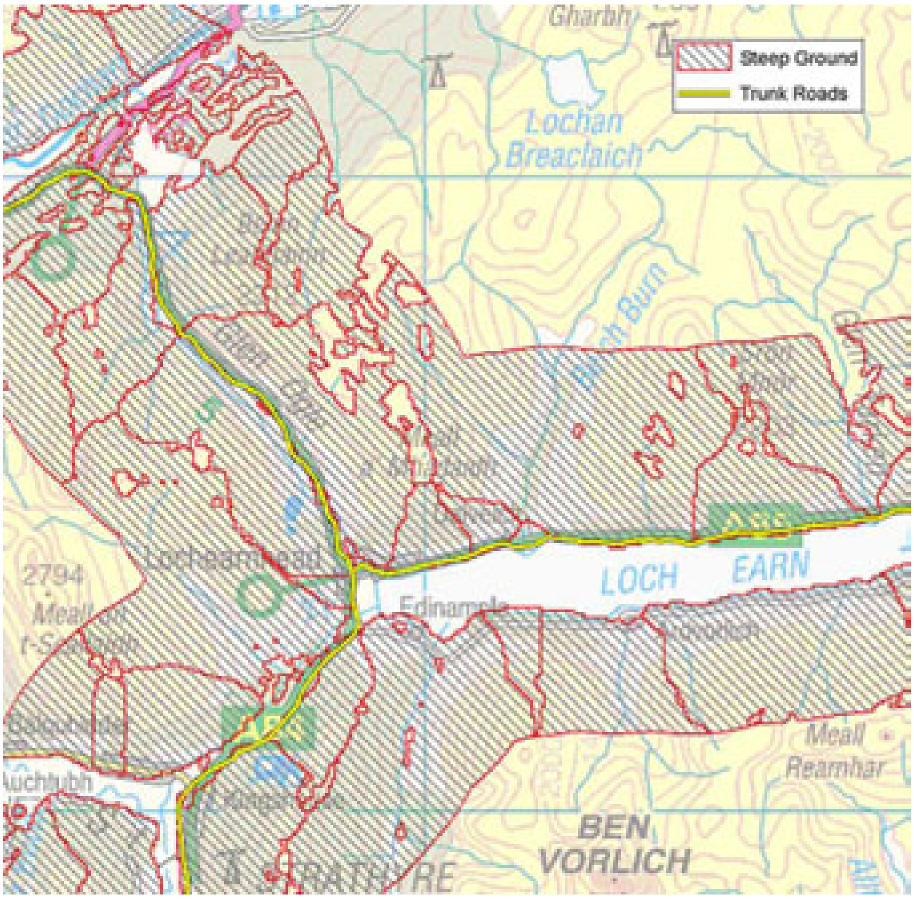

Figure 4.8 – Ground sloping greater than 5 degrees in the Glen Ogle area. (OS Data © Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

Zonal statistics, in ArcMap were applied to the intersected shapefiles to find the average height of each polygon. The height was abstracted from the NEXTMap DTM.

Every flat polygon was interrogated. If the flat polygon was within 150m of a steep polygon, and the average height of the flat polygon was larger than the average height of the steep polygon, then the steep polygon was interrogated. If the steep polygon was within 150m of a trunk road, and the average height of the steep polygon was higher than the average height of the road, then the flat polygon that originally intersected the steep polygon was exported to another layer. (The statistics for each road segment have already been supplied as part of the project deliverables. These statistics include average height of road segments, which have been used here.) This exercise was repeated for each flat polygon.
The algorithm used is detailed in Table A.5 (Appendix A).

4.3.3.4 Peat Limitations

This is a fully automated methodology, and is only as accurate as the data used.

The methodology identifies areas of flat ground above both steep ground and roads. It does not necessarily identify the ideal profile for peat flow.

4.3.4 Stream Channels

Stream channels are often associated with debris flows. This is primarily because they may focus the flow of water during extreme events and supply large volumes of water that can mobilise available material. They may also act as collectors for loose material during moderate flows forming debris dams and at times of extreme flow there is the possibility of their actively promoting landsliding of additional material from the walls of the channel and from these debris dams. Thus the working group concluded that identifiable streams should be buffered for an appropriate distance from their centre line to take into account the erosion catchment area and nature of the adjacent material. Discussions within the working group suggested that a buffer, at least, as wide as an assumed 15° side slope should be employed. For a 3m deep channel this would give a buffer width of ±15m and for a 10m deep channel a ±50m buffer.

Using this method, it was found that the buffer covered very large areas of ground. Therefore, for the first iteration of the dataset, it is proposed to use a 50 m buffer centred on stream channels and to score this 10.

4.3.4.1 Analytical Method

The location of streams were automatically generated from NEXTMap digital terrain models using hydrological modelling techniques. The NEXTMap dataset is detailed in Section 4.2.2.

ESRI’s hydrologic modelling toolset from the Spatial Analyst extension in ArcGIS 9.1 was used to generate the stream network. A filter of 1500m was used to ensure that the correct density of streams was identified. Full details of the method are given in by Tarboten et al (1991). As described above, the automatically generated stream network was buffered to a width of 50 m. Any ground within this buffer zone has been given a score of 10.

4.3.4.2 Results

Figure 4.9 shows the stream locations calculated from the DTM in the example areas. The low-lying Inverness area has many more streams present than the steeper and more deeply-incised Glen Ogle area.

4.3.5 Slope Angle

Slope angle influences the balance of stabilising and destabilising forces on all slopes. When the destabilising forces exceed the shear strength of the materials forming the slope the failure occurs. Therefore, the steeper the slope the greater is the susceptibility of the material to initiate a debris flow.

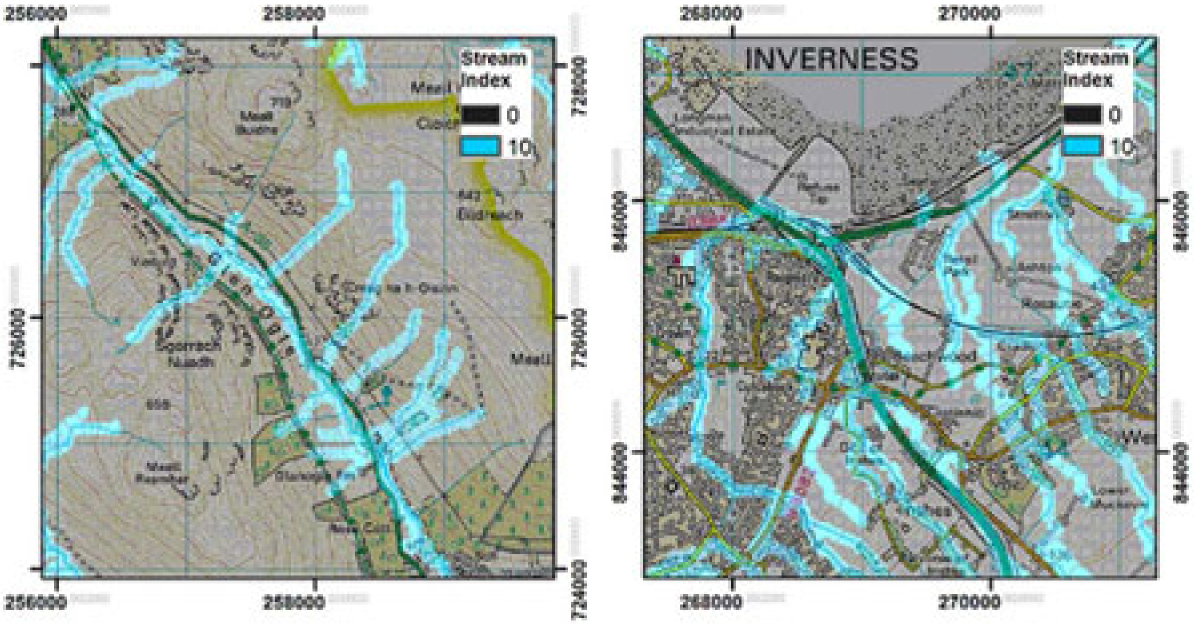

Figure 4.9 – Excerpts from the GIS showing the processed stream data as extracted from the Digital Terrain Model for two areas; (left) Glen Ogle and (right) Inverness. (OS Data © Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

4.3.5.1 Analytical Method

The slope categories significant in the generation of debris flows that were indicated by Winter et al. (2005a) were modified following further discussions within the working group, based on the experience of those present. These were used as the criteria to allocate scores to be included in the overall debris flow hazard assessment Table A.6 (Appendix A)

4.3.5.2 Results

Figure 4.10 shows the effect of these classifications in the two example areas. Slope is one of the most significant factors in the initiation of debris flows and as can be seen in the diagrams, in the low-lying Inverness area the slope index is very low. In Glen Ogle the pale colours indicate high slope values above the A85.

4.3.6 Weighting of Causal Factors

It was recognised by the working group that it would be important to include some form of weighting factor into the algorithm to allow the relative importance of each factor to be expressed. Although it is impossible to understand, in detail, the precise interaction between each of the factors described, the working group generated a series of weighting factors. These are based upon the knowledge and experience of members of working group involved in the investigation and management of debris flows in Scotland. This allowed different scenarios to be modelled in working group meetings to use real-world examples to validate the model results. The factors are given in Table A.7 (Appendix A).

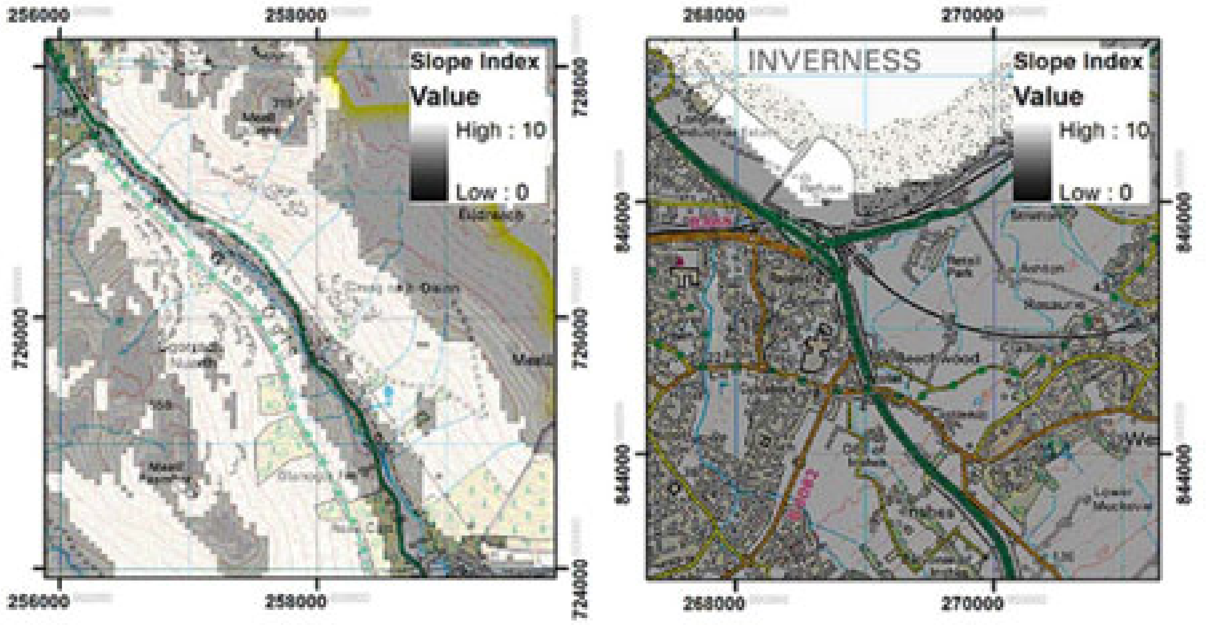

Figure 4.10 – Excerpts from the GIS showing the processed slope index values as extracted from the Digital Terrain Model for two areas; (left) Glen Ogle and (right) Inverness. (OS Data © Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

4.4 GIS METHODOLOGY

The five variables listed in Section 4.2 (availability of debris material, water conditions, vegetation and land use, stream channels, and slope angle) have been combined in a geographical information system (GIS) in order to analyse their distribution and be able to spatially combine their contributing hazard scores.

The system used to prepare data was ESRI's ArcGIS 9.1 and ArcWorkstation 9.1. For example, the geology was selected and clipped (cut-out) to the area of interest, and the stream network was 'cleaned' to remove anomalous areas such as lochs from the dataset. Once the datasets were clean and ready for analysis they were converted into grids and processed using ESRI's ArcWorkstation 9.1. ArcWorkstation is a command line driven GIS. Although it doesn't display the data graphically, so certain processor-intensive functions can be performed more efficiently.

All data were converted into grids with a cell size of 25 m. This was necessary in order to process the data efficiently, though the conversion process was not always straightforward. Grids are a very efficient way of processing large volumes of data and they are ideal when applying weighting factors. Using a simple arithmetic grid calculator, it is possible to multiple every cell in a grid by a certain amount. This enables any final weighting factor to be easily incorporated into the methodology. The weighting factor for each variable is then applied to the grid and resultant grids are added together to produce a final model representing the landslide potential.

Figure A.1 (Appendix A) shows a series of flow charts that summarise each of the methodologies.

4.5 RESULTS

The results of the study are presented as GIS layers available separately to this report. They are presented as ArcView format shapefiles for inclusion in further GIS analysis and as a table summarised against Transport Scotland's road network sections. Please refer to the limitations statement and contract Intellectual Property Rights statements for terms of use.

For those who do not have access to full GIS, ArcReader is available as a free download from http://www.esri.com/software/arcgis/arcreader/index.html using this tool the GIS format outputs can be viewed, simply use the <Scottish landslide.pmf> (ArcReader published map document) to view the data. The landslide data are provided with the Scottish trunk road network and local road network that BGS were provided with, that has been built into a network that can be viewed in the ArcReader software. For convenience, also located on the data DVD is a coastline as downloaded from the National Oceanic and Atmospheric Administration (NOAA) World Vector Shoreline website and Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Model. These two products can be freely distributed. When analysing the Scottish Landslide Data against the SRTM data care should be taken as the Landslide data were produced using a more accurate and validated Digital Terrain Model. Geotiff (Georegistered tiff images) have been created to load into any GIS or CAD software, or Adobe Acrobat format PDF files have been created for data inspection.

In order to present the data in this form, a legend was developed that summarised the data into classes Table A.7 (Appendix A) show the class values used. The classes are identified on an A to E scale, where A has the least potential to initiate debris flow landslides and E has the highest potential. Figure 4.10 shows the landslide hazard layers for the two example areas. As one would expect from the topography and general lack of contributory factors, the Inverness area in the diagram has very low potential for debris flow initiation. In contrast, the Glen Ogle area shows several areas of high potential mainly focused along stream channels. Certain of these channels were the initiators and focus of the landslide events of August 2004 that began the present study.

That the models identify these areas, indicates that the working group have been able identify the principal factors that led to the 2004 events (Figure 4.11). However the power of the GIS technique is that these same groups of factors have been identified for the whole of the Scottish road network as can be seen in the diagrams Figure 4.12 and 4.13. This is a 1:2,000,000 printout from the final landslide hazard layer. At this scale it is impossible to see the detail included in the 1:50000 modelling, however an overall indication of the level of hazard from debris flows across the Scottish Road network is possible.

The data is also presented in a tabulated form found on the data DVD as ScottishRoadLandslideStatistics.mdb. In this form the data were summarised using the database primary key of the trunk road network that BGS originally received. This allows users with no access to GIS to open the data in a spreadsheet or Microsoft Access database. Because of restrictions in field name lengths, these statistics are produced against shortened names. For a full explanation of these see Table A.9 (Appendix A).

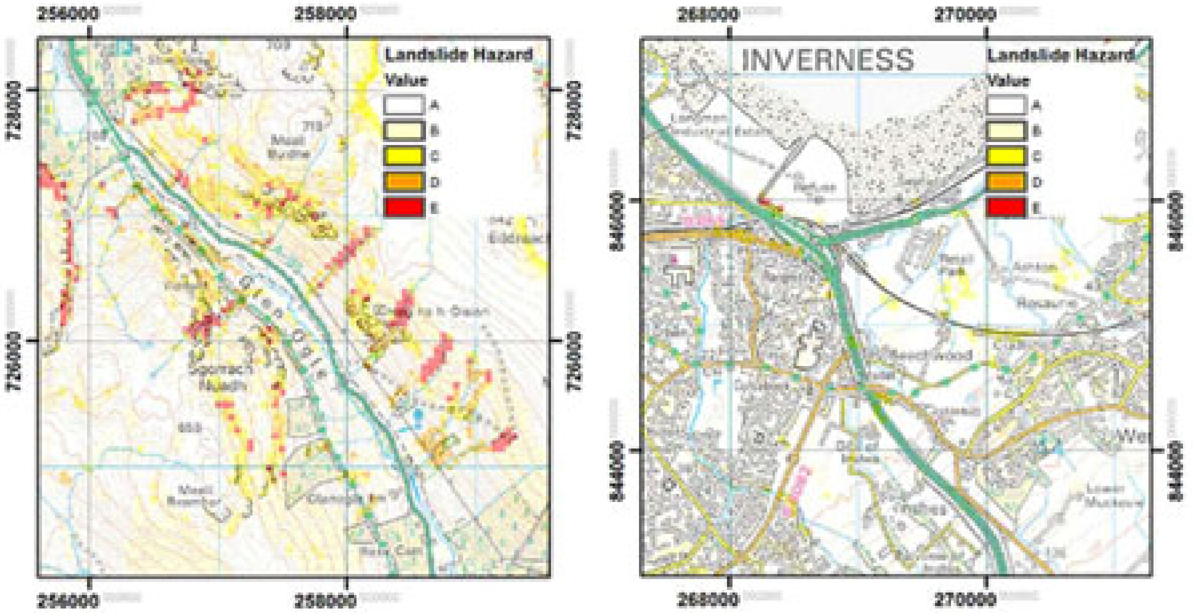

Figure 4.11 – Excerpts from the GIS showing the landslide hazard assessment for two areas: (left) Glen Ogle and (right) Inverness. (OS Data © Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

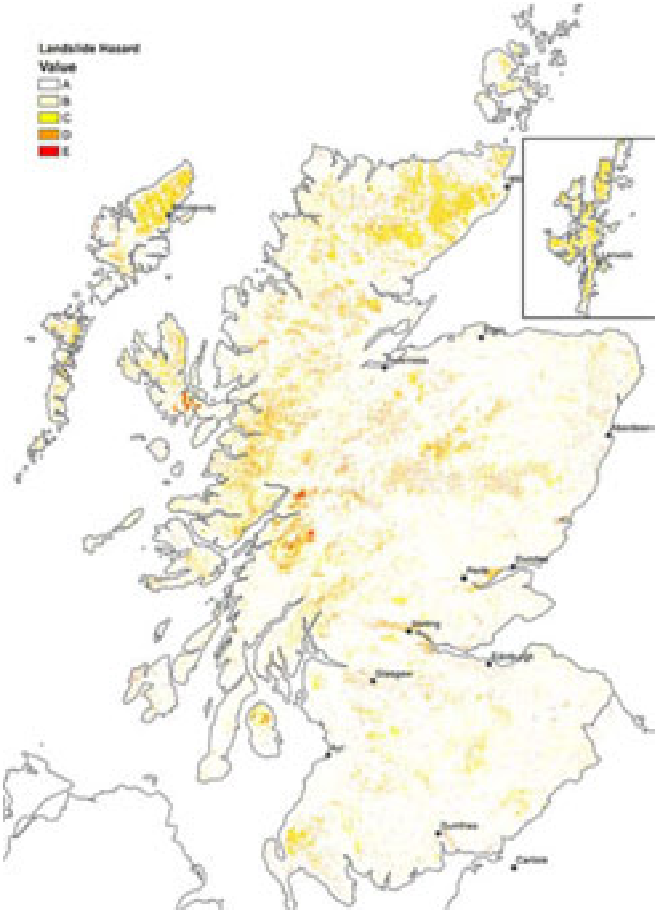

Figure 4.12 – Indicative 1:2,000,000 debris flow hazard across Scotland. For more detail please refer to the digital data available separately. (Note that as reproduced herein the map is not to scale.)

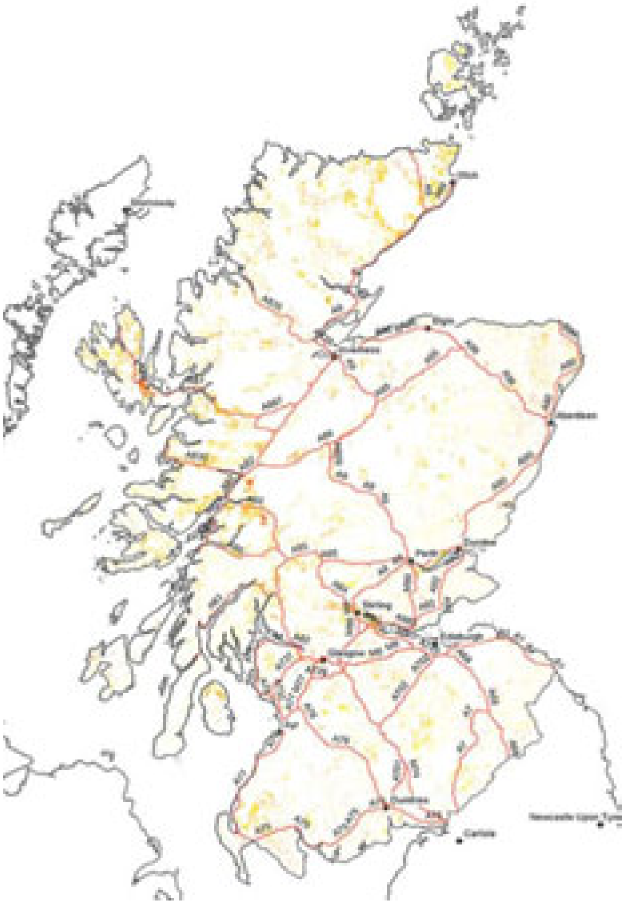

Figure 4.13 – Indicative 1:2,000,000 debris flow hazard across Scotland showing the Trunk Road Network. For more detail please refer to the digital data available separately. (Note that as reproduced herein the map is not to scale.)

4.5.1 Limitations

This has been a desk-based study, undertaken by BGS and the working group. Resources were not available for field survey. The results presented here from the first part of a landslides study. Because of the techniques employed in the processing of these data, there are some notable areas where misleading results could be inferred. These errors relate to factors that are not simple to encode into a system generated in the way described in the foregoing chapters. Figure 4.14 indicates an example of the errors that should be expected. In the Montrose basin, Raised Marine deposits of sand silt and clay, classified in our assessment as having moderate potential as source material for landslides have steeply sided gullies incised into them, which are highlighted by the slope model. This leads to a high score for landslide potential, especially when considering the land classification of bare ground and the presence of streams. In this instance, with extra knowledge that these deposits do not sit above a road, we can assume that they will not be involved in debris flow activity, however, the computer system does not know this fact, nor would it be straightforward on a national-scale to calculate this. It is at this stage that human intervention is required.

Figure 4.14 – Data anomalies in the Montrose Basin. (OS Data © Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

4.6 CONCLUSIONS

A methodology has been agreed by the Scottish Road Network Debris Flow Hazard Project Group to provide an outline assessment of debris hazard to selected sections of the Scottish Road Network.

The selection of factors to be included in the study was based upon relevance, usability and availability over the whole of Scotland.

Factors represented in the GIS methodology are the availability of debris material, water conditions, land cover, proximity of stream channels and slope angle. These have been combined using a GIS to estimate the hazard to the road network from debris flows.

The results have been tested against a number of areas where the degree and spatial extent of debris flow hazard are reasonably well known by members of the working party. The results of these tests have been used to 'tune' the methodology to better represent real world conditions.

The datasets provide a reasonable estimation of the hazard to the Scottish Road Network, as carried out at a national scale and are fit for purpose for use in helping to determine priority areas for the next phase of work in the Scottish Road Network Debris Flow Assessment.

5 INTERPRETATION OF THE GIS-BASED ASSESSMENT

by M G Winter, F Macgregor and L Shackman

The GIS-based assessment (Section 4) covers, to all intents and purposes, the entirety of Scotland and can thus be applied to both trunk and local road networks in any part of the country. This section and those that follow it detail the work that has been undertaken on the trunk road network to obtain a greater understanding of the hazards that exist and their relative rankings (see Section 3.2). The results of the assessment have also been distributed to local authorities for use in assessing their networks.

The interpretation of the GIS-based assessment imagery and relating this to the road network as it exists on the ground is, in many ways, the key to the study. While the GIS-based assessment deals with the potential for triggering debris flow, the interpretation detailed in this section of the report assesses the potential for such flows to reach the network. This then allows the prioritisation of sites (Section 6), the development of the levels of exposure of road-users, the consequent hazard rankings (Section 7) and the assignment of management strategies that result (Sections 8 and 9).

It should be stressed that this interpretation phase was configured to be an entirely desk-based exercise underpinned by comparing digital mapping (and low resolution aerial photography where available) with the GIS-based results, and augmenting this with extensive individual knowledge of the routes and adjacent landscape on the network.

5.1 DESCRIPTION OF DATA

Imagery of various types was utilised in the process of relating the GIS-based information to potential hazards affecting the network. Initially the layer derived from the GIS-based assessment was used (see Figure 5.1). Other layers available within the GIS included land elevation contours, the local and trunk road network, elevation data and coastline were used where appropriate. In addition, flat areas above roads, which were identified as part of the GIS-based hazard assessment process, were available as a layer as were the results of bespoke assessments of the superficial geology which were made as part of the project for areas where such information was not otherwise available.

Digital, two-dimensional Ordnance Survey mapping at 1:50,000 scale (Figure 5.2) was used to relate the GIS imagery to salient features of the network. The purpose of this was to aid perception of the nature of the terrain in areas where potential hazards had been identified. This was supplemented by relatively low resolution, two-dimensional aerial photography (Figure 5.3), where this was available at the time the interpretation was undertaken.

Ordnance Survey and low resolution aerial photography were examined in two-dimensions and, where clearer information about the topography of the landscape was required, in three-dimensions also (Figures 5.2 and 5.3). All viewing of the imagery was undertaken digitally, via a computer monitor, and latterly a 24-inch wide-screen device was used to allow the two main sets of imagery to be viewed side-by-side.

5.2 METHOLOGY AND OUTCOMES

The Scottish trunk road network comprises some 3,200 kilometres of route length. This network is of a widely varying nature, ranging from heavily trafficked motorways to, in certain localities, single-track roads providing essential transport and communications links for remote communities. The entire network was inspected in detail using the available imagery in order to achieve a valid interpretation of the GIS-based assessment. An essential factor within the process was the need to ensure consistency in the interpretative outputs, and this was built into the methodology.

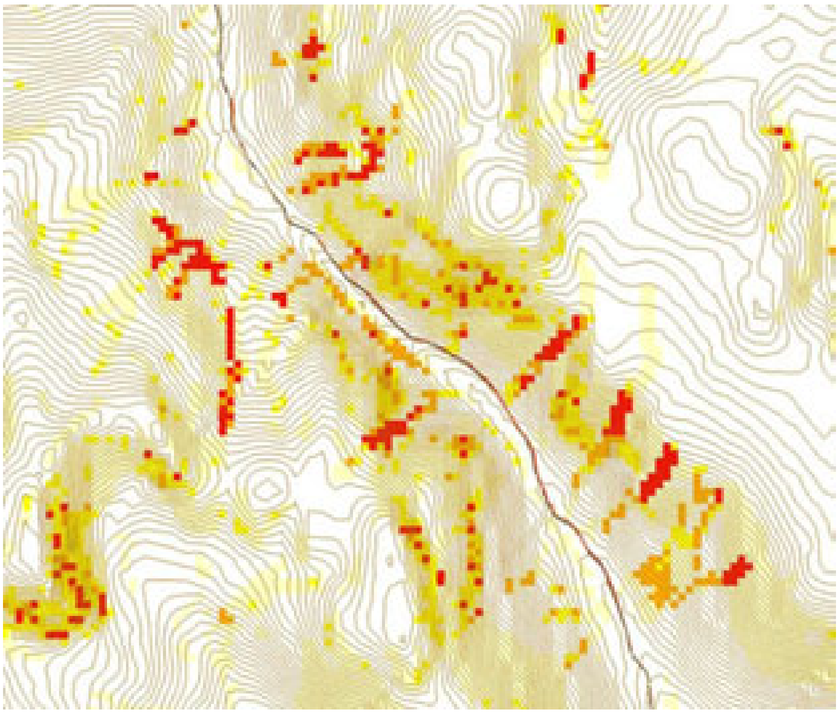

Figure 5.1 – GIS-based imagery for A85 Glen Ogle. The length of road shown is approximately 5km.

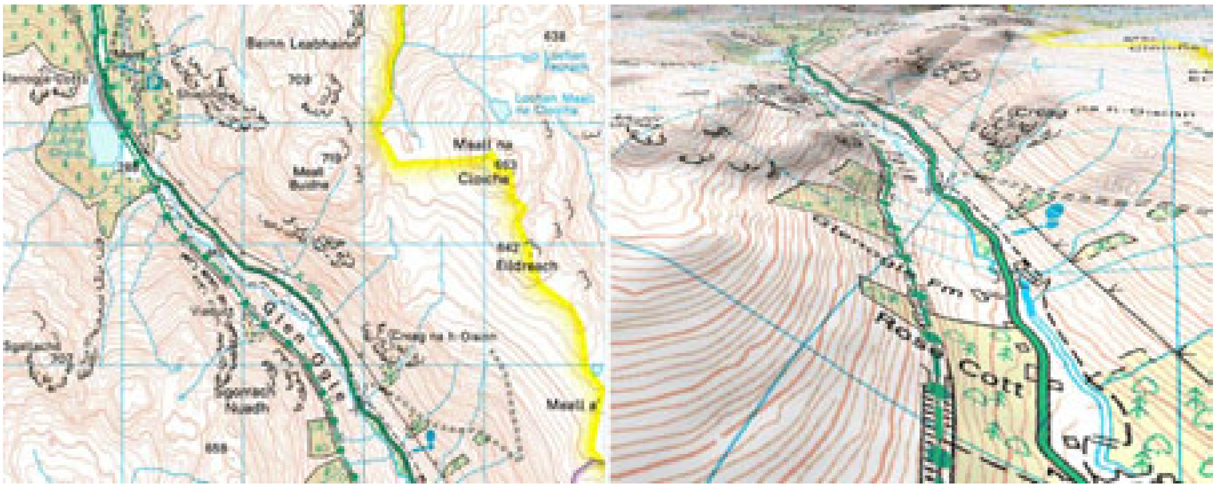

Figure 5.2 – Digital Ordnance Survey mapping at 1:50,000 for A85 Glen Ogle in: (left) two-dimensions; (right) three-dimensions. (Note that the image itself is not to scale.) (© Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

A two-phase approach was taken to the interpretation of the GIS-based assessment. The first phase primarily entailed selecting lengths of route for further study. At the same time account was taken of lengths of road that could become vulnerable to hazards if major works, such as realignment, were to be undertaken and, also, of data anomalies (see Section 4.5.1). The second phase of the interpretation then prioritised the route lengths selected in the first phase for further study in the form of site-specific assessments.

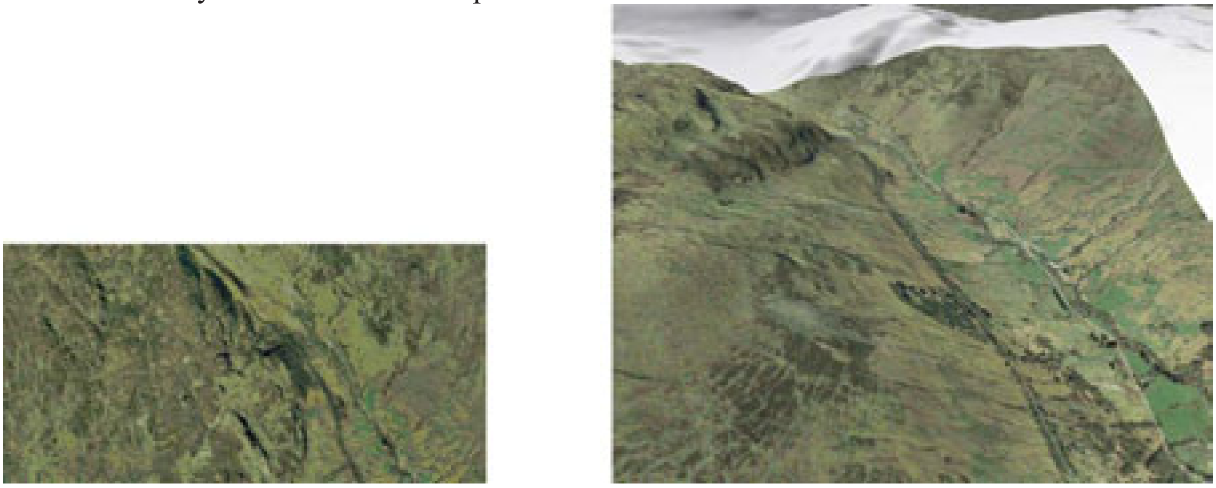

Figure 5.3 – Relatively low resolution aerial photography imagery for A85 Glen Ogle in: (left) two-dimensions; (right) three-dimensions. Note that the white areas represent those for which the aerial photography was not available.

The assessments entailed a close visual examination of the available imagery. In particular, given the spatially-distributed potential for debris flow trigger conditions defined by the GIS-based hazard assessment, an informed judgement was made of the existence of plausible flow paths that could allow debris flow to reach the road. Clearly the process by which such triggers propagate flows downslope are complex (e.g. Hungr *et al*., 2005; van Asch, 2006), proceeding through a sequence of erosion and deposition to the final runout zone, and potentially reaching a distal piece of infrastructure, such as, in this case, a road. However, using highly detailed approaches such as mathematical and numerical models, while appropriate to a small number of sites, would involve disproportionate resources in order to allow their implementation across a significant portion of the Scottish trunk road network. The assessment and interpretation presented here is thus regional, rather than local, and semi-quantitative/qualitative, rather than quantitative. It is, however, above all, appropriate to the problem under consideration, the area to be covered and the resources available.

The interpretative process was thus focused upon the morphology of the ground between areas of potential hazard and the road itself. Slope angles, the presence of stream channels that might aid the passage of debris and any potential barriers to flow were, amongst other factors, considered in all their forms. Consequently the interpretation may be summarised as a semi-quantitative/qualitative determination of potential debris flow tracks and run-out zones to determine whether they intersect with the trunk road asset. Figure 5.4 illustrates how the GIS-based assessment and its subsequent interpretation allowed sites of ‘high hazard’ were progressively identified n a systematic manner.

As the time of writing this report the editors are not aware of any instance of a systematic interpretation of the GIS-based assessment having been carried out for all or part of the local road network.

At an early stage in the development process it was decided that the interpretation of the GIS-based assessment would be carried out in its entirety by the project management team. This decision was taken in order to ensure consistency of output which would follow naturally from familiarity with the various facets of the development of the project as a whole.

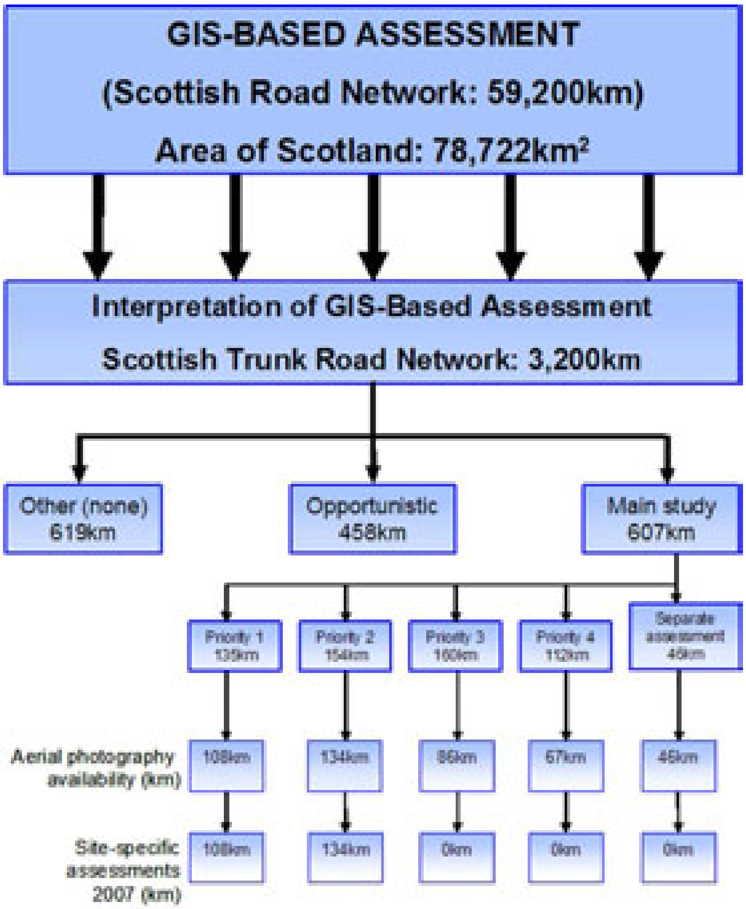

Figure 5.4 – Diagram illustrating the process by which the GIS-based assessment and its subsequent interpretation 'home-in' upon sites of high hazard.

One particular aspect to be taken account of was that of the team becoming more familiar with the interpretative process itself as the work progressed, and the need to establish the effects, if any, of this familiarity on the outputs. This was addressed by revisiting, as a conclusion to the interpretative process, a selection of the route sections which had been examined early in the exercise to verify that the outputs remained consistent.

5.2.1 Initial Interpretation and Outcomes

The specific methodology for undertaking the initial interpretation was to deal with the network on a route-by-route basis, working consistently from one end of the route to the other, and identifying sites of interest as they occurred by means of the route name followed by a numerical identifier (e.g. the thirty-seventh section identified on the A9 route would be coded as A9-37). Sites showing potential indicators of hazard on the GIS-based assessment imagery were be categorised under three descriptors, namely:

- Other (None): Although indicators were present on the GIS-based imagery, assessment had established that no potential hazard was present and these sites were considered benign in terms of the asset under consideration. As examples, there are localities where the GIS-based algorithms interpret flat, wet, low-lying ground as a hazard (see Section 4.5.1), or, in other situations, where an identified hazard would be directed to a location away from, or more remote from the road in question. For route lengths so categorised no further action is required.

- Opportunistic: This descriptor was used for localities where the hazards and risks were assessed to be less than would justify a main detailed study as part of this project, but would be required to be considered and assessed if and when any major works were planned – reconstruction or realignment for example. For route lengths so categorised no further action is required until specific plans to alter, upgrade or otherwise affect the route are planned.
- Main Study: These sites would be the lengths of route where significant potential hazards had been identified. These would be the sites recommended to be taken forward for full detailed assessment as part of this study. Care was to be taken that such Main Study sections were subdivided into separate sections such that all the individual sections exhibited hazards of consistent character. For route lengths so categorised further interpretation is required (see Section 5.2.2) with a view to site-specific inspections being carried out as appropriate and on a programmed basis.

For the full 3,200km of trunk road route length, imagery from the two main sources (i.e. Ordnance Survey and the GIS-based assessment) was inspected, along with the low resolution aerial photography where available. Three-dimensional views were used to assist in the process where appropriate.

The inspection progressed along the route in question until an area of interest was identified. In all cases, a swathe of several kilometres to each side of the road in question was inspected on the GIS-based imagery, in order to identify any more remote hazards, in addition to ones closer to the road.

For each area of potential hazard identified from the GIS-based assessment, the potential for any debris flow to reach the road infrastructure was determined as described previously. Any section of road that was identified as being potentially vulnerable to a hazard was then marked-up by category on a 'master' 1:50,000 Ordnance Survey plan.

In cases where flat low-lying land was indicated as a potential 'hazard', as a function of the way in which the GIS-based assessment was undertaken (see above and Section 4.5.1), a simple extrapolation from the 'hazard zone' to the road was made in order to rapidly define the route length and preclude it from further consideration, consequently marking it as 'Other (None)'.

The three categories, as previously described, were colour coded as follows:

- Other (None) – **Grey**.
- Opportunistic – **Purple**.
- Main Study – **Red**.

Figure 5.5 illustrates an area of the GIS-based assessment imagery for the A9 at Glen Garry, while Figure 5.6 illustrates the two-dimensional Ordnance Survey mapping with identified route lengths corresponding to the above categories.

Table 5.1 summarises the results for this initial interpretation, the results of which are presented in full in Appendix B.1 (Table B.1). In total 1,684km of the trunk road network was categorised as either Other (None), Opportunistic or Main Study. Table 5.1 shows how these categorisations relate to the total length of the network.

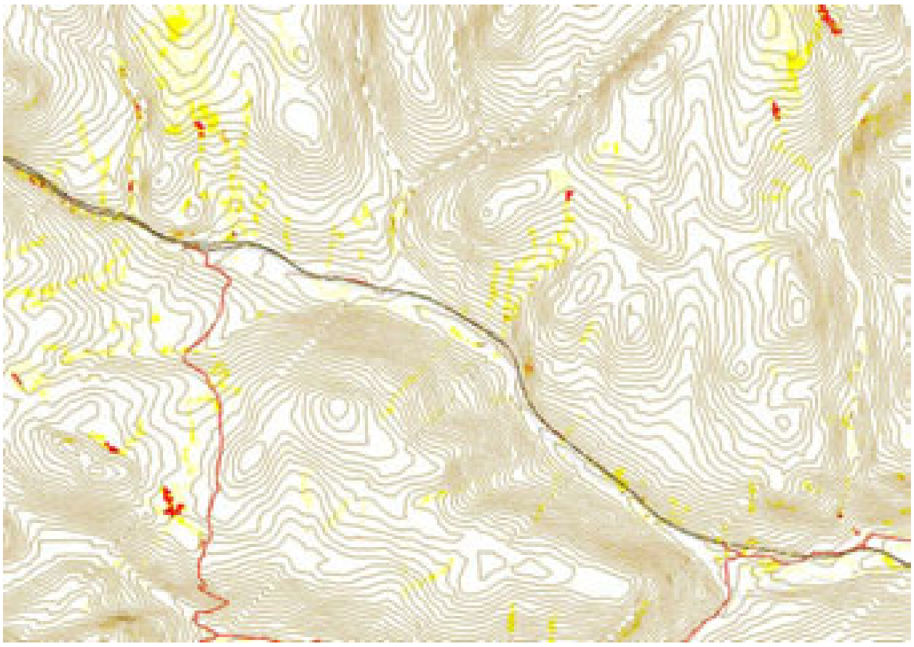

Figure 5.5 – GIS-based imagery for A9 Glen Garry. Not to scale.

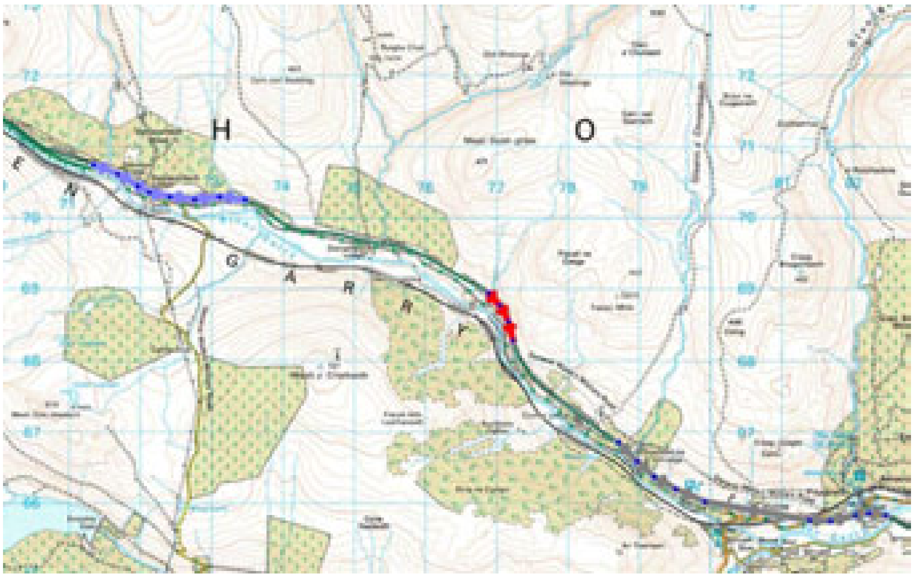

Figure 5.6 – Ordnance Survey two-dimensional imagery for A9 Glen Garry showing lengths categorised as Opportunistic (A9-36), Main Study (A9-37) and Other (None) (A9-38) as viewed from left to right. Digital Ordnance Survey imagery at 1:50,000 is shown but the image itself is not to scale. (© Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

5.2.2 Secondary Interpretation and Outcomes

With some 607km of the network falling into the Main Study category as an outcome of the initial imagery-based assessment, it was considered that further prioritisation of the Main Study sites would be necessary for reasons of allocating available resources for the detailed inspection phase.

Table 5.1 – Initial outcomes from the interpretation of the GIS-based imagery.

	Route Lengths Assessed (km)	Percentage of Route Lengths Assessed (%)	Percentage of Network (%)
Other (None)	619	37	19
Opportunistic	458	27	14
Main Study	607	36	19
Total	**1,684**	**100**	**53**

Accordingly the Main Study sites on the network were critically reassessed for severity of potential hazard and ranked in priority categories ranging from 1 (most severe) to 4 (lesser severity). At that point, relatively arbitrary hazard values (out of a nominal 100 'maximum') of 80, 60, 40 and 20 were then assigned on an interim basis to Priority 1, 2, 3 and 4 sites respectively. These interim values would then be confirmed, or modified appropriately, as part of the detailed site inspection phase described later in this report. A score of 80 was also assigned at this juncture to the two sites selected for Separate Assessment (see below).

The hazards identified through the process described here are clearly variable within sections and between sections. This raises the issue of how to determine the aggregate hazard within any given section length. In reality this variability means that it would be inappropriate to use length as a multiplicand in the exposure scoring (see Section 7.2) and as a result the effects of section length have been incorporated into the process used to assign the hazard priorities. Notwithstanding this some relatively short sections, of high potential hazard and/or high traffic are likely to remain in the group of higher hazard ranking evolved in Section 7.2.

In addition, two significant sections of the network, the A82 through Glen Coe and parts of the A87 on Skye (and amounting to a total of 46km), were identified for separate evaluation as a result of their particular characteristics. Both of these localities are considered to be of a different character to the bulk of the sites. They are predominantly affected by scree (talus) slopes rather than more heavily weathered and finer-grained materials. In addition, these areas, particularly the A82 in Glen Coe, have been subject to intense commercial and academic study over many years. Thus, any resources used to assess the risk in these areas would be best allocated to a literature review, at least initially. It was thus considered that best value would not be derived from detailed site-specific assessments that are recommended for other 'Main Study' sites in Section 6.

This resulted in the Main Study network length of 607km being subdivided into the various categories as shown in Table 5.2, the results of which are presented in full in Appendix B (Tables B.2 to B.6).

Figure 5.7 illustrates an area of the GIS-based assessment imagery for the A82 at Loch Ness, while Figure 5.8 illustrates the two-dimensional Ordnance Survey mapping with identified route lengths corresponding to the categories in Table 5.2.

5.3 SELECTION OF ROUTES FOR SITE-SPECIFIC ASSESSMENTS

The secondary categorisation exercise identified some 607km of the trunk road network subdivided into four fairly equal quarters of approximately 110km to 160km each (plus a total of slightly less than 50km for the two separate assessments). This provided the basis for a staged annual process of carrying out the detailed site inspections, within the anticipated limits of annual budget for this work.

Table 5.2 – Secondary outcomes from the interpretation of the GIS-based imagery.

	Route Lengths Assessed (km)	Percentage of Main Study Route Lengths (%)	Percentage of Route Lengths Assessed (%) (See Table 5.1)	Percentage of Network (%)
Priority 1	**135**	**22**	**8**	**4**
Priority 2	**154**	**25**	**9**	**5**
Priority 3	**160**	**26**	**9**	**5**
Priority 4	**112**	**19**	**7**	**4**
Separate Assessment	**46**	**8**	**3**	**1**
Total	**607**	**100**	**36**	**19**

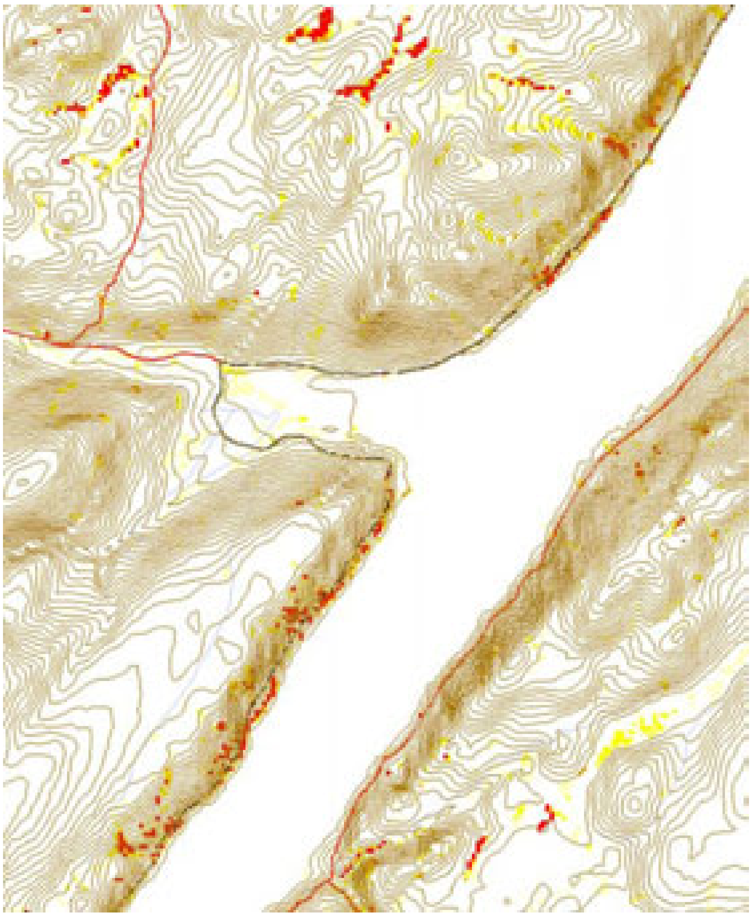

Figure 5.7 – GIS-based imagery for A82 Loch Ness. Not to scale.

However, the availability of the essential, higher resolution, recent aerial photography for many of the sites in question, placed constraints on the sequencing. Transport Scotland had contracted to obtain the imagery necessary for this exercise. For the surveys planned for Summer 2007, however, imagery was not available for a number of Priority 1 and 2 sites, not least on the Arrochar to Inverary section of the A83. The absent areas were due for flying at some time in 2007, so the imagery needed to complete the remaining detailed site inspections (in all Priorities) would be to hand for 2008. As a result, a decision was taken to use the available high resolution aerial photography imagery to undertake detailed site inspections for

Priority 1 and 2 sites in 2007. Details of coverage available in early 2007 are given in Appendix B.3 (Tables B.7 to B.11).

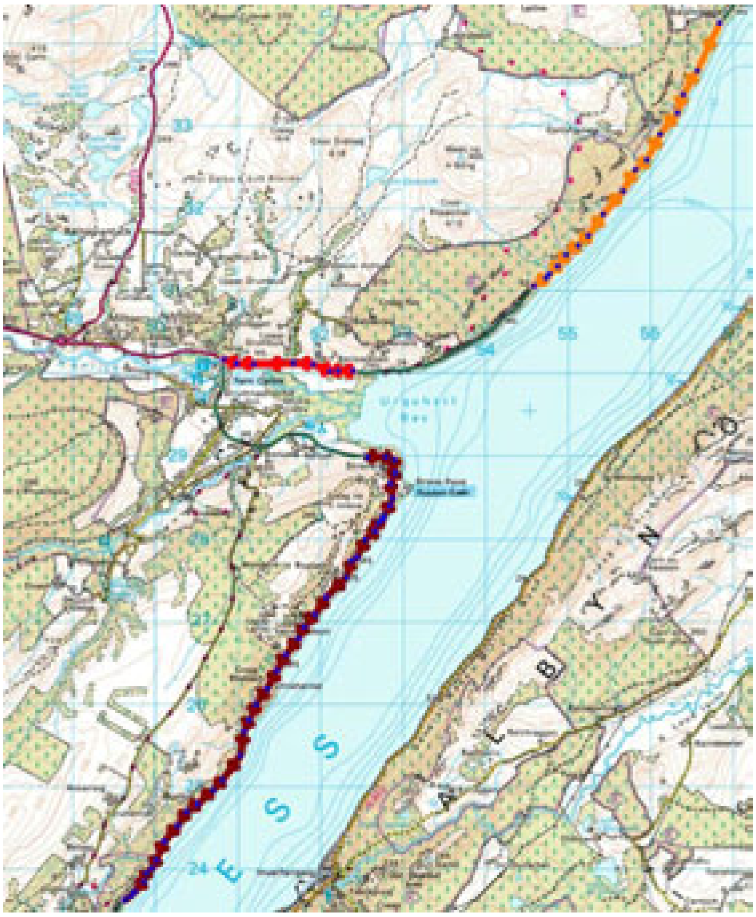

Figure 5.8 – Ordnance Survey two-dimensional imagery for A82 Loch Ness. Showing lengths categorised at Priority 3 (A82-03), Priority 1 (A82-04) and Priority 2 (A82-05) from top to bottom. Digital Ordnance Survey imagery at 1:50,000 is shown but the image itself is not to scale. (© Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

While not all of the Priority 1 and 2 routes were located in the North West Unit, by far the majority were. For this reason the decision was taken that the site inspection work for 2007, and potentially for subsequent years, would be primarily undertaken by the North-West Unit Operating Company (Scotland TranServ).

As a result of the above considerations, it was decided that the detailed site inspections would be carried out for all of the Priority 1 and 2 sites that had aerial photography available in 2007. Scotland TranServ, as Operating Company, for the North-West Unit, would resource a suitable team to do the work. In addition the TranServ team would also undertake the four non-NW Category 1 and 2 sites for which aerial photography was available, namely on the A77 at Glen App (South-West Unit) and on the A95 (North-East Unit). Scotland TranServ liaised with Amey, the South-West Unit Operating Company, for purposes of the A77 site and with BEAR Scotland for those on the A95.

6 METHODOLOGY FOR SITE-SPECIFIC ASSESSMENTS

by M G Winter, F Macgregor and L Shackman

6.1 INTRODUCTION

The site-specific inspection of those parts of the trunk road network identified as being subject to debris flow hazards is a necessary element within the process of hazard assessment. These inspections have three main purposes:

1. To validate the hazards derived from the GIS-based assessment (Section 4) and their interpretation (Section 5).
2. To provide an interpretation of data that was not available during the GIS-based assessment.
3. To provide an assessment at a larger scale than the GIS-based assessment could permit.

There are essentially three stages to the site-specific assessment process (Section 6.2):

- Desk study.
- Preliminary site inspection.
- Detailed site inspection (where necessary).

The management of the trunk road network in Scotland is undertaken on the basis of four units run by Operating Companies employed by Transport Scotland, as follows:

- South-West Unit (currently Amey).
- North-West Unit (currently Scotland TranServ).
- North-East Unit (currently BEAR Scotland).
- South-East Unit (currently BEAR Scotland).

In the first instance it was anticipated that in the main it would be Priority 1 sites, which exclusively occur in the North-West Unit, that would be assessed initially during the summer of 2007. However, the lack of availability of aerial photography in Scotland meant that only around 44% of the 135km of Priority 1 lengths identified would be able to be examined. Nonetheless, broadening the assessment out to include the 66% of Priority 2 lengths for which aerial photography was available (including those lengths in the South-West and North-East Units) raised the total lengths to be examined to 161km (Tables B.7 to B.11). These 2007 inspections form part of a process which will be ongoing in successive years.

The site-specific assessments carried out formed the end point of a staged hazard assessment process for a given route that began with the GIS-based assessment. Interpretation of this data using Ordnance Survey 1:50,000 mapping and low resolution aerial photography meant that many of the factors that would inform an assessment of this nature were already implicit.

The site-specific assessments were therefore to supplement and validate the initial process by utilising high resolution aerial photography and initial site inspections from road level. Where appropriate more detailed inspection of any given site was subsequently conducted and involved excursions from road level to the adjacent hillsides.

The work centred on various locations across the Scottish trunk road network, predominantly in the north-west sector (see Tables B.7 and B.8). The site evaluation element of the work involved inspecting adjacent hillsides up to, potentially, two to three kilometres from the trunk road itself; such inspections and the maximum distance of the inspection from the road were dependent upon the needs of the site.

6.2 THE INSPECTION PROCESS

The primary evaluation of hazards was achieved through the GIS-based assessment. It was then supplemented by site-specific studies involving the use of aerial photography and site visits. The intention of this latter exercise was thus to validate and make relatively small adjustments to the scores derived from the GIS-based exercise.

Factors such as lithology and water condition were not able to be readily assessed, in most cases, from the type of imagery available (see Section 6.2.1). These factors did, however, form a key part of the GIS-based assessment, which has been a major contributor to deciding on the areas to be subject to site-specific inspections. Notwithstanding this however, the site inspection process did provide an essential opportunity to validate assessments made in regard to at least some of these factors on the ground.

The site inspection process was reported primarily through the completion of a standardised Microsoft Excel® spreadsheet at each of the three main stages of the process (Table 6.1). In addition, a short report (*circa*. One or two pages) was prepared for each site with photographs to illustrate specific features and decisions made on scoring.

As noted above the site inspection process involved three main stages as described below.

1. *Desk study:* These activities were intended to be carried out prior to embarking upon on-site activities.

Key desk study activities included the assembly and printing out of relevant information including OS Map imagery (1:50,000 and/or 1:25,000), high resolution aerial photography, and the GIS-based assessment.

This information then enabled those carrying out the inspections to familiarise themselves with the detail of the OS mapping, to reconcile the positioning of the OS detail with the GIS-based assessment imagery and to examine the GIS-based assessment imagery with respect to detail features on the OS mapping.

Attention was then focused on the high resolution aerial photography in order to obtain an overview of the area and then to enable a virtual inspection of particular features. The printed imagery was marked-up and notes made to enable the site-specific spreadsheet (Table 6.1) to be preliminarily completed.

2. *Preliminary Site Inspection:* This was intended to allow a provisional, but necessarily limited, view of the site setting. This was achieved by a drive-through of the length of road in question, with the inspector as a passenger, stopping as necessary to observe and note features from road level. Photographs were taken to illustrate features and decisions made.

Table 6.1 – Reporting spreadsheet for site-specific inspections.

Scottish Road Network Landslides Study - Site-Specific Assessments

DATA ENTRY ONLY TO GREYED OUT CELLS

Route Code: A82-05
Start NGR: NH 52566 28987
Action: Main Study

OC Unit: NW
End NGR: NH 49631 23632
Priority: 2

Length: 6,770 m

[1] Scores are not progressive: i.e. either the full score is applied or none at all is applied.

	Feature	Information Source and Quality OS Mapping	GIS-Based Assessment	Aerial Photography	Site Inspection	Factor Effect on Score	Possible Scores[1]	Remarks	SCORE Initial Drive Through	SCORE Desk Study	SCORE Detailed Site Inspection
1	***Water***										
A	Streams roughly parallel to line of maximum slope	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
B	Concentrated dendritic stream patterns	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
C	Evidence of restriction and/or debris accumulation in stream(s)	None	None	Good	Very Good	+	0 or 5	Independent of 1A and 1B	0	0	0
D	Large flat catchment at/close to head of slope	Variable	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
E	Large culverts under road	Poor	None	Good	Very Good	-	-10 or 0	Subjectively capable of accommodating large water/debris volumes	0	0	0
2	***Instability***										
A	Evidence of historical instability (with no soil/fresh rock exposure)	None	None	Good	Good	+	0 or 5	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
B	Evidence of recent instability (with soil/fresh rock exposure) - e.g. scarps, debris fans, etc	None	None	Good	Good	+	0 or 10	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
C	Areas of shallow sloped peat/soft ground high on hillside/near to stream	Poor	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
D	Oversteepening near to toe of slope	Poor	None	Poor	Very Good	+	0 or 5	Can lead to localised instability as well as potentially increasing velocity of toe	0	0	0
3	***Slope/Topography***										
A	Convex sloped hillside	Good	None	Poor	Very Good	+	0 or 5	Convex slopes often associated with debris flow as profile encourages acceleration	0	0	0
B	Road located part-way up 'S'-shape of hillside	Good	None	Good	Very Good	+	0 or 10	Increases hazard to road user as flow likely to be fast-moving at road level	0	0	0
C	Potentially protective features alongside and local to the road (e.g. embankments) that would not be immediately apparent from OS mapping	Poor	None	Variable	Very Good	+	-10 or 0	Decreases hazard to road user as flow likely to be arrested by barrier	0	0	0
4	***Vegetation and Land-Use***										
A	Aforestation close to the road (below hazard and above road) either less (+5) or more (-5)	Poor	None	Good	Very Good	-	-5, 0 or 5	Can slow or stop flow(s), thus preventing them from reaching the road	0	0	0
B	Agricultural ploughing trending down slope and towards stream channels	None	None	Variable	Very Good	+	0 or 5	Encourages water and associated erosion into the stream and flow propogation	0	0	0
C	Largely exposed rock on hillside	Poor	None	Good	Very Good	-	-10 or 0	No/limited material to form a flow	0	0	0
D	Forest (or other) roads on slope following the contours above trunk road (especially if in combination with streams, as per 1A above)	Good	None	Good	Poor	+	0 or 5	Can concentrate water into a particular location on the slope, accumulate debris for later flows and/or accelerate flow by venturi effect at culverts	0	0	0
								Additive / Subtractive Hazard Score	**0**	**0**	**0**
								Adjusted Additive / Subtractive Hazard Score	**0**	**0**	**0**

From the notes made further entries to the site-specific spreadsheets were made (Table 6.1) as appropriate and an evaluation was made as to whether further excursion up the hillside was required. This essentially involved answering the questions:

> "Will the information obtained make a substantive improvement to the evaluation?"
>
> "If so, will a more detailed site assessment (as in (3) below) provide adequate answers for the purposes of the spreadsheet?"

If the answer to both questions (above) was "yes" then proceeding to further detailed site inspection was deemed to be required, otherwise not. In actuality the decision to proceed with further inspections was made in all cases. A number of factors may have, however, informed such decisions. It was appreciated that the inspectors were not, and nor could they have been, party to the complete assessment process. The information available to them, and their experience of the complete process, may thus have proved to be insufficient to allow them to decide, with confidence, not to undertake further inspections.

3. *Detailed site inspection:* This process essentially completed the hazard assessment process by relating the information considered thus far (which was either image/data-based or a physical view from a remote location) to the ground itself. In practice the detailed site inspection comprised a walkover from road level and excursions up slope (or down where necessary) as required, but typically every 0.5km to 1.0km. Further entries were then made to the site-specific spreadsheet (Table 6.1) and the scores obtained at this stage taken as final scores. Photographs were taken to illustrate both the features encountered on site and the decisions made, as appropriate.

6.2.1 Aerial Photography

The orthographic digital aerial photographs were supplied as 25cm resolution JPEG images with both JGW and TAB files for the purposes of geo-referencing by Getmapping.

A typical example of such an image for Glen Ogle (south-west corner NN 570 260, or 2570 7260 using the eight-digit referencing system applied to the filenames of the images supplied) is illustrated in Figure 6.1. The original image was 33.87cm square at a resolution of 300ppi (300 pixels per inch or 118.11 pixels per centimetre) and has been scaled for use in this report. Both the north and south debris flows at Glen Ogle are annotated on the image, but note that the source areas appear in the images of adjacent areas to the north and east (see Figure 6.2).

The aerial photograph in Figure 6.1 and other adjacent images have been digitally 'stitched' together to give more extensive coverage in Glen Ogle. Key features are marked on the image as described in the figure heading. Of particular interest, in addition to the different elements of the debris flows are the subsequent carriageway repairs and the rockfalls/rock slides that cross the old railway line on the west side of the glen. The railway line was closed in 1965 when the line, already scheduled for closure, was blocked by one or more major landslides. It is believed that these may have been one or both of the rock-based landslides illustrated in Figure 6.2.

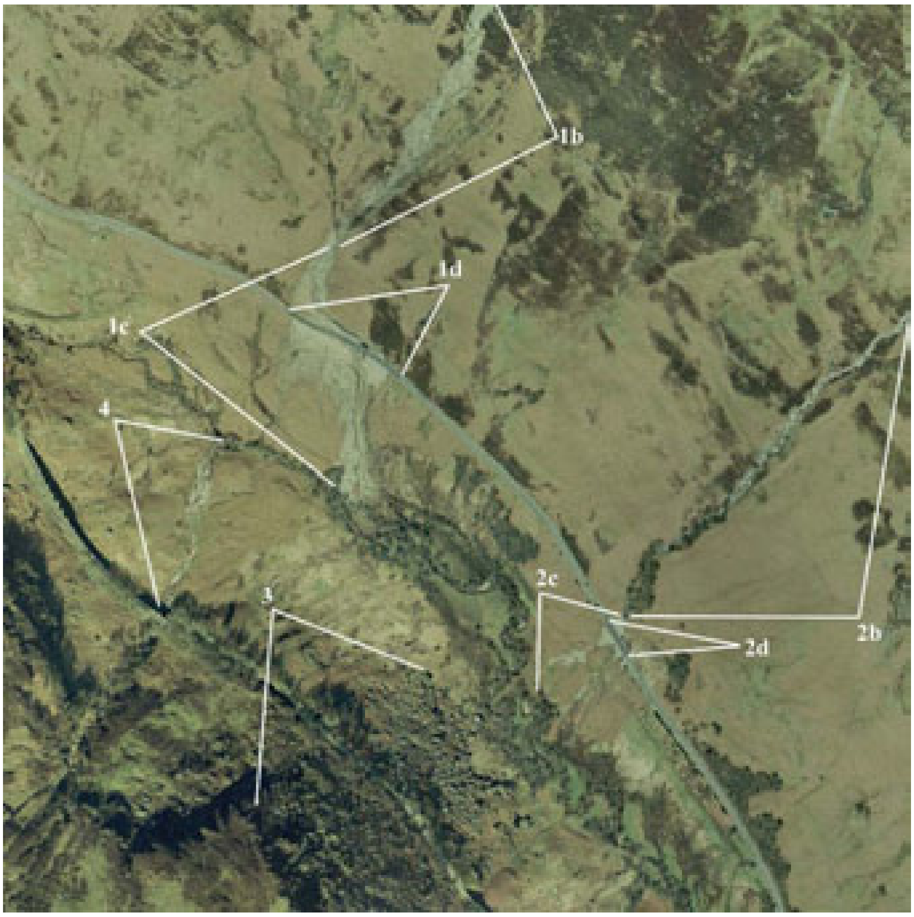

Figure 6.1 – Aerial photograph showing the northerly (N) and southerly (S) debris flows that occurred in Glen Ogle in August 2004 with key features marked. The photograph represents a 1km by 1km square; north is to the top.

Key: 1. North debris flow: (a) potential source areas, (b) debris track, (c) runout/debris fan and (d) subsequent carriageway repair.
2. South debris flow: (a) potential source areas, (b) debris track, (c) runout/debris fan and (d) subsequent carriageway repair.
3. Historic rock falls.
4. Other debris flows assumed to have occurred in August 2004.

6.3 SITE-SPECIFIC ASSESSMENT RESULTS

The data collection spreadsheet (Table 6.1) contains four main categories, in each of which between three and five sub-categories are scored. The four main categories are as follows:

- Water.
- Instability.
- Slope/topography.
- Vegetation and land-use.

It is important to note that the scores which derive from the site-specific assessment are additive to the scores established from the interpretation of the GIS-based interpretation. This reflects the importance of information new to the hazard assessment process, as any information available to the GIS-based assessment and/or its interpretation is prevented from influencing scoring at the site-specific assessment stage.

Figure 6.2 – Aerial photograph showing a large part of Glen Ogle. The image was made by stitching 12 adjacent 1km by 1km photographs, including Figure 6.1, in a 4km (vertical) by 3km (horizontal) grid; north is to the top and the marked features are as for Figure 6.1.

In addition, limits were placed upon the amount by which the scores could go up or down. This was intended to ensure that the maximum score was restricted in any instance to a nominal 100 also that lower ranked sites could not automatically jump to an inappropriately higher category (and *vice versa*).

The initial hazard scores based upon the interpretation of the GIS-based assessment, the allowable adjustments and the associated possible range of final score for each of Priority 1 to 4 are given in Table 6.2.

Table 6.2 – Adjustments to hazard scores from site-specific assessments.

Priority	Initial Score	Allowable Adjustment	Resulting Range
1	80	-30/+20	50 to 100
2	60	-30/+40	30 to 100
3	40	-30/+60	10 to 100
4	20	-20/+65	0 to 85

Summary results from the site-specific assessments are given in Table 6.3 and example score sheets and associated reports are given in Appendix C, along with a more detailed breakdown of the scores.

Table 6.3 shows that the average increase in the hazard score as a result of the site-specific inspections was around 13. In order to ensure that those Priority 1 and 2 sites that were not inspected due to a lack of aerial photography were not effectively downgraded when it came to determining what actions should be taken, an across-the-board increase of 10 was applied to the scores for the un-inspected Priority 1 and 2 sites; the final hazard scores are presented in Appendix D.

Table 6.3 – Summary hazard scores.

Route Code	Priority	Initial Score	Score After Site Inspection	Change in Score After Site inspection
A77-11	2	60	80	20
A82-02	1	80	100	20
A82-04	1	80	80	0
A82-05	2	60	65	5
A82-08	1	80	90	10
A82-09	1	80	80	0
A82-17	1	80	100	20
A82-26	2	60	80	20
A82-34	1	80	100	20
A83-05	1	80	100	20
A83-06	2	60	85	25
A85-08	1	80	100	20
A85-09	2	60	100	40
A85-15	1	80	90	10
A86-03	1	80	80	0
A86-09	1	80	80	0
A86-10	2	60	75	15
A86-11	2	60	75	15
A86-12	1	80	90	10
A87-07	2	60	60	0
A87-09	1	80	95	15
A87-12	1	80	100	20
A87-13	2	60	90	30
A87-15	1	80	100	20
A87-20	2	60	75	15
A828-01	2	60	90	30
A830-05	2	60	70	10
A835-07	1	80	90	10
A887-01	2	60	65	5
A9-11	1	80	100	20
A9-34	2	60	60	0
A9-35a	2	60	70	10
A9-35b	1	80	90	10
A95-05	2	60	70	10
A95-08	2	60	65	5
A95-09	2	60	60	0
		Average Increase P1 & P2		13.33
		Average Increase P1		12.50
		Average Increase P2		14.17

7 HAZARD RANKINGS

by M G Winter, F Macgregor and L Shackman

7.1 INTRODUCTION

The landslides study was commissioned to assess debris flow hazards on the Scottish road network and address the risks resulting from these as they affect Transport Scotland's road network and the road users. The risk to life and limb was identified at the outset of this project by Transport Scotland's senior management as the primary concern with socio-economic impacts being secondary (but nonetheless important).

Risk is classically defined in terms of landslides (Cruden and Varnes, 1996; Culshaw, 2005) as follows:

$$R = H \times E \times V \tag{7.1}$$

where R is the risk.
H is the hazard.
E denotes the elements at risk.
V is the vulnerability of the elements at risk to the hazard.

In this work the result of this equation (risk) is described as Hazard Ranking, R_H, as it is recognised that the work reported does not consider all aspects of risk.

The hazard is as determined in Section 6. The elements at risk, namely the road and the associated road users, are either present or not at a given plan location. The elements at risk may thus be represented by a binary switch that is set to unity in all cases considered (i.e. where a road and road users are present). The vulnerability equates to risk to life and limb of road users and the socio-economic impacts, including diversionary effects, of temporary closure due to landslides. The binary switch allows a simplification of Equation 7.1 and for the purposes of this study may be rewritten as:

$$R_H = H \times E_X \tag{7.2}$$

where E_X represents the vulnerability of road users to life and limb risks and the potential socio-economic impacts.

The approach taken herein mirrors that typically followed for landslide hazard and risk assessment, as described above. It builds upon the approach outlined by Winter *et al*. (2005a) in the precursor to this report and is not a modification of the approach proposed by Clayton (2001), as has been stated by Anon (2006a).

7.2 EXPOSURE SCORES

The exposure of life and limb may be represented, at a simple level, by the surrogate of traffic flow. It is accepted that sightlines and other factors that influence visibility of the road ahead could also be used to refine the exposure of life and limb (e.g. McMillan & Matheson, 1997). However, in this study two issues rendered this additional complication inappropriate: first, to a large extent traffic flows relate to the type of road alignment in place and thus to the quality of the sight lines; second, the extent of the route lengths considered meant that a simple and straightforward approach was, in this case, more suitable.

Similarly, the socio-economic aspects of exposure may be represented not only by the traffic flow and but also by the existence, length and quality of any diversion necessary.

As with the different elements that make up the GIS-based hazard assessment (Section 4), the different elements of exposure must also be added together in order to achieve an overall score. Relevant categories were determined and scores then assigned for both traffic flow and diversionary aspects of exposure for each site. The scores for these individual factors were then weighted to reflect their relative importance and then summed to produce the overall exposure score.

The traffic categories used by Transport Scotland reflect the traffic flows over the entire network. The lowest flow category comprises those roads with an Annual Average 2-way 24-hour Daily Flow (AADF) of less than 10,000 vehicles per day. It was apparent at the outset of the work to define the traffic flow scores that this lowest category would cover a large proportion of the vulnerable sites identified in Section 5. This would mean that the use of the standard traffic flow categories would not effectively differentiate between the various sites and a decision was therefore made to use alternative categories. These new categories and their associated exposure scores (E_{XT}) were defined as follows:

AADF ≤ 2,500 vehicles per day, $E_{XT} = 1.0$.
2,500 < AADF ≤ 7,500 vehicles per day, $E_{XT} = 1.5$.
7,500 < AADF ≤ 25,000 vehicles per day, $E_{XT} = 2.0$.
AADF > 25,000 vehicles per day, $E_{XT} = 2.5$.

Traffic data was sourced from the Scottish Road Traffic Database operated by Transport Scotland.

The diversion scores (E_{XD}) were based upon an informed judgement of the potential consequences of a closure on the network within a given location section. Where the diversion was short and effective (e.g. by other trunk and/or ‘A’-roads) then the consequences were defined as ‘Limited’. Where the diversion was long, by difficult means (e.g. ‘C’, ‘D’ and/or unclassified road) or does not exist (in practical terms) the consequences were defined as ‘More significant’. ‘Significant’ represents the middle ground between these two extremes and the diversion scores were defined as follows:

Limited, $E_{XD} = 0$.
Significant, $E_{XD} = 1$.
More significant, $E_{XD} = 2$.

For any given site, weightings were then applied to the two exposure scores. The two weighted scores were then added together to give a total score for exposure. The weightings applied reflect the paramount importance of reducing the exposure to risks related to life and limb of the travelling public, and for this reason the traffic score was weighted more heavily than the largely disruption-focused diversion score. It should however be noted that the traffic score does itself include significant elements that relate to the potential disruption to road users.

The score of the final exposure score is thus given by:

$$E_X = (E_{XT} \times 1.0) + (E_{XD} \times 0.5) \tag{7.3}$$

Accordingly, Equation (7.2) may thus be rewritten as follows:

$$R_H = H \times [(E_{XT} \times 1.0) + (E_{XD} \times 0.5)] \tag{7.4}$$

The final exposure scores are detailed in Appendix D.1.

It could be argued that either the hazard or the exposure (and therefore hazard ranking) should be influenced by the length of the section in question in a very direct sense by, for example, taking the Elements at Risk part of Equation 7.1 to be the length of road. This type of approach is suited to risks such as that of a tanker over-turning on a straight road – that is, risks that are entirely uniform along the full length of the section (see also Section 5.2.2). However, there are a number of factors that count against this approach, and these are as follows:

1. The relation between length and the probability of event occurrence is not a constant. The hazards contained within a given section length are variable in terms of their spacing and magnitude and the profile of any hazard score along a given length is therefore also variable. It would therefore not be correct to proportion the exposure according to the length of the section in question.
2. Effects of length have already been accounted for appropriately in the process in which priorities were assigned to the lengths (see Section 5.2.2). Thus, hazard scores should be viewed as providing aggregate scores over the length of the identified hazard rather than average scores at any given point within the length.
3. The purpose of the work was also to rank hazards rather than to perform an all-encompassing risk assessment.
4. The hazards and hazard rankings are intended to apply to each likely point of potential incident on a route length and therefore it would be inappropriate to undertake a length-based approach.
5. A length-based approach does not lend itself readily to spatial assessments (such as those relating to debris flows) as opposed to purely linear hazards (such as that of a fuel tanker overturning).

7.3 HAZARD RANKINGS

The overall hazard ranking scores were thus able to be computed by taking the results presented in Section 6 and applying them, along with the exposure scores, to Equation 7.4. The detailed final hazard ranking scores obtained are then able to be set-out and are presented in tabular form in Appendix D.2. A truncated form of the table, detailing sites with final hazard ranking scores of 100 or greater, is presented as Table 7.1 and the geographical distribution of the sites is illustrated in Figure 7.1.

In Section 3, Figure 3.1 identified site rankings in terms of Low, Medium, High and Very High Hazard Ranking. An explanation of these categorisations was given in the text.

The distinction that was made between Low and Medium Hazard Ranking sites (Winter *et al.*, 2005a) has been superseded by the development of Traffic Scotland's Emergency Standard Diversion Routes (ESDR) (see also Section 8.3.1). This means that the actions planned for Medium Hazard Ranking sites are in the process of being implemented for all sites, including Low Hazard Ranking sites; the 'do nothing' scenario thus becoming redundant.

Table 7.1 – Sites with a hazard ranking score of 100 or greater.

Route Code	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	Hazard Score	Exposure Score	Hazard Ranking (Risk) Score = Hazard × Exposure	Locality
A82-17	NW	NN 28766 96227	NN 21391 85632	13,400	1	100	2.5	250	Loch Lochy
A85-09	NW	NN 50672 28326	NN 38766 25266	12,900	2	100	2.5	250	Glen Dochart
A82-08	NW	NH 45761 19182	NH 43486 16747	3,410	1	90	2.5	225	N of Invermoriston
A82-37	NW	NN 34026 00456	NS 34556 97686	3,300	1	90	2.5	225	Inverbeg and N
A9-12	NW	ND 02175 14804	NC 93895 09663	10,200	1	90	2.5	225	S of Helmsdale
A9-35b	NW	NN 66562 72101	NN 69762 71546	3,310	1	90	2.5	225	N Glen Garry
A82-09	NW	NH 42981 16557	NH 42451 16667	581	1	80	2.5	200	Invermoriston
A82-26	NW	NN 05220 59568	NN 07550 58357	2,720	2	80	2.5	200	E of Ballachulish
A82-34	NW	NN 33296 20776	NN 31776 09196	13,500	1	100	2.0	200	N Loch Lomond
A85-08	NW	NN 58437 24970	NN 55677 29396	5,480	1	100	2.0	200	Glen Ogle
A9-11	NW	ND 08775 20794	ND 02860 15349	11,200	1	100	2.0	200	N of Helmsdale
A83-02	NW	NN 26901 03861	NN 23021 07837	6,310	1	90	2.0	180	Ardgarten to Rest & be Thankful
A83-04	NW	NN 23421 09592	NN 19096 09927	4,360	1	90	2.0	180	Glen Kinglas
A9-44	NW	NO 00212 47141	NO 00472 43871	3,320	1	90	2.0	180	N of Dunkeld
A87-19	NW	NG 64039 23632	NG 48718 29902	26,100	Separate Assessment	90	2.0	180	Southern Skye - N of Broadford
A82-36	NW	NN 31916 04456	NN 34026 00456	4,610	2	70	2.5	175	S of Tarbet
A9-35a	NW	NN 63982 83957	NN 64987 73046	11,900	2	70	2.5	175	S of Dalwhinnie
A83-06	NW	NN 19221 12717	NN 11260 08848	9,170	2	85	2.0	170	Clachan to Strone Point
A82-05	NW	NH 52566 28987	NH 49631 23632	6,770	2	65	2.5	163	S of Drumnadrochit
A77-11	SW	NX 05214 72439	NX 08694 63338	9,990	2	80	2.0	160	S of Glen App
A82-02	NW	NH 60696 39243	NH 57346 34993	5,520	1	100	1.5	150	N end of Loch Ness
A83-05	NW	NN 18406 11247	NN 19406 12512	1,620	1	100	1.5	150	Cairndow
A87-12	NW	NH 03370 12016	NG 96289 14946	8,620	1	100	1.5	150	E Glen Shiel
A87-15	NW	NG 94469 21121	NG 88269 26106	8,650	1	100	1.5	150	Loch Duich
A87-09	NW	NH 11495 10731	NH 09725 11731	2,080	1	95	1.5	143	W Loch Cluanie
A830-05	NW	NM 90195 80853	NM 76679 82314	15,500	2	70	2.0	140	Glenfinnan to Lochailort
A9-45	NW	NO 03452 41486	NO 04062 40886	877	2	70	2.0	140	S of Dunkeld
A82-27	NW	NN 10700 58212	NN 27671 52992	19,900	Separate Assessment	90	1.5	135	Glen Coe
A828-01	NW	NN 05175 59653	NM 99145 54983	8,540	2	90	1.5	135	W of Ballachulish
A835-07	NW	NH 38284 70387	NH 28554 73906	11,400	1	90	1.5	135	Lubfearn to W Loch Glascarnoch
A85-15	NW	NN 13191 28352	NN 03135 29863	12,400	1	90	1.5	135	Dalmally to W Pass of Brander
A86-12	NW	NN 25591 81307	NN 22966 81947	2,770	1	90	1.5	135	Inverroy to Spean Bridge
A87-13	NW	NG 96259 14951	NG 94614 17946	3,790	2	90	1.5	135	W Glen Shiel
A82-07	NW	NH 47461 21012	NH 46411 19822	1,620	3	50	2.5	125	N of Alltsigh
A82-16	NW	NN 29996 98177	NN 28981 96572	1,960	3	50	2.5	125	Loch Oich to Loch Lochy
A82-23	NW	NN 04505 66337	NN 03765 65377	1,260	3	50	2.5	125	N of Corran Ferry
A82-24	NW	NN 02295 63258	NN 02645 62728	688	3	50	2.5	125	S of Corran Ferry
A82-38	NW	NS 34556 97686	NS 35196 87156	11,100	3	50	2.5	125	N & S of Luss
A83-18	NW	NR 84819 80506	NR 86284 74006	7,040	3	50	2.5	125	S of Inverneill
A83-20	NW	NR 86794 69696	NR 86529 69066	687	3	50	2.5	125	N Tarbet
A9-24	NW	NH 72341 35783	NH 75841 34579	4,040	3	50	2.5	125	N of Loch Moy
A9-27	NW	NH 82171 26569	NH 87652 24074	6,660	3	50	2.5	125	Slochd
M90-09	NE	NO 14377 13430	NO 13887 15335	3,200	3	50	2.5	125	N of Glen Farg
A82-04	NW	NH 52391 30037	NH 50831 30172	1,590	1	80	1.5	120	Drumnadochit
A86-03	NW	NN 67317 95722	NN 67162 95417	357	1	80	1.5	120	Glentruim House
A86-09	NW	NN 48856 87552	NN 47661 86407	1,730	1	80	1.5	120	Aberarder (Loch Laggan)
A86-10	NW	NN 47516 86247	NN 37536 81267	11,600	2	75	1.5	113	Loch Laggan and Reservoir
A86-11	NW	NN 33266 80957	NN 27646 81067	6,180	2	75	1.5	113	Tulloch to Roy Bridge
A7-06	SE	NT 40762 02692	NY 38842 96252	7,160	2	70	1.5	105	S of Teviothead
A835-09	NW	NH 19553 80586	NH 18168 85540	5,320	2	70	1.5	105	S of Loch Broom
A1-06	SE	NT 79571 67434	NT 85681 62704	8,630	3	50	2.0	100	Penmanshiel to Howburn
A7-01	SE	NT 48882 32523	NT 48142 31013	1,840	3	50	2.0	100	N of Selkirk
A76-04	SW	NS 85832 04117	NS 81022 07857	6,570	3	50	2.0	100	S of Sanquhar
A77-10	SW	NX 09284 77378	NX 05214 72439	6,640	3	50	2.0	100	Glen App
A83-01	NW	NN 29616 05036	NN 28391 03881	1,760	3	50	2.0	100	W of Succoth
A83-07	NW	NN 11260 08848	NN 11395 10083	1,260	3	50	2.0	100	E Loch Shira
A83-10	NW	NN 04495 04203	NN 02915 03179	1,910	3	50	2.0	100	E of Auchindrain Folk Museum
A83-12	NW	NS 01725 99834	NR 98995 97649	3,550	3	50	2.0	100	W of Furnace
A83-21	NW	NR 86034 68451	NR 85284 68076	839	3	50	2.0	100	W of Tarbet
A830-04	NW	NM 90855 80478	NM 90205 80848	867	3	50	2.0	100	Glenfinnan
A830-06	NW	NM 76679 82314	NM 71574 84404	6,080	3	50	2.0	100	Lochailort to Prince's Cairn
A835-04	NW	NH 43565 58802	NH 40650 59367	3,110	3	50	2.0	100	S of Garve
A84-03	NW	NN 57047 14530	NN 58487 13465	1,900	3	50	2.0	100	N Loch Lubnaig
A9-09	NW	ND 15325 29325	ND 13145 25995	4,350	3	50	2.0	100	S of Dunbeath
A9-10	NW	ND 12010 23055	ND 11670 22435	1,110	3	50	2.0	100	Berriedale
M74-09	M74	NS 95997 16852	NS 96337 16502	492	3	50	2.0	100	Elvanfoot

In terms of the High and Very High Hazard Ranking sites the primary intention is to concentrate on exposure reduction and a mixture of exposure and hazard reduction respectively. The distinction between these two approaches is more fully described in Section 8, but, in summary, the key issue is one of cost, with hazard reduction generally being significantly more expensive than exposure reduction.

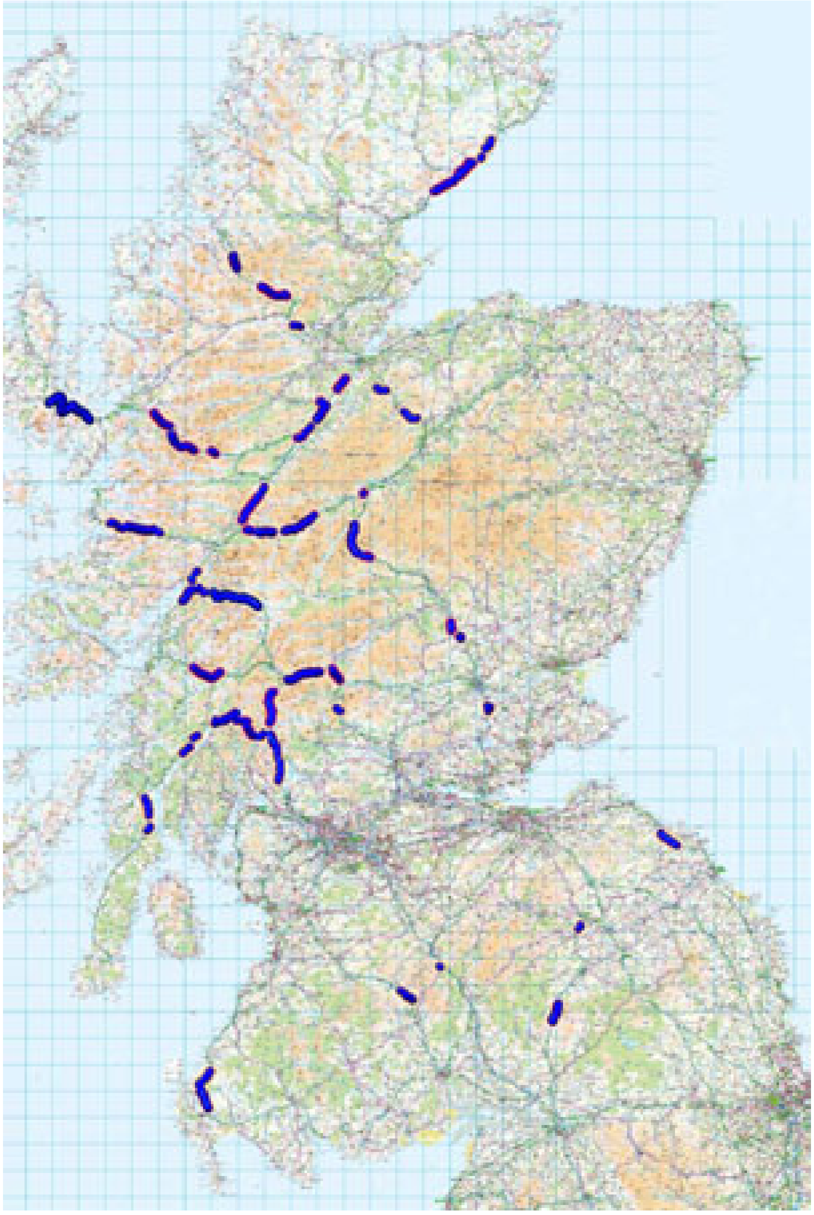

Figure 7.1 – Sites with a hazard ranking score of 100 or greater. (© Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

The cost of hazard reduction measures, beyond routine drainage maintenance and improvement measures, is such that embarking upon such work needs to be considered very carefully. Indeed, the costs need to be set within the context of the overall maintenance and construction budgets operated by Transport Scotland. Additionally, any intended work should be reviewed in terms of existing programme plans for significant upgrading and/or realignment of existing routes (see also Section 8.2).

Table 7.1 details those sites determined to be of High and Very High Hazard Ranking.

7.4 RE-INSPECTION PROGRAMME

In Section 3, Figure 3.1 indicates a Monitoring and Feedback activity in the flowchart. An essential component of that activity is having in place an effective programme for re-inspection of slopes identified as being hazardous or potentially so. As an overall consideration, the GIS-based assessment should be re-visited in (say) 10 years to take account of:

1. New and improved data sets.
2. New and improved technologies for handling such date sets.

This work would also require reinterpretation of the GIS-based assessment (either manually as reported here or automatically if technology, including processing power, allows).

In terms of re-inspection of the sites themselves, those with a hazard score of (say) 70 (i.e. Priority 2 sites with the 10 uplift added for site-specific inspection) and above, should also be subject to a reassessment exercise. This would go some way towards taking account of temporal changes to the volume and nature of material available for triggering debris flows.

The combination of revisiting the GIS-based assessment, interpretation and site-specific re-inspection after the interval suggested, should also ensure that the appreciation of debris flow hazard to the network remains soundly-based in future years.

7.5 ROCK SLOPES

Clearly debris flows are not the only hazards that may affect roads in Scotland and amongst the others are those presented by falls of geological material from rock slopes and cliffs alongside the network. Between 1994 and 1999 Transport Scotland (in a previous guise) initiated and operated a structured programme of rock slope risk assessment and management on the trunk road network (McMillan, 1995; McMillan & Matheson, 1997). The process involved the computation of a Hazard Index that then determined the actions required in terms of further inspections and more detailed surveys to determine Hazard Ratings.

The Hazard Index categories that were developed are as follows:

- Urgent detailed inspection (hazard rating survey).
- Detailed inspection (hazard rating survey).
- Review in five years.
- No action.

In recent years, a review of progress with both inspections and recommended remedial works was undertaken (Blair & McMillan, 2004). This review identified the sites at which urgent detailed inspections had been required to be undertaken as part of the Hazard Rating process. Whilst most of those had been, indeed, undertaken prior to the review, some outstanding inspections were identified, as follows:

- A82 Tyndrum to Fort William (one outstanding Hazard Rating survey).
- A87 Invergarry to Cluanie (two outstanding Hazard Rating surveys).
- A887 Invermoriston to Moriston Bridge (one outstanding Hazard Rating survey).
- A86 Newtonmore to Spean Bridge (two outstanding Hazard Rating surveys).
- A82 Fort William to Fort Augustus (one outstanding Hazard Rating survey).

The 2004 review is, of course, unable to detail how many of the sites flagged for detailed inspection have now been inspected.

Transport Scotland is currently assessing the future actions required to address those Hazard Rating surveys and re-inspections that remain to be carried out.

8 MANAGEMENT OF HIGH AND VERY HIGH HAZARD RANKING AREAS

by M G Winter, F Macgregor and L Shackman

The process described in the previous section culminates in a decision on whether the hazard ranking, in the context of the safe operation of the road network at any location, is acceptable or not. At those locations where the hazard ranking is deemed unacceptable, some form of mitigative action is required. To reduce the hazard ranking (or risk) to the road user to acceptable levels, either the magnitude of the hazard and/or the potential exposure or losses that are likely to arise as a result of any debris flow, must be reduced.

The reduction of the exposure of road users forms the main focus of the work here. In this case the debris flow event is taken as a given and either the number of people exposed to the hazard must be reduced, for example by closure of the road, or warning must be given to exercise caution at appropriate times and places.

To reduce the hazard itself, physical intervention is required but in many cases the options will be of higher cost and more intrusive. It is anticipated that relatively few locations will justify expenditure to this degree.

8.1 TECHNIQUES FOR EXPOSURE REDUCTION

The reduction of exposure lends itself to the use of a simple and easily-remembered, three-part management tool (Winter *et al*., 2005a) as Detection-Notification-Action (DNA), as follows:

- *Detection:* The identification of either the occurrence of an event (e.g. by instrumentation/monitoring or observation) or by the measurement and/or forecast of precursor conditions (e.g. rainfall).
- *Notification:* The notification of either the likely or actual occurrence of an incident to the authorities: including the Police, Traffic Scotland, Transport Scotland and the relevant Operating Company.
- *Action:* The proactive process by which intervention reduces the exposure of the road user to the hazard, by for example road closure or traffic diversion. This also includes the dissemination of hazard(s) and exposure information by for example signs, media announcements and 'landslide patrols' in marked vehicles.

In the current situation, the DNA approach to mitigation must be reactive to debris flow events. There may be a case for reacting to extremely heavy rainfall events. However, a caveat to this is the need to consider carefully at what levels the triggers should be set, insofar as the relation between rainfall and landslides/debris flows in Scotland is by no means fully understood.

In the longer-term, the detection of precursor triggering conditions (i.e. rainfall) may enable both the *Notification* and *Action* phases to be taken in anticipation of the occurrence of major events. However, to do this an extensively enhanced rainfall detection network will be required across Scotland. Even once this is in place it is fully expected that it will require some considerable time and effort to ensure that sufficient data has been obtained and analysed so as to be able to introduce a reliable warning system. Even then atypical events, which are not the subject of warnings, and false alarms are to be expected. A programme of public and media education and awareness-raising is likely to be desirable to minimise any potential adverse reaction to such scenarios. Such an approach is discussed in more detail in Section 9 and by Winter *et al*. (2007c).

8.1.1 Event Occurrence

Detection: The movement of slope material can be monitored in real time and used as a management tool. Monitoring instruments such as tilt meters and acoustic sensors can be installed and located so as to record movement from potential debris flow or positioned such that notification is received if debris reaches or gets close to a road (e.g. trip wires).

If movement monitoring is being considered, it must be appreciated that the seeding area for debris flows can be very large and can be located high on the hillside. This introduces considerable difficulty in pinpointing the optimum location for the installation of the monitoring system and raises uncertainty as to whether the debris will reach the road. As an example, an instrumented fence is used on the Scottish rail network at Glen Douglas to recognise when material impinges upon the line. Similarly, a system to detect rock falls and debris flows is used at the Pass of Brander above the A85 at Loch Awe to raise an alarm to shut the line and stop trains.

Whether such a system would be sufficient in isolation, and in the context of a road, is questionable. It is, however, considered that in conjunction with rainfall monitoring and possibly the deployment of operatives, the likelihood of road users being affected by debris flow events could be reduced significantly. It is likely that any instrumentation would be electronic with remote reading of data sent back to a central control point. The range of possible electronic instrumentation types (data sent to a central control point) is presented in Winter *et al*. (2005a) but includes the following: borehole or shallow inclinometers, tilt meters, ‘trip wire’, ‘ball of string’, acoustic meters, and remote sensing. The selection of appropriate instrumentation is a highly site-specific activity and thus requires very detailed evaluation of a number of factors, not least physical access and availability of telecommunications.

An alternative approach is to use visual observation to detect debris flow events either by closed-circuit television or, more practically given the constraints imposed by darkness and poor visibility, for long stretches of hillside, by introducing ‘landslide patrols’ during periods of high rainfall. It is essential that such landslide patrol operatives are trained in what to look for and that patrol vehicles should operate in pairs for safety reasons. Given the wide range of locations at which debris flow activity may be experienced the use of patrols might prove to be a more practical alternative, the costs of instrumenting and monitoring extensive lengths of slope being potentially prohibitive. Furthermore, the issue of inadvertent activation of systems such as trip wires by, for example, livestock and hill-walkers would need to be addressed in the context of the road network, access to which is less constrained than is the case for the rail network. In addition, the value of observations made by the general public should not be underestimated, especially given the proliferation and ubiquity of mobile telecommunications.

Notification: In the immediate aftermath of the occurrence of a debris flow event, notification must reach the Police, the Operating Company and the infrastructure owner. The decision must then be made rapidly as to what action is to be taken (see below). The nature of debris flows is such that in most cases the road will be blocked and therefore closed to all intents and purposes. It is important that such closures are formalised at safe locations distant from further potential events.

It is important to note that if landslide patrols, comprising trained personnel, are used as part of the *Detection* process then the functions of that role must also be extended to ensure that the proper authorities are notified promptly. It should also be noted that the effectiveness of such patrols for detection will be extremely limited in other than full daylight. It may well be that such patrols have more value in rendering assistance to the public in the aftermath of an event than in actually spotting an impending flow.

Action: Following a debris flow a number of positive options for action are available. First the road length (or lengths) affected could be closed and the appropriate pre-planned diversion routes put in place. However, it is important to note that closing the road only in the area immediately adjacent to the event is not an adequate response. Debris flow propensity generally affects long lengths of hillside and an evaluation of the vulnerable area must be performed in order to ensure that an appropriate length of road is closed.

Closure might, for example, be achieved by installing barriers similar to the snow gates present on some of Scotland's roads (Figure 8.1). Such an approach is applied to the Sea-to-Sky Highway in British Columbia, a route well-known for its propensity to disruption due to debris flow, and gates are in place on this route for the specific purpose of closing the road in the event of debris flow (Figure 8.2).

Figure 8.1 – Snow gates on the A9. These are used to close the road over Drumochter Pass when it is impassable due to snowfall. These and similar installations could also be used to close the road in the event of debris flow.

A road closure may only be ordered by the Police. However, in practice, such decisions are usually made in consultation with and/or on the recommendation of other appropriate bodies. In this case such bodies are likely to include Traffic Scotland, who collate and distribute information about the factors likely to affect traffic flows, and the relevant Operating Company.

Warning the public of hazards is an important feature of any *Action* programme. In Scotland there is a variety of potential means of making public announcements when either debris flows have occurred or there is heightened likelihood of their occurrence in an area. This might involve real-time systems such as traffic information websites, variable message signs (VMS) (Figure 8.3) and media (radio, TV and web) announcements notifying drivers that their potential exposure to the hazards posed by debris flows is real and present. Announcements could also be linked into traffic guidance systems. The overt use of landslide patrols, as describe above, can assist in this process by heightening the awareness of road users to potential hazards.

Figure 8.2 – Gates used to effect road closure following landslide events on the Vancouver to Whistler, Sea-to-Sky Highway, British Columbia, Canada.

Figure 8.3 – A variable message sign located on the A9. The network of such signs in Scotland is being significantly increased and will form a crucial part of the strategy for warning road users of hazards including landslides.

Static signs may also be used to convey both general information on the nature and locations of potential hazards and also to convey specific instructions (Winter *et al*., 2007a) (see Section 8.1.3).

It is important to ensure that measures such as the provision of signs, especially VMS, and landslide gates are at suitably strategic locations on the network. Such locations should allow drivers to make, and implement, a decision as to whether they proceed with their planned route, use an alternative or cancel their journey. For example, the VMS sign illustrated in Figure 8.3 is located on the approach to a major interchange and the snow gates illustrated in Figure 8.1 are located at the beginning of a stretch of dual carriageway where provision is made for traffic to be able to turn around.

The purpose of any road closure is to ensure that road-users are strongly discouraged from entering high risk areas. VMS signs may be used to alert the public to road closures that may be on their route and also to provide information at times of heightened hazard. In general such signs work on a basis of:

- Problem.
- Location.
- Effect.
- Guidance.

VMS signs are based upon either a 3 by 18 or a 4 by 15 character grid and thus suitable wording for signs might include:

RISK OF WATER
ON ROAD AHEAD
DRIVE CAREFULLY
(PREPARE TO STOP)

Or

RISK OF DEBRIS
ON ROAD AHEAD
DRIVE CAREFULLY
(PREPARE TO STOP)

The text in parentheses is intended for use on 4 by 15 character grid signs and would be omitted on 3 by 18 signs.

Correctly-trained operatives also could be deployed on high hazard ranking sections of road during periods of predicted or actual high rainfall. One approach might be that these operatives, in their vehicles, could escort people through the high hazard ranking sections of road in convoy. However, it must be understood that while this moves platoons of traffic past a potential hazard in a relatively short time, if a convoy were to be hit, the outcome could be more serious than might otherwise be the case.

In all cases, re-opening of the road, or its return to normal operation, can only occur after a thorough inspection of the road and the adjacent slopes has been undertaken to ensure that the likelihood of further debris flow events is at an acceptably low level. Current (and recommended) practice is to undertake ground-based inspections only when the adverse weather has abated and only to reopen the road once such inspections indicate that the residual hazard and exposure are again at an acceptable level.

In terms of public information, there is a strong argument for pre-empting the potential incidence of debris flow events, particularly in areas where these are relatively frequent (e.g. A83) and having pre-prepared Press Releases and Ministerial Briefings available in advance. Such information could be located within part of a ‘Core Briefing’.

8.1.2 Precursor (Preparatory or Trigger) Conditions

This subject is discussed in more detail in Section 9 in terms of both the underpinning science and the detailed operational issues that will need to be addressed. However, it is appropriate to detail the management strategy in terms of DNA at this juncture.

Detection: Debris flows are initiated, in the main, by heavy rainfall in combination with other conditions. Forecast and real-time rainfall data for an area with adverse topographic or other conditions is extremely useful information. If high rainfall is forecast or recorded in such areas then the potential for debris flows will be higher. In certain parts of the world weather forecasting and thereafter rainfall monitoring in real time are two of the controlling factors in landslide management. For example, the very successful system run in Hong Kong, as well as systems developed in other parts of the world (see Section 9), monitors rainfall and passes information on the resulting heightened likelihood of landslide activity to the public.

In the case of Hong Kong, a comprehensive network of automatic rain gauges covers much of the region to record and send data to a central control point for real time analysis. This is combined with short-term forecast data to enable managers to monitor the development of rainfall events and make informed decisions in an expedient fashion.

Whilst a predictive capability is under development in Scotland (Winter *et al*., 2007c; see also Section 9) with the intention of reducing the exposure of road users to the effects of debris flows, it must be understood that in Hong Kong, for example, around 30 years of experience has been acquired. This means that a sound knowledge of the relation between rainfall and landslides is in place relating to the local climate and geology. It is clear that some considerable time would be required to build a similar knowledge base for Scotland, possibly a minimum of five years. A significant investment in instrumentation, data analysis and maintenance would however also be required. Notwithstanding this, ongoing developments of the rainfall radar network mean that it can reasonably be expected that the use of these techniques will become an increasingly rich source of data in the future.

Notification: In Hong Kong, the conditions for issuing a ‘Landslip Warning’ are that a prediction has been made that numerous (more than about 15) landslides will occur. At this point the relevant Government bodies must make a rapid and effective decision to issue the warning. In Scotland, a decision as to which geographical area the warning should be applied will need to be made.

Action: Once again in Hong Kong, if the conditions for a landslip warning are met then the public are alerted to reduce their exposure to possible danger from landslides. Pre-defined procedures are also executed to ensure that resources are mobilised to deal with incidents. In addition, the issue of a landslip warning triggers an emergency system within various Government Departments that mobilizes staff and resources to deal with landslide incidents. Although a landslip warning is issued when it is predicted that numerous landslides will occur, it is accepted that isolated landslides may occur from time to time when a landslip warning is not in force and that landslip warnings will occasionally be issued and not be followed by landslides. Landslip warnings are issued by means of website notices, media announcements and notices prominently displayed in public buildings and areas.

Such a system implemented in Scotland would mean that, once warnings are received that heavy rain is forecast or falling in an area recognised as being of high or very high hazard ranking, a number of options are available for action. These are broadly similar to those described under event occurrence. However, in the case of road closures it is necessary to be aware of a significant disbenefit of this approach if applied in anticipation of any event occurrence. In contrast to the situation in Hong Kong (where a landslip warning is issued only when multiple events are forecast), the relatively rare occurrence of Scottish debris flows – at least those that interact with the trunk road network – and the high levels of rainfall that Scotland receives, means that a number of false alarms could be expected. The public at large could, potentially, become desensitized to what could be seen as an overly conservative approach.

An alternative approach could be to simply notify the public of the heightened likelihood of debris flow development in an area, as described above, and to take no further action until an event occurred.

8.1.3 Static Signing to Reduce Exposure

Static signing can provide a valuable addition to the *Action*-based signing described in Section 8.1.1. Static signing has the advantage of being permanent, indicating zones of hazard and also of raising awareness of such hazards.

A brief review of the manner in which landslides (and some other) hazards are portrayed on static signs in other parts of the world is presented in Appendix E. In essence, most countries use a symbol similar to standard rock fall symbol used in the United Kingdom (Figure 8.4). This may be accompanied by a sub-plate indicating the distance over which the hazard exists. In the UK, at present, this sign specifically relates to rock fall (TSRGD, 2002).

Figure 8.4 – UK rockfall sign (TSRGD, 2002: Diagram 559) indicating risk of falling or fallen rocks.

However, the aim herein is to determine a form of sign suitable for signing other types of landslides, primarily debris flow. In the absence of other models and suitable graphics for other types of landslide it is recommended that the standard rock fall sign be adopted for signing other types of landslide by the addition of a sub-plate stating 'Landslides'. The sub-plate should also indicate the distance (in miles or yards: TSRGD, 2002, Schedule 16, Regulation 17(1), Item 6) over which the hazard extends (e.g. Figure 8.5). Alternatively, signs could be placed at both ends of the hazard length with 'Landslides' on the sub-plate at the start of the section and either 'End' on the sub-plate at the finish or no sub-plate at all with the symbols scored through. It should be noted that the use of such non-standard symbols, in specific instances, would require approval from Scottish Ministers. Additionally, changes to the Regulations (TSRGD, 2002) would require the agreement of the UK Government as represented by the Department for Transport.

Figure 8.5 – Indicative for of proposed signing for debris flow hazard.

It is important to ensure that such signs are not over-used. It is recommended that they be restricted to sites of significant landslide hazard ranking (those with a hazard ranking of 100 or greater) as identified in Section 7. At some sites, those with availability of electrical power or suitability for solar power, flashing lights may be provided to give a degree of temporal alert in line with the VMS signs described above. This approach has the potential to overcome the potential for such signs becoming ignored due to familiarity. In time, these, along with the VMS network, could be linked into a landslide warning system as described in Section 9.

Other types of sign warn specifically of actions to be taken to minimise the exposure of hazards related to stream-based debris flows (Figure 8.6).

8.1.4 Education to Reduce Exposure

In British Columbia, more general hazard information signs (Figure 8.7) are located in lay-bys and indicate areas in, and routes on, which hazards might be encountered. Signs which give information on the nature and background to the hazards are also provided. Both of these types of sign, in addition to providing information on the type and location of the hazard, provide advice on what not to do in the hazard areas.

Figure 8.6 – Sign indicating exposure reduction measures for stream-based debris flow hazards (Vancouver to Whistler, Sea-to-Sky Highway in British Columbia in Canada).

Figure 8.7 – Landslide hazard information sign (Vancouver to Whistler, Sea-to-Sky Highway in British Columbia in Canada).

Static educational materials could play a valuable role in helping the public to understand the nature of landslide hazards in Scotland and also of placing such hazards in a balanced context. Such information should describe the geological and geomorphological setting of the area and include landslides as one of the inevitable consequences of the setting. Including reference to landslides in the broad natural history of the area would also help in the dissemination of such worthwhile information.

An excellent example of the type of sign in question is located beside the A938 at Dulnain Bridge. It primarily illustrates the manner in which the distinctive Roche Moutonée features were formed during glacial times, but also provides information on the local flora and fauna as well as a small fire hazard warning (Figure 8.8).

Figure 8.8 – Educational sign adjacent to the A938 at Dulnain Bridge near Grantown-on-Spey.

Suitable locations for similar educational materials might include National Park Gateways, service areas (e.g. Bankfoot, House of Bruar and Ralia on the A9) and could be integrated into other information sources at these locations with the agreement of the operators. The involvement of the Local Authorities, Scottish Natural Heritage and, where appropriate, the National Park Authorities and the Forestry Commission would be beneficial.

An information leaflet (see Appendix F) has been drafted for posting on the Transport Scotland website and possibly for wider circulation at a later date. The leaflet is intended to help the process of informing and educating the public as to the nature of landslides and what to do and what not to do in the event of being caught up in such an event. It particularly focuses upon the need to adopt a precautionary approach in terms of individual exposure to landslide risk.

8.2 TECHNIQUES FOR HAZARD REDUCTION

The challenge with hazard reduction is in identifying locations that are of sufficiently high hazard ranking to warrant spending significant sums of money on engineering works. The costs associated with installing remedial works over long lengths of road are difficult to justify in economic terms and may well be unaffordable. Moreover the environmental impact of such engineering work should not be underestimated, having a lasting visual impact at the least and potentially other more serious impacts. It is considered that such works should be limited to locations where their worth can be proven.

Notwithstanding this, simple measures such as ensuring that that channels and gullies are kept open can be effective in terms of hazard reduction. This requires that the maintenance regime is fully effective both in routine terms and also in response to periods of high rainfall, flood and slope movement.

It is also important that maintenance and construction projects currently in design take the opportunity to limit any hazards by incorporating, where suitable, measures to achieve higher capacity or better forms of drainage, or debris traps. In particular, critical review of the alignment of culverts and other conduits close to the road should be carried out as part of any planned maintenance or construction activities.

Typically, achieving a reduction in the hazard will entail physical engineering works to change the nature of a slope or road to reduce the potential for either initiation and/or the potential for a debris flow to reach the road once initiated. Debris flows are dynamic in nature and quite often originate some distance above the road; when they reach the road they are relatively fast-moving, high-energy flows. The energy of these systems is a significant factor in determining the nature of the engineering works that can be used to effectively reduce the hazard to the road and its user. Hence, there are three broad approaches to the selection of hazard reduction works:

- *Road Protection:* Accept that debris flows will occur and take measures to protect the road. Potential solutions include debris basins, lined debris channels, debris flow shelters, overshoots and barriers (including ditches, walls and fences).
- *Debris Flow Prevention:* Carry out engineering works to reduce the opportunity for a debris flow to occur.
- *Road Realignment:* Realign the road.

These options are also reviewed in detail by Winter *et al*. (2005a; 2006b; 2007a). In the context of this project and the Scottish environment, it is anticipated that few of any such actions will be appropriate to deal with the widely-dispersed hazards extant on the Scottish trunk road network. Their use should be limited to locations where their worth can be demonstrated within the broader context of construction and maintenance budgets and priorities. However, it is worth outlining the potential measures that might be used in appropriate situations.

8.2.1 Road Protection

In relation to the road protection approach there are not many examples of this kind of engineering work in Scotland or the rest of the UK, but in some upland areas of mainland Europe such engineering is relatively commonplace. The energy of the debris flow is such that any rigid barrier constructed to protect the road would have to be designed for very high loads. In essence a debris flow has significant momentum and to bring it to a sudden stop, as is the case with a rigid barrier, would require the dissipation of a lot of energy, instantaneously imparting very high loads. Examples of solutions which have proved feasible are described in the following paragraphs.

An Austrian Standard for the 'Design of [debris flow] structural mitigation measures' is currently in draft and is based upon the requirements of Eurocode 1 (Huebl & Proske, 2008). In time this document, as well as those by VanDine (1996) and Couture & VanDine (2004), may prove to be a useful source should such structures be required.

Debris Basins: Each debris basin comprises a large decant structure and a downstream barrier designed and constructed as an earthfill dam capable of retaining water to full height in the event of the drainage outlet(s) becoming completely blocked (Figures 8.9 and 8.10). The basin illustrated in Figure 8.9 is estimated to be approximately 200m across with a well-defined stream bed running towards the outlet structure (Figure 8.10). The outlet structure is not insignificant in size (Figure 8.11), however compared to the basin as a whole (Figure 8.9) it appears relatively small. One or more debris basins may be used in a given catchment.

Figure 8.9 – Debris basin showing the downstream barrier and drainage outlet, Mackay Creek, North Vancouver, British Columbia, Canada.

Figure 8.10 – Debris basin showing the downstream barrier and drainage outlet, Mackay Creek, North Vancouver, British Columbia, Canada.

In larger examples a concrete spillway is often incorporated into the downstream face of the barrier to protect the earthfill from erosion in the event of overtopping. Irregular surface features may be used to slow the passage of the debris (Figures 8.12 and 8.13). The channel below the structure may be lined with either concrete or with concrete/boulders to control both flood flows and debris flows in the event of over-topping (Couture & VanDine 2004) The former approach will facilitate rapid movement of water and debris downslope while the latter will slow the flows and provide a degree of temporary retention as described below.

Figure 8.11 – Downstream drainage outlet of debris basin, Mackay Creek, North Vancouver, British Columbia, Canada. The black disc visible on the base of the structure is 72mm in diameter.

Such structures on the scale used in British Columbia may not be viable in Scotland for a number of reasons, including the smaller scale landscape along with aesthetic and other environmental considerations. However, where cyclical hazards are identified as having a short return period, smaller scale structures may be appropriate (e.g. Figure 8.14).

Lined Debris Channels: Where storage space upstream of the road is limited an alternative approach may be taken by allowing material to move safely beneath the road and on to a safe repository area, usually a large body of water such as the sea or a loch, or similar. Couture & VanDine (2004) illustrate the use of a steel-fibre reinforced shotcrete lining in smooth well-aligned stream channels in order to move material smoothly and swiftly below the road (Figure 8.15). It is also recognised that relatively low cost, simple improvements to channel flow down to and beneath the road may have a beneficial effect; this may be achieved by widening culverts, for example. An alternative approach is illustrated in Figures 8.16 and 8.17, where boulders have been embedded into the concrete channel lining in order so as to provide a degree of retardation to the flow of water and debris.

Debris Flow Shelters: Rock shelters or 'avalanche shelters' are engineered structures that form canopies over a section of road subject to high hazard levels from rock fall or debris flows. These structures are usually formed from reinforced concrete. There is a Scottish example of such a structure on the A890 north-east of Stromeferry (Figure 8.18) in the north-west highlands (see Winter *et al*., 2005a). This structure straddles both the road and railway at that location. Energy is dissipated by placing a depth of granular material on the roof on which the debris flow lands.

Figure 8.12 – Concrete spillway on the downstream face of a debris basin barrier, Charles Creek, Sea-to-Sky Highway, British Columbia, Canada. The drainage outlet may be seen in the centre of the spillway.

Figure 8.13 – Detail of a concrete spillway on the downstream face of a debris basin barrier, Harvey Creek, Sea-to-Sky Highway, British Columbia, Canada. The drainage outlet may be seen in the centre of the spillway.

Figure 8.14 – Debris stilling basins at Frenchman's Burn, A890 Stromeferry, Highland. (Courtesy of Ian Nettleton, Coffey Geotechnics.)

Figure 8.15 – Stream/debris channel, Alberta Creek, Sea-to-Sky Highway, British Columbia, Canada.

Figure 8.16 – Stream/debris channel, Harvey Creek, Sea-to-Sky Highway, British Columbia, Canada.

Figure 8.17 – Detail of stream/debris channel, Harvey Creek, Sea-to-Sky Highway, British Columbia, Canada.

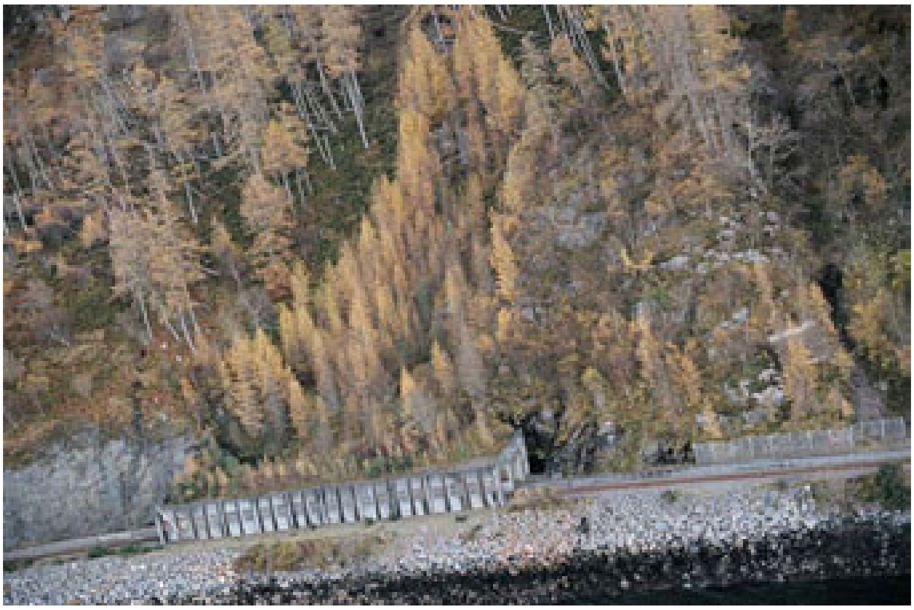

Figure 8.18 – Stone shelter on A890 north-east of Stromeferry.

Debris Flow Overshoots: In situations where the energy is anticipated to be very high, modifications can be made to debris flow shelters to allow the debris flows to pass over the top of the structure. This is done by shaping the top of roof of the shelter such that the falling material passes over the structure without dissipating its energy. This shaping or profiling involves constructing a 'ski-jump'-type reinforced concrete structure. Flow material simply slides over the roof and continues down the hillside.

Barriers and Fences: Fences can be constructed to act as effective barriers to halt debris flows. Such fences are designed to be flexible so that the kinetic energy of the debris flow is dissipated over a short period of time, thus reducing the forces that the structure has to cater for. These systems have been shown to work well. Such a fence has been installed on the Inverness to Kyle of Lochalsh railway in Scotland (see Winter *et al*., 2005a). Such fences do however require maintenance after the impact of a debris flow. A related approach has been taken to the arrest of rockfalls using highly flexible fences with fixed end-points only (see Figures 8.19 and 8.20).

Flexible fixed-position fence structures are commonplace in upland areas of mainland Europe and, while the UK does not have engineering design standards for such structures, experience is available and formalised procedures do exist, particularly in Switzerland.

Less flexible barriers may also be used to trap or divert debris flow and may be formed using stiffer components. Such structures may include gabion baskets as illustrated in Figure 2.28. However, more common are check dams and baffles which are used to slow and partially arrest flow within a defined channel. Barriers may also be constructed across hillsides in order to protect larger areas where open hillside flows are a risk and/or channelised flows may breach the stream course.

VanDine (1996) cites the use of check dams and baffles and also gives some design guidance for such structures. VanDine also relates the use of low cost earth mounds that act as impediments to debris flow. However, one of the main issues with the use of such structures, low cost or otherwise, is that they are effective in slowing and arresting flow primarily in the debris fan area. The situation in Scotland is that most, if not all, of the roads potentially affected by debris flow are located in either the high energy transport zone or the upper reaches of the debris fan. Roads located on debris fans frequently run close to a loch side and therefore the opportunity for the use of these types of measure tend to be limited.

Figure 8.19 – Flexible rockfall catch fence, Abbey Craig, Stirling.

Figure 8.20 – Flexible fence with a fallen rock that has been successfully arrested, Abbey Craig, Stirling.

Rigid barriers were built as debris flow defence structures at Sarno to the east of Naples in Italy following the events of May 1998 in which 159 people were killed (see also Appendix G.3.2) (Versace, 2007). At Sarno itself a series of debris basins has been constructed. That illustrated in Figure 8.21 has a capacity of around 176,000m^3. Rigid barriers in the form of combination reinforced concrete barrier-and-trench structures extend across the foot of the hills for up to a kilometre either side of the basin; check dams have also been constructed in the main stream channels (Versace *et al*., 2007). The works have been the subject of extensive landscaping and sports fields and other facilities such as cycle tracks (e.g. Figure 8.22) have been incorporated. The cost of the works, including the ancillary works, has been estimated at between €20M and €30M (Versace *et al*., In Press).

Figure 8.21 – Debris basin with a capacity of approximately 176,000m^3 at Sarno in Italy.

Figure 8.22 – Debris basin with a peripheral cycle track at Sarno in Italy.

In addition to the problems of locating barriers suitably, there remains the issue that (whatever type of barrier is used) provision must be made for maintenance – particularly to allow the regular removal of retained material.

8.2.2 Debris Flow Prevention

The engineering solutions applicable to the prevention of debris flow will depend greatly upon the individual circumstances. Debris flows can have a relatively large source area and be initiated very high up on the hillside above the road. In most circumstances the opportunities for carrying out conventional remedial works that would restrain the material before it starts to move are considered to be very limited. There may be particular conditions where a combination of techniques such as gravity retaining structures, anchoring or soil nailing may be applicable. However, in general terms the cases where these are both practicable and economically viable are likely to be limited.

The link between debris flows and intense rainfall has been established previously in this document. As a result, effective runoff management can reduce the potential for debris flow initiation. In the circumstances of the debris flows that occurred in the summer of 2004, it is considered that on-hill drainage improvement would have had little impact because of the scale of the events. In other locations and situations positive action to improve drainage might well have a beneficial effect. Such measures could include improving channel flow and forming drainage around the crest of certain slopes to take water away in a controlled manner.

8.2.3 Road Realignment

Road realignment is undertaken as part of Transport Scotland's route improvement activities in order to improve the road in terms of both alignment and junction layout, in particular to reduce accidents and to ensure compliance with current design standards. In cases where the debris flow hazard ranking is high and other factors indicate that some degree of reconstruction is required, road realignment may be a viable option. This type of expedient has historically been used on the Scottish rail network, for instance at Stromeferry, Penmanshiel and Dolphinston, where hazards have been sufficiently significant to justify the high cost of such realignments.

Figure 8.23 shows the A86 trunk road at Loch Laggan. At this site there were clear signs of distress to the carriageway caused by an extensive series of what are, individually, relatively minor landslides. However, taken collectively they posed a serious threat to the stability of the road and combined with the steep hillside, the narrow existing carriageway with a poor alignment, and the need to undertake a full depth reconstruction of the pavement the decision was made to realign the road (Figure 8.24).

Figure 8.23 – Deformation of the A86 carriageway alongside Loch Laggan due to a series of minor landslides.

Figure 8.24 – Aerial photograph showing the realignment of the A86 carriageway alongside Loch Laggan. The new alignment may be seen to the north-west of the old alignment (north is towards the top of the image).

8.2.4 Drainage

Clearly it is important that issues surrounding drainage and culverts are considered. These fall into two main categories.

First, routine inspection and clearing of drainage channels and culverts must be seen as a priority on the trunk road network and its surroundings. Ensuring that ditches and culverts on the trunk road network are kept clear forms part of the responsibilities of the Operating Companies. The issue of more distant stream channels and the potential for these to temporarily dam and subsequently promote debris flow is however more difficult. Nonetheless, a degree of cooperation with land owners immediately adjacent to high hazard ranking areas of the trunk road network, in order that mutually beneficial improvements to the drainage regime may be undertaken, could prove productive and is an approach that should be pursued.

Second, major systemic improvements to the drainage at road level, including enlarged/enhanced culverts and other drainage features to accommodate debris should be considered. Increasing the capacity of drainage systems also fits well with the changes to UK National Standards (DMRB 4.2.3 HD33/06) implemented in response to forecast climate change. These are also described in the example case study (Section 8.3.2). In addition to capacity it is important that alignment and shape are optimised – there should be a predisposition towards straightness and cross-sections should be based upon efficient circular and square shapes. The importance of carefully considering the drainage provision at the slope-road interface is highlighted in Section 8.3.2. There would be benefit in a using a more formalised approach for drainage auditing, inspection and maintenance on sites at risk from debris flow.

8.2.5 Land Management

The presence of forestry is known to be a positive feature in the minimisation of debris flow in terms of both occurrence and magnitude. However, more importantly, commercial deforestation can significantly increase the propensity for debris flow. Indeed, the effects of forestry have frequently been identified as, at least, partial causes or propagators of debris flows in areas such as the Pacific NW of the USA (Brunengo, 2002).

Logging or deforestation can have a dramatic effect on the drainage patterns of a slope, reducing root moisture uptake and slope reinforcement due to the root systems, increasing infiltration in some areas while removing physical constraints on downslope water flow in others. Furthermore, it is considered that the effects of deforestation can leave land in a more susceptible condition than it might have been if the tree-planting had not been undertaken in the first place.

The practice of clear-felling, whilst not so widespread as it once was in Scotland, can have particularly severe effects as the whole hillside is denuded of vegetation. Where the practice of clear-felling has been abandoned in favour of leaving areas of trees standing then this has largely been from the point of view of improving the aesthetics of the remaining hillside. While this is in itself a laudable objective, there is a clear need to adjust and adapt such practices in order that hillside stability is not decreased in addition to addressing aspects (as notably used in British Columbia in Canada) that could be of great benefit to the practices adopted in Scotland. This should be seen as a priority follow-up to this project in order to begin the process of ensuring that the current situation is not made worse by potentially ill-considered deforestation operations over the coming decade. This process will require dialogue with the Forestry Commission.

8.3 MANAGEMENT ACTIONS

The overall objective behind this study work is to improve the safety of the road-using public allied to improving journey-time reliability. It is also recognised that by better managing the effects of landslides the effects of severance on remote communities are reduced, and this contributes to the objectives of accessibility and social inclusion.

To deliver this overall objective the following management actions (which are in effect the ‘A’ of the DNA, or Detection–Notification–Action, process described earlier), as described more fully in Sections 8.1 and 8.2, are considered essential:

- Integration of landslide-specific requirements into the VMS network.
- The erection of static signs to indicate the beginning, extent and end of sites of significant landslide hazard ranking (sites with a hazard ranking of 100 or greater) as identified in Section 7.
- The implementation of a systematic landslide patrols approach.

- Consideration of the need for landslide gates at locations where a physical closure may be deemed necessary. An obvious hazard area where such an approach would be appropriate is the A83 in the Rest and be Thankful area.
- In consultation with other stakeholder organisations, the provision of information signs in lay-bys, rest areas and at entry points to National Parks for example. Suitable sites for such provision might also include the rest areas on the A9 at Ralia and House of Bruar and the lay-by at Duck Bay on the A82.
- The content of the draft leaflet on ‘Scottish Roads and Landslides’ (Appendix F) should form part of the material for the information signs described above. The leaflet should be made available in electronic form (on the Transport Scotland and Traffic Scotland websites) and in possibly in hardcopy at the sites described above at a later date.
- The need for more systematic reviewing of the drainage provision in areas at risk from debris flows should be considered by Transport Scotland.
- A strategy for dealing with land management issues in the light of debris flow potential should be considered by Transport Scotland in consultation with other stakeholders such as the Forestry Commission.
- The proactive detection of debris flows by means of rainfall monitoring is set-out in detail in Section 9 and forms a vital part of the management actions described here.

8.3.1 Closure and Decision Points

Traffic Scotland is responsible for the management of traffic on the Scottish trunk road network. Decisions on potential closure points should be undertaken in consultation with them and the local police force. Work in terms of Emergency Standard Diversion Routes (ESDRs) and Transport Scotland’s Asset Management Plan (AMP) is ongoing and will determine both closure points and diversion routes to be implemented in response to all types of incident across the network, including landslides.

However, in terms of any potential landslide incident, or series of incidents, there would be a number of potential types of closure and decision point. These would be:

1. *Primary destination decision point:* Early signing of closures in order to enable traffic to remain on direct primary routes to destination – most suited to long distance traffic. This type of decision is being developed, along with diversionary routes for the entire trunk road network, by the ESDR study being undertaken by Transport Scotland.
2. *Junction-based decision point:* The point of closure beyond which only traffic with a need for access to points between this closure and that described at item (3) below should pass. This essentially diverts through traffic whilst allowing local traffic maximum use of the available network. Diversions are signed from this point. This type of signing is also, to a large extent, being undertaken via the ESDR. Locations for static signs are identified by the start and end National Grid References of the High and Very High Hazard Ranking sites detailed in Table 7.1.
3. *Point of physical closure:* This is the point at which traffic is prohibited from passing because the road is either unsafe and/or not passable. This is very much a site-/case-specific issue and the point of closure will depend upon the location of incident(s) and the likelihood of further nearby incidents, amongst other factors. Physical closures are more a matter for the Operating Company.

Clearly, in some situations, two or more of the decision/closure points described in items (1) to (3) above may coincide.

For example, assume a hypothetical blockage of the road due to a landslide on the A87 in Glen Shiel (between Cluanie Inn and Glen Shiel). This example illustrates the three types of diversion/closure (Figure 8.25).

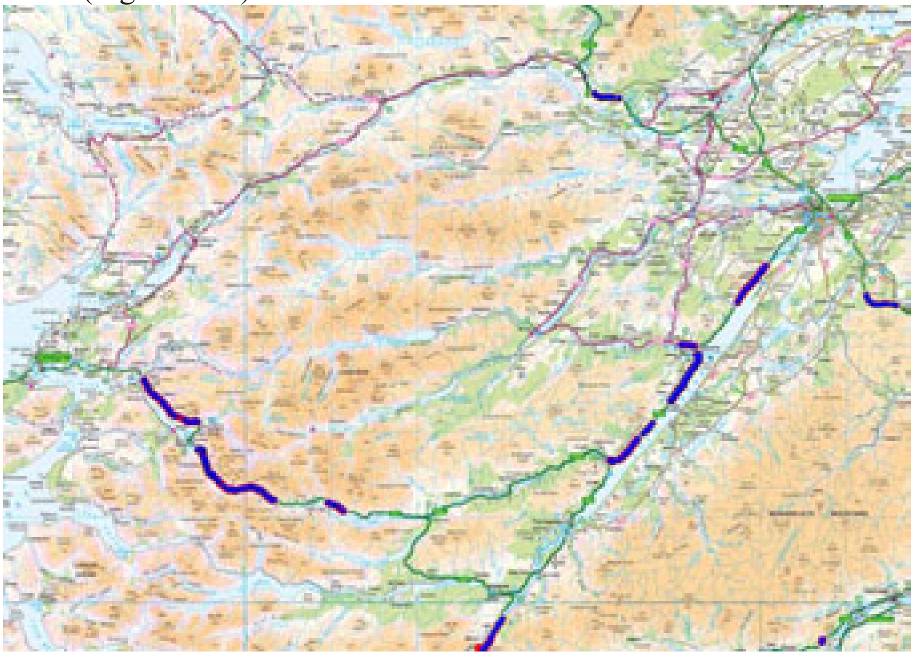

Figure 8.25 – Map showing the A87 between the A82 and Kyle of Lochalsh (the base map is 1:250,000 but is here not to scale). Prioritised route sections highlighted as part of the GIS-assessment interpretation process (see Section 5) are also shown. (© Crown Copyright. All rights reserved Scottish Government 100020540, 2008.)

In terms of primary destination decisions, westbound traffic (e.g. for Kyle of Lochalsh) from the A82 south of Invergarry would be signed to follow the A82 to Inverness and then to follow the A9, A835, A832 and A890 to Kyle of Lochalsh. Conversely traffic from Inverness intending to follow the A87 westbound would be signed to follow the same diversion route but from Inverness.

In terms of junction-based decisions, the road would be closed to westbound traffic, ‘except for local access’, at the A87/A887 junction at Bun Loyne and physical closure would be effected just to the west of Cluanie Inn.

For eastbound traffic, the primary destination decision would be made at the junction with the A87 and the A890 to the east of Kyle of Lochalsh with traffic directed to follow the A890, A832, A835 and A9 for Inverness. The junction-based decision would be effected at the same point with a closure placed ‘except for local access’ on the A87. Physical closure of the A87 would be effected just to the east of Shiel Bridge.

8.3.2 Case Study

Longer-term actions to deal with landslide issues come in a variety of forms, ranging from relatively cost-effective improvement to drainage through high cost defence structures to complete realignment of a section of road.

A good example illustrating this range of actions is provided by the A83 between Ardgarten and the Rest and be Thankful. Recent incidents (October 2007, see Section 2.3, and April

2008) at this location highlighted a potential need for action and a number of possibilities are highlighted below.

Two of the key issues relating to the former incident were the small size of the culvert at this location and the open ditch drain alongside the road at the toe of the slope. The open ditch drain carries water from further up the hill towards the Rest and be Thankful and discharges through this culvert (and others further down the road). The sizing of the upper culvert, whilst not being the most critical factor in terms of the above event, has the potential to cause problems, in terms of blockage and subsequent over-topping, similar to those that occurred at Glen Ogle in August 2004 (see Section 2.2). Also, the drainage ditch at the toe of the slope blocked during the October 2007 event at the A83 and water from it was, as a result, diverted across the road. This caused a separate erosive event downhill of the road and consequent loss of stability of the road structure itself.

In the first instance it seems clear that some short to medium-term action in terms of the drainage provision along the stretch of the A83 between Ardgarten and the Rest and be Thankful is required. Certainly a reconfiguring of the drainage ditch at the toe of the slope, such that it is covered and therefore much less likely to block, is required. In tandem with this work, an assessment of the capacity of the current culverts along this length should be made with a view to increasing capacity and improving shape (cross-sectional and longitudinal) where appropriate. The feasibility of providing debris traps also should be considered between the toe of the slope and the road itself or, indeed, on higher ground if necessary due to space constraints. While it is accepted that it may be difficult to configure such traps on the steep hillside, serious consideration should be given to including them where it is possible to do so. Their location and size should be considered in the light of the potential volumes of debris. It must be emphasised that all such actions should be undertaken along the complete section from Ardgarten to the Rest and be Thankful and not solely in the immediate locality of any incidents which occur or have occurred.

Larger scale construction measures, such as debris shelters have been suggested as a possible solution to the debris flow problem in this area. However, these can only be implemented in the longer term; they are typically not only massive and expensive structures; they are also visually intrusive. If such large scale engineering works are to be contemplated it may be more acceptable to engineer the level of the road in order to allow debris to pass below it –but this would effectively entail a total reconstruction of the road on, or close to, the existing alignment. The disruption to traffic during such lengthy construction operations would need to be fully taken into account should such an option be considered.

A more effective but potentially more costly long-term action may be to realign the road on the opposite side of the valley, possibly at a lower altitude than the current route. This is an action that should not be considered lightly. While recent debris flows have not been observed historically on that side of the valley the disruption to the landscape caused by the construction and maintenance of a road could well lead to a change from the current situation. A decision to take up such an option should only be contemplated after thorough review of all of the information available, including the GIS-based assessment (see Section 4), and a thorough desk-based and walkover investigation of the site to assess the geomorphological, geological and geotechnical issues and potential hazards and risks. In addition, the effects of ongoing deforestation works (as at June 2008) on the opposite side of the valley should be taken into account.

The foregoing considers a variety of options for remediating the hazards and risks for a length of the A83 of around 6.3km. Whilst few would argue other than that this is the most badly affected section of this route in term of debris flows, it is by no means the only length of this route to be so affected, as was demonstrated by the events of August 2004 (see Section 2.2). The main recommendation for long-term action at the A83 is that a thorough Route Action Plan (RAP) be undertaken. This should take into account the landslide potential in the area in addition to the customary considerations such as the strategic nature of the route, traffic levels (including the likely future demand) and level of service required.

9 LANDSLIDES, CLIMATE, RAINFALL AND FORECASTING

by M G Winter, A Motion, F Macgregor, J Dent and P Dempsey

9.1 INTRODUCTION

One of the primary factors influencing debris flow occurrence is water. Heavy rainfall and/or snowmelt trigger the majority of flows as the water mobilises the loose sediment and/or infiltrates into the soil (e.g. McMillan *et al*., 2005).

However, in Scotland the amount of rain that falls during storm events, or in the weeks preceding, and leads to debris flows is currently unknown. Certain of the proposals presented by Winter *et al*. (2005), in response to the debris flow events of August 2004, included a recommendation to install a system of rain gauges. This was intended initially to gain a better understanding of the amount of rain that has to fall to cause these instabilities but with the intention that, in the longer term, a management strategy would be able to be developed: e.g. a protocol for action, potentially including road closure or increased surveillance when predetermined levels of rainfall are exceeded.

The recommendations for future work included (amongst other things) case studies being 'assembled from around the world' in order to capture experience of how rainfall data were collected, analysed and interpreted for the purpose of producing a landslide warning system. These case studies are presented in Appendix G.

Empirical evidence indicates that many Scottish debris flows are triggered by short intense rainfall events preceded by periods of heavy (antecedent) rainfall. However, Crosta (2004) indicates that the 'meteo-climate' factors associated with landslide events worldwide are characterised by an extreme variability. They can be sub-divided into short-term (short intense rainfall, snow melting, etc.) and long-term components (antecedent rainfall, snow melting, etc.). Interestingly, Crosta recognises snow melt as both a short and a long-term component depending upon the rate of melting.

Crosta (2004) also indicates that shallow, flow-type landslides are more likely to be triggered by intense rainfall events and that longer duration rainfall is likely to be involved in more deep-seated landslides. However, his comments are inextricably linked to soil type: assuming that flows occur in granular soils and that deep-seated landslides occur in clayey soils. Winter *et al*. (2005d) noted that debris flows, and in particular their triggering events, in Scotland are by no means confined purely to granular soils and that such generalisations need to be treated with some caution.

Crosta (2004) goes on to state that rainfall analysis is the most frequently adopted approach for forecasting landslides and that worldwide observations have been collected to identify the minimum and maximum rainfalls over various periods of time critical to the triggering of landslides.

In this section of the report observations and approaches to understanding landslides and their rainfall triggers taken from around the world are identified and set in the context of the generalised climate of Scotland. A series of analyses of rainfall events that have led to debris flow has been undertaken in order to develop a tentative rainfall threshold for debris flow formation in Scotland.

9.2 CLIMATIC INFLUENCES ON LANDSLIDES

9.2.1 Rainfall Patterns and Landslides

Landslides are often cited as being caused by storm rainfall and the link between high intensity rainfall and debris flows has been documented in Japan (Fukuoka, 1980), New Zealand (Selby, 1976) and Brazil (Jones, 1973) amongst other places. However, the influence of antecedent rainfall prior to storm events was clear from the events experienced in Scotland in August 2004 (Winter *et al*., 2007a).

In a study based in the Santa Cruz Mountains of California, Wieczorek (1987) noted that no debris flows were triggered before 28cm of rainfall had accumulated in each season. This clearly acknowledges the importance of pre-storm, or antecedent, rainfall, a factor that has also been recognised in studies in Southern California (Campbell, 1975), New Zealand (Eyles, 1979) and Alaska (Sidle and Swanson, 1982). Wieczorek (1987) also notes that in the case of high permeability soils such as those found in Hong Kong (Brand *et al*., 1984), the period of antecedent rainfall may be short or even that the amount of necessary antecedent rainfall may be supplied by the early part of the storm event itself.

9.2.2 Scotland's Rainfall Climate

The climate of Scotland in terms of its rainfall may be very broadly divided into east and west (see Figures 9.1 and 9.2). Data presented by the Meteorological Office (Anon, 1989) indicate that in the east rainfall generally peaks in August while in the west the maximum rainfall levels are reached during the wider period September to January (Figure 9.1). Although rainfall levels in the west are relatively low in August they do increase from a low point in May. Both scenarios indicate that soils may undergo a transition from a dry to a wetter state at or around August, giving rise to an increased potential for debris flow and other forms of landslide activity. The central area, as represented by Pitlochry in Figure 9.1, has a mix between the rainfall characteristics of the 'east' and the 'west'. The rainfall peak is both lower and shorter (December and January) than in the west, but there are also small sub-peaks in August and October. A broadly similar pattern is found for Perth.

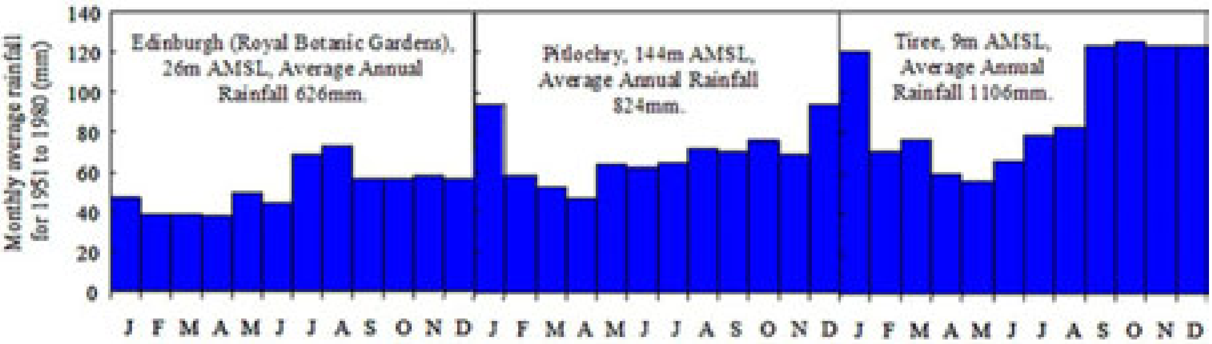

Figure 9.1 – Average rainfall patterns for selected locations in Scotland. Edinburgh is in the east of Scotland, Pitlochry in the centre and Tiree in the west.

Clearly, the soil-water conditions necessary for debris flows may be generated either by long periods of rainfall or by shorter intense storms. It is however widely accepted that Scottish debris flow events are usually preceded by extended periods of heavy (antecedent) rainfall in company with intense storms.

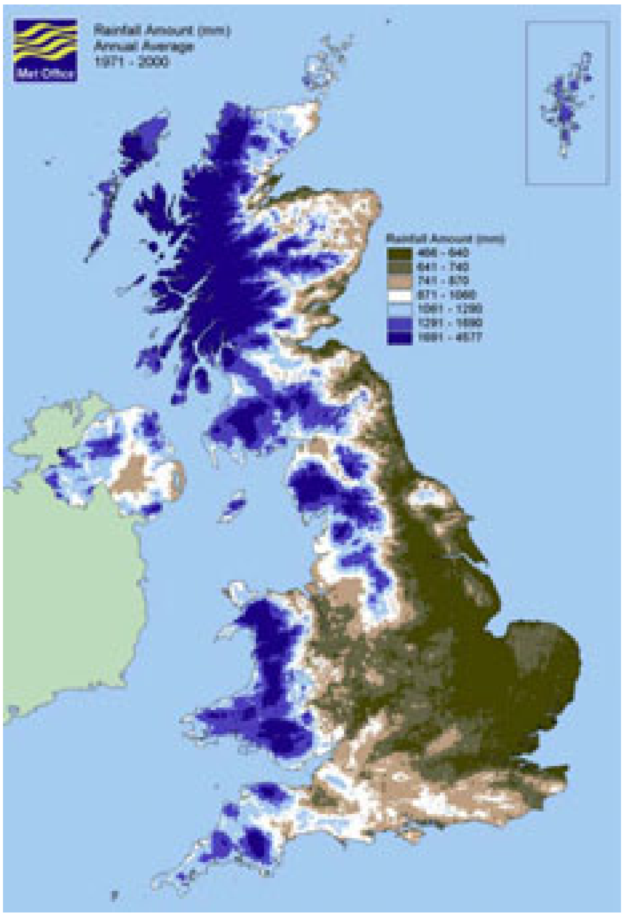

Figure 9.2 – Example of Meteorological Office 30-year monthly average rainfall data for October (image courtesy of the Met Office).

9.2.3 Climate Change

The links between greenhouse gas emissions, the rise in the global temperature anomaly and consequent climate change are well-established. Indeed, the Stratigraphy Commission of the Geological Society of London has proposed that the influence of man has supplanted natural forces as the main driver of environmental processes at the Earth's surface and suggest the formalisation of a new geological epoch, the Anthropocene Epoch, including the last two centuries (Zalasiewicz *et al*., 2008a; 2008b).

The UKCIP02 (UK Climate Impacts Programme) report considers three periods: the 2020s, the 2050s and the 2080s. In general terms small changes are noted in the predictions for the 2020s. These changes increase slightly for the 2050s and slightly further still for the predictions for the 2080s, reflecting the temporal trends in temperature and precipitation. Whilst climate models generally predict averages and the associated error limits can be substantial, it is also important to note that annual variability is predicted to increase for many climate factors. This means that changes in the averages, as described above for example, may mask more significant variability effects.

Climate change models for Scotland in the 2080s (www.ukcip.org.uk) indicate that there will be a decrease in the precipitation in the summer with an increase in the winter, while overall precipitation levels are expected to decrease (Galbraith *et al*., 2005a). The climate models, however, are generally considered to be incapable of predicting localised summer storms.

Such storms are believed to be at least partially responsible for triggering the events of August 2004, and it must be concluded that climate change data may not give a full picture of the relation between precipitation and landslides[5].

Taking the analysis of the UKCIP02 data further, predicted changes in the number of 'intense' wet days generally indicate a net increase of less than one day per annum by the 2080s, with slightly fewer intense wet days in the summer and more in the winter. However, by the 2080s extreme storm event rainfall depths are predicted to increase by between 10% and 30%, with intense winter rainfall increasing slightly more than this, and spring/autumn rainfall by slightly less. Summer extreme rainfall depths are predicted to increase by between 0% and 10%.

Peak fluvial flows are anticipated to increase progressively during the twenty-first century. Eastern Scotland is expected to experience larger increases than north-west Scotland for example. The occurrence of snow and the associated contribution of snowmelt to both fluvial flow and groundwater are, on the other hand, predicted to decrease. Reductions in snowfall are predicted to be greater for the eastern and southern parts of Scotland and least for the central upland areas.

Changes in the factors discussed above, coupled with increased potential evapotranspiration, particularly in the summer, and a longer growing season – leading to increased root uptake – are expected to have substantial effects on soil moisture. The models predict a 10% to 30% decrease in soil moisture for summer/autumn and an increase of 3% to 5% in the winter. The winter figures reflect the fact that soils can only contain a finite amount of water and most Scottish soils are already close to saturation in the winter.

Reduced soil moisture during the summer and autumn months may mean that the short-term stability of some slopes formed from granular materials is enhanced by suction pressures (often described as negative pore water pressures). Soils under high levels of suction are vulnerable to rapid inundation, and a consequent reduction in the stabilising suction pressures, under precisely the conditions that tend to be created by such as short duration, localised summer storms. In addition, non-granular soils may form low-permeability crusts during extended dry periods as a result of desiccation. Providing that these crusts do not crack excessively due to shrinkage, then runoff to areas of vulnerable granular deposits may be increased. Such actions could lead to the rapid development of instabilities in soil deposits, potentially creating conditions conducive to the formation of debris flows. The complicating factors are the potential inability of current climate models to resolve storm events and the precise nature of the localised failure mechanisms that will lead to the initiation of any individual debris flow. It is highly unlikely that the measurement of soil suction could provide a practical and reliable means of debris flow forecast.

Vegetation will also be affected by climate change. Lower overall levels and changed patterns of rainfall might be expected to increase the pressure on vegetation and thus to reduce its beneficial effect upon slope stability. Additionally, extended periods of exceptionally dry weather could potentially lead to wildfires and associated debris flow such as those described by Cannon *et al*. (2008).

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[5] Notwithstanding this, emerging UKCIP08 data is expected to allow much more sophisticated modelling, including weather generators to produce rainfall data.

The importance of the potential effects of climate change impacts on slope stability is exemplified by the existence of an Engineering and Physical Sciences Research Council (EPSRC) Network: Climate change impact forecasting for slopes (CLIFFS) (Dixon *et al*., 2006). This is funded to provide a 'talking-shop' for such issues and to develop collaborative working arrangements to study such impacts and to develop coping strategies.

9.2.4 Mechanics of Unsaturated Slope Failure

That rainfall can cause landslides was dramatically demonstrated in February 2005 when catastrophic landslides occurred during intense rainfall in both California in the U.S. and British Columbia in Canada. Property destruction and tragic loss of life were the results of the various landslides. Over approximately a seven-month period, the Malibu area of California received and accumulation of over 585mm (23 inches) of precipitation. Then, in February 2005, the area received an additional 228mm (9 inches) over a period of about four days, at which time the landsides occurred (GeoSlope, 2005).

Analyses by GeoSlope, replicating the rainfall conditions experienced in California and British Columbia in February 2005 yielded some interesting results. The analysis confirmed that a typical model slope remained stable for seven months during which 585mm of cumulative rainfall fell but became unstable after a further 228mm over a period of four days. In general, the failure could not be attributed to increased positive pore water pressures as the failure surface did not penetrate below the water table. GeoSlope attributed the failure to decreases in suction. This type of behaviour corresponds well with that predicted from unsaturated soil mechanics theory (Wheeler *et al*., 2003) and the broad style of this type of failure mechanism is supported by experiment (Springman *et al*., 2003).

9.5 GENERALISED FORECASTING METHODS

Caine (1980) and Innes (1983) attempted to empirically quantify the amount of rainfall required to initiate debris flow events. Caine (1980) suggested a threshold for debris flow initiation, based upon worldwide data, albeit predominantly from North and South America, could be expressed in terms of a limiting curve, below which debris flow activity is unlikely to occur:

$$I = 14.8D^{-0.39} \tag{9.1A}$$

where I is the rainfall intensity (in mm/hour) and D is the duration of rainfall (in hours).

Caine (1980) suggested that the relation in Equation 9.1A is valid for durations between 10 minutes and 10 days (i.e. across more than three orders of magnitude). It was acknowledged that snowmelt caused by rainfall could significantly increase the apparent rate of rainfall (by up to 4mm/hour) rendering the relation invalid.

A second relation was proposed in the paper, but no description of its use was given. It is essentially an upper bound curve to the lower bound curve of Equation 9.1A. Its potential use is not immediately apparent, but it is reported here for completeness:

$$I = 388D^{-0.514} \tag{9.1B}$$

Innes (1983) developed a similar (lower bound) curve illustrating the rainfall amount-duration relation that has been reported as triggering a debris flow:

$$T = 4.9355D^{0.5041} \tag{9.2}$$

where T is the total rainfall in the period (in mm) and D is the rainfall duration (in hours).

Debris flows in Scotland indicate that anything between 10mm to 75mm of rainfall per hour may be required to initiate these flows, the latter value being significantly in excess of that predicted by the equations developed by Caine (1980). Current annual rainfall in Britain ranges from 1,000mm to 5,000mm (Met Office) and, therefore, these figures represent significant amounts of rain falling in a short time. An early warning system in California suggests that for a rainfall of approximately 15mm per hour, the threshold time for the onset of mud/debris flows varies from 8 to 14 hours depending on slope angles and available material (Bryant, 1991).

Therefore, in the context of antecedent and storm event rainfall triggering landslides, the equations presented above will not provide a complete solution to the identification of likely periods of debris flow activity.

9.4 CASE STUDIES

The review contained in Appendix G highlights a wide range of geographical areas in which landslides are caused by rainfall. Many of these areas are the subject of studies that include the back analysis of rainfall and other records in an attempt to define the levels of rainfall which provide conditions likely to lead to landslides; these are summarised in Table 9.1. While relatively few studies report on the active forecasting of the conditions likely to lead to landslides, many authors of such studies state that the methodologies that they have produced either could be, or will be, used for such purposes. In short the back analysis of such work is widely reported while its use for actual forecasting is less so.

A wide range of methodologies is used in the back analyses, however, these are dominated by intensity-duration analyses which appears to be a viable and well-established way forward. However, an alternative in the form of an analysis of the percentage of mean annual precipitation (MAP) versus duration also shows some promise. This appears to be only a very slight modification of the intensity-duration approach but has the apparent potential advantage of being normalised for local precipitation conditions. A much wider-ranging review of the different approaches to the development of rainfall thresholds is presented by a group of Italian researchers (Anon, 2007a). They identify 16, often subtly, different approaches to the development of rainfall thresholds for landslides in North and South America, Europe, Asia, Africa, and Indonesia and Oceania.

The intensity-duration pattern of each storm during, or immediately after, which landslides have occurred can be analysed. For each storm/landslide event a series of points can be plotted on a graph with intensity on the y-axis and duration on the x-axis. Different durations can be analysed to determine their associated intensities for a given storm/landslide event, giving multiple data points representing multiple durations. Further events can then be analysed in the same fashion. If the same durations are used in the analysis, a series of vertical columns of data points will result, each one representing landslide events corresponding to varying storm intensities at a given duration. The lower boundary of these data points then represents the storm threshold for rainfall-induced landslides.

It is important to note that most analyses consider both storm and antecedent rainfall, the latter usually for periods between five and more than 40 days. Those geographical areas in which antecedent is not considered, or considered over shorter periods, tend to be those in which storm rainfall is particularly intense and/or geological and geomorphological conditions favour the rapid onset of instability. It has proved feasible to plot the intensity-duration relations derived for a number of different areas on the plot presented in Figure 9.3.

Table 9.1 – Summary of landslide forecasting/event causation methodologies.

Country/Region	Data Used in Analysis	Analysis	Rainfall type
Australia	Rainfall records/ rainfall and other site- based monitoring	Intensity-duration: back analysis leading to forecast	Storm and antecedent
Hong Kong SAR	Rainfall monitoring (extensive)	Intensity-duration: forecast	Storm (24 hours)
Italy, NW Tuscany	Rainfall records	Rainfall intensity-time: back analysis	Storm and antecedent
Italy, Sarno	Rainfall records	Cumulative rainfall-time: back analysis	Storm and antecedent
Italy, W Liguria	Rainfall records	Intensity-duration: back analysis	Storm and antecedent
Italy, Piedmont	Rainfall records	Intensity/normalised intensity-duration: back analysis	Mainly storm
Italy, Dolomites	Rainfall records	Intensity/normalised intensity-duration: back analysis	Storm and antecedent
Jamaica	Rainfall records	Intensity/normalised intensity-duration: back analysis	Storm and antecedent (for shallow and deep-seated landslides respectively)
Nepal	None	None	Mainly storm
Norway	Rainfall records	Intensity/normalised intensity-duration: back analysis	Storm and antecedent
Singapore	Rainfall records	1 day versus 5 day rainfall	Storm and antecedent
Slovenia	Rainfall records	Recurrence duration	Storm and antecedent
Switzerland	Rainfall records	Intensity-duration: back analysis	Storm and antecedent
United Kingdom, NW England	Rainfall records/site- based rainfall monitoring	Various intensity-duration figures: back analysis leading to forecast	Storm and antecedent
United Kingdom, SW England	Rainfall records/soil moisture deficit	Percentage of long-term average in a period: back analysis leading to forecast	Storm and antecedent
United Kingdom, Scottish Highlands	Rainfall records/ river gauging	14 day cumulative rainfall	Storm and antecedent
USA, California	Rainfall records	Intensity-duration relation: back analysis	Mainly storm, although antecedent acknowledged as important
USA, Washington State	Rainfall records/site-based rainfall monitoring	Intensity-duration/antecedent water index: back analysis	Storm and antecedent

The back analysis of Scottish events was therefore taken forward on the basis of an analysis of both intensity-duration and of a form of normalised intensity-duration, in this case intensity/MAP-duration.

9.5 A TRIGGER THRESHOLD FOR SCOTLAND

9.5.1 Introduction

In terms of forecasting conditions potentially leading to debris flow, the current rainfall gauge network in Scotland is sparse in most of the areas of interest. In addition, the rainfall radar system covers some of the areas of interest at a resolution of 2km, but most are at a resolution of just 5km. Accordingly, data are not available on a routine basis for the key areas of interest.

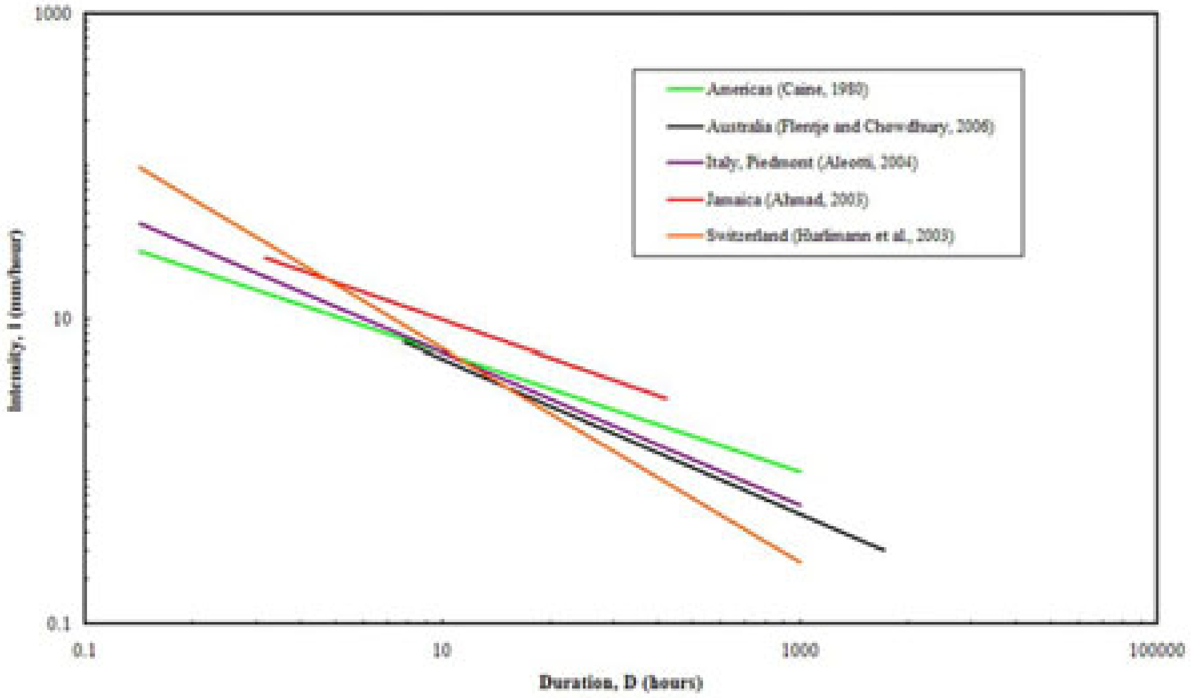

Figure 9.3 – Comparison of landslide trigger thresholds based on rainfall intensity-duration for different parts of the world.

At the time of writing, two rainfall gauges are to be installed, as part of a trial, on land adjacent to the A83 between Ardgarten and Cairndow. Experience indicates that this area is probably one of the most active debris flow areas in Scotland; certainly it is one of the areas of the major road network most frequently affected by such events. Whilst a requirement for planning permission has created significant delay, it is hoped that the installation of these rain gauges will be completed in time to be functional during the landslide seasons of 2008: July to August and November to January (Winter *et al*., 2005a).

A back analysis, using analytical techniques to retrospectively examine historical radar data obtained in the lead up to known landslide events, has been undertaken and is reported in Section 9.5.2 to 9.5.4. The events to be studied encompass a wide geographical area and a diverse range of geological settings[6]. The data are used to develop a preliminary threshold based upon rainfall in terms of rainfall intensity-duration. The data have also been analysed with the intensity normalised for mean annual precipitation (MAP); this is intended to allow possible further comparison with threshold data produced for other regions of the world.

An additional element to this approach can be to undertake the same type of analysis for storm events that do not trigger landslides (Winter *et al*., 2007c). This allows the threshold to be defined from below as well as from above, lending an additional degree of surety to the process. Figure 9.4 illustrates the development of a purely hypothetical threshold in this manner. It should, however, be noted that, while the approach is sound, it is difficult to justify

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[6] It should be noted that these techniques as developed and used do not necessarily lend themselves to use on a routine, real-time basis. In addition, issues surrounding the shadow effects in mountainous regions have only been partially resolved.

the expenditure of resources to analyse ‘non-events’. Accordingly, no such analysis has been undertaken for this purpose.

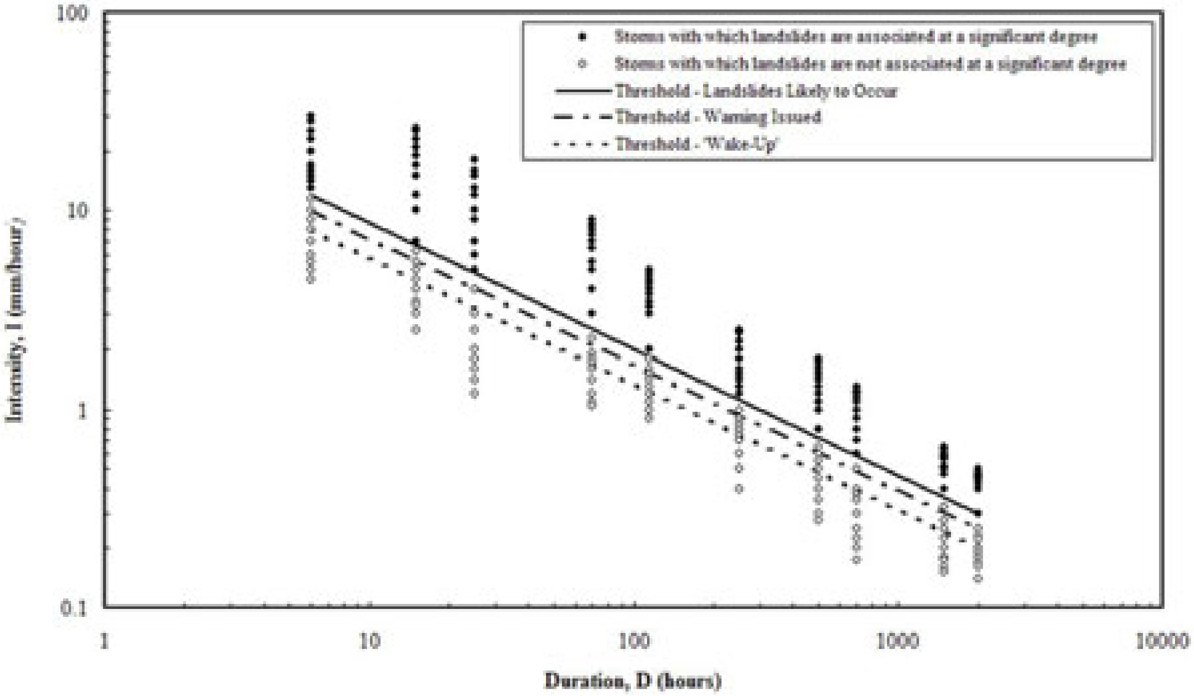

Figure 9.4 – Development of a purely hypothetical rainfall intensity-duration threshold for landslides.

The hypothetical rainfall data of Figure 9.4 have been utilised to develop three (also hypothetical) threshold levels:

- A threshold level above which landslides might be expected to occur.
- A lower threshold level at which a warning could be issued and action taken. This is set at this lower level so as to give adequate lead-in time for notifications and actions to be effective.
- A still lower threshold level is set at which instruments are checked and key personnel alerted to the possibility of the development of conditions likely to lead to landslides. This would be a precursor to the issue of a landslide warning.

It is important to recognise that threshold levels developed in this way are in no way absolute. They may simply represent the transition between the landslide density and/or short-term frequency in a given area reaching a limit that is significant in the context of infrastructure operation, for example. This transition is likely to be more complex in larger areas of varied and complex geology such as Scotland.

Observation of debris flow events in the trial area will allow further development and/or validation of the preliminary threshold (as developed in Section 9.5.4), by analysing the rainfall data collected in the lead-up to the events. Furthermore, it may also be feasible to analyse the rainfall leading up to storms that do not lead to debris flow events. Thus, the threshold above which landslides may be expected to occur can be defined using data points lying both above and below it which improves confidence in its accuracy.

Once sufficient confidence in the threshold has been established, the objective is to introduce the system as routine in forecasting debris flow events in this area. Essentially, the forecast will be used as the detection element of the DNA (detection-notification-action) sequence in the management procedures described in Section 8 of this report.

Provided that the system proves successful, it is envisaged that the system be introduced to other areas prone to rainfall-induced debris flows.

9.5.2 Threshold Development

The work to develop a rainfall threshold for debris flow potential was assisted by a sub-contract to the UK's Meteorological Office to examine rainfall conditions at specific locations where landslides disruptive to the road system have occurred. A set of 16 events of known location and for which an apparently robust estimate of timing was available were selected for the study, as follows:

1. October 2001: Stromeferry Bypass, Loch Carron.
2. January 2003: Rest and be Thankful, Glen Croe.
3. November 2003: Rest and be Thankful, Glen Croe.
4. January 2004: Rest and be Thankful, Glen Croe.
5. February 2004: Laide, Wester Ross.
6. August 2004: Glen Kinglas
7. August 2004: Cairndow.
8. August 2004: Glen Ogle, Lochearnhead.
9. August 2004: Dunkeld, Perthshire.
10. August 2004: Pitcalnie, Nigg, Easter Ross.
11. August 2004: Eathie, Black Isle.
12. October 2004: Avoch-Fortrose, Black Isle.
13. December 2004: Cnoc Fhionn, Shiel Bridge-Glenelg.
14. January 2005: Letterfinlay, Loch Lochy.
15. September 2005: A87 Junction, Inverinate-Morvich.
16. September 2005: Kylerhea Glen, Skye.

The locations of the analysed landslide events and the rain gauges used in the analyses are illustrated in Figure 9.5, along with the coverage from Met Office weather radar installations.

9.5.3 Objectives

The overall objective of the work described in this section and Section 9.5.4 was to investigate the pattern of rainfall events associated with landslide occurrences and to analyse the data for both short duration and extended antecedent periods, in order to test analytical methods that could have an application to forecasting similar events in the future. The following objectives were thus set, as follows:

- To extract comprehensive data sets of rainfall from rain gauge and radar sources for each of the 16 events.
- To analyse the data in order to make four graphical representations for each of the 16 events:
  i) Cumulative rainfall over an extended antecedent period (up to 150 days).
  ii) Storm rainfall, presented as accumulation and intensity for a period of 18-24 hours leading up to the time (if known) of the landslide occurrence.

iii) The relation between intensity (mm/hr) and duration for the combined storm and antecedent periods.

iv) The relation between rainfall intensity as a function of mean annual precipitation (Intensity/MAP) and duration of the storm and antecedent period.

- To compare all of the intensity-duration relations for individual events and also on the basis of temporal and geographical spread.
- To prepare a spreadsheet for analysis of future events ('Future Back Analysis'), based on the methods for data manipulation and analysis above.

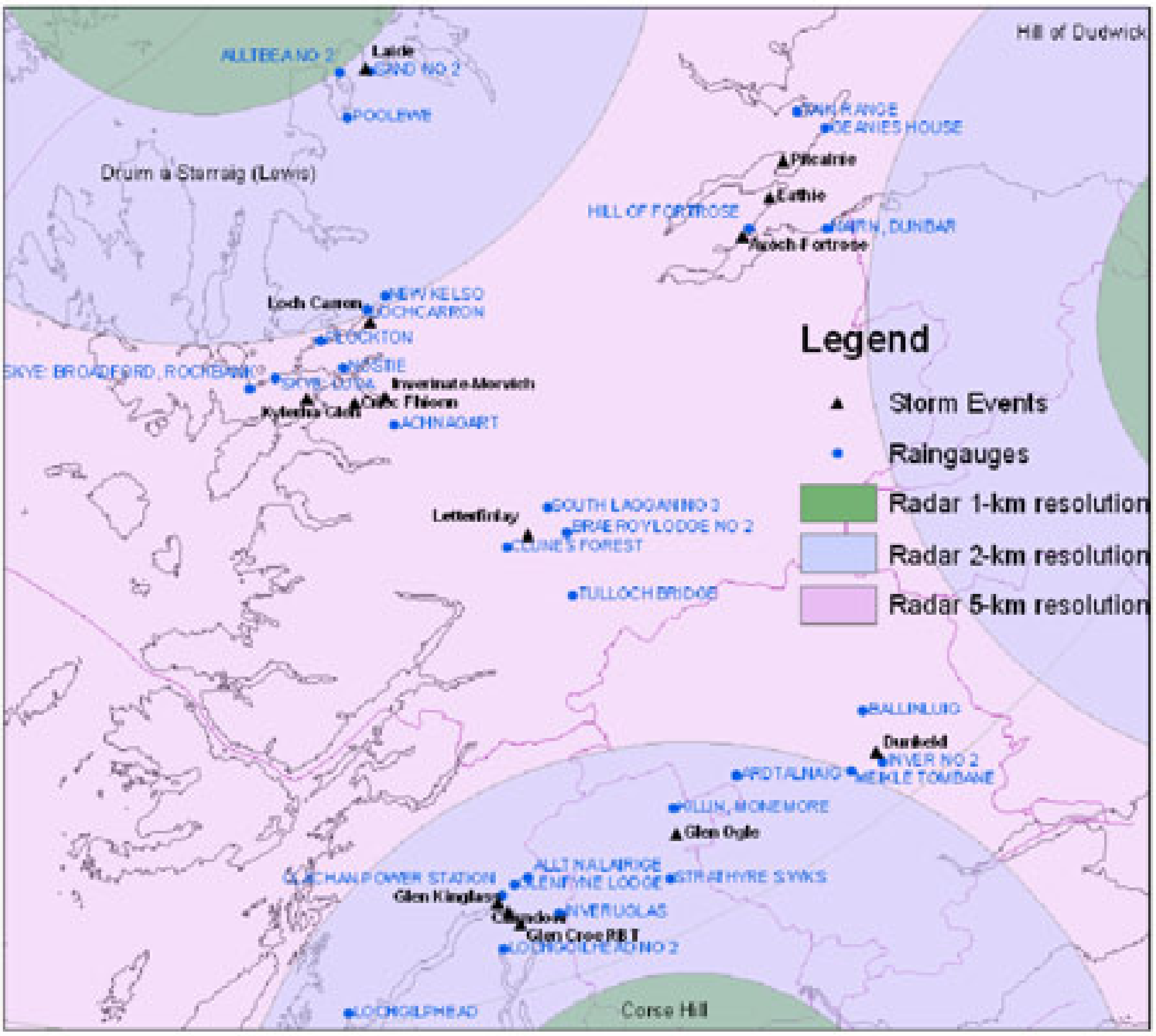

Figure 9.5 – Location of landslides, rain gauges and radar (prepared by P Dempsey and J Dent of the Met Office).

The form of the analyses, the results for individual events and associated discussion are given in Appendix H. The following section details combinations of intensity-duration data from, the 16 analysed events, which may be used to develop event thresholds.

9.5.4 Results

Intensity-duration plots for different combinations of the 16 events analysed are presented in Appendix H. These include plots for Events 1 to 8 and Events 9 to 16 in order that the data for each event to be seen more clearly. The results are discussed in more detail in Appendix H.

In terms of understanding the important issue of how rainfall may cause debris flow, groups of plots for intensity-duration are presented for summer and winter events and also for events that occurred in the eastern and western parts of Scotland. While the details of the data are discussed in Appendix H, perhaps the most important observation is that all of the data sets broadly occupy the same space on the intensity-duration diagrams and that there is thus no compelling case for different thresholds for summer and winter events or for events that occur in the east and west of Scotland.

It is thus appropriate to combine all of the intensity-duration data for the 16 events onto a single diagram (Figure 9.6).

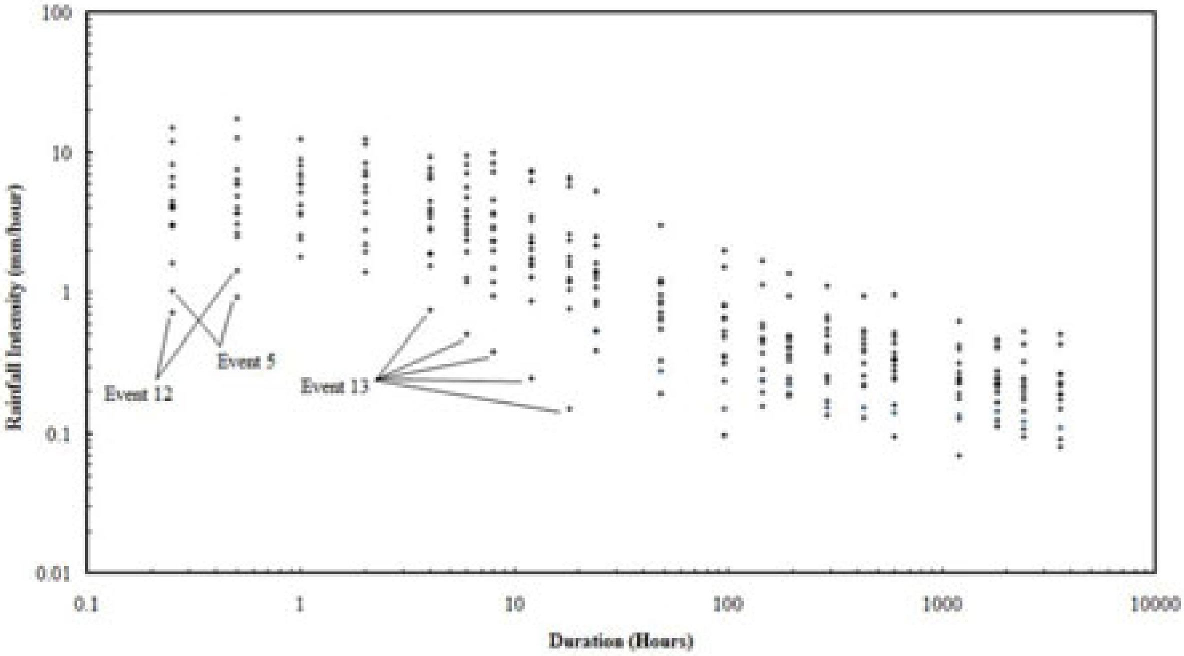

Figure 9.6 – Combined plot of intensity versus duration data for the 16 analysed debris flow events.

As might be expected there is a considerable amount of scatter in the data. However, the key point is that once certain 'outlying' data points are removed from consideration (Appendix H), then a reasonably clear tentative trigger threshold can be drawn (Figure 9.7). The blue crosses on Figure 9.7 represent data that are considered to be 'outliers' and as a result were not considered in the formulating the tentative threshold (illustrated in Figure 9.7 by red dots connected by a red line).

Clearly there is an issue as to how such a threshold may be used in so far as that illustrated in Figure 9.7 is tentative, requiring validation from future events. Indeed such work is ongoing, concentrating upon the Rest and be Thankful area as previously described.

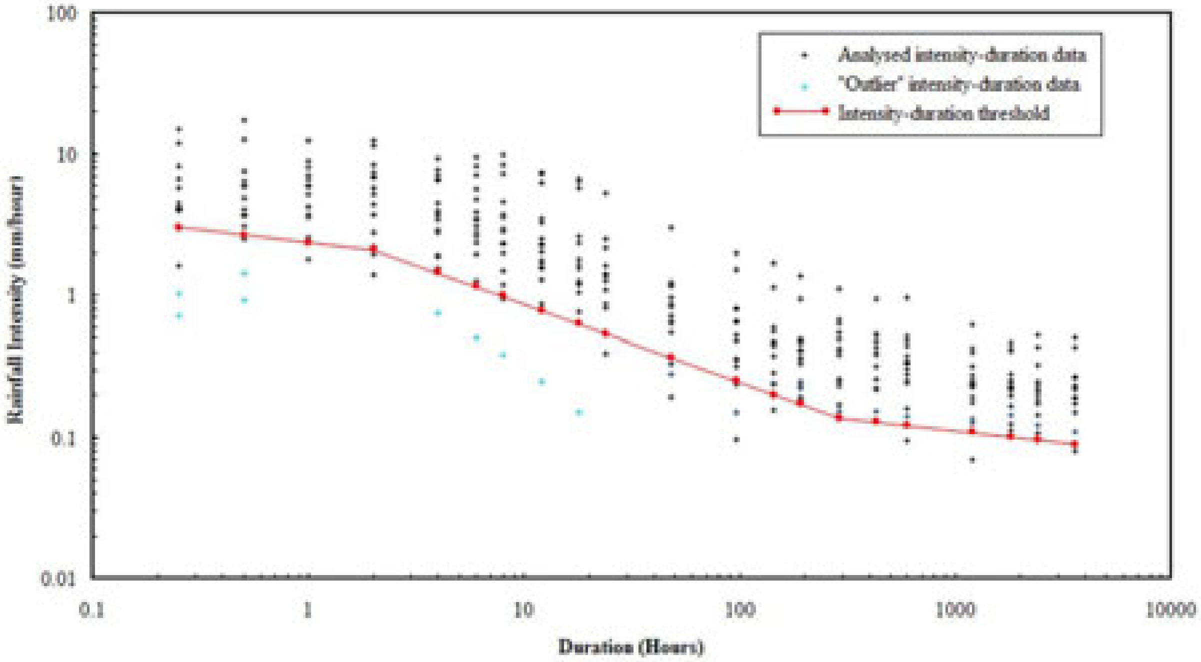

Figure 9.7 – Tentative trigger threshold for Scottish debris flows in terms of intensity-duration.

Once validated, however, and with any suitable adjustments made it should be possible to set both 'Wake-Up' and 'Warning' thresholds, as described in Section 9.5.1 (Figure 9.4). There does, of course, remain the question as to how these thresholds should be operated.
In viewing the data there is a tendency to view the data from a position equivalent to time, *t*=0 (although as the scale is logarithmic this is simply a very low number). In real terms this, of course, corresponds to the time of the actual event. Therefore, the data must be viewed as if from a point in time in advance of the event.

It is suggested that the 'Wake-Up' be viewed from a point of view of three days (*t*=36 hours) in advance of any potential event, with the 'Warning' being viewed from the point of view of half of one-day (*t*=12 hours) and actual event threshold being observed from the point of view of a very short time in advance of any actual event. These viewpoints are illustrated in Figure 9.8 (which is based upon Figure 9.4) with the threshold observation point being set at time, *t*=6 hours. These timings have been assigned very much on an initial basis and require further work prior to the finalisation of a fully-developed threshold suitable for implementation.

Early testing of the threshold has been undertaken using the results of an analysis of the storm that led to the debris flow event at the A83 Rest and be Thankful on 28 October 2007 (see Section 2.3). The analysis was performed in precisely the same manner as those analyses reported earlier and which facilitated the development of the tentative rainfall intensity-duration threshold (Figure 9.7). The important difference is, however, that the October 2007 analysis was carried out after the tentative threshold had been determined, thus providing some degree of validation to the threshold. The threshold and the new data are both illustrated in Figure 9.9. It can be clearly seen that for the major part of the precursor period the data plot well above the tentative threshold; only during the last two hours before the landslide event do the data plot below the threshold. This may mean that by a point in time two hours before the event the rainfall had been sufficient to cause the debris flow to be inevitable. The break in the data at 288 hours (12 days) is also interesting. This coincides with a change in the slope of the threshold and may imply that this approximates to the longest period before the event that is significant; it may thus be reflective of the true limit of the antecedent period. This is, however, a very tentative conclusion and needs to be verified or otherwise by further data sets (Winter *et al.*, 2008).

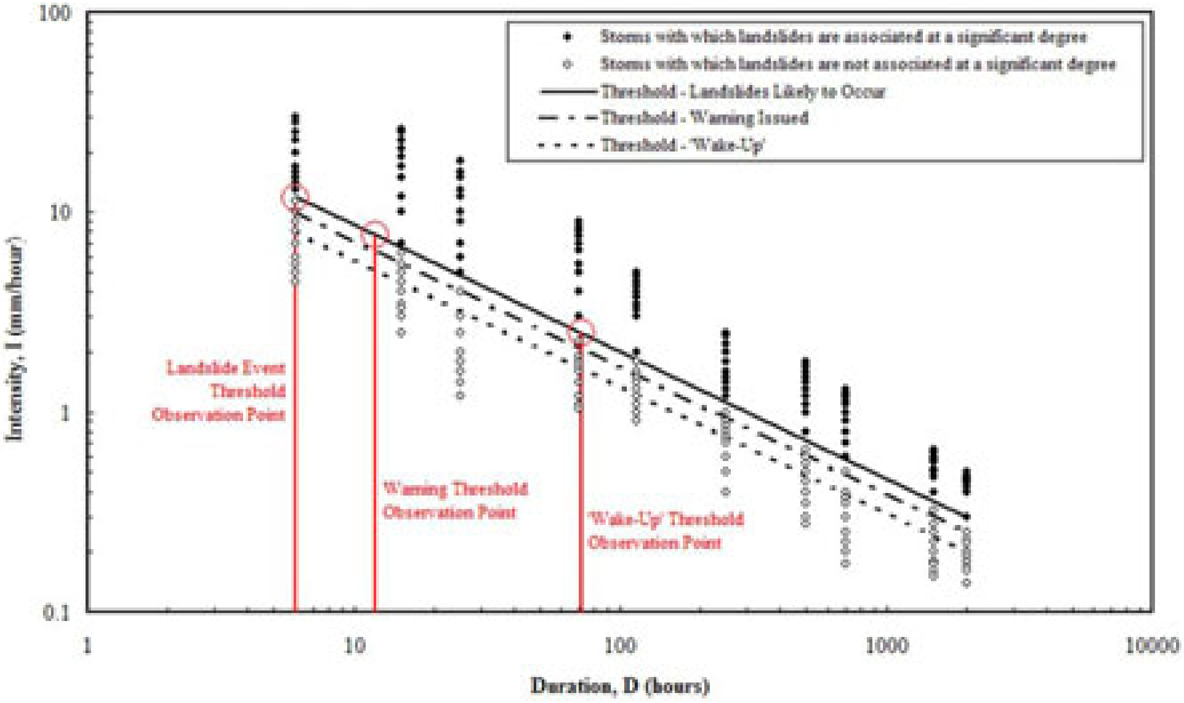

Figure 9.8 – Hypothetical rainfall intensity-duration threshold for landslides, illustrating observation points for the different thresholds, described in Figure 9.4 may be used.

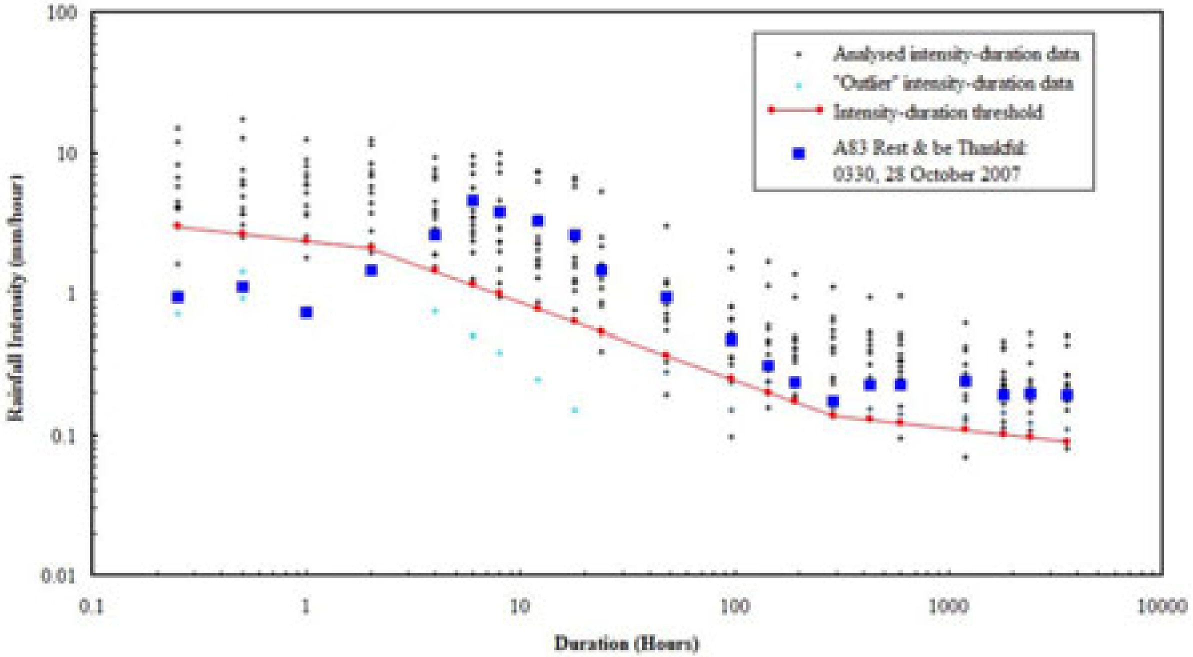

Figure 9.9 – Tentative trigger threshold for Scottish debris flows in terms of intensity-duration showing the back analysis of the October 2007 event at the A83 Rest and be Thankful.

9.6 SUMMARY

Clearly weather and climate are key influences upon the triggering of debris flows in Scotland. In addition climate change models generally indicate a potential for such events to become more frequent and/or more intense in the future.

The ability to forecast conditions during which such events may occur is important now, but is likely to become still more important in the future. Such forecasts potentially enable the Detection and Notification of such events prior to their occurrence. In some circumstances it may even be appropriate to take action in advance of such events.

A wide variety of international approaches to the back analysis and forecast of landslide events resulting from rainfall has been studied. It was found that, back analyses to determine the relations between rainfall and debris flow events are relatively common. However, the implementation of practical systems to forecast the likelihood of debris flow events occurring seems to be relatively rare – albeit with notable exceptions.

A tentative debris flow trigger threshold, in terms of rainfall intensity-duration, has now been developed for Scotland. This threshold needs to be tested against observations in the future to validate it use prior to its implementation as a management tool. Notwithstanding this, the first test of the threshold (in the form of the October 2007 event at the A83 Rest and be Thankful) indicates that it has the potential to be successful. Work is ongoing to capture and analyses further such data for the purposes of validation.

A series of high quality data sets from a variety of geographical locations will be needed in order to validate and/or modify the threshold prior to its introduction to the management of the road network in any formal sense. Further data will also be required to enable the limit of the antecedent period of rainfall that influences the formation of debris flows. Given the frequency of such major events in Scotland it is estimated that this process may take of the order of approximately five years.

During this five year period there is a need to develop a system to allow the ‘real-time’ capture and analysis of appropriate rainfall data, including forecast rainfall data, to enable the forecast of potential debris flow events. This work could be most effectively taken forward in collaboration with the Met Office as both expertise in meteorology and landslides is required.

Once confidence in the threshold has been established working simulations and trials of its use should be conducted. This would enable lower thresholds for ‘Wake-Up’ and ‘Warning’ thresholds, as described in Figure 9.4 for Figure 9.8, to be set. It would also enable firm rules for the use and operation of the threshold to be set, again as described in Figure 9.8.

10 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

by M G Winter, F Macgregor and L Shackman

10.1 SUMMARY AND CONCLUSIONS

The landslide events of August 2004 had a substantial effect on the operation of Scottish trunk road network and led to wide-ranging media and political interest. The nature of these events broadly conformed to the relatively fast-moving, shallow debris flow-type of landslide with which this report primarily deals. There have since been other debris flows of a similar nature including, for example, those that affected the A9 in 2006 and the A83 in 2007, as well as a wide range of similar occurrences that affected the local road network. In general the events detailed in this report confirm that landslides typically occur in Scotland in two seasons, namely:

- Summer: July and August.
- Winter: November to January (with events sometimes occurring in October).

The work reported here forms the major component of Transport Scotland's response to the August 2004 events and builds upon an earlier report (Winter *et al*., 2005) which described the background and objectives behind the work presented. The findings from the work have already been widely presented on both nationally and internationally.

Consideration of the socio-economic aspects of landslide risk illustrates the diverse approaches taken by different societies and cultures. These considerations support the principle that the landscape itself has both a social and an environmental value and that a drive towards risk mitigation and/or reduction is only one part of the wider picture.

Notwithstanding this, the core of the work addressed by this report is the assessment and ranking of hazards presented by debris flows.

The hazard assessment process involves the GIS-based spatial determination of zones of susceptibility which are then related to the trunk road network by means of plausible flow paths to determine specific hazard locations. The approach taken, using a GIS-based assessment, enabled large volumes of data to be analysed relatively quickly and was able to rapidly deliver a scientifically-sound platform for the assessment. This desk-based approach to hazard assessment was then supplemented by site-specific inspections, including site walkovers, to give a hazard score for each site of interest.

The subsequent hazard ranking process involved the development of exposure scores predicated primarily upon the risk to life and limb, but also taking some account of the socio-economic impact of debris flow events.

Finally, these scores were combined with the hazard scores to give site-specific scores for hazard ranking from which a listing of high hazard ranking sites in Scotland was produced.

An approach to the management and mitigation of debris flow hazards has also been developed. Two approaches are described:

- Exposure reduction, which involves for example education, warning, signing and road closure.

- Hazard reduction, which includes engineering measures that protect the road, reduce the opportunity for debris flow to occur, or involve realignment of the road.

Most of the recommendations (see Section 10.2) are based upon the reduction of the exposure of the road users to debris flow hazards as a reaction to events and utilise lower cost and less environmentally intrusive approaches rather than the typically high cost, environmentally intrusive approach of specific hazard reduction. Exposure reduction is predicated upon the simple and easily-remembered, three-part management tool, Detection-Notification-Action (DNA).

Weather and climate are clearly key influences upon the triggering of debris flows in Scotland and climate change models generally indicate that such events may become more frequent and/or more intense in the future. In the longer term the ability to forecast of debris flow from rainfall data is clearly desirable in order to allow, at least, the Detection and Notification aspects of the DNA process to be carried out in advance of events.

In support of this a variety of international approaches to the back analysis and forecast of landslide events resulting from rainfall have been researched and described. Back analysis of the rainfall associated with a selection of Scottish debris flow events has enabled a tentative debris flow trigger threshold, in terms of rainfall intensity-duration, to be proposed. This threshold, however, needs to be further validated against observations in the future and it is estimated that at least five years of data will be required prior to implementing such a system. Work is currently in progress to develop the dataset and validate the threshold. During the development period a system will also need to be put in place to allow 'real-time' capture and analysis of data to enable forecasting.

The work presented in this report gives Transport Scotland the means to apply appropriate management measures to the sites of highest risk on the trunk road network. Specific recommendations to achieve this and to further develop and improve the management process are given in the following section.

10.2 RECOMMENDATIONS

1. Recommendations in terms of the management of the effects of debris flows are, in the first instance, targeted towards reactive exposure reduction. To deliver the overall objective the following management actions (which are in effect the 'A' of the DNA, or Detection–Notification–Action, process described earlier) are considered essential:
    a) Integration of landslide-specific requirements into the VMS network.
    b) The erection of static signs to indicate the beginning, extent and end of sites of significant landslide hazard ranking (initially sites with a hazard ranking of 100 or greater). These may include flashing lights for periods of higher likelihood.
    c) The implementation of a systematic landslide patrols approach.
    d) Consideration of the need for landslide gates at locations where a physical closure may be deemed necessary. An obvious hazard area where such an approach would be appropriate is the A83 in the Rest and be Thankful area.
    e) In consultation with other stakeholder organisations, the provision of information signs in lay-bys, rest areas and at entry points to National Parks for example. Suitable sites for such provision might also include the rest areas on the A9 at Ralia and House of Bruar and the lay-by at Duck Bay on the A82.

f) The draft leaflet on 'Scottish Roads and Landslides' should form part of the material for the signs described in item (e) above. It should also be made available in electronic form (on the Transport Scotland and Traffic Scotland websites) and possibly in hard copy at the sites described in item (e) above at a later date.

g) The need for more systematic reviewing of the drainage provision in areas at risk from debris flows should be considered by Transport Scotland.

h) A strategy for dealing with land management issues in the light of debris flow potential should be considered by Transport Scotland in consultation with other stakeholders such as the Forestry Commission.

2. In addition, appropriate physical hazard reduction measures should be considered as part of the planning and design process for all sites of high hazard ranking which are scheduled for major maintenance, reconstruction and/or realignment.

3. Weather and climate are key influences on the triggering of debris flows in Scotland and climate change models indicate the potential for such events to become more frequent and/or more severe. Accordingly, the proactive detection of debris flows by means of rainfall monitoring forms a vital part of the longer term management strategy to reduce the exposure of the road using public to debris flow hazards. This then gives the potential to enable Detection, Notification and even some Actions to be undertaken prior to debris flow events. Specific recommendations to action this include the following:

a) The tentative debris flow trigger threshold that has been developed for Scotland should be tested against future observations to validate its use prior to introduction. Such work is ongoing and the first test of the threshold is reported herein. In view of the effort and the events-based data required to undertake this validation process, a period of five years is considered likely to be needed prior to its formal introduction to the management of the road network.

b) The above-mentioned work will also need to consider the most appropriate antecedent period for the forecast of conditions likely to lead to debris flow in Scotland.

c) A system to allow the 'real-time' capture and analysis of appropriate rainfall data, including forecast rainfall data, should be developed to enable the forecast of potential debris flow events. It is recommended that this work be taken forward in collaboration with the Met Office.

d) Once confidence in the threshold has been established simulations of its use should be undertaken. This will enable to lower thresholds for 'Wake-Up' and 'Warning' thresholds to be set, as well as enabling firm rules for the use and operation of the threshold to be set.

4. In addition to the implementation of the recommendations described above, other key issues should be addressed in the future. These include more detailed study of the progressive effects of climate change on debris flows in Scotland, in particular as climate change models improve. An evaluation of the economic impacts of debris flow events will also provide valuable information to aid the decision-making process in terms of management actions and priorities, particularly where higher cost actions are considered.

5. Although, the practice of clear-felling is not as widespread as it once was in Scotland, forestry practices can have a significant impact on the stability of hillsides. Learning from international best practice, particularly that from British Columbia in Canada, in terms of forestry harvesting to maintain hillside stability should be seen as a priority; this will require dialogue with the Forestry Commission.

6. The site-specific inspection programme should be extended through 2008 and subsequent years. A programme for 2008 is in place at the time of writing.

7. The GIS-based assessment should be revisited in (say) 10 years to take account of:
   a) New and improved data sets.
   b) New and improved technologies for handling such data sets.

This work would also require a reinterpretation of the GIS-based assessment.

8. Once the GIS-based assessment and interpretation has been revisited, the sites themselves should be reassessed to take account of changes in land-use and other anthropogenic factors, as well as any short-term geomorphological processes. It is recommended that those sites with a hazard score of (say) 70 should also be subject to the site-based reassessment exercise. The combination of revisiting the GIS-based assessment, interpretation and site-specific reinspection after the interval suggested, should ensure that the appreciation of debris flow hazard to the network remains soundly based in future years.

9. In respect of rock slopes, Transport Scotland is currently assessing the future actions required to address those Hazard Rating surveys and reinspections that remain to be carried out.

10. The two routes identified for ‘Separate Assessment’ should be the subject of specific studies designed to take into account the particular character of these sites. In particular, these studies will need to examine the wealth of information that has been accumulated on these sites in the past and also the nature of the predominantly scree slopes to assess the hazards and risk at these sites while ensuring that the outputs are broadly compatible with the outputs from the site-specific studies reported here.

ACKNOWLEDGEMENTS

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Transport Scotland, Scottish Executive and its successor organisations retain full usage rights of the outputs and contracted deliverables from the GIS-based assessment reported in Section 4. Such usage is by its own staff and by its agents employed in the operating, maintaining and constructing the road network. In addition, hazard maps in electronic form have been supplied to relevant local authorities. The output forms part of a wider assessment of the hazards (and associated exposure and hazard rankings) posed to the Scottish road network and it users by debris flow type landslides. It is intended for use in the operation, maintenance and construction of the network. It is neither intended nor suitable for, and should not be put to, any other use.

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APPENDIX A – SUPPLEMENTARY INFORMATION FOR THE GIS ASSESSMENT

by M Harrison, A Gibson, A Forster, D Entwisle and G Wildman

Table A.1 – Criteria used to interpret BGS ROCK codes to indicate source material availability.

Score	Criteria
10	• Granular superficial material – sand, gravel, boulders including silt and clay if they are minor components. Diamicton is assumed to be granular and capable of being mobilised. • Loose material such as talus. • Material that might reasonably be assumed to be so on a worst-case scenario such as made ground and fill • If dense lodgement till could be distinguished from the above materials it could be assigned a lower rating, perhaps 5 might be appropriate on the basis that material in the near surface zone would be sufficiently weathered to become mobilised in the same way as a less dense melt out till would be mobilised.
9	• Materials at the finer end of the coarse materials with some silt and clay but not enough to stabilise the material if copious water were present.
8	• Materials with clay and silt listed as the major component. • Probably sufficient fine material to stop debris flow mobilisation unless the components are present as discrete bodies that could be mobilised and the finer components then incorporated. • Their potential for being mobilised may be overestimated at this score and subdivision and rescoring on geomorphological grounds may improve this. Possibly raised deposits go to score of 7 or 6 and the flat lying deposits go to a score of 1. • Materials in the highest class of the accumulation model are assigned this score as described in Section 4.2.2
7	• Landslip and worked ground are included in this group on the basis that they are probably loose and at residual strength but may be fine-grained.
6	• No mapped materials are assigned to this score but accumulation materials as identified by the methodology described in Section 4.2.2 are assigned this value.
5	• This score has been assigned to bedrock lithologies that were considered the most likely to develop a significant regolith that could be mobilised by flowing water. Thus the regolith would be predominantly the result of physical weathering and comprise coarse material either through the induced fracturing along incipient discontinuities (schists, pelites semipelite etc) under the influence of freeze/thaw activity or lesser thermal effects or the break up of inter-mineral bonds by the break down of some of the mineral components (coarse grained igneous rocks, granites, migmatites etc). • The working party report noted that schist and granite were associated with debris flows, an observation that supports this classification.
4	• This score has been assigned to bedrock lithologies that appear less likely to generate a granular regolith because: – They comprise mixed sedimentary rock with lithologies that contain some clay rich components that may soften and bind the regolith together e.g. undivided cyclic sedimentary rocks, 'sandstone, siltstone, mudstone', greywacke. – Are mainly stronger and have a lesser propensity for breaking along discontinuities than the pelite/ semipelite lithologies. These lithologies are the more gneissose semipelites. – Also included here are fine grained igneous rocks such as basaltic and andesitic lavas that are assumed to have large numbers of discontinuities due to cooling joints or a rubbly fabric that would assist their weathering, along with tuffs which are all known, in some instances to weather to a granular regolith.
3	• Sedimentary conglomerates are included on the basis that the individual components might weather out of a weaker matrix.
2	• These materials are assumed to have relatively few discontinuities that would allow them to form an extensive granular regolith and to be relatively resistant to chemical weathering. Although some of the basic igneous intrusions would be more likely to form clay-rich weathering products than the other lithologies in this group. • These materials include sandstones, psammites, and minor igneous intrusions (both basic and acidic).
1	• These materials are those which are considered unlikely to be mobilised as a debris flow because – They are too silty or clayey. – They are limestones that would dissolve rather than form a regolith. – They are high-grade metamorphic psammite/gneiss and would be unlikely to form a regolith due to their strength and chemical stability.

Table A.2 – Criteria used to determine the rating of available debris material score from the deceleration data.

Deceleration Range	Material Score
0.0 to 0.025	8
0.025 to 1	6

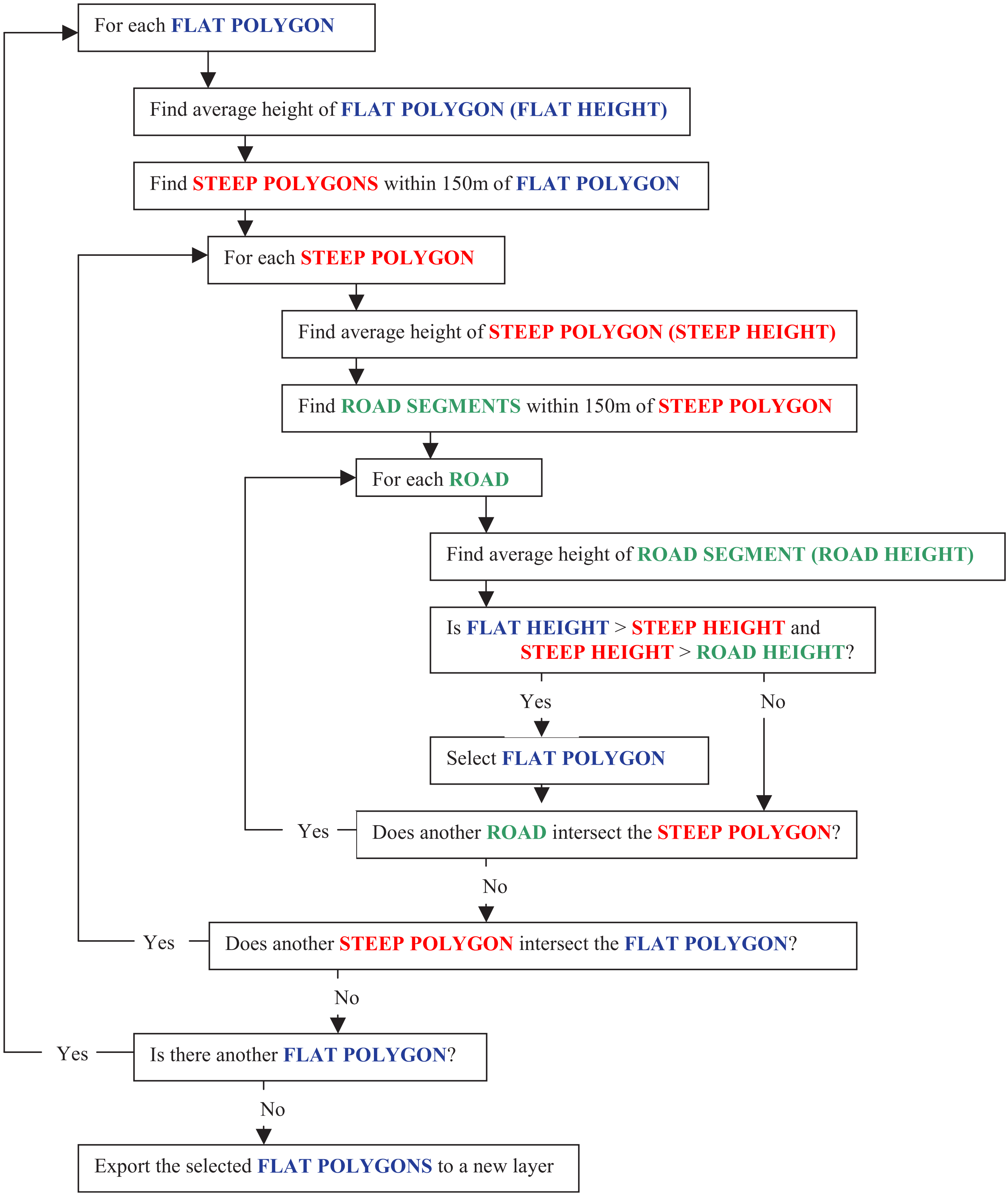
Table A.3 – Criteria used to interpret BGS ROCK_D codes to indicate hydrogeological influence upon debris flow formation.

Score	**Criteria**
10	• Formations including superficial and bedrock deposits of silts and clays with little permeability due to their fine particle size and bedrock formations of gneissic or plutonic formations whose low porosity and very widely spaced discontinuity spacing results in a low permeability.
9	• These formations comprise metamorphic rocks expected to have very low porosity and widely spaced, tight discontinuity spacing.
8	• These formations comprise fine-grained metamorphic rocks (pelite), uniform sandstone (quartzite) and mixed sequences of mudstone/siltstone/sandstone that might be expected to have slightly more discontinuities than the previous class.
7	• These formations comprise sandstone, minor igneous intrusions (i.e. not plutonic), limestone, conglomerate and lava which are likely to have moderately spaced discontinuities that might be expected to form a three dimensional pattern rather than a planar one and thus promote downward drainage.
6	• These comprise clay or silt rich superficial deposits that may have a small under drainage capacity if they contain discrete units of coarse material and a small number of lithologies with properties that are not easily predicted such as landslip, fault crush and worked ground.
5	• No materials are assigned to this score.
4	• No materials are assigned to this score.
3	• No materials are assigned to this score.
2	• No materials are assigned to this score.
1	• These materials are superficial deposits that are or may be expected to contain significant amounts of sand and/or gravel that would allow some under drainage of overlying material.
0.1	• These are superficial deposits that comprise primarily sand and gravel which would offer significant under drainage possibly to the extent that the passage of a debris flow on low slope angles could be slowed and pore water from antecedent rainfall might be dissipated relatively quickly.

Table A.4 – Criteria used to interpret CEH Landcover rating for debris flow hazard potential.

Score	Landcover 2000 Level 1	Landcover 2000 Level 2	Landcover 2000 Level 3	CEH Code	Comments
1	Sea/estuary	Sea/estuary	Sea, estuary	22.1	Not applicable - effect neutral
1	Water (inland)	Water (inland)	Water (inland)	13.1	Not applicable - effect neutral
1	Littoral rock and sediment	Littoral rock	Rock and rock with algae	20.1	Bare coastal slope may promote debris flows otherwise not
1		Littoral sediment	Mud, sand and sand with algae	21.1	Not applicable - effect neutral
1		Saltmarsh	Saltmarsh (Grazed/ungrazed)	21.2	Not applicable - effect neutral
1	Supra-littoral rock and sediment	Supra-littoral rock	Rock	18.1	Bare coastal slope may promote debris flows otherwise not
1		Supra littoral sediment	Shingle, vegetated shingle, dune, dune scrub	19.1	Bare coastal slope may promote debris flows otherwise not
1	Bog	Bog	Bog: shrub, grass/shrub, grass/herb Peat >0.5 m.	12.1	Not applicable separate assessment
0.85	Dwarf shrub heath	Dwarf shrub heath	Dwarf shrub heath (ericaceous/gorse) Peat <0.5 m thick	10.1	Some reinforcement by shrubs, better than grass.
0.9		Open shrub heath	Open shrub heath (ericaceous/gorse)	10.2	Some reinforcement by shrubs, better than grass.
0.9	Montane habitats	Montane habitats	Montane vegetation	15.1	Mixed, reinforcement depends on vegetation type - better than
0.7	Broad-leaved/mixed woodland	Broad-leaved/mixed woodland	Scrub, open birch and deciduous mixed, broadleaved	1.1	Good stabilising effect through root reinforcement and soil
0.7	Coniferous woodland	Coniferous woodland	Conifers, new plantation and felled	2.1	Good stabilising effect through root reinforcement and soil
1.2	Arable and horticulture	Cereals	Barley, maize, oats % wheat	4.1	Bare ground - no root strengthening, loose condition
1.2		Arable horticulture	Bare, root crops, cropped legumes, linseed, rape, mustard,	4.2	Bare ground - no root strengthening, loose condition
0.9		Non rotational horticulture	Orchard, ley, set aside	4.3	Mixed, orchards 0.75 but ley and set aside 0.9. Will be mostly ley
0.95	Improved grassland	Improved grassland	Intensive grazing, hay/silage cut, grazing marsh	5.1	Slight reinforcement - better than bare ground.
0.9		Setaside grass	Grass set aside	5.2	Some reinforcement - better than bare ground.
0.9	Neutral grassland	Rough grass	Rough grass	6.1	Some reinforcement - better than bare ground.
0.9		Managed neutral grass	Grass (neutral/improved)	6.2	Some reinforcement - better than bare ground.
0.9	Calcareous grassland	Calcareous grass	Calcareous (managed, rough)	7.1	Some reinforcement - better than bare ground.
0.9	Acid grassland	Acid grass	Acid	8.1	Some reinforcement - better than bare ground.
0.9			Acid with *Juncus*	8.1	Some reinforcement - better than bare ground.
0.9			Acid *Nardus*/*Festuca*/*Molinia*	8.1	Some reinforcement - better than bare ground.
0.85	Bracken	Bracken	Bracken	9.1	Stoloniferous roots reinforce ground.
1	Fen, marsh, swamp	Fen, marsh, swamp	Swamp, fen/marsh, fen willow	11.1	Not applicable separate assessment
1.1	Built up areas, gardens	Suburban/rural developed	Suburban/rural developed	17.1	General infiltration impeded but potential for focused drainage
1.1		Continuous Urban	Urban residential/commercial	17.2	General infiltration impeded but potential for focused drainage
1.1	Inland bare ground	Inland bare ground	Despoiled/semi-natural	16.1	Bare ground - no root strengthening

Table A.5 – Algorithm for generation of flat areas above roads



Key

- **FLAT AREAS**: Areas with slopes less than 2 degrees. Intersected by catchments and roads. Clipped by a 3km buffer of the roads.
- **STEEP AREAS**: Areas with slopes greater than 5 degrees. Intersected by catchments and roads. Clipped by a 3km buffer of the roads.
- **ROADS**: Trunk roads only

Table A.6 – Criteria used to assess slope angle as part of debris flow hazard assessment.

Score	Slope Angle (degrees)	
0.5	0-7	Generally stable and only influencing the run-out characteristics of a debris flow.
1	8 - 15	Slopes within this range that occurred between a road and an area of debris flow hazard were likely to maintain the movement of the debris flow and facilitate its impact on the road although it was unlikely to be sufficiently steep to allow the initiation of a debris flow within it.
6	16 - 30	It appears that debris flows may be initiated on slopes within this range but it would be equally likely that additional material would be incorporated within this zone.
9	31 – 45	This slope range is considered the most likely to initiate debris flows based on the experience of the working group. This would appear to be sensible in that the peak angle of shearing resistance of dry granular material might be expected to be in this range (BS8002:1994).
10	Slope > 45	It is logical that slopes in the >45^0 class should have a factor or weighting greater than the 31- 45 class in recognition of the increased driving force associated with the increase in the down slope component of shear stress.

Table A.7 – Weightings for the assessed factors. Min, Max, Range and Mean values given before weighting.

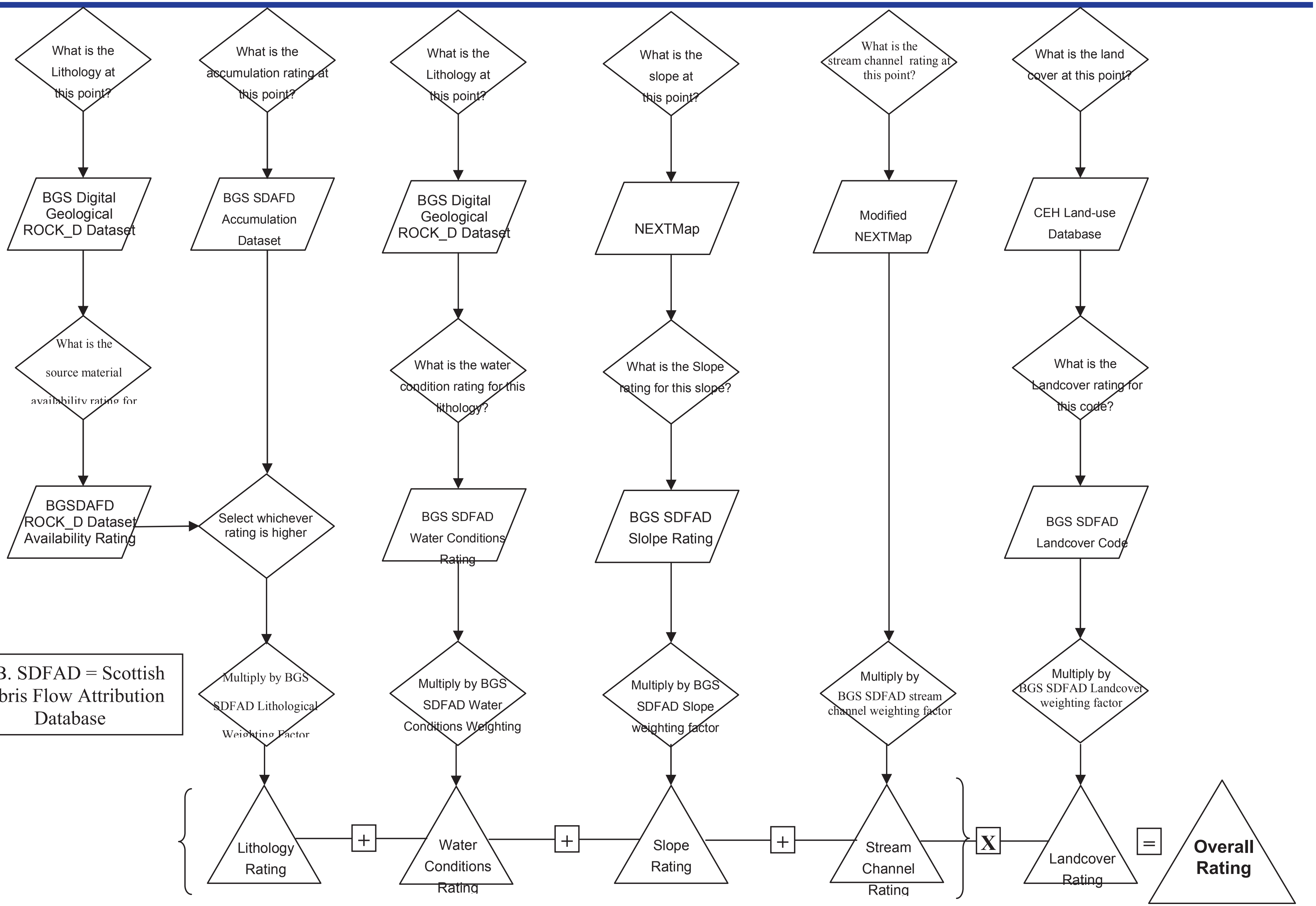
Factor	Weighting	Maximum Value	Minimum Value	Range	Mean
Lithology	x 1	10	1	9	6.68
Water conditions	x 1	10	0.1	9.9	4.33
Vegetation	x 0.75	1.2	0	1.2	0.92
Stream channel	x 0.75	10	0	10	0.88
Slope angle	x 1.25	10	0.1	9.9	2.08

Table A.8 – Class values for final data.

Class	Value
A	0-12.0
B	12.1-15.0
C	15.1-16.5
D	16.6-18.0
E	>18.1

Table A.9 – Shortened Field names for statistics calculated from the landslide data against the trunk road network.

Group of statistics calculated by road section	Number of points along section (only valid for trunk road network)	POINT_NO
	X-coordinate of start point of road section	START_X
	Y-coordinate of start point of road section	START_Y
	X-coordinate of end point of road section	END_X
	Y-coordinate of end point of road section	END_Y
	Length of section	S_LENGTH
	Highest point along section	S_HIGH
	Lowest point along section	S_LOW
	Average height along section	S_MEAN
Group of statistics calculated on catchments intersecting the road section. These are the areas that would be likely to yield material for a debris flow. (from intersection of NEXTMap DTM, NEXTMap slope model and catchments)	Number of catchments intersected	C_COUNT
	Total catchment area (m^2) intersected	C_AREA
	Highest point in catchment	C_HIGH
	Lowest point in catchment	C_LOW
	Average height in catchment	C_MEAN
	Maximum slope	C_MAX_SLOPE
	Minimum slope	C_MIN_SLOPE
	Average slope	C_AVE_SLOPE
Group of statistics calculated within the intersected catchments (from debris flow hazard grid and NEXTMap DTM)	Maximum debris flow hazard score	H_MAX
	Maximum debris flow hazard class	H_MAX_CLASS
	Minimum debris flow hazard score	H_MIN
	Minimum debris flow hazard class	H_MIN_CLASS
	Average debris flow hazard score	H_MEAN
	Average debris flow hazard class	H_MEAN_CLASS
Group of statistics calculated within the intersected catchments (from component hazard grids)	Maximum lithology score	H_LITH_MAX
	Minimum lithology score	H_LITH_MIN
	Average lithology score	H_LITH_MEAN
	Maximum water conditions score	H_WATER_MAX
	Minimum water conditions score	H_WATER_MIN
	Average water conditions score	H_WATER_MEAN
	Maximum vegetation score	H_VEG_MAX
	Minimum vegetation score	H_VEG_MIN
	Average vegetation score	H_VEG_MEAN
	Maximum stream channel score	H_STREAM_MAX
	Minimum stream channel score	H_STREAM_MIN
	Average stream channel score	H_STREAM_MEAN
	Maximum slope angle score	H_SLOPE_MAX
	Minimum slope angle score	H_SLOPE_MIN
	Average slope angle score	H_SLOPE_MEAN



N.B. SDFAD = Scottish Debris Flow Attribution Database

Figure A.1 - Methodology Flowchart.

APPENDIX B –GIS-BASED ASSESSMENT INTERPRETATION RESULTS

by M G Winter and F Macgregor

B.1 INITIAL INTERPRETATION

In this section the results of the initial interpretation of the GIS-based assessment is presented. This details sections of the trunk road network that were defined as candidates for Main Study, Opportunistic and Other (None) as described in Section 5.

‘Comments on Hazards’ were made as *aide memoire* to the authors for use during the process and were not intended to provide any kind of definitive statement regarding the hazards.

Table B.1 – Initial interpretation results.

Route Code	OC Unit	Start-NGR	End-NGR	Comments on Hazards	Section Length (m)		
					Other (None)	Oppor-tunistic	Main Study
A1-01	SE	NT 34092 70664	NT 36312 71134	Associated with flat, wet ground	2,290	-	-
A1-02	SE	NT 36582 71194	NT 40152 73634	Flat ground on top of hill to south of road	-	-	4,440
A1-03	SE	NT 51222 74684	NT 52102 74734	Associated with higher ground to north	-	-	-
A1-04	SE	NT 57352 76494	NT 59302 76664	Associated with higher ground to south and river valley to north	-	-	-
A1-05	SE	NT 68091 77354	NT 75751 73294	Lots of hazard areas associated with relatively well-incised stream beds up to 50m (over 2.5-3km) above road level	8,990	-	-
A1-06	SE	NT 79571 67434	NT 85681 62704	Hazards on high ground to south and, especially, to north	-	-	8,630
A1-07	SE	NT 87461 62554	NT 88870 62304	Associated with relatively flat ground to far side of river valley	1,460	-	-
A1-08	SE	NT 94330 61174	NT 97410 57054	Hazards above and below road	-	-	5,560
A6091-01	SE	NT 56812 34153	NT 54162 33943	Associated with distant far side of valley to north and minor issues with Eildon Hills to south	2,690	-	-
A68-01	SE	NT 37772 66853	NT 39162 64513	Hazards associated with hills/streams to west	-	-	-
A68-02	SE	NT 44662 60043	NT 45252 59473	Hazards associated with Fala Moor	-	-	821
A68-03	SE	NT 45762 59403	NT 46882 58863	Steep hillside/valley below road	-	-	-
A68-04	SE	NT 46982 58703	NT 47622 57493	Associated with flat, wet ground	1,370	-	-
A68-05	SE	NT 47722 57303	NT 48202 55263	Steep hillside/valley below road	-	-	-
A68-06	SE	NT 51102 52293	NT 53652 47083	Hazards associated with streams in hills to east more likely to affect local road A697 and Lauder	6,050	-	-
A68-07	SE	NT 55452 43913	NT 57172 37943	Hazards either side of road must either rise to reach road or take very convoluted route(s)	6,680	-	-
A68-08	SE	NT 57172 37943	NT 57802 33753	Hazards either other side of valley (road 35m above river) or associated with flat ground	4,330	-	-
A68-09	SE	NT 59182 30703	NT 63472 24533	Hazards associated with relatively flat, wet ground	1,920	-	-
A68-10	SE	NT 62432 26413	NT 63472 24533	Hazards associated with low-lying rivers	2,360	-	-
A68-11	SE	NT 65672 21333	NT 66302 15483	Associated with river bed road	6,800	-	-
A68-12	SE	NT 67581 14083	NT 68261 12323	Associated with hazards on steep-sided river valleys either side of road	-	-	1,960
A68-13	SE	NT 68531 10723	NT 68691 09563	Associated with hazard on hill to west of road	-	-	1,190
A7-01	SE	NT 48882 32523	NT 48142 31013	Associated with hill to east of road	-	-	1,840
A7-02	SE	NT 47852 27103	NT 47512 23403	Associated with low hills to either side and closer to road	-	-	-
A7-03	SE	NT 47292 21753	NT 50732 15783	Strongly identified hazards associated relatively flat ground, mainly to west of road	-	-	-
A7-04	SE	NT 47402 12702	NT 46642 11812	Associated with hill to far side of river	1,190	-	-
A7-05	SE	NT 46492 11652	NT 44922 10092	Associated with hills to west of road	-	-	2,350
A7-06	SE	NT 40762 02692	NY 38842 96252	Associated with hills either side of road and also closer to the road	-	-	7,160
A7-07	SE	NY 38842 96252	NY 36812 90032	Associated with hills either side of road	-	-	6,690
A7-08	SE	NY 37152 80982	NY 38332 78042	Associated with flat area above hill to west of road	-	-	3,280

Table B.1 (Continued) – Initial interpretation results.

Route Code	OC Unit	Start-NGR	End-NGR	Comments on Hazards	Section Length (m)		
					Other (None)	Oppor-tunistic	Main Study
A701-01	SW	NX 99222 79586	NX 99402 80916	Hazard associated with river below road and	1,340	-	-
A701-02	SW	NY 00702 86347	NY 02282 88317	Hazards associated with flat ground and behind	2,570	-	-
A701-03	SW	NY 03302 89297	NY 05742 91657	Hazards on hill above road to north (hazards to	-	-	3,440
A701-04	SW	NY 07282 95907	NY 08432 99387	Associated with flat, wet ground (see also M74-13)	3,690	-	-
A701-05	SW	NT 08402 01287	NT 08262 01987	Two roads and railway between hazard (low on hill) and trunk road	714	-	-
A702-01	SE	NT 24572 65238	NT 24402 64808	Small but significant area above Bogside	-	-	-
A702-02	SE	NT 21482 61128	NT 19312 59218	Hazards to west of road (associated with flat wet ground distant on far side of valley to east)	-	-	-
A702-03	SE	NT 19312 59218	NT 16362 56348	Associated with flat wet ground distant on far side	4,160	-	-
A702-04	SE	NT 16362 56348	NT 15942 55128	Associated with high stream valleys to north-west	-	-	-
A702-05	SE	NT 14752 51758	NT 13582 49938	Hazard above road to west - some associated	-	-	-
A702-06	SE	NT 13582 49938	NT 11342 47888	To east mainly associated with flat, wet ground	3,040	-	-
A702-07	SE	NT 09802 45888	NT 08902 44588	Hazards on hill to west of road	-	-	-
A702-08	SE	NT 04342 37898	NT 03732 37448	Associated with Biggar and river valley	777	-	-
A702-09	SE	NT 02522 35028	NT 01832 33537	Hazards associated with stream to south	-	-	-
A702-10	SE	NS 95492 28817	NS 94382 26887	Hazards associated with stream to south	-	-	-
A720-01	SE	NT 17507 72623	NT 18127 70973	Associated with flat, wet ground	1,800	-	-
A720-02	SE	NT 20297 68933	NT 24457 67833	Hazards associated with high ground to south (to north associated with development)	-	-	-
A720-03	SE	NT 25137 67463	NT 27257 66953	Associated with flat, wet ground	2,190	-	-
A720-04	SE	NT 27437 66933	NT 31797 68013	Associated with river valleys distant to north and	4,580	-	-
A725-01	SW	NS 69132 56584	NS 73342 62764	Associated with development	8,370	-	-
A726-01	SW	NS 52331 54029	NS 53401 54409	Associated with flat, wet ground	1,160	-	-
A726-02	SW	NS 53401 54409	NS 55931 53559	Hazards on low rolling hills to south of road	-	-	-
A737-01	SW	NS 46761 65360	NS 44121 64000	Associated with flat, wet ground	3,050	-	-
A737-02	SW	NS 42771 63780	NS 41021 62160	Associated with development in Johnstone	2,430	-	-
A737-03	SW	NS 40741 61580	NS 40121 60890	Small hazard area on hill above road, but with two road and the railway to cross before reaching trunk road	928	-	-
A737-04	SW	NS 38931 59990	NS 37371 58990	Hazard area on hill above road	-	-	-
A737-05	SW	NS 35971 56431	NS 35481 55171	Hazard area on hill above road	-	-	-
A737-06	SW	NS 34151 52731	NS 31881 50961	Associated with flat ground	2,990	-	-
A737-07	SW	NS 29371 47071	NS 29831 44361	Hazard on hill above road	-	-	-
A75-01	SW	NX 08743 60958	NX 09904 60428	Associated with flat, wet ground	1,280	-	-
A75-02	SW	NX 10904 59768	NX 14844 57557	Associated with flat, wet ground	4,620	-	-
A75-03	SW	NX 21104 57507	NX 31565 62335	Hazards on hills and on long, flat run-out zones closer to road	-	-	-
A75-04	SW	NX 32570 62890	NX 40260 64739	Associated with flat ground near to and further from road	8,370	-	-
A75-05	SW	NX 43180 65089	NX 45560 63139	Hazards low on slope above road	-	-	-
A75-06	SW	NX 47170 58239	NX 57161 54518	Hazards low and higher on hills above road	-	-	-
A75-07	SW	NX 60681 54428	NX 68191 55937	Hazards associated with rolling, but broadly flat	8,640	-	-
A75-08	SW	NX 68271 56027	NX 68881 57487	Hazards on hill above road	-	-	-
A75-09	SW	NX 69381 57917	NX 77261 64267	Hazards associated with rolling, but broadly flat ground and river	10,600	-	-
A75-10	SW	NX 77261 64267	NX 79531 68257	Hazards associated with rolling, but broadly flat ground	4,890	-	-
A75-11	SW	NX 83191 72797	NX 84181 73307	Associated with flat, wet ground	1,130	-	-
A75-12	SW	NX 89092 74667	NX 92542 75147	Associated with flat, wet ground and river	3,540	-	-
A75-13	SW	NX 98292 77986	NY 05782 74846	Associated with flat, wet ground and river	8,450	-	-
A75-14	SW	NY 07587 73106	NY 08587 72291	Source of hazard unlikely to direct towards trunk	1,290	-	-
A75-15	SW	NY 13742 69536	NY 15572 68626	Associated with flat, wet ground	2,050	-	-
A75-16	SW	NY 23902 66896	NY 27742 67026	Associated with flat, wet ground	3,860	-	-
A751-01	SW	NX 09034 62578	NX 09304 61438	Associated with flat, wet ground	1,230	-	-
A76-01	SW	NX 93222 82877	NX 92372 84077	Hazard on hill above road	-	-	-
A76-02	SW	NX 91432 85457	NX 91192 86797	Hazard on hill above road	-	-	-
A76-03	SW	NS 86172 00127	NS 85832 04117	Hazards below/close to road and low on hills above	-	-	-
A76-04	SW	NS 85832 04117	NS 81022 07857	Hazards above and below the road	-	-	6,570
A76-05	SW	NS 78932 09117	NS 77122 11008	Hazards above and below the road	-	-	2,650
A76-06	SW	NS 75922 11348	NS 75072 11558	Hazards above the road	-	-	-
A76-07	SW	NS 74482 11748	NS 73982 12058	Associated with flat, wet ground	588	-	-
A76-08	SW	NS 72052 12288	NS 67591 12988	Hazards on high ground to south of road, those to	-	-	-
A76-09	SW	NS 67591 12988	NS 62931 13078	Hazards on high ground to south of road	-	-	4,770
A76-10	SW	NS 61311 14598	NS 59921 15528	Associated with flat, wet ground	1,710	-	-

Table B.1 (Continued) – Initial interpretation results.

Route Code	OC Unit	Start-NGR	End-NGR	Comments on Hazards	Section Length (m)		
					Other (None)	Oppor-tunistic	Main Study
A76-11	SW	NS 58981 17198	NS 56981 18669	Hazards high on hill and beyond minor roads and	-	-	-
A76-12	SW	NS 54361 22419	NS 50251 26529	Associated with flat, wet ground	5,950	-	-
A76-13	SW	NS 50251 26529	NS 48921 29579	Associated with river meanders below road	3,400	-	-
A76-14	SW	NS 48841 29809	NS 48471 31399	Associated with river below road	1,630	-	-
A76-15	SW	NS 45971 35200	NS 44131 36500	Associated with flat, wet ground (see A77-02)	2,290	-	-
A77-01	SW	NS 45381 41850	NS 44831 39850	Associated with flat, wet ground	2,270	-	-
A77-02	SW	NS 44291 37160	NS 43561 34960	Associated with flat, wet ground (see A76-15)	2,330	-	-
A77-03	SW	NS 39991 32800	NS 39621 32260	Associated with flat, wet ground	655	-	-
A77-04	SW	NS 36851 28390	NS 37521 27620	Associated with river	1,030	-	-
A77-05	SW	NS 36631 23300	NS 35490 19280	Associated with ground in river valleys and behind	4,310	-	-
A77-06	SW	NS 32600 13320	NS 32240 12461	Hazard on hill above, may wish to extend to cover	-	-	-
A77-07	SW	NS 27355 08396	NS 24365 07576	Hazards close to road and higher on hills mainly	-	-	-
A77-08	SW	NS 22475 06587	NS 22115 06417	Associated with stream	420	-	-
A77-09	SW	NX 18475 96447	NX 09114 84888	Hazards close to road, below road and on hills	-	-	-
A77-10	SW	NX 09284 77378	NX 05214 72439	Hazards on hills above road	-	-	6,640
A77-11	SW	NX 05214 72439	NX 08694 63338	Hazards on hills above road	-	-	9,990
A78-01	SW	NS 23681 74832	NS 22951 74262	Associated with stream high on hill above road (and railway)	-	-	-
A78-02	SW	NS 19660 70562	NS 20120 60292	Hazards on hills high above road and occasionally closer to road	-	-	-
A78-03	SW	NS 20130 60142	NS 20810 58622	Hazards on steep hills to the other side of Largs	1,850	-	-
A78-04	SW	NS 21010 56092	NS 20710 53872	Hazards on hills above road	-	-	-
A78-05	SW	NS 20120 50532	NS 19790 48672	Area of flat ground below road	1,920	-	-
A78-06	SW	NS 25610 43671	NS 28170 42611	Hazards on hill above road - peat slide?	-	-	2,880
A78-07	SW	NS 32451 41461	NS 33241 39811	Associated with development in Irvine	1,850	-	-
A78-08	SW	NS 33071 36481	NS 33851 33621	Associated with flat ground	2,970	-	-
A78-09	SW	NS 33851 33621	NS 34991 31230	Slopes above reservoir (others mainly sloping away from the road)	-	-	-
A78-10	SW	NS 35591 28740	NS 36621 28710	Associated with flat ground	1,030	-	-
A8-01	SE	NS 75982 62159	NS 75322 62289	Associated with Eurocentral development	673	-	-
A8-02	SW	NS 40111 73020	NS 32621 74491	Associated with relatively flat ground and development in Port Glasgow	7,870	-	-
A80-01	SE	NS 78807 78539	NS 78597 77879	Associated with flat land	739	-	-
A80-02	SE	NS 73367 73409	NS 69317 69949	Associated with loch, rivers and flat ground below road	5,380	-	-
A82-01	NW	NH 63426 42643	NH 62456 41753	Hazards on hillside distant to north of road	1,320	-	-
A82-02	NW	NH 60696 39243	NH 57346 34993	Hazards above and (potentially) below the road	-	-	5,520
A82-03	NW	NH 56836 34253	NH 54586 31063	Hazards above and (potentially) below the road	-	-	3,970
A82-04	NW	NH 52391 30037	NH 50831 30172	Hazard high above road	-	-	1,590
A82-05	NW	NH 52566 28987	NH 49631 23632	Hazards above and (potentially) below the road	-	-	6,770
A82-06	NW	NH 49631 23632	NH 47481 21007	Hazards mainly at or about road level	-	-	-
A82-07	NW	NH 47461 21012	NH 46411 19822	Hazards above road and close to road	-	-	1,620
A82-08	NW	NH 45761 19182	NH 43486 16747	Hazards above road and close to road	-	-	3,410
A82-09	NW	NH 42981 16557	NH 42451 16667	Hazard high above road	-	-	581
A82-10	NW	NH 42411 16052	NH 40211 12102	Hazards above road and close to road	-	-	4,870
A82-11	NW	NH 40211 12102	NH 38591 10422	Some hazards high above road	-	-	-
A82-12	NW	NH 38381 10322	NH 37896 09252	Hazard high on hill to west of road	-	-	1,420
A82-13	NW	NH 37106 07022	NH 35476 05222	Hazards low on hill/flat ground	2,440	-	-
A82-14	NW	NH 34476 03812	NH 33836 03542	Hazards on hill to east - possibility of large scale	-	-	828
A82-15	NW	NH 33261 02912	NH 32901 02442	Hazard high on hill to west of road	-	-	600
A82-16	NW	NN 29996 98177	NN 28981 96572	Hazards high on hill to east and west of road,	-	-	1,960
A82-17	NW	NN 28766 96227	NN 21391 85632	Hazards high on hillside to east of road	-	-	13,400
A82-18	NW	NN 20921 85012	NN 22236 81747	Hazards on hill above road (to east/north),	-	-	-
A82-19	NW	NN 21021 81257	NN 19566 80562	Hazards high on hillside to east of road	-	-	-
A82-20	NW	NN 19536 80567	NN 15885 78337	Wet, relatively flat ground below road	4,310	-	-
A82-21	NW	NN 14330 77217	NN 10420 74202	Largely associated with flat ground	5,560	-	-
A82-22	NW	NN 06765 69682	NN 05115 67322	Relatively distant hazards with convoluted pathways or relatively low level hazards	-	-	-
A82-23	NW	NN 04505 66337	NN 03765 65377	Hazards high on hillside to east of road	-	-	1,260
A82-24	NW	NN 02295 63258	NN 02645 62728	Hazards high on hillside to east/north of road	-	-	688
A82-25	NW	NN 02720 61448	NN 05245 60872	Hazards on hillside to east/north of road	-	-	-
A82-26	NW	NN 05220 59568	NN 07550 58357	Hazards high on hillside to west/south of road	-	-	2,720
A82-27	NW	NN 10700 58212	NN 27671 52992	Hazards high on hills either side of road in	-	-	19,900
A82-28	NW	NN 30321 51011	NN 30821 46431	Picking flat/wet ground/water	5,130	-	-
A82-29	NW	NN 31141 43721	NN 29741 38561	Hazards on hillside to east of road	-	-	5,550
A82-30	NW	NN 30001 37751	NN 32261 34091	Hazards on hillside to south/west	-	-	-

Table B.1 (Continued) – Initial interpretation results.

Route Code	OC Unit	Start-NGR	End-NGR	Comments on Hazards	Section Length (m)		
					Other (None)	Oppor-tunistic	Main Study
A82-31	NW	NN 32251 34076	NN 32991 31481	Hazards on hillside to east	-	-	2,940
A82-32	NW	NN 34926 28821	NN 37246 26351	Hazards high on hills either side of the road	-	-	-
A82-33	NW	NN 37206 24191	NN 34126 21306	Hazards high on hills either side of the road	-	-	-
A82-34	NW	NN 33296 20776	NN 31776 09196	Hazards high on hills to west of the road	-	-	13,500
A82-35	NW	NN 32126 08806	NN 32966 05936	Relatively minor hazards on hills to west of road and close to road level	-	-	-
A82-36	NW	NN 31916 04456	NN 34026 00456	Hazards high on hills to west of the road	-	-	4,610
A82-37	NW	NN 34026 00456	NS 34556 97686	Hazards high on hills to west of the road	-	-	3,300
A82-38	NW	NS 34556 97686	NS 35196 87156	Hazards high on hills to west of the road	-	-	11,100
A82-39	SW	NS 38646 79206	NS 38621 78451	Elevated flat ground, considered relatively benign	755	-	-
A82-40	SW	NS 41586 74955	NS 46976 73045	Potential hazards on hillsides to east/north of road	-	-	-
A823M-	NE	NT 12517 84284	NT 11077 84719	Flat ground	1,510	-	-
A828-01	NW	NN 05175 59653	NM 99145 54983	Hazards high above the road	-	-	8,540
A828-02	NW	NM 97015 53528	NM 95755 52323	Hazards above road	-	-	-
A828-03	NW	NM 92495 47429	NM 96370 44903	Hazards above road	-	-	-
A828-04	NW	NM 96370 44903	NM 97685 44688	Hazard zone above road associated with minor, but steeply incised, stream	-	-	1,480
A828-05	NW	NM 96570 42418	NM 94985 41384	Hazards associated with the distant hills above the B845	2,080	-	-
A828-06	NW	NM 91560 40034	NM 90810 36694	Hazards on hills above road	-	-	-
A828-07	NW	NM 90930 36354	NM 91080 34664	Associated with flat land	1,710	-	-
A83-01	NW	NN 29616 05036	NN 28391 03881	Hazards high on hills including Beinn Narnain	-	-	1,760
A83-02	NW	NN 26901 03861	NN 23021 07837	Hazards high on hills to east (in Cobbler, Beinn	-	-	6,310
A83-03	NW	NN 23676 09287	NN 23421 09592	Hazards oblique to road	-	-	-
A83-04	NW	NN 23421 09592	NN 19096 09927	Hazards on hill above road	-	-	4,360
A83-05	NW	NN 18406 11247	NN 19406 12512	Hazards on hill above road	-	-	1,620
A83-06	NW	NN 19221 12717	NN 11260 08848	Hazards on hill above road	-	-	9,170
A83-07	NW	NN 11260 08848	NN 11395 10083	Known landslide area - generally translational and deeper-seated than debris flow	-	-	1,260
A83-08	NW	NN 11115 10288	NN 10540 09813	Hazards on hill close to road	-	-	-
A83-09	NW	NN 08690 07363	NN 05200 04603	Hazards on hill above road	-	-	-
A83-10	NW	NN 04495 04203	NN 02915 03179	Hazards on hill above road	-	-	1,910
A83-11	NW	NN 02405 01899	NN 02370 01329	Associated with flat, wet ground	578	-	-
A83-12	NW	NS 01725 99834	NR 98995 97649	Hazards on hill above road	-	-	3,550
A83-13	NW	NR 97710 96109	NR 94400 92425	Hazards on hill above road	-	-	-
A83-14	NW	NR 92385 91145	NR 91675 89355	Hazards on hill above road	-	-	-
A83-15	NW	NR 89920 85520	NR 86709 85931	Hazards on hill above road	-	-	-
A83-16	NW	NR 85339 86581	NR 85059 85051	Associated with development and Crinnan Canal	1,670	-	-
A83-17	NW	NR 85059 85051	NR 85099 81941	Hazards on hill above road	-	-	-
A83-18	NW	NR 84819 80506	NR 86284 74006	Hazards on hill above road	-	-	7,040
A83-19	NW	NR 86204 72311	NR 86079 71241	Hazards on hill above road	-	-	-
A83-20	NW	NR 86794 69696	NR 86529 69066	Hazards on hill above road	-	-	687
A83-21	NW	NR 86034 68451	NR 85284 68076	Hazards on hill above road	-	-	839
A83-22	NW	NR 84859 67791	NR 84319 66552	Hazards on hill above road	-	-	-
A830-01	NW	NN 11305 76787	NN 07775 77177	Would be opportunistic but for the development	3,740	-	-
A830-02	NW	NN 03215 78427	NM 96535 79328	Hazards to north of road	-	-	-
A830-03	NW	NM 96520 79313	NM 90855 80478	Hazards mainly to north, but occasionally to south	-	-	6,550
A830-04	NW	NM 90855 80478	NM 90205 80848	Hazards from valley to north of Glenfinnan	-	-	867
A830-05	NW	NM 90195 80853	NM 76679 82314	Hazards mainly to north, but occasionally to south	-	-	15,500
A830-06	NW	NM 76679 82314	NM 71574 84404	Hazards mainly to north, but occasionally to south	-	-	6,080
A830-07	NW	NM 71594 85114	NM 68999 84984	Hazards to north of road, particularly from Borrodale Burn	-	-	2,830
A830-08	NW	NM 68309 85069	NM 67364 86204	Hazard(s) to south of road/possibly away from	-	-	-
A830-09	NW	NM 65924 87309	NM 67014 90359	Hazards on very flat peat bog and hills above peat	-	-	-
A830-10	NW	NM 67519 93549	NM 67529 95558	Hazards close to road	-	-	-
A835-01	NW	NH 58485 52248	NH 55345 54918	Potential peat area to north	-	-	-
A835-02	NW	NH 50385 54878	NH 48615 54908	Steep slopes to north of road	-	-	1,780
A835-03	NW	NH 45870 55868	NH 45445 56608	Steep slope/river to loch	-	-	889
A835-04	NW	NH 43565 58802	NH 40650 59367	Steep slopes/rivers to lochs and hazards on hill	-	-	3,110
A835-05	NW	NH 40635 59407	NH 38875 62497	Hazards highlighted high on slopes to south of road and close to road	-	-	3,700
A835-06	NW	NH 40325 63937	NH 40344 69227	Hazards highlighted, mainly associated with	-	-	6,110
A835-07	NW	NH 38284 70387	NH 28554 73906	Hazards high on slopes mainly to south, but also	-	-	11,400
A835-08	NW	NH 27084 74686	NH 20223 78236	Hazards high on slopes to south and north of road	-	-	8,000
A835-09	NW	NH 19553 80586	NH 18168 85540	Hazards high on slopes to south/west and	-	-	5,320
A835-10	NW	NH 18163 85575	NH 13298 94065	Hazards high on slopes to north/east of road	-	-	10,400

Table B.1 (Continued) – Initial interpretation results.

Route Code	OC Unit	Start-NGR	End-NGR	Comments on Hazards	Section Length (m) Other (None)	Oppor-tunistic	Main Study
A84-01	NW	NN 57967 21610	NN 57642 21200	Close to road and associated with almost flat	523	-	-
A84-02	NW	NN 56102 15910	NN 56387 15220	Very close to the road	-	-	-
A84-03	NW	NN 57047 14530	NN 58487 13465	Hazards on hill to east of road	-	-	1,900
A84-04	NW	NN 58487 13465	NN 58637 10880	Hazards on hill to east of road	-	-	2,700
A84-05	NW	NN 58637 10880	NN 60537 08540	Hazards on hill to east of road	-	-	4,050
A84-06	NW	NN 60727 08425	NN 62777 07975	Hazards on hill above the road - largely urbanised close to road	2,190	-	-
A84-07	NW	NN 65037 06655	NN 72377 01745	Shallow slope up to hazard zones (see also A9-54)	-	-	-
A84-08	NW	NS 71872 98990	NS 77372 95409	Associated with flat, wet land	6,640	-	-
A85-01	NW	NO 02072 25790	NN 99552 24980	Below road, associated with relatively flat, wet road	2,670	-	-
A85-02	NW	NN 96792 24280	NN 94412 23740	Below road, associated with relatively flat, wet	2,450	-	-
A85-03	NW	NN 82522 22890	NN 81132 22590	Hazards above road	-	-	-
A85-04	NW	NN 80042 22810	NN 77762 22310	Hazards above road	-	-	-
A85-05	NW	NN 76017 22030	NN 73997 23080	Hazards on Ben Halton, route to road is highly	2,570	-	-
A85-06	NW	NN 72247 23400	NN 69957 24180	Hazards on hills to either side of road	-	-	-
A85-07	NW	NN 69657 24050	NN 59937 23870	Hazards on hills - extended on 'precautionary principle' lines to some degree	-	-	-
A85-08	NW	NN 58437 24970	NN 55677 29396	Hazards on hill to east of the road - Glen Ogle	-	-	5,480
A85-09	NW	NN 50672 28326	NN 38766 25266	Hazards on hills mainly to south of road, but some to north should be checked (very distant from road)	-	-	12,900
A85-10	NW	NN 32426 30696	NN 31541 31196	Hazards on hill to south (less so to the north)	-	-	-
A85-11	NW	NN 31551 31216	NN 30461 31731	Lochan intervenes to south, apparently minor	1,210	-	-
A85-12	NW	NN 30461 31731	NN 22586 27147	Hazards on hills to north and south	-	-	9,590
A85-13	NW	NN 19646 27552	NN 17336 27352	Hazards on hills to north	-	-	2,360
A85-14	NW	NN 14216 27772	NN 13586 28342	Associated with flat, wet ground	850	-	-
A85-15	NW	NN 13191 28352	NN 03135 29863	Hazards on hills, mainly to north but possibly to	-	-	12,400
A85-16	NW	NM 97280 32389	NM 93710 34709	Minor hazards, mainly at road level and/or on relatively flat ground	4,580	-	-
A85-17	NW	NM 92050 34189	NM 91120 34369	Associated with flat, wet ground	975	-	-
A85-18	NW	NM 89565 33854	NM 87325 32585	Hazards at road level	2,860	-	-
A86-01	NW	NH 74802 00442	NN 70462 98457	Hazards remote and with convoluted routes to	4,980	-	-
A86-02	NW	NN 69702 97757	NN 67497 95832	Lower grade hazards on hill side to north of road	-	-	-
A86-03	NW	NN 67317 95722	NN 67162 95417	Hazard in stream bed to north of road	-	-	357
A86-04	NW	NN 65241 94627	NN 61511 94377	Hazards on hills to north of road	-	-	-
A86-05	NW	NN 61351 93662	NN 60561 93617	Hazard zone close to the road on hill to south	-	-	-
A86-06	NW	NN 58916 91842	NN 58341 90957	Minor' hazards distant from road on other side of the valley	1,150	-	-
A86-07	NW	NN 55996 90417	NN 55356 89707	Hazards high on slopes to north of road	-	-	987
A86-08	NW	NN 54331 89767	NN 52936 89547	Hazards high on slopes to north of road	-	-	1,520
A86-09	NW	NN 48856 87552	NN 47661 86407	Hazards converging on Aberardour from north-east, north-west west. Survey effort likely to be greater than road length implies	-	-	1,730
A86-10	NW	NN 47516 86247	NN 37536 81267	Multiple hazards high on hills to north of road. At	-	-	11,600
A86-11	NW	NN 33266 80957	NN 27646 81067	Hazards on slopes above road	-	-	6,180
A86-12	NW	NN 25591 81307	NN 22966 81947	Known debris flow area, relatively little picked up by GIS. Possibly due to model being unable to resolve multiple small streams on the hillside	-	-	2,770
A87-01	NW	NH 27390 02537	NH 26630 02737	Hazard on hill to north of road	-	-	-
A87-02	NW	NH 22910 02827	NH 21820 02857	Hazard on hill to north of road	-	-	-
A87-03	NW	NH 20770 03107	NH 19850 03587	Hazards highlighted close to road	1,180	-	-
A87-04	NW	NH 19080 05367	NH 20600 07847	Hazard on hill to east/north of road	-	-	-
A87-05	NW	NH 20810 08272	NH 21480 09512	Relatively flat ground	1,500	-	-
A87-06	NW	NH 20680 09972	NH 19000 10072	Relatively flat ground	1,750	-	-
A87-07	NW	NH 18930 10072	NH 14330 09991	Hazards on hills to north of road	-	-	5,070
A87-08	NW	NH 14330 09991	NH 11495 10731	Hazards on hills to north of road	-	-	3,100
A87-09	NW	NH 11495 10731	NH 09725 11731	Hazards on hills to north of road	-	-	2,080
A87-10	NW	NH 09725 11731	NH 06790 11496	Hazards on hills to north of road	-	-	3,270
A87-11	NW	NH 06790 11496	NH 03370 12016	Hazards on hills to north and south of road	-	-	3,670
A87-12	NW	NH 03370 12016	NG 96289 14946	Hazards on hills to north and south of road	-	-	8,620
A87-13	NW	NG 96259 14951	NG 94614 17946	Hazards on hills to south of road	-	-	3,790
A87-14	NW	NG 93894 18781	NG 94539 20406	Hazards on hills to north/east of road	-	-	2,490
A87-15	NW	NG 94469 21121	NG 88269 26106	Hazards on hills to north/east of road	-	-	8,650

Table B.1 (Continued) – Initial interpretation results.

Route Code	OC Unit	Start-NGR	End-NGR	Comments on Hazards	Section Length (m)		
					Other (None)	Oppor-tunistic	Main Study
A87-16	NW	NG 87279 27306	NG 81529 27146	Hazards on hills to north/east of road	-	-	-
A87-17	NW	NG 78464 27176	NG 76869 27196	Hazards on hills to north/east of road	-	-	-
A87-18	NW	NG 70229 24681	NG 64079 23582	Hazards on hills to south of road	-	-	-
A87-19	NW	NG 64039 23632	NG 48718 29902	Hazards on hills to west of road	-	-	26,100
A87-20	NW	NG 47808 31921	NG 47428 41300	Hazards on hills to east and west of road	-	-	10,000
A87-21	NW	NG 47238 44210	NG 46858 45750	Relatively flat ground	1,590	-	-
A87-22	NW	NG 46818 45880	NG 42318 50959	Hazards on hills to north/east of road	-	-	7,050
A87-23	NW	NG 41928 52009	NG 39948 56709	Hazards on hills to north/east of road	-	-	-
A87-24	NW	NG 39057 59388	NG 39367 64097	Hazards on hills to east of road	-	-	5,460
A876-01	SE	NS 92137 86939	NS 90502 85829	Flat ground	1,999	-	-
A887-01	NW	NH 42031 16827	NH 35170 15427	Hazards on hills mainly to north of road	-	-	8,150
A887-02	NW	NH 32540 14347	NH 32030 14177	Hazard on hill to north of road	-	-	540
A887-03	NW	NH 29500 12297	NH 22830 10597	Hazards on hills to south of road	-	-	7,170
A889-01	NW	NN 63672 85732	NN 63592 87222	Hazards high on hill to west of road, albeit with a	-	-	-
A889-02	NW	NN 63612 87272	NN 63501 91802	Potential peat slides, with additional triggers from higher hills in some cases	-	-	-
A889-03	NW	NN 62721 93022	NN 61501 93712	Hazards high on hill to west of road	-	-	-
A9-01	NW	ND 12099 66142	ND 12979 64672	Presumed area of peat, very flat	-	-	-
A9-02	NW	ND 13454 63922	ND 13954 63182	Distant and shallow slope between source and road, possible peat	-	-	-
A9-03	NW	ND 14074 63082	ND 14464 62502	Distant and shallow slope between source and	-	-	-
A9-04	NW	ND 15618 60147	ND 15611 59323	Northerly fork, more or less follows local	-	-	-
A9-05	NW	ND 16875 54022	ND 16930 51167	Source distant from and sliding away from trunk road	2,860	-	-
A9-06	NW	ND 16930 51167	ND 17630 47546	Source potentially sliding away from trunk road	3,990	-	-
A9-07	NW	ND 17630 47546	ND 18435 38856	Potential sliding above and below road	-	-	8,880
A9-08	NW	ND 19930 33576	ND 19860 33511	Not considered significant	-	-	-
A9-09	NW	ND 15325 29325	ND 13145 25995	Possible sliding above road, flat areas (possible peat) above steep slopes.	-	-	4,350
A9-10	NW	ND 12010 23055	ND 11670 22435	Is the road sufficiently high relative to the burn(s)	-	-	1,110
A9-11	NW	ND 08775 20794	ND 02860 15349	Steep slopes, streams and high hazards above	-	-	11,200
A9-12	NW	ND 02175 14804	NC 93895 09663	Steep slopes, streams and high hazards above road	-	-	10,200
A9-13	NW	NC 91505 06703	NC 90525 04472	Hazards either on flat ground with hill partially	2,690	-	-
A9-14	NW	NC 86535 01442	NC 83355 00092	Road and burn (which could lead debris to road) both well-protected by current forestry	-	-	-
A9-15	NW	NH 79255 98716	NH 77810 98351	Possible hazard below power lines, other hazards related to rock slopes or flat ground on hill with no realistic route to trunk road	-	-	-
A9-16	NW	NH 77680 94421	NH 78050 93731	Hazard likely in forestry and road protected by further current forestry	794	-	-
A9-17	NW	NH 75480 89756	NH 74925 89191	Hazard at edge of/in forestry - likely to affect local road if anything	819	-	-
A9-18	NW	NH 76505 83865	NH 77100 82615	Hazard in forestry (possibly forestry between hazard and road), road well-protected by current forestry	1,410	-	-
A9-19	NW	NH 79590 78520	NH 77985 76140	Shallow slopes, with potentially protecting forestry	-	-	-
A9-20	NW	NH 72170 71805	NH 66475 68999	Shallow slopes, road well-protected. Hazards	6,470	-	-
A9-21	NW	NH 60445 54178	NH 60245 52498	Relatively shallow slopes, where slope is towards the trunk road a preferential (steeper) path approximately towards the roundabout exists	-	-	-
A9-22	NW	NH 72401 39864	NH 71901 38349	Below road at north end and possible cutting/natural slope problem to south	-	-	1,660
A9-23	NW	NH 71831 38009	NH 71926 36963	Possible incursion at north end, southerly hazard appears to run away from road	-	-	-
A9-24	NW	NH 72341 35783	NH 75841 34579	Potential hazard either side of road	-	-	4,040
A9-25	NW	NH 77636 33479	NH 78406 32544	Flat ground in valley bottom picked up	1,230	-	-
A9-26	NW	NH 79446 31549	NH 79896 29814	At north, distant, long runout and will impact	-	-	-
A9-27	NW	NH 82171 26569	NH 87652 24074	Potential hazard either side of road, including from	-	-	6,660
A9-28	NW	NH 90932 19984	NH 91077 18858	Potential hazard lower than road and railway	1,140	-	-
A9-29	NW	NH 90942 18043	NH 90432 16903	Potential hazard to west of road, parallel forest	-	-	1,290
A9-30	NW	NH 89357 13978	NH 84707 07948	Potential hazard to west of road, also to be	-	-	8,550

Table B.1 (Continued) – Initial interpretation results.

Route Code	OC Unit	Start-NGR	End-NGR	Comments on Hazards	Section Length (m)		
					Other (None)	Oppor-tunistic	Main Study
A9-31	NW	NH 84077 07068	NH 83582 06708	Flat ground in valley bottom picked up	613	-	-
A9-32	NW	NH 82847 05923	NH 76697 01277	Various hazards to west of road, mainly on	-	-	-
A9-33	NW	NN 75712 99377	NN 69222 95207	Various hazards to east of road, mainly on	-	-	-
A9-34	NW	NN 68007 91922	NN 67812 90722	Potential hazards either side of the road, broadly focussed on stream channels	-	-	1,260
A9-35a	NW	NN 63982 83957	NN 64987 73046	Potential hazards to east of road	-	-	11,900
A9-35b	NW	NN 66562 72101	NN 69762 71546	Potential hazards to east of road	-	-	3,310
A9-36	NW	NN 71347 70751	NN 73477 70261	Potential hazards to east of road	-	-	-
A9-37	NW	NN 76882 68936	NN 77237 68286	Potential hazards to east of road, especially at	-	-	761
A9-38	NW	NN 78702 66861	NN 82462 65831	Minor potential hazards in north, road well-protected from Falls of Bruar	4,080	-	-
A9-39	NW	NN 87887 64441	NN 88877 64291	Picking up Shierglas Quarry	1,010	-	-
A9-40	NW	NN 91592 60991	NN 91612 60786	Possibly picking up flat ground below road,	-	-	-
A9-41	NW	NN 93307 57561	NN 93802 57496	Flat ground in valley bottom picked up (possibly	504	-	-
A9-42	NW	NN 95622 56541	NN 97602 53981	Potential hazards separated from road by long	3,240	-	-
A9-43	NW	NN 99127 50551	NN 99522 49631	Potential hazards to east of road, some possibly	-	-	-
A9-44	NW	NO 00212 47141	NO 00472 43871	Potential hazards to east of road, as is the old A9	-	-	3,320
A9-45	NW	NO 03452 41486	NO 04062 40886	Potential hazards to west of road	-	-	877
A9-46	NW	NO 06917 36595	NO 07127 35615	Wet, flat/sloping away from road ground	-	-	1,010
A9-47	NW	NO 09247 27975	NO 09707 26245	Picking up flat ground both adjacent to road and other side of River Almond	1,810	-	-
A9-48	NW	NO 03237 19070	NO 02157 18030	Below road, considered relatively benign	1,510	-	-
A9-49	NW	NO 00547 17590	NN 99737 16930	On crest of gentle, undulating slope 2km+ form	1,050	-	-
A9-50	NW	NN 98367 15840	NN 94822 12320	Multiple potential hazards to south of road, mainly distal and with other roads/railway between hazards and A9	-	-	-
A9-51	NW	NN 92652 10440	NN 92332 09820	Picking up flat, wet areas on golf course	724	-	-
A9-52	NW	NN 89722 08660	NN 88732 08510	Steep -sided gully, but descent is relatively gentle	-	-	-
A9-53	NW	NN 88252 08560	NN 85552 08150	Picking up flat, wet areas above railway but below road	2,790	-	-
A9-54	NW	NN 78422 02709	NN 76902 01729	Shallow slope up to hazard zones (see also A84-07)	-	-	-
A90-01	NW	NO 13597 22455	NO 14982 22355	Potential hazards from Kinnoull Hill, flat ground to	-	-	1,410
A90-02	NE	NO 15007 22340	NO 21547 23330	Flat ground	7,810	-	-
A90-03	NE	NO 23562 25200	NO 33057 30525	Flat ground	11,300	-	-
A90-04	NE	NO 42022 37811	NO 41917 38426	Flat ground/residential	625	-	-
A90-05	NE	NO 42077 39351	NO 42367 40011	Flat ground/residential and river running away from road	721	-	-
A90-06	NE	NO 71881 70787	NO 74611 75017	Potential hazards form hills to east of road (flat ground to west)	-	-	-
A90-07	NE	NO 78061 79477	NO 80980 81247	Relatively flat ground, picking up river beds	3,520	-	-
A90-08	NE	NO 81690 81677	NO 81950 81807	Relatively benign to trunk road	291	-	-
A90-09	NE	NO 83680 82677	NO 86080 84467	Picking up river parallel to road, relatively flat ground	3,080	-	-
A90-10	NE	NO 85710 85507	NO 86760 87262	Picking up rivers below road and flat ground	2,580	-	-
A90-11	NE	NO 86910 87252	NO 90260 93212	Extensive local road network and other	-	-	-
A90-12	NE	NO 90760 94052	NO 93050 99972	Relatively flat ground. Cliffs and flat spots picked up below road	6,750	-	-
A90-13	NE	NJ 93190 01052	NJ 93030 01562	Relatively flat ground	535	-	-
A90-14	NE	NJ 92990 03502	NJ 91300 09143	Various effects caused by residential and other development	6,860	-	-
A90-15	NE	NJ 94659 12323	NJ 97219 22503	Relatively flat ground	10,700	-	-
A90-16	NE	NJ 97259 23803	NJ 96899 28883	Relatively flat ground	5,450	-	-
A90-17	NE	NJ 97079 29623	NJ 98184 31313	Possible hazards associated with valley sides,	-	-	-
A90-18	NE	NJ 98794 31943	NJ 99164 32278	Stream below road	499	-	-
A90-19	NE	NK 02634 35093	NK 10483 39402	Relatively flat ground	9,220	-	-
A90-20	NE	NK 10493 39412	NK 12753 42282	Narrow corridor, relatively step ground above and	-	-	-
A90-21	NE	NK 10978 48202	NK 10518 48732	Area associated with river to west and below road	722	-	-
A90-22	NE	NK 10498 50972	NK 00409 59423	Relatively flat ground	13,700	-	-
A90-23	NE	NK 00219 59588	NJ 99879 60598	Potential source on lower part of hill which is	-	-	-
A90-24	NE	NJ 99934 62074	NJ 99894 63204	Flat ground	1,230	-	-
A92-01	NE	NT 14162 89194	NT 18002 91884	Flat ground	4,740	-	-
A92-02	NE	NT 22412 93844	NT 27262 95194	Flat ground	5,060	-	-
A92-03	NE	NO 28542 03324	NO 28462 05175	Flat ground	870	-	-
A92-04	NE	NO 29322 08575	NO 29642 09625	Flat ground	1,100	-	-
A92-05	NE	NO 30612 13085	NO 31272 14405	Flat ground	1,480	-	-

Table B.1 (Continued) – Initial interpretation results.

Route Code	OC Unit	Start-NGR	End-NGR	Comments on Hazards	Section Length (m)		
					Other (None)	Oppor-tunistic	Main Study
A92-06	NE	NO 31412 14605	NO 32362 17485	Potential hazards, mainly to east of road	-	-	-
A92-07	NE	NO 33032 17890	NO 34932 20015	Relatively flat ground	3,050	-	-
A92-08	NE	NO 36512 21005	NO 37062 21355	Potential hazard form north side of Darklaw Hill	-	-	-
A92-09	NE	NO 39292 22355	NO 39952 22785	Potential hazard from hill to north of road	-	-	-
A92-10	NE	NO 41142 24205	NO 41892 24765	Flat ground	943	-	-
A92-11	NE	NO 42552 26635	NO 42522 27125	Flat ground	486	-	-
A92-12	NE	NO 42587 27990	NO 42452 28740	Bridge approach cutting and sloping ground below bridge	842	-	-
A92-13	NE	NO 41747 30771	NO 40737 30326	Flat ground/developed	1,150	-	-
A95-01	NE	NJ 41836 51081	NJ 41516 50936	Flat ground	353	-	-
A95-02	NE	NJ 40071 50151	NJ 35271 50661	Potential hazards on steep slopes to south of road	-	-	-
A95-03	NE	NJ 34666 50181	NJ 33431 47576	Potential hazards on steep slopes to south of road	-	-	-
A95-04	NE	NJ 33336 47211	NJ 31727 45906	Potential hazards on steep slopes to south of road	-	-	2,210
A95-05	NE	NJ 30452 44976	NJ 29417 44886	Not highlighted by GIS, but sufficient external	-	-	1,230
A95-06	NE	NJ 28567 44776	NJ 28117 43931	Potential hazard(s) apparently within/close to top	-	-	1,020
A95-07	NE	NJ 24857 41160	NJ 24532 40610	Flat ground with only shallow slope to road	639	-	-
A95-08	NE	NJ 14757 34755	NJ 10537 32135	Significant hazards on steep slopes to south of road	-	-	5,880
A95-09	NE	NJ 08337 29844	NJ 06512 27039	Significant hazards on steep slopes to south of road	-	-	3,480
A95-10	NE	NJ 04257 26229	NJ 03597 26304	Flat ground	741	-	-
A95-11	NE	NJ 00017 24534	NH 99882 24094	Flat ground	460	-	-
A95-12	NE	NH 98102 22534	NH 97182 22489	Flat ground, hazard possibly caused by presence	934	-	-
A96-01	NE	NJ 87955 10718	NJ 87575 10978	Flat ground	461	-	-
A96-02	NE	NJ 86585 11248	NJ 83085 12268	Steep ground to north of road	-	-	-
A96-03	NE	NJ 83070 12273	NJ 81600 12603	Flat, wet ground	1,510	-	-
A96-04	NE	NJ 80205 13263	NJ 78345 15698	Relatively flat ground	3,170	-	-
A96-05	NE	NJ 74341 23334	NJ 74136 23604	Flat ground	339	-	-
A96-06	NE	NJ 74116 23634	NJ 73901 24254	Potential sources high on hill above burn	-	-	-
A96-07	NE	NJ 73666 25194	NJ 69301 25699	Steep ground south of road and potential sources	-	-	-
A96-08	NE	NJ 68256 27139	NJ 65351 29854	Potential sources on hills to south of road, also on less steep hills to north of road (albeit with river nearer to road)	-	-	-
A96-09	NE	NJ 64886 30595	NJ 64251 32035	Relatively flat ground	1,600	-	-
A96-10	NE	NJ 64336 33985	NJ 64196 34300	Potential hazard other side of river valley to road and at or below road level	345	-	-
A96-11	NE	NJ 61926 34570	NJ 59281 34705	Potential sources high on hill top south of road	-	-	-
A96-12	NE	NJ 55366 38130	NJ 54251 39135	Relatively flat ground, sloping slightly away from road	1,580	-	-
A96-13	NE	NJ 50746 41300	NJ 49186 43240	Potential sources high on hill to north	-	-	-
A96-14	NE	NJ 48346 44611	NJ 47906 45106	Potential sources for slippage into river	-	-	-
A96-15	NE	NJ 44101 49041	NJ 43376 49706	Steep hill side to south of road	-	-	-
A96-16	NE	NJ 40966 51606	NJ 37971 55461	Some indications that there may be potential for	-	-	-
A96-17	NE	NJ 37971 55461	NJ 35196 57876	Potential in one of the burns, hillside to north currently forested	-	-	-
A96-18	NE	NJ 29111 61106	NJ 26451 61336	Flat, wet ground at either end (possible picked up loch at east end)	2,740	-	-
A96-19	NE	NJ 22991 62646	NJ 22771 62686	Flat ground	224	-	-
A96-20	NE	NJ 17191 62996	NJ 09841 60986	Flat ground/sloping away from road	7,860	-	-
A96-21	NE	NJ 08831 60516	NJ 08311 60396	Minor hill/sloping approximately sub-parallel to	534	-	-
A96-22	NE	NH 95601 56395	NH 94261 55915	Flat ground/sloping away from road	1,440	-	-
A96-23	NE	NH 85291 55675	NH 74251 48754	Relatively flat ground and/or sloping away from	13,100	-	-
A977-01	NE	NS 93247 87564	NS 93102 89514	Flat ground/residential	2,060	-	-
A985-01	NE	NT 12297 83529	NT 11807 83484	Flat ground/residential	515	-	-
A985-02	NE	NT 11082 83544	NT 09262 83469	Picking up river below road	1,840	-	-
A985-03	NE	NT 08387 84259	NT 08212 84559	Flat ground	347	-	-
A985-04	NE	NT 06397 84599	NT 05947 84719	Picking up river in valley bottom north and south	466	-	-
A985-05	NE	NT 01507 86849	NT 00822 86919	Potential hazards from river in gorge	-	-	-
A985-06	NE	NS 94217 86994	NS 92897 87309	Flat ground	1,460	-	-
A99-01	NW	ND 32670 43472	ND 32685 42887	Possibly caused by railway above road	-	-	-
A99-02	NW	ND 30415 38956	ND 30450 39051	Point Hazard - Restricted by plantation above road	-	-	-
A99-03	NW	ND 30025 38056	ND 29570 37486	Burn at either end, above and below road	-	-	-
A99-04	NW	ND 24660 36236	ND 24090 35791	If anything mainly north end, southern river	747	-	-
A99-05	NW	ND 22915 35276	ND 22685 35091	Probably swamp source above road	-	-	-

Table B.1 (Continued) – Initial interpretation results.

Route Code	OC Unit	Start-NGR	End-NGR	Comments on Hazards	Section Length (m)		
					Other (None)	Oppor-tunistic	Main Study
M73-01	SW	NS 70797 69709	NS 69897 65739	Associated with relatively flat ground often below	4,270	-	-
M74-01	SW	NS 64827 62304	NS 71317 58574	Associated with flat ground and development in	8,360	-	-
M74-02	SW	NS 73357 55944	NS 77607 50753	Associated with flat, wet ground	6,900	-	-
M74-03	SW	NS 77267 49493	NS 78557 44703	Associated with flat, wet ground	5,060	-	-
M74-04	SW	NS 82907 38693	NS 84447 35423	Associated with higher ground to east of road	-	-	-
M74-05	SW	NS 84577 35003	NS 84827 34193	Associated with flat, wet ground	849	-	-
M74-06	M74 DBFO	NS 86017 32083	NS 87187 28733	Associated with valley bottom	3,610	-	-
M74-07	M74	NS 88477 27343	NS 92277 25652	Associated with flat, wet ground	4,290	-	-
M74-08	M74 DBFO	NS 92997 24432	NS 95657 17582	Largely oblique to road and also in valley bottom	-	-	-
M74-09	M74	NS 95997 16852	NS 96337 16502	Small area above road but below ancient fort	-	-	492
M74-10	M74	NS 99647 15192	NT 00347 14192	Small area to west of road, railway and minor road	1,230	-	-
M74-11	M74	NT 01567 13372	NT 03047 12552	Small areas associated with Tinny Bank	-	-	-
M74-12	M74	NT 03047 12552	NT 07597 03312	Variously associated with high ground above road	-	-	-
M74-13	M74	NY 09627 99202	NY 10217 93342	Main hazard well above road across river valley to	-	-	-
M74-14	M74 DBFO	NY 10337 90212	NY 11777 86111	Associated with flat, wet ground distant from, but slightly above road	4,440	-	-
M74-15	M74 DBFO	NY 13687 80271	NY 14837 79081	Associated with flat, wet ground adjacent to/below the road	1,710	-	-
M74-16	M74 DBFO	NY 22167 73751	NY 31587 68511	Associated with flat, wet ground	11,100	-	-
M77-01	SW	NS 56351 64209	NS 53631 58479	Associated with development in Glasgow and areas of open, flat, wet land	7,180	-	-
M77-02	SW	NS 52131 53549	NS 49121 46849	Rolling ground, possibly drumlinised	-	-	-
M8-01	SE	NT 17772 70688	NT 17272 70398	Associated with relatively flat ground often below	578	-	-
M8-02	SE	NT 13612 71458	NT 12482 71218	Associated with quarry	1,170	-	-
M8-03	SE	NT 11072 71148	NT 10472 71318	Associated with river Almond	627	-	-
M8-04	SE	NT 03342 70328	NS 96712 65818	Associated with flat ground	8,160	-	-
M8-05	SE	NS 94652 65448	NS 79132 61908	High rolling, boggy ground broadly level with the road. Possible peat slides?	-	-	-
M8-06	SW	NS 68962 64449	NS 47391 65740	Associated with flat ground and development in Glasgow	25,500	-	-
M8-07	SW	NS 47391 65740	NS 44361 71230	Associated with flat, wet ground	6,980	-	-
M80-01	SW	NS 80287 88509	NS 80617 84909	Relatively flat land and picking up quarry at	3,660	-	-
M80-02	SW	NS 80207 83339	NS 78947 79559	Associated with relatively flat land and river	4,790	-	-
M80-03	SW	NS 66347 69679	NS 63617 68199	Associated with loch, rivers and flat ground below	3,160	-	-
M876-01	SE	NS 90502 85829	NS 89052 84844	Flat ground	1,810	-	-
M876-02	SE	NS 86827 84834	NS 85232 83914	Flat ground	1,870	-	-
M898-01	SW	NS 44801 70290	NS 45541 71320	Associated with flat, wet ground	1,330	-	-
M9-01	SE	NS 77912 98129	NS 77792 93059	Flat ground	5,170	-	-
M9-02	SE	NS 84992 86349	NS 93002 79569	Flat ground	11,400	-	-
M9-03	SE	NT 11517 74483	NT 12517 75509	Flat ground	1,570	-	-
M90-01	NE	NT 12302 83279	NT 13207 84819	Flat ground	1,890	-	-
M90-02	NE	NT 13592 87604	NT 13107 88564	Flat ground	1,080	-	-
M90-03	NE	NT 13402 92164	NT 13497 92794	Picked up opencast workings	639	-	-
M90-04	NE	NT 13377 93854	NT 13127 96904	Mainly heavily forested and shallow slopes	3,250	-	-
M90-05	NE	NT 13057 97104	NT 12932 98029	Flat ground	934	-	-
M90-06	NE	NO 12167 05264	NO 14347 09365	Shallow streams and quarry	5,640	-	-
M90-07	NE	NO 13587 10345	NO 13857 11450	Shallow streams and quarry	1,150	-	-
M90-08	NE	NO 13857 11450	NO 14367 12225	Potential hazards to either side of road on steep	-	-	933
M90-09	NE	NO 14377 13430	NO 13887 15335	Potential hazards to either side of road on steep	-	-	3,200
M90-10	NE	NO 13647 15770	NO 13292 19330	Flat ground	3,700	-	-
M90-11	NE	NO 13062 19515	NO 12312 20095	Potential hazards to east of road, possibly	-	-	953
M90-12	NE	NO 13147 21865	NO 13597 22455	Imported embankment fill possibly imposing unsustainable topography on recorded lithology	-	-	-
M90-13	NE	NO 11742 20535	NO 10817 21240	Potential hazards either side of road, relatively	-	-	-
M90-14	NE	NT 13552 87774	NT 14012 89094	Flat ground	1,490	-	-

B.2 SECONDARY INTERPRETATION

In this section the results of the second stage interpretation of the GIS-based assessment is presented. This divides the sections of the trunk road network that were defined as candidates for Main Study into Priorities 1 to 4 and identifies two sections for Separate Assessment as described in Section 5.

'Comments on Prioritisation' were made as *aide memoire* to the authors for use during the process and were not intended to provide any kind of definitive statement regarding the hazards.

Table B.2 – Secondary interpretation results: Priority 1.

Route Code	OC Unit	Start-NGR	End-NGR	Section Length (m) Priority 1	Comments on Prioritisation	Initial Hazard Score
A82-02	NW	NH 60696 39243	NH 57346 34993	**5,520**	Consistent high hazards on slope and ground above. May be sufficiently steep that source and entrainment potential are limited	80
A82-04	NW	NH 52391 30037	NH 50831 30172	**1,590**	Hazards relatively distant and indirect	80
A82-08	NW	NH 45761 19182	NH 43486 16747	**3,410**	Variable but high hazards on slopes above road	80
A82-09	NW	NH 42981 16557	NH 42451 16667	**581**	Substantial hazard above road which rests at bottom of slope	80
A82-17	NW	NN 28766 96227	NN 21391 85632	**13,400**	Includes area at Letterfinlay with recent debris flow history, also close proximity of loch	80
A82-34	NW	NN 33296 20776	NN 31776 09196	**13,500**	Significant hazards associated with potentially high exposure (road immediately above loch)	80
A82-37	NW	NN 34026 00456	NS 34556 97686	**3,300**	Significant hazards in Glen Douglas junction area	80
A83-02	NW	NN 26901 03861	NN 23021 07837	**6,310**	Historically active area, supported by GIS-based assessment	80
A83-04	NW	NN 23421 09592	NN 19096 09927	**4,360**	Historically active area, supported by GIS-based assessment	80
A83-05	NW	NN 18406 11247	NN 19406 12512	**1,620**	Historically active area, partially supported by GIS-based assessment	80
A835-07	NW	NH 38284 70387	NH 28554 73906	**11,400**	Numerous complex and significant hazards, many of which are potentially cumulative from multiple stream tributaries	80
A85-08	NW	NN 58437 24970	NN 55677 29396	**5,480**	Recent history of debris flow activity	80
A85-15	NW	NN 13191 28352	NN 03135 29863	**12,400**	Severe hazards - for much of this section the road and hazards are above Loch Awe	80
A86-03	NW	NN 67317 95722	NN 67162 95417	**357**	Hazards appear intense, close to road, and above very steep section	80
A86-09	NW	NN 48856 87552	NN 47661 86407	**1,730**	Major hazards associated with very steep hillside and ground behind 'top' nearer to road. Direction of latter hazard is sidelong to road.	80
A86-12	NW	NN 25591 81307	NN 22966 81947	**2,770**	Known area of hazard (albeit believed to be relatively small scale) that model does not identify too strongly. A very useful area for model validation.	80
A87-09	NW	NH 11495 10731	NH 09725 11731	**2,080**	Focussed around one particularly severe stream-	80
A87-12	NW	NH 03370 12016	NG 96289 14946	**8,620**	Substantial hazards from hills either side of road	80
A87-15	NW	NG 94469 21121	NG 88269 26106	**8,650**	Repeated stream-based hazards from hillside above road which sits immediately above loch	80
A9-11	NW	ND 08775 20794	ND 02860 15349	**11,200**	Extreme intensity of hazards to north of Helmsdale. Possible activity in October 2006.	80
A9-12	NW	ND 02175 14804	NC 93895 09663	**10,200**	Less extreme hazards to south of Helmsdale than to north, but events of October 2006 indicate that this area should be examined	80
A9-35b	NW	NN 66562 72101	NN 69762 71546	**3,310**	Intense, high stream-based hazard section - high up and extensive	80
A9-44	NW	NO 00212 47141	NO 00472 43871	**3,320**	Limited hazard potential highlighted by GIS, but events of August 2004 indicate that further assessment would be prudent. Hazards are more closely associated with localised geotechnical issues (cut slope stability management) than longer distance debris flow events	80

Table B.3 (Continued) – Secondary interpretation results: Priority 2.

Route Code	OC Unit	Start-NGR	End-NGR	Section Length (m) Priority 2	Comments on Prioritisation	Initial Hazard Score
A7-06	SE	NT 40762 02692	NY 38842 96252	**7,160**	Route not critically susceptible	60
A77-11	SW	NX 05214 72439	NX 08694 63338	**9,990**	Hazards primarily on flat ground behind head of slope, although some in head of gulley(s) - higher priorities elsewhere	60
A82-05	NW	NH 52566 28987	NH 49631 23632	**6,770**	More significant, although looks worse than probably is as some 'hazards' are related to relatively flat ground at lochside below road	60
A82-26	NW	NN 05220 59568	NN 07550 58357	**2,720**	Hazard (perception) perhaps amplified by recent debris flows above Ballachulish	60
A82-36	NW	NN 31916 04456	NN 34026 00456	**4,610**	Variable stream-based hazards	60
A828-01	NW	NN 05175 59653	NM 99145 54983	**8,540**	Hazard (perception) perhaps amplified by recent debris flows above Ballachulish near adjacent section of A82	60
A828-04	NW	NM 96370 44903	NM 97685 44688	**1,480**	One intense gulley-focussed zone	60
A83-06	NW	NN 19221 12717	NN 11260 08848	**9,170**	Severe stream-based hazards, but less history of events	60
A830-05	NW	NM 90195 80853	NM 76679 82314	**15,500**	Sporadic , intense hazard zones, mainly associated with streams	60
A835-09	NW	NH 19553 80586	NH 18168 85540	**5,320**	Very steep ground on NE side with stream-related hazards	60
A85-09	NW	NN 50672 28326	NN 38766 25266	**12,900**	Some stream-based hazards especially on N flank of Ben More	60
A86-10	NW	NN 47516 86247	NN 37536 81267	**11,600**	Substantial hazards present, but of variable direction and with benches affording at least some protection the road - there are areas with greater perceived hazards	60
A86-11	NW	NN 33266 80957	NN 27646 81067	**6,180**	Some localised hazard close to road but on steep slope (above) and in stream channel on high ground	60
A87-07	NW	NH 18930 10072	NH 14330 09991	**5,070**	Significant hazards, both stream and open hillside based	60
A87-13	NW	NG 96259 14951	NG 94614 17946	**3,790**	Still high hazards but mainly from the opposite side of valley from road	60
A87-20	NW	NG 47808 31921	NG 47428 41300	**10,000**	Relatively boggy with many stream-based hazards, albeit oblique to the road	60
A887-01	NW	NH 42031 16827	NH 35170 15427	**8,150**	Reduced compared to adjacent A82 Priority 1 section(s) on the basis of lower strategic importance	60
A9-34	NW	NN 68007 91922	NN 67812 90722	**1,260**	Hazard towards crest of hill above steepening	60
A9-35a	NW	NN 63982 83957	NN 64987 73046	**11,900**	General severe stream-based hazards to east of road	60
A9-45	NW	NO 03452 41486	NO 04062 40886	**877**	Hazards on hill, probably on open ground in forestry	60
A95-05	NE	NJ 30452 44976	NJ 29417 44886	**1,230**	Some problems reported in the past, but may be small scale as nothing highlighted by assessment	60
A95-08	NE	NJ 14757 34755	NJ 10537 32135	**5,880**	Hazards on steep slope to south of road	60
A95-09	NE	NJ 08337 29844	NJ 06512 27039	**3,480**	Hazards on steep slope to south of road	60

Table B.4 – Secondary interpretation results: Priority 3.

Route Code	OC Unit	Start-NGR	End-NGR	Section Length (m) Priority 3	Comments on Prioritisation	Initial Hazard Score
A1-06	SE	NT 79571 67434	NT 85681 62704	8,630	Localities not known to be generally susceptible	40
A68-12	SE	NT 67581 14083	NT 68261 12323	1,960	River provides potential debris trap	40
A7-01	SE	NT 48882 32523	NT 48142 31013	1,840	Potential likely to be limited	40
A7-05	SE	NT 46492 11652	NT 44922 10092	2,350	Potential significantly less than further south	40
A7-07	SE	NY 38842 96252	NY 36812 90032	6,690	Route not critically susceptible	40
A76-04	SW	NS 85832 04117	NS 81022 07857	6,570	Relatively indirect, but less so than A76-05 and variable hazards	40
A77-10	SW	NX 09284 77378	NX 05214 72439	6,640	Hazards primarily on flat ground behind head of slope - also rebuild scheme in progress	40
A82-03	NW	NH 56836 34253	NH 54586 31063	3,970	Comparably low level hazards, albeit road adjacent to loch	40
A82-07	NW	NH 47461 21012	NH 46411 19822	1,620	Comparably low level hazards, albeit road adjacent to loch	40
A82-10	NW	NH 42411 16052	NH 40211 12102	4,870	Comparably low level hazards, albeit road adjacent to loch	40
A82-14	NW	NH 34476 03812	NH 33836 03542	828	Hazard potential, but runout relatively indirectly 'aimed' at road	40
A82-15	NW	NH 33261 02912	NH 32901 02442	600	Initiation within and long(ish) travel entirely through a large area of forest, albeit road close to	40
A82-16	NW	NN 29996 98177	NN 28981 96572	1,960	Relatively long runout with intervening canal	40
A82-23	NW	NN 04505 66337	NN 03765 65377	1,260	Most runout opportunities parallel to road and forestation above	40
A82-24	NW	NN 02295 63258	NN 02645 62728	688	Hazards high on hillside but with relatively long runout through Inchree and forestation	40
A82-38	NW	NS 34556 97686	NS 35196 87156	11,100	Some areas of concern, but higher priorities both	40
A83-01	NW	NN 29616 05036	NN 28391 03881	1,760	Hazards, but largely within a forested area and no known history	40
A83-07	NW	NN 11260 08848	NN 11395 10083	1,260	Historic area of translational slides, rather than	40
A83-10	NW	NN 04495 04203	NN 02915 03179	1,910	Possible limited source material, marginal 2 or 3	40
A83-12	NW	NS 01725 99834	NR 98995 97649	3,550	Main hazard element probably associated with quarry	40
A83-18	NW	NR 84819 80506	NR 86284 74006	7,040	Lower grade hazards. Mainly close to road over a long stretch - rockfall and deep-seated slides	40
A83-20	NW	NR 86794 69696	NR 86529 69066	687	Lower grade hazards. Mainly relatively distant, with longish runout or separated by	40
A83-21	NW	NR 86034 68451	NR 85284 68076	839	Lower grade hazards. Mainly relatively distant, with longish runout or separated by	40
A830-04	NW	NM 90855 80478	NM 90205 80848	867	Railway, etc between hazards and road	40
A830-06	NW	NM 76679 82314	NM 71574 84404	6,080	Recently realigned on high ground relative to	40
A835-04	NW	NH 43565 58802	NH 40650 59367	3,110	Hazards largely associated with lochans on hilltop	40
A835-06	NW	NH 40325 63937	NH 40344 69227	6,110	Hazards largely sourced within/beyond extensive forested areas adjacent to road	40
A835-10	NW	NH 18163 85575	NH 13298 94065	10,400	Generally lower level hazards, with possible exception of Creag Mhor which may be a function	40
A84-03	NW	NN 57047 14530	NN 58487 13465	1,900	Main potential form steep valley at south end of stretch	40
A85-12	NW	NN 30461 31731	NN 22586 27147	9,590	Much of the hazards appear to be associated with elevated rock outcrops, with exceptions	40
A86-07	NW	NN 55996 90417	NN 55356 89707	987	Largely one stream-based hazard grouping on constantly steep ground	40
A86-08	NW	NN 54331 89767	NN 52936 89547	1,520	Two main hazard groups - possibly mainly associated with flat/shallow slope ground	40
A87-14	NW	NG 93894 18781	NG 94539 20406	2,490	Lower less direct hazards	40
A87-22	NW	NG 46818 45880	NG 42318 50959	7,050	Much on relatively flat ground below road, some above road	40
A887-02	NW	NH 32540 14347	NH 32030 14177	540	High hazard distant and high on hill	40

Table B.4 (Continued) – Secondary interpretation results: Priority 3.

Route Code	OC Unit	Start-NGR	End-NGR	Section Length (m) Priority 3	Comments on Prioritisation	Initial Hazard Score
A9-09	NW	ND 15325 29325	ND 13145 25995	4,350	Some hazards directed towards the trunk road	40
A9-10	NW	ND 12010 23055	ND 11670 22435	1,110	Landslide activity at viewed by Helen Reeves (BGS) from ND 11021 22050 (see note and photographs) on far valley side. This is very indirect to road even if following river path. Possible activity in October 2006.	40
A9-24	NW	NH 72341 35783	NH 75841 34579	4,040	Hazard area associated with water course - extensive forestry below and road sited on opposite wall of valley	40
A9-27	NW	NH 82171 26569	NH 87652 24074	6,660	Hazards close to the road - possibly reduced due to localised embankment. Hazards further south on high ground well defended by rail, forestry and local road.	40
A9-30	NW	NH 89357 13978	NH 84707 07948	8,550	Generally, where hazards are highest the runout between the base of the hills and the road is longer	40
A95-04	NE	NJ 33336 47211	NJ 31727 45906	2,210	Hazards associated with higher ground to either side of road	40
M74-09	M74 DBFO	NS 95997 16852	NS 96337 16502	492	Close to road on engineered slope	40
M90-09	NE	NO 14377 13430	NO 13887 15335	3,200	Hazards in close proximity to road on flatter ground rather than high on hillside	40

Table B.5 – Secondary interpretation results: Priority 4.

Route Code	OC Unit	Start-NGR	End-NGR	Section Length (m) Priority 4	Comments on Prioritisation	Initial Hazard Score
A1-02	SE	NT 36582 71194	NT 40152 73634	4,440	A very marginal 'red' assessment in any case	20
A1-08	SE	NT 94330 61174	NT 97410 57054	5,560	Hazard from cliffs below road and rail are routinely	20
A68-02	SE	NT 44662 60043	NT 45252 59473	821	Shallow slope from Fala Moor to road	20
A68-13	SE	NT 68531 10723	NT 68691 09563	1,190	Current forestation and sources distal and indirect	20
A7-08	SE	NY 37152 80982	NY 38332 78042	3,280	Less direct hazard	20
A701-03	SW	NY 03302 89297	NY 05742 91657	3,440	Relatively distant hazard contained within area of forestry	20
A76-05	SW	NS 78932 09117	NS 77122 11008	2,650	Relatively indirect	20
A76-09	SW	NS 67591 12988	NS 62931 13078	4,770	Hazards in likely area of peat with long, well-drained runout to road	20
A78-06	SW	NS 25610 43671	NS 28170 42611	2,880	Hazards apparently less severe from brief air photo inspection that GIS might suggest	20
A82-12	NW	NH 38381 10322	NH 37896 09252	1,420	Long track through forest and then long runout through Fort Augustus	20
A82-29	NW	NN 31141 43721	NN 29741 38561	5,550	Hazards high on hills and with railway and long(ish) runout to road	20
A82-31	NW	NN 32251 34076	NN 32991 31481	2,940	Relatively low level hazards associated with lochan on Beinn Odhar	20
A830-03	NW	NM 96520 79313	NM 90855 80478	6,550	Sporadic and relatively distant hazards	20
A830-07	NW	NM 71594 85114	NM 68999 84984	2,830	Road subject to route amendments and road relatively well-protected from potential hazards	20
A835-02	NW	NH 50385 54878	NH 48615 54908	1,780	Relatively limited hazards	20
A835-03	NW	NH 45870 55868	NH 45445 56608	889	Relatively limited hazards	20
A835-05	NW	NH 40635 59407	NH 38875 62497	3,700	Relatively limited hazards	20
A835-08	NW	NH 27084 74686	NH 20223 78236	8,000	Relatively limited hazards	20
A84-04	NW	NN 58487 13465	NN 58637 10880	2,700	Relatively limited hazards	20
A84-05	NW	NN 58637 10880	NN 60537 08540	4,050	Relatively limited hazards	20
A85-13	NW	NN 19646 27552	NN 17336 27352	2,360	Hazards mainly on far side of river, some of which are low on hillside	20
A87-08	NW	NH 14330 09991	NH 11495 10731	3,100	Substantially lower hazard levels compared to surrounds	20
A87-10	NW	NH 09725 11731	NH 06790 11496	3,270	Lower ground and less direct hazards with at least some runout	20
A87-11	NW	NH 06790 11496	NH 03370 12016	3,670	Substantially lower hazard levels compared to surrounds	20
A87-24	NW	NG 39057 59388	NG 39367 64097	5,460	Some above road, some on long runout	20
A887-03	NW	NH 29500 12297	NH 22830 10597	7,170	Relatively low level hazards	20
A9-07	NW	ND 17630 47546	ND 18435 38856	8,880	Generally relatively flat ground, but with real and observable hazards	20
A9-22	NW	NH 72401 39864	NH 71901 38349	1,660	Largely low and close to the road, with one possible exception	20
A9-29	NW	NH 90942 18043	NH 90432 16903	1,290	Relatively minor, near-field hazards	20
A9-37	NW	NN 76882 68936	NN 77237 68286	761	Relatively localised hazards with some higher associated with stream	20
A9-46	NW	NO 06917 36595	NO 07127 35615	1,010	Very limited hazard potential, possibly could have had a lower original ranking	20
A90-01	NW	NO 13597 22455	NO 14982 22355	1,410	Main hazards are to west where local road is much closer than M90	20
A95-06	NE	NJ 28567 44776	NJ 28117 43931	1,020	Hazards associated with river cliffs on far side of valley	20
M90-08	NE	NO 13857 11450	NO 14367 12225	933	Hazards in very close proximity to road on flatter ground rather than high on hillside	20
M90-11	NE	NO 13062 19515	NO 12312 20095	953	Debris flow hazards are highly indirect - rock fall a more direct hazard	20

Table B.6 – Secondary interpretation results: Separate Assessments.

Route Code	OC Unit	Start-NGR	End-NGR	Section Length (m) Separate Assessment	Comments on Prioritisation	Initial Hazard Score
A82-27	NW	NN 10700 58212	NN 27671 52992	**19,900**	Multiple hazards and hazard types - much previous work carried out on Glencoe in the past on various areas and hazard types. Recommend a Desk Study reconciliation to account for this	-
A87-19	NW	NG 64039 23632	NG 48718 29902	**26,100**	Model shows intense/extreme large hazard areas	-

B.3 AERIAL PHOTOGRAPHY AVAILABILITY AND INSPECTIONS INSTRUCTED IN 2007

Table B.7 – Aerial photography availability and inspections instructed for Priority 1 sites in 2007.

Route	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	Aerial Photography Available	Inspection Instructed
A82-02	NW	NH 60696 39243	NH 57346 34993	5,520	**1**	Yes	Yes
A82-04	NW	NH 52391 30037	NH 50831 30172	1,590	**1**	Partial	No
A82-08	NW	NH 45761 19182	NH 43486 16747	3,410	**1**	Yes	Yes
A82-09	NW	NH 42981 16557	NH 42451 16667	581	**1**	Yes	Yes
A82-17	NW	NN 28766 96227	NN 21391 85632	13,400	**1**	Yes	Yes
A82-34	NW	NN 33296 20776	NN 31776 09196	13,500	**1**	Partial	No
A82-37	NW	NN 34026 00456	NS 34556 97686	3,300	**1**	Partial	No
A83-02	NW	NN 26901 03861	NN 23021 07837	6,310	**1**	No	No
A83-04	NW	NN 23421 09592	NN 19096 09927	4,360	**1**	No	No
A83-05	NW	NN 18406 11247	NN 19406 12512	1,620	**1**	Partial	No
A835-07	NW	NH 38284 70387	NH 28554 73906	11,400	**1**	Partial	No
A85-08	NW	NN 58437 24970	NN 55677 29396	5,480	**1**	Partial	Yes
A85-15	NW	NN 13191 28352	NN 03135 29863	12,400	**1**	Yes	Yes
A86-03	NW	NN 67317 95722	NN 67162 95417	357	**1**	Yes	Yes
A86-09	NW	NN 48856 87552	NN 47661 86407	1,730	**1**	Yes	Yes
A86-12	NW	NN 25591 81307	NN 22966 81947	2,770	**1**	Yes	Yes
A87-09	NW	NH 11495 10731	NH 09725 11731	2,080	**1**	Yes	Yes
A87-12	NW	NH 03370 12016	NG 96289 14946	8,620	**1**	Yes	Yes
A87-15	NW	NG 94469 21121	NG 88269 26106	8,650	**1**	Partial	No
A9-11	NW	ND 08775 20794	ND 02860 15349	11,200	**1**	Partial	No
A9-12	NW	ND 02175 14804	NC 93895 09663	10,200	**1**	No	No
A9-35b	NW	NN 66562 72101	NN 69762 71546	3,310	**1**	Yes	Yes
A9-44	NW	NO 00212 47141	NO 00472 43871	3,320	**1**	No	No

Table B.8 – Aerial photography availability and inspections instructed for Priority 2 sites in 2007.

Route	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	Aerial Photography Available	Inspection Instructed
A7-06	SE	NT 40762 02692	NY 38842 96252	7,160	**2**	No	No
A77-11	SW	NX 05214 72439	NX 08694 63338	9,990	**2**	Yes	Yes
A82-05	NW	NH 52566 28987	NH 49631 23632	6,770	**2**	Yes	Yes
A82-26	NW	NN 05220 59568	NN 07550 58357	2,720	**2**	Yes	Yes
A82-36	NW	NN 31916 04456	NN 34026 00456	4,610	**2**	No	No
A828-01	NW	NN 05175 59653	NM 99145 54983	8,540	**2**	Partial	No
A828-04	NW	NM 96370 44903	NM 97685 44688	1,480	**2**	No	No
A83-06	NW	NN 19221 12717	NN 11260 08848	9,170	**2**	Partial	No
A830-05	NW	NM 90195 80853	NM 76679 82314	15,500	**2**	Partial	No
A835-09	NW	NH 19553 80586	NH 18168 85540	5,320	**2**	No	No
A85-09	NW	NN 50672 28326	NN 38766 25266	12,900	**2**	Yes	Yes
A86-10	NW	NN 47516 86247	NN 37536 81267	11,600	**2**	Yes	Yes
A86-11	NW	NN 33266 80957	NN 27646 81067	6,180	**2**	Yes	Yes
A87-07	NW	NH 18930 10072	NH 14330 09991	5,070	**2**	Yes	Yes
A87-13	NW	NG 96259 14951	NG 94614 17946	3,790	**2**	Yes	Yes
A87-20	NW	NG 47808 31921	NG 47428 41300	10,000	**2**	Yes	Yes
A887-01	NW	NH 42031 16827	NH 35170 15427	8,150	**2**	Yes	Yes
A9-34	NW	NN 68007 91922	NN 67812 90722	1,260	**2**	Yes	Yes
A9-35a	NW	NN 63982 83957	NN 64987 73046	11,900	**2**	Yes	Yes
A9-45	NW	NO 03452 41486	NO 04062 40886	877	**2**	No	No
A95-05	NE	NJ 30452 44976	NJ 29417 44886	1,230	**2**	Yes	Yes
A95-08	NE	NJ 14757 34755	NJ 10537 32135	5,880	**2**	Yes	Yes
A95-09	NE	NJ 08337 29844	NJ 06512 27039	3,480	**2**	Yes	Yes

Table B.9 – Aerial photography availability and inspections instructed for Priority 3 sites in 2007.

Route	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	Aerial Photography Available	Inspection Instructed
A1-06	SE	NT 79571 67434	NT 85681 62704	8,630	**3**	No	No
A68-12	SE	NT 67581 14083	NT 68261 12323	1,960	**3**	No	No
A7-01	SE	NT 48882 32523	NT 48142 31013	1,840	**3**	No	No
A7-05	SE	NT 46492 11652	NT 44922 10092	2,350	**3**	No	No
A7-07	SE	NY 38842 96252	NY 36812 90032	6,690	**3**	No	No
A76-04	SW	NS 85832 04117	NS 81022 07857	6,570	**3**	No	No
A77-10	SW	NX 09284 77378	NX 05214 72439	6,640	**3**	Partial	No
A82-03	NW	NH 56836 34253	NH 54586 31063	3,970	**3**	Yes	No
A82-07	NW	NH 47461 21012	NH 46411 19822	1,620	**3**	Yes	No
A82-10	NW	NH 42411 16052	NH 40211 12102	4,870	**3**	Yes	No
A82-14	NW	NH 34476 03812	NH 33836 03542	828	**3**	Yes	No
A82-15	NW	NH 33261 02912	NH 32901 02442	600	**3**	Yes	No
A82-16	NW	NN 29996 98177	NN 28981 96572	1,960	**3**	Yes	No
A82-23	NW	NN 04505 66337	NN 03765 65377	1,260	**3**	Partial	No
A82-24	NW	NN 02295 63258	NN 02645 62728	688	**3**	Partial	No
A82-38	NW	NS 34556 97686	NS 35196 87156	11,100	**3**	Partial	No
A83-01	NW	NN 29616 05036	NN 28391 03881	1,760	**3**	No	No
A83-07	NW	NN 11260 08848	NN 11395 10083	1,260	**3**	partial	No
A83-10	NW	NN 04495 04203	NN 02915 03179	1,910	**3**	Yes	No
A83-12	NW	NS 01725 99834	NR 98995 97649	3,550	**3**	Yes	No
A83-18	NW	NR 84819 80506	NR 86284 74006	7,040	**3**	No	No
A83-20	NW	NR 86794 69696	NR 86529 69066	687	**3**	Partial	No
A83-21	NW	NR 86034 68451	NR 85284 68076	839	**3**	Partial	No
A830-04	NW	NM 90855 80478	NM 90205 80848	867	**3**	Partial	No
A830-06	NW	NM 76679 82314	NM 71574 84404	6,080	**3**	Partial	No
A835-04	NW	NH 43565 58802	NH 40650 59367	3,110	**3**	Partial	No
A835-06	NW	NH 40325 63937	NH 40344 69227	6,110	**3**	Partial	No
A835-10	NW	NH 18163 85575	NH 13298 94065	10,400	**3**	Partial	No
A84-03	NW	NN 57047 14530	NN 58487 13465	1,900	**3**	Yes	No
A85-12	NW	NN 30461 31731	NN 22586 27147	9,590	**3**	Yes	No
A86-07	NW	NN 55996 90417	NN 55356 89707	987	**3**	Yes	No
A86-08	NW	NN 54331 89767	NN 52936 89547	1,520	**3**	Yes	No
A87-14	NW	NG 93894 18781	NG 94539 20406	2,490	**3**	Yes	No
A87-22	NW	NG 46818 45880	NG 42318 50959	7,050	**3**	Yes	No
A887-02	NW	NH 32540 14347	NH 32030 14177	540	**3**	Yes	No
A9-09	NW	ND 15325 29325	ND 13145 25995	4,350	**3**	Partial	No
A9-10	NW	ND 12010 23055	ND 11670 22435	1,110	**3**	Partial	No
A9-24	NW	NH 72341 35783	NH 75841 34579	4,040	**3**	Yes	No
A9-27	NW	NH 82171 26569	NH 87652 24074	6,660	**3**	Yes	No
A9-30	NW	NH 89357 13978	NH 84707 07948	8,550	**3**	Yes	No
A95-04	NE	NJ 33336 47211	NJ 31727 45906	2,210	**3**	Yes	No
M74-09	M74	NS 95997 16852	NS 96337 16502	492	**3**	No	No
M90-09	NE	NO 14377 13430	NO 13887 15335	3,200	**3**	Yes/1999-2000	No

Table B.10 – Aerial photography availability and inspections instructed for Priority 4 sites in 2007.

Route	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	Aerial Photography Available	Inspection Instructed
A1-02	SE	NT 36582 71194	NT 40152 73634	4,440	**4**	Partial/1999-2000	No
A1-08	SE	NT 94330 61174	NT 97410 57054	5,560	**4**	Partial/1999-2000	No
A68-02	SE	NT 44662 60043	NT 45252 59473	821	**4**	Partial/1999-2000	No
A68-13	SE	NT 68531 10723	NT 68691 09563	1,190	**4**	No	No
A7-08	SE	NY 37152 80982	NY 38332 78042	3,280	**4**	Partial/1999-2000	No
A701-03	SW	NY 03302 89297	NY 05742 91657	3,440	**4**	No	No
A76-05	SW	NS 78932 09117	NS 77122 11008	2,650	**4**	No	No
A76-09	SW	NS 67591 12988	NS 62931 13078	4,770	**4**	No	No
A78-06	SW	NS 25610 43671	NS 28170 42611	2,880	**4**	Yes	No
A82-12	NW	NH 38381 10322	NH 37896 09252	1,420	**4**	Yes	No
A82-29	NW	NN 31141 43721	NN 29741 38561	5,550	**4**	Yes	No
A82-31	NW	NN 32251 34076	NN 32991 31481	2,940	**4**	Yes	No
A830-03	NW	NM 96520 79313	NM 90855 80478	6,550	**4**	Partial	No
A830-07	NW	NM 71594 85114	NM 68999 84984	2,830	**4**	Yes	No
A835-02	NW	NH 50385 54878	NH 48615 54908	1,780	**4**	Partial/1999-2000	No
A835-03	NW	NH 45870 55868	NH 45445 56608	889	**4**	No	No
A835-05	NW	NH 40635 59407	NH 38875 62497	3,700	**4**	Partial	No
A835-08	NW	NH 27084 74686	NH 20223 78236	8,000	**4**	No	No
A84-04	NW	NN 58487 13465	NN 58637 10880	2,700	**4**	Yes	No
A84-05	NW	NN 58637 10880	NN 60537 08540	4,050	**4**	Yes	No
A85-13	NW	NN 19646 27552	NN 17336 27352	2,360	**4**	Yes	No
A87-08	NW	NH 14330 09991	NH 11495 10731	3,100	**4**	Yes	No
A87-10	NW	NH 09725 11731	NH 06790 11496	3,270	**4**	Yes	No
A87-11	NW	NH 06790 11496	NH 03370 12016	3,670	**4**	Yes	No
A87-24	NW	NG 39057 59388	NG 39367 64097	5,460	**4**	Partial	No
A887-03	NW	NH 29500 12297	NH 22830 10597	7,170	**4**	Yes	No
A9-07	NW	ND 17630 47546	ND 18435 38856	8,880	**4**	Yes	No
A9-22	NW	NH 72401 39864	NH 71901 38349	1,660	**4**	Partial/1999-2000 & 2004-06	No
A9-29	NW	NH 90942 18043	NH 90432 16903	1,290	**4**	Yes	No
A9-37	NW	NN 76882 68936	NN 77237 68286	761	**4**	Yes	No
A9-46	NW	NO 06917 36595	NO 07127 35615	1,010	**4**	Partial/1999-2000	No
A90-01	NW	NO 13597 22455	NO 14982 22355	1,410	**4**	Yes/1999-2000	No
A95-06	NE	NJ 28567 44776	NJ 28117 43931	1,020	**4**	Yes	No
M90-08	NE	NO 13857 11450	NO 14367 12225	933	**4**	Yes/1999-2000	No
M90-11	NE	NO 13062 19515	NO 12312 20095	953	**4**	Yes/1999-2000	No

Table B.11 – Aerial photography availability and inspections instructed for Separate Assessment sites in 2007.

Route	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	Aerial Photography Available	Inspection Instructed
A82-27	NW	NN 10700 58212	NN 27671 52992	19,900	**Separate Assessment**	Yes	No
A87-19	NW	NG 64039 23632	NG 48718 29902	26,100	**Separate Assessment**	Yes	No

APPENDIX C – RESULTS FROM SITE-SPECIFIC ASSESSMENTS

by Scotland TranServ

C.1 SAMPLE SITE INSPECTION REPORTS AND SCORE SHEETS

Some of the photographs presented in this section were taken on mobile telephone cameras; the resulting images are of low quality as a consequence.

C.1.1 Sample Report for A82-17

Location:	Loch Lochy	*Date:*	21-06-07
Grid Reference:	NN 280960	*Weather Conditions:*	Sunny with occasional showers.
Route Number:	A82 -17	*Observations made by:*	B. Lynch , P.Egan

Desk Study

Reasons for scoring: (+5) Large catchment area visible from aerial photography, NGR location NN240880. (+5) Historical instability from aerial photography, NGR location NN280940. (+5) Peat and soft ground present in aerial photography on top of ridge NGR locations NN270920, NN280930.
Further investigation required: Drive-by incorporating an inspection of historical instability, possible deforestation and forest roads.

Drive-By

Reasons for scoring: (0) Large catchment area not deemed large enough to merit plus 5 (+5) Evidence of debris accumulation in stream (Figure 1) NGR location NN280940 (+5) Historical instability (Figure 2) NGR location NN280940 (+10) Recent instability present across the site (Figure 3,4,5) NGR locations NN280940, NN240890, NN220870 (+5) Peat and soft ground present NGR locations NN270920, NN280930. (+5) Deforestation close to the road (Figure 6, 7) NGR location NN210850
Further investigation required: Further investigation may be required it establish the extent of catchment area and the amount of peat / soft ground present.
Limitations/Problems encountered: Very poor sight lines towards the site from the A82 – 17, gained permission from forestry service to drive the great glen way through Clunes forest.

Walkover Survey

Reasons for scoring:
Features/differences noted from drive-by & desk study: Debris accumulation, flat catchment, recent instability and deforestation.

Figure C.1 – NGR location NN280940 (debris in stream).

Figure C.2 – NGR location NN280940 (historical instability).

Figure C.3 – NGR location NN280940 (recent instability).

Figure C.4 – NGR location NN240890 (recent instability).

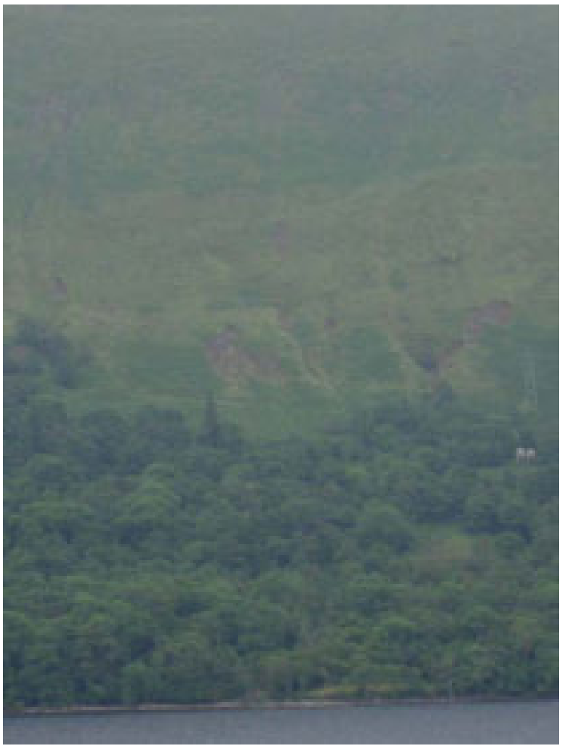


Figure C.5 – NGR location NN220870 (recent instability).

Figure C.6 – NGR location NN210850 (deforestation).

Figure C.7 – NGR location NN210850 (deforestation).

C.1.2 Sample Report for A82-08

Location:	Loch Ness	*Date:*	23/24-07-07
Grid Reference:	NH 4519	*Weather Conditions:*	Dry, Clear
Route Number:	A82 - 08	*Observations made by:*	P.Egan, B.Lynch

Desk Study

Reasons for scoring:
(+5) Evidence of deforestation shown on NGR Location NH440170 (Figures C.8 and C.9)

Further investigation required:
Access to forest road to inspect deforestation and new track NGR Location NH430190.

Drive-By

Reasons for scoring:
(+5) Deforestation present at NGR Location NH440170 (Figures C.8 and C.9)

Further investigation required:
Access to forest road to inspect deforestation and new track NGR Location NH430190.

Limitations/Problems encountered:
Access to Great Glen cycle route as entry is restricted. Key / permission obtained from Fort Augustus Forestry Services. Lack of adequate sightlines from the trunk road.

Walkover Survey

Reasons for scoring:
(+5) Deforestation present at NH440170 NGR Location (Figures C.8 and C.9)
(+5) Debris accumulation in stream at NH430190 NGR Location (Figures C.10 and C.11)

Features/differences noted from drive-by & desk study:
New road shown on aerial photo did not seem to pose a threat to the site.
Debris accumulation in stream.

Figure C.8 – Previous Deforestation at NGR Location NH440170.

Figure C.10 – Debris in stream at NGR Location NH440190.

Figure C.9 – Previous Deforestation present at NGR Location NH440170.

Figure C.11 – Debris in stream at NGR Location NH440190.

C.1.3 Sample Report for A85-09

Location:	Glen Dochart	*Date:*	15/06/07
Grid Reference:	NN 5028	*Weather Conditions:*	Dry and sunny
Route Number:	A85 - 09	*Observations made by:*	B.Lynch, P.Egan

Desk Study

Reasons for scoring: (+5) Large flat catchment area – Stob Lúib and Creag Loisgte. (Figure C.12) NN480250 (+5) Evidence of historical instability. (Figures C.13 and C.14) NGR locations NN470270 NN510270 (+5) Deforestation present. (Figure C.15) NGR location NN440270 (+5) Forest road present running parallel to trunk road below – Meall Thairbh. (Figure C.16)
Further investigation required: Drive- by incorporating an inspection of deforestation, forest roads, flat catchment area and instability.

Drive-By

Reasons for scoring: (+5) Evidence of debris in streams (Figure C.18) NGR location NN420240 (+5) Large flat catchment area – Stob Lúib and Creag Loisgte (Figure 1). (+5) Evidence of historical instability (Figure 2, 3). (+10) Recent instability present area of Meall Diamh (Figure C.19). NGR location NN420240 (+5) Peat and soft ground present. (+5) Deforestation present (Figure C.15). (+5) Forest road present running parallel to trunk road below – Meall Thairbh (Figure C.16).
Further investigation required: Climb path by BenMore Burn to investigate instability. Investigate forest track at the foot of Ben More.
Limitations/Problems encountered: Access to Ben More Glen

Walkover Survey

Reasons for scoring: (+10) Recent instability present area of Meall Diamh (Figure C.18). (+5) Forest road present running parallel to trunk road below – Meall Thairbh (Figure C.16).
Features/differences noted from drive-by & desk study:

Figure C.12 – NGR location NN480250. Large flat catchment area – Stob Lúib and Creag Loisgte.

Figure C-15 – NGR location NN440270 (deforestation).

Figure C.13 – NGR location NN470270.

Figure C.16 – NGR location NN440270 (forest road).

Figure C-14 – NGR location NN510270 (evidence of historical instability).

Figure C.17 – NGR location NN420240 (debris accumulation in stream).

Figure C.18 – NGR location NN420240 (recent instability).

C.1.4 Sample Report for A87-13

Location:	Glen Shiel	*Date:*	20/07/07
Grid Reference:	NG 9614	*Weather Conditions:*	Dry, Bright
Route Number:	A87-13	*Observations made by:*	C.Boler, N.Horsburgh

Desk Study

Reasons for scoring:

(+5) Concentrated dendritic streams on aerial photography NGR location NG950150 & NG950140
(+5) Evidence of historical instability NGR locationNG954167
(+5) Deforestation in area NGR location NG940170
(+5) New forestry road around NGR location NG940170

Further investigation required:

Drive-by incorporating an inspection of deforestation and recent instability.

Drive-By

Reasons for scoring:

(+5) Deforestation in area NGR location NG940170 – replanted only saplings (Figure C.19)

Further investigation required:

Inspection of debris in streams and recent instability.

Limitations/Problems encountered:

Walkover Survey

Reasons for scoring:

(+10) Evidence of recent instability (Figures C.20 and C.21)
(Zero) Evidence of accumulation of debris in streams.
(Zero) Forestry road – Unable to find as very overgrown.
(+5) Historical instability NGR location NG954 167 (Figure C.22)

Features/differences noted from drive-by & desk study:

Recent instability

Figure C.19 – Previous deforestation around NG940170, taken from NGR location NG951177 looking west.

Figure C.21 – Recent instability (below lower outcrop in centre of picture), taken from NGR location NG962 149 looking west.

Figure C.20 – Recent instability, taken from NGR location NG951175 looking west.

Figure C.22 – Historical instability, taken from NGR location NG958 152 looking west.

C.1.5 Sample Report for A835-07

Location:	Loch Glascarnoch	*Date:*	07/08/07
Grid Reference:	NH 3870	*Weather Conditions:*	Dry, Bright
Route Number:	A835-07	*Observations made by:*	P.Egan, B.Lynch

Desk Study

Reasons for scoring:
(+5) Peat/Soft ground NGR location NH320690, NH310700
(+5) Deforestation NGR location NH340690, NH330690, NH330700, NH310700

Further investigation required:
Investigate suspected further deforestation on site.

Drive-By

Reasons for scoring:
(+5) Peat/Soft ground NGR location NH320690 (Figure C.26)
(+5) Deforestation NGR location NH340690, NH330690, NH330700, NH310700, NH310710, NH300710, NH300720, NH280720, NH280730, NH270720, NH270730 (Figures C.23 to C.25)

Further investigation required:
Climb Meallan Gharuidhe NGR location NH320700 to gain elevated views of deforestation.

Limitations/Problems encountered:
Lack of aerial photography west and north of NGR location NH310700

Walkover Survey

Reasons for scoring:
(+5) Peat/Soft ground NGR location NH320690 (Figure C.26)
(+5) Deforestation NGR location NH340690, NH330690, NH330700, NH310700, NH310710, NH300710, NH300720, NH280720, NH280730, NH270720, NH270730 (Figures C.23 to C.25)

Features/differences noted from drive-by & desk study:
Note: Evidence of excavator activities at NGR location NH320700, NH320710 to rear of new mast not marked on OS mapping. Excavator left behind numerous bucket sized pits which have now become water logged.

Figure C.23 – Deforestation NGR location NH330700.

Figure C.24 – Deforestation NGR location NH330690.

Figure C.25 – Deforestation NGR location NH310710, NH300710, NH300720.

Figure C.26 – Peat/Soft ground NGR location NH320690.

C.1.6 Sample Report for A9-11

Location:	Helmsdale	*Date:*	30-31/7/07
Grid Reference:	ND0820	*Weather Conditions:*	Clear
Route Number:	A9-11	*Observations made by:*	P.Egan, B.Lynch

Desk Study

Reasons for scoring:
(+10) Recent instability NGR location ND050200 (Figures C.27 and C.28)
(+5) Peat/Soft ground present NGR location ND030180 (Figures C.29 and C.30)
(+5) Deforestation close to road NGR location ND040170 and ND080210 (Figures C.31 and C.32)
(+5) Roads/track shown on aerial photography to second BT Antenna which does not appear on OS mapping NGR location ND030180 (Figures C.33 and C.34)

Further investigation required:
Investigate new road and peat/soft ground on Creag Thraraidh near BT antenna. Examine extend of deforestation and instability.

Drive-By

Reasons for scoring:
(+10) Recent instability NGR location ND050200
(+5) Peat/Soft ground present NGR location ND030180
(+5) Deforestation close to road NGR location ND040170 and ND080210
(+5) Roads/track to second BT Antenna
New forest roads on each side of stream NGR location ND040170 (Figures C.35 and C.36)

Further investigation required:
Gain access to BT antenna roads to examine Peat/Soft ground and new roads

Limitations/Problems encountered:
Lack of aerial photography for southern section of site (Helmsdale) NGR locations ND020150/160 ND030150/160

Walkover Survey

Reasons for scoring:
(+10) Recent instability NGR location ND050200
(+5) Peat/Soft ground present NGR location ND030180
(+5) Deforestation close to road NGR location ND040170 and ND080210
(+5) Roads/track to second BT Antenna
New forest roads on each side of stream NGR location ND040170

Features/differences noted from drive-by & desk study:
New forest tracks located each side of stream NGR location ND040170 (Figures C.35, C.36)

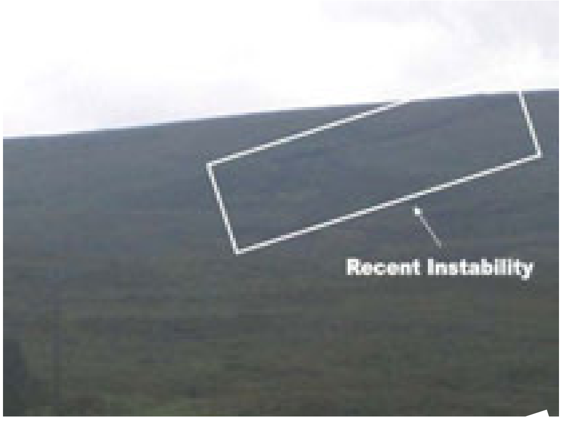


Figure C.27 – Recent instability (upper right part of slope) NGR location ND050200 taken from NGR location ND080200 facing West.

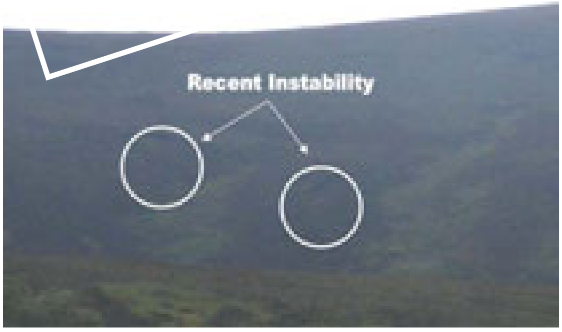


Figure C.28 – Recent instability (either side of the centre of the area illustrated in the picture) NGR location ND050190 taken from NGR location ND080200 facing West.

Figure C.29 – Peat/Soft ground located next to new BT antenna road facing South East NGR location ND030180.

Figure C.30 – Peat/Soft ground NGR location ND030180.

Figure C.31 – Deforestation located by Creagan Cosach (above break in slope) NGR location ND080210 taken from NGR location ND080200 facing North.

Figure C.32 – Deforestation NGR location ND040170 taken from NGR location ND048174 facing West.

Figure C.33 – New road to second BT antenna facing West NGR location ND030180.

Figure C.35 – New road next to stream facing North NGR location ND040170.

Figure C.34 – New road to second BT antenna facing South East NGR location ND030180.

Figure C.36 – Second new road on opposite side of stream facing North West NGR location ND040170.

C.1.7 Sample Report for A9-35a

Debris Flow Study

Location:	Drumochter	*Date:*	14/06/07
Grid Reference:	NN 6383	*Weather Conditions:*	Dry and sunny
Route Number:	A9 – 35a	*Observations made by:*	B.Lynch, P.Egan C.Boler, N.Horsburgh

Desk Study

Reasons for scoring: (+10) Recent instability present (Figure C.37) (+5) Roads/ tracks present to the rear of Drumochter Lodge (Figures C.38 to C.40)
Further investigation required: Investigation of roads/ tracks behind Drumochter Lodge and evidence of instability. Check Culverts Sizes (Figure C.42 to C.44) and accumulation of debris in streams (Figure C.41)

Drive-By

Reasons for scoring: (+10) Evidence of recent instability (Figure C.37) (+5) Roads/ tracks present to the rear of Drumochter Lodge. (Figures C.38 to C.40)
Further investigation required: Investigate tracks to rear of Drumochter Lodge.
Limitations/Problems encountered:

Walkover Survey

Reasons for scoring: (+10) Evidence of recent instability (Figure C.37) (0) Roads/ tracks present to the rear of Drumochter Lodge as low lying roads not affecting drainage of hills. (Figures C.38 to C.40)
Features/differences noted from drive-by & desk study: Roads/Tracks

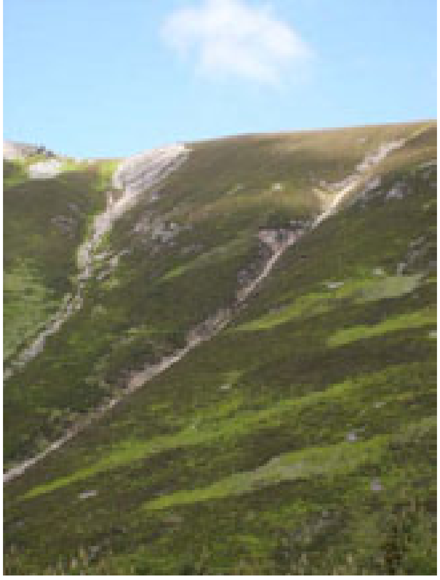


Figure C.37 – Evidence of recent instability NGR location NN630760.

Figure C.38 – Tracks present to rear of Drumochter lodge NGR location NN630790.

Figure C.39 – Tracks present to rear of Drumochter Lodge NGR location NN630790.

Figure C.40 – Drainage installed on tracks present behind Drumochter lodge NGR location NN630790.

Figure C.41 – Possible source of debris accumulation in streams.

Figure C.42 – Bridge NGR location NN630800.

Figure C.43 – Old Masonry Bridge extended to form large culvert NGR location NN640730

Figure C.44 – Large Culvert NGR location NN630750.

C.1.8 Sample Report for A95-08

Location:	Advie	*Date:*	06/09/07
Grid Reference:	NJ14757 34755	*Weather Conditions:*	Cloudy
Route Number:	A95 - 08	*Observations made by:*	C.Boler N.Horsburgh

Desk Study

Reasons for scoring: + 5 Concentrated dentritic streams in area around NGR location NJ140330
Further investigation required: Drive-by incorporating an inspection of forestry and hillside

Drive-By

Reasons for scoring: (Zero) – Deforestation in Woods of Knockfrink - replanted
Further investigation required:
Limitations/Problems encountered:

Walkover Survey

Reasons for scoring: (Zero) - Instability on Creag n Tarmachain around NGR location NJ140100. Zero scored as approximately 3km to the south-east of the road. Irrigation stream installed alongside the track running south opposite Mains of Advie from Burn of Corie Seileach. Not shown on OS map.
Features/differences noted from drive-by & desk study:

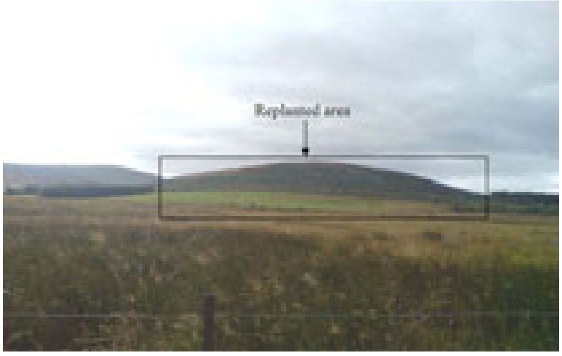


Figure C.45 – Deforestation (replanted on hill in centre of picture), taken from NGR location NJ120335 looking south-east towards the Woods of Knockfrink.

Figure C.46 – Irrigation stream, taken from NGR location NJ135338 looking west.

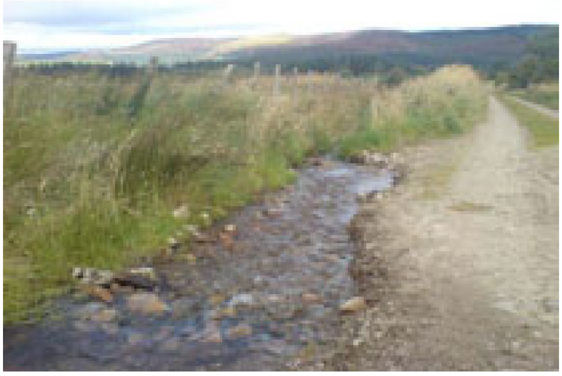


Figure C.47 – Irrigation stream, taken from NGR location NJ135338 looking north.

C.2.1 Sample Score Sheets

Table C.1 – Site inspection hazard score sheet for A82-17.

Scottish Road Network Landslides Study - Site-Specific Assessments

DATA ENTRY ONLY TO GREYED OUT CELLS

Route Code: A82-17 **OC Unit:** NW
Start NGR: NN 28766 96227 **End NGR:** NN 21391 85632 **Length:** 13,400 m
Action: Main Study **Priority:** 1

[1] Scores are not progressive: i.e. either the full score is applied or none at all is applied.

	Feature	Information Source and Quality							SCORE	SCORE	SCORE
		OS Mapping	GIS-Based Assessment	Aerial Photography	Site Inspection	Factor Effect on Score	Possible Scores[1]	Remarks	Initial Drive Through	Desk Study	Detailed Site Inspection
1	*Water*										
A	Streams roughly parallel to line of maximum slope	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
B	Concentrated dendritic stream patterns	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
C	Evidence of restriction and/or debris accumulation in stream(s)	None	None	Good	Very Good	+	0 or 5	Independent of 1A and 1B	5	0	5
D	Large flat catchment at/close to head of slope	Variable	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	5	0
E	Large culverts under road	Poor	None	Good	Very Good	-	-10 or 0	Subjectively capable of accommodating large water/debris volumes	0	0	0
2	*Instability*										
A	Evidence of historical instability (with no soil/fresh rock exposure)	None	None	Good	Good	+	0 or 5	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	5	5	5
B	Evidence of recent instability (with soil/fresh rock exposure) - e.g. scarps, debris fans, etc	None	None	Good	Good	+	0 or 10	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	10	0	10
C	Areas of shallow sloped peat/soft ground high on hillside/near to stream	Poor	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	5	5	5
D	Oversteepening near to toe of slope	Poor	None	Poor	Very Good	+	0 or 5	Can lead to localised instability as well as potentially increasing velocity of toe	0	0	0
3	*Slope/Topography*										
A	Convex sloped hillside	Good	None	Poor	Very Good	+	0 or 5	Convex slopes often associated with debris flow as profile encourages acceleration	0	0	0
B	Road located part-way up 'S'-shape of hillside	Good	None	Good	Very Good	+	0 or 10	Increases hazard to road user as flow likely to be fast-moving at road level	0	0	0
C	Potentially protective features alongside and local to the road (e.g. embankments) that would not be immediately apparent from OS mapping	Poor	None	Variable	Very Good	+	-10 or 0	Decreases hazard to road user as flow likely to be arrested by barrier	0	0	0
4	*Vegetation and Land-Use*										
A	Aforestation close to the road (below hazard and above road) either less (+5) or more (-5)	Poor	None	Good	Very Good	-	-5, 0 or 5	Can slow or stop flow(s), thus preventing them from reaching the road	5	0	5
B	Agricultural ploughing trending down slope and towards stream channels	None	None	Variable	Very Good	+	0 or 5	Encourages water and associated erosion into the stream and flow propogation	0	0	0
C	Largely exposed rock on hillside	Poor	None	Good	Very Good	-	-10 or 0	No/limited material to form a flow	0	0	0
D	Forest (or other) roads on slope following the contours above trunk road (especially if in combination with streams, as per 1A above)	Good	None	Good	Poor	+	0 or 5	Can concentrate water into a particular location on the slope, accumulate debris for later flows and/or accelerate flow by venturi effect at culverts	0	0	0
								Additive / Subtractive Hazard Score	**30**	**15**	**30**
								Adjusted Additive / Subtractive Hazard Score	**20**	**15**	**20**

Table C.2 – Site inspection hazard score sheet for A82-08.

Scottish Road Network Landslides Study - Site-Specific Assessments

DATA ENTRY ONLY TO GREYED OUT CELLS

Route Code: A82-08 **OC Unit:** NW
Start NGR: NH 45761 19182 **End NGR:** NH 43486 16747 **Length:** 3,410 m
Action: Main Study **Priority:** 1

[1] Scores are not progressive: i.e. either the full score is applied or none at all is applied.

	Feature	Information Source and Quality				Factor Effect on Score	Possible Scores[1]	Remarks	SCORE	SCORE	SCORE
		OS Mapping	GIS-Based Assessment	Aerial Photography	Site Inspection				Initial Drive Through	Desk Study	Detailed Site Inspection
1	***Water***										
A	Streams roughly parallel to line of maximum slope	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
B	Concentrated dendritic stream patterns	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
C	Evidence of restriction and/or debris accumulation in stream(s)	None	None	Good	Very Good	+	0 or 5	Independent of 1A and 1B	0	0	5
D	Large flat catchment at/close to head of slope	Variable	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
E	Large culverts under road	Poor	None	Good	Very Good	-	-10 or 0	Subjectively capable of accommodating large water/debris volumes	0	0	0
2	***Instability***										
A	Evidence of historical instability (with no soil/fresh rock exposure)	None	None	Good	Good	+	0 or 5	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
B	Evidence of recent instability (with soil/fresh rock exposure) - e.g. scarps, debris fans, etc	None	None	Good	Good	+	0 or 10	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
C	Areas of shallow sloped peat/soft ground high on hillside/near to stream	Poor	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
D	Oversteepening near to toe of slope	Poor	None	Poor	Very Good	+	0 or 5	Can lead to localised instability as well as potentially increasing velocity of toe	0	0	0
3	***Slope/Topography***										
A	Convex sloped hillside	Good	None	Poor	Very Good	+	0 or 5	Convex slopes often associated with debris flow as profile encourages acceleration	0	0	0
B	Road located part-way up 'S'-shape of hillside	Good	None	Good	Very Good	+	0 or 10	Increases hazard to road user as flow likely to be fast-moving at road level	0	0	0
C	Potentially protective features alongside and local to the road (e.g. embankments) that would not be immediately apparent from OS mapping	Poor	None	Variable	Very Good	+	-10 or 0	Decreases hazard to road user as flow likely to be arrested by barrier	0	0	0
4	***Vegetation and Land-Use***										
A	Aforestation close to the road (below hazard and above road) either less (+5) or more (-5)	Poor	None	Good	Very Good	-	-5, 0 or 5	Can slow or stop flow(s), thus preventing them from reaching the road	5	5	5
B	Agricultural ploughing trending down slope and towards stream channels	None	None	Variable	Very Good	+	0 or 5	Encourages water and associated erosion into the stream and flow propogation	0	0	0
C	Largely exposed rock on hillside	Poor	None	Good	Very Good	-	-10 or 0	No/limited material to form a flow	0	0	0
D	Forest (or other) roads on slope following the contours above trunk road (especially if in combination with streams, as per 1A above)	Good	None	Good	Poor	+	0 or 5	Can concentrate water into a particular location on the slope, accumulate debris for later flows and/or accelerate flow by venturi effect at culverts	0	0	0
								Additive / Subtractive Hazard Score	**5**	**5**	**10**
								Adjusted Additive / Subtractive Hazard Score	**5**	**5**	**10**

Table C.3 – Site inspection hazard score sheet for A85-09.

Scottish Road Network Landslides Study - Site-Specific Assessments

DATA ENTRY ONLY TO GREYED OUT CELLS

Route Code: A85-09
Start NGR: NN 50672 28326
Action: Main Study

OC Unit: NW
End NGR: NN 38766 25266
Priority: 2

Length: 12,900 m

	Feature	Information Source and Quality							SCORE	SCORE	SCORE
		OS Mapping	**GIS-Based Assessment**	**Aerial Photography**	**Site Inspection**	**Factor Effect on Score**	**Possible Scores**[1]	**Remarks**	Initial Drive Through	Desk Study	Detailed Site Inspection
1	***Water***										
A	Streams roughly parallel to line of maximum slope	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
B	Concentrated dendritic stream patterns	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
C	Evidence of restriction and/or debris accumulation in stream(s)	None	None	Good	Very Good	+	0 or 5	Independent of 1A and 1B	5	0	5
D	Large flat catchment at/close to head of slope	Variable	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	5	5	5
E	Large culverts under road	Poor	None	Good	Very Good	-	-10 or 0	Subjectively capable of accommodating large water/debris volumes	0	0	0
2	***Instability***										
A	Evidence of historical instability (with no soil/fresh rock exposure)	None	None	Good	Good	+	0 or 5	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	5	5	5
B	Evidence of recent instability (with soil/fresh rock exposure) - e.g. scarps, debris fans, etc	None	None	Good	Good	+	0 or 10	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	10	0	10
C	Areas of shallow sloped peat/soft ground high on hillside/near to stream	Poor	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	5	0	5
D	Oversteepening near to toe of slope	Poor	None	Poor	Very Good	+	0 or 5	Can lead to localised instability as well as potentially increasing velocity of toe	0	0	0
3	***Slope/Topography***										
A	Convex sloped hillside	Good	None	Poor	Very Good	+	0 or 5	Convex slopes often associated with debris flow as profile encourages acceleration	0	0	0
B	Road located part-way up 'S'-shape of hillside	Good	None	Good	Very Good	+	0 or 10	Increases hazard to road user as flow likely to be fast-moving at road level	0	0	0
C	Potentially protective features alongside and local to the road (e.g. embankments) that would not be immediately apparent from OS mapping	Poor	None	Variable	Very Good	+	-10 or 0	Decreases hazard to road user as flow likely to be arrested by barrier	0	0	0
4	***Vegetation and Land-Use***										
A	Aforestation close to the road (below hazard and above road) either less (+5) or more (-5)	Poor	None	Good	Very Good	-	-5, 0 or 5	Can slow or stop flow(s), thus preventing them from reaching the road	5	5	5
B	Agricultural ploughing trending down slope and towards stream channels	None	None	Variable	Very Good	+	0 or 5	Encourages water and associated erosion into the stream and flow propogation	0	0	0
C	Largely exposed rock on hillside	Poor	None	Good	Very Good	-	-10 or 0	No/limited material to form a flow	0	0	0
D	Forest (or other) roads on slope following the contours above trunk road (especially if in combination with streams, as per 1A above)	Good	None	Good	Poor	+	0 or 5	Can concentrate water into a particular location on the slope, accumulate debris for later flows and/or accelerate flow by venturi effect at culverts	5	5	5
								Additive / Subtractive Hazard Score	**40**	**20**	**40**
								Adjusted Additive / Subtractive Hazard Score	**40**	**20**	**40**

[1] Scores are not progressive: i.e. either the full score is applied or none at all is applied.

Table C.4 – Site inspection hazard score sheet for A87-13.

Scottish Road Network Landslides Study - Site-Specific Assessments

DATA ENTRY ONLY TO GREYED OUT CELLS

Route Code: A87-13
Start NGR: NG 96259 14951
Action: Main Study

OC Unit: NW
End NGR: NG 94614 17946
Priority: 2

Length: 3,790 m

[1] Scores are not progressive: i.e. either the full score is applied or none at all is applied.

	Feature	**Information Source and Quality**				**Factor Effect on Score**	**Possible Scores**[1]	**Remarks**	**SCORE** Initial Drive Through	**SCORE** Desk Study	**SCORE** Detailed Site Inspection
		OS Mapping	**GIS-Based Assessment**	**Aerial Photography**	**Site Inspection**						
1	***Water***										
A	Streams roughly parallel to line of maximum slope	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
B	Concentrated dendritic stream patterns	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	5	5	5
C	Evidence of restriction and/or debris accumulation in stream(s)	None	None	Good	Very Good	+	0 or 5	Independent of 1A and 1B	0	0	0
D	Large flat catchment at/close to head of slope	Variable	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
E	Large culverts under road	Poor	None	Good	Very Good	-	-10 or 0	Subjectively capable of accommodating large water/debris volumes	0	0	0
2	***Instability***										
A	Evidence of historical instability (with no soil/fresh rock exposure)	None	None	Good	Good	+	0 or 5	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	5	5	5
B	Evidence of recent instability (with soil/fresh rock exposure) - e.g. scarps, debris fans, etc	None	None	Good	Good	+	0 or 10	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	10
C	Areas of shallow sloped peat/soft ground high on hillside/near to stream	Poor	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
D	Oversteepening near to toe of slope	Poor	None	Poor	Very Good	+	0 or 5	Can lead to localised instability as well as potentially increasing velocity of toe	0	0	0
3	***Slope/Topography***										
A	Convex sloped hillside	Good	None	Poor	Very Good	+	0 or 5	Convex slopes often associated with debris flow as profile encourages acceleration	0	0	0
B	Road located part-way up 'S'-shape of hillside	Good	None	Good	Very Good	+	0 or 10	Increases hazard to road user as flow likely to be fast-moving at road level	0	0	0
C	Potentially protective features alongside and local to the road (e.g. embankments) that would not be immediately apparent from OS mapping	Poor	None	Variable	Very Good	+	-10 or 0	Decreases hazard to road user as flow likely to be arrested by barrier	0	0	0
4	***Vegetation and Land-Use***										
A	Aforestation close to the road (below hazard and above road) either less (+5) or more (-5)	Poor	None	Good	Very Good	-	-5, 0 or 5	Can slow or stop flow(s), thus preventing them from reaching the road	5	5	5
B	Agricultural ploughing trending down slope and towards stream channels	None	None	Variable	Very Good	+	0 or 5	Encourages water and associated erosion into the stream and flow propogation	0	0	0
C	Largely exposed rock on hillside	Poor	None	Good	Very Good	-	-10 or 0	No/limited material to form a flow	0	0	0
D	Forest (or other) roads on slope following the contours above trunk road (especially if in combination with streams, as per 1A above)	Good	None	Good	Poor	+	0 or 5	Can concentrate water into a particular location on the slope, accumulate debris for later flows and/or accelerate flow by venturi effect at culverts	5	5	5
								Additive / Subtractive Hazard Score	**20**	**20**	**30**
								Adjusted Additive / Subtractive Hazard Score	**20**	**20**	**30**

Table C.5 – Site inspection hazard score sheet for A835-07.

Scottish Road Network Landslides Study - Site-Specific Assessments

DATA ENTRY ONLY TO GREYED OUT CELLS

Route Code: A835-07
Start NGR: NH 38284 70387
Action: Main Study

OC Unit: NW
End NGR: NH 28554 73906
Priority: 1

Length: 11,400 m

	Feature	Information Source and Quality							SCORE	SCORE	SCORE
		OS Mapping	GIS-Based Assessment	Aerial Photography	Site Inspection	Factor Effect on Score	Possible Scores[1]	Remarks	Initial Drive Through	Desk Study	Detailed Site Inspection
1	*Water*										
A	Streams roughly parallel to line of maximum slope	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
B	Concentrated dendritic stream patterns	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
C	Evidence of restriction and/or debris accumulation in stream(s)	None	None	Good	Very Good	+	0 or 5	Independent of 1A and 1B	0	0	0
D	Large flat catchment at/close to head of slope	Variable	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
E	Large culverts under road	Poor	None	Good	Very Good	-	-10 or 0	Subjectively capable of accommodating large water/debris volumes	0	0	0
2	*Instability*										
A	Evidence of historical instability (with no soil/fresh rock exposure)	None	None	Good	Good	+	0 or 5	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
B	Evidence of recent instability (with soil/fresh rock exposure) - e.g. scarps, debris fans, etc	None	None	Good	Good	+	0 or 10	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
C	Areas of shallow sloped peat/soft ground high on hillside/near to stream	Poor	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	5	5	5
D	Oversteepening near to toe of slope	Poor	None	Poor	Very Good	+	0 or 5	Can lead to localised instability as well as potentially increasing velocity of toe	0	0	0
3	*Slope/Topography*										
A	Convex sloped hillside	Good	None	Poor	Very Good	+	0 or 5	Convex slopes often associated with debris flow as profile encourages acceleration	0	0	0
B	Road located part-way up 'S'-shape of hillside	Good	None	Good	Very Good	+	0 or 10	Increases hazard to road user as flow likely to be fast-moving at road level	0	0	0
C	Potentially protective features alongside and local to the road (e.g. embankments) that would not be immediately apparent from OS mapping	Poor	None	Variable	Very Good	+	-10 or 0	Decreases hazard to road user as flow likely to be arrested by barrier	0	0	0
4	*Vegetation and Land-Use*										
A	Aforestation close to the road (below hazard and above road) either less (+5) or more (-5)	Poor	None	Good	Very Good	-	-5, 0 or 5	Can slow or stop flow(s), thus preventing them from reaching the road	5	5	5
B	Agricultural ploughing trending down slope and towards stream channels	None	None	Variable	Very Good	+	0 or 5	Encourages water and associated erosion into the stream and flow propogation	0	0	0
C	Largely exposed rock on hillside	Poor	None	Good	Very Good	-	-10 or 0	No/limited material to form a flow	0	0	0
D	Forest (or other) roads on slope following the contours above trunk road (especially if in combination with streams, as per 1A above)	Good	None	Good	Poor	+	0 or 5	Can concentrate water into a particular location on the slope, accumulate debris for later flows and/or accelerate flow by venturi effect at culverts	0	0	0
								Additive / Subtractive Hazard Score	**10**	**10**	**10**
								Adjusted Additive / Subtractive Hazard Score	**10**	**10**	**10**

[1] Scores are not progressive: i.e. either the full score is applied or none at all is applied.

Table C.6 – Site inspection hazard score sheet for A9-11.

Scottish Road Network Landslides Study - Site-Specific Assessments

DATA ENTRY ONLY TO GREYED OUT CELLS

Route Code: A9-11 **OC Unit:** NW
Start NGR: ND 08775 20794 **End NGR:** ND 02860 15349 **Length:** 11,200 m
Action: Main Study **Priority:** 1

[1] Scores are not progressive: i.e. either the full score is applied or none at all is applied.

	Feature	Information Source and Quality							SCORE	SCORE	SCORE
		OS Mapping	GIS-Based Assessment	Aerial Photography	Site Inspection	Factor Effect on Score	Possible Scores[1]	Remarks	Initial Drive Through	Desk Study	Detailed Site Inspection
1	*Water*										
A	Streams roughly parallel to line of maximum slope	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
B	Concentrated dendritic stream patterns	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
C	Evidence of restriction and/or debris accumulation in stream(s)	None	None	Good	Very Good	+	0 or 5	Independent of 1A and 1B	0	0	0
D	Large flat catchment at/close to head of slope	Variable	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
E	Large culverts under road	Poor	None	Good	Very Good	-	-10 or 0	Subjectively capable of accommodating large water/debris volumes	0	0	0
2	*Instability*										
A	Evidence of historical instability (with no soil/fresh rock exposure)	None	None	Good	Good	+	0 or 5	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
B	Evidence of recent instability (with soil/fresh rock exposure) - e.g. scarps, debris fans, etc	None	None	Good	Good	+	0 or 10	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	10	10	10
C	Areas of shallow sloped peat/soft ground high on hillside/near to stream	Poor	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	5	5	5
D	Oversteepening near to toe of slope	Poor	None	Poor	Very Good	+	0 or 5	Can lead to localised instability as well as potentially increasing velocity of toe	0	0	0
3	*Slope/Topography*										
A	Convex sloped hillside	Good	None	Poor	Very Good	+	0 or 5	Convex slopes often associated with debris flow as profile encourages acceleration	0	0	0
B	Road located part-way up 'S'-shape of hillside	Good	None	Good	Very Good	+	0 or 10	Increases hazard to road user as flow likely to be fast-moving at road level	0	0	0
C	Potentially protective features alongside and local to the road (e.g. embankments) that would not be immediately apparent from OS mapping	Poor	None	Variable	Very Good	+	-10 or 0	Decreases hazard to road user as flow likely to be arrested by barrier	0	0	0
4	*Vegetation and Land-Use*										
A	Aforestation close to the road (below hazard and above road) either less (+5) or more (-5)	Poor	None	Good	Very Good	-	-5, 0 or 5	Can slow or stop flow(s), thus preventing them from reaching the road	5	5	5
B	Agricultural ploughing trending down slope and towards stream channels	None	None	Variable	Very Good	+	0 or 5	Encourages water and associated erosion into the stream and flow propogation	0	0	0
C	Largely exposed rock on hillside	Poor	None	Good	Very Good	-	-10 or 0	No/limited material to form a flow	0	0	0
D	Forest (or other) roads on slope following the contours above trunk road (especially if in combination with streams, as per 1A above)	Good	None	Good	Poor	+	0 or 5	Can concentrate water into a particular location on the slope, accumulate debris for later flows and/or accelerate flow by venturi effect at culverts	5	5	5
								Additive / Subtractive Hazard Score	**25**	**25**	**25**
								Adjusted Additive / Subtractive Hazard Score	**20**	**20**	**20**

Table C.7 – Site inspection hazard score sheet for A9-35a.

Scottish Road Network Landslides Study - Site-Specific Assessments

DATA ENTRY ONLY TO GREYED OUT CELLS

Route Code: A9-35a
Start NGR: NN 63982 83957
Action: Main Study

OC Unit: NW
End NGR: NN 64987 73046
Priority: 2

Length: 11,900 m

	Feature	Information Source and Quality							SCORE	SCORE	SCORE
		OS Mapping	GIS-Based Assessment	Aerial Photography	Site Inspection	Factor Effect on Score	Possible Scores[1]	Remarks	Initial Drive Through	Desk Study	Detailed Site Inspection
1	*Water*										
A	Streams roughly parallel to line of maximum slope	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
B	Concentrated dendritic stream patterns	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
C	Evidence of restriction and/or debris accumulation in stream(s)	None	None	Good	Very Good	+	0 or 5	Independent of 1A and 1B	0	0	0
D	Large flat catchment at/close to head of slope	Variable	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
E	Large culverts under road	Poor	None	Good	Very Good	-	-10 or 0	Subjectively capable of accommodating large water/debris volumes	0	0	0
2	*Instability*										
A	Evidence of historical instability (with no soil/fresh rock exposure)	None	None	Good	Good	+	0 or 5	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
B	Evidence of recent instability (with soil/fresh rock exposure) - e.g. scarps, debris fans, etc	None	None	Good	Good	+	0 or 10	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	10	10	10
C	Areas of shallow sloped peat/soft ground high on hillside/near to stream	Poor	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
D	Oversteepening near to toe of slope	Poor	None	Poor	Very Good	+	0 or 5	Can lead to localised instability as well as potentially increasing velocity of toe	0	0	0
3	*Slope/Topography*										
A	Convex sloped hillside	Good	None	Poor	Very Good	+	0 or 5	Convex slopes often associated with debris flow as profile encourages acceleration	0	0	0
B	Road located part-way up 'S'-shape of hillside	Good	None	Good	Very Good	+	0 or 10	Increases hazard to road user as flow likely to be fast-moving at road level	0	0	0
C	Potentially protective features alongside and local to the road (e.g. embankments) that would not be immediately apparent from OS mapping	Poor	None	Variable	Very Good	+	-10 or 0	Decreases hazard to road user as flow likely to be arrested by barrier	0	0	0
4	*Vegetation and Land-Use*										
A	Aforestation close to the road (below hazard and above road) either less (+5) or more (-5)	Poor	None	Good	Very Good	-	-5, 0 or 5	Can slow or stop flow(s), thus preventing them from reaching the road	0	0	0
B	Agricultural ploughing trending down slope and towards stream channels	None	None	Variable	Very Good	+	0 or 5	Encourages water and associated erosion into the stream and flow propogation	0	0	0
C	Largely exposed rock on hillside	Poor	None	Good	Very Good	-	-10 or 0	No/limited material to form a flow	0	0	0
D	Forest (or other) roads on slope following the contours above trunk road (especially if in combination with streams, as per 1A above)	Good	None	Good	Poor	+	0 or 5	Can concentrate water into a particular location on the slope, accumulate debris for later flows and/or accelerate flow by venturi effect at culverts	5	5	0
								Additive / Subtractive Hazard Score	**15**	**15**	**10**
								Adjusted Additive / Subtractive Hazard Score	**15**	**15**	**10**

[1] Scores are not progressive: i.e. either the full score is applied or none at all is applied.

Table C.8 – Site inspection hazard score sheet for A95-08.

Scottish Road Network Landslides Study - Site-Specific Assessments

DATA ENTRY ONLY TO GREYED OUT CELLS

Route Code: A95-08
Start NGR: NJ 14757 34755
Action: Main Study

OC Unit: NE
End NGR: NJ 10537 32135
Priority: 2

Length: 5,880 m

	Feature	Information Source and Quality				Factor Effect on Score	Possible Scores[1]	Remarks	SCORE Initial Drive Through	SCORE Desk Study	SCORE Site Inspection
		OS Mapping	GIS-Based Assessment	Aerial Photography	Site Inspection						
1	*Water*										
A	Streams roughly parallel to line of maximum slope	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	0	0	0
B	Concentrated dendritic stream patterns	Good	None	Good	Poor	+	0 or 5	Only 1A or 1B may be scored (if at all)	5	5	5
C	Evidence of restriction and/or debris accumulation in stream(s)	None	None	Good	Very Good	+	0 or 5	Independent of 1A and 1B	0	0	0
D	Large flat catchment at/close to head of slope	Variable	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
E	Large culverts under road	Poor	None	Good	Very Good	-	-10 or 0	Subjectively capable of accommodating large water/debris volumes	0	0	0
2	*Instability*										
A	Evidence of historical instability (with no soil/fresh rock exposure)	None	None	Good	Good	+	0 or 5	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
B	Evidence of recent instability (with soil/fresh rock exposure) - e.g. scarps, debris fans, etc	None	None	Good	Good	+	0 or 10	Such evidence may include, but is not excluded to, scarps, debris fans and grabens.	0	0	0
C	Areas of shallow sloped peat/soft ground high on hillside/near to stream	Poor	Good	Poor	Very Good	+	0 or 5	Potential source/accumulation of debris	0	0	0
D	Oversteepening near to toe of slope	Poor	None	Poor	Very Good	+	0 or 5	Can lead to localised instability as well as potentially increasing velocity of toe	0	0	0
3	*Slope/Topography*										
A	Convex sloped hillside	Good	None	Poor	Very Good	+	0 or 5	Convex slopes often associated with debris flow as profile encourages acceleration	0	0	0
B	Road located part-way up 'S'-shape of hillside	Good	None	Good	Very Good	+	0 or 10	Increases hazard to road user as flow likely to be fast-moving at road level	0	0	0
C	Potentially protective features alongside and local to the road (e.g. embankments) that would not be immediately apparent from OS mapping	Poor	None	Variable	Very Good	+	-10 or 0	Decreases hazard to road user as flow likely to be arrested by barrier	0	0	0
4	*Vegetation and Land-Use*										
A	Aforestation close to the road (below hazard and above road) either less (+5) or more (-5)	Poor	None	Good	Very Good	-	-5, 0 or 5	Can slow or stop flow(s), thus preventing them from reaching the road	0	0	0
B	Agricultural ploughing trending down slope and towards stream channels	None	None	Variable	Very Good	+	0 or 5	Encourages water and associated erosion into the stream and flow propogation	0	0	0
C	Largely exposed rock on hillside	Poor	None	Good	Very Good	-	-10 or 0	No/limited material to form a flow	0	0	0
D	Forest (or other) roads on slope following the contours above trunk road (especially if in combination with streams, as per 1A above)	Good	None	Good	Poor	+	0 or 5	Can concentrate water into a particular location on the slope, accumulate debris for later flows and/or accelerate flow by venturi effect at culverts	0	0	0
								Additive / Subtractive Hazard Score	**5**	**5**	**5**
								Adjusted Additive / Subtractive Hazard Score	**5**	**5**	**5**

[1] Scores are not progressive: i.e. either the full score is applied or none at all is applied.

C.2 HAZARD SCORES

Table C.9 – Hazard assessment scores for sites inspected in 2007.

Route Code	Priority	Initial Score	Desk Study		Initial Drive Through		Detailed Inspection		Total After Detailed Inspection			Increase From Site Inspection Process	Scorer's Comments
			Raw Data	Adjusted	Raw Data	Adjusted	Raw Data	Adjusted	Raw	Adjusted	Reduction (R - A)		
A77-11	2	60	20	20	0	0	20	20	80	80	0	20	
A82-02	1	80	20	20	5	5	20	20	100	100	0	20	
A82-04	1	80	0	0	0	0	0	0	80	80	0	0	No hazard reported
A82-05	2	60	10	10	20	20	5	5	65	65	0	5	
A82-08	1	80	5	5	5	5	10	10	90	90	0	10	
A82-09	1	80	0	0	0	0	0	0	80	80	0	0	No evidence of problems
A82-17	1	80	30	20	15	15	30	20	110	100	10	20	
A82-26	2	60	20	20	5	5	20	20	80	80	0	20	
A82-34	1	80	25	20	20	20	30	20	110	100	10	20	
A83-05	1	80	30	20	15	15	30	20	110	100	10	20	
A83-06	2	60	25	25	15	15	25	25	85	85	0	25	
A85-08	1	80	45	20	35	20	55	20	135	100	35	20	
A85-09	2	60	40	40	20	20	40	40	100	100	0	40	
A85-15	1	80	10	10	-5	-5	10	10	90	90	0	10	
A86-03	1	80	0	0	5	5	0	0	80	80	0	0	
A86-09	1	80	0	0	0	0	0	0	80	80	0	0	
A86-10	2	60	20	20	10	10	15	15	75	75	0	15	
A86-11	2	60	15	15	15	15	15	15	75	75	0	15	
A86-12	1	80	10	10	15	15	10	10	90	90	0	10	
A87-07	2	60	0	0	0	0	0	0	60	60	0	0	
A87-09	1	80	5	5	10	10	15	15	95	95	0	15	
A87-12	1	80	30	20	40	20	30	20	110	100	10	20	
A87-13	2	60	20	20	20	20	30	30	90	90	0	30	
A87-15	1	80	5	5	0	0	20	20	100	100	0	20	
A87-20	2	60	5	5	5	5	15	15	75	75	0	15	
A828-01	2	60	20	20	15	15	30	30	90	90	0	30	
A830-05	2	60	10	10	0	0	10	10	70	70	0	10	
A835-07	1	80	10	10	10	10	10	10	90	90	0	10	
A887-01	2	60	5	5	5	5	5	5	65	65	0	5	
A9-11	1	80	25	20	25	20	25	20	105	100	5	20	
A9-34	2	60	0	0	5	5	0	0	60	60	0	0	
A9-35a	2	60	15	15	15	15	10	10	70	70	0	10	
A9-35b	1	80	10	10	0	0	10	10	90	90	0	10	
A95-05	2	60	10	10	0	0	10	10	70	70	0	10	
A95-08	2	60	5	5	5	5	5	5	65	65	0	5	
A95-09	2	60	0	0	0	0	0	0	60	60	0	0	
											Average Increase P1 & P2	**13.33**	
											Average Increase P1	**12.50**	
											Average Increase P2	**14.17**	

APPENDIX D – HAZARD, EXPOSURE AND HAZARD RANKING RESULTS

by M G Winter and F Macgregor

D.1 EXPOSURE SCORES

Table D.1 – Exposure scores for Priority 1 sites.

Route Code	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	AADT Evaluated (veh/day)	AADT Exposure Score	Commentary on AADT Exposure Score	Diversion Exposure Score	Diversion Implications	Exposure Score
A82-02	NW	NH 60696 39243	NH 57346 34993	5,520	**1**	4,356	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A82-04	NW	NH 52391 30037	NH 50831 30172	1,590	**1**	4,356	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A82-08	NW	NH 45761 19182	NH 43486 16747	3,410	**1**	2,910	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A82-09	NW	NH 42981 16557	NH 42451 16667	581	**1**	2,910	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A82-17	NW	NN 28766 96227	NN 21391 85632	13,400	**1**	3,493	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A82-34	NW	NN 33296 20776	NN 31776 09196	13,500	**1**	3,723	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A82-37	NW	NN 34026 00456	NS 34556 97686	3,300	**1**	7,886	2.0	7,500<AADT=25,000	1	Significant	**2.5**
A83-02	NW	NN 26901 03861	NN 23021 07837	6,310	**1**	4,294	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A83-04	NW	NN 23421 09592	NN 19096 09927	4,360	**1**	4,294	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A83-05	NW	NN 18406 11247	NN 19406 12512	1,620	**1**	1,395	1.0	AADT=2,500	1	Significant	**1.5**
A835-07	NW	NH 38284 70387	NH 28554 73906	11,400	**1**	1,610	1.0	AADT=2,500	1	Significant	**1.5**
A85-08	NW	NN 58437 24970	NN 55677 29396	5,480	**1**	3,977	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A85-15	NW	NN 13191 28352	NN 03135 29863	12,400	**1**	3,223	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A86-03	NW	NN 67317 95722	NN 67162 95417	357	**1**	1,066	1.0	AADT=2,500	1	Significant	**1.5**
A86-09	NW	NN 48856 87552	NN 47661 86407	1,730	**1**	1,256	1.0	AADT=2,500	1	Significant	**1.5**
A86-12	NW	NN 25591 81307	NN 22966 81947	2,770	**1**	1,256	1.0	AADT=2,500	1	Significant	**1.5**
A87-09	NW	NH 11495 10731	NH 09725 11731	2,080	**1**	2,170	1.0	AADT=2,500	1	Significant	**1.5**
A87-12	NW	NH 03370 12016	NG 96289 14946	8,620	**1**	2,170	1.0	AADT=2,500	1	Significant	**1.5**
A87-15	NW	NG 94469 21121	NG 88269 26106	8,650	**1**	2,170	1.0	AADT=2,500	1	Significant	**1.5**
A9-11	NW	ND 08775 20794	ND 02860 15349	11,200	**1**	1,950	1.0	AADT=2,500	2	More significant	**2.0**
A9-12	NW	ND 02175 14804	NC 93895 09663	10,200	**1**	2,565	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A9-44	NW	NO 00212 47141	NO 00472 43871	3,320	**1**	12,162	2.0	7,500<AADT=25,000	0	Limited	**2.0**
A9-35b	NW	NN 66562 72101	NN 69762 71546	3,310	**1**	8,327	2.0	7,500<AADT=25,000	1	Significant	**2.5**

Table D.2 – Exposure scores for Priority 2 sites.

Route Code	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	AADT Evaluated (veh/day)	AADT Exposure Score	Commentary on AADT Exposure Score	Diversion Exposure Score	Diversion Implications	Exposure Score
A7-06	SE	NT 40762 02692	NY 38842 96252	7,160	**2**	2,032	1.0	AADT=2,500	1	Significant	**1.5**
A77-11	SW	NX 05214 72439	NX 08694 63338	9,990	**2**	3,746	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A82-05	NW	NH 52566 28987	NH 49631 23632	6,770	**2**	2,910	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A82-26	NW	NN 05220 59568	NN 07550 58357	2,720	**2**	5,314	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A82-36	NW	NN 31916 04456	NN 34026 00456	4,610	**2**	7,886	2.0	7,500<AADT=25,000	1	Significant	**2.5**
A828-01	NW	NN 05175 59653	NM 99145 54983	8,540	**2**	2,800	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A828-04	NW	NM 96370 44903	NM 97685 44688	1,480	**2**	1,902	1.0	AADT=2,500	0	Limited	**1.0**
A83-06	NW	NN 19221 12717	NN 11260 08848	9,170	**2**	3,803	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A830-05	NW	NM 90195 80853	NM 76679 82314	15,500	**2**	1,140	1.0	AADT=2,500	2	More significant	**2.0**
A835-09	NW	NH 19553 80586	NH 18168 85540	5,320	**2**	1,775	1.0	AADT=2,500	1	Significant	**1.5**
A85-09	NW	NN 50672 28326	NN 38766 25266	12,900	**2**	3,175	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A86-10	NW	NN 47516 86247	NN 37536 81267	11,600	**2**	1,256	1.0	AADT=2,500	1	Significant	**1.5**
A86-11	NW	NN 33266 80957	NN 27646 81067	6,180	**2**	1,256	1.0	AADT=2,500	1	Significant	**1.5**
A87-07	NW	NH 18930 10072	NH 14330 09991	5,070	**2**	2,170	1.0	AADT=2,500	1	Significant	**1.5**
A87-13	NW	NG 96259 14951	NG 94614 17946	3,790	**2**	2,170	1.0	AADT=2,500	1	Significant	**1.5**
A87-20	NW	NG 47808 31921	NG 47428 41300	10,000	**2**	2,207	1.0	AADT=2,500	0	Limited	**1.0**
A887-01	NW	NH 42031 16827	NH 35170 15427	8,150	**2**	963	1.0	AADT=2,500	0	Limited	**1.0**
A9-34	NW	NN 68007 91922	NN 67812 90722	1,260	**2**	7,426	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A9-45	NW	NO 03452 41486	NO 04062 40886	877	**2**	13,170	2.0	7,500<AADT=25,000	0	Limited	**2.0**
A9-35a	NW	NN 63982 83957	NN 64987 73046	11,900	**2**	8,344	2.0	7,500<AADT=25,000	1	Significant	**2.5**
A95-05	NE	NJ 30452 44976	NJ 29417 44886	1,230	**2**	2,094	1.0	AADT=2,500	0	Limited	**1.0**
A95-08	NE	NJ 14757 34755	NJ 10537 32135	5,880	**2**	2,265	1.0	AADT=2,500	0	Limited	**1.0**
A95-09	NE	NJ 08337 29844	NJ 06512 27039	3,480	**2**	2,265	1.0	AADT=2,500	0	Limited	**1.0**

Table D.3 – Exposure scores for Priority 3 sites.

Route Code	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	AADT Evaluated (veh/day)	AADT Exposure Score	Commentary on AADT Exposure Score	Diversion Exposure Score	Diversion Implications	Exposure Score
A1-06	SE	NT 79571 67434	NT 85681 62704	8,630	**3**	7,919	2.0	7,500<AADT=25,000	0	Limited	**2.0**
A68-12	SE	NT 67581 14083	NT 68261 12323	1,960	**3**	2,529	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A7-01	SE	NT 48882 32523	NT 48142 31013	1,840	**3**	9,170	2.0	7,500<AADT=25,000	0	Limited	**2.0**
A7-05	SE	NT 46492 11652	NT 44922 10092	2,350	**3**	2,378	1.0	AADT=2,500	1	Significant	**1.5**
A7-07	SE	NY 38842 96252	NY 36812 90032	6,690	**3**	2,032	1.0	AADT=2,500	1	Significant	**1.5**
A76-04	SW	NS 85832 04117	NS 81022 07857	6,570	**3**	2,968	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A77-10	SW	NX 09284 77378	NX 05214 72439	6,640	**3**	3,183	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A82-03	NW	NH 56836 34253	NH 54586 31063	3,970	**3**	4,356	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A82-07	NW	NH 47461 21012	NH 46411 19822	1,620	**3**	2,910	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A82-10	NW	NH 42411 16052	NH 40211 12102	4,870	**3**	2,478	1.0	AADT=2,500	0	Limited	**1.0**
A82-14	NW	NH 34476 03812	NH 33836 03542	828	**3**	2,183	1.0	AADT=2,500	0	Limited	**1.0**
A82-15	NW	NH 33261 02912	NH 32901 02442	600	**3**	2,183	1.0	AADT=2,500	0	Limited	**1.0**
A82-16	NW	NN 29996 98177	NN 28981 96572	1,960	**3**	3,493	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A82-23	NW	NN 04505 66337	NN 03765 65377	1,260	**3**	5,578	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A82-24	NW	NN 02295 63258	NN 02645 62728	688	**3**	5,578	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A82-38	NW	NS 34556 97686	NS 35196 87156	11,100	**3**	7,886	2.0	7,500<AADT=25,000	1	Significant	**2.5**
A83-01	NW	NN 29616 05036	NN 28391 03881	1,760	**3**	4,847	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A83-07	NW	NN 11260 08848	NN 11395 10083	1,260	**3**	3,803	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A83-10	NW	NN 04495 04203	NN 02915 03179	1,910	**3**	2,995	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A83-12	NW	NS 01725 99834	NR 98995 97649	3,550	**3**	2,995	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A83-18	NW	NR 84819 80506	NR 86284 74006	7,040	**3**	2,805	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A83-20	NW	NR 86794 69696	NR 86529 69066	687	**3**	2,805	1.5	2,500<AADT=7,500	2	More significant	**2.5**
A83-21	NW	NR 86034 68451	NR 85284 68076	839	**3**	2,118	1.0	AADT=2,500	2	More significant	**2.0**
A830-04	NW	NM 90855 80478	NM 90205 80848	867	**3**	1,140	1.0	AADT=2,500	2	More significant	**2.0**
A830-06	NW	NM 76679 82314	NM 71574 84404	6,080	**3**	973	1.0	AADT=2,500	2	More significant	**2.0**
A835-04	NW	NH 43565 58802	NH 40650 59367	3,110	**3**	2,942	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A835-06	NW	NH 40325 63937	NH 40344 69227	6,110	**3**	2,276	1.0	AADT=2,500	1	Significant	**1.5**
A835-10	NW	NH 18163 85575	NH 13298 94065	10,400	**3**	1,775	1.0	AADT=2,500	1	Significant	**1.5**
A84-03	NW	NN 57047 14530	NN 58487 13465	1,900	**3**	3,465	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A85-12	NW	NN 30461 31731	NN 22586 27147	9,590	**3**	2,418	1.0	AADT=2,500	0	Limited	**1.0**
A86-07	NW	NN 55996 90417	NN 55356 89707	987	**3**	1,256	1.0	AADT=2,500	1	Significant	**1.5**
A86-08	NW	NN 54331 89767	NN 52936 89547	1,520	**3**	1,256	1.0	AADT=2,500	1	Significant	**1.5**
A87-14	NW	NG 93894 18781	NG 94539 20406	2,490	**3**	2,170	1.0	AADT=2,500	1	Significant	**1.5**
A87-22	NW	NG 46818 45880	NG 42318 50959	7,050	**3**	2,124	1.0	AADT=2,500	0	Limited	**1.0**
A887-02	NW	NH 32540 14347	NH 32030 14177	540	**3**	963	1.0	AADT=2,500	0	Limited	**1.0**
A9-09	NW	ND 15325 29325	ND 13145 25995	4,350	**3**	2,228	1.0	AADT=2,500	2	More significant	**2.0**
A9-10	NW	ND 12010 23055	ND 11670 22435	1,110	**3**	2,228	1.0	AADT=2,500	2	More significant	**2.0**
A9-24	NW	NH 72341 35783	NH 75841 34579	4,040	**3**	8,674	2.0	7,500<AADT=25,000	1	Significant	**2.5**
A9-27	NW	NH 82171 26569	NH 87652 24074	6,660	**3**	8,426	2.0	7,500<AADT=25,000	1	Significant	**2.5**
A9-30	NW	NH 89357 13978	NH 84707 07948	8,550	**3**	6,889	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A95-04	NE	NJ 33336 47211	NJ 31727 45906	2,210	**3**	2,094	1.0	AADT=2,500	0	Limited	**1.0**
M74-09	M74	NS 95997 16852	NS 96337 16502	492	**3**	16,478	2.0	7,500<AADT=25,000	0	Limited	**2.0**
M90-09	NE	NO 14377 13430	NO 13887 15335	3,200	**3**	26,419	2.5	AADT>25,000	0	Limited	**2.5**

Table D.4 – Exposure scores for Priority 4 sites.

Route Code	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	AADT Evaluated (veh/day)	AADT Exposure Score	Commentary on AADT Exposure Score	Diversion Exposure Score	Diversion Implications	Exposure Score
A1-02	SE	NT 36582 71194	NT 40152 73634	4,440	**4**	28,682	2.5	AADT>25,000	0	Limited	**2.5**
A1-08	SE	NT 94330 61174	NT 97410 57054	5,560	**4**	10,090	2.0	7,500<AADT=25,000	0	Limited	**2.0**
A68-02	SE	NT 44662 60043	NT 45252 59473	821	**4**	7,852	2.0	7,500<AADT=25,000	0	Limited	**2.0**
A68-13	SE	NT 68531 10723	NT 68691 09563	1,190	**4**	2,529	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A7-08	SE	NY 37152 80982	NY 38332 78042	3,280	**4**	3,576	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A701-03	SW	NY 03302 89297	NY 05742 91657	3,440	**4**	4,833	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A76-05	SW	NS 78932 09117	NS 77122 11008	2,650	**4**	4,062	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A76-09	SW	NS 67591 12988	NS 62931 13078	4,770	**4**	2,932	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A78-06	SW	NS 25610 43671	NS 28170 42611	2,880	**4**	15,262	2.0	7,500<AADT=25,000	0	Limited	**2.0**
A82-12	NW	NH 38381 10322	NH 37896 09252	1,420	**4**	2,478	1.0	AADT=2,500	0	Limited	**1.0**
A82-29	NW	NN 31141 43721	NN 29741 38561	5,550	**4**	3,125	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A82-31	NW	NN 32251 34076	NN 32991 31481	2,940	**4**	3,117	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A830-03	NW	NM 96520 79313	NM 90855 80478	6,550	**4**	1,140	1.0	AADT=2,500	2	More significant	**2.0**
A830-07	NW	NM 71594 85114	NM 68999 84984	2,830	**4**	973	1.0	AADT=2,500	2	More significant	**2.0**
A835-02	NW	NH 50385 54878	NH 48615 54908	1,780	**4**	3,903	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A835-03	NW	NH 45870 55868	NH 45445 56608	889	**4**	2,942	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A835-05	NW	NH 40635 59407	NH 38875 62497	3,700	**4**	2,942	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A835-08	NW	NH 27084 74686	NH 20223 78236	8,000	**4**	1,693	1.0	AADT=2,500	1	Significant	**1.5**
A84-04	NW	NN 58487 13465	NN 58637 10880	2,700	**4**	3,465	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A84-05	NW	NN 58637 10880	NN 60537 08540	4,050	**4**	3,465	1.5	2,500<AADT=7,500	1	Significant	**2.0**
A85-13	NW	NN 19646 27552	NN 17336 27352	2,360	**4**	2,285	1.0	AADT=2,500	0	Limited	**1.0**
A87-08	NW	NH 14330 09991	NH 11495 10731	3,100	**4**	2,170	1.0	AADT=2,500	1	Significant	**1.5**
A87-10	NW	NH 09725 11731	NH 06790 11496	3,270	**4**	2,170	1.0	AADT=2,500	1	Significant	**1.5**
A87-11	NW	NH 06790 11496	NH 03370 12016	3,670	**4**	2,170	1.0	AADT=2,500	1	Significant	**1.5**
A87-24	NW	NG 39057 59388	NG 39367 64097	5,460	**4**	1,238	1.0	AADT=2,500	0	Limited	**1.0**
A887-03	NW	NH 29500 12297	NH 22830 10597	7,170	**4**	963	1.0	AADT=2,500	0	Limited	**1.0**
A9-07	NW	ND 17630 47546	ND 18435 38856	8,880	**4**	1,678	1.0	AADT=2,500	1	Significant	**1.5**
A9-22	NW	NH 72401 39864	NH 71901 38349	1,660	**4**	9,753	2.0	7,500<AADT=25,000	1	Significant	**2.5**
A9-29	NW	NH 90942 18043	NH 90432 16903	1,290	**4**	6,889	1.5	2,500<AADT=7,500	0	Limited	**1.5**
A9-37	NW	NN 76882 68936	NN 77237 68286	761	**4**	8,295	2.0	7,500<AADT=25,000	1	Significant	**2.5**
A9-46	NW	NO 06917 36595	NO 07127 35615	1,010	**4**	14,601	2.0	7,500<AADT=25,000	0	Limited	**2.0**
A90-01	NW	NO 13597 22455	NO 14982 22355	1,410	**4**	35,535	2.5	AADT>25,000	0	Limited	**2.5**
A95-06	NE	NJ 28567 44776	NJ 28117 43931	1,020	**4**	2,693	1.5	2,500<AADT=7,500	0	Limited	**1.5**
M90-08	NE	NO 13857 11450	NO 14367 12225	933	**4**	26,419	2.5	AADT>25,000	0	Limited	**2.5**
M90-11	NE	NO 13062 19515	NO 12312 20095	953	**4**	35,608	2.5	AADT>25,000	0	Limited	**2.5**

Table D.5 – Exposure scores for Special Assessment sites.

Route Code	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	AADT Evaluated (veh/day)	AADT Exposure Score	Commentary on AADT Exposure Score	Diversion Exposure Score	Diversion Implications	Exposure Score
A82-27	NW	NN 10700 58212	NN 27671 52992	19,900	Separate	3,999	1.5	2,500<AADT=7,500	0	Limited	1.5
A87-19	NW	NG 64039 23632	NG 48718 29902	26,100	Separate	1,954	1.0	AADT=2,500	2	More significant	2.0

D.2 FINAL HAZARD SCORES AND HAZARD RANKINGS

Table D.6 – Hazard scores, exposure scores and hazard rankings for sites with a hazard ranking of 100 or greater.

Route Code	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	Initial Hazard Score (from GIS-Based Assessment and Interpretation)	Final Additive Hazard Score from Site Inspections	Finalised Hazard Score	Exposure Score	Hazard Ranking (Risk) Score = Hazard * Exposure	Locality
A82-17	NW	NN 28766	NN 21391	13,400	1	80	20	100	2.5	250	Loch Lochy
A85-09	NW	NN 50672	NN 38766	12,900	2	60	40	100	2.5	250	Glen Dochart
A82-08	NW	NH 45761	NH 43486	3,410	1	80	10	90	2.5	225	N of Invermoriston
A82-37	NW	NN 34026	NS 34556	3,300	1	80	-	90	2.5	225	Inverbeg and N
A9-12	NW	ND 02175	NC 93895	10,200	1	80	-	90	2.5	225	S of Helmsdale
A9-35b	NW	NN 66562	NN 69762	3,310	1	80	10	90	2.5	225	N Glen Garry
A82-09	NW	NH 42981	NH 42451	581	1	80	00	80	2.5	200	Invermoriston
A82-26	NW	NN 05220	NN 07550	2,720	2	60	20	80	2.5	200	E of Ballachulish
A82-34	NW	NN 33296	NN 31776	13,500	1	80	20	100	2.0	200	N Loch Lomond
A85-08	NW	NN 58437	NN 55677	5,480	1	80	20	100	2.0	200	Glen Ogle
A9-11	NW	ND 08775	ND 02860	11,200	1	80	20	100	2.0	200	N of Helmsdale
A83-02	NW	NN 26901	NN 23021	6,310	1	80	-	90	2.0	180	Ardgarten to Rest & Be Thankful
A83-04	NW	NN 23421	NN 19096	4,360	1	80	-	90	2.0	180	Glen Kinglas
A9-44	NW	NO 00212	NO 00472	3,320	1	80	-	90	2.0	180	N of Dunkeld
A87-19	NW	NG 64039 23632	NG 48718 29902	26,100	Separate Assessment	80	-	90	2.0	180	Southern Skye - N of Broadford
A82-36	NW	NN 31916	NN 34026	4,610	2	60	-	70	2.5	175	S of Tarbet
A9-35a	NW	NN 63982	NN 64987	11,900	2	60	10	70	2.5	175	S of Dalwhinnie
A83-06	NW	NN 19221	NN 11260	9,170	2	60	25	85	2.0	170	Clachan to Strone Point
A82-05	NW	NH 52566	NH 49631	6,770	2	60	5	65	2.5	163	S of Drumnadrochit
A77-11	SW	NX 05214	NX 08694	9,990	2	60	20	80	2.0	160	S of Glen App
A82-02	NW	NH 60696	NH 57346	5,520	1	80	20	100	1.5	150	N end of Loch Ness
A83-05	NW	NN 18406	NN 19406	1,620	1	80	20	100	1.5	150	Cairndow
A87-12	NW	NH 03370	NG 96289	8,620	1	80	20	100	1.5	150	E Glen Shiel
A87-15	NW	NG 94469	NG 88269	8,650	1	80	20	100	1.5	150	Loch Duich
A87-09	NW	NH 11495	NH 09725	2,080	1	80	15	95	1.5	143	W Loch Cluanie
A830-05	NW	NM 90195	NM 76679	15,500	2	60	10	70	2.0	140	Glenfinnan to Lochailort
A9-45	NW	NO 03452	NO 04062	877	2	60	-	70	2.0	140	S of Dunkeld
A82-27	NW	NN 10700 58212	NN 27671 52992	19,900	Separate Assessment	80	-	90	1.5	135	Glen Coe
A828-01	NW	NN 05175	NM 99145	8,540	2	60	30	90	1.5	135	W of Ballachulish
A835-07	NW	NH 38284	NH 28554	11,400	1	80	10	90	1.5	135	Lubfearn to W Loch
A85-15	NW	NN 13191	NN 03135	12,400	1	80	10	90	1.5	135	Dalmally to W Pass of Brander
A86-12	NW	NN 25591	NN 22966	2,770	1	80	10	90	1.5	135	Inverroy to Spean Bridge
A87-13	NW	NG 96259	NG 94614	3,790	2	60	30	90	1.5	135	W Glen Shiel
A82-07	NW	NH 47461	NH 46411	1,620	3	40	-	50	2.5	125	N of Alltsigh
A82-16	NW	NN 29996	NN 28981	1,960	3	40	-	50	2.5	125	Loch Oich to Loch Lochy
A82-23	NW	NN 04505	NN 03765	1,260	3	40	-	50	2.5	125	N of Corran Ferry
A82-24	NW	NN 02295	NN 02645	688	3	40	-	50	2.5	125	S of Corran Ferry
A82-38	NW	NS 34556	NS 35196	11,100	3	40	-	50	2.5	125	N & S of Luss
A83-18	NW	NR 84819	NR 86284	7,040	3	40	-	50	2.5	125	S of Inverneill
A83-20	NW	NR 86794	NR 86529	687	3	40	-	50	2.5	125	N Tarbet
A9-24	NW	NH 72341	NH 75841	4,040	3	40	-	50	2.5	125	N of Loch Moy
A9-27	NW	NH 82171	NH 87652	6,660	3	40	-	50	2.5	125	Slochd
M90-09	NE	NO 14377	NO 13887	3,200	3	40	-	50	2.5	125	N of Glen Farg
A82-04	NW	NH 52391	NH 50831	1,590	1	80	0	80	1.5	120	Drumnadochit
A86-03	NW	NN 67317	NN 67162	357	1	80	0	80	1.5	120	Glentruim House
A86-09	NW	NN 48856	NN 47661	1,730	1	80	0	80	1.5	120	Aberarder (Loch Laggan)
A86-10	NW	NN 47516	NN 37536	11,600	2	60	15	75	1.5	113	Loch Laggan and Reservoir
A86-11	NW	NN 33266	NN 27646	6,180	2	60	15	75	1.5	113	Tulloch to Roy Bridge
A7-06	SE	NT 40762 02692	NY 38842	7,160	2	60	-	70	1.5	105	S of Teviothead
A835-09	NW	NH 19553	NH 18168	5,320	2	60	-	70	1.5	105	S of Loch Broom
A1-06	SE	NT 79571 67434	NT 85681 62704	8,630	3	40	-	50	2.0	100	Penmanshiel to Howburn
A7-01	SE	NT 48882 32523	NT 48142 31013	1,840	3	40	-	50	2.0	100	N of Selkirk
A76-04	SW	NS 85832	NS 81022	6,570	3	40	-	50	2.0	100	S of Sanquhar
A77-10	SW	NX 09284	NX 05214	6,640	3	40	-	50	2.0	100	Glen App
A83-01	NW	NN 29616	NN 28391	1,760	3	40	-	50	2.0	100	W of Succoth
A83-07	NW	NN 11260	NN 11395	1,260	3	40	-	50	2.0	100	E Loch Shira
A83-10	NW	NN 04495	NN 02915	1,910	3	40	-	50	2.0	100	E of Auchindrain Folk Museum
A83-12	NW	NS 01725	NR 98995	3,550	3	40	-	50	2.0	100	W of Furnace
A83-21	NW	NR 86034	NR 85284	839	3	40	-	50	2.0	100	W of Tarbet
A830-04	NW	NM 90855	NM 90205	867	3	40	-	50	2.0	100	Glenfinnan
A830-06	NW	NM 76679	NM 71574	6,080	3	40	-	50	2.0	100	Lochailort to Prince's Cairn
A835-04	NW	NH 43565	NH 40650	3,110	3	40	-	50	2.0	100	S of Garve
A84-03	NW	NN 57047	NN 58487	1,900	3	40	-	50	2.0	100	N Loch Lubnaig
A9-09	NW	ND 15325	ND 13145	4,350	3	40	-	50	2.0	100	S of Dunbeath
A9-10	NW	ND 12010	ND 11670	1,110	3	40	-	50	2.0	100	Berriedale
M74-09	M74	NS 95997	NS 96337	492	3	40	-	50	2.0	100	Elvanfoot

Table D.7 – Hazard scores, exposure scores and hazard rankings for sites with a hazard ranking of less than 100.

Route Code	OC Unit	Start-NGR	End-NGR	Length (m)	Priority	Initial Hazard Score (from GIS-Based Assessment and Interpretation)	Final Additive Hazard Score from Site Inspections	Finalised Hazard Score	Exposure Score	Hazard Ranking (Risk) Score = Hazard * Exposure	Locality
A87-07	NW	NH 18930	NH 14330	5,070	**2**	60	0	**60**	**1.5**	**90**	Loch Cluanie
A9-34	NW	NN 68007	NN 67812	1,260	**2**	60	0	**60**	**1.5**	**90**	Crubenmore
A1-02	SE	NT 36582 71194	NT 40152 73634	4,440	**4**	20	-	**30**	**2.5**	**75**	W of Tranent
A68-12	SE	NT 67581 14083	NT 68261 12323	1,960	**3**	40	-	**50**	**1.5**	**75**	Camptown
A7-05	SE	NT 46492 11652	NT 44922 10092	2,350	**3**	40	-	**50**	**1.5**	**75**	Branxholme to Newmill
A7-07	SE	NY 38842	NY 36812	6,690	**3**	40	-	**50**	**1.5**	**75**	Ewes (N of Langholm)
A82-03	NW	NH 56836	NH 54586	3,970	**3**	40	-	**50**	**1.5**	**75**	N of Drumnadrochit
A835-06	NW	NH 40325	NH 40344	6,110	**3**	40	-	**50**	**1.5**	**75**	N of Garve
A835-10	NW	NH 18163	NH 13298	10,400	**3**	40	-	**50**	**1.5**	**75**	S of Ullapool
A86-07	NW	NN 55996	NN 55356	987	**3**	40	-	**50**	**1.5**	**75**	E of Kinloch Laggan
A86-08	NW	NN 54331	NN 52936	1,520	**3**	40	-	**50**	**1.5**	**75**	Kinloch Laggan
A87-14	NW	NG 93894	NG 94539	2,490	**3**	40	-	**50**	**1.5**	**75**	Shile Bridge
A87-20	NW	NG 47808	NG 47428	10,000	**2**	60	15	**75**	**1.0**	**75**	S of Portree
A9-22	NW	NH 72401	NH 71901	1,660	**4**	20	-	**30**	**2.5**	**75**	Daviot
A9-30	NW	NH 89357	NH 84707	8,550	**3**	40	-	**50**	**1.5**	**75**	Aviemore
A9-37	NW	NN 76882	NN 77237	761	**4**	20	-	**30**	**2.5**	**75**	N of Calvine
A90-01	NW	NO 13597	NO 14982	1,410	**4**	20	-	**30**	**2.5**	**75**	Kinnoull Hill
M90-08	NE	NO 13857	NO 14367	933	**4**	20	-	**30**	**2.5**	**75**	N of Glenfarg
M90-11	NE	NO 13062	NO 12312	953	**4**	20	-	**30**	**2.5**	**75**	Craigend
A828-04	NW	NM 96370	NM 97685	1,480	**2**	60	-	**70**	**1.0**	**70**	W of Creagan
A95-05	NE	NJ 30452 44976	NJ 29417 44886	1,230	**2**	60	10	**70**	**1.0**	**70**	Craigellachie
A887-01	NW	NH 42031	NH 35170	8,150	**2**	60	5	**65**	**1.0**	**65**	W of Invermoriston
A95-08	NE	NJ 14757 34755	NJ 10537 32135	5,880	**2**	60	5	**65**	**1.0**	**65**	S of Tormore
A1-08	SE	NT 94330 61174	NT 97410 57054	5,560	**4**	20	-	**30**	**2.0**	**60**	Burnmouth
A68-02	SE	NT 44662 60043	NT 45252 59473	821	**4**	20	-	**30**	**2.0**	**60**	S of Fala
A76-05	SW	NS 78932	NS 77122	2,650	**4**	20	-	**30**	**2.0**	**60**	Sanquhar
A76-09	SW	NS 67591	NS 62931	4,770	**4**	20	-	**30**	**2.0**	**60**	S of New Cumnock
A78-06	SW	NS 25610	NS 28170	2,880	**4**	20	-	**30**	**2.0**	**60**	Stevenston
A830-03	NW	NM 96520	NM 90855	6,550	**4**	20	-	**30**	**2.0**	**60**	E of Glenfinnan
A830-07	NW	NM 71594	NM 68999	2,830	**4**	20	-	**30**	**2.0**	**60**	Beasdale Station
A835-03	NW	NH 45870	NH 45445	889	**4**	20	-	**30**	**2.0**	**60**	Contin
A835-05	NW	NH 40635	NH 38875	3,700	**4**	20	-	**30**	**2.0**	**60**	Garve
A84-04	NW	NN 58487	NN 58637	2,700	**4**	20	-	**30**	**2.0**	**60**	S Loch Lubnaig
A84-05	NW	NN 58637	NN 60537	4,050	**4**	20	-	**30**	**2.0**	**60**	Pass of Leny
A9-46	NW	NO 06917	NO 07127	1,010	**4**	20	-	**30**	**2.0**	**60**	Bankfoot
A95-09	NE	NJ 08337 29844	NJ 06512 27039	3,480	**2**	60	0	**60**	**1.0**	**60**	Cromdale
A82-10	NW	NH 42411	NH 40211	4,870	**3**	40	-	**50**	**1.0**	**50**	S of Invermoriston
A82-14	NW	NH 34476	NH 33836	828	**3**	40	-	**50**	**1.0**	**50**	Aberchalder
A82-15	NW	NH 33261	NH 32901	600	**3**	40	-	**50**	**1.0**	**50**	S of Bridge of Oich
A85-12	NW	NN 30461	NN 22586	9,590	**3**	40	-	**50**	**1.0**	**50**	W of Tyndrum
A87-22	NW	NG 46818	NG 42318	7,050	**3**	40	-	**50**	**1.0**	**50**	N of Portree
A887-02	NW	NH 32540	NH 32030	540	**3**	40	-	**50**	**1.0**	**50**	Dundreggan
A95-04	NE	NJ 33336 47211	NJ 31727 45906	2,210	**3**	40	-	**50**	**1.0**	**50**	Maggieknockater
A68-13	SE	NT 68531 10723	NT 68691 09563	1,190	**4**	20	-	**30**	**1.5**	**45**	Hass (N of Carter Bar)
A7-08	SE	NY 37152	NY 38332	3,280	**4**	20	-	**30**	**1.5**	**45**	N of Canonbie
A701-03	SW	NY 03302	NY 05742	3,440	**4**	20	-	**30**	**1.5**	**45**	Forest of Ae
A82-29	NW	NN 31141	NN 29741	5,550	**4**	20	-	**30**	**1.5**	**45**	Bridge of Orchy
A82-31	NW	NN 32251	NN 32991	2,940	**4**	20	-	**30**	**1.5**	**45**	N of Tyndrum
A835-02	NW	NH 50385	NH 48615	1,780	**4**	20	-	**30**	**1.5**	**45**	E of A832 Junction (Marybank)
A835-08	NW	NH 27084	NH 20223	8,000	**4**	20	-	**30**	**1.5**	**45**	Braemore Junction
A87-08	NW	NH 14330	NH 11495	3,100	**4**	20	-	**30**	**1.5**	**45**	Loch Cluanie
A87-10	NW	NH 09725	NH 06790	3,270	**4**	20	-	**30**	**1.5**	**45**	Cluanie Inn
A87-11	NW	NH 06790	NH 03370	3,670	**4**	20	-	**30**	**1.5**	**45**	W of Cluanie Inn
A9-07	NW	ND 17630	ND 18435	8,880	**4**	20	-	**30**	**1.5**	**45**	Achavanich
A9-29	NW	NH 90942	NH 90432	1,290	**4**	20	-	**30**	**1.5**	**45**	Kinveachy to Avielochan
A95-06	NE	NJ 28567 44776	NJ 28117 43931	1,020	**4**	20	-	**30**	**1.5**	**45**	W of Craigellachie
A82-12	NW	NH 38381	NH 37896	1,420	**4**	20	-	**30**	**1.0**	**30**	Fort Augustus
A85-13	NW	NN 19646	NN 17336	2,360	**4**	20	-	**30**	**1.0**	**30**	E of Dalmally
A87-24	NW	NG 39057	NG 39367	5,460	**4**	20	-	**30**	**1.0**	**30**	S of Uig
A887-03	NW	NH 29500	NH 22830	7,170	**4**	20	-	**30**	**1.0**	**30**	E of A887/A87 Junction

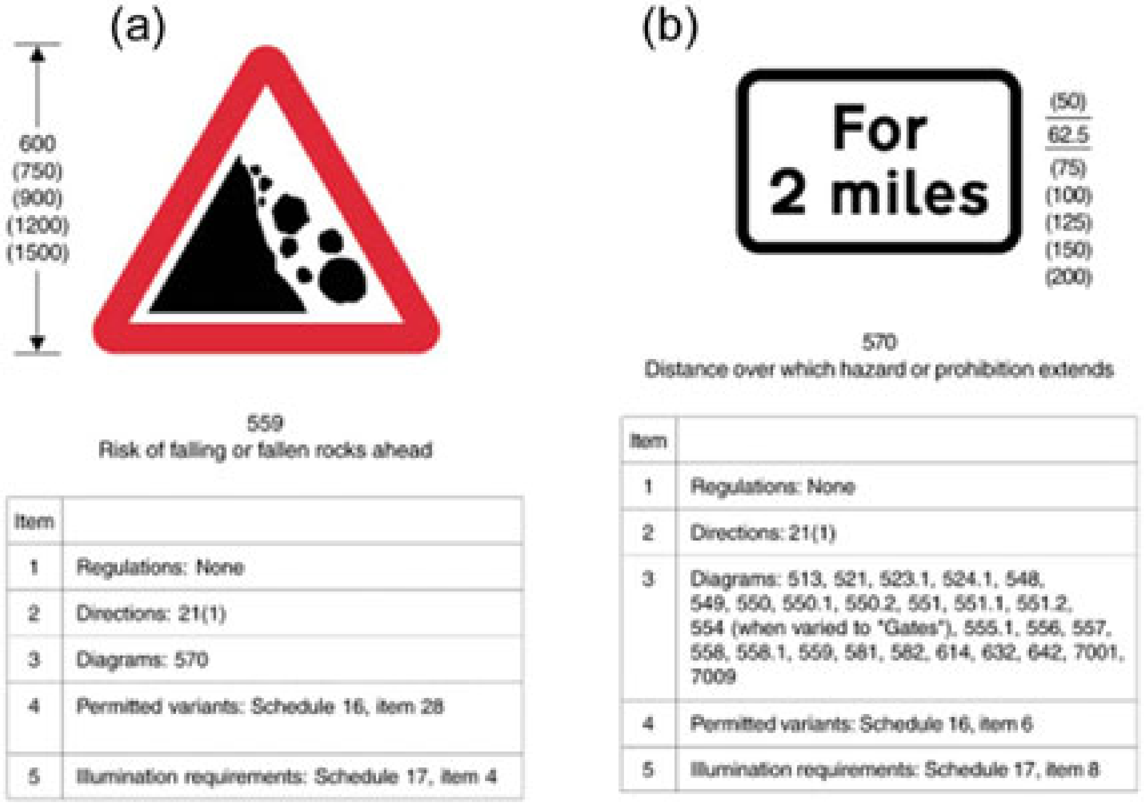
APPENDIX E – A BRIEF INTERNATIONAL REVIEW OF THE SIGNING OF LANDSLIDE AND OTHER HAZARDS

by M G Winter

In this appendix a brief and selective review of the approach to the signing of landslide hazards in a road environment in both the United Kingdom.

E.1 UNITED KINGDOM

Figure E.1 illustrates the sign typically used to indicate rockfall in the United Kingdom.



559
Risk of falling or fallen rocks ahead

Item	
1	Regulations: None
2	Directions: 21(1)
3	Diagrams: 570
4	Permitted variants: Schedule 16, item 28
5	Illumination requirements: Schedule 17, item 4

570
Distance over which hazard or prohibition extends

Item	
1	Regulations: None
2	Directions: 21(1)
3	Diagrams: 513, 521, 523.1, 524.1, 548, 549, 550, 550.1, 550.2, 551, 551.1, 551.2, 554 (when varied to "Gates"), 555.1, 556, 557, 558, 558.1, 559, 581, 582, 614, 632, 642, 7001, 7009
4	Permitted variants: Schedule 16, item 6
5	Illumination requirements: Schedule 17, item 8

Figure E.1 – UK rockfall sign (a) indicating risk of falling or fallen rocks (TSRGD, 2002: Diagram 559) and (b) sub-plate to show distance over which the hazard extends (TSRGD, 2002: Diagram 570).

Item 4 (Figure E.1a) indicates that the symbol may be reversed if appropriate and Item 5 that if the sign is not illuminated then it must be reflectorised.

A sub-plate may be added to the main sign in the UK to indicate the distance over which the hazard is extant. Item 4 (Figure E.1b) indicates the manner in which the distance may be expressed, while Item 5 indicated that illumination/reflectance should be the same as for the main sign.

E.2 NEW ZEALAND

In New Zealand 'international' graphics are used on signs, although the warning symbol is placed on a diamond rather than the more usual triangle. Signs with a yellow background are used for permanent signs and signs with an orange background for temporary hazards (Figure E.2): http://www.landtransport.govt.nz/roadcode/about-signs/main-types.html#warning. A sub-plate indicating 'Caution Slip' or 'Caution Washout' is often used indicating that the signs are often used to indicate landslides in a more general sense than simply rockfall (G Pinches, Personal Communication, 2007).

Figure E.2 – New Zealand sign warning of a temporary landslide hazard.

Figure E.3 illustrates an alternative approach to signing rockfall hazards in New Zealand.

Figure E.3 – New Zealand sign warning of a temporary landslide hazard. (Photograph courtesy of Thomas Glade.)

E.3 GREECE

In Greece the sign illustrated in Figure E.4 is used for rockfalls. It is understood that landslides are not generally signed in any systematic fashion (P Marinos, Personal Communication, 2007).

Figure E.4 – Greek sign warning of a rockfall hazard.

E.4 CANADA

In British Columbia in Canada signs are standardized in a catalogue: http://www.th.gov.bc.ca/publications/eng_publications/electrical/Sign_Cat_2003.pdf.

These include a Slide Area/End Slide Area (Figure E.5a and E.5b). While this is not overly descriptive it appears to be intended to decrease the time spent by motorists in the section of concern, and therefore intending to reduce the temporal probability factor of the hazard equation.

There is also a rockfall sign (Figure E.5c), similar to the one used in the UK (Figure E.1a), however this is stated to indicate ‘watch for rock on road ahead’. Other signs in use include ‘road subject to flooding’ (Figure E.5d) to which a sub-plate indicating the distance over which the hazard is extant may be added (K Turner, Personal Communication, 2007).

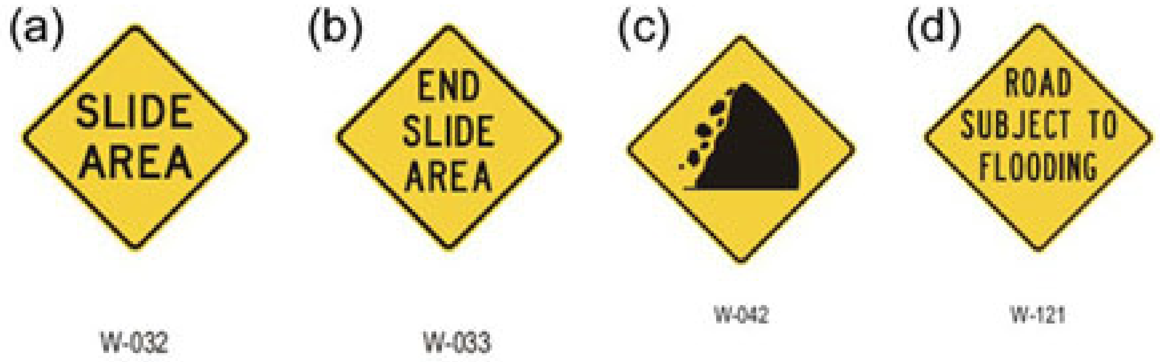


Figure E.5 – Landslide and other warning signs used in British Columbia in Canada: sign indicating the beginning (a) and end (b) of a slide area; (c) indicating ‘watch for rock on road ahead’; and (d) road subject to flooding.

Other signs in use in British Columbia include warning signs for stream-based debris flows (Figure E.6). More general hazard information signs (Figure E.7) are located in lay-bys which indicate areas in, and routes on, which hazards might be encountered whilst and also give information on the nature and background to the hazards. Both types of sign, in addition to providing information on the type and location of the hazard give advice on what not to do in the hazard areas.

Figure E.6 – Sign indicating stream-based debris flow hazard on the Vancouver to Whistler, Sea-to-Sky Highway in British Columbia in Canada.

Figure E.7 – Landslide hazard information sign on the Vancouver to Whistler, Sea-to-Sky Highway in British Columbia in Canada.

E.5 HONG KONG SAR

In Hong Kong essentially the same sign is used for rockfall hazards as in the UK (Figure E.8).

Figure E.8 – Rockfall road sign in Hong Kong. (Photograph courtesy of Thomas Glade.)

Figure E.9 illustrates the symbol used to warn of landslips in Hong Kong as part of the warning system described in Appendix G. The symbol is used in the media and on the internet as well as on public warning signs (Chan and Mak, 2007).

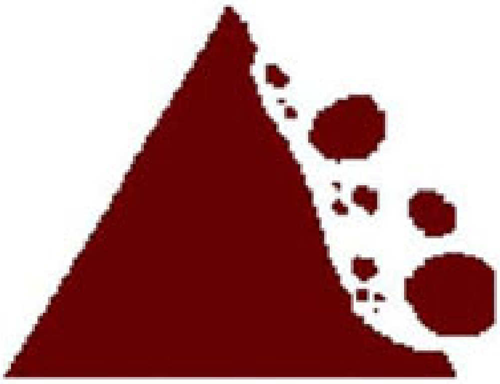


Figure E.9 – Landslip warning sign in Hong Kong (from Chan and Mak, 2007).

A variety of other signs are used in relation to landslide hazards in Hong Kong, including those forming part of the slope registration system and general information signs intended to give warning of landslide risk to residents and pedestrians. Of perhaps most interest in the context of roads is the use of the same symbol sign as that illustrated in Figure E.8 to indicate not only the start of a landslide hazard, but also the distance over which the hazard is extant (Figure E.10) and the end of the hazard area (Figure E.11).

Figure E.10– Rockfall road sign in Hong Kong indicating the start of the hazard and the distance over which it is extant.

Figure E.11 – Rockfall road sign in Hong Kong indicating the end of the hazard.

E.6 CROATIA

In Croatia the same sign is used for rockfall hazards as in the UK (Figure E.12) with the use of a distance sub-plate also being a common factor albeit that the distance is quoted in metres rather than in miles and/or yards.

Figure E.12 – Rockfall sign in Croatia.

E.7 UNITED STATES OF AMERICA

A wide variety of signing for landslides may be encountered in the United States of America (USA). These include signs dealing with quite specific types of landslide hazard (Figure E.13).

Figure E.13 – Rock avalanche sign Lassen Volcanic National Park. (Photograph courtesy of T Glade.)

More typically the signs indicate a particular type of hazard, often with an indication of the distance over which the hazard is extant (Figure E.14 and E.15).

Figure E.14 – Rockfall sign Palo Duro Canyon State Park, Texas.

Figure E.15 – Rockfall hazards associated with the sign illustrated in Figure E.14, Palo Duro Canyon State Park, Texas.

Other hazards are often signed in a similar fashion. For example, hazards associated with streams that become active during and after heavy rainfall are sign as illustrated in Figures E.16 and E.17. In this case a maximum speed limit is imposed.

Figure E.16 – Water hazard sign Palo Duro Canyon State Park, Texas.

Figure E.17 – Water hazard associated with the sign illustrated in Figure E.16, Palo Duro Canyon State Park, Texas.

Such signs are not restricted to relatively lightly trafficked park roads but are also used on heavily trafficked interstate highways. Figures E.18 to E.120 illustrate

Figure E.18 – Water hazard sign Interstate 28, Hale County, Texas.

Figure E.19 – Water hazard sign Interstate 28, Hale County, Texas.

Figure E.20 – Water hazard associated with the signs illustrated in Figures E.18 and E.19, Interstate 28, Hale County, Texas.

Similarly, less effective signing in relation to hazards may be encountered in the USA. Figure E.21 shows a sign for a ‘Tornado Shelter’ – the relevant text is in black on a white sub-plate below the large blue sign to the right of the picture. The large blue sign promotes the rest area which includes the tornado shelter (Figure E.22

Figure E.21– Sign for ‘Tornado Shelter’ at a rest area Interstate 28, Hale County, Texas. The white ‘Tornado Shelter’ sign is on a white background and is located below the blue ‘Rest Area Next Right’ sign to the right of the picture.

Figure E.22– The rest area associated with the sign illustrated in Figure E.19, showing the building containing the ‘Tornado Shelter’, Interstate 28, Hale County, Texas.

APPENDIX F – DRAFT TRANSPORT SCOTLAND LEAFLET: SCOTTISH ROADS AND LANDSLIDES

by M G Winter, F Macgregor and L Shackman

Landslides are a natural part of the group of processes by which mountainous landscapes erode over the course of time.

F.1 PRECAUTIONS FOR SAFER JOURNEYS

It is important that a precautionary approach is followed when travelling in the more mountainous areas of Scotland during periods when landslides are likely. Landslides are most likely during and immediately after periods of very heavy rainfall, especially if the heavy rain follows an extended rainy period. Landslides are most prevalent in the periods July to August and October to January.

Simple precautions that you can take to minimise the chances of your journey being disrupted during periods when landslides are more likely include the following:

- Avoid unnecessary journeys, particularly those during the hours of darkness.
- If you must travel, allow extra time for your journey.
- Check the weather forecast prior to your journey.
- During your journey
  - Take account of driver information messages on the road network.
  - Take account of travel announcements on the radio.
- In very mountainous areas it is inadvisable to stop on bridges or adjacent to water courses.
- Take frequent rest periods away from the road in safe stopping areas such as towns and villages rather than immediately adjacent to the road in open country.
- Provided that the weather and other conditions permit, it is best to continue your journey than to stop on the open road for long periods.
- Be alert to the possibility of water or debris on the road and be prepared to stop unexpectedly.

F.2 CONTEXT

Scotland is renowned for some of the most spectacular mountain landscapes in the World. Such natural beauty attracts visitors who make use of the landscape for a variety of recreational purposes (Figure F.1).

The mountain landscape of Scotland is developing actively, as are all such landscapes. The current period of activity began around 10,000 years ago towards the end of the last ice advance and retreat to affect the area north of Scotland. All of this means that landslides happen fairly frequently in Scotland. Most occur high on the hillsides and do not have any effect on Scotland’s resident population, its visitors or its infrastructure.

However, occasionally, an episode of significant magnitude will inevitably occur. Such an episode was experienced in August 2004 when rainfall substantially in excess of the norm fell in parts of Scotland.

The rainfall was both intense and long lasting and a large number of sudden and rapid landslides, in the form of debris flows, were experienced in the hills of Scotland. A small number of these affected the trunk road network, notably the A83 between Glen Kinglas and to the north of Cairndow (9 August), the A9 to the north of Dunkeld (11 August), and the A85 at Glen Ogle (18 August) (Figure F.2).

Figure F.1 – A86 Loch Laggan.

While major injuries were avoided in August 2004, some 57 people were taken to safety by helicopter after being trapped between the two debris flows on the A85 in Glen Ogle (Figure F.3). The A85 was closed for four days and the events on the A83 and the A9 meant that they were closed for two days. The disruption experienced by local and tourist traffic, as well as to goods vehicles, was substantial.

Figure F.2 – A83 Cairndow.

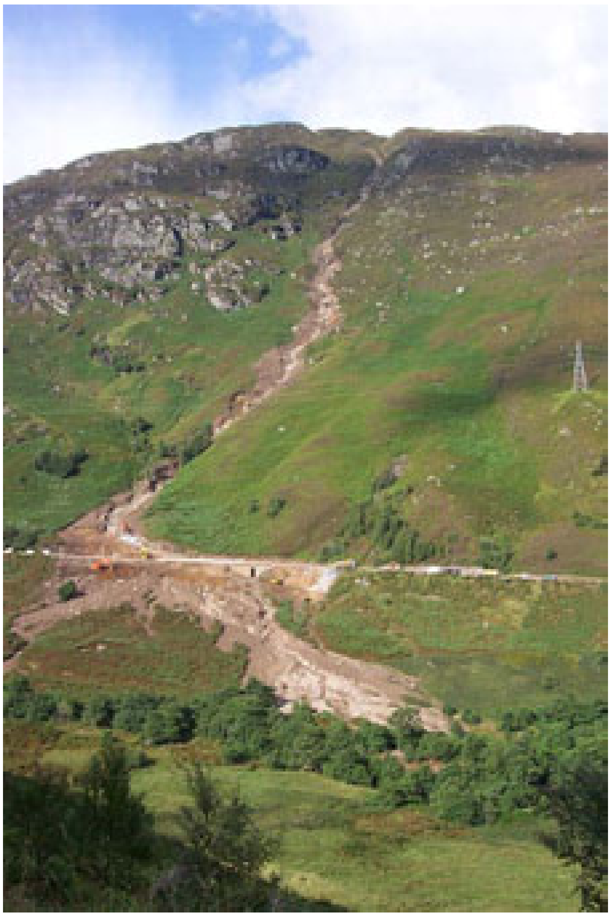


Figure F.3 – A85 Glen Ogle.

F.3 TRANSPORT SCOTLAND ACTIONS

Following the events of August 2004, Transport Scotland commissioned studies on debris flows and their management. Initial results were published in Summer 2005 and an implementation report in Autumn 2008 (available from www.transportscotland.gov.uk).

The initial study specifically dealt with the following issues:

- Considering the options for undertaking a detailed review of side slopes adjacent to the trunk road network and recommending a course of action.
- Outlining possible mitigation measures and management strategies that might be adopted.
- Undertaking an initial review to identify obvious areas that have the greatest potential for similar events in the future.

The 2008 study includes a detailed review of the network to identify the locations of greatest hazard, to rank those hazards and to develop appropriate management and mitigation measures that may be targeted at appropriate sites. A suite of management actions is currently being implemented on the network.

The overall objective of these studies is to ensure that in the future Transport Scotland has a system in place for assessing and managing the hazards posed by debris flows. In addition, the system will rank the hazards on the network in terms of their relative potential effects on road users. Whilst it is acknowledged from the outset that it is not possible to prevent the occurrence of such events this system will ensure that the exposure of road users to the consequences of future debris flow events is minimised.

APPENDIX G – LANDSLIDES AND RAINFALL: CASE STUDIES

by M G Winter, I M Nettleton and J A Parsons

Systems to forecast conditions likely to lead to debris flows have been developed for many regions of the world. In this section a selection of case studies is presented. These have been selected to illustrate specific points and on the basis that information on them is relatively easily available.

G.1 AUSTRALIA

Flentje and Chowdhury (2006) describe an observational approach to continuous real time monitoring of landslides in the Wollongong city area. Their work encompasses the monitoring of individual slopes, for which the development of pore water pressures and mass movement are related to site-specific measured rainfall. In addition, five stations measuring rainfall, among other parameters, have been established within the Wollongong area (approximately 25km by 15km) to enable alerts to be broadcast in response to rainfall events likely to lead to landslides.

Flentje and Chowdury (2006) represent the intensity, frequency and duration (IFD) of the local rainfall record and they compare this to the threshold proposed by Caine (1980), and reported here as Equation 10.1A, in Figure G.1.

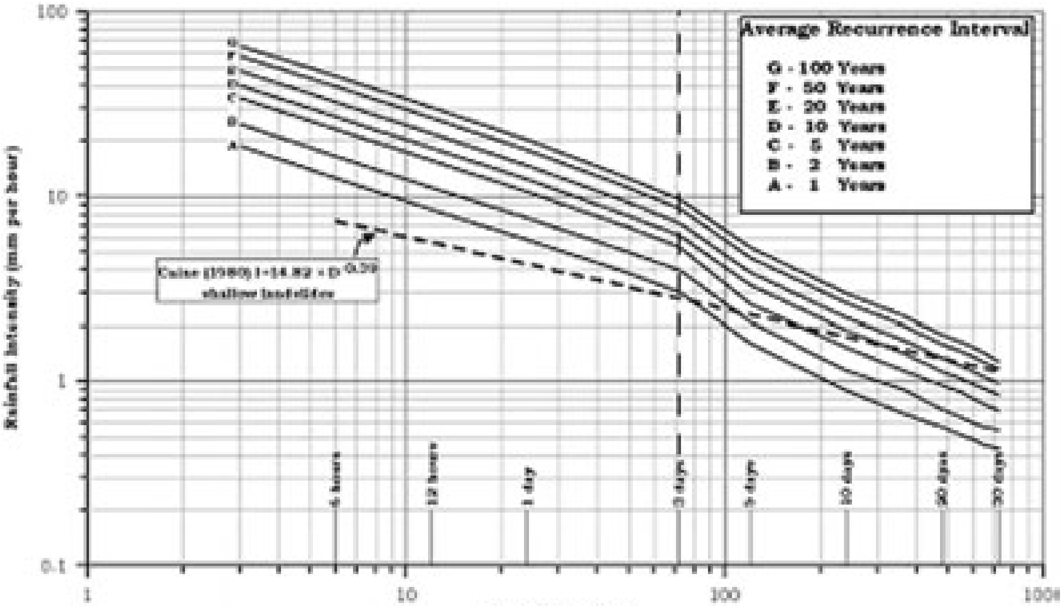


Figure G.1 – Rainfall intensity, frequency and duration analysis of the historical record for a rainfall station in the Wollongong area (from Flentje and Chowdhury, 2006).

Flentje and Chowdhury (2006) have developed both site-specific and regional rainfall triggering thresholds, primarily for deep-seated landslides. The site-specific data is of lesser interest in the current context, but the regional threshold is of considerable interest. Their work involved the spatial and temporal distribution of rainfall that occurred during and prior to an extreme event during August 1998. Data from a total of 147 rainfall stations (including 36 pluviometers) within the region have been analysed and interpolated to give the cumulative rainfall at each landslide location.

The spatial distributions of cumulative rainfall over different antecedent time periods were analysed. The antecedent time periods of six hours and 12 hours prior to 0700 hours on 7 August and 1, 3, 5, 7, 30, 60, 90 and 120 days prior to 0900 hours on the 17, 18 and 19 August were considered in various analyses. Figure G.2 shows the rainfall intensity-durations for each antecedent rainfall period as a series of 142 data points making up each of a series of vertical columns of data points – each vertical column represents one antecedent period and each landslide recorded is represented by one data point in each vertical column.

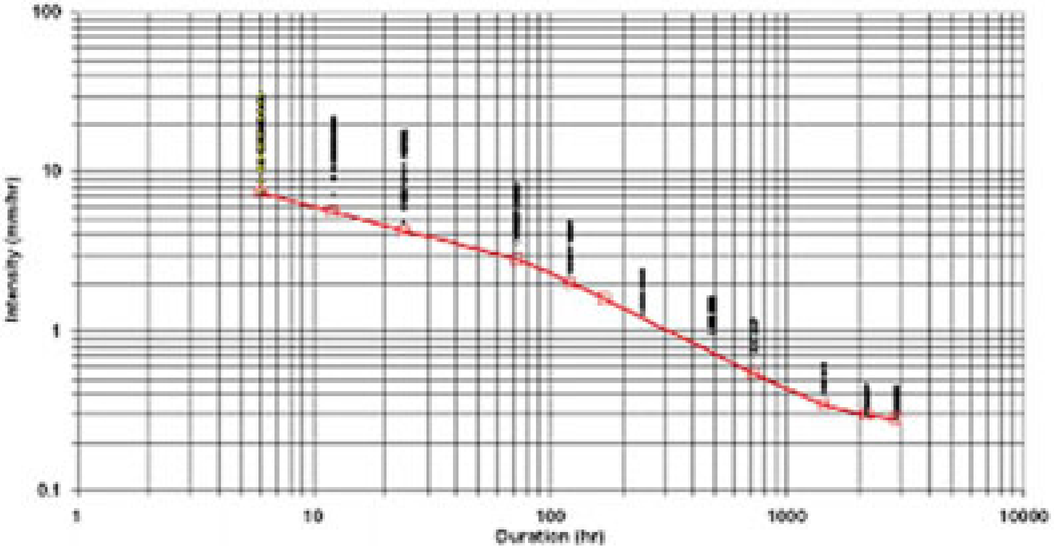


Figure G.2 – The lower bound intensity-duration 'regional landslide triggering rainfall threshold' for the city of Wollongong during the extreme August 1998 event (from Flentje and Chowdhury, 2006).

The red curve extending across the graph near the base of each vertical column of data points represents the lower bound intensity-duration 'regional rainfall threshold' for the city of Wollongong for the August 1998 event. The authors emphasise that their threshold is for the Wollongong area and may not be applicable to other areas. In particular their work considers the particular morphology of the flows and slides that are experienced in their areas. They also emphasise that the regional threshold may be at significant variance with that for individual landslide sites.

They state that the shorter duration thresholds (six hour to three days for their study area) are most relevant for shallow debris flow and that this is supported by the work of Wieczorek (1987) amongst others. However, this may be seen as something of a simplification as Wieczorek actually states that 28cm of antecedent rainfall was required before debris flows would be triggered.

Leventhal and Walker (2005) also note that rainfall is a key trigger factor in the Australian Geomechanics Society (AGS, 2000) system for landslide risk assessment and management.

G.2 HONG KONG SAR

This case study summarises the methods of collating rainfall data used in Hong Kong and how rainfall data has been used to develop a landslide warning system. The Geotechnical Engineering Office (GEO) has been particularly active in investigating the distribution, nature and probable causes of landslide occurrences in natural terrain, and in assessing the hazards of such events. To describe all of their studies and how they interact is however considered outwith the remit of this case study. Instead, only those studies which directly impact on the rainfall correlation with landslides are described. The historic papers collected into a volume to commemorate 30 years of slope safety practice in Hong Kong together provide a comprehensive account of the work undertaken in that part of the world (Anon, 2007b).

While much of this section discussed the rainfall threshold work in Hong Kong for natural terrain landslides, it is important to note that as yet the landslip warning system used in Hong Kong takes into account only the rainfall threshold analyses of man-made slopes.

G.2.1 Key Dates

Early-1970s: Two man-made slopes collapsed on 18 June, killing a total of 138 people: 71 at the Sua Ma Ping Estate in Kowloon (Figure G.3) and 67 at Po Shan Road, in Mid-Levels on Hong Kong Island (Figure G.4). In 1976, another failure at Sau Mau Ping killed a further 18 people.

Figure G.3 – Sua Ma Ping Estate landslide, 18 June 1972. A 40m high road embankment collapsed after 232mm of rain.

1977: The Geotechnical Control Office (now called the Geotechnical Engineering Office, GEO) was formed and development of the Landslip Preventative Measures (LPM) Programme begun. The LPM programme was developed to inspect, and produce an inventory of, all man-made slopes and retaining structures in Hong Kong, although ‘special projects’ involving natural terrain studies were also undertaken. Substandard slopes were, and to some extent are still being, systematically upgraded to progressively reduce the landslide risk from man-made slopes which affect the community, whilst also trying to improve aesthetics of the slope. A major exercise to ‘educate the public’ of the dangers of landslides was also begun.

Mid-1979: GEO undertook a mapping exercise of Hong Kong to identify areas of colluvium, which led to a systematic terrain classification based on i) slope gradient; ii) terrain component (hillcrest, foot slope, side slope, etc); and iii) erosion and instability. This later became known as the Geotechnical Area Studies Programme, GASP.

Figure G.4 – Po Shan Road Landslide, Mid-Levels, Hong Kong Island 18 June 1972. The landslide occurred on a steep hillside above a temporary excavation and demolished a 12-storey building.

Early-1980s: GEO started collecting and reviewing data and producing annual reports (since 1984) of rainfall and landslides in Hong Kong. Rainfall gauge coverage significantly improves from 1985, and in addition rainfall data also began to be collected at five minute intervals (throughout the year).

1994: GEO started using consultants to design and supervise construction of LPM, and to investigate and report on selected landslides.

1995: GEO commenced the Natural Terrain Landslide Study (NTLS) (Evans *et al*., 1999; Ng *et al*., 2003). This formed part of a series of integrated studies to investigate the distribution, nature and probable causes of natural terrain landslides and to assess the hazard from such events. Phase 1 produced the Natural Terrain Landslide Inventory (NTLI) (King, 1999) from a review of high level aerial photographs taken between 1945 and 1994. Phase 2 used GIS to examine the spatial distribution of landslides with respect to geology, slope angle, geomorphology, vegetation and slope aspect, etc, to determine causal factors and a preliminary assessment of hazard. Of these, geology and slope angle were found to be most important in determining natural terrain landslide susceptibility at a regional scale. Phase 3 produced regional natural terrain landslide susceptibility and hazard maps, together with detailed studies of some areas with a high incidence of landsliding that are close to existing or proposed developments. Phase 3 also developed procedures for the hazard and risk assessment of natural terrain in Hong Kong, the investigation of hydrological and hydrogeological influences on landslide susceptibility and the continued study into the nature, occurrence and frequency of exceptionally large natural terrain landslides.

The Slope Safety Technical Review Board was then established. This comprises a panel of three to four renowned experts who interact extensively with GEO, reviewing and advising on various aspects of slope engineering.

1999: The National Landslide Inventory (NTLI) was formed (King, 1999) containing information on more than 26,700 landslides on natural terrain. The associated 'Landslide Investigation' methodology was developed (in conjunction with Professor Norbert Morgenstern of the University of Alberta in Canada).

2000: Landslide Investigations became part of the LPM programme.

2004: The Landslide Potential Index was developed – this measures the relative severity of a rainstorm relative to its potential to cause landslides.

G.2.2 Existing Rain Gauge Network in Hong Kong

Rain gauge networks are operated by four separate bodies including the Hong Kong Observatory (HKO), the Water Supplies Department, the GEO of the Civil Engineering Department, and the Drainage Services Department (DSD) of the HKSAR Government. Altogether these four departments are responsible for operating and maintaining more than 200 (as of 2001) of the rainfall, tidal and hydrological gauging stations in the territory.

The rain gauge stations are automatic telemetric stations that transmit data at five minute intervals throughout the year, during both the wet and dry seasons. Telemetric readers in Hong Kong are generally powered from mains electricity as the majority are in built up areas. However, each station has a 72 hour backup battery power in case of a supply failure and a number are now self-powered through solar power and wind power. In Hong Kong it is also necessary to protect the equipment from extremes in temperature (80°C in summer inside equipment cases) and humidity (95% relative humidity).

A typical Hong Kong gauging station may contain the following equipment:
i) Data logger.
ii) Rainfall gauge.
iii) Telemetry connection.
iv) Incoming power supply.
v) Backup power for at least three days.
vi) Lightning protection system (unlikely to be required for the Scottish situation)
vii) Ventilation fan controlled by thermostat (again unlikely to be required for the Scottish situation).

Examining items (i) and (ii) above in more detail:
i) Data Logger – this would tend to be a programmable logic controller (PLC) or a remote terminal unit (RTU). The PLC is easier to install, programme and support but the RTU has superior communication capability, more memory, and is normally designed for extremes in temperature and humidity. The information is transmitted to a central location, generally a PC, via data link/dial up or via wireless transmission. If there is a break in the transmission or an equipment problem, the stored data will be automatically re-transmitted to the office in the next available transmission. Stored data can also be retrieved from site at any time. The data are all in text (ASCII format) for easy transmission and reading. Once the text is received, it is saved in a database such as

Oracle or MS SQL. The latter is preferred as it is compatible with Excel™ from which graphical representations (e.g. bar charts) of the rainfall readings can be produced.

ii) Rain Gauge – this would tend to be a Casella tipping bucket, which tips when the rainfall depth reaches 0.5mm. A 0.2mm tipping bucket may be more suitable for a non-tropical (Scottish) situation. In locating a rain gauge the following rules of thumb are observed:
   - The rain gauge should be positioned on a reasonably level and flat surface.
   - There should be no obstructions in the vicinity. Normally, the height of any object should be less than 1/4 to 1/3 of the horizontal distance from the bucket.
   - The rain gauge should be positioned to avoid tall buildings and trees as these can cause eddies which may affect the amount of rain collected.
   - Areas that may be susceptible to flooding should be avoided.
   - The rain gauge should be positioned in an area where the discharge water from the gauge can drain away quickly.

G.2.3 Determination of a Rainfall Threshold

Initially, correlations of rainfall intensity with landslide activity in Hong Kong concentrated on failures of man-made slopes, as these are incidents that tend to affect developed areas and are therefore reported. There is general agreement that it is possible to define rainfall threshold above which failures of man-made slopes increase in frequency (Lumb, 1975; Brand *et al*., 1984; Au, 1993; Premchitt *et al*., 1994).

Thresholds for natural terrain landslides are not so easy to derive, and have not as yet been implemented, as the failure mechanisms may differ and records of events are harder to obtain. However, given that 60% of the land area of Hong Kong is classed as 'Natural Terrain' and the ever increasing demand for land pushes new developments and infrastructure closer to the natural terrain, the GEO realised the need to get a better understanding of landslide susceptibility. Hence the Natural Terrain Landslide Studies were set up as a special project, within the LPM programme of works, part of which looked at the correlation between rainfall and natural terrain landsliding.

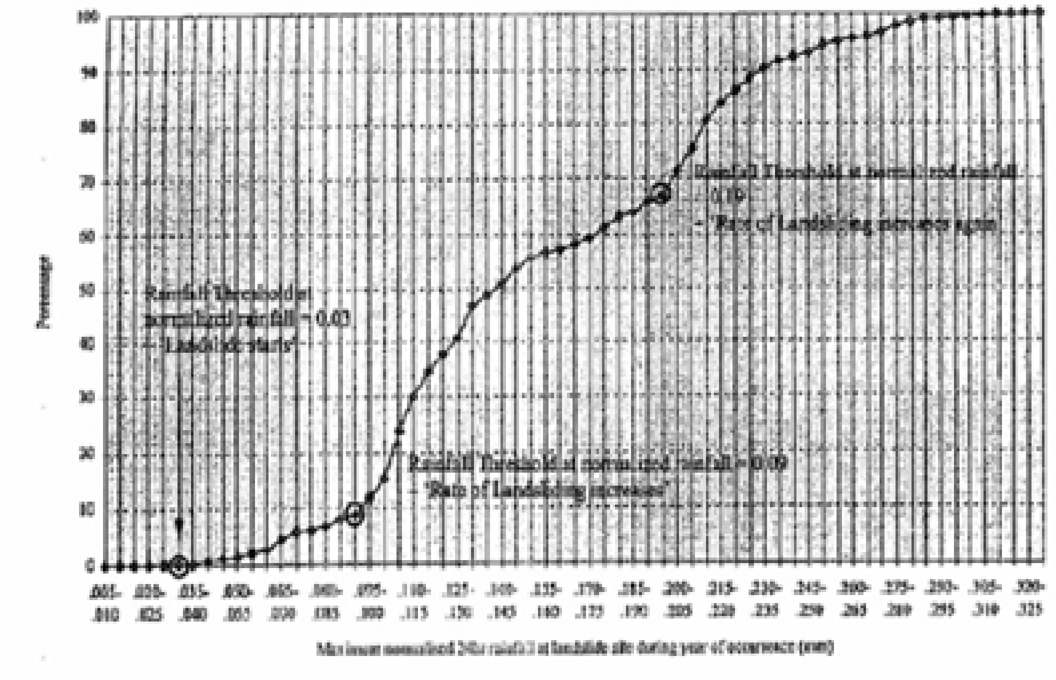
Evans (1996) was the first to look at the distribution of rainfall over HK and noted that annual rainfall is not uniform, even when expected elevation effects are taken into account. The coastal periphery, outlying islands and the northern New Territories appear to be significantly drier than elsewhere. This led to the suggestion that absolute rainfall thresholds for landslides on natural terrain may also vary across Hong Kong, all other factors being equal. 'Normalised' rainfall, in which rainfall at a site is recorded as a proportion of the mean annual rainfall at that site, was considered to be a more appropriate tool for investigating natural terrain landslide susceptibility.

The NTLI allowed Evans (1997) to carry out a semi-quantitative assessment of possible rainfall thresholds (Annex G.1). The method adopted is summarised by Ko (2005) and included as Appendix B for information. Firstly, he looked at aerial photographs for the period between 1985 to 1994 (corresponding to the time when spatial rain gauge coverage was significantly improved) to locate and record natural terrain landslides, from which he produced a series of 1:100,000 plans for each year (1985 to 1994). He then plotted isohyets (lines on a map connecting points that receive equal amounts of rainfall) of the rolling 24 hour rainfall for all significant rainstorms for the same period and superimposed these on the 1:100,000 landslide plans. (Most of this information was obtained from the annual rainfall and landslide reports produced by GEO.)

The plots of rainfall and landslides were examined and for each landslide the maximum rolling 24-hour rainfall in the year of occurrence was recorded. This figure was reduced to a normalised value by dividing it by the approximate mean annual rainfall at the landslide site. A major limitation of this process was obviously that the maximum recorded rainfall may not necessarily have triggered the landslide.

Evans found that there were three points of abrupt change in the gradient (Figure G.5), which were taken as rainfall thresholds where significant increase in the number of natural terrain landslides would occur. Examination of his plots of annual rainfall and landslide distribution showed that for the majority of Hong Kong, where mean average rainfall is in the range 2,000 to 2,400mm, landslide densities of 1 per km^2 or more are usually associated with 24 hour rainfall maxima of at least 200mm (0.09 normalised or 9% of annual mean precipitation), while higher densities of over 10 per km^2 tend to be associated with 24 hour maxima of at least 400mm (19% of mean annual precipitation). It should be noted that these thresholds were average values, and did not take into account any contributing factors such as geology, slope, etc. He defined approximate landslide densities as the following:

a) Low density – less than 1 landslide per km^2.
b) Medium density – 1 to 10 landslides per km^2.
c) High density – over 10 landslides per km^2.



Note : Extracted from Evans (1997)

Figure G.5 – Cumulative percentage of natural terrain landslides against normalised maximum rolling 24-hour rainfall (1985 to 1994).

G.2.4 Landslide Warning System

The GEO manages and operates the Landslip Warning System with the Hong Kong Observatory (HKO). Landslip warnings are issued by the HKO in consultation with GEO when the recorded and forecast rainfall meets the warning criteria. It is important to note that, as of December 2007, the warnings were based upon man-made slopes and not on natural terrain landslides.

The existing Landslip Warning Criterion (Yu *et al.*, 2003) operates by summing the number of landslide incidents for each of the vulnerable areas, based on the correlation between landslide density (number per km^2) and rolling 24-hour rainfall of selected rain gauges. The Landslip Warning level was initially set at 10 landslides, on the basis that on average about 10% of reported landslides were major incidents and that casualties were only caused by major incidents. (This approach is similar to that described above for the unimplemented natural terrain landslide system.)

The landslide warning system was revised in 2001 following a review of landslide statistics. This revealed that, whilst on average major landslides account for about 10% of the total number of reported landslides, the percentage of major landslides was not constant but increased with increasing numbers of landslides (i.e. the percentage of major landslides increased with increasing size of storm event). For smaller rainstorm events, or at the early stages of larger events, the 'first' major landslide often occurred after about fifteen landslides were reported to GEO. Therefore, the warning level was increased from 10 to 15 predicted landslides in October 2001.

The action levels for the issuing of Landslip Warnings are as follows:

i) Consultation Level – consultation between HKO and GEO begins when 10 or more rain gauges record rolling rainfall of more than 100mm in 24 hours.

ii) Alert Level – this is a situation wherein continued monitoring of rainfall, and liaison, takes place. This level arises when the average rainfall required to reach 'warning level' is less than 100mm in 24 hours.

iii) Warning Level – Landslip Warning issued by HKO after consultation with GEO. The rainfall level has achieved that set for 15 or more predicted landslides.

Following recommendations made by Pun *et al*. (1999), a performance review of the Landslip Criteria is continuously undertaken. Improvements are made to take into account the experience gained from the operation of the system and correlations between landslide and rainfall are refined.

It is also of interest that the Hong Kong Observatory also operates a Rainstorm Warning to alert the public to heavy rainfall events. It should be noted that the Landslip Warnings are independent from the Rainstorm Warnings, which are set at Amber, Red and Black for 30mm, 50mm and 70mm of rain in 1 hour expected within 24 hours respectively. More emphasis is placed on the rainstorm warnings by the press and TV and during 'Black Rain' events, schools and offices are closed, which has led to some complaints about loss of profits from some business sectors. However, on the whole, both types of warnings are well received by the public.

G.2.5 Further Developments and Proposals for Future Studies in Hong Kong

Evans' (1996; 1997) studies were recently updated in 2005 by Ko (2005), to include landslide data up to the year 2000 (an increase of 75% in the number of landslides), and used geostatistical analyses and GIS to process and analyse data, thus removing human error and improving efficiency and accuracy. Ko concluded that the plots and thresholds produced by Evans had limitations in the establishment of landslide warning criteria because they looked at maximum rolling 24 hour rainfall recorded in a year and not during a storm event. Ko subsequently used statistics to correlate the year-based 24 hour maximum to a storm-based maximum (the reader is referred to Appendix D of Ko, 2005). It is unclear, however, if the landslip warning system has been reviewed in light of her findings and recommendations.

Ko recommended that further refinements were achievable through the use of GIS. These refinements would include the effects of elevation (by locating rain gauges in higher natural terrain), terrain attributes (geology, slope gradient, etc) and terrain susceptibility classification into their rainfall-natural terrain landslide correlation. She also recommended other methods of looking at rainfall data including, the following:

i) Other means of normalisation of rainfall (using rainfall return period instead of the mean annual rainfall at a given site).
ii) Using different durations of rainfall (a maximum three hour rolling with antecedent 30 day rainfall) instead of the 24 hour rolling maximum.
iii) Formulation of a natural terrain landslide warning criterion.

G.2.6 Success?

The only 'measure of success' that is published relates to man-made slopes (Anon, Undated; Sun and Evans, 1999). Since the adoption of the LPM programme, risk assessment calculations indicate that the overall landslide risk arising from old substandard man-made slopes to the whole community of Hong Kong has been reduced to about 50% of the risk that existed in 1977. The Hong Kong Government's demanding (but achievable) objective is to further reduce the landslide risk from old man-made slopes to below 25% of the 1977 level by the year 2010.

To put the risk of natural terrain landslides into perspective (Wong *et al*., 2004), of the 50 fatalities recorded between 1980 and 2003, 16 were as a result of natural terrain landslides and a significant number of these were associated with squatter areas. The historical natural terrain landslide data indicate that the landslide risk from natural hillsides is lower than that from man-made slopes in Hong Kong. However, the data may not fully reflect the inherent landslide risk to the community. Some landslides were 'near miss' incidents that could well have resulted in more serious consequences and the situation will only worsen as more new developments take place on, or close to steep natural hillsides.

The Hong Kong Government's preferred approach is not to carry out stabilisation works to large areas of natural terrain, which would be both impractical and environmentally damaging, but to mitigate the risk through adjustments to the layout of new developments and provision of buffer zones and defence measures (e.g. debris resisting barriers).

G.3 ITALY

A number of case studies have been published describing the effects of rainfall on landslides in Italy, most importantly a national system for the real-time prediction of hydro-geological hazards (floods and landslides). The rainfall detection element of the system is based on a comprehensive radar network (Casagli, 2006)

G.3.1 North Western Tuscany, June 1996

D'Amato Avanzi *et al*. (2004) report a series of rainfall induced shallow landslides which occurred on 9 June 1996 in the Apuan Alps in north western Tuscany, Italy. The associated rainstorm was concentrated over a 150km^2 area and 474mm the rainfall corresponded to 21% of the annual mean.

Some 647 main landslides were recorded and were estimated to have caused damage to the value of hundreds of millions of Euros, in addition to causing the deaths of 14 people. The June 1996 storm occurred after a dry month (17.2mm of rainfall at Pomezzana). Figure G.6 shows the recorded rainfall at two gauges in the affected area. At Pomezzana 474mm of rain was recorded in about 12 hours, with a maximum intensity of 158mm/hour, whilst at Fornovolasco 420mmof rain fell in about 10 hours, before the instrument was destroyed by either a flood or a landslide. At gauges some 7km to 10km away only a few millimetres of rainfall was recorded.

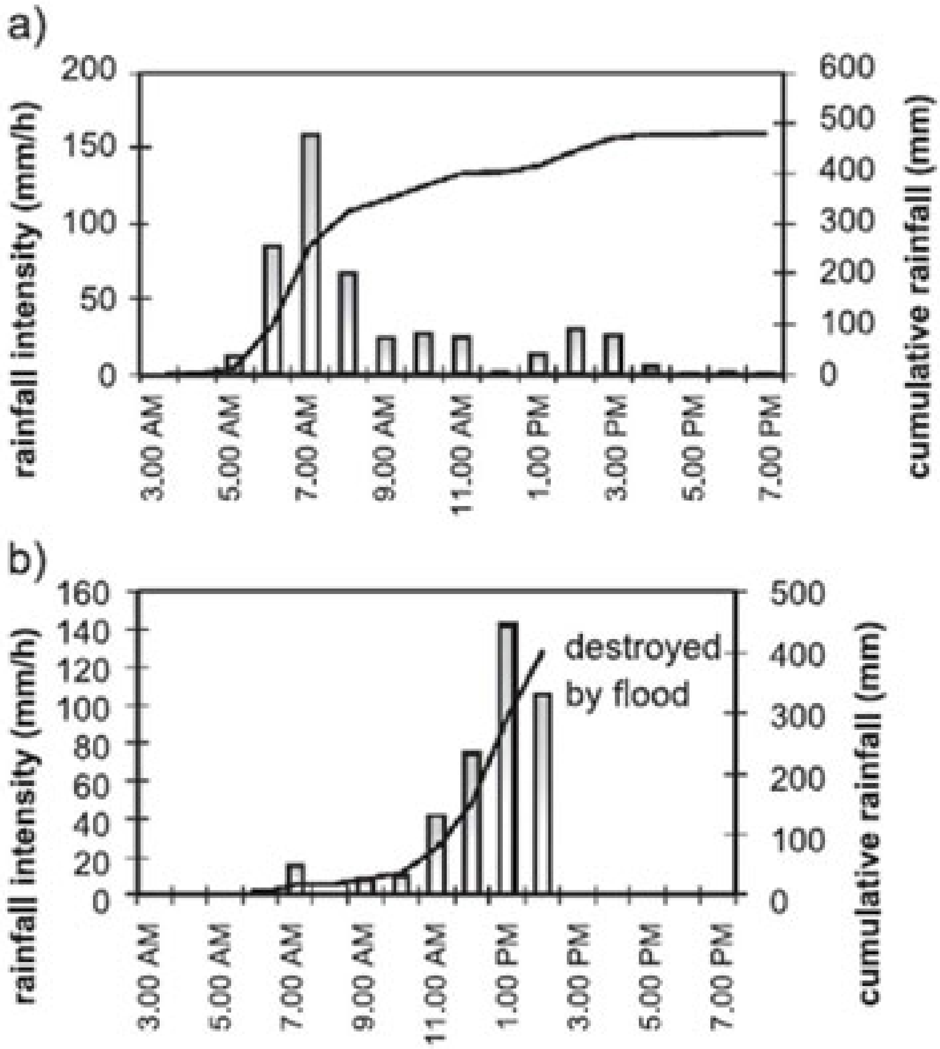


Figure G.6 – Rainfall data from the 9 June 1996 study areas: (a) Pomezzana (597m asl) and Fornovolasco (470m asl) rainfall gauges (from D'Amato Avanzi *et al*., 2004).

While D'Amato Avanzi *et al*. (2004) give few insights into the relations between rainfall and landslides their paper provides some interesting and useful analyses. For example, they show that in this area and on this occasion by far and away the majority of landslides occurred in shallow overburden of between 0.5m and 2m thick.

G.3.2 Sarno, May 1998

Frattini *et al*. (2004) describe a series of more than 400 landslides which occurred in May 1998 near Sarno, to the east of Naples and Vesuvius, in pyroclastic soils. The landslides were triggered by a storm event and destroyed houses and infrastructure in addition to killing a total of 159 people. The events broadly classify as soil slip-debris flows or soil slip-mud flows, with velocities from very to extremely rapid and with high water content (Cruden and Varnes, 1996). According to the Pierson and Costa (1987) classification these would be described as slurry flows evolving into hyperconcentrated flows, with estimated velocities of 9.3m/s to 10m/s (see Figure 2.3 of Winter *et al*., 2005a).

Detailed rainfall gauge information was not available from within the authors' study area, making rainfall analysis very difficult due to both the high areal variability of intense rainfall and orographic effects. However, data from five gauges was reported and Figure G.7 illustrates this data along with the locations of the rainfall gauges relative to the study area.

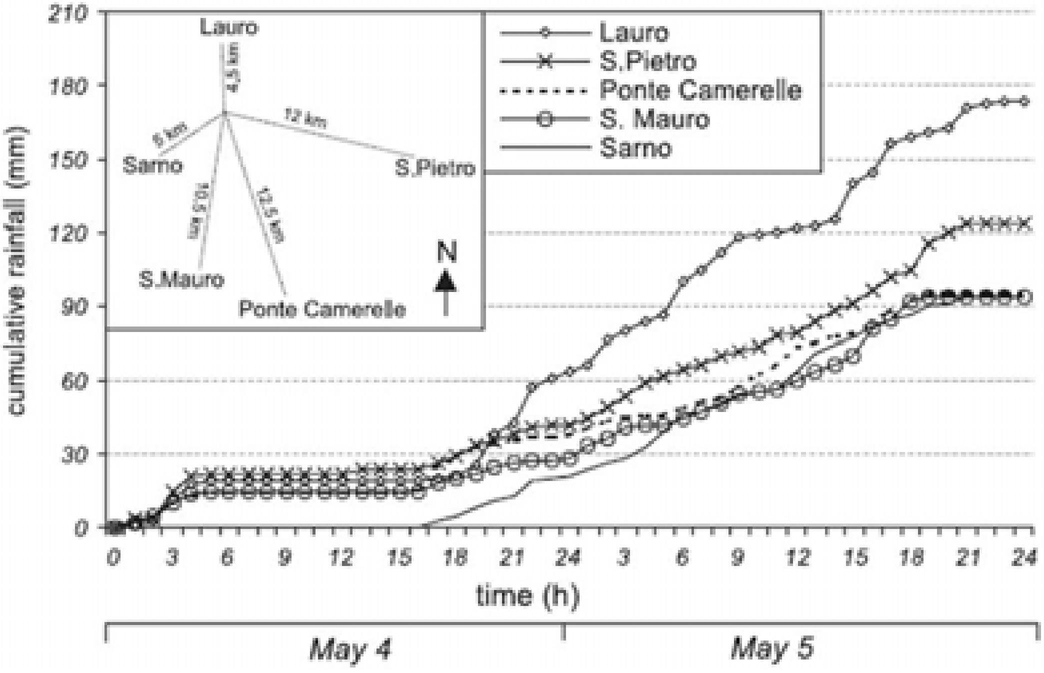


Figure G.7 – Cumulative rainfall for 4 to 5 May 1998 recorded by rainfall gauges at Lauro (4.5km north of the study area; 192m above sea level, asl); S. Pietro (12km east; 215m asl); Ponte Camerelle (12.5km south; 97m asl); S. Mauro (10.5km south; 31m asl); and Sarno (5.5km south-east; 36m asl) (from Frattini *et al*., 2004).

The data from the Lauro gauge was considered to be most relevant to the events due both to its distance from the hillside initiation areas and also its position with respect to the path of the storm. The cumulative rainfall recorded by the Lauro gauge during the 48 hour event was 173mm. The first low intensity fall occurred between 0000 and 0500 hours on 4 May and after a break of 11 hours it rained continuously until the early morning of 6 May. A maximum rainfall intensity of 15mm/hour was recorded at 1500 on 5 May and the mean intensity over the 48 hour period was 3.6mm/hour (Frattini *et al*., 2004).

Antecedent rainfall between 28 April and 3 May contributed a further 61.4mm and the rainfall return period was relatively short, with a maximum return period of 33 years for the 24 hour rainfall recorded on 5 May at Lauro. However, this must be set against the events occurring at the end of the rainy season and if this period is considered then the return period rises to greater than 100 years (Figure G.8).

The authors maintain that antecedent rainfall played a significant part in the triggering of this series of landslides, not least because of the high water retention (up to 100% of dry weight) of the volcaniclastic deposits. In such case rainfall infiltration over a prolonged period of time can cause significant increases in the unit weight making such an effect potentially more significant than in some other materials.

The rainfall and other data acquired by Frattini *et al*. (2004) were used to drive a hydrological model and there is no evidence that this has been used in any way to attempt to forecast future events. Indeed, Frattini *et al*. stated that they believe that such hydrological models were impractical for reliable physically-based distributed modelling, largely due to their complexity, associated data requirement and the difficulties associated with calibration.

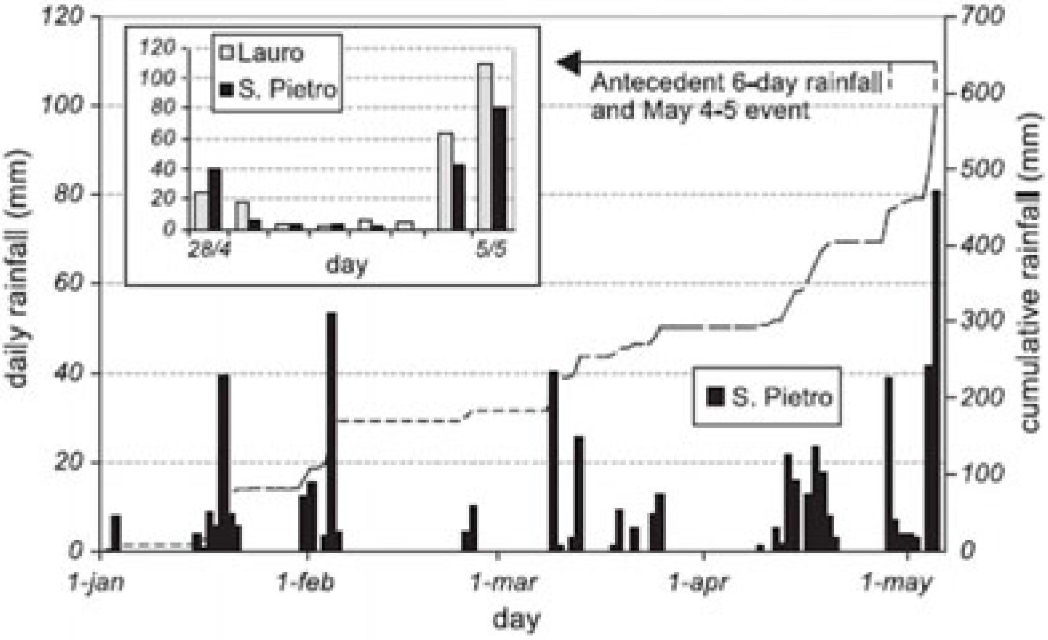


Figure G.8 – Antecedent and event rainfall at the S. Pietro gauge, 215m asl and 12km to the east of the study area. The inset upper left shows the daily rainfall for late-April and early-May (from Frattini *et al*., 2004).

Sirangelo and Braca (2004) studied the same area as Frattini *et al*. (2004), but from a substantially different viewpoint. Their work involved the creation of a hydrological model, based upon a back analysis of the May 1998 events. The model produced is highly complex and comprises two parts:

- 'Rainfall-Landslide' for correlating precipitation and landslide occurrence, intended for model calibration through the reproduction of historic events.
- 'Stochastic Rainfall' for real-time forecasting of landslide events.

The model has been operated using data from the Sarno events and predictions performed over a period of approximately four years. The model enables three levels of elevated landslide potential status to be implemented, as follows:

- Attention status: with real time monitoring of instruments (when the mobility function, dependent upon the antecedent rainfall, reaches 40% of its critical value).
- Alert status: involving civil protection agencies (when the mobility function reaches 60% its critical value).
- Alarm status: involving the evacuation of the local population (when the mobility function reaches 80% its critical value).

During the period October 1999 to May 2002, 21, five and one respectively of each of the above status levels were implemented.

The 'Rainfall-Landslide' model is currently being used as a warning system for the Sarno area by the local authorities. However, it would appear that no events have as yet been successfully forecast using the system.

G.3.3 Imperia Province, Western Liguria, November 2000

From mid-October to 22 November 2000, the Western Liguria Region (Figure G.9) experienced prolonged and intense rainfall, with cumulative values exceeding 1,000mm in 45 days. This was followed on 23 November by a high intensity storm of 180mm of rain in 24 hours.

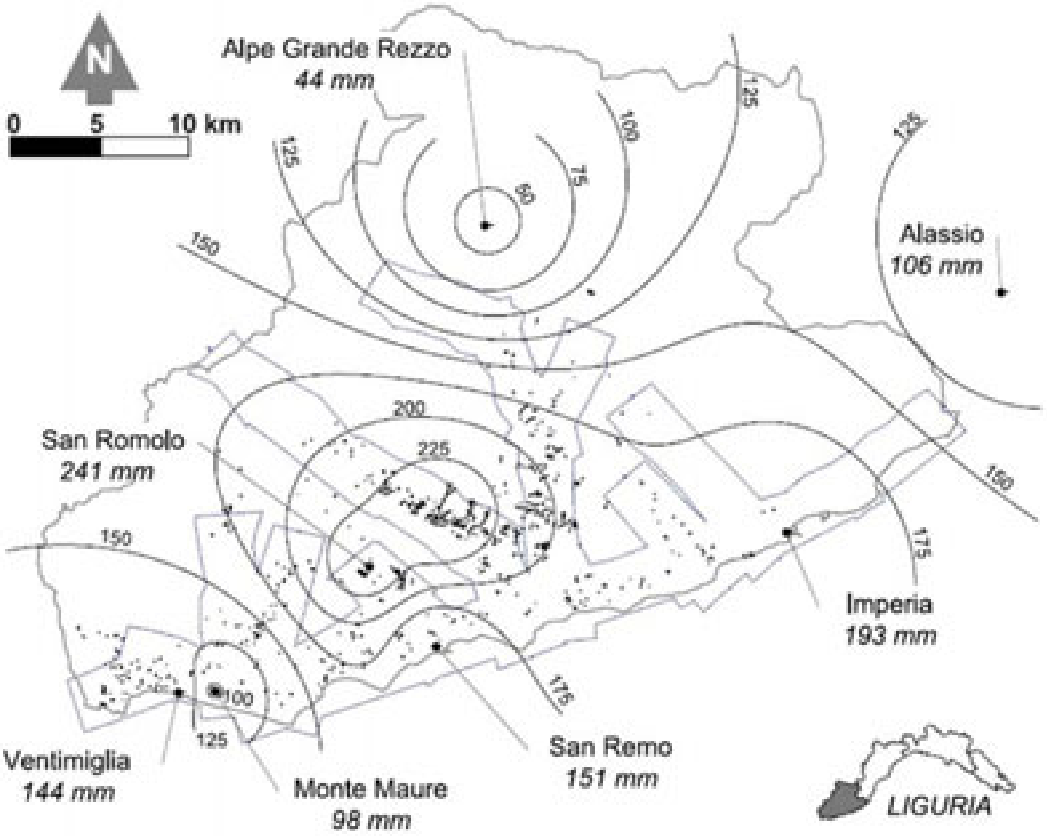


Figure G.9 – Cumulative rainfall distribution for 23 November in Imperia Province. The grey lines show the extent the post-event aerial photography. Black dots show the locations of rainfall gauges. Irregular black lines show the locations of landslides, which have been exaggerated for illustration purposes (from Guzzetti *et al.*, 2004).

More than 1,000 landslides, including debris flows and a few large complex slides, were triggered causing severe damage to roads, private homes and agriculture as well as leading to three deaths. The landslides commenced between eight and 10 hours after the start of the storm and the most intense areal landslide activity occurred as a consequence of rainfall intensities of 8mm/hour to 10mm/hour (Guzzettti *et al*., 2004). Mean annual precipitation ranges from between 750mm and 1,250mm in the west to between 1,350mm and 1,850 in the central and eastern parts of the region.

Figure G.9 relates the spatial distribution of cumulative rainfall in Imperia Province to landslide activity. Although this Province has experienced less rainfall and fewer landslides than others within Liguria Region. The map shows that the highest intensity rainfall coincides with the area in which landslides were most abundant.

Figure G.10 shows patterns of rainfall intensity versus duration for a gauge at Imperia (Figure G.10a) and the synthetised rainfall pattern constructed for San Romolo (Figure G.10b), the latter based on a cumulative rainfall fof 241.2mm (i.e. at the San Romolo gross measurement gauge) and the same intensity as recorded at the Imperia gauge. Each graph begins at 15 minutes (0.25 hours) at the left hand side of the graph and ends at 28 hours on the right hand side. The times of landslide occurrence as observed at nearby Ceriana are over-plotted. Figure G.10c corrects the timings of landslides for a two-hour apparent lag time observed between the highest intensity rainfall at Imperia and Ceriana.

G.3.4 Piedmont Region

In dealing with debris flows and soil slips triggered by short intensity storms in the Piedmont Regionof NW Italy, Aleotti (2004) usefully defines some of the key rainfall parameters relating to the potential to trigger landslides (Figure G.11).

Aleotti (2004) proposes an equation similar in form to equation (10.1A) as follows:

$$I = 19D^{-0.50} \tag{G.1}$$

This equation is claimed to account for 90% of the available data for which rainfall is believed to have led to landslides in the Region. It has been refined by normalising the intensity of the rainfall (*NI*) with respect to the mean annual precipitation (*MAP*) such that two equations collectively describe the triggering threshold, as follows:

$$NI = 0.76D^{-0.33} \tag{G.2}$$

and

$$NI = 4.62D^{-0.79} \tag{G.3}$$

where the normalised intensity (*NI*) is expressed as a percentage by $I/MAP \times 100$.

Finally, Aleotti (2004) expresses the critical normalised intensity in terms of the normalised critical rainfall (NCR) to encompass 90% of events studied, as follows:

$$NI = -0.09 \times \ln(NCR) + 0.54 \tag{G.4}$$

where the $NCR = R/MAP \times 100$.

Aleotti (2004) used hourly rainfall in the study, but appears to have analysed only the storm events taking no account of longer-term antecedent rainfall perhaps accounting for some of the poor correlations reported.

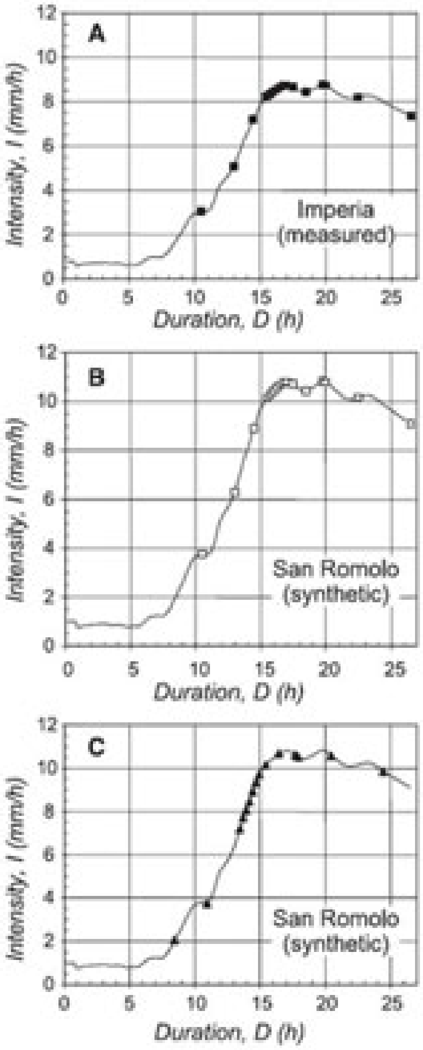


Figure G.10 – Landslide timings at Ceriana relative to intensity-duration plots: (a) rain gauge at Imperia; (b) synthetically derived rainfall at San Romolo; (c) synthetic San Remolo data corrected for a two hour time lag (from Guzzetti *et al.*, 2004).

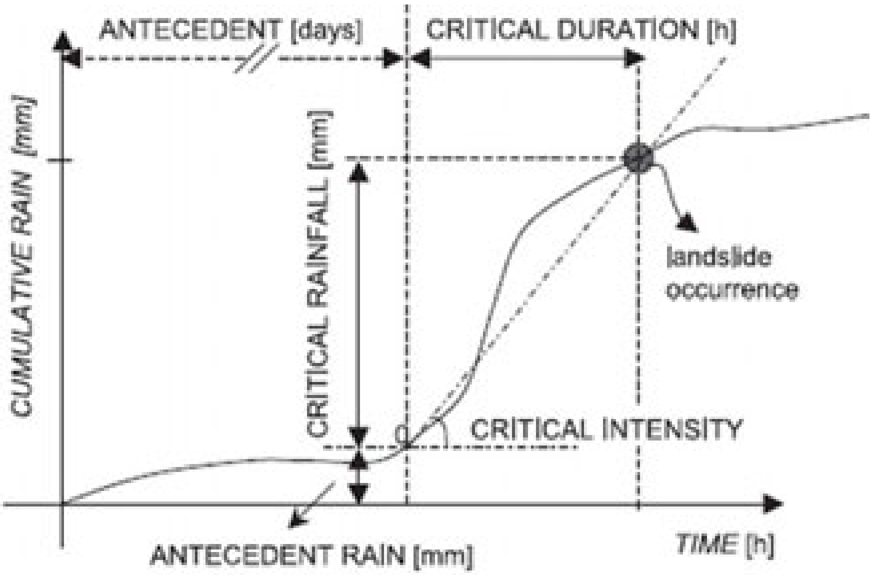


Figure G.11 – Definition of rainfall parameters (from Aleotti, 2004).

G.3.5 Dolomites

In recent years there have been a number of debris flow events that have exposed the population of the Cancia area of the Dolomites to significant risk. In response, an alarm and monitoring system was set up with data from three rain gauges being monitored during debris flow events.

Data from the rain gauges was analysed, taking into account the elevation of the gauges, to determine debris flow initiation and rainfall relations. The findings were then compared with results from geologically similar areas in the Eastern Alps.

The geology of the area is typically Triassic to Jurassic of the Dolomitic stratigraphic sequence. The deposits that have proved susceptible to debris flows are gravels with a low content of sand and fine particles.

The climatic zone is a cold Alpine Climate (Köppen Class D) with an annual rainfall of 1,000mm, which falls mainly in spring and summer.

The drainage basin for the Cancia debris flow area covers a surface area of approximately 1.8km^2, and the profile of the debris flow channel is shown in Figure G.12. Debris flows are recorded from 1868 (100,000m^3) to 1996 (40,000 m^3 to 45,000m^3), with activity over period 1986 to 1996 being one event every 1 to 2 years.

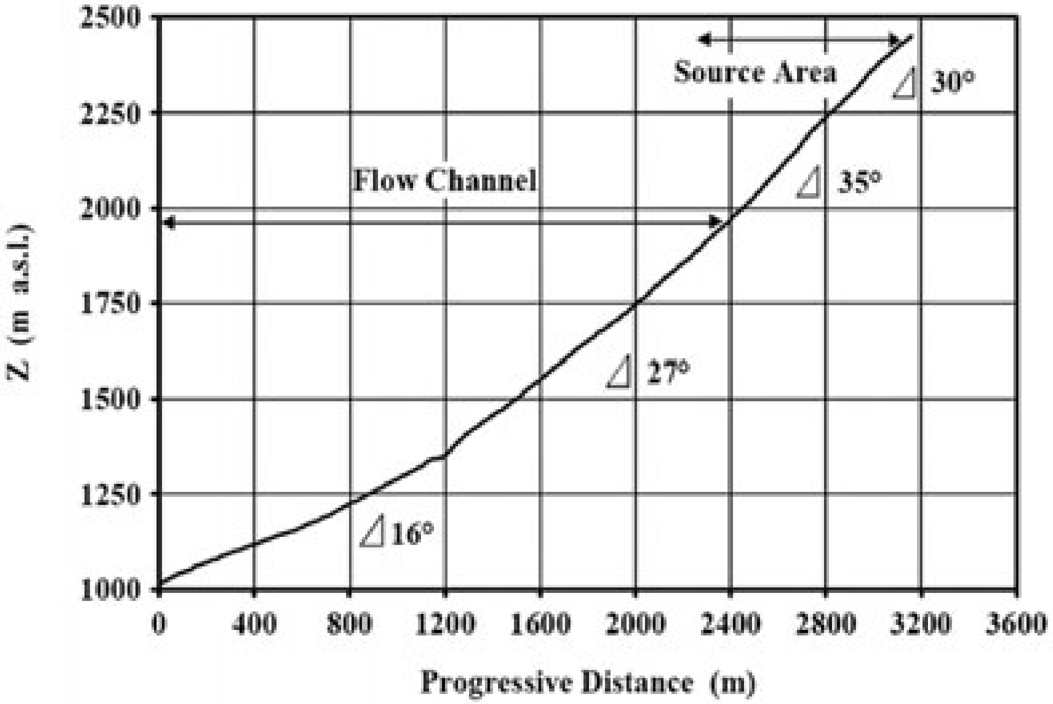


Figure G.12 – Longitudinal profile of a flow channel, the upper part of the source area and mean slope angles in the different sectors (from Bacchini and Zannoni, 2002).

Thresholds based on Ceriani *et al.* (1994) were found to be too high, with most of the observed events falling in the stable zone (Figure G.13). Thresholds were developed for debris flows in terms of mean intensity (*I*), duration (*D*) and mean annual precipitation

(MAP). These utilised normalised rainfall and normalised intensity expressed as a percentage of the MAP (Figure G.13).

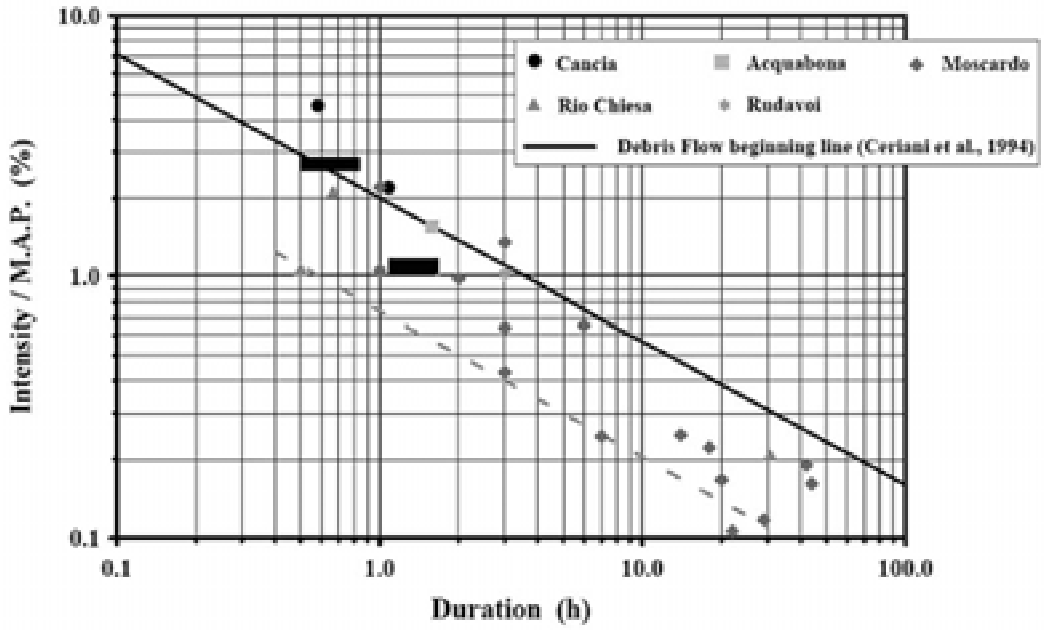


Figure G.13 – Normalised rainfall intensity (intensity/MAP) versus duration and debris flow correlation. The dashed line shows the debris flow threshold proposed for the study area (from Bacchini and Zannoni, 2002).

Thresholds for debris flows, written in terms of the normalised rainfall (R_n = R/MAP) were as follows:

$$R_n = R / MAP = -1.36 \times \ln(I) + 3.93 \qquad \text{(G.5)}$$

where $I > 2$ mm/hour.

$$I_n / MAP = 0.74D^{-0.36} \qquad \text{(G.6)}$$

Normalised rainfall and normalised rainfall intensity should only be used in limited areas where the annual frequency of rain storms is fairly constant (Wilson, 2000).

Typically, triggering rainfall events were found to be 20mm to 30mm in 1 or 2 hours (i.e. not particularly high rainfall levels) but due to the short duration relative to the data reading frequency they may be of intermediate intensity. The role of storm cells in defining rainfall intensities leading to potential debris flow conditions is thus clear.

Rainfall thresholds were found to be an unsuitable medium for the purposes of debris flow prediction but useful in determining a suitable level at which actions by management and monitoring personnel might be undertaken as part of an overall management strategy.

G.4 JAMAICA

Landslides are a common occurrence and a recurring problem on the mountainous island of Jamaica (R Ahmad, 2006; Personal Communication, 2006). These are usually associated with tropical storms, including hurricanes, the paths of which often pass close to the island. Typically, disruption and damage takes a number of forms, including:

- Severance of transport routes leading to stranded communities.
- Loss of income through economic activity, including loss of productive agricultural areas, especially coffee farms and farm-to-market access roads.
- Closed schools.
- Damage to property and community facilities.
- Interruption to domestic water supplies.
- Addition of sediment to river profiles raising channel levels and thus increasing future flood hazard.

In particular the social fabric of communities may be severely disrupted by many of these consequences and, in addition, individuals are exposed to the trauma of evacuation and the loss of their homes. Much of the impact of such landslides is due to transported landslide debris, especially along debris chutes and deposition areas, which may often be far removed from the landslide source.

Ahmad (2003) reports the development of two thresholds:

- For debris flows that commonly develop from shallow landslides during intense rainfall.
- For deep-seated landslides that are usually triggered by prolonged rainfall.

Also noted is the fact that rainfall amounts for storms that did not trigger landslides are equally important in that they allow the population of the threshold graph from both directions. The threshold established by Ahmad (2003) is presented in Figure G.14.

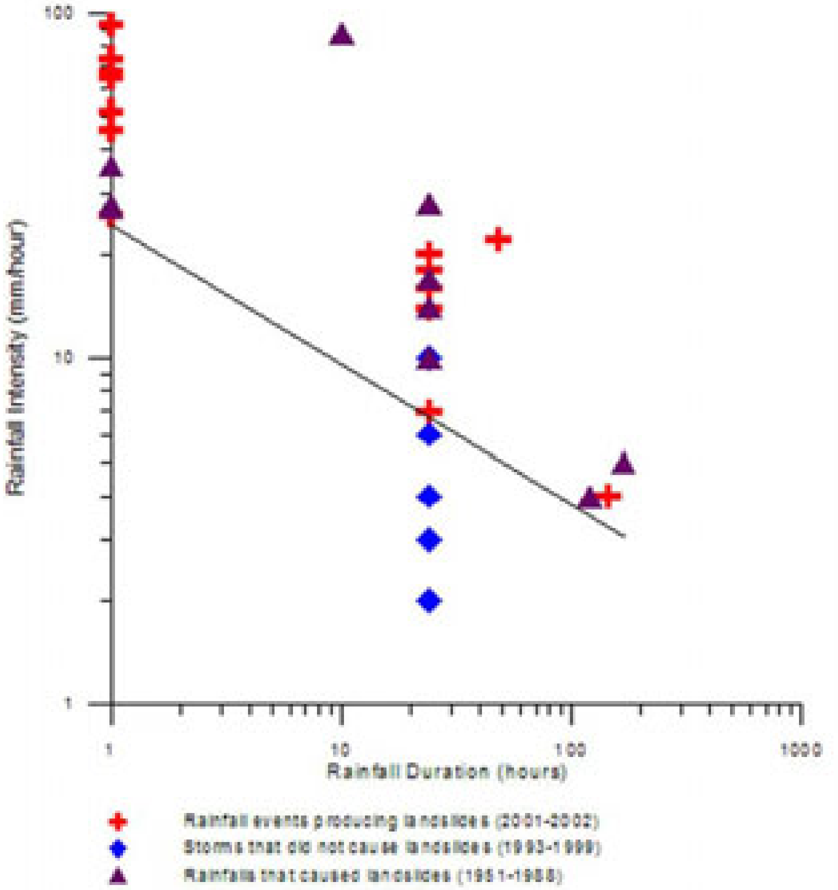


Figure G.14 – Rainfall intensity-duration threshold for shallow landslides in eastern Jamaica, using data from 19 storms between 1951 and 2002 (from Ahmad, 2003).

Ahmad (2003) notes that the rainfall threshold relation is defined for storm durations between 1 and 168 hours and average rainfall intensities between 2 and 93mm/hour. The threshold relation indicates that, for rainfall of short duration (about 1 hour), intensities greater than 36mm/hour are required to trigger landslides.

There is a relation between landslide characteristics and the position of the landslide-triggering storm on the threshold line. Storms near the short-duration/high-intensity end of the threshold line trigger mostly shallow landslides (e.g. Figure G.15) by causing an excess pore pressure in shallow colluvial zones.

In contrast, storms near long-duration/low-intensity end of the threshold have triggered the largest, deepest landslides in eastern Jamaica (e.g. Figures G.16 and G.17).

Figure G.15 – Shallow landslide induced by rainfall between Ramble and Somerset on the Yallahs River in St Thomas Parish, eastern Jamaica. The road followed the shoulder of the hill to either side of the landslide.

Figure G.16 – Deep rainfall induced landslide on the A2 road between Whitehall and Martins in St Mary Parish, eastern Jamaica.

Figure G.17 – Deep rainfall-induced landslide on the B1 road at Section in Portland Parish, eastern Jamaica.

G.5 NEPAL

Landslides in Nepal are often associated with high intensity rainfall in combination with the highly active slope processes that, in such an active mountain environment, are driven by gravity. Monsoon rainfall patterns mean that more than 80% of the annual rainfall occurs within a four month period between June and September, with the 50-year average for Kathmandu in July being around 375mm. At the Arughat Bazar rainfall gauge (near the Privthi Highway, H04: Figure G.18) in excess of 550mm of rain fell in August 2000; while the highest recorded rainfall in a 24 hour period was at Kulekhani, where 540mm of rain fell on the 19 and 20 July 1993, an average of 22.5mm/hour. Sunuwar *et al*. (2005) compare this to figures reported by Wieczorek (1996) of 6.3mm/hour for the triggering of landslides in California.

Rainfall-induced landslides are thus frequent and often block the major roads of Nepal, causing particular problems of the effects of severance of access for rural populations. There appears to be no effort to forecast landslides using rainfall data in Nepal; there remains a suspicion that conditions are sufficiently extreme that such an exercise might be unproductive in that the entire monsoon season would be seen as high risk period.

G.6 NORWAY

Experience in Norway has indicated that 8% to 10% annual precipitation in one day (24hrs) is likely to lead to debris flows in ‘exposed’ (or susceptible) locations (U Domass, Personal Communication, 2006). If there is significant antecedent rainfall (several days) then this threshold may be lower.

Figure G.18 – Privthi Highway, H04, Nepal.

An investigation of 30 debris flows in Norway was undertaken by Sanderson *et al.* (2005). The work indicates that steep Norwegian slopes are often partially covered with glacial till, which in many places is itself covered with colluvium. The silt and clay content of these is typically in the range of 10% to 30% (Jorgensen, 1978). The upper 0.5m to 1.0m of soil has high permeability due roots and organisms, and this enables frost to influence the structure of the soil profile. The permeability of the lower soil is much lower.

Norway comprises two climatic areas:

- Marine west coast climate (western Norway), typically 1,000 to 3,000mm annual rainfall falling in predominantly south-westerly winds during the passage of warm fronts. Daily rainfall can exceed 200mm.
- Continental sub-arctic climate (eastern Norway), typically 300 to 1,000mm annual rainfall falling predominantly during convective summer storms.

Slope aspect plays an important role with the greatest rainfall on windward slopes (south-west facing slopes). The high relief on the west coast also leads to large differences in precipitation even over small distances. South-west facing slopes are also most prone to intense meltwater production due to the exposure to wind and solar radiation.

Field measurements indicate the presence of slip surfaces along a relatively impermeable layer at 0.5m to 1.0m depth. This surface is a boundary between relatively high permeability material and underlying lower permeability material, leading to increased pore pressures.

Climatic monitoring stations in the areas of the 30 debris flows investigated record the following information three times a day (at 0700, 1300 and 1900):

1. Precipitation.
2. Snow depth.
3. Air temperature/humidity.
4. Wind speed/direction.

Records of precipitation and calculated snowmelt over the 12 hour, 24 hour, 7 day, 15 day and monthly time periods were assessed. For the continental climatic areas debris flows activity was found to be most frequent in April and May, whilst for the marine climate August to December were the most active months. For the marine west coast climate areas the weather patterns triggering the majority of events were:

1. Heavy rainfall of one day duration with a concentrated period of 1 hour to 4 hours.
2. Rainfall in combination with snowmelt over 3 days to 7 days.

Two examples of this are:

- In this example event the 24-hour precipitation in excess of 64mm, with the 24-hour rainfall return period being >150 years. The period prior to this had been relatively dry, with only 29.5mm of precipitation over 14 days.
- In the second example event the probable cause was rainfall and snow melt, yielding 190mm in a week (211% of monthly average) – a figure corresponding to a return period of several decades.

The resulting intensity-duration relations for the sites studies were compromised by a high degree of uncertainty, mainly due to following factors:

1. The widespread rain gauge network does not cover all local regions where heavy precipitation is experienced.
2. The frequency of recordings was too low to reflect variations in precipitation with time – Sanderson *et al*. (2005) found that climatic stations recording at 6 and 12 hour frequencies could not be used for generation of water supply/debris flow relations.
3. The rate of snowmelt depends largely on wind speed.

Caine (1980) plotted rainfall intensity against duration for worldwide debris flows and found a lower bound as given in Equation (9.1A)

Sanderson *et al.* (2005) discuss the fact that time is a very significant factor, with rainfall over as little as one hour being potentially critical in the generation of debris flow (Figure G.19). Also identified was a lower intensity-duration threshold (Figure G.20), derived from the 30 debris flows, and this is expressed as:

$$P = 1.2D^{0.6} \tag{G.7}$$

where P is the 'critical water supply' expressed as a percentage of mean annual precipitation and D is duration (hours).

For example, the 12-hour critical water supply expressed as a percentage of mean annual precipitation is given by:

$$P_{12hourCrit} = 1.2 \times 12^{0.6} = 5.33\% \tag{G.8}$$

If the mean annual precipitation is then 2,000mm then the 'critical rainfall level', $R_{12hour\ Crit}$, is $(2{,}000 \times 5.33)/100 = 106.6$mm.

Sanderson *et al.* (2005) conclude that debris flows exhibit the following characteristics:

1. They are triggered by rare climatic events with return periods of 50 years or more.
2. They show short response times to climatic events (e.g. 4 to10 hours).
3. Many recent cases are apparently due to human activity affecting slope hydrological regime: e.g. forest roads, forest harvesting.

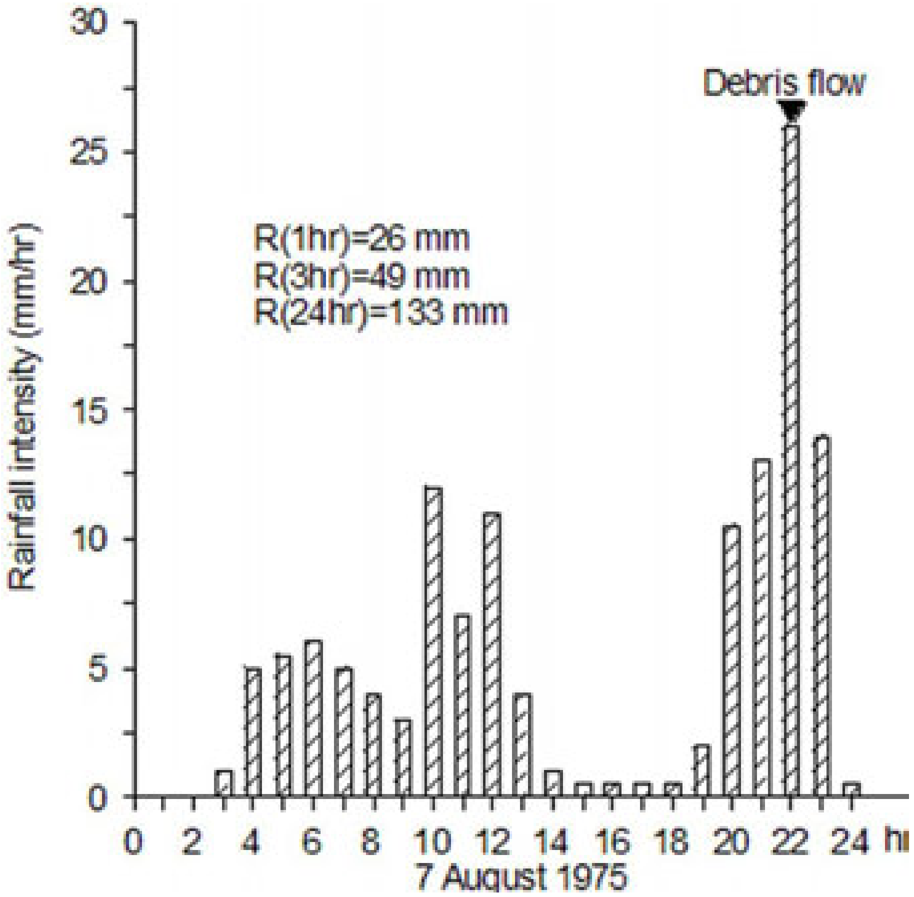


Figure G.19 - Debris flow trigger due to intense rainfall within the west-coast climatic region (after Sanderson *et al.*, 2005).

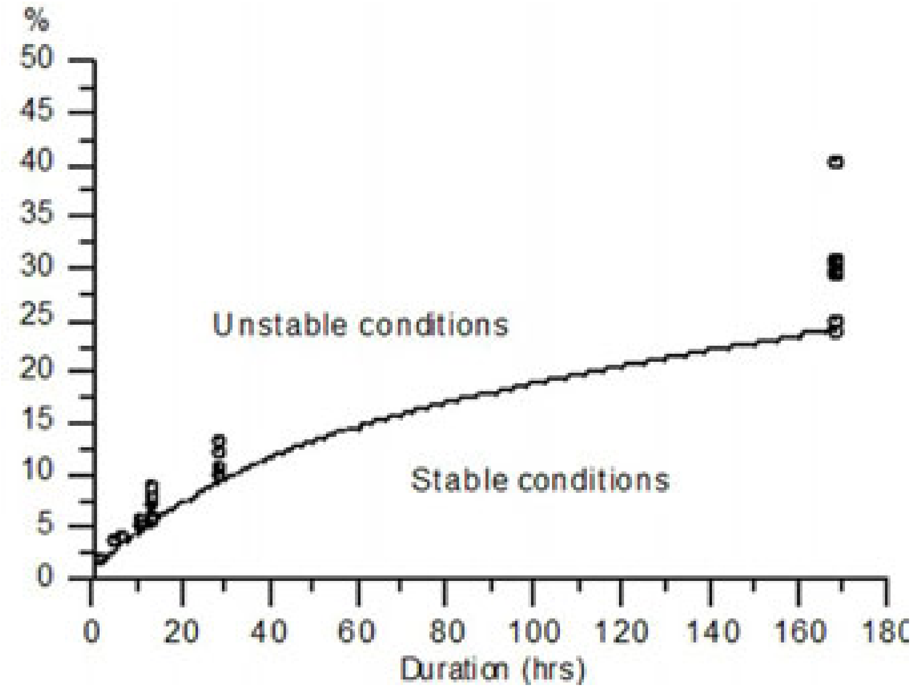


Figure G.20 - Critical water supply for debris flow initiation. Data points indicate water supply in debris flow events (after Sanderson *et al.*, 2005).

G.7 SINGAPORE

Toll (2001; 2006) reports on rainfall leading to landslides in Singapore and presents a graph of the rainfall occurring on the day of the landslide against that in the five days preceding the landslide (Figure G.21).

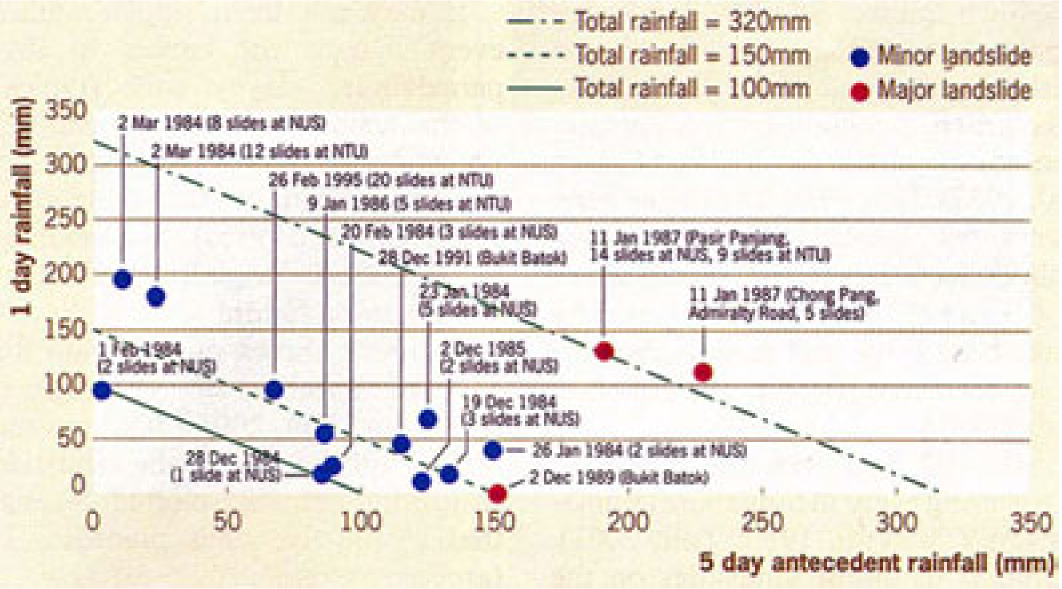


Figure G.21 – Rainfall events leading to landslides in Singapore (from Toll, 2006).

While a few minor landslides have occurred after intense one-day rainfalls with little antecedent rainfall others have occurred with low one-day rainfall and higher antecedent rainfalls. Toll (2006) concludes that this indicates that total rainfall, over an extended period, is more important that either daily or antecedent rainfall.

The solid diagonal line in Figure G.21 represents a total rainfall of 100mm in a six-day period appears to define the minimum rainfall conditions that can lead to minor landslides in Singapore.

G.8 SLOVENIA

Mikoš *et al*. (2004) report on a study of two debris flows that occurred near Stože in NW Slovenia on 15 and 16 November 2000.

A rain gauge at the nearby village of Log pod Mangartom recorded 1,638mm (more than 60% of the average annual precipitation) in the 48 days leading up to the events (average rainfall intensity 1.42mm/hour), corresponding to a return period of more than 100 years. Other rainfall depths for shorter durations within the same time window (481.6mm in 7 days, 174.0mm in 24 hours, 70mm in 1 hour) had recurrence intervals of much less than 100 years (Table G.1).

Several short periods of intense rainfall events were recorded in Log pod Mangartom during 2000, as follows:

- 407.4mm (11 to 13 October).
- 380.2mm (14 to 16 November).
- Daily rainfall of 174mm (12 October).

- Daily rainfall of 165.3mm (14 November, a day before the first landslide).

These levels of rainfall are not extreme for the area. In contrast, the precipitation depths for one and two months measured at the gauge were extreme, with return periods of around 100 years. Only the measured rainfall intensity of 1.42mm/hour in the last 1,152 hours (48 days) lies outside the collected historical data for critical rainfall intensity and duration (Crosta, 2004); all others of shorter duration lie within these

Table G.1 – Measured rainfall depths at rainfall gauging station in Log pod Mangartom compared with statistical values given for different recurrences intervals for that station (reference period 1961 to 1990) (from Mikoš *et al.*, 2004).

Duration	Recurrence interval (years)						Measured	
	2	5	10	25	50	100	[mm]	Period
1 Day	170	226	263	309	344	378	174.0	12.10.2000
7 Days	359	453	515	594	652	710	481.6	11.11.–17.11.2000
1 Month	496	684	808	966	1082	1198	1042.7	18.10.–17.11.2000
2 Months	756	1018	1192	1411	1574	1735	1666.4	18.9.–17.11.2000

The comparison with empirical (Caine, 1980) rainfall-intensity relations shows that all measured data in Log pod Mangartom in late-Autumn 2000 lie above but close to the lower bound threshold for shallow landslides worldwide (Equation 10.1A). Only the rainfall intensity of 70mm/hour measured in a one hour period on the evening of 16 November 2000 came close to Caine's upper bound threshold (Equation 10.1B).

G.9 SWITZERLAND

Debris flows are a geomorphological process common in the Swiss Alps, and in 2000 four significant flows (between 5,000m^3 and 35,000m^3) occurred which were monitored by debris flow observation stations. These comprised video cameras, ultrasonic devices, radar, geophones and rain gauges (Hurlimann *et al*., 2003).

The debris flows occurred in the Illbach and Schipfenbach catchments, both of which appear to be characterised by channelised debris flow activity.

The Schipfenbach monitoring system incorporated a rainfall gauge recording every 10 minutes. This indicated a rather dry June period (Figure G.22a) followed by a high July rainfall of 189mm. During a 3 hour period before the debris flow the maximum intensity was 11mm/hr, yielding a total rainfall for 6 August of 106mm. Comparing this event to Zimmermann *et al.* (1997) the authors proposed a relation between intensity and duration as follows:

$$I = 32D^{-0.70} \tag{G.9}$$

Hurlimann *et al*. (2003) concluded that the threshold was most likely too high. However, they did establish that the critical rainfall fell in a period of 4 to 24 hours before the event.

Rainfall gauges were not installed in the Illbach catchment until after the 2000 events. However, the authors indicate that the 100 year return rainfall intensity is between 35mm/hour and 57mm/hr for 0.5 hour and 1.0 hour rainfall durations.

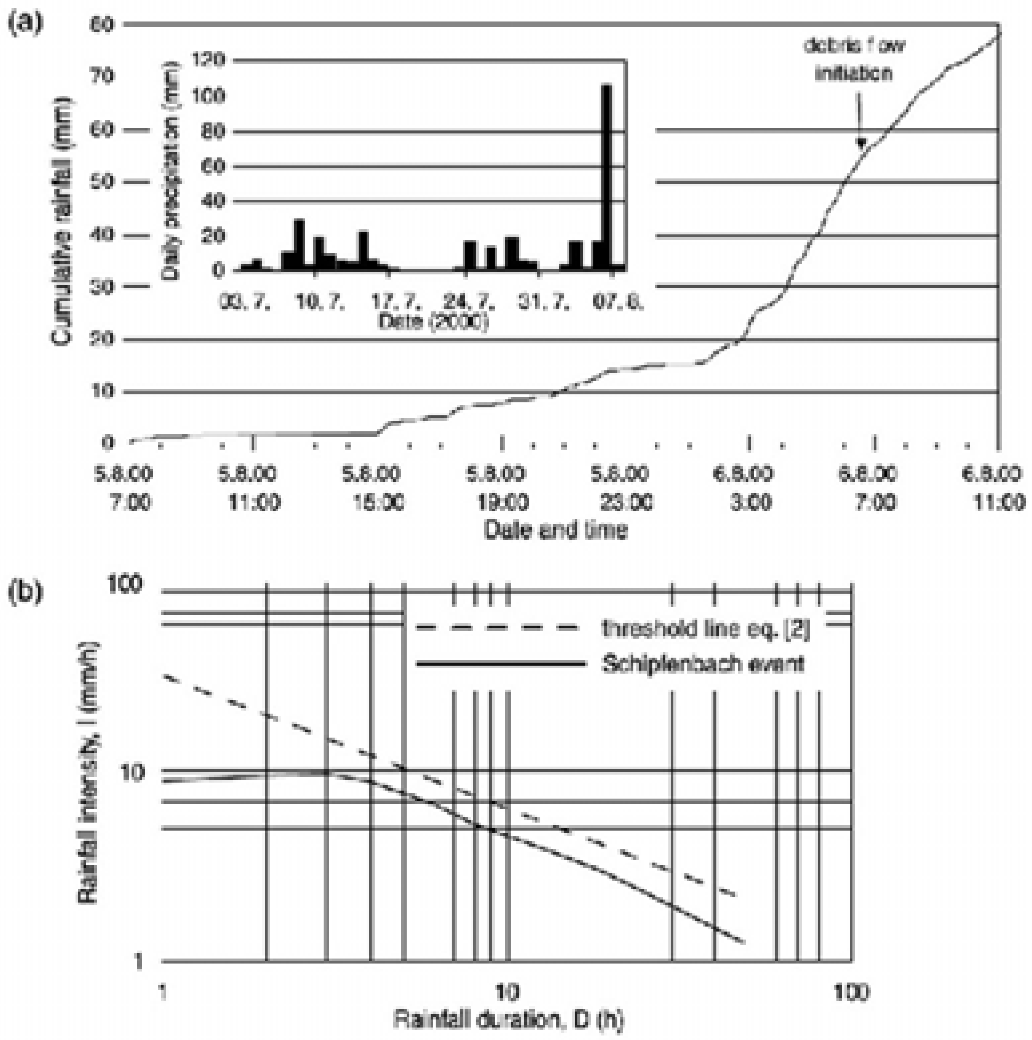


Figure G.22 – Precipitation analysis of the Schipfenbach debris flow. (a) Cumulative rainfall during the 24 hour prior to the debris flow event (the arrow indicates the time of initiation). Inset shows the daily precipitation during the month prior to the debris flow. (b) Comparison between the climatic threshold for debris flow initiation in the outer parts of the Swiss Alps and the data for the Schipfenbach event (after Hurlimann *et al.,* 2003). (Note: Equation 2 referred to in Figure G.22a is reproduced as Equation G.9 in this report.)

The superficial deposits in the Illbach catchment typically comprise 35% to 40% sand with less than 5% clay. The Schipfenbach catchment superficial deposits typically comprise 45% to 70% gravel with a clay fraction of less than 5%.

The authors concluded that:

- The debris flows were triggered by intense rainfall leading to in-channel mobilisation.
- Large landslides in both catchments provided debris for flows.
- Ultrasonic and radar measurements were practicable for defining debris flow hydrographs (channelised debris flows).
- Monitoring indicated a wide spectrum of flow behaviour even within the same channel.
- A critical factor was the rainfall in a period of 4 hours to 24 hours before the debris flow.

G.10 UNITED KINGDOM

G.10.1 North-West England

A rainfall and early warning system was set up to monitor the condition of earthworks on the Settle to Carlisle line following a landslide which caused a train derailment at Ais Gill, Cumbria on 31 January 1995

Rainfall gauges were installed at several locations where earthworks were classed as 'Poor'. Hourly, daily, weekly and 28 day rainfall levels were recorded and trigger levels set. These trigger levels were based on a study by Lancaster University of rainfall levels that had caused landslides in Cumbria.

The levels set were as follows:
1. 24-hour total threshold set at 80mm.
2. Antecedent Precipitation Index (API) threshold set at 130mm.
3. 30-day total threshold set at 300mm.

The system was used to put in place train speed restrictions when trigger levels were exceeded. The system was removed two years later when remedial measures had been undertaken on the railway earthworks.

G.10.2 South-West England

Network Rail (Personal Communication, 2006) report on a system on trial in southern England incorporating three levels of alert status, as follows:
Alert Status:
1. Earthwork Failures Likely.
2. Earthwork Failures Possible.
3. Earthwork Failures Unlikely.
4. Embankment Desiccation Possible.

The alert levels are based on Soil Moisture Deficit (SMD) (Figure G.23) and rainfall as a percentage of the Long Term Average (LTA). The threshold rainfall is defined as 175% of the LTA.

G.10.3 Scottish Highlands

A series of debris flows occurred in the Scottish Highlands between 1999 and 2001 adjacent to the A890 Stromeferry Bypass road and the railway which runs on a close by. As the debris flows had been triggered by rainfall events, a review of existing rainfall data was undertaken (Nettleton *et al*., 2005a).

The nearest automated rainfall gauge was at Plockton 10km to the west, on a low relief peninsula, and was not initially considered to be representative of the rainfall at Stromeferry. However, assessment of the 1999 to 2001 daily rainfall data from this gauge indicated a good correlation of peak rainfall events with debris flow activity. In particular, the 14-day cumulative rainfall indicated clear peaks that correspond well with the January 1999 and October 2001 debris flow events and the smaller event of October 2000, thus indicating the importance of antecedent as well as high intensity rainfall.

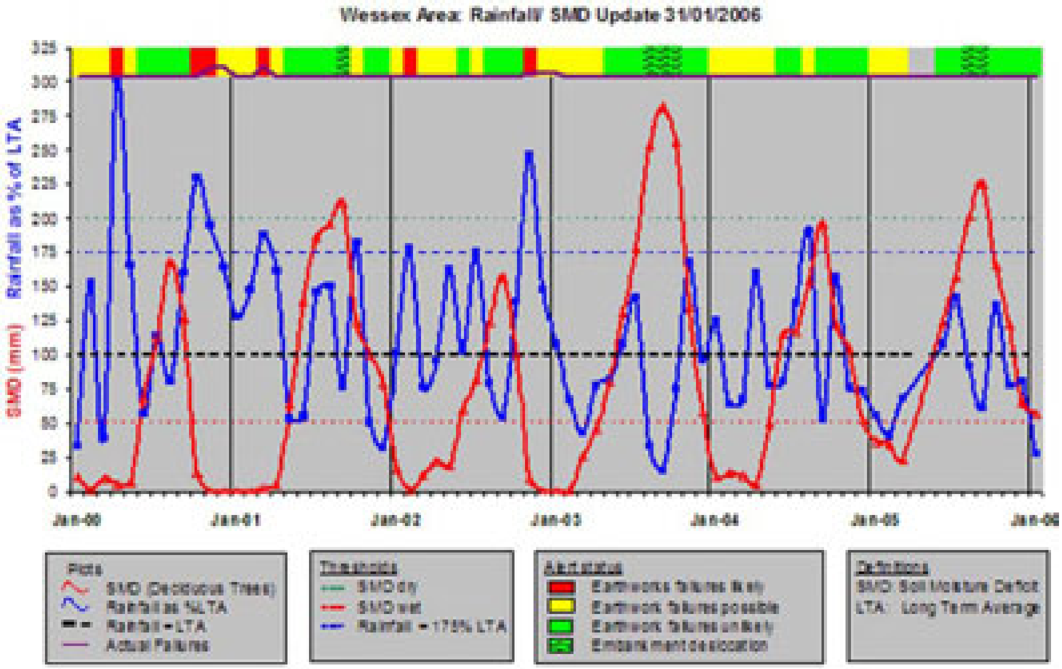


Figure G.23 – Soil Moisture Deficit (SMD) and rainfall graph (from Network Rail, Personal Communication, 2006).

Figure G.24 shows a graph of the normalized rainfall from the gauge at Plockton and a Scottish Environmental Protection Agency (SEPA) river flow-gauging station some 5km north-east of Stromeferry at the head of Loch Carron. There are good correlations between both sets of data and debris flow occurrence, probably as the principal weather fronts track in from the west. This indicates that the Plockton rainfall is, in fact, representative of the Stromeferry/River Carron catchments in terms of peak events. The magnitude of rainfall is however likely to be lower at Plockton due to its lower relief. There is a rainfall and river flow peak in November/December 1999 which has no corresponding debris flow event, but this may be because the main gully in question had a major clear out in January 1999.

For an early warning system at Stromeferry an automated local rain gauge, appropriate trigger levels and some form of automated barrier or signs would be required (Nettleton *et al.*, 2005a). Figure G.24 suggests that a trigger level for the 14 day antecedent rainfall could be developed based on the Plockton rainfall. Similar trigger levels would have to be developed for daily rainfall and a range of other antecedent rainfall periods.

The current rainfall readings are only daily and the response of the system to high intensity rainfall events correspondingly would be limited. Hence, a system recording hourly rainfall would be required to provide greater response sensitivity to high intensity events which follow a moderate antecedent build-up.

G.11 UNITED STATES OF AMERICA

Between 1986 and 1995 the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) undertook an exploratory program for predicting debris flows in the San Francisco Bay area. Circular 1283 (Anon, 2005) presents the findings and recommendations of a joint USGS/NOAA task force tasked with developing a plan for the implementation and operation of a NOAA/USGS system to issue joint Outlooks, Watches and Warnings for areas deemed to be at risk from debris flows as a result of current or forecast precipitation.

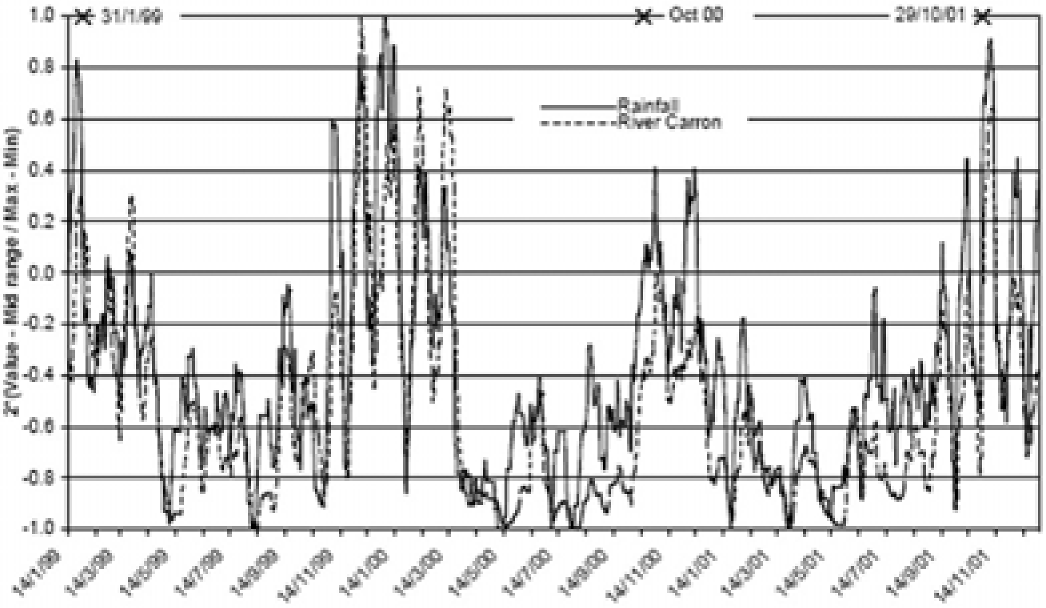


Figure G.24 – Normalised graph of 14 day cumulative rainfall at Plockton and River Carron flow for 1999 to 2001 showing the major debris flow events (from Nettleton *et al.*, 2005a).

The task force reviewed several operational rainfall intensity-duration landslide warning systems from around the world, including:

- Hong Kong (Chan *et al.*, 2003)
- San Francisco Bay 1986-1995 (Wilson 1997)
- Rio de Janeiro (1998-2003, 42 warnings) (D'Orsi *et al.,* 2004)
- The State of Oregon (Mills 2002)
- Lyme Regis, UK (Cole and Davis 2002)
- Seattle, Washington (Godt *et al.*, 2005)

The task force identified that an antecedent rainfall threshold and an intensity duration threshold would be required for a warning system. To achieve this, methods for quantitative precipitation estimation (QPE) and quantitative precipitation forecasting (QPF) were reviewed.

The report provides elements of a worked up proposal for the research and development of a full debris flow warning system.

G.11.1 California

Wieczorek (1987) studied debris flows in the Santa Cruz Mountains of California over a 10-year period, including 110 debris flows triggered during 10 storms. Analysis of the rainfall records indicated that two conditions had to be met for debris flows to be initiated: antecedent rainfall had to exceed a minimum threshold, and the storm rainfall had to exceed certain a level of intensity for a specified duration.

In the low permeability clay, silt and clayey silt soils of the study area, antecedent rainfall was found to be important over periods from seven days to two months. Seasonal rainfall of at least 28cm was observed prior to any debris flows being triggered. It was also found that rainfall values during the preceding seven to 30 days accounted for about 80% of the antecedent seasonal value and that the seven to 30 day antecedent rainfall values for storms that triggered debris flow was about twice that of storms that did not trigger debris flows.

Wieczorek (1987) derived the expression defining the storm events capable of triggering debris flows, provided that sufficient antecedent rainfall had fallen, as follows:

$$D = 0.90/(I - 0.17) \qquad \text{(G.10)}$$

where I is the rainfall intensity (in cm/hour) and D is the duration of rainfall (in hours).

The equation is best defined within the range of intensities 0.5cm/hour to 1.0cm/hour and the relation is assumed to be asymptotic at its extremes.

Figure G.25a shows a plot of duration for different levels of intensity for a number of storms and the threshold (Equation G.10) separates those that did and those that did not trigger debris flows. Each of these storms followed antecedent rainfall of at least 28cm. Each storm is represented by a family of data points, each point corresponding to a duration of particular intensity. In contrast, Figure G.25b illustrates storms that were not associated with at least 28cm of antecedent rainfall. While in Figure G.25a the intensity-duration data sited to the right of the curve defined by Equation (G.10) generally triggered debris flows and those sited to the left of the curve did not, in Figure G.25b none of the data are associated with debris flow activity.

The data presented by Wieczorek (1987) presents a very simple, threshold-based approach to coping with the effects of antecedent rainfall. While the intensity-duration approach then used to deal with the subsequent storm rainfall is potentially difficult to achieve in real-time this is broadly true for all related approaches.

G.11.2 Washington State (Seattle)

The Seattle area experiences shallow landslides in the colluvium deposits triggered during or immediately following heavy rainfall or snowmelt. Previous studies in the Seattle area have indicated that both antecedent and storm rainfall have significant effect. Seattle has a dense network of rain gauges with hourly recordings dating back over 25 years. This coupled with records of landslides (Laprade *et al.,* 2000) has enabled development of empirical rainfall / slope stability models (Godt, 2004).

Recent analysis of data between 1933 and 1997 showed a combination of three day triggering rainfall and 15-day antecedent precipitation can be used to forecast when three or more landslides can be expected during a three day period (Chleborad, 2003).

The Seattle rain gauge network comprises 17 tipping bucket gauges providing a dense coverage (2km to 5km between gauges). Mean rainfall intensity, I_{mean}, and duration, D, were compiled from rainfall gauge data. A rainstorm was defined as a period of rain bounded by at least 3 hours of no rainfall. Analysis of six rainstorms, which triggered shallow landslides, between 1978 and 1997 yielded a rainfall intensity-duration graph with a threshold defined by:

$$I = 82.73D^{-1.13} \qquad \text{(G.11)}$$

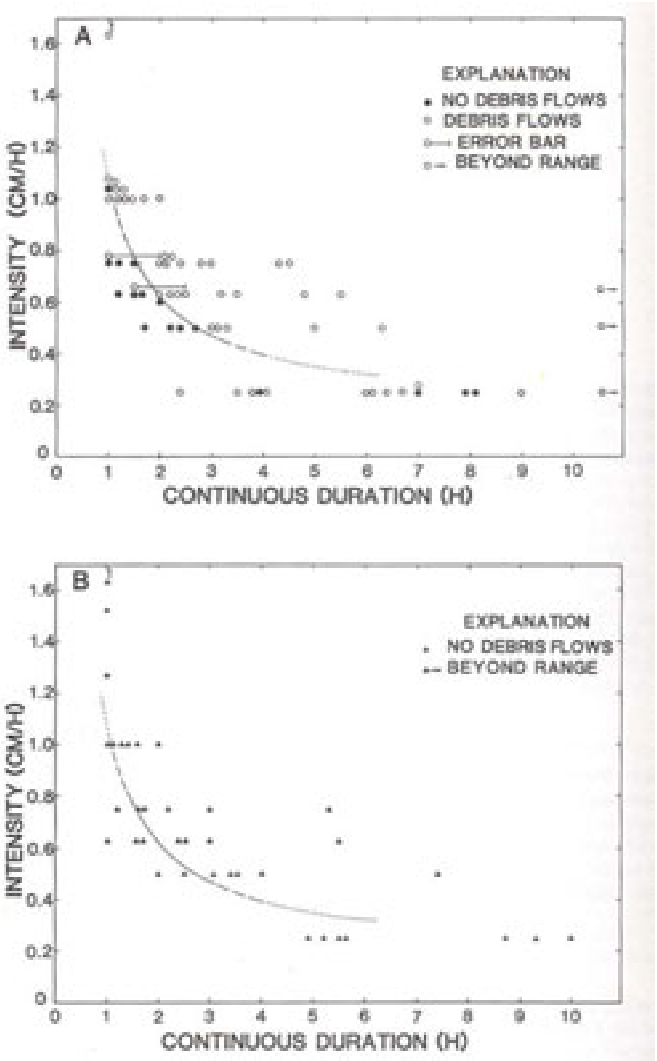


Figure G.25 – Intensity-duration data for storms in the Santa Cruz Mountains in California: (a) data for storms following 28cm of antecedent rainfall; (b) data for storms that did not follow 28cm of antecedent rainfall (from Wieczorek, 1987).

The authors employed the Antecedent Water Index (AWI), calibrated with measurements of soil-water content and rainfall to provide a general assessment of the soil-moisture conditions (Figure G.26).

A decision tree for assigning warnings was developed based on the AWI and the rainfall threshold, as shown in Figure G.27.

The authors concluded that, based on landslide events during the previous 25 year period, the rainfall intensity-duration and the water balance model would have flagged some 56 rainstorms that exceeded the intensity-duration threshold, with three rainstorms below the intensity-duration threshold ('Null') which were associated with evidence of shallow landsliding.

Some 28 rainstorms were assigned a 'Watch' status and evidence of shallow landsliding was noted in 42.9% of these. A further 13 rainstorms were assigned a 'Warning' status and shallow landsliding occurred in 61.5% of these.

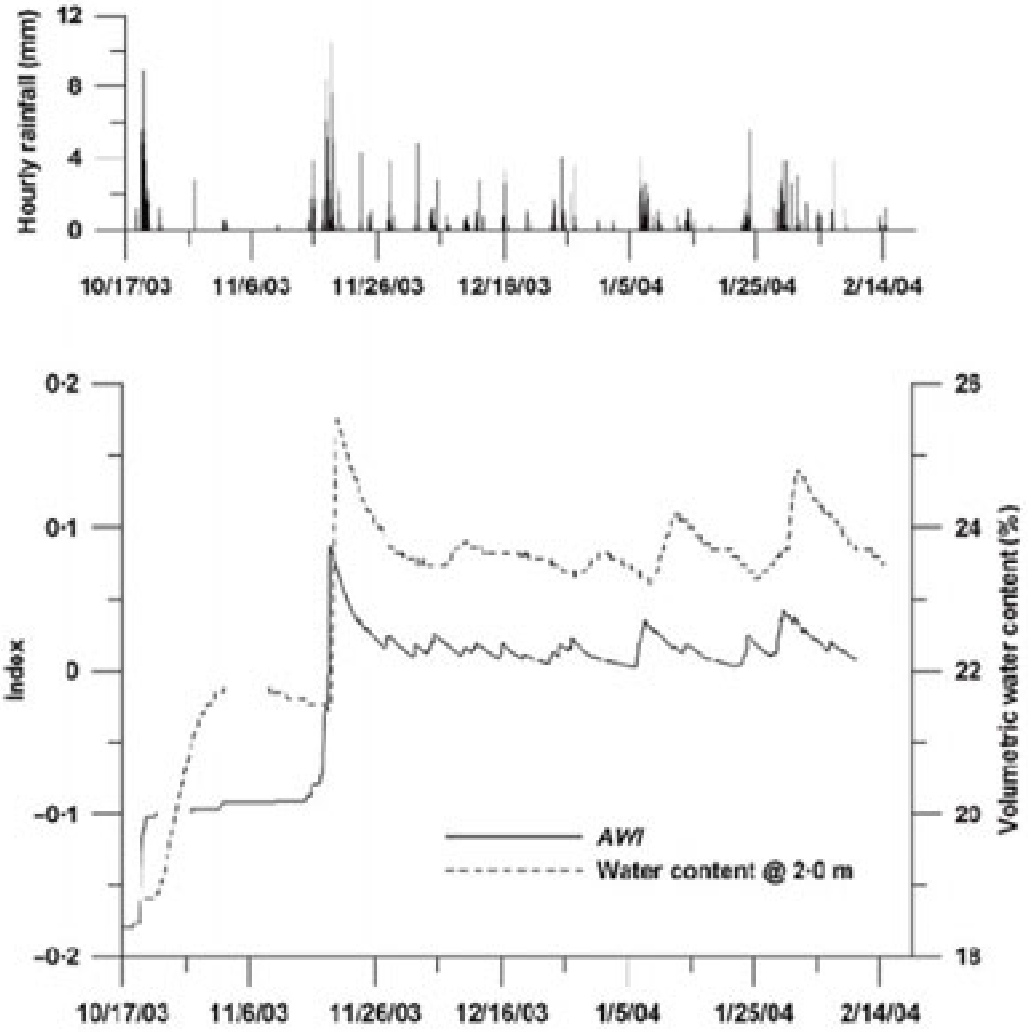


Figure G.26 – Rainfall, volumetric water content, and the Antecedent Water Index (AWI) for the Edmonds field site for the period 17 October 2003 to 14 February 2004 (from Godt *et al.*, 2005).

This research was also applied specifically for rail transportation (Baum *et al.,* 2005). For this application rain gauges were normally set to record hourly but this increased to every 15 minutes during times of high precipitation (>2.54mm/hour). The data were transmitted by radio telemetry system and graphs were produced on a web server in near to real time.

For this application the alerts were as follows:
1. Advisory – Days in advance.
2. Watch – 3 hours to 72 hours in advance.
3. Warning – Near real time.

G.12 OTHER REGIONS AND COUNTRIES

Other regional studies of landslide risk assessment that have been studied in order to obtain information useful to this work include:

Albania: Bozo *et al*. (2005) report on landslide risk assessment for roads and include rainfall events as one of the seven most important factors in their triggering. Around half of all landslides in Albania are thought to occur during or just after ‘rainy weather’. It is not, however, entirely clear how this is translated into an assessment mechanism although it seems likely that seismic activity is more of a potential trigger than in Scotland.

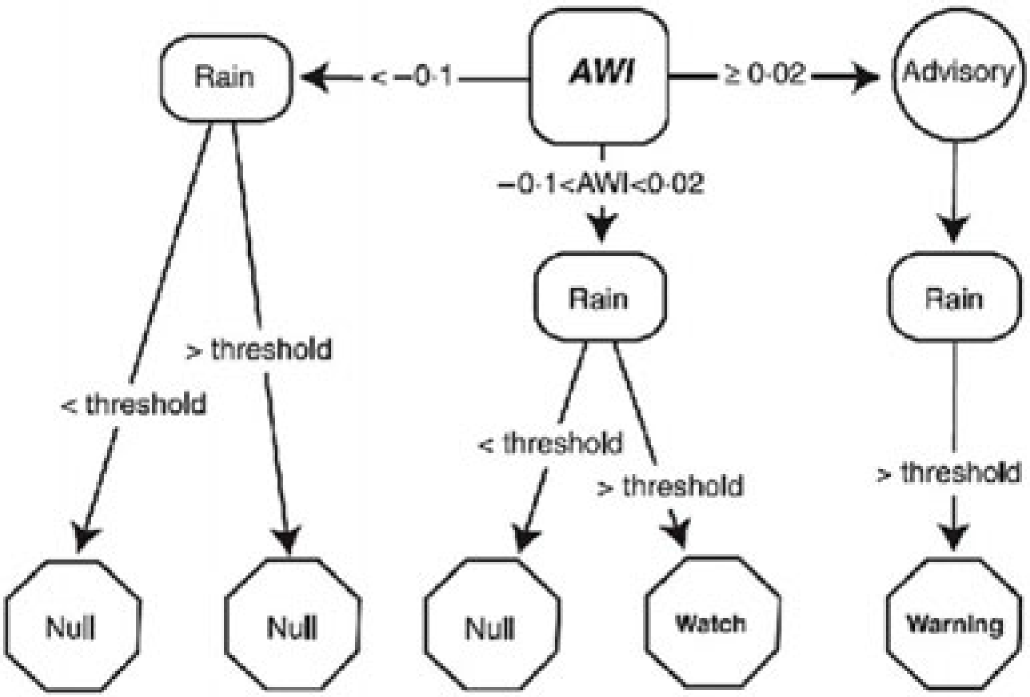


Figure G.27 – Decision tree for assigning warnings (from Godt *et al.*, 2005).

Brazil: Ortigao *et al*. (2001) report on a system based upon intensity and accumulated 96-hour rainfall. This system appears to be adapted more to slower moving landslides that may be triggered by relatively short periods of rainfall with little or no influence from longer term antecedent rainfall.

Mainland China: Zhou and Chan (2005) note that the understanding of debris flow mechanics is at a relatively immature level of understanding and that qualitative evaluation parameters currently predominate over quantitative ones. Other recent work on regional landslide management in China has been conducted by Wen *et al*. (2005) and Yin and Wang (2005).

Columbia: Montero Olarte and Ojeda Moncayo (2005) report that 70% of the Columbian national road network suffers the consequences of frequent obstruction or destruction due to the actions of rainfall-triggered landslides and that landslides in Columbia are mainly triggered by rainfall.

Cuba: Castellanos Abella and van Westen (2005) report on a proposed landslide risk assessment method for Cuba. Rainfall is equally ranked with seismic activity as a triggering factor.

Ethiopia: Woldearegay *et al*. (2005) report on landslide hazard mitigation strategies for the northern highlands of Ethiopia. While the authors implicitly acknowledge the role of rainfall in this region (where the bimodal annual average can vary between 500mm and 2,000mm their paper pays relatively little attention to this issue).

United States of America (Alaska): Sidle and Swanston (1976) estimated a return period of less than two years for a storm that caused a small debris flow in Alaska. They also noted that around 54% of the rain fell in the final three hours of the storm (total duration 10 hours). This early work perhaps points to the importance of the relation between intensity and duration in understanding how debris flows are triggered.

ANNEX G.1 – METHOD ADOPTED IN PRELIMINARY ASSESSMENT BY EVANS (1997) (Extracted from Ko, 2005)

A.1 INTRODUCTION

This Appendix summarizes the preliminary assessment by Evans (1997) on the relationship between rainfall and natural terrain landslide initiation.

A.2 ASSUMPTIONS

Rainfall and natural terrain landslide data between 1985 and 1994 were considered. It was assumed that a natural terrain landslide known to have taken place in a year occurred during the most severe rainstorm that resulted in the maximum rolling 24-hour rainfall at the landslide location in the year. Also, it was assumed that the natural terrain landslide was triggered by the maximum rolling 24-hour rainfall at the landslide location, i.e. it was initiated at the time when the rolling 24-hour rainfall reached the maximum value.

Due to the insufficient GIS capability at the time of the assessment, rainfall data that were readily available at the time were adopted and the rainfall-natural terrain landslide data were extracted manually, with approximation made in a subjective manner by visual inspection.

A.3 DATA

A.3.1 Rainfall

The assessment used the sets of isohyets of the maximum rolling 24-hour rainfall given in GEO's annual Rainfall and Landslide Reports for selected major rainstorms. Table A.1 lists the major rainstorm events considered in the assessment. Isohyets of mean annual rainfall were obtained from Lam and Leung (1995). The isohyets of maximum rolling 24-hour rainfall of the major rainstorm events in each year were transposed manually onto a 1:100,000 scale topographical plan of Hong Kong (Figure A.1).

It should be noted that these rainfall isohyets are strictly speaking not isohyets of the location-specific maximum rolling 24-hour rainfall that occurred in the year. They are isohyets of location-specific total rainfall in a 24-hour period. In this 24-hour period, the maximum rolling 24-hour rainfall was recorded at the location where the rolling 24-hour rainfall was the heaviest in the rainstorm.

A.3.2 Natural Terrain Landslides

The natural terrain landslides in each year were extracted from the Natural Terrain Landslide Inventory and were transferred manually to the 1:100,000 scale topographical plan containing the rainfall isohyets of the selected major rainstorms in the year.

A.4 ASSESSMENT OF RAINFALL-NATURAL TERRAIN LANDSLIDE RELATIONSHIP

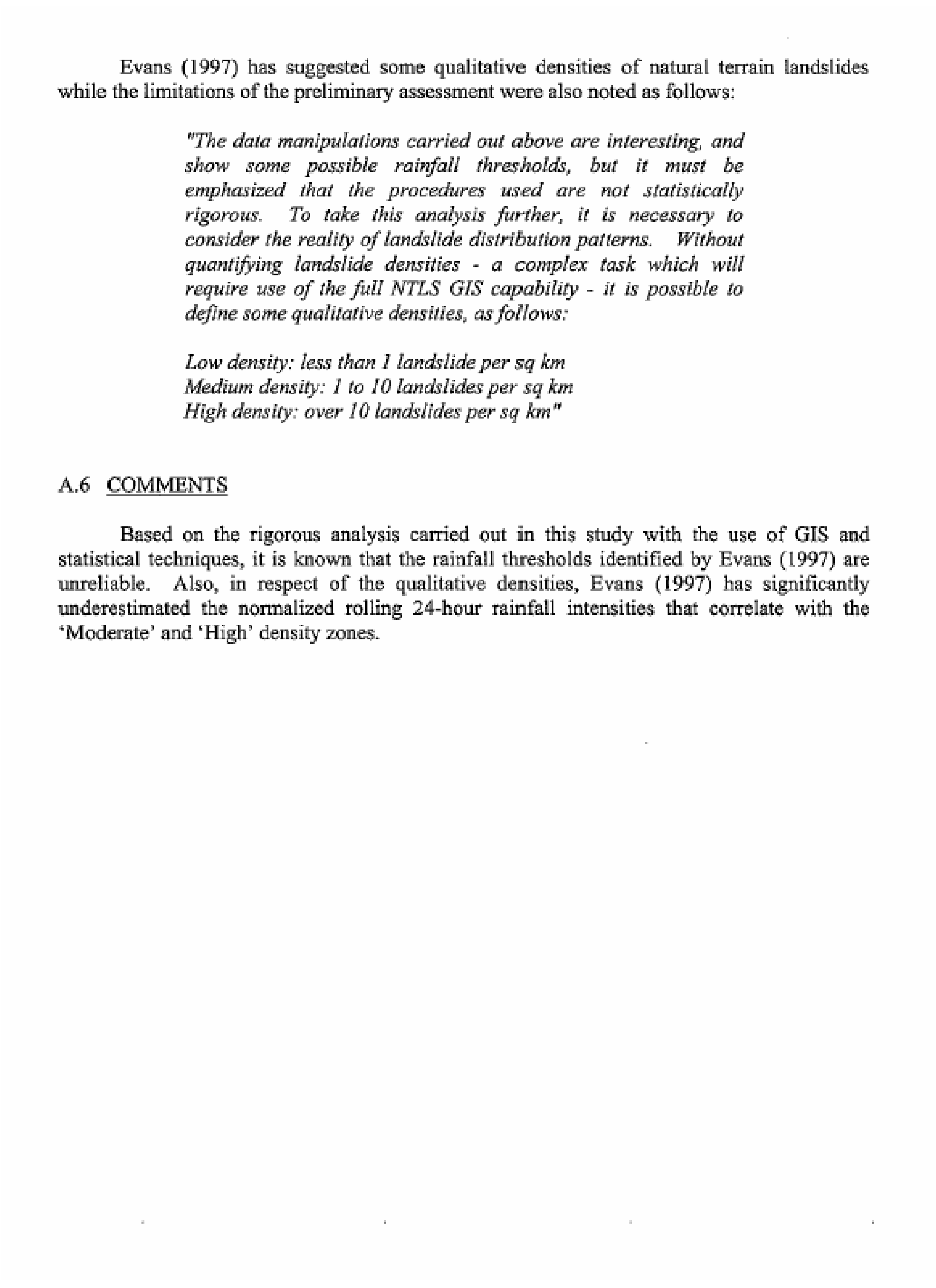
For each natural terrain landslide, the corresponding rainfall data were extracted manually from the 1:100,000 plan showing the isohyets of maximum rolling 24-hour rainfall and the mean annual rainfall. The greatest value of the isohyets that bound each natural terrain landslide was taken as the maximum rolling 24-hour rainfall that triggered the natural terrain landslide. Mean annual rainfall at each natural terrain landslide location was read off from the nearest isohyet of mean annual rainfall. The normalized value was the maximum rolling 24-hour rainfall divided by the mean annual rainfall at the natural terrain landslide location.

Based on this method, a rainfall-natural terrain landslide database was compiled for all the natural terrain landslides from 1985 to 1994.

A.5 FINDINGS

Using the database, plots of cumulative distribution of natural terrain landslides against maximum rolling 24-hour rainfall and against normalized maximum rolling 24-hour rainfall were produced (Figure 1 and 2). Points of abrupt changes in the gradient was noted from the cumulative plot against normalized maximum rolling 24-hour rainfall. These points were taken as rainfall thresholds where significant increase in the number of natural terrain landslides would occur. The identified rainfall thresholds were:

	Threshold I Start of Landsliding	Threshold II Start of Landsliding at Medium Densities	Threshold III Start of Landsliding at High Densities
Mean Annual Rainfall <2000 mm (Deep Bay, North NT, outlying islands, coasts of Mirs Bay & Sai Kung)	40 - 60 mm (0.03)	130 -180 mm (0.09)	270 - 380 mm (0.19)
Mean Annual Rainfall 2000-2400 mm (most of the developed areas of Hong Kong, Kowloon & the NT, plus Lantau)	60 - 70 mm (0.03)	180 - 220 mm (0.09)	380 - 450 mm (0.19)
Mean Annual Rainfall >2400 mm (The Tai Mo Shan-Tate's Cairn-Ma On Shan central uplands, with Sha Tin)	70 - 110 mm (0.03)	220 - 340 mm (0.09)	450 - 720 mm (0.19)



Evans (1997) has suggested some qualitative densities of natural terrain landslides while the limitations of the preliminary assessment were also noted as follows:

> *"The data manipulations carried out above are interesting, and show some possible rainfall thresholds, but it must be emphasized that the procedures used are not statistically rigorous. To take this analysis further, it is necessary to consider the reality of landslide distribution patterns. Without quantifying landslide densities - a complex task which will require use of the full NTLS GIS capability - it is possible to define some qualitative densities, as follows:*
>
> *Low density: less than 1 landslide per sq km*
> *Medium density: 1 to 10 landslides per sq km*
> *High density: over 10 landslides per sq km"*

A.6 COMMENTS

Based on the rigorous analysis carried out in this study with the use of GIS and statistical techniques, it is known that the rainfall thresholds identified by Evans (1997) are unreliable. Also, in respect of the qualitative densities, Evans (1997) has significantly underestimated the normalized rolling 24-hour rainfall intensities that correlate with the 'Moderate' and 'High' density zones.

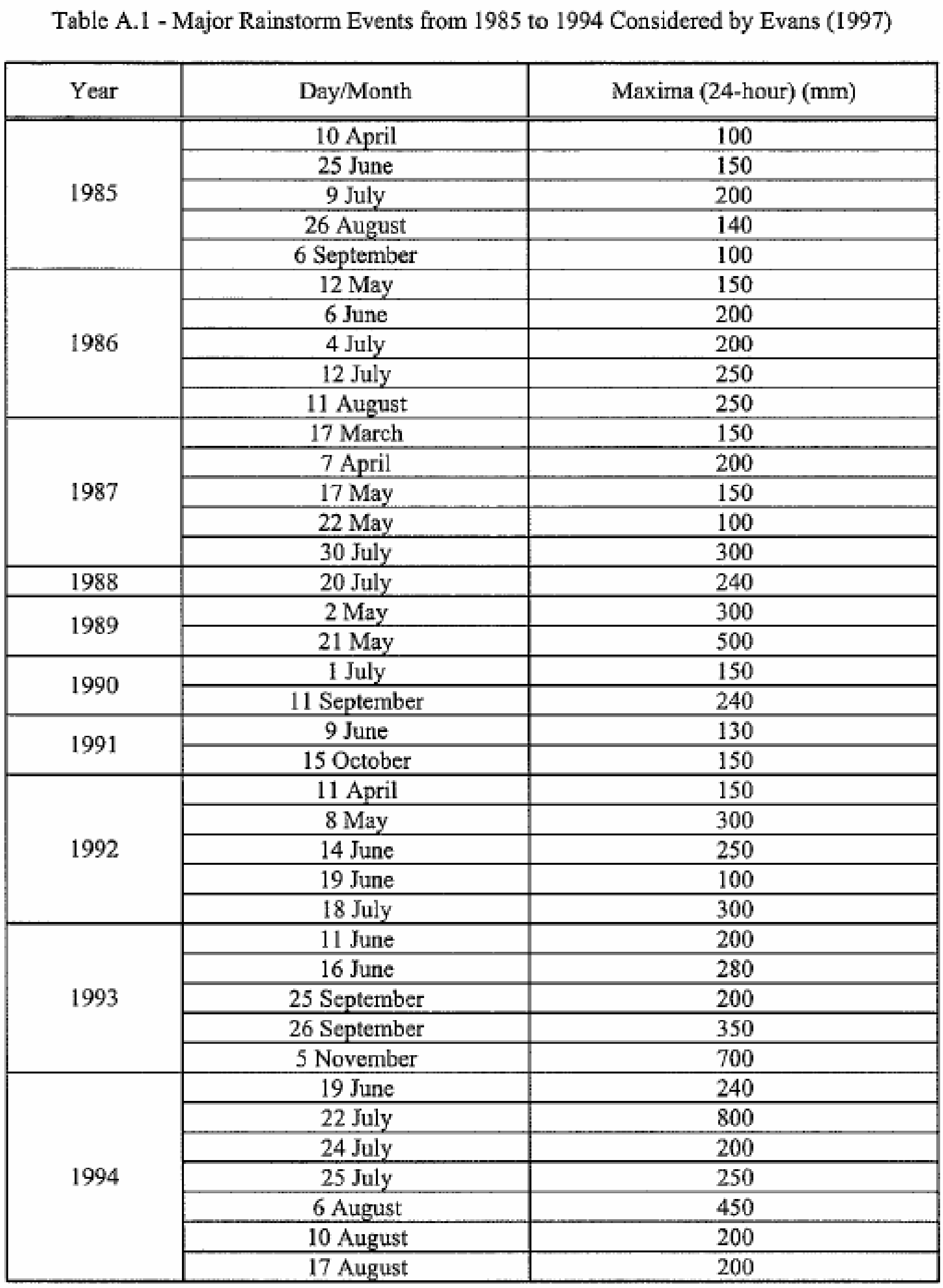


Table A.1 - Major Rainstorm Events from 1985 to 1994 Considered by Evans (1997)

Year	Day/Month	Maxima (24-hour) (mm)
1985	10 April	100
	25 June	150
	9 July	200
	26 August	140
	6 September	100
1986	12 May	150
	6 June	200
	4 July	200
	12 July	250
	11 August	250
1987	17 March	150
	7 April	200
	17 May	150
	22 May	100
	30 July	300
1988	20 July	240
1989	2 May	300
	21 May	500
1990	1 July	150
	11 September	240
1991	9 June	130
	15 October	150
1992	11 April	150
	8 May	300
	14 June	250
	19 June	100
	18 July	300
1993	11 June	200
	16 June	280
	25 September	200
	26 September	350
	5 November	700
1994	19 June	240
	22 July	800
	24 July	200
	25 July	250
	6 August	450
	10 August	200
	17 August	200

APPENDIX H – DEVELOPMENT OF A RAINFALL TRIGGER THRESHOLD FOR DEBRIS FLOW

by P Dempsey, J Dent and M G Winter

H.1 METHODOLOGY AND SAMPLE RESULTS

Records of debris flow events identified by members of the Working Group were scrutinized for their suitability in terms of undertaking an analysis of the rainfall leading up to their occurrence. This produced a set of 16 events each of which met more than one of the following criteria:

- The debris flow had caused disruption at a known road location.
- The timing of the debris flow was relatively well-defined (in some cases, on main routes, there was good knowledge of timing).
- There was good coverage at the site of rainfall data from both gauges and radar.

The coverage of radar was considered of importance, as it is likely that any future general predictive model may rely more strongly on radar data. This is because rain gauge distribution in the Highlands and Islands is sparse, particularly tipping bucket rain gauges reporting by telemetry (Anon, 2006b) – which would be necessary for real-time information gathering.

The following rainfall information was extracted from records for each of the 16 events.

- Daily rainfall from the three stations closest to the location of the landslide, for a period of 150 days prior to the event. The rain gauges were selected based on the NGR of the debris flow: for each station a distance and bearing from the landslide location is given.
- Hourly rainfall from the tipping bucket rain gauge (TBR) closest to the landslide location for the 4-5 day period covering the time of the event. Distance and bearing information is also given.
- Radar measurements of rainfall intensity at intervals of five minutes (for 2km pixels) or 15 minutes (5km pixels) for the pixel square that includes the debris flow location. Similarly to the TBR data, the radar data covers a period of two to three days previous to and including the storm event.
- Radar measurements of rainfall intensity for a three by three array of pixels, which includes the debris flow location pixel at its centre.

Rain gauge data is summarised in Table H.1 and the location of debris flows and rain gauges, along with the coverage from Met Office weather radar installations is give in Figure 9.5.

Analyses of the storm events were carried out, generally for a period of 18 hours, and also for an antecedent period of 150 days prior to the event. The method is described below, in Section H.1.1, using the results for Event 1 as an example. The results for all 16 events analysed are presented in summary form and discussed in Section H.2.

Where possible, the storm rainfall information was analysed back from the point when the debris flow occurred, the assumption being that this time marks a point when an intensity or accumulation threshold which causes the debris flow process to occur had been reached. This information was not available for all events, so an initial time had to be chosen from the period of most intense rainfall. The hourly rainfall data from the most relevant TBR were examined to establish an initial starting point.

Table H.1 – Summary of information available for all analysed events.

Event Number, Location, Date (month/year)	NGR and Road Number	Daily Rain gauge Locations (Distance, km and bearing from landslide location)			Hourly Rain Gauge Location	Max. Hourly Rainfall, mm (gauge)	Time, Date of Max. Rainfall (gauge)	Max. Hourly Rainfall, mm (radar)	Time, Date of Max. Rainfall (radar)
		1	2	3					
1. L Carron, Stromeferry Bp (10/01)	NG 910373: A890	Loch Carron (2.7 NNW)	New Kelso (6.4 NNE)	Plockton (11.5 WSW)	Lusa, Skye (24.0 SW)	3.6	1000, 30/10	5.8	1500, 29/10
2. Glen Croe, Rest & be Thankful (01/03)	NN 235071: A83	Lochgilphead (6.5 SSW)	Clachan Pwr St (7.2 NW)	Inveruglas (8.8 ENE)	Sloy (9.0 ENE)	5.4	0400, 25/01	6.7	0400, 25/01
3. Glen Croe, Rest & be Thankful (11/03)	NN 234072: A83	Lochgilphead (6.5 SSW)	Clachan Pwr St (7.2 NW)	Inveruglas (8.8 ENE)	Sloy (9.0 ENE)	7.4	0900, 29/11	10.5	1100, 29/11
4. Glen Croe, Rest & be Thankful (01/04)	NN 235070: A83	Lochgilphead (6.5 SSW)	Clachan Pwr St (7.2 NW)	Inveruglas (8.8 ENE)	Sloy (9.0 ENE)	3.0	1800, 18/01	5.4	1800, 18/01
5. Laide, Wester Ross (02/04)	NG 901924: Uncl	Sand 2 (1.2 SE)	Aultbea (5.6 WSW)	Poolewe (11.3 SSW	Aultbea (5.6 WSW)	4.6	0600, 05/02	2.7	0600, 05/02
6. Glen Kinglas (08/04)	NN 208096: A83	Clachan P.S. (3.7, NNW)	Glenfyne Lodge (6.0, N)	Lochgilpead (8.0, S)*(1)	Sloy (11.3, E)	9.4	2200, 08/08	13.7	2200, 08/08
7. Cairndow, Glenfyne (08/04)	NN 186115: A83	Clachan P.S. (1.8, NNE)	Glenfyne Lodge (5.3, NE)	Allt na Lairige (8.6, NE)*(2)	Sloy (13.6, E)	9.4	2200, 08/08	14.1	2200, 08/08
8. Dunkeld, Perth (08/04)	NO 005443: A9	Inver No.2 (2.5, SSE)	Meikle Tombane (7.0, SW)	Ballinluig (9.4, NNW)	Faskally (17.8 NNW)	17.6	1200, 09/08	13.1	1200, 09/08
9. Glen Ogle, Lochearnhead (08/04)	NN 573266 (N) / NN 576262 (S): A85	Killin, Monemore (5.6, N)	Strathyre S.Wks. (10.0, S)	Ardtalnaig (18.1, NE)	Tyndrum No. 3 (21.4, W)	6.2	1100, 18/08	12.7	1700, 18/08
10. Pitcalnie, Easter Ross (08/04)	NH 804722: U150A	Tain Range (10.9, N)	Gleanies House (11.5, NE)	Hill of Fortrose (16.6, SSW)	Tain Range (10.9, N) *(3)	12.8	0400, 19/08	5.7	0200, 19/08
11. Eathie, Black Isle (08/04)	NH 775643: U231	Hill of Fortrose (8.3, SSW)	Nairn, Dunbar (13.9, ESE)	Tain Range (19.3, NNE)	Tain Range (19, NNE)	4.0	1600, 18/08 & 0500, 19/08	4.1	0100, 19/08
12. Avoch-Fortrose, Black Isle (10/04)	NH 717559: A832	Hill of Fortrose (1.9, NE)	Allangrange Hse (9.5, WSW)	Inverness (10.8 SSW)	Tain Range (29.0, NNE)	5.6	08:00, 21/10	3.8	0700, 21/10
13. Cnoc Fhionn, Shiel Br/Glenelg (12/04)	NG 876198: C46	Nostie (7.8, NNW)	Achnagart (9.7, ESE)	Plockton (15.4, NNW) *(4)	Skye Lusa (17.7, WNW)	5.6	07:00, 06/12	5.8	1100, 06/12
14. Letterfinlay, Loch Lochy (01/05)	NN250912: A82	Clunes Forest (5.3, WSW)	South Laggan no.3 (7.2, NE)	Braeroy Lodge (8.7, E)	Tulloch Bridge (16.3, SE)	5.0	19:00, 06/01	8.0	0300, 07/01
15. Inverinate-Morvich (09/05)	NG 944212: U152W	Achnagart (6.3, SSE)	Plockton (18.6, NW)	No Gauge	Skye Lusa (24.0, W)	15.6	17:00, 13/09	7.5	1600, 13/09
16. Kylerhea Glen, Skye (09/05)	NG 775208: C72	Skye Lusa (8.0, WNW)	Broadford, Rockbank (12.5, W)	Plockton (12.0, N)	Skye Lusa (8.0, WNW)	15.6	17:00, 13/09	5.0 (4.6)	0900, 13/09 (16:00, 13/9)

Timing for hourly rain gauge and radar maxima is for hour-ending. *Additional rain gauge information

(1) Allt Na Lairige (8.7, NNE). (2) Lochgilphead (10.0, S). (3) Kinloss (30.0 ESE). (4) Skye Lusa (17.7, WNW).

However, because the TBR rain gauge was, in most cases, at some distance from the landslide location (sometimes in excess of 20 km), the hourly radar rainfall record at the radar pixel covering the debris flow location was also inspected to select the timing of the maximum fall. This information is recorded in Table H.1. Where a clear start time from either rainfall intensity or time of debris flow events was not readily identifiable, this may have introduced some discrepancy in the results; to some extent this has been taken into account in the interpretation of the results. The detailed examination of storm rainfall depth and intensity is made using the radar data from the pixel containing the landslide location. Radar pixels cover fixed grid locations on either a 2 km or 5 km grid, depending on the distance from the observing radar. The coverage of the rainfall radar network in Scotland is shown in Figure 9.5. Although there are a number of ways in which errors can arise in radar rainfall estimation, it is considered that using radar represents a consistent approach. The use of TBR data introduces the problems that the gauge locations are variable in respect of landslide location and intervening topography, as well as distance and aspect. This, in addition to any movement in the rain producing system, may introduce unquantifiable errors in quantity and timing.

H.1.1 Results for Event 1

The radar data were processed to provide the cumulative rainfall from the storm event, and the average intensity over the various fixed intervals, as shown in Table H.2.

Table H.2 – Storm rainfall summary for radar pixel at Stromeferry, Loch Carron, Event 1.

Time before peak rainfall (hours)	0.25	0.5	1	2	4	6	8	12	18
Total Rainfall (mm)	1.7	3.0	5.9	11.3	13.5	15.6	15.8	28.0	47.5
Rainfall intensity (mm/hr)	6.6	5.9	5.9	5.7	3.4	2.6	2	2.3	2.6

The rainfall intensity was divided by mean annual precipitation (1961-1990) to provide the intensity/MAP function shown in Table H.3.

Table H.3 – Storm rainfall summary for radar pixel at Stromeferry, Loch Carron, Event 1.

Time before peak rainfall (hours)	0.25	0.5	1	2	4	6	8	12	18
Intensity/MAP	0.339	0.303	0.303	0.293	0.175	0.134	0.103	0.118	0.134

Mean annual precipitation values were provided by the Met Office for two standard periods 1961 to 1990 and 1971 to 2000. The value used in calculations is that for the closest daily rainfall station, for the 1961 to 1990 period. There are some differences in the figures for the two periods: the former was chosen as there is a view that this figure is less influenced by the extremes experienced in the 1990s, and may be less affected by the early manifestations of human-induced climate change. For the reference rain gauges used, the 1971 to 2000 average is consistently greater than the 1961 to 1990 average by between 3% and 5%, which will not however have a significant influence on the intensity/MAP values.

The analysis of the antecedent daily rainfall was carried out by calculating cumulative rainfall totals over fixed periods prior to the date of the debris flow event. Where possible the analysis of the antecedent daily data was carried out for the rain gauge nearest the debris flow location. Where this gauge had missing data, data for the next nearest rain gauge were used. Table H.4 shows an example of the antecedent data tabulation.

Table H.4 – Antecedent rainfall and intensity, New Kelso daily rain gauge, Event 1.

Antecedent days	1	2	4	6	8	12	18	25	50	75	100	150
Rainfall total (mm)	33.4	39.6	61.4	66.2	70.0	74.0	96.0	152.6	270.8	415.0	516.0	674.6
Intensity (mm/hr)	1.39	0.83	0.64	0.46	0.36	0.26	0.22	0.25	0.23	0.23	0.22	0.19
Intensity/ MAP (%)	0.0715	0.0424	0.0329	0.0236	0.0187	0.0132	0.0114	0.0131	0.0116	0.0178	0.0221	0.0289

Three analyses were carried out on the daily rain gauge data. Firstly, the interval data were reversed to give an incremental total commencing at T-150 (Day 0) up to the day before the debris flow event (e.g. Table H.5). Secondly the interval data was converted to an average intensity over the relevant period (mm/hr). Finally the intensity was converted to a dimensionless function, intensity/MAP by dividing intensity by the mean annual precipitation (MAP), the result being expressed as a percentage (see Table H.4).

Table H.5 – Antecedent rainfall (from T-150 days), New Kelso daily rain gauge, Event 1.

Day	0	50	75	100	125	132	138	142	144	146	148	149
Incremental rainfall (mm)	0.0	158.6	259.6	403.8	522.0	578.6	600.6	604.6	608.4	613.2	635.0	641.2

The data contained in Tables H.2 to H.5 are also presented graphically. Figure H.1 shows the plots for storm rainfall, as accumulation and average intensity (Table H.2). Figure H.2 shows cumulative antecedent rainfall (Table H.5). Figure H.3 shows a log-log plot of intensity against duration for the combined storm and antecedent period (Tables H.2 and H.4). Figure H.4 is a log-log plot of the intensity function and combines storm and antecedent intensity data (Tables H.3 and H.4). Where feasible, a best-fit straight line was fitted.

Because radar data were used for the storm period analyses, spatial variability was examined by comparison with a three-by-three array of local radar pixels. Radar information was extracted at five or 15-minute intervals, as appropriate to the distance from the radar source. A data array for the storm duration was also analysed for the same time intervals as the intensity and accumulation analyses. Tabulations for each storm were prepared, as shown in Table H.6. The data from Table H.6 is presented graphically to compare the 18-hour accumulation in the grid array, as in Figure H.5. The location of the landslide is shown in the central pixel (5) in Figure H.5. Further data from the other events are presented in H.2.1.

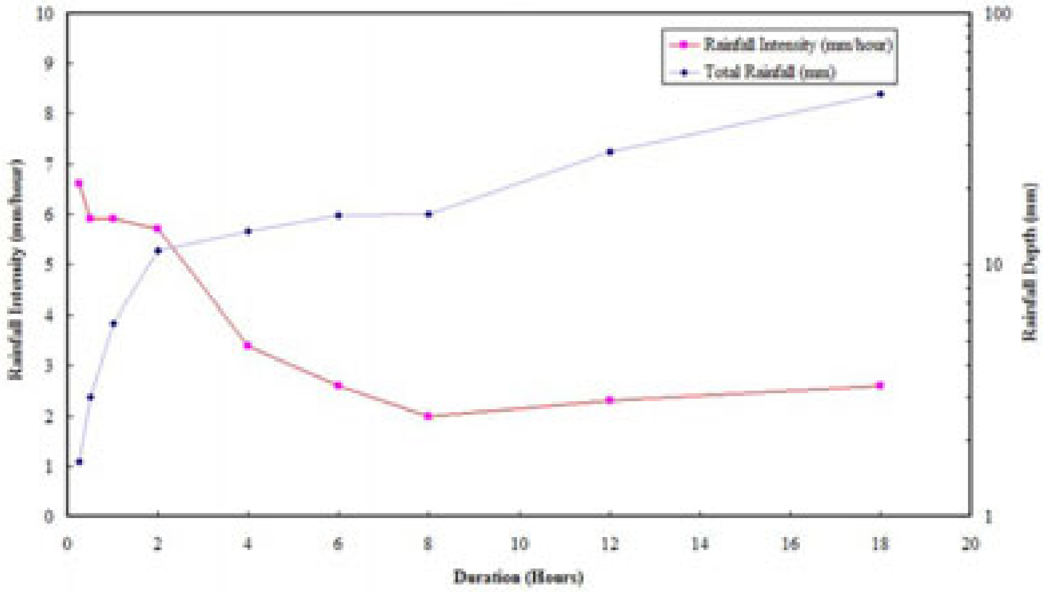


Figure H.1 – Storm Rainfall Intensity and Accumulation, 5 km radar for Event 1.

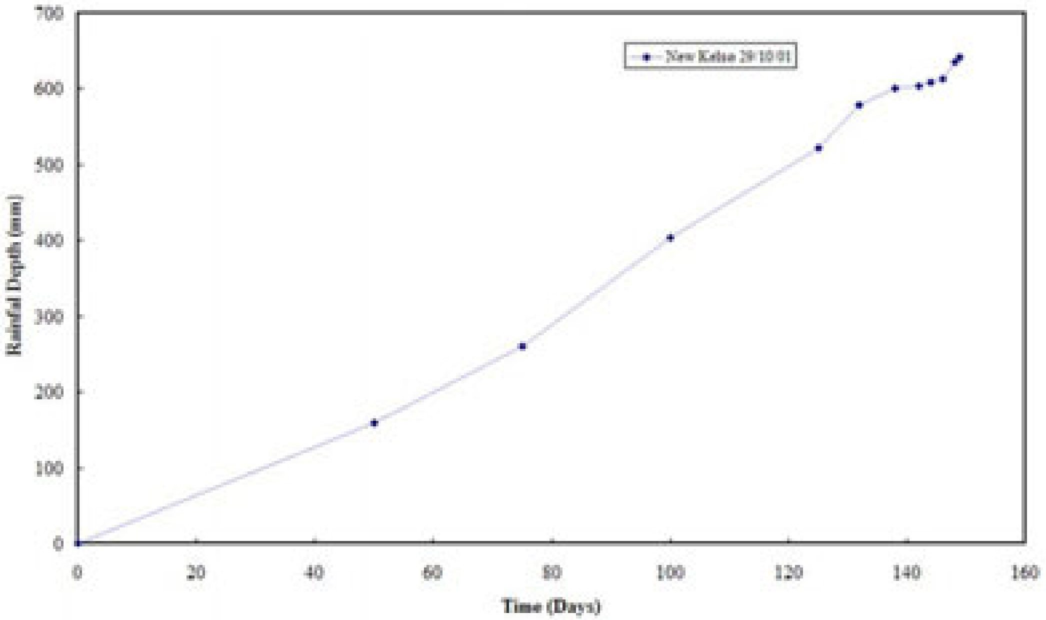


Figure H.2 – Graph of Cumulative Antecedent Rainfall, Event 1.

Table H.6 – Storm rainfall accumulation (depth-mm and duration) for each radar pixel.

Pixel Duration	1	2	3	4	5	6	7	8	9
18 hour	56.3	31.3	67.6	52.4	47.6	54.0	50.5	40.7	88.3
12 hour	33.0	17.5	34.1	31.8	28.0	30.3	31.5	25.4	49.4
8 hour	19.8	10.4	16.8	18.4	15.8	16.6	17.9	14.8	26.8
6 hour	19.6	9.8	16.8	18.2	15.7	16.6	17.9	14.8	26.8
4 hour	17.5	8.8	13.8	15.5	13.4	13.2	13.6	11.8	22.1
2 hour	15.2	7.3	12.7	11.6	11.3	12.3	11.6	9.4	19.4
1 hour	7.7	3.9	6.5	6.0	5.9	6.4	5.9	4.8	10.0
30 minutes	4.2	2.0	3.4	3.1	3.0	3.2	2.9	2.3	5.0
15 minutes	2.2	1.1	1.7	1.7	1.6	1.7	1.5	1.3	2.5

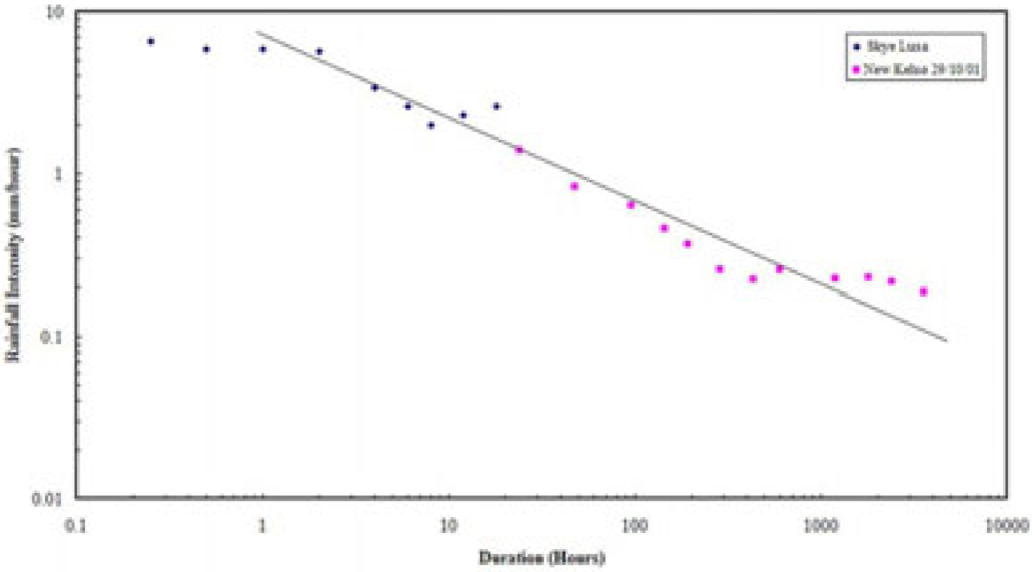


Figure H.3 – Combined storm and antecedent period rainfall intensity, Event 1.

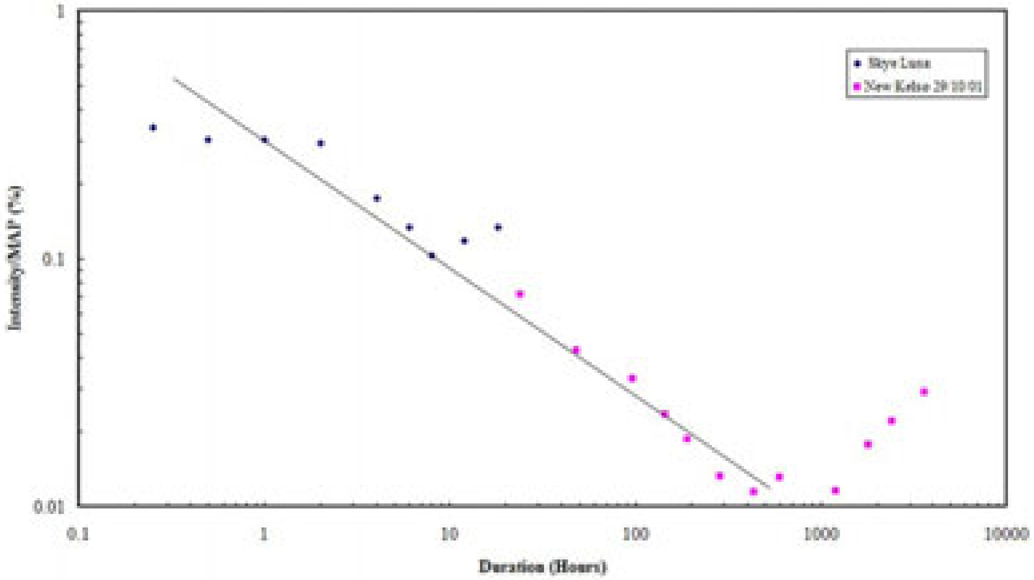


Figure H.4 – Intensity/MAP Function for storm and antecedent period, Event 1.

H.2 DISCUSSION OF RESULTS

The individual tables and graphs for Events 2 to 16 are not presented here, in the interests of conciseness. Summary data are tabulated in Section H.2.1 and presented graphically in both Section H.2.1 and in Figure 9.6. The data from Table H.6 is presented graphically to compare the 18-hour accumulation in the grid array, as in Figure H.5.

In discussing the analysed data it is important to recall the purpose of the analysis, namely to identify a lower threshold of rainfall intensity, across a range of rainfall durations, and which then defines the conditions likely to lead to debris flow events. Thus when examining any set of data it is important that scatter and 'outliers' on the low part of the graph are identified and dealt with as such. However, any 'outliers' amongst the high rainfall-intensity data have no influence on the threshold being developed and are therefore of relatively little significance in this exercise.

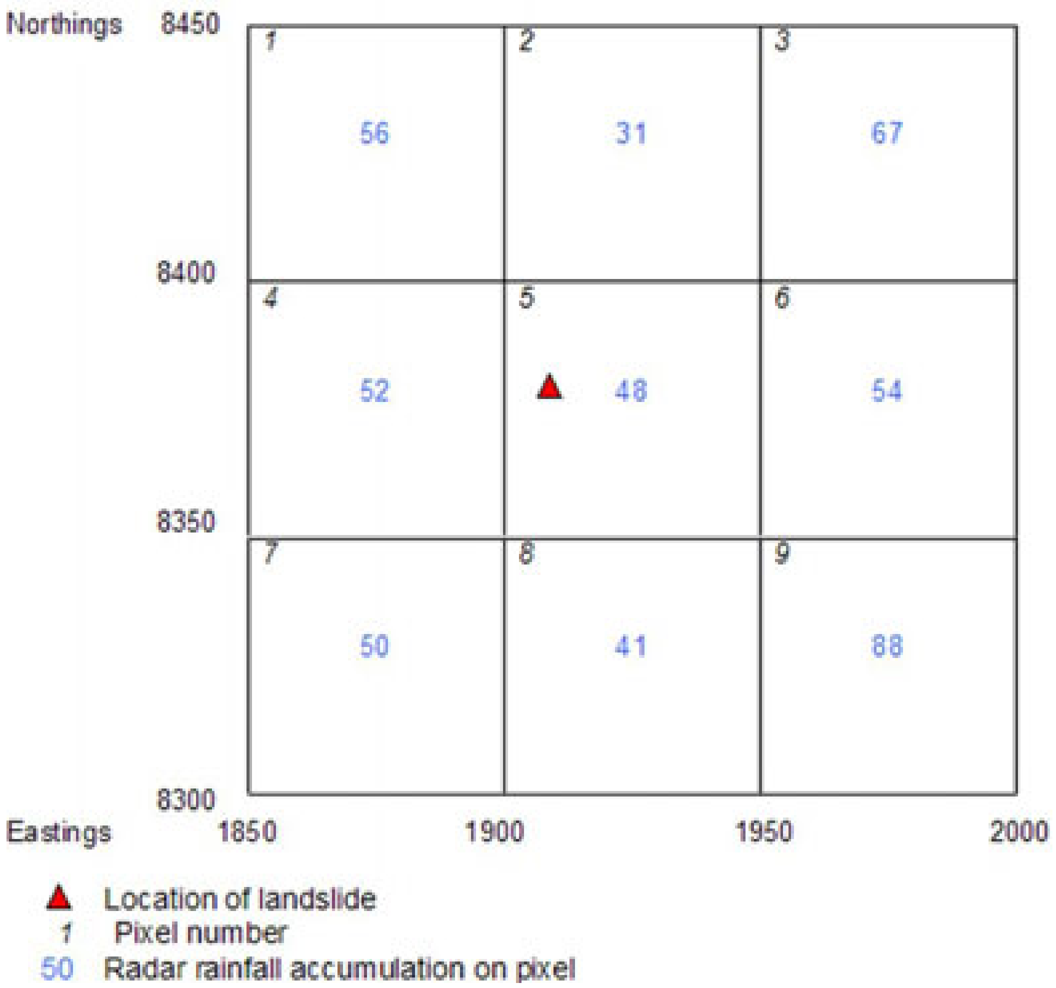


Figure H.5 – Grid analysis for 18-hour rainfall, Event 1.

H.2.1 General Discussion of Results

As might be expected, no consistent pattern emerged from the various analyses to identify what might be considered a typical event. Some events contained high intensity storm rainfalls, but many did not. Similarly there were some very high antecedent rainfall totals associated with events, especially for winter events. On the other hand, there were some – mostly summer events – where, although antecedent totals were high, the period closest to the storm did not contain high rainfall quantities. It may however be informative to compare summary statistics from the events, in anticipation that they may provide possible indicators for a future predictive approach (Table H.7).

Note that in Table H.7, the maximum intensity value is that for a five-minute radar measurement at the location of the pixel within the two hour period before the nominated event start-time.

The intensity-duration relations have been arranged in a number of combined plots. Figures H.6 and H.7 show the grouping of Events 1 to 8 and 9 to 16 respectively, largely to allow the use of symbols to identify the different events. Figure 9.6 combines the intensity-duration data as a scatter diagram (i.e. without recourse to the identification of the different events). It is this diagram and data that is used to determine the intensity-duration threshold. Overall, there was good grouping of data from most events: some of the data from below 1-hour (i.e. at the start of the storm) form outliers. Only Event 5 (Figure H.6) and Events 13 and 14 (Figure H.7) produced relations that plot separately from the rest of the group over a significant portion of the duration of the range. Indeed the data for Event 14 being of high intensity will not influence the trigger threshold selection process. The near event data (<1hour) for Event 12 also plots in a seemingly anomalous juxtaposition to the rest of the data (Figure H.7).

Table H.7 – Summary statistics from all events.

Event No.	Max. Storm Intensity (mm/hr)	Ave. Intensity 0-2hrs (mm/hr)	Ave. Storm Intensity, 18 hrs (mm/hr)	Antecedent 4-Day Rainfall (mm)	Antecedent 12-Day Rainfall (mm)	Antecedent 50-Day Rainfall (mm)
1	6.6	5.7	2.6	70.2	90.4	328.0
2	8.6	5.14	2.61	46.4	141.8	213.2
3	10.2	7.01	1.56	50.1	156.1	277.9
4	8.9	5.19	1.19	34.6	195.3	476.5
5	6.6	2.22	0.77	77.8	110.8	379.9
6	23.4	8.39	5.75	62.3	70.7	300.8
7	50.0	11.42	6.37	62.3	70.7	300.8
8	7.0	3.71	1.64	144.5	183.2	285.8
9	44.8	12.35	2.37	22.7	121.6	231.7
10	10.6	4.4	1.55	34.2	38.8	82.8
11	7.8	2.75	1.25	63.8	67.6	153.0
12	4.4	1.94	1.03	18.4	51.9	177.9
13	3.1	1.41	0.15	76.9	118.4	513.3
14	9.4	7.33	6.59	189.7	317.3	742.5
15	9.6	6.81	1.78	9.3	38.8	329.6
16	5.7	3.75	1.21	30.6	49.0	294.0

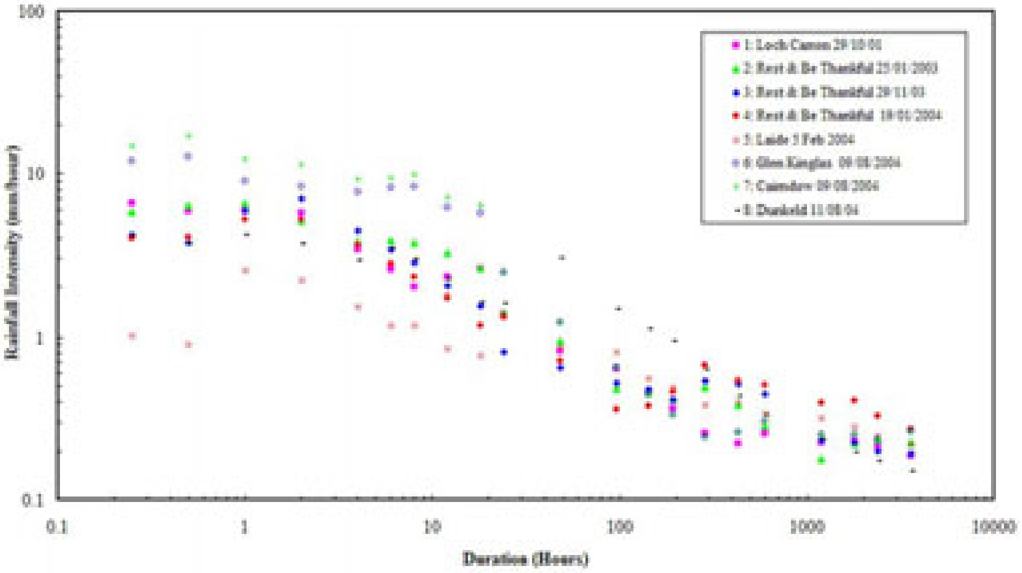


Figure H.6 – Combined plot of intensity versus duration for events 1 to 8.

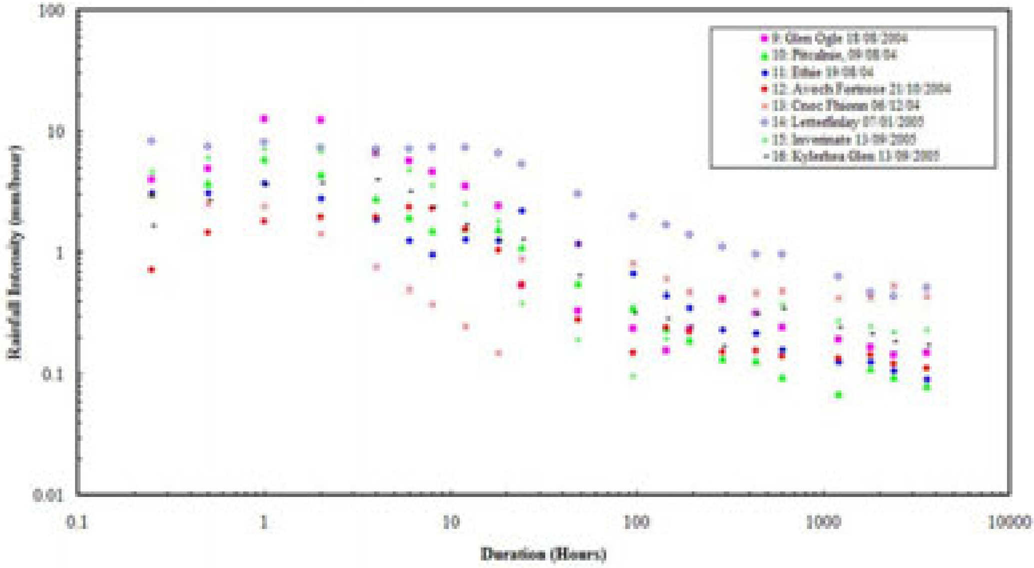


Figure H.7 – Combined plot of intensity versus duration for events 9 to 16.

As has been previously noted (Section 2.4), the occurrence of landslide events in Scotland may show some degree of seasonality, with events concentrated in late-summer (August-September) and in winter (November to February). Combined plots of intensity-duration relations for these sets of storms are shown in Figures H.8 and H.9. The single October event has been placed in the 'winter' set.

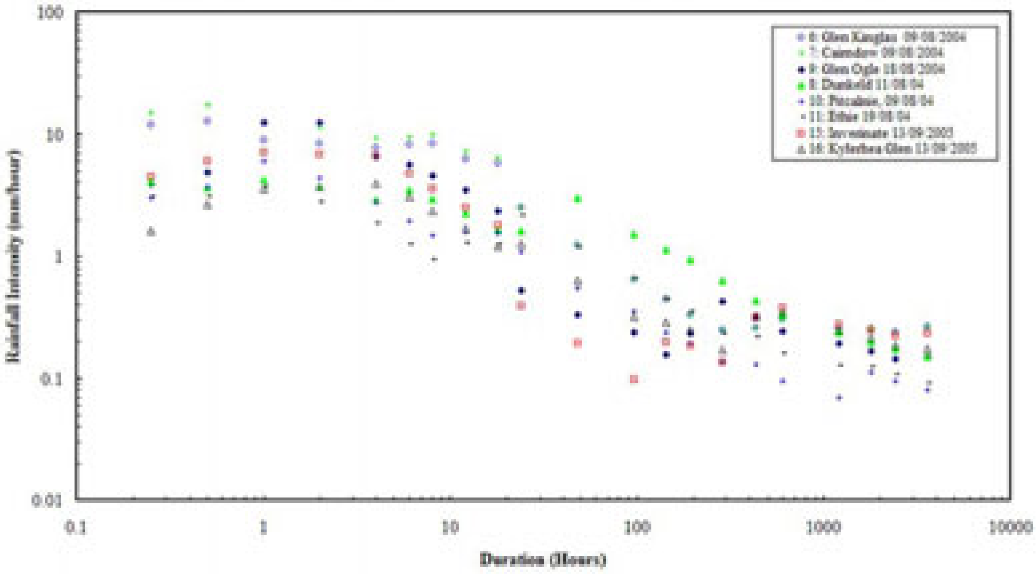


Figure H.8 – Combined plot of intensity versus duration for late summer storms.

Good grouping was achieved over the 'core' part of the time range, from two hours to 1,000 hours. At the early time ranges, the scatter was generally less that in the later time ranges, which may be explained by inaccuracies in the estimated time of the landslide events or, indeed, in terms of the maximum rainfall intensity. It may also be that the rainfall events did not contain very high, short-duration intensities. This is often a feature of rainfall systems over Scotland, in contrast to the higher intensities often experienced in southern England, which are associated with greater convective activity. The Inverinate data (Event 15) included some outliers in the 10 to 100 hour range, and also at the longer time ranges. The scatter tends to become wider at the longer time ranges, which is to be expected, as this period covers mid-summer, where extended dry periods can occur and would provide irregularities.

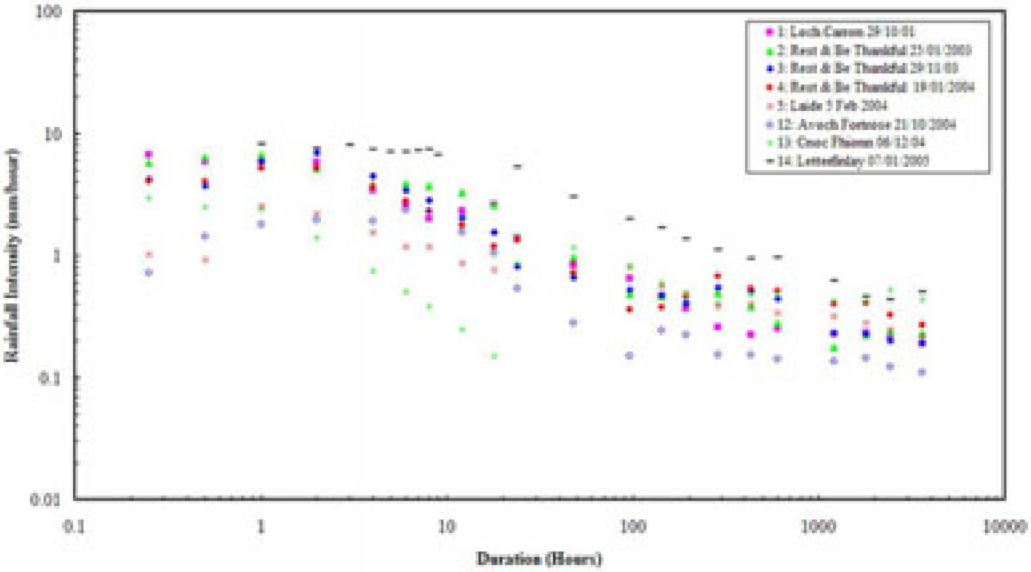


Figure H.9 – Combined plot of intensity versus duration for winter storms.

The winter data indicated less and more consistent scatter over the core range for most of the events, although there were some notable outliers above (Letterfinlay, Event 14), and below (Cnoc Fhionn, Event 13, and Avoch Fortrose, Event 12) the main group. The sub-2-hour data did not fit well with the rest of the relation, for the same reasons as mentioned above.

The influence of the wide difference in mean annual precipitation (MAP) between eastern and western locations has been noted in the discussion of individual events. Landslides in the Black Isle and Easter Ross locations have occurred in association with small-magnitude storm events in comparison other locations, and these may be the result of site influences, rather than rainfall. Plots have however been produced for groupings of 'east' and 'west' locations, in Figures H.10 and H.11.

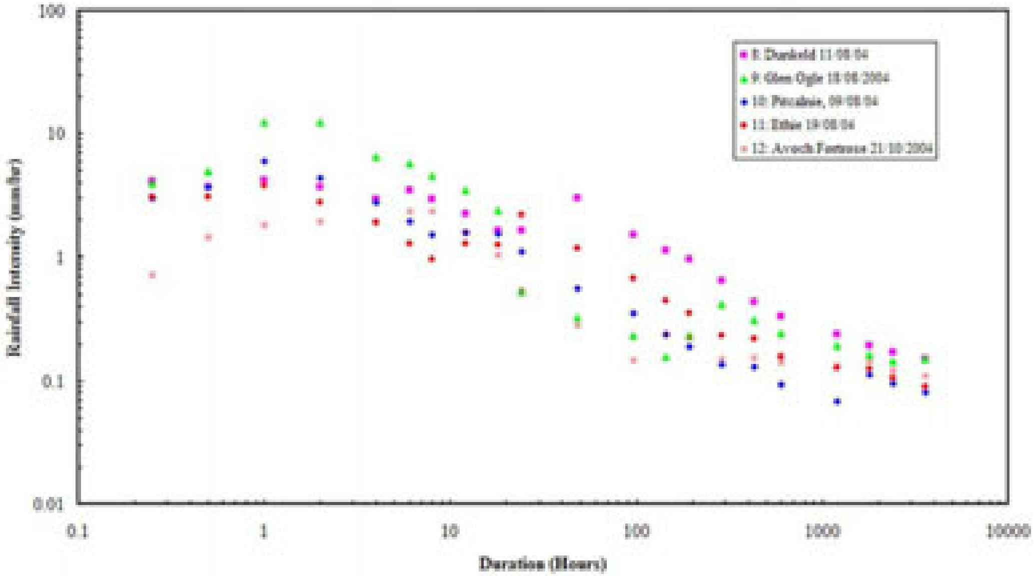


Figure H.10 – Combined plot of intensity versus duration for storms in the eastern areas.

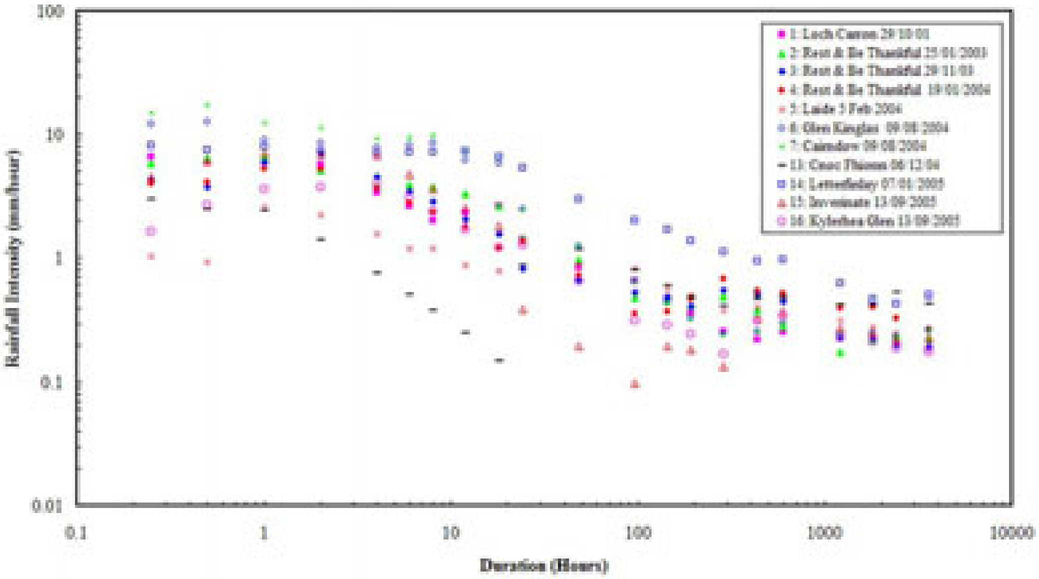


Figure H.11 – Combined plot of intensity versus duration for storms in the western areas.

The group of eastern events showed a consistently good linear relation over the full duration range, apart from the first two hours. The general trend of the grouping for the eastern sites was much steeper than for the western group. This can be explained by the greater incidence and persistence of wetter conditions in the west of Scotland. Cnoc Fhionn (Event 13) and Inverinate (Event 15) produced low outliers over parts of the middle time range. Letterfinlay (Event 14) produced a range of high outliers, which is to be expected, as this storm included by far the highest antecedent rainfall total for all the events.

A method for 'Future Back Analysis' (Annex H.1), whereby a specially designed data-feed is available, has been developed to allow the analysis of future events to assist in the validation of the threshold developed in Section 9.5.

H.3 CONCLUSIONS

The analysis of rainfall leading up to debris flow events has successfully demonstrated methods for producing tabular and graphical outputs suitable for the consistent analysis of such events. The methods cover both the short-term behaviour of storm rainfall and the analysis of rainfall over an extended antecedent rainfall period.

Only Events 5, 12 and 13 produced relations for which a significant portion of the data plot was below the general mass and therefore indicate either a potentially lower threshold than might otherwise be expected or, more likely, that some of these data are outliers.

The work reported demonstrates the usefulness of analysing the rainfall intensities recorded at the radar pixel that covers the site location. Although having TBRs close to the site overcomes the problem of rain gauges being remote from the location, the use of radar data would provide a useful check, and also provides in-fill if any gaps occur in the TBR record. It is a straightforward process to request single or multi-pixel data retrospectively for the site from the Met Office, as these data are routinely archived at five or 15-minute intervals. The analysis of the data to produce into tabular and graphical output would be the same as for the

TBR data, but an extra step is required to convert the radar rainfall data), into an accumulation in mm over specified intervals. (The radar rainfall data is expressed as intensity (×32) in mm/hr over the time unit, five or 15 minutes.)

The analysis method can be adapted with only minor modifications to produce a spreadsheet for the input of data for future events. The final structure of the spreadsheet will depend on how the data is delivered from the field to a data archive, which in turn has to be updated and accessed at regular intervals.

ANNEX H.1 – SYSTEM FOR FUTURE BACK ANALYSIS

‘Future Back Analysis’ refers to the analysis of events that will be carried out once two new TBRs have been installed at a monitoring site, anticipated to be close to the Rest-and-be-Thankful landslide location. The TBR data will not be available in real-time (i.e. by telemetry), but will be archived by SEPA in a readily available database (referred to here as the core database).

To be compatible with the analysis of historic events, the TBR data needs to be converted to 15-minute clock hour units: i.e. 0900-0915, 0915-0930, and so on. In designing the analysis spreadsheet, it has been assumed that this initial processing from raw data will be carried out in the core database.

The 15-minute data will need to be downloaded at regular intervals to provide a project database, which can then be accessed to populate the spreadsheet. Given that requests for data will be on-demand after a reported event, or after a known incidence of heavy rainfall in the general area of the selected sites, it is suggested that the project database be updated monthly. Once an event needing analysis occurs, data from the end of the last complete month needs to be accessed from the core database. Access to and transfer of data from the core to the project database is to be agreed between TRL and SEPA.

The analysis of future events will largely follow the method used in the analysis of past events (using Tabulations 1 and 2), as follows:

i) The 15-minute data from the project database will be ingested into the first column of the spreadsheet.
ii) From this data array, the analysis start-time will be identified (either the maximum 15-minute accumulation in the storm event or the known time of landslide), and all daily data will be summed (for the standard period 0900-0900hrs GMT), and daily data out to T-150 will be placed in one column (Column 2).
iii) From this column, summations of data will be made for intervals over the storm antecedent period commencing at day T-1 out to T-150.
iv) Using this data, Tabulation 1 is constructed. Row 4 of the tabulation is the function of intensity/mean annual precipitation. The value for MAP will be obtained as a grid value for the site from the Met Office’s NCIC (National Climate Information Centre) gridded national dataset of annual average rainfall or from the nearest long-term rain gauge.
v) The data in Row 2 of the tabulation is re-organised to produce cumulative totals of antecedent rainfall commencing at T-150 (Day 0) for periods of 50, 75, 100, 125, 132, 138, 142, 144, 146, 148, and149 days (Row 6).
vi) A graph (points and line) is constructed from Rows 6 and 7 of Tabulation 1: i.e. time in days versus rainfall accumulation (Graph 1).
vii) Using the 15 minute data in Column1, calculations will be carried out backwards from the start-time to provide cumulative totals at intervals of 15 and 30 minutes, and 1, 2, 4, 6, 8, 12 and 18 (or 24 hours if an extended continuous event is apparent).
viii) Using this data, Tabulation 2 is constructed.
ix) A graph (points and line) is constructed showing Rows 2 and 3 versus time (Row 1) (Graph 2).
x) Tabulation 1, Row 3 and Tabulation 2, Row 3 contain rainfall intensity data. This is to be plotted on a log-log scale against a combined time scale (0.25 hours to 150 days) using the intervals in Tabulation 2, Row 1 and Tabulation 1, Row 1 (Graph 3).

xi) Tabulation 1, Row 4 and Tabulation 2, Row 4 contain data for the function of intensity (mm/h) divided by mean annual rainfall (mean annual precipitation, MAP), expressed as a percentage. The two sets of data, time (Row 1, Tabulation 2 and Row 1, Tabulation 1) versus Intensity/MAP (%) are to be plotted on a single graph as points only, using logarithmic scales for both axes (Graph 4).

A summary of the spreadsheet data and products, presented as tables and graphs, is given below. The template for the spreadsheet data and tables are illustrated Tables H.8 to H.10.

Tabulation 1 – Table to be populated to allow the analysis of 150-day antecedent rainfall.

1	**Antecedent days**	1	2	4	6	8	12	18	25	50	75	100	150
2	**Rainfall total (mm)**												
3	**Intensity (mm/hr)**												
4	**Intensity (mm/hr)/MAP (%)**												
5	***Incremental rainfall from day-150***												
6	**Day from T-150**	0	50	75	100	125	132	138	142	144	146	148	149
7	**Incremental rainfall**												

Tabulation 2 – Table to be populated to allow the analysis of storm rainfall.

1	**Time before start point (hours)**	0.25	0.5	1	2	4	6	8	12	18
2	**Rainfall (mm)**									
3	**Rainfall intensity (mm/hr)**									
4	**Intensity/MAP (%)**									

Graph 1 – Antecedent Rainfall.

Cumulative rainfall (mm) versus time, T-150 to T0 (days), arithmetic scales.

Graph 2 – Storm rainfall, accumulation and intensity.

Rainfall intensity (mm/hr) and cumulative rainfall (mm) versus time 0 to 24 (hrs), arithmetic scales.

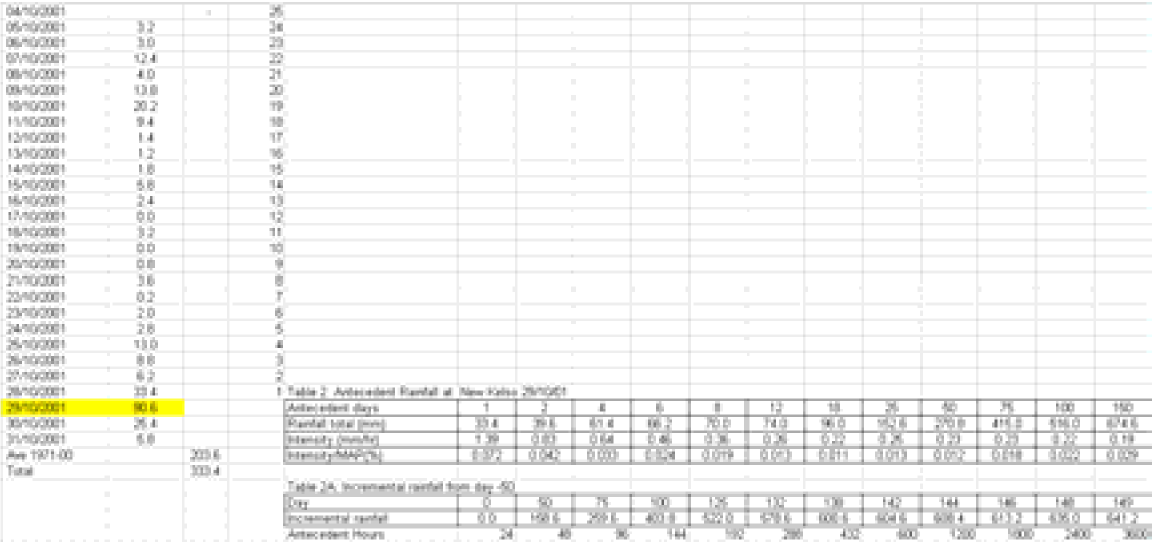
Graph 3 – Intensity versus Duration.

Rainfall intensity (mm/hr) versus time 0.1 to 150 days, log-log scale.

Graph 4 – Intensity/MAP function.

Rainfall intensity (mm/hr)/MAP (mm) as percentage versus time 0.1 to 150 days, log-log scale.

Table H.8 – Hourly rain gauge data.



04/10/2001			25
05/10/2001	3.2		24
06/10/2001	3.0		23
07/10/2001	12.4		22
08/10/2001	4.0		21
09/10/2001	13.8		20
10/10/2001	20.2		19
11/10/2001	9.4		18
12/10/2001	1.4		17
13/10/2001	1.2		16
14/10/2001	1.8		15
15/10/2001	5.8		14
16/10/2001	2.4		13
17/10/2001	0.0		12
18/10/2001	3.2		11
19/10/2001	0.0		10
20/10/2001	0.8		9
21/10/2001	3.6		8
22/10/2001	0.2		7
23/10/2001	2.0		6
24/10/2001	2.8		5
25/10/2001	13.0		4
26/10/2001	8.8		3
27/10/2001	6.2		2
28/10/2001	33.4		1
29/10/2001	90.6		
30/10/2001	25.4		
31/10/2001	5.8		
Ave 1971-00		203.6	
Total		333.4	

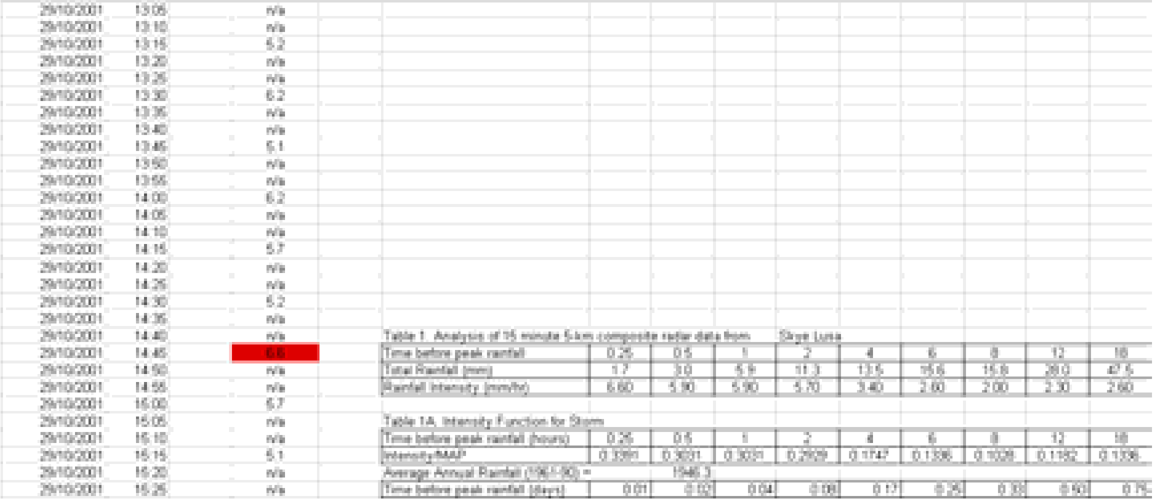
Table 2. Antecedent Rainfall at New Kelso 29/10/01

Antecedent days	1	2	4	6	8	12	18	26	50	75	100	150
Rainfall total (mm)	33.4	39.6	61.4	66.2	70.0	74.0	96.0	162.6	270.8	415.8	516.0	674.6
Intensity (mm/hr)	1.39	0.83	0.64	0.46	0.36	0.26	0.22	0.26	0.23	0.23	0.22	0.19
Intensity/MAP(%)	0.072	0.042	0.033	0.024	0.019	0.013	0.011	0.013	0.012	0.018	0.022	0.029

Table 2A. Incremental rainfall from day -50

Day	0	50	75	100	125	132	138	142	144	146	148	149
Incremental rainfall	0.0	158.6	259.6	403.8	522.0	578.6	600.6	604.6	608.4	613.2	636.0	641.2
Antecedent Hours	24	48	96	144	192	288	432	600	1200	1800	2400	3600

Table H.9 – 15 minute radar rainfall data.



29/10/2001	13:05	n/a
29/10/2001	13:10	n/a
29/10/2001	13:15	6.2
29/10/2001	13:20	n/a
29/10/2001	13:25	n/a
29/10/2001	13:30	6.2
29/10/2001	13:35	n/a
29/10/2001	13:40	n/a
29/10/2001	13:45	6.1
29/10/2001	13:50	n/a
29/10/2001	13:55	n/a
29/10/2001	14:00	6.2
29/10/2001	14:05	n/a
29/10/2001	14:10	n/a
29/10/2001	14:15	5.7
29/10/2001	14:20	n/a
29/10/2001	14:25	n/a
29/10/2001	14:30	5.2
29/10/2001	14:35	n/a
29/10/2001	14:40	n/a
29/10/2001	14:45	6.6
29/10/2001	14:50	n/a
29/10/2001	14:55	n/a
29/10/2001	15:00	6.7
29/10/2001	15:05	n/a
29/10/2001	15:10	n/a
29/10/2001	15:15	5.1
29/10/2001	15:20	n/a
29/10/2001	15:25	n/a

Table 1. Analysis of 15 minute 5-km composite radar data from Skye Lusa

Time before peak rainfall	0.25	0.5	1	2	4	6	8	12	18
Total Rainfall (mm)	1.7	3.0	5.9	11.3	13.5	15.6	15.8	28.0	47.5
Rainfall intensity (mm/hr)	6.60	5.90	5.90	5.70	3.40	2.60	2.00	2.30	2.60

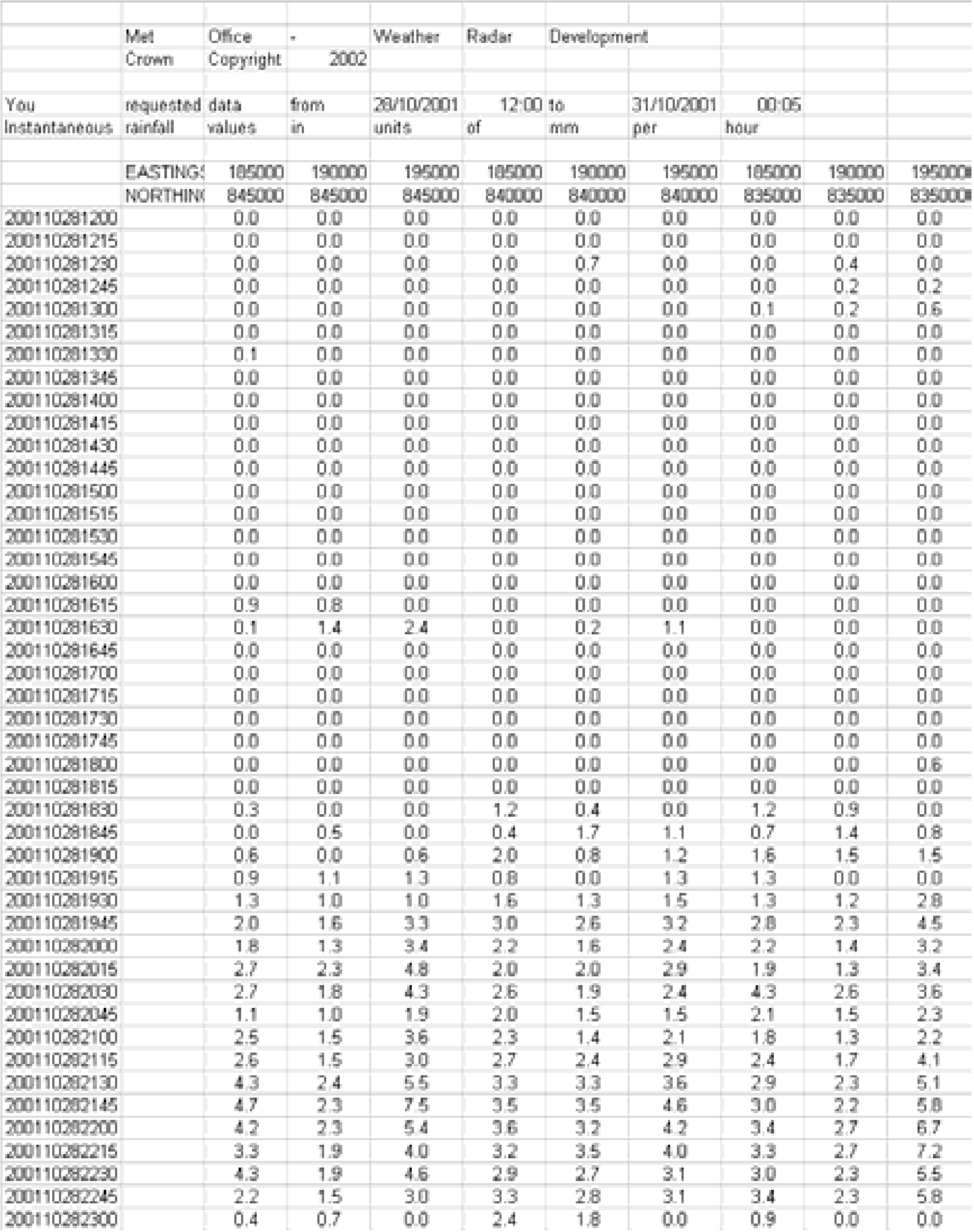
Table 1A. Intensity Function for Storm

Time before peak rainfall (hours)	0.25	0.5	1	2	4	6	8	12	18
Intensity/MAP	0.3391	0.3031	0.3031	0.2929	0.1747	0.1336	0.1028	0.1182	0.1336

Average Annual Rainfall (1961-90) = 1946.3

Time before peak rainfall (days)	0.01	0.02	0.04	0.08	0.17	0.25	0.33	0.50	0.75

Table H.10 – Gridded radar rainfall data: template for 15 minute rainfall data.



	Met	Office	-	Weather	Radar	Development				
	Crown	Copyright	2002							
You	requested	data	from	28/10/2001	12:00	to	31/10/2001	00:05		
Instantaneous	rainfall	values	in	units	of	mm	per	hour		
	EASTING	185000	190000	195000	185000	190000	195000	185000	190000	195000
	NORTHIN	845000	845000	845000	840000	840000	840000	835000	835000	835000
200110281200		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281215		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281230		0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.4	0.0
200110281245		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
200110281300		0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.6
200110281315		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281330		0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281345		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281400		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281415		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281430		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281445		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281500		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281515		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281530		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281545		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281600		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281615		0.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281630		0.1	1.4	2.4	0.0	0.2	1.1	0.0	0.0	0.0
200110281645		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281700		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281715		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281730		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281745		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281800		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
200110281815		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200110281830		0.3	0.0	0.0	1.2	0.4	0.0	1.2	0.9	0.0
200110281845		0.0	0.5	0.0	0.4	1.7	1.1	0.7	1.4	0.8
200110281900		0.6	0.0	0.6	2.0	0.8	1.2	1.6	1.5	1.5
200110281915		0.9	1.1	1.3	0.8	0.0	1.3	1.3	0.0	0.0
200110281930		1.3	1.0	1.0	1.6	1.3	1.5	1.3	1.2	2.8
200110281945		2.0	1.6	3.3	3.0	2.6	3.2	2.8	2.3	4.5
200110282000		1.8	1.3	3.4	2.2	1.6	2.4	2.2	1.4	3.2
200110282015		2.7	2.3	4.8	2.0	2.0	2.9	1.9	1.3	3.4
200110282030		2.7	1.8	4.3	2.6	1.9	2.4	4.3	2.6	3.6
200110282045		1.1	1.0	1.9	2.0	1.5	1.5	2.1	1.5	2.3
200110282100		2.5	1.5	3.6	2.3	1.4	2.1	1.8	1.3	2.2
200110282115		2.6	1.5	3.0	2.7	2.4	2.9	2.4	1.7	4.1
200110282130		4.3	2.4	5.5	3.3	3.3	3.6	2.9	2.3	5.1
200110282145		4.7	2.3	7.5	3.5	3.5	4.6	3.0	2.2	5.8
200110282200		4.2	2.3	5.4	3.6	3.2	4.2	3.4	2.7	6.7
200110282215		3.3	1.9	4.0	3.2	3.5	4.0	3.3	2.7	7.2
200110282230		4.3	1.9	4.6	2.9	2.7	3.1	3.0	2.3	5.5
200110282245		2.2	1.5	3.0	3.3	2.8	3.1	3.4	2.3	5.8
200110282300		0.4	0.7	0.0	2.4	1.8	0.0	0.9	0.0	0.0

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7.2 The Road Well Traveled: Implications of Climate Change for Pavement Infrastructure in Southern Canada (Methodology Section)

THE ROAD WELL-TRAVELED:

Implications of Climate Change for Pavement Infrastructure in Southern Canada

Brian N. Mills[1], Susan L. Tighe[2], Jean Andrey[3], James T. Smith[2], Suzanne Parm[3] and Ken Huen[2]

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FINAL TECHNICAL REPORT March 2007

3.0 IMPACT OF CLIMATE VARIABILITY AND CHANGE ON CANADIAN PAVEMENT PERFORMANCE: CASE STUDIES

General methods for assessing the potential impacts of climate change on various aspects of society, economy and environment have been developed over the past two decades, largely based on approaches rooted in applied climatology or the hazards and risk assessment literature (Kates, 1985; Burton *et al*., 1993; Bruce *et al.*, 2001). The leading international source of guidance on climate change impact assessment is the Intergovernmental Panel on Climate Change (IPCC), an organization that is responsible for periodic reviews of the scientific literature on aspects of climate change science, impacts and adaptation assessment, and emissions mitigation (IPCC, 2001, 2007). Carter *et al*. (1994) and IPCC-TGCIA (1999) propose several generic steps in a framework to guide climate impacts and adaptations assessment: 1) problem definition, 2) selection of method, 3) testing of method, 4) selection of scenarios, 5) assessment of biophysical and socio-economic impacts, 6) assessment of autonomous adjustments, 7) evaluation of adaptation strategies. While this study implicitly focuses on steps 1 through 5, important adaptation issues are introduced in the discussion, conclusion and recommendation sections (Sections 3.3., 4.1., 4.2).

The review of pavement design and management practices and engineering models and approaches used to monitor, assess and predict flexible pavement performance revealed that climate—and thus potentially climate change—is an important consideration in at least three deterioration processes: thermal cracking, frost heave and thaw weakening, and rutting. Two sets of case studies were undertaken in this research to investigate these generalized impacts of climate change in greater detail. The first involved examining deterioration-relevant climate indicators that are routinely applied or referenced in the management of pavement infrastructure. The second set of case studies were conducted using the Mechanistic-Empirical Pavement Design Guide (MEPDG) and software, a new tool developed through the Unites States NCHRP/AASHTO. A description of each set of studies, including underlying methods, data requirements, and results is provided below.

3.1 Analysis of Deterioration-relevant Climate Indicators

Three deterioration-relevant climate indicators were chosen to illustrate the potential effects of climate change on an aspect of each of the processes outlined in the previous section:

- extreme minimum daily temperature;
- 7-day average maximum daily temperature; and
- freezing and thawing indices.

The first two are important indicators of climatic conditions conducive to thermal cracking and rutting, respectively, and are applied in the selection of appropriate asphalt binders. Freezing and thawing indices are useful indicators of frost/thaw depths and thus pavement strength; they are particularly important in managing traffic loads.

Analysis of Climate Change Impacts

The analysis of potential climate change impacts consisted of several steps that are outlined in Figure 7 beginning with the identification of 17 Canadian study sites (Table 4). The primary criteria for selection were location (southern Canada), proximity to test sections in the Long Term Pavement Performance (LTPP) program (more relevant for the MEPDG analyses), and availability of daily records of temperature[11]. Most of the selected sites are airport locations. Collectively the Census Metropolitan Areas (CMAs) or Census Agglomerations (CAs) represented by the sites include over 53 percent of the Canadian population and encompass a wide range of the environmental conditions experienced in southern Canada. Baseline time series of daily minimum, maximum and mean temperature data for the period 1951-2001 were obtained from the Environment Canada climate archive for each of the sites listed in Table 4.

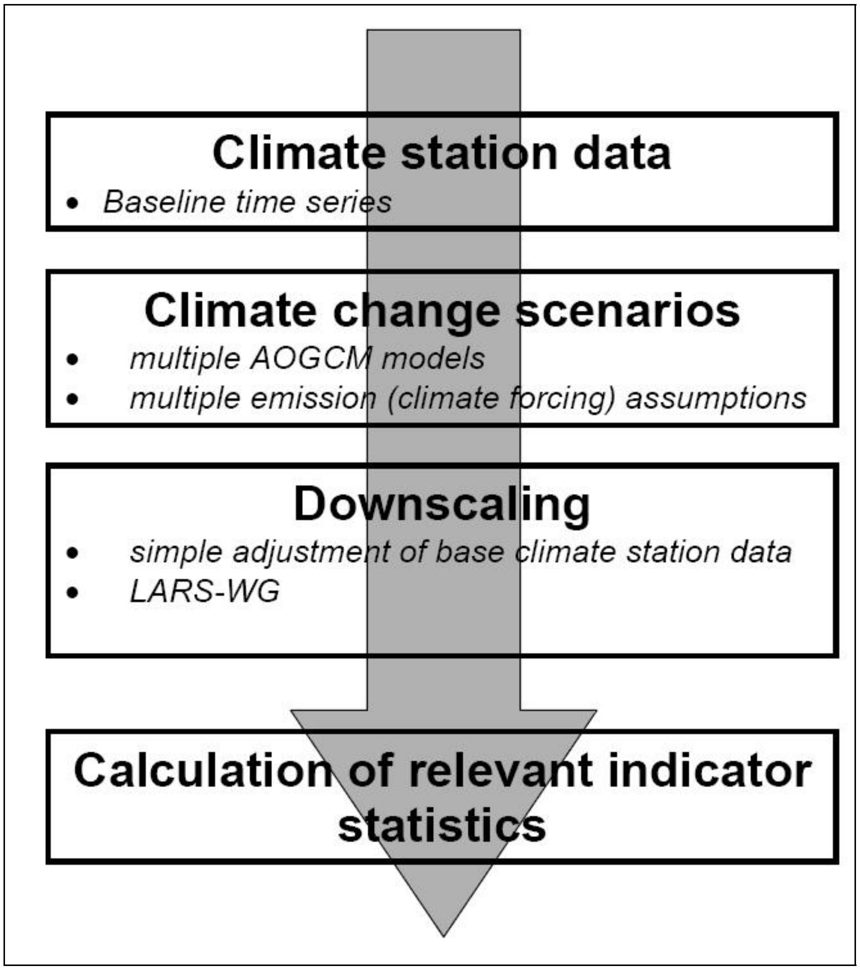

Figure 7. Steps in the analysis of climate change impacts

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[11] Additional stations in Ontario were analyzed for use in other research projects.

Table 4. Case study site locations and characteristics

City (MSC Observing Station reference)	Latitude	Longitude	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Vancouver (1108447)	49.2	123.1	4.3	10.1	1199.0
Kelowna (1123970)	49.9	119.4	429.5	7.7	380.5
Calgary (3031093)	51.0	114.0	1084.1	4.1	412.6
Edmonton (3012205)	53.5	113.5	723.3	2.4	482.7
Regina (4016560)	50.5	104.6	577.3	2.8	388.1
Winnipeg (5023222)	50.0	97.2	238.7	2.6	513.7
Thunder Bay (6048261)	48.4	89.3	199.0	2.5	711.6
North Bay (6085700)	46.4	78.4	370.3	3.8	1007.7
Muskoka (6115525)	44.9	79.3	281.9	4.9	1098.6
Windsor (6139525)	42.3	82.9	189.6	9.4	918.3
Toronto (6158733)	43.7	79.6	173.4	7.5	792.7
Ottawa (6106000)	45.3	75.7	114.0	6.0	943.5
Montreal (7025250)	45.5	73.6	35.7	6.2	978.9
Quebec (7016294)	46.8	71.2	74.4	4.0	1207.7
Fredericton (8101500)	46.0	66.7	20.7	5.3	1143.3
Halifax (8202250)	44.6	63.6	145.4	6.3	1452.2
St. John’s (8403506)	47.6	52.7	140.5	4.7	1513.7

*from 1971-2000 climate normals (Environment Canada http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html)

Climate Change Scenarios

Coupled general circulation models of the atmosphere and ocean (AOGCMs) are the only credible tools presently available to quantitatively estimate the transient global climate response to scenarios of future greenhouse gases, sulphate aerosols and other elements that affect climate forcing (IPCC-TGCIA, 1999). While the scientific community is quite confident that anthropogenic activities will lead to significant warming of global air temperature and a general increase in precipitation over the next century, there remains considerable uncertainty concerning potential climatic changes at local and regional scales and at specific points in time (Houghton *et al*., 2001). It is therefore recommended that scenarios from multiple AOGCM experiments (different models and assumptions concerning future emission patterns) be considered in analyses of climate impacts.

After considering available resources, required levels of effort, and choices made in recent comparable climate impact assessments, two climate change scenarios were adopted for analysis in the current study: one based on the A2x[12] emission experiment from the Canadian Centre for Climate Modelling and Analysis Coupled Global Climate Model 2 (CGCM2A2x), the other from the B21 experiment run through the Hadley Climate Model 3 (HadCM3B21). More information

---

[12] the CGCM2 A2x scenario is actually an ensemble or average of three separate A2 experiments for which the model was initialized differently. Similarly, the HadCM3 B21 scenario is the first experiment in its B2 series.

concerning the basis of the emission scenarios, which are grouped into four families (A1, A2, B1, B2) having similar demographic, societal, political, economic and technological assumptions over the next century, is provided in IPCC (2000). The specifications of the CGCM2 and HadCM3 climate models, and performance in relation to other internationally recognized models, are also well-documented elsewhere (Flato *et al*., 2000; Flato and Boer, 2001; Gordon *et al*., 2000; CMIP, 2001).

Raw scenario surface temperature (minimum, maximum, mean) and precipitation (total) data for each model and experiment were obtained through the Canadian Climate Scenarios Network (CCSN, 2005). Monthly data were available for baseline (1961-1990) and three future 30-year temporal windows centred on the 2020s, 2050s, and 2080s. Given that the average design life of pavement infrastructure is about 20-30 years, only the 2050s scenarios were examined in the current study. The data consisted of output for climate model grid cells, each of which spans 2.5 (HadCM3) to 3.75 (CGCM2) degrees latitude and 3.75 (both models) degrees longitude (i.e., over 100,000 km^2). Each site in Table 4 was assigned to the model grid cell in which it was located, except when the cell was designated as ‘water’ in the model specifications; in these cases, the nearest ‘land’ cell was used. Scatterplots of potential changes in annual and seasonal mean temperature and precipitation were prepared to indicate the position or severity of the CGCM2A2x and HadCM3B21 experiment results relative to other AOGCM scenarios for each site. Examples of annual scatterplots for the most northern (Edmonton) and southern (Windsor) study sites are provided in Figures 8-9. In general the CGCM2A2x and HadCM3B21 scenarios are average and conservative, respectively, when compared to other AOGCMs and experiments. Tables of the monthly values for the CGCM2Ax and HadCM3B21 that were used for each site are provided in Appendix A.

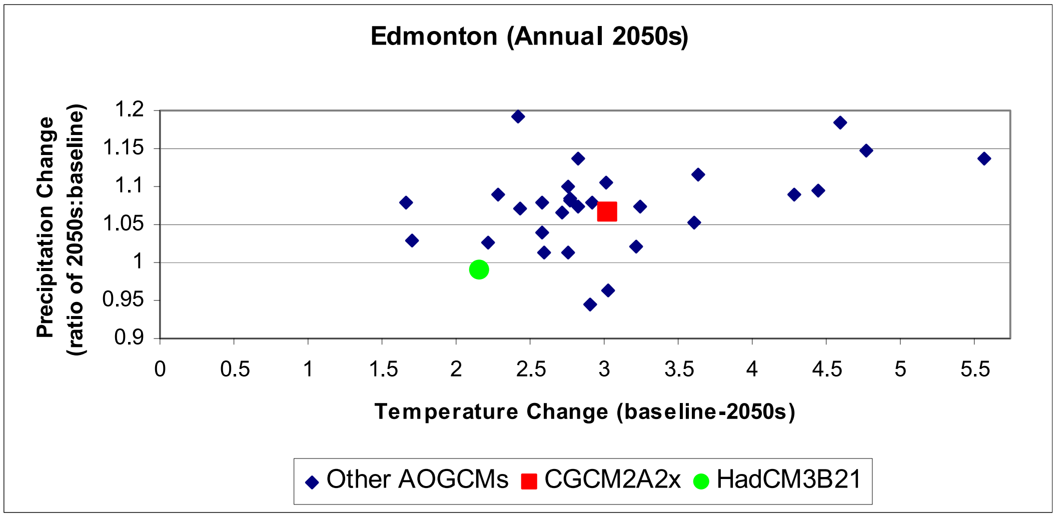


Figure 8. Scatterplot of potential changes in mean annual temperature and precipitation (Edmonton case study)

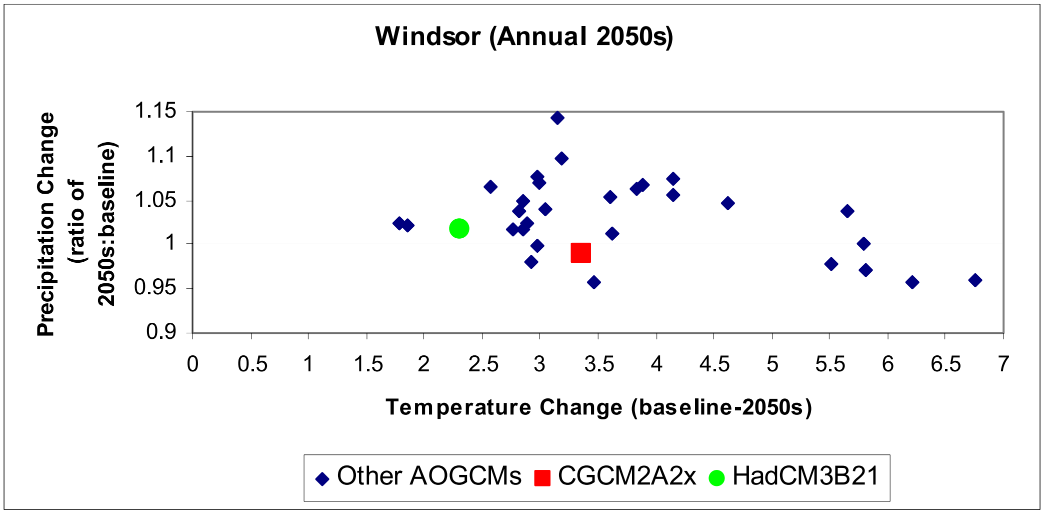


Figure 9. Scatterplot of potential changes in mean annual temperature and precipitation (Windsor case study)

Downscaling

As noted, the spatial resolution of AOGCM output is very coarse such that daily or monthly time series of variables are generally not suitable for direct input into climate impact analyses. Instead, the output is normally downscaled to match the scale at which the impact exposure unit is modeled (e.g., a point on a road network, hydrologic basin, city, etc.). Barrow *et al.* (2004) describe several downscaling techniques ranging in sophistication from simply adjusting historic time series by an average change factor derived from output for a particular AOGCM cell (e.g., increase mean January temperature by 4°C or precipitation by 15 percent) to developing a high resolution dynamic regional climate model nested within a coarser AOGCM (e.g., Goyette *et al.* 2001). Statistical weather generators (e.g., Semenov *et al.*, 1998; Wilks and Wilby, 1999; Wilby *et al.*, 2002) fall between these extremes, both in terms of sophistication and ease-of-use, and were the tools chosen in the current study.

LARS-WG, a stochastic weather generator developed and described in detail by Semenov *et al.* (1998), was used to produce 3 random, synthetic, 50-year daily time series for the baseline and each climate change scenario. LARS-WG was first parameterized for each site using the 1951-2000 daily temperature and precipitation data obtained from Environment Canada. LARS-WG preserves the basic statistics of the original data in simulating a synthetic series; thus it allows the user to examine a degree of random variability in the baseline. LARS-WG allows the user to insert monthly factors (i.e., changes in mean and standard deviations of temperature, mean precipitation) that are applied to the baseline parameters of a particular site and thus incorporated into the simulation of future daily time series. As with the baseline, 3 separate 50-year simulations of future daily data were completed for each site and scenario (CGCM2A2x, HadCM3B21). These data were then used to generate time series and calculate basic summary statistics for each of the deterioration-relevant climate indicators permitting comparison between baseline and changed climate states. The calculation methods and results are discussed in the next section.

Performance Grade Asphalt Cement Selection

Extreme minimum daily temperature and 7-day average maximum daily temperature indicators are used to assist in the selection of performance grade (PG) asphalt binders or asphalt cements (PGAC) (USFHWA, 2002; OHMPA, 1999) that have been appropriately rated using extensive laboratory material testing. A suitable PGAC will minimize thermal cracking under cold temperatures while simultaneously minimizing traffic-induced rutting under hot temperatures. A reliability factor, most often 98 percent over the design life of the pavement structure, is associated with each PGAC and is determined as part of the calculations for each design. Grades are assigned in 6°C increments for both minimum and maximum pavement temperatures as illustrated in Table 5.

Table 5. Example performance grade asphalt binders/cements (USFHWA, 2002; OHMPA, 1999)

Extreme Minimum Pavement Temperature (°C)	**7-day Maximum Pavement Temperature (°C)**					
	40	**46**	**52**	**58**	**64**	**70**
-40	PG 40-40	PG 46-40	PG 52-40	PG 58-40	PG 64-40	PG 70-40
-34	PG 40-34	PG 46-34	PG 52-34	PG 58-34	PG 64-34	PG 70-34
-28	PG 40-28	PG 46-28	PG 52-28	PG 58-28	PG 64-28	PG 70-28
-22	PG 40-22	PG 46-22	PG 52-22	PG 58-22	PG 64-22	PG 70-22
-16	PG 40-16	PG 46-16	PG 52-16	PG 58-16	PG 64-16	PG 70-16
-10	PG 40-10	PG 46-10	PG 52-10	PG 58-10	PG 64-10	PG 70-16

For example, a PG 58-28 asphalt cement meets a minimum daily surface pavement temperature requirement of -28°C, and an average 7-day maximum temperature of 58°C, with 98 percent reliability over its design life (Haas *et al*., 2004). The minimum PG threshold refers to surface pavement temperatures while the maximum PG threshold refers to a temperature within the pavement, normally about 20mm from the surface (OHMPA, 1999). In practice, maximum temperature PG thresholds are adjusted upward one or more increments to account for traffic and load considerations (e.g., sections of Highway 401 in southern Ontario that are subject to stopped or slow moving heavy truck traffic) (USFHWA, 2002; OHMPA, 1999).

While continuous 50-year records of air temperature data are available throughout North America, similarly extensive datasets for pavement temperature are not as common or reliable. Several empirical formulae relating air and pavement temperatures have been developed through the Superpave and Long Term Pavement Performance (LTPP) programs to assist engineers in the design and binder selection process. The most recent equations cited by the USFHWA (2002) are described below:
For maximum pavement temperature:

$$T_{pmax} = 54.3254.32+0.78T_{airmax}-0.0025Lat^{2}-15.14\log_{10}(H+25)+z(9+0.61\sigma_{Tairmax}{}^{2})^{0.5} \qquad (4)$$

where:

T_{pmax} = maximum pavement temperature at depth, °C
T_{airmax} = average annual extreme 7-day mean maximum daily air temperature, °C
Lat = latitude of location, decimal degrees
H = depth from surface, mm
z = z-score for appropriate level of reliability assuming standard normal distribution (z=2.055, 98% reliability)
$\sigma_{Tairmax}$ = standard deviation of annual extreme 7-day mean maximum daily air temperature, °C

For minimum pavement temperature:

$$T_{pmin} = -1.56+0.72T_{airmin}-0.004Lat^2+6.26\log_{10}(H+25)-z(4.4+0.52\sigma_{Tairmin}{}^2)^{0.5} \quad (5)$$

where:

T_{pmin} = minimum pavement temperature at depth, °C

T_{airmin} = average annual extreme minimum daily air temperature, °C

Lat = latitude of location, decimal degrees

H = depth from surface, mm

z = z-score for appropriate level of reliability assuming standard normal distribution (z=2.055, 98% reliability)

$\sigma_{Tairmin}$ = standard deviation of annual extreme minimum daily air temperature, °C

While more sophisticated heat-balance and finite-difference models have been developed to determine temperatures throughout the pavement structure (e.g., Yavuzturk *et al*., 2005), the Superpave formulae are more commonly used in practice and are based on LTPP climate and pavement data from over 30 North American sites. Nevertheless, for comparison the authors also applied two additional formulae derived from 3 years of Road Weather Information System (RWIS) pavement and air temperature data from 3 sites in Ontario (MTO, 2006). These RWIS stations better capture the latitudes of the Canadian sites examined in the current study. The data are plotted in Figures 10-11 and the best fit (approximate r-squared values of 0.97) second-order, polynomial equations are noted below for each relationship.

For maximum pavement temperature:

$$T_{pmax} = 3.0305+0.007T_{airmax}{}^2+1.1715T_{airmax} \quad (6)$$

where:

T_{pmax} = maximum pavement temperature (~20mm depth), °C

T_{airmax} = 7-day mean maximum daily air temperature, °C

For minimum pavement temperature:

$$T_{pmin} = 2.0722+0.0051T_{airmin}{}^2+1.0453T_{airmin} \quad (7)$$

where:

T_{pmin} = minimum pavement surface temperature, °C

T_{airmin} = minimum daily air temperature, °C

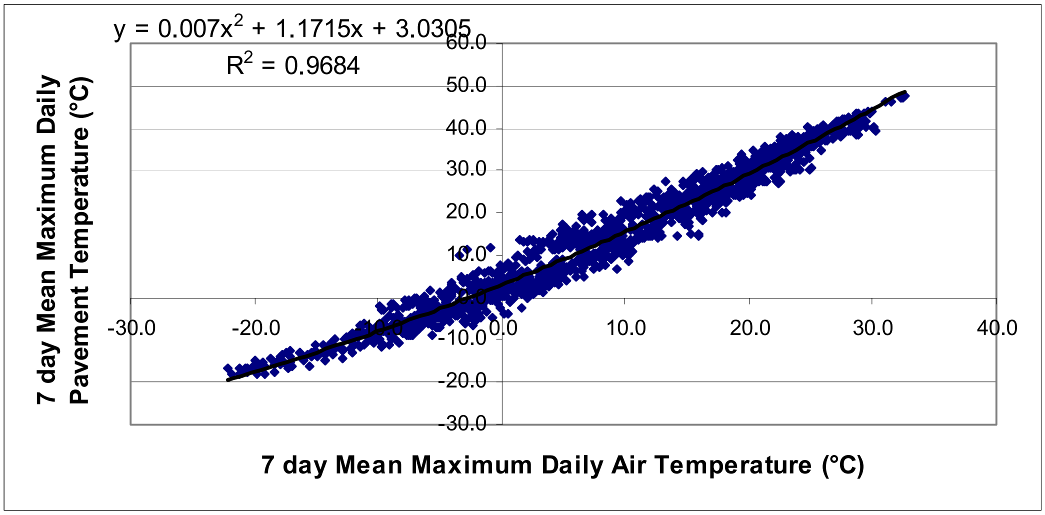


Figure 10. Relationship between 7-day mean maximum daily air and pavement temperatures

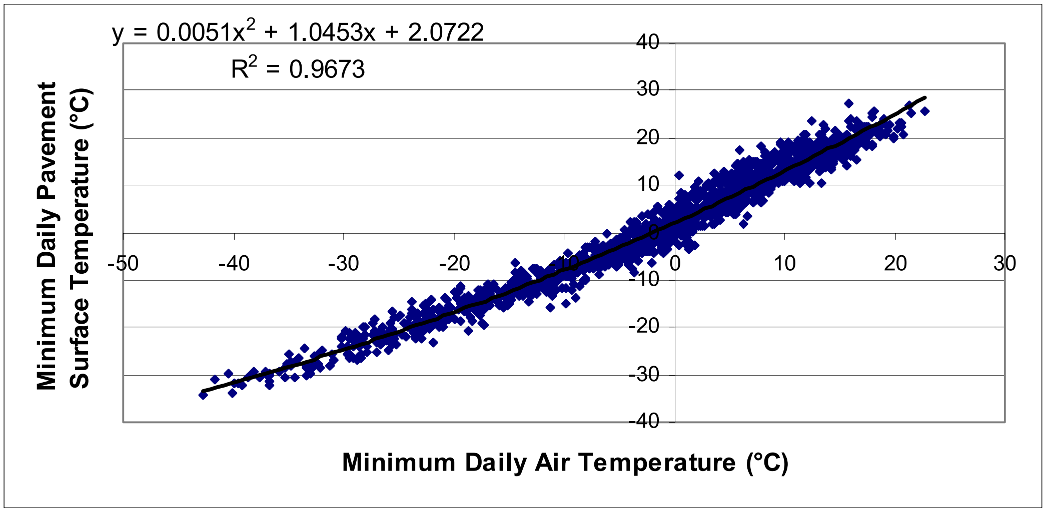
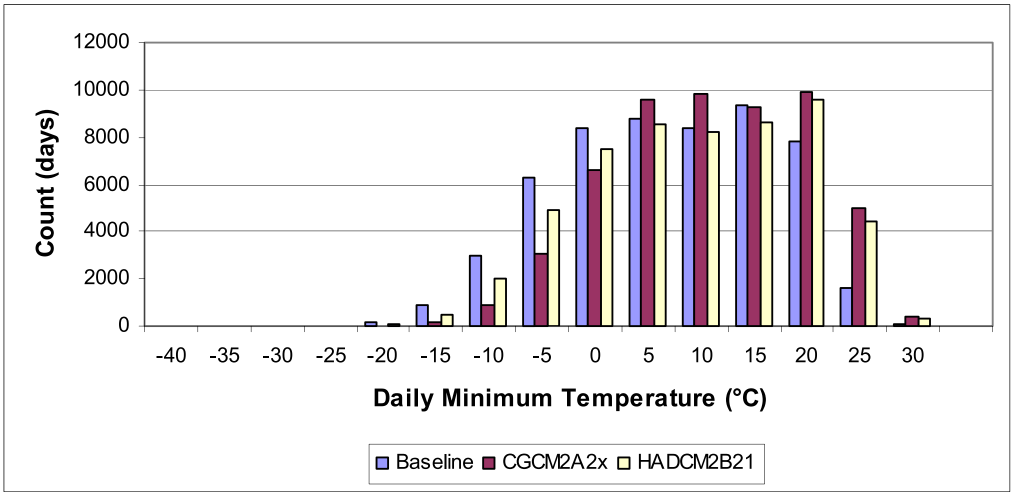


Figure 11. Relationship between minimum daily air and pavement surface temperatures

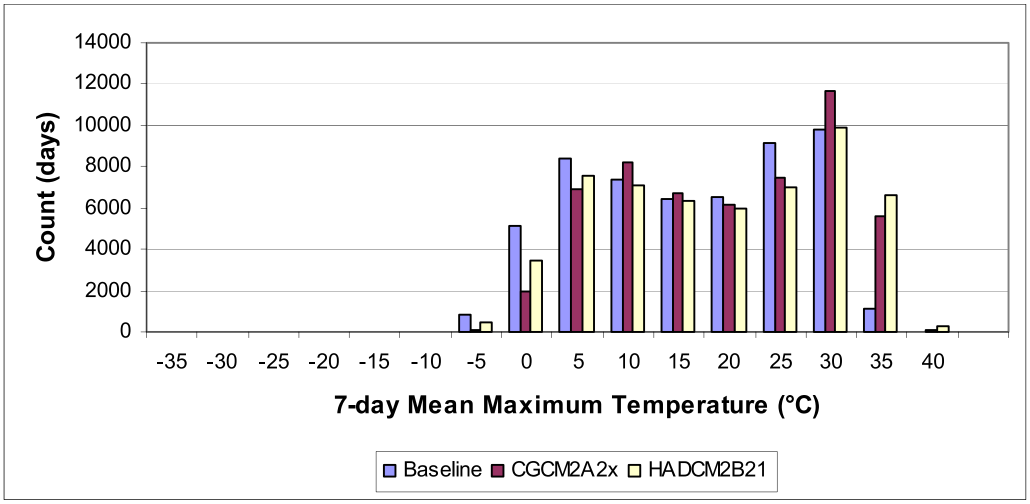
Performance Grade Analysis Results

Daily minimum and 7-day mean maximum temperatures are expected to increase with climate change at all of the sites examined. In general, the CGCM2A2x scenarios yield the greater changes in both minimum and 7-day mean maximum temperature variables. For example, Figures 12-13 show the distribution of all daily minimum and 7-day mean maximum temperatures for the Windsor site under baseline and future climate conditions. Every day in each of the 3, 50-year simulations for the baseline, CGCM2A2x, and HadCM3B21 scenarios is represented in Figures 12-13. Comparable results for all sites are included in Appendix B. From this daily data, time series of the minimum temperature and the highest 7-day mean maximum temperature observed in each year of the simulation are extracted for the calculation of performance grades. These variables are referred to as the *annual extreme minimum daily temperature* and *annual extreme 7-day mean maximum temperature* throughout this report. Minimum, maximum, and quartile statistics of these variables for the Windsor site are presented in Figures 14-15.



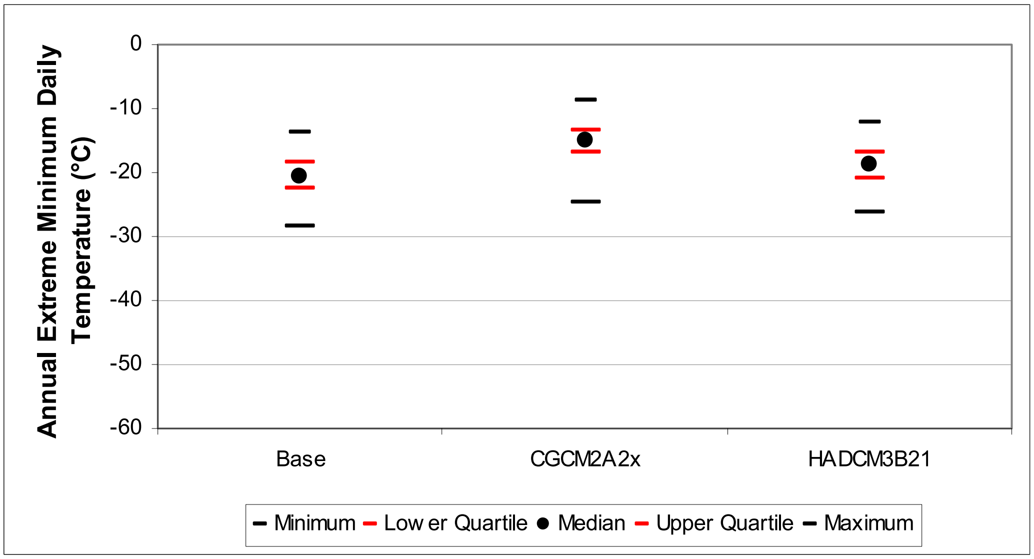
Notes: 1) based on 3, 50-year synthetic series (54750 days)
2) x-axis labels refer to upper limit (i.e., 0 category includes values greater than -5 and less than or equal to 0)

Figure 12. Daily minimum air temperature statistics for Windsor site under baseline and future scenarios



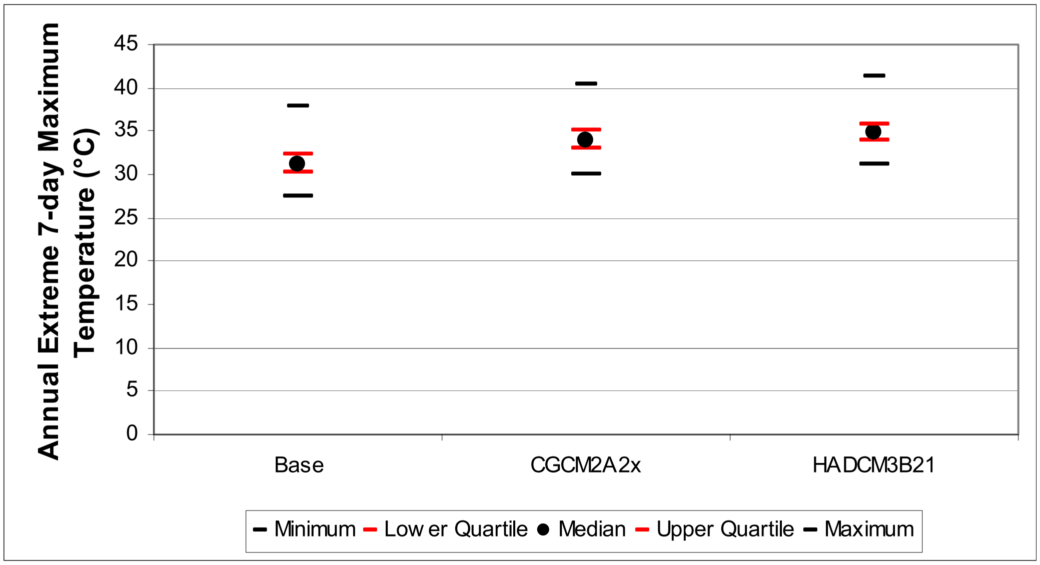
Notes: 1) based on 3, 50-year synthetic series (54750 days)
2) x-axis labels refer to upper limit (i.e., 0 category includes values greater than -5 and less than or equal to 0)

Figure 13. Seven-day mean daily maximum air temperature statistics for Windsor site under baseline and future scenarios



Notes: based on 3, 50-year synthetic series (150 values)

Figure 14. Annual extreme minimum daily air temperature statistics for Windsor site under baseline and future scenarios



Notes: based on 3, 50-year synthetic series (150 values)

Figure 15. Annual extreme 7-day mean maximum air temperature statistics for Windsor site under baseline and future scenarios

The annual extreme minimum daily temperature and annual extreme 7-day mean maximum temperature data for Windsor and the other sites were then applied to the Superpave and RWIS-based pavement temperature formulae to estimate PG ratings. As presented in equations 4 and 5, the Superpave formulae require average and standard deviation values for each variable in order to calculate a PG temperature at 98 percent reliability (assuming a normal distribution). For the RWIS-based equations, the PG temperature at 98 percent reliability was estimated by applying the 98th percentile for each temperature variable in the formulae. Results for the minimum PG temperature threshold are presented in Figure 16-17. Baseline low temperature thresholds determined using the Superpave algorithm ranged from -16°C (Vancouver) to -46°C (Edmonton). Relative to the baseline, no change in PG rating occurred at any of the sites under the HadCM3B21 scenario while 7 of 17 sites warmed up by one category under the CGCM2A2x scenario.

Baseline thresholds estimated using the Ontario RWIS-based algorithm were similar to those derived from the Superpave formula—the one exception was the Edmonton site where, with a value of -46°C, the Superpave baseline was one increment lower (colder). As with the Superpave PG rating, the HadCM3B21 results indicate no change relative to the RWIS-based baseline while PG ratings for 7 of 17 sites increased by one increment under the CGCM2A2x scenario. The specific sites that changed were not completely identical under the two algorithms, with Edmonton and Kelowna only changing under the Superpave and RWIS-based approaches, respectively.

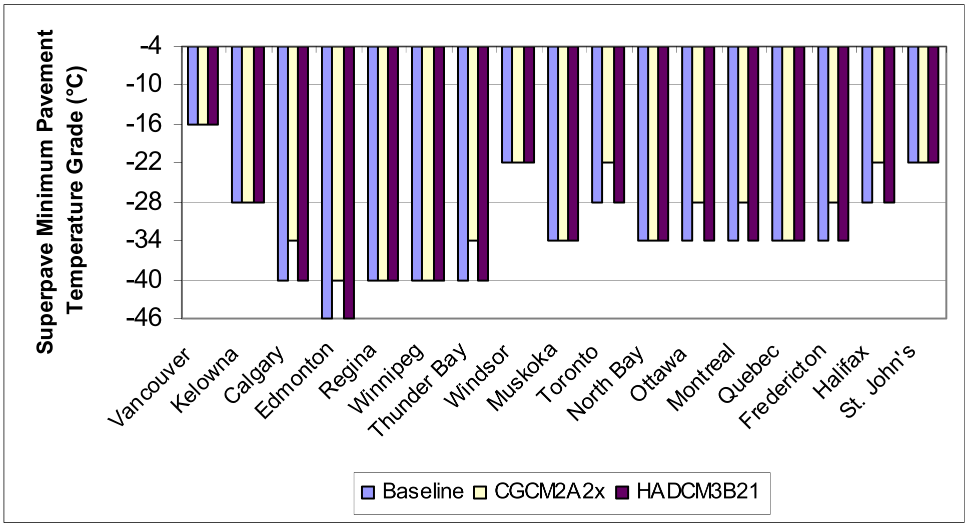


Figure 16. Low PG rating thresholds estimated using the Superpave algorithm under baseline and future scenarios for all sites

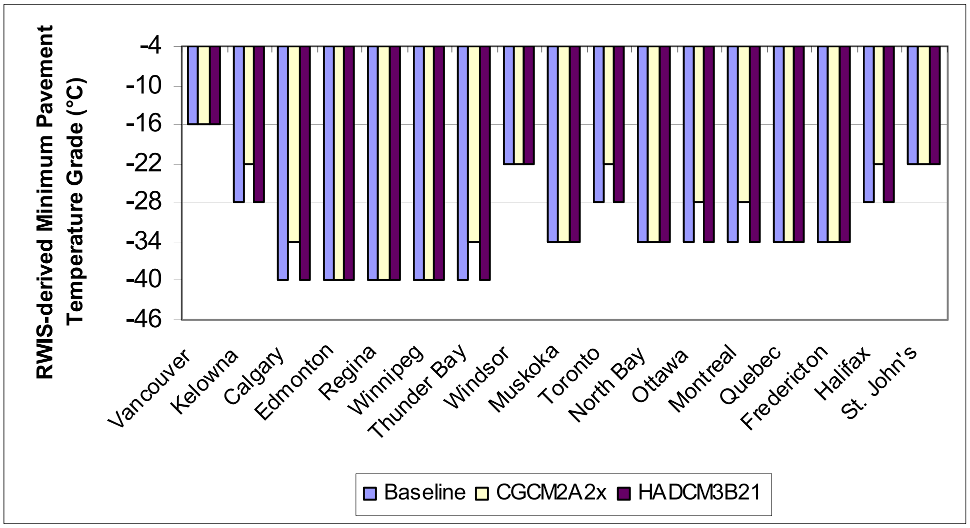


Figure 17. Low PG rating thresholds estimated using the RWIS-based algorithm under baseline and future scenarios for all sites

Results for the maximum PG temperature threshold are presented in Figure 18-19. Baseline high temperature thresholds determined using the Superpave algorithm were either 52°C (Vancouver, Calgary, Edmonton, North Bay, Halifax, St. John's) or 58°C (Kelowna, Regina, Winnipeg, Thunder Bay, Windsor, Muskoka, Toronto, Ottawa, Montreal, Fredericton). The upper limit of this range expanded to 64°C (Kelowna, Windsor) after results from the climate change scenarios were considered. PG ratings for 6 of 17 sites increased by one category under the HadCM3B21 scenario relative to the baseline; ratings for four of these sites also increased by one increment under the CGCM2A2x scenario.

Baseline thresholds estimated using the Ontario RWIS-based algorithm ranged from 46°C (Vancouver, North Bay, Halifax, St. John's) to 58°C (Kelowna, Regina, Windsor). Results were one category lower than those derived from the Superpave formula for 12 sites and identical for the remaining 5 locations. The climate change scenarios produced thresholds ranging from 46°C (Vancouver) to 70°C (Kelowna). PG ratings at 13 sites increased by at least one increment under the HadCM3B21 climate change scenario (Kelowna increased by two categories) and eleven of these sites also increased by one increment under the CGCM2A2x scenario. The higher PG estimates under the RWIS-based formula are likely a product of the limited range of data upon which the equation was derived. As shown in Figure 7, the highest 7-day mean maximum air temperature considered in the 3-year dataset is less than 35°C which is much lower than the 98th percentile values that were analysed in the baseline and climate change scenarios. This issue is not apparent for the extreme minimum equation as the RWIS data captured the full range of values in the baseline and climate change scenarios. Regardless, the differences illustrate the importance of using long time series of data whenever possible when developing empirical relationships.

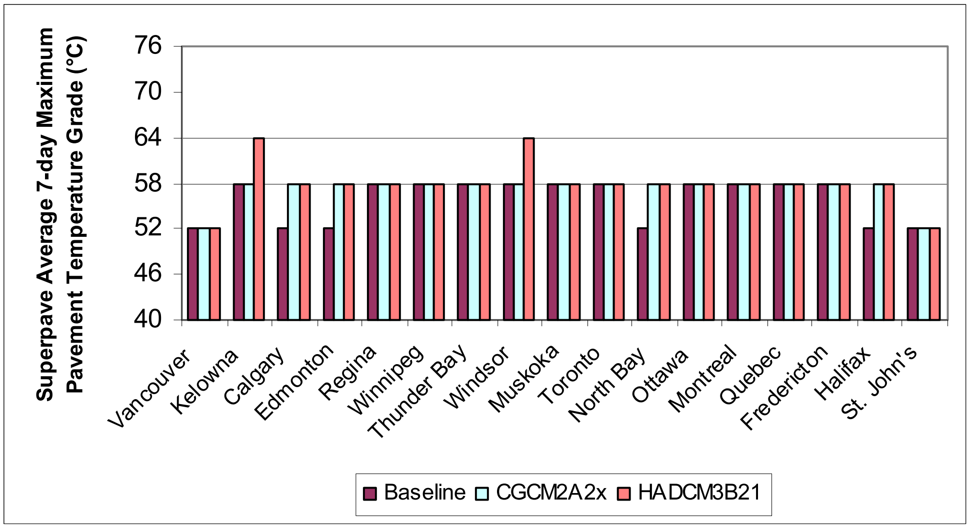


Figure 18. High PG rating thresholds estimated using the Superpave algorithm under baseline and future scenarios for all sites

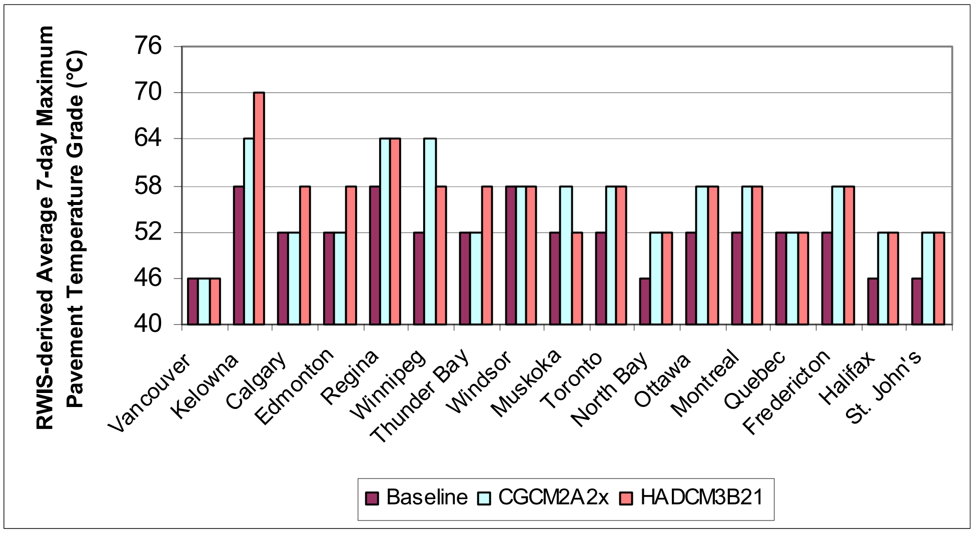


Figure 19. High PG rating thresholds estimated using the RWIS-based algorithm under baseline and future scenarios for all sites

A complete summary of results from the PG analysis is presented in Table 6. Detailed results for each site are provided in Appendix B.

Table 6. PG analysis summary of Superpave- and RWIS-based results

	Superpave-based Performance Grade Estimates			Ontario RWIS-based Performance Grade Estimates		
Site	**Baseline**	**CGCM2A2x**	**HadCM3B21**	**Baseline**	**CGCM2A2x**	**HadCM3B21**
Vancouver	PG 52-16	PG 52-16	PG 52-16	PG 46-16	PG 46-16	PG 46-16
Kelowna	PG 58-28	PG 58-28	PG 64-28	PG 58-28	PG 64-22	PG 70-28
Calgary	PG 52-40	PG 58-34	PG 58-40	PG 52-40	PG 52-34	PG 58-40
Edmonton	PG 52-46	PG 58-40	PG 58-46	PG 52-40	PG 52-40	PG 58-40
Regina	PG 58-40	PG 58-40	PG 58-40	PG 58-40	PG 64-40	PG 64-40
Winnipeg	PG 58-40	PG 58-40	PG 58-40	PG 52-40	PG 64-40	PG 58-40
Thunder Bay	PG 58-40	PG 58-34	PG 58-40	PG 52-40	PG 52-34	PG 58-40
North Bay	PG 52-34	PG 58-34	PG 58-34	PG 46-34	PG 52-34	PG 52-34
Muskoka	PG 58-34	PG 58-34	PG 58-34	PG 52-34	PG 58-34	PG 52-34
Windsor	PG 58-22	PG 58-22	PG 64-22	PG 58-22	PG 58-22	PG 58-22
Toronto	PG 58-28	PG 58-22	PG 58-28	PG 52-28	PG 58-22	PG 58-28
Ottawa	PG 58-34	PG 58-28	PG 58-34	PG 52-34	PG 58-28	PG 58-34
Montreal	PG 58-34	PG 58-28	PG 58-34	PG 52-34	PG 58-28	PG 58-34
Quebec	PG 58-34	PG 58-34	PG 58-34	PG 52-34	PG 52-34	PG 52-34
Fredericton	PG 58-34	PG 58-28	PG 58-34	PG 52-34	PG 58-34	PG 58-34
Halifax	PG 52-28	PG 58-22	PG 58-28	PG 46-28	PG 52-22	PG 52-28
St. John's	PG 52-22	PG 52-22	PG 52-22	PG 46-22	PG 52-22	PG 52-22

Freezing and Thawing Indices

As noted previously, freezing and thawing indices are used to establish Winter Weight Premiums (WWPs) and Spring Load Restrictions (SLRs) and to empirically model the depth of frost within the pavement structure, a key determinant of its strength or structural adequacy. Assumptions used in the calculation of the Freezing Index (FI) and Thawing Index (TI) chosen for the study are summarized in Table 7.

For the purposes of this case study, an FI threshold of 156 degree days for WWP was drawn from research performed by Minnesota DoT (2004). FI calculations commence each season (October 1-May 31) following the first day that mean daily temperature falls below 0°C. Degrees below (above) zero are added (subtracted) each day and accumulated until the threshold is reached and sustained for 7 days, a surrogate for frost penetration to a sufficient depth (~40cm) to increase pavement strength and justify extra loads on roads subject to SLRs.

Thawing index (TI) calculations were based on a modified Minnesota approach as applied in recent work by Leong *et al.* (2005) and adjusted slightly by the authors. More specifically, once a site reached the critical freezing index noted previously, a daily thawing index (degree day count) was calculated for those days when the mean daily air temperature exceeded a reference value (-2°C). This value approximately corresponds to a temperature of 0°C at the base of the asphalt layer (i.e., to account for pavement response to radiation even though air temperatures are below 0°C). SLRs are assumed to be required in order to mitigate pavement damage when the cumulative daily TI reaches and sustains a critical value (13 degree days). To ensure that the thaw is prolonged sufficiently to affect the structure, additional criteria—attainment of at least 30 degree-days within seven days and an average TI of 21.5 degree-days—were applied to establish the recommended SLR date.

It should be noted that the specific thresholds or constants used in calculating freezing and thawing indices vary by jurisdiction and/or practice. Complementary studies are being completed by the authors in order to explore the implications of these, using sensitivity analysis. More specifically, the following decision points are being explored:

- Should the freezing index be adjusted for winter thaws?
- How much freezing is required to change the moduli of the pavement?
- When there is enough freezing, at what temperature should the thawing index calculation be initiated?
- How should low temperatures be treated after the thawing index calculation has been initiated?
- How should the first possible date for thaw-related damage be determined?
- When should SLRs/WWPs be implemented and monitored to minimize pavement damage?

The results of this work, as applied to two sites—Edmonton International Airport and Toronto Pearson International Airport for the months of September through April, from 1971 to 2000—will be reported in a Master’s thesis in Geography at the University of Waterloo (Parm, 2007). A separate study, initiated by the University of Waterloo in partnership with the Ministry of Transportation of Ontario, is also examining these issues within the context of utilizing Road Weather Information Systems (RWIS) to control load restrictions on gravel and surface treated highways (Huen *et al*., 2006).

Table 7. Freeze and thaw analysis calculation assumptions adopted in the analysis

VARIABLE	CONDITION
Freezing Index (FI) Calculations	
Season begins/ends	October 1/May 31
Reference Temperature	0°C
FI threshold (day 1)	≥156
FI threshold (day 2-7 mean)	≥156
Thawing Index Calculations	
Season begins/ends	October 1/May 31
Reference Temperature	-2°C
TI threshold (day 1)	≥13
TI threshold (day 2-7 minimum)	≥13
TI threshold (day 2-7 maximum)	≥30
TI threshold (day 2-7 mean)	≥21.5

Freeze-Thaw Indicator Results

The freeze-thaw analysis consisted of comparing the timing of critical FI and critical TI and the length of the 'freeze' season—taken to be the sum of days between FI and TI—for baseline and climate change scenarios. Results for the Winnipeg case study site are shown in Figures 20-21 for illustration while similar accounts for the remaining sites are profiled in Appendix B. Median values are reported for the timing of critical FI and TI while both median and mean statistics are used to interpret changes in freeze season length.

Days to critical freeze and thaw thresholds, counted from October 1, are plotted in Figure 20 for each of the 150 seasons contained within the baseline, CGCM2A2x, and HadCM3B21 time series. On average at the Winnipeg site, critical freeze index values were reached within 61, 66, and 68 days for the baseline, CGCM2A2x, and HadCM321 scenarios, respectively. The slight delay of about one week in median freeze-up under climate change relative to the baseline was accompanied by a reduction in the median length of time for thawing to occur. Critical thawing index was achieved within 187, 172, and 182 days for the baseline, CGCM2A2x, and HadCM321 scenarios, respectively. Figure 21 summarizes the distribution of freeze season lengths calculated for the Winnipeg site. Although the baseline time series contained the year with the shortest freeze season duration, the average season length dropped from a baseline of 122 to 101 days under the CGCM2A2x scenario.

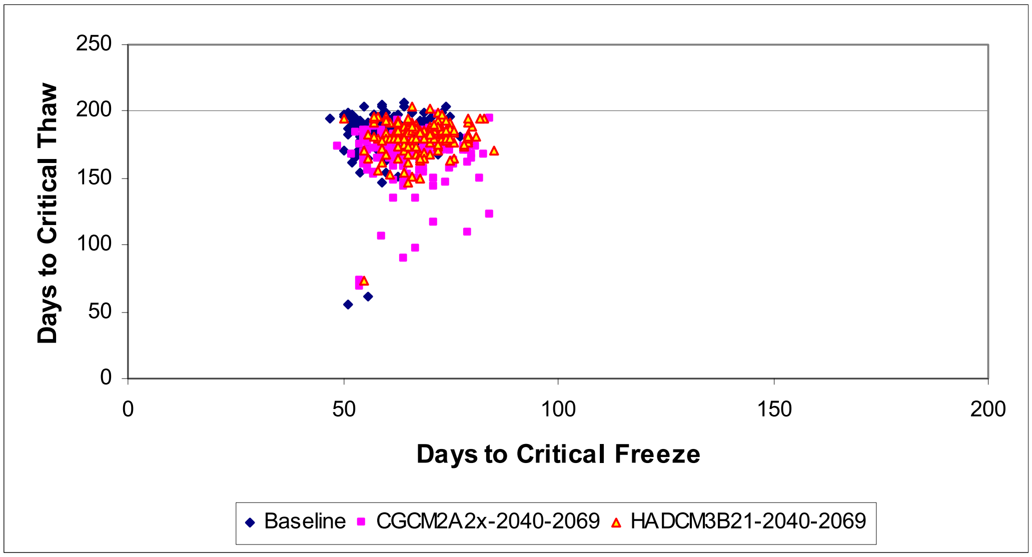


Figure 20. Days (from October 1) to reach critical freeze and thaw indices at the Winnipeg site under baseline and future scenarios

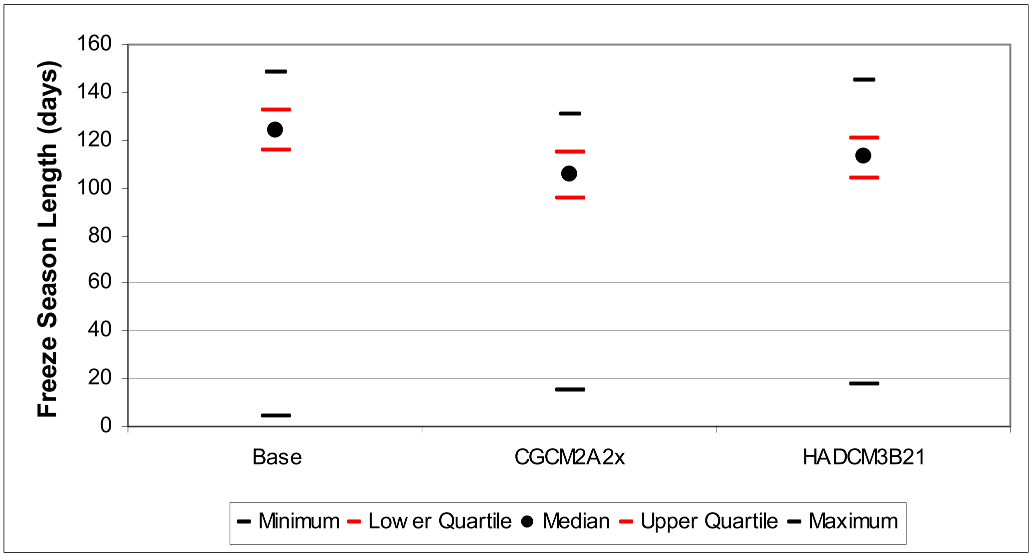


Figure 21. Freeze season length at the Winnipeg site under baseline and future scenarios.

The relative results for Winnipeg are similar to those analyzed for the other sites. In principle, warmer (or warming) climates are associated with greater lengths of time until critical FI is achieved and shorter periods until critical TI conditions are met. The median number of days to attain critical FI and TI are presented for all sites in Figures 22-23. With exception of Vancouver, where freeze thresholds were never satisfied in any of the baseline or future scenarios, the baseline median duration until freeze ranged from 58 days (Edmonton) to 116 days (St. John's). The corresponding baseline median number of days until thaw ranged from 131 (Kelowna) to 187 (Winnipeg).

Under the climate change scenarios studied, the number of days required to achieve critical FI and TI substantially increased and decreased, respectively. Assuming that CGCM2A2x conditions prevail, Kelowna, Windsor, Toronto and St. John's join Vancouver in the subset of sites where over 50 percent of all seasons fail to reach critical FI (and therefore TI); elsewhere the median duration before reaching critical FI increases from 4 days (North Bay) to 27 days (Halifax) while critical TI is achieved 10 days (Thunder Bay) to 31 days (Muskoka) earlier. Critical FI is reached under the HadCM3B21 scenario in at least 50 percent of seasons at all sites (except Vancouver). Under this scenario, median values for most sites increase by about 1-2 weeks relative to the baseline, except for Kelowna, Toronto, Windsor, Halifax and St. John's, where the median increased by up to 28 days. Critical TI is reached earlier in the season under the HadCM3B21 scenario at all sites except Kelowna, with median values ranging from 2 (Regina) to 14.5 (Halifax) less than the baseline. Median values increased at Kelowna by 3 days.

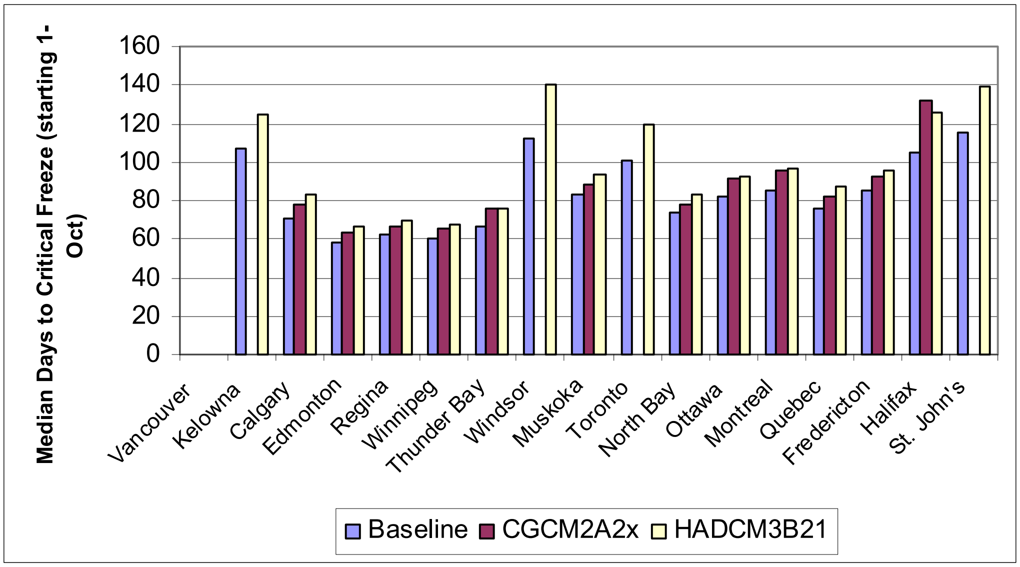


Figure 22. Median number of days required to reach the critical freeze index for all sites under baseline and future climate scenarios.

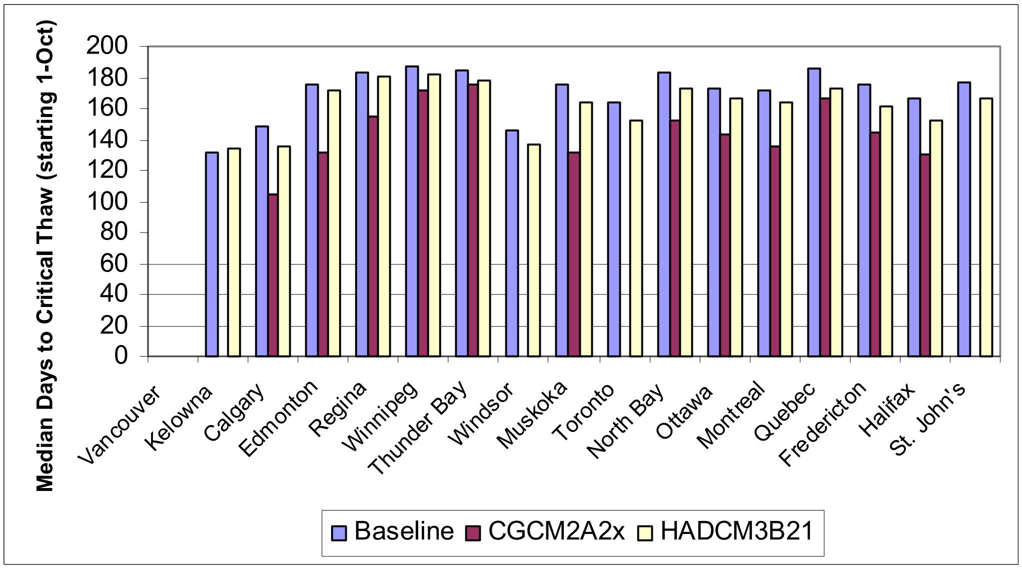


Figure 23. Median number of days required to reach the critical thaw index for all sites under baseline and future climate scenarios.

Combining the FI and TI results allows examination of changes in the duration of the freeze season. Mean and standard deviation freeze season lengths for all of the study sites are presented in Figures 24-25. Baseline mean values ranged from 0 days in Vancouver to 122 days in Winnipeg. Vancouver, Kelowna and Windsor were the only sites that experienced ‘freeze-free’ seasons under baseline conditions (Figure 26). Baseline standard deviations were similar for most sites (generally 15-20 days) except for Vancouver (no freeze seasons therefore no variability) and Calgary and Edmonton where the influence of periodic winter chinook conditions likely introduces greater variability.

The mean duration of the freeze season dropped substantially under the climate change scenarios examined, from roughly 8 percent at Winnipeg (HadCM3B21) to 98 percent at the St. John’s and Windsor sites (CGCM2A2x). The CGCM2A2x scenario consistently produced greater reductions in season length than the HadCM3B21 scenario. At least one in three seasons might be ‘freeze-free’ under the CGCM2A2x at the Vancouver, Kelowna, Toronto, Halifax and St. John’s sites while rare (~1 in 100) occurrences might also occur in Calgary, Muskoka and Ottawa. As expected, where the mean season length remained relatively long under the climate change scenarios (i.e., > 50 days), the standard deviation increased relative to the baseline. At sites where the mean season length was less than 50 days, the standard deviation under climate change was reduced relative to the baseline.

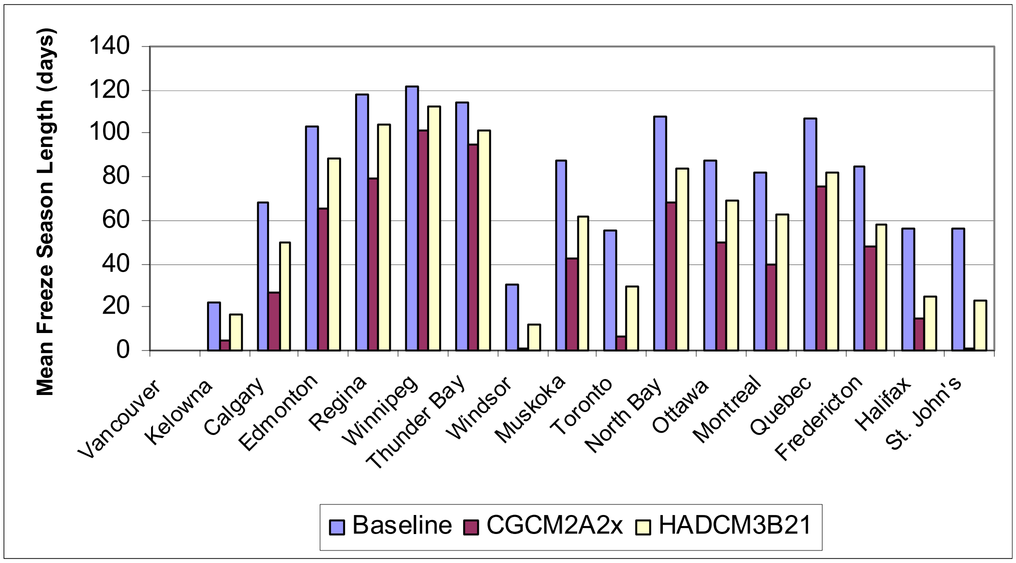


Figure 24. Mean freeze season length for all sites under baseline and future climate scenarios.

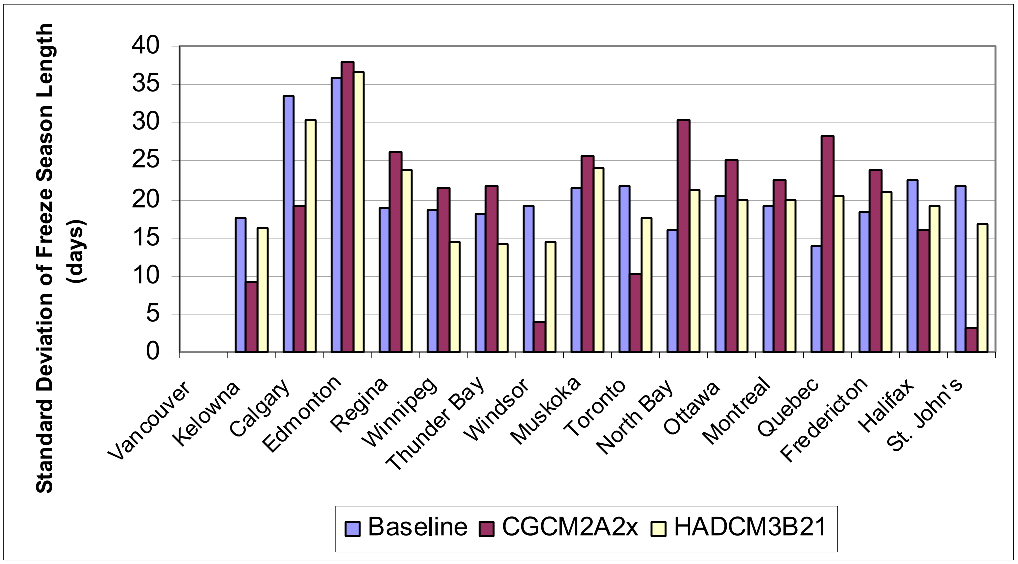


Figure 25. Standard deviation of freeze season length for all sites under baseline and future climate scenarios.

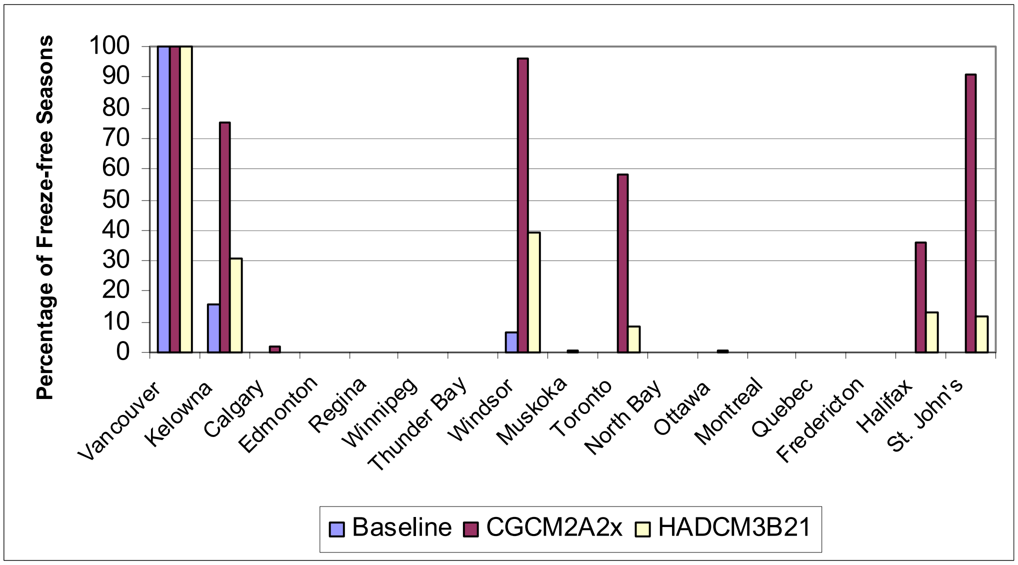


Figure 26. Occurrence of 'freeze-free' seasons for all sites under baseline and future climate scenarios.

3.2 Mechanistic-Empirical Pavement Design Guide (MEPDG) Application

The analysis of deterioration-relevant climate indicators revealed important implications that may result from climate change. However, the analysis was conducted independent of adjustments in several factors important in determining future patterns of deterioration, including other environmental variables (e.g., moisture) and those related to pavement structure, traffic, construction, and maintenance. The next set of case studies were designed to begin probing how the combination of such factors might affect the deterioration and performance of pavement sections over time as measured in terms of International Roughness Index (IRI), cracking (both load- and environment-related), and permanent deformation or rutting. The United States NCHRP/AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) and software were used to conduct the case studies, in part because of the interest in applying MEPDG in Canada. The Transportation Association of Canada has established a pooled fund study, with representation from all provincial departments of transportation as well as several large Canadian municipalities, in order to adapt the MEPDG for Canadian conditions.

Methods and Data

MEPDG is being developed to assist engineers in making decisions about asphalt and concrete pavement design and rehabilitations based on the application of state-of-the-practice mechanistic-empirical principles (NCHRP, 2004b). It allows the user to test various assumptions or scenarios concerning the variables noted above. In doing so, it provides output concerning the progression of pavement deterioration and performance and the adequacy of various pavement designs. The primary inputs required to run MEPDG include:

- general site and project information (e.g., design type, design life, construction and opening dates);
- analysis parameters (e.g., initial and terminal IRI, various forms of cracking, permanent deformation), critical values, and reliability (used to account for error in predictions of various distresses);
- traffic assumptions (e.g., lane alignment, baseline volume and future growth and distribution of truck traffic);
- pavement structure (e.g., specification of layer thicknesses and material properties); and
- climate (e.g., station location and elevation, groundwater table level, hourly temperature data).

A comprehensive description of all of these inputs and underlying mechanistic-empirical engineering principles, methods, and assumptions is beyond the scope of this report but is accessible from NCHRP (2004b). In addition to the incorporation of mechanistic approaches and the flexible user interface software, a key improvement in MEPDG from past design guides (e.g., AASHTO, 1993) is the development of the Enhanced Integrated Climate Model (EICM). The EICM is a one-dimensional coupled heat and moisture flow program that simulates changes in the behaviour and characteristics of pavement and subgrade material in response to climatic conditions (ARA Inc., 2004; NCHRP 2004b). This feature permits the calculation of transient distresses throughout the life of the pavement that are not tied to one particular test site or location. It must be noted that MEPDG is still being refined and improved and, although useful for exploratory studies such as the current investigation, it is not yet suitable as the primary decision input for pavement construction and rehabilitation (NCHRP, 2006a, 2006b).

Six test sites were selected from the Long Term Pavement Performance (LTPP) program (U.S. Department of Transportation, 2007) for analysis. The LTPP is composed of American, Canadian, and Danish test sites that are used to study the effect of different factors on the long term performance of pavements. There are approximately 129 test sites and 285 test sections across Canada (Table 8). Although each Canadian province is represented, almost 90 percent of sites are located in Alberta, Manitoba, Ontario, Quebec and Saskatchewan. The selected test sites are profiled in Table 9 and represent a range of pavement structures and materials that are found in Canada. Baseline traffic, pavement structure, and pavement material characteristics were extracted from the LTPP database (U.S. Department of Transportation, 2007) while climate data for the nearest suitable climate observing station were obtained from Environment Canada. The climate data consisted of hourly records of air temperature, relative humidity, cloud amount, and wind speed, and 6-hourly or daily records of precipitation for the period 1990-2005. Since MEPDG requires hourly data, the 6-hourly and daily precipitation amounts were distributed evenly across respective periods[13]. The percent sunshine variable required by MEPDG was derived from hourly cloud amount information. A detailed account of the material properties, default values, and assumptions used for each site is provided in Appendix C.

Table 8. Summary of LTPP test sites in Canada

Province	Total test sites	Percent of total test sites	Total test sections	Percent of total test sections
Alberta	19	14.7	32	11.2
British Columbia	4	3.1	9	3.2
Manitoba	23	17.8	85	29.8
New Brunswick	4	3.1	9	3.2
Newfoundland	3	2.3	5	1.8
Nova Scotia	1	0.8	5	1.8
Ontario	27	20.9	45	15.8
Prince Edward Island	3	2.3	9	3.2
Quebec	18	14.0	29	10.2
Saskatchewan	27	20.9	57	20.0
Total	**129**	**100.0**	**285**	**100.0**

A 20-year design life, commencing during the month of August, was chosen for the analysis of pavement performance for all MEPDG applications. The key analysis parameters and associated design thresholds are defined in Table 10. Limits, for example an IRI value of 2.7 m/km, are used as triggers for pavement repair, rehabilitation, and reconstruction decisions. A reliability factor is also assigned to each parameter to account for the various uncertainties in predicting future pavement deterioration. Results for the standard MEPDG output (average or 50 percent reliability) and 90 percent reliability level are reported in the current project. A reliability of 50 percent might represent a typical design criterion for a local or collector road while a reliability of 90 percent would be applied to a principal arterial or freeway.

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[13] Tests were conducted to determine the effect of different downscaling approaches. MEPDG results were found to be insensitive to different approaches to distributing precipitation amounts thus the simple method was adopted.

Table 9. Case study site characteristics

PROVINCE	British Columbia	Alberta	Manitoba	Ontario	Quebec	Newfoundland
LTPP Site Identification	82-1005	81-1804	83-6450	87-1806	89-1021	85-1808
Climatic Region	Wet-freeze	Dry-freeze	Wet-freeze	Wet-freeze	Wet-freeze	Wet-freeze
Climate station reference	1108447 Vancouver International Airport	3012205 Edmonton International Airport	5023222 Winnipeg International Airport	6158733 L.B. Pearson International Airport	7025250 P.E. Trudeau International Airport	8403506 St. John's Airport
Latitude (degrees)	49.2	53.5	50.0	43.7	45.5	47.6
Longitude (degrees)	-123.1	-113.5	-97.2	-79.6	-73.6	-52.7
Elevation (m)	4.3	723.3	238.7	173.4	35.7	140.5
Traffic						
2-way AADTT**	1240	1420	498	2744	1912	256
Percentage of truck traffic in design lane	100	100	100	100	100	100
Pavement Structure						
Layer 1: Asphalt (cm)	9.7	8.4	5.1	4.1	5.3	8.1
Layer 2: Asphalt (cm)	-	-	5.6	10.2	-	-
Layer 3: Base (cm)	23.9	32.8	11.4	18.0	7.9	11.4
Layer 4: Subbase (cm)	31.0	24.6	10.7	79.2	38.1	43.2
Pavement Material						
Base	Crushed gravel	Crushed gravel	Crushed gravel	Crushed gravel	Crushed gravel	Crushed gravel
Subbase	River-run gravel	River-run gravel	River-run gravel	A-4	Crushed gravel	Crushed gravel
Subgrade**	SM	SM	SM	ML	SP	GW

* Average Annual Daily Truck Traffic

** SM-silty sand or silty gravelly sand, GW-gravel or sandy gravel, well-graded; ML-silts, sandy silts, or diatomaceous soils; SP-sand or gravelly sand, poorly graded

MEPDG was applied to the case study sites in order to evaluate changes in pavement performance. A series of analyses were conducted to understand the separate and combined influence of climate and climate change, pavement structure, and traffic growth as described below:

1) *Influence of climate and climate change alone*. Monthly scenarios for the CGCM2A2x and HadCM3B21 climate modeling experiments that were used in the freeze-thaw and PG analyses discussed previously (see Appendix A) were applied to the MEPDG control data at each site assuming no change in baseline traffic volume.
2) *Influence of structure type and baseline traffic volume*. The various structural types and baseline traffic volumes represented in the 6 case sites (see Appendix C) were evaluated using baseline and CGCM2A2x climate change scenarios for one location (Winnipeg, Manitoba).
3) *Combined influence of traffic growth and climate change*. Experiments from analysis 1 were re-run assuming a 4 percent increase in Annual Average Daily Truck Traffic (AADTT) and compared.

In total, 48 runs of MEPDG were completed in this analysis. Results are described in the following section.

Table 10. Analysis parameters used in MEPDG application (20-year design life)

Analysis Parameter	Limit/threshold	Reliability (%)
International Roughness Index (IRI)* (m/km)	2.7	50/90
AC longitudinal cracking (m/km)	378.8	50/90
AC alligator cracking (% surface coverage)	25.0	50/90
AC transverse cracking (m/km)	189.4	50/90
AC deformation (mm)	6.4	50/90
Total deformation (mm)**	19.1	50/90

*initial IRI=0.79 m/km **for all layers (asphalt, base, subbase, subgrade)

Influence of Climate and Climate Change Alone

Potential mid-century changes in precipitation and temperature relative to the climate model baseline (1961-1990) were extracted for each site and used to adjust hourly values in the baseline time series. For illustration, the scenarios applied to the Manitoba (Winnipeg) site are graphed in Figure 27. Significant variation is observed between months and between the CGCM2A2x and HadCM3B21 scenarios for both mean temperature (-0.2°C to +6.7°C) and precipitation (-18.2% to +50.1%) variables. The scenario data for all sites are documented in Appendix A. Only the climatic inputs were adjusted for the first analysis—baseline pavement structure and traffic variables remained constant as defined in Table 8.

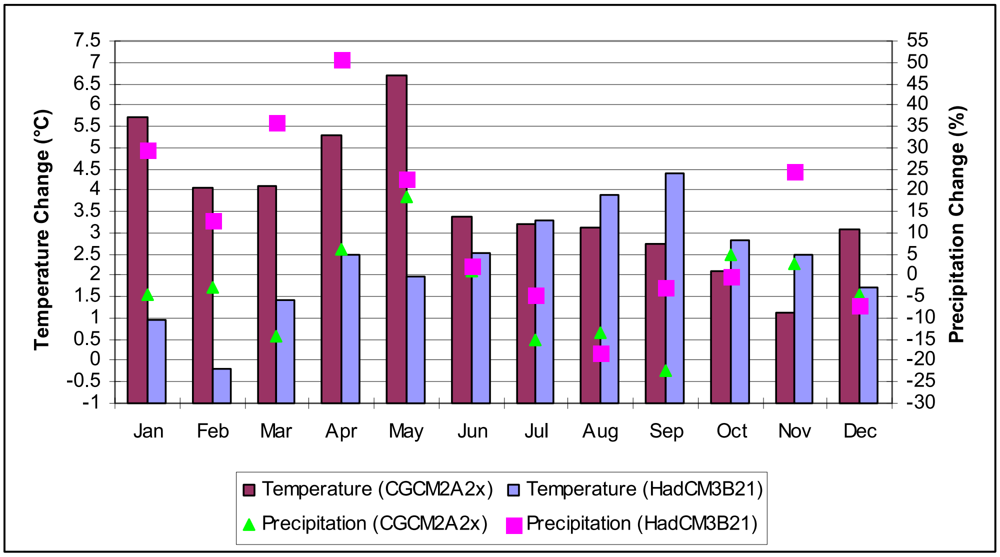

Figure 27. CGCM2A2x and HadCM3B21 temperature and precipitation change scenarios (2050s) for the Manitoba site (Winnipeg)

Changes in Pavement Deterioration

Baseline and climate change scenario results for all performance parameters and all sites are summarized in Table 11. Baseline values (reported in either m/km or mm) and relative percent changes for each climate scenario represent conditions at the completion of the 20-year design life (i.e., terminal results). Performance parameter values under baseline conditions varied considerably among the sites. For example, IRI values ranged from 1.55 m/km at the B.C. site to 2.54 m/km at the Manitoba site, reflecting differences in structure, traffic loads, and climate. The only distress variable that remained relatively constant across most sites was transverse cracking. Initiated by extreme cold temperatures, transverse cracking lengths quickly reached maximum values of about 400 m/km at all sites except the British Columbia (Vancouver) location which experiences the mildest climate among the sites analyzed. This result likely indicates an over-prediction of this particular form of cracking and underlying issues with the distress algorithms and assumptions within the MEPDG. In practice, it is believed that by adopting the PGAC, a significant portion of the transverse thermal cracking can be addressed.

Table 11. MEPDG pavement performance results for all sites (climate change alone)

Case Study Site	IRI (% change)*	Cracking (% change)*			Deformation (% change)*	
		Longitudinal	Alligator	Transverse	AC	Total**
British Columbia (baseline)	1.55 m/km	6.8 m/km	0.7%	19.1 m/km	2.1 mm	10.7 mm
CGCMA2x	-0.7	-1.9	7.5	-96.9	16.9	3.8
HadCM3B21	1.9	0.0	10.5	87.1	19.3	4.8
Alberta (baseline)	2.34 m/km	551.1 m/km	28.9%	399.6 m/km	5.5 mm	19.0 mm
CGCMA2x	1.3	9.3	11.4	0.0	22.7	-0.5
HadCM3B21	1.7	5.8	7.3	0.0	31.8	4.7
Manitoba (baseline)	2.54 m/km	450.8 m/km	48.2%	399.6 m/km	2.9 mm	14.5 mm
CGCMA2x	2.0	2.9	6.0	0.0	35.9	-0.9
HadCM3B21	2.4	2.9	5.8	0.0	34.1	2.3
Ontario (baseline)	1.92 m/km	33.3 m/km	4.6%	399.6 m/km	4.2 mm	12.1 mm
CGCMA2x	1.0	1.7	10.5	0.0	27.0	9.0
HadCM3B21	1.6	5.7	13.1	0.0	28.9	10.3
Quebec (baseline)	2.12 m/km	1647.7 m/km	0.5%	399.6 m/km	5.3 mm	21.8 mm
CGCMA2x	-0.9	0.0	4.4	0.0	13.9	-3.2
HadCM3B21	-0.5	-0.7	2.2	0.0	16.8	-0.8
Newfoundland (baseline)	1.79 m/km	5.3 m/km	0.1%	399.6 m/km	1.2 mm	9.1 mm
CGCMA2x	-1.1	5.4	14.3	0.0	21.9	-1.1
HadCM3B21	-0.6	4.3	14.3	0.0	21.9	0.6

*results rounded to one decimal (except absolute IRI values)
**includes all layers (asphalt, base, subbase, and subgrade)

As noted, the primary objective of the MEPDG analysis was to evaluate relative, not absolute, changes in pavement performance between baseline and future climate change scenarios. The most significant differences between baseline and future climate scenarios were observed for the asphalt concrete (AC) rutting parameter. AC rutting increased at all sites, from a minimum of 14 percent at the Quebec site (CGCM2A2x scenario) to a maximum of 36 percent at the Manitoba location (CGCM2A2x scenario). Increases relative to the baseline were similar (within in a few percent) for both climate change scenarios except for the Alberta site where the HadCM3B21 scenario produced about 9 percent more AC rutting than the CGCM2A2x scenario. Much less change was observed for the total rutting parameter which suggests that deformation was reduced in the lower layers thus compensating for AC rutting. Changes in total rutting ranged from a reduction of 3 percent at the Quebec site (CGCM2A2x scenario) to an increase of about 10 percent at the Ontario site (HadCM3B21 scenario). As with rutting in the AC layer, the changes relative to the baseline for both climate scenarios were consistently within a few percentage points of each other. However, the direction of the changes differed for the Alberta, Manitoba, and Newfoundland sites with slight reductions under the CGCM2A2x climate and small increases in total rutting under HadCM3B21 conditions.

In general, modest increases under climate change conditions were observed for the various cracking parameters relative to the baseline. A slight rise in longitudinal cracking was reported for most sites except for British Columbia and Quebec, where no change or small decreases were recorded. Somewhat larger increases, from 2 (Quebec site, HadCM3B21 scenario) to 14 (Newfoundland site, CGCM2A2x scenario) percent, were observed for alligator cracking. The high relative changes at the Newfoundland site are associated with very small absolute changes in baseline cracking though. In terms of transverse cracking, deterioration reached maximum values of approximately 400 m/km under each of the climate change scenarios tests as it did for the baseline run at 5 of the 6 sites, resulting in a zero net change. At the warmer British Columbia site, transverse cracking was virtually eliminated under the CGCM2A2x scenario (97 percent reduction) and almost doubled (87 percent increase) under HadCM3B21 conditions. Despite issues with this form of cracking in MEPDG, the British Columbia results for the CGCM2A2x scenario are intuitively consistent with our understanding of cracking processes and may be more representative of future patterns in much of southern Canada than results from the other sites. The increase in cracking stemming from the HadCM3B21 scenario is coincident with a regional area of relative cooling during the early winter period that is somewhat anomalous when compared to most areas in Canada.

The least amount of change between baseline and future climate scenarios was observed for the IRI performance parameter. Very small changes (i.e., less than 3 percent) in terminal IRI were observed under the CGCM2A2x and HadCM3B21 climate scenarios examined. Slight decreases in roughness were apparent at the two eastern (both scenarios) and British Columbia (CGCM2A2x scenario) sites while slight increases were apparent at the remaining locations.

Changes in the Timing of Maintenance Requirements

Terminal values of performance indicate the state of a pavement at the end of its service life. Just as important is the time-dependent evolution of deterioration relative to maintenance, rehabilitation and reconstruction thresholds. Parameter limits associated with a 20-year design life as defined in Table 10 were used to explore changes in the timing of maintenance requirements. Figures 28a-33b summarize when these limits were exceeded at the various sites for baseline and climate change scenarios. Figures denoted with an "a" or "b" show results obtained at the 50 and 90 percent reliability levels, respectively.

At the 50 percent reliability level, 11 out of 36 possible parameter limits (6 sites x 6 parameters) were exceeded at some point during the 20-year design life under baseline climate conditions.

Thresholds were not achieved for any parameter at the British Columbia site or for the IRI and AC rutting parameters at any of the sites. Total rutting (all layers), longitudinal cracking, and alligator cracking criteria were met at 1 (Quebec, 10.9 years), 3 (Alberta, 14.8 years; Manitoba, 17.1 years; Quebec, 2.8 years), and 2 (Alberta, 17 years; Manitoba, 8.1 years) sites, respectively. With the exception of British Columbia, all sites reached transverse cracking thresholds early during the first winter season. As noted previously, transverse cracking would be negligible based on a proper PG selection.

After analyzing the climate change scenarios, two parameter limits (13 of 36) were added to those exceeded under baseline conditions. As with the baseline, no parameter limits were reached for the British Columbia site and IRI criteria were not met at any site under the CGCM2A2x or HadCM3B21 climate change scenarios. For most other parameters and sites, the general influence of climate change was to reduce the amount of time until maintenance, rehabilitation or reconstruction thresholds were met. The reductions ranged from less than 1 year (Manitoba, alligator cracking, CGCM2A2x and HadCM3B21 scenarios) to over 5 years (Alberta, AC rutting, HadCM3B21 scenario). Results for the Quebec site (total rutting, longitudinal cracking) and for the transverse cracking parameter were just the opposite, with climate change inducing a slight delay in the timing when limits were reached.

General results similar to those noted for the 50 percent reliability level were also realized at the 90 percent level. As expected, the more stringent failure criterion produced a greater number of exceedances (16 out of 30[14]) much earlier during the design life under baseline conditions, but the overall patterns remained similar. For example, no limits were reached at the British Columbia site. While IRI thresholds were not met at any site at the 50 percent reliability level, 3 sites exceeded thresholds at 90 percent reliability (Alberta, 14.3 years; Manitoba, 12.4 years; Quebec, 17.8 years). Total rutting, longitudinal cracking, and alligator cracking criteria were met at 2 (Alberta, 8 years; Quebec, 4.3 years), 4 (Alberta, 1.8 years; Manitoba, 1.8 years; Ontario, 11.8 years; Quebec, 0.7 years), and 2 (Alberta, 5.2 years; Manitoba, 2.1 years) sites, respectively. All sites other than British Columbia reached transverse cracking thresholds early during the first winter season.

The parameter limits reached under the climate change scenarios were identical to those achieved under baseline conditions at the 90 percent reliability level. Once again, no thresholds were exceeded at the British Columbia site. At the remaining sites and consistent with observations at the 50 percent reliability level, the general effect of the climate change scenarios at the 90 percent reliability level was to shorten the length of time before IRI, longitudinal cracking, and alligator cracking thresholds were met and to delay the timing of reaching transverse cracking and total rutting limits. This pattern was not followed at the Alberta site, where total rutting thresholds were met earlier under the HadCM3B21 scenario, and at the Quebec site where additional time was required to meet IRI thresholds under both climate change scenarios. In all cases, the relative change between the baseline and climate change scenarios was less than one year.

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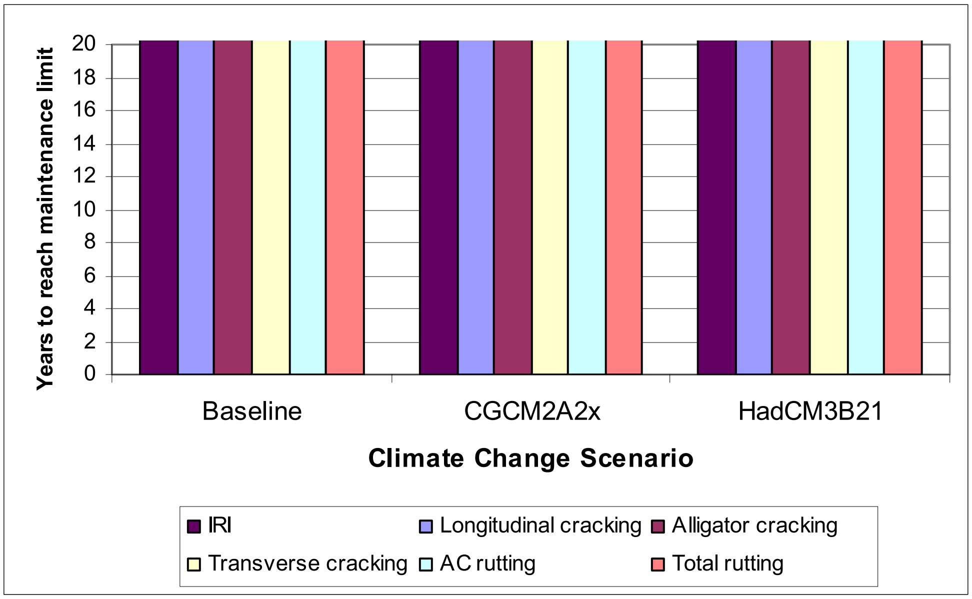
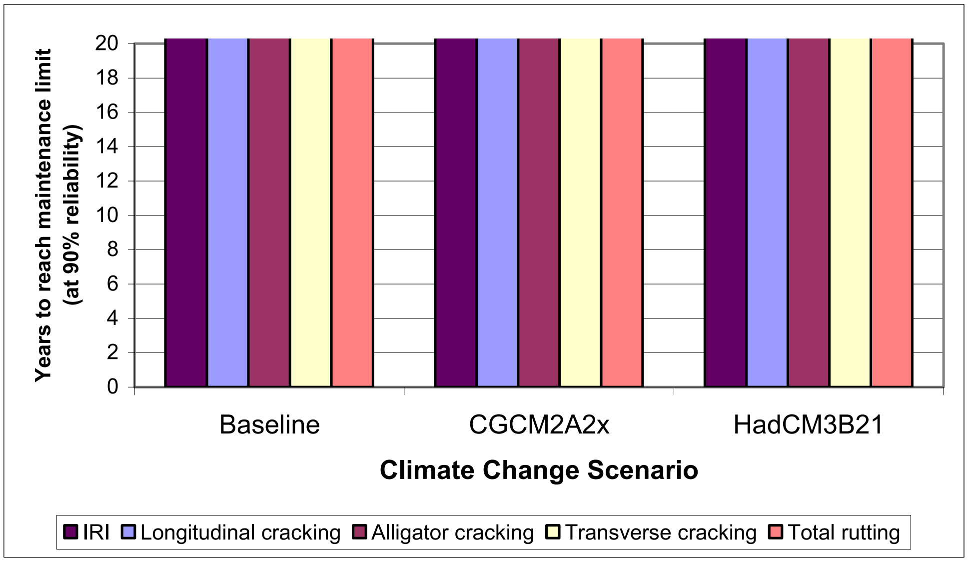
[14] MEPDG does not provide an output for the AC rutting parameter for reliability levels other than the standard 50 percent level thus the total number of parameter limits is 30 (6 sites x 5 parameters).



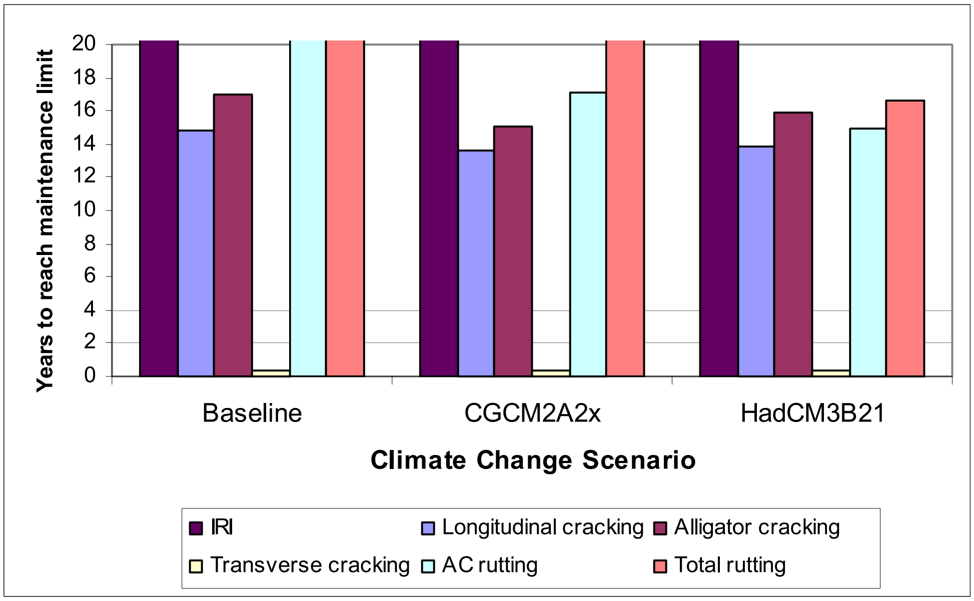
*values greater than 20 years indicate parameter limits not reached during design life

Figure 28a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the British Columbia site (Vancouver)



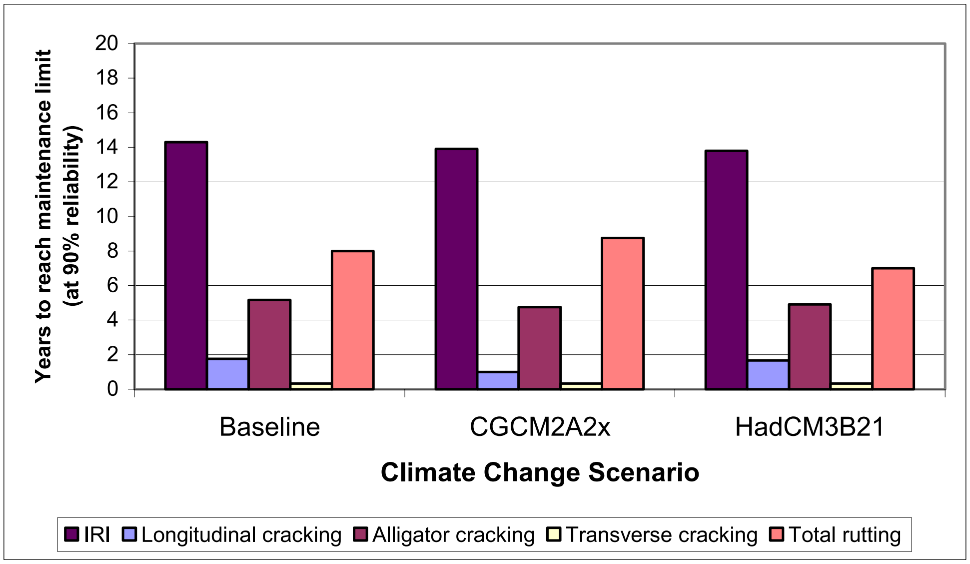
*values greater than 20 years indicate parameter limits not reached during design life

Figure 28b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the British Columbia site (Vancouver)



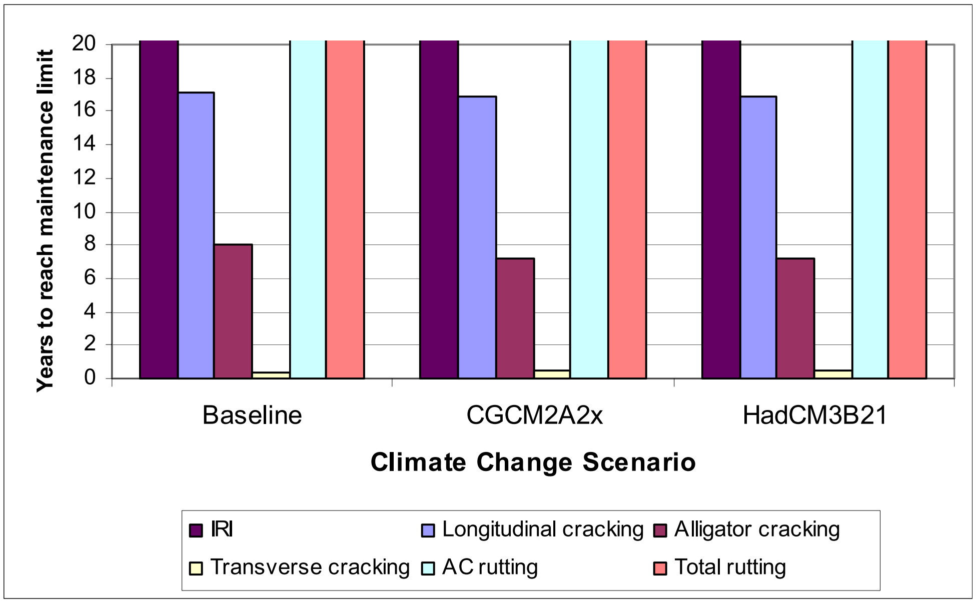
*values greater than 20 years indicate parameter limits not reached during design life

Figure 29a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Alberta site (Edmonton)



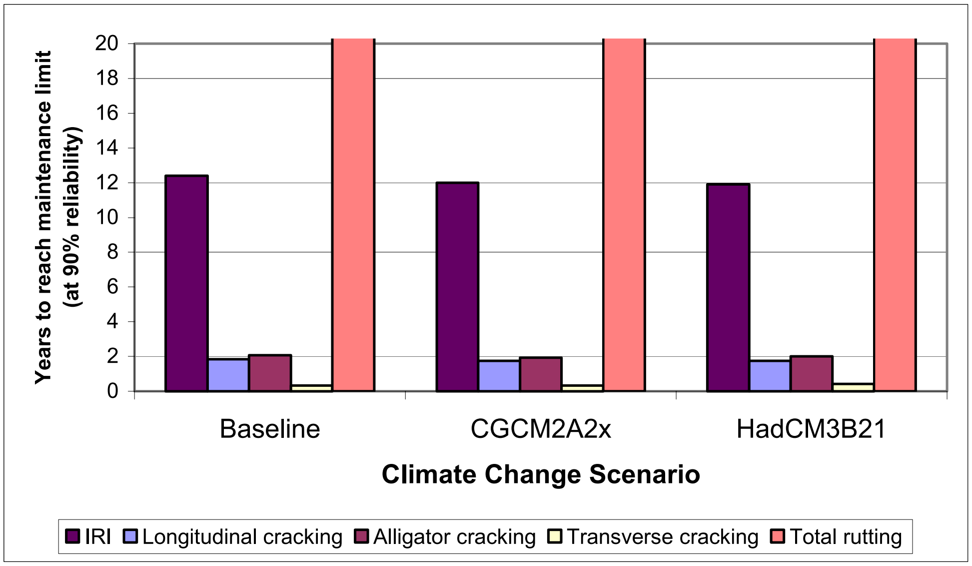
*values greater than 20 years indicate parameter limits not reached during design life

Figure 29b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Alberta site (Edmonton)



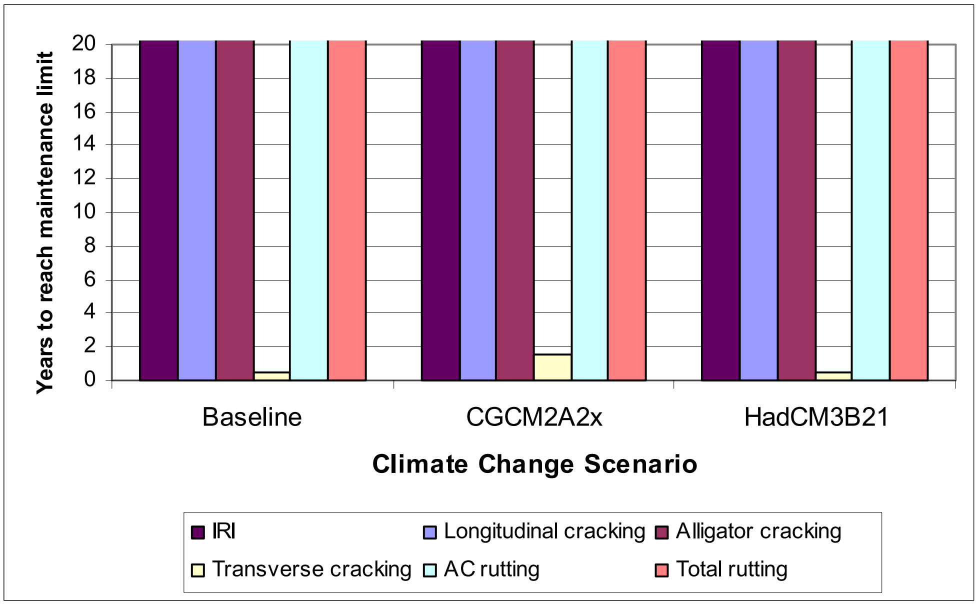
*values greater than 20 years indicate parameter limits not reached during design life

Figure 30a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Manitoba site (Winnipeg)



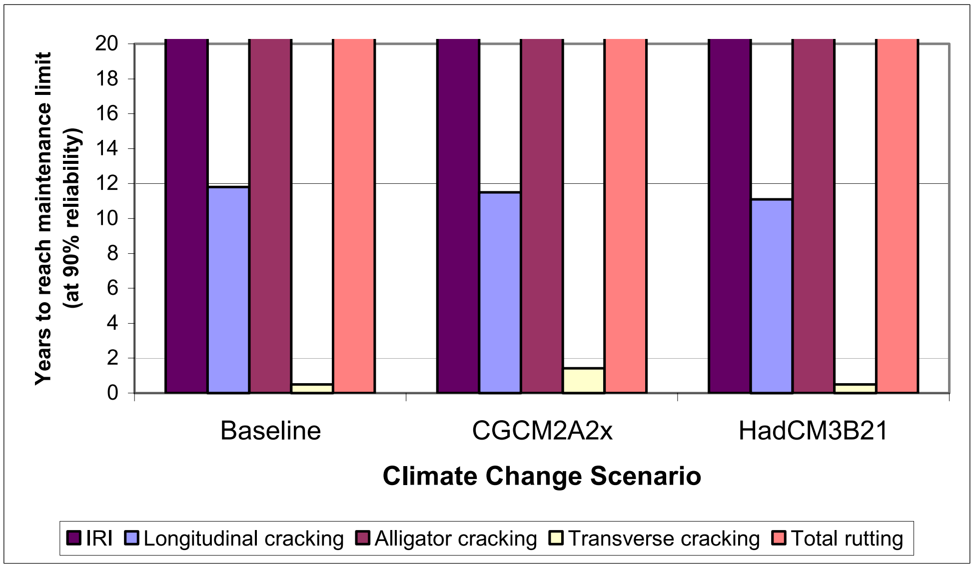
*values greater than 20 years indicate parameter limits not reached during design life

Figure 30b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Manitoba site (Winnipeg)



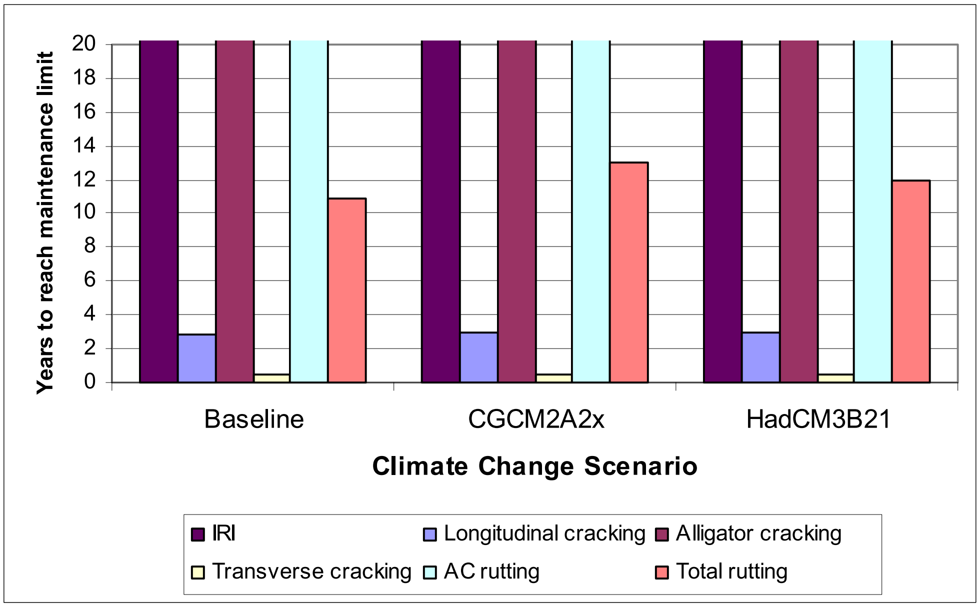
*values greater than 20 years indicate parameter limits not reached during design life

Figure 31a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Ontario site (Toronto)



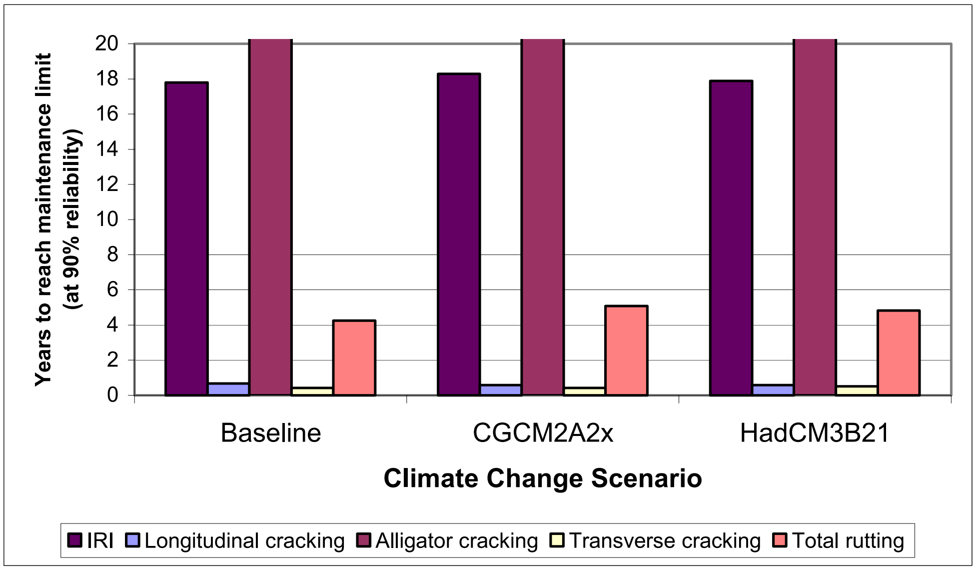
*values greater than 20 years indicate parameter limits not reached during design life

Figure 31b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Ontario site (Toronto)



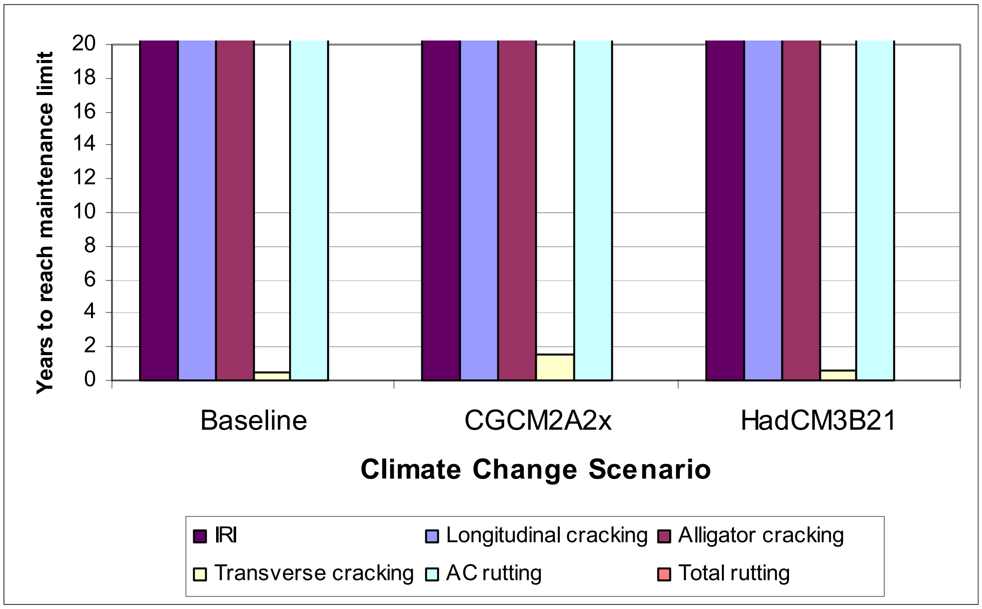
*values greater than 20 years indicate parameter limits not reached during design life

Figure 32a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Quebec site (Montreal)



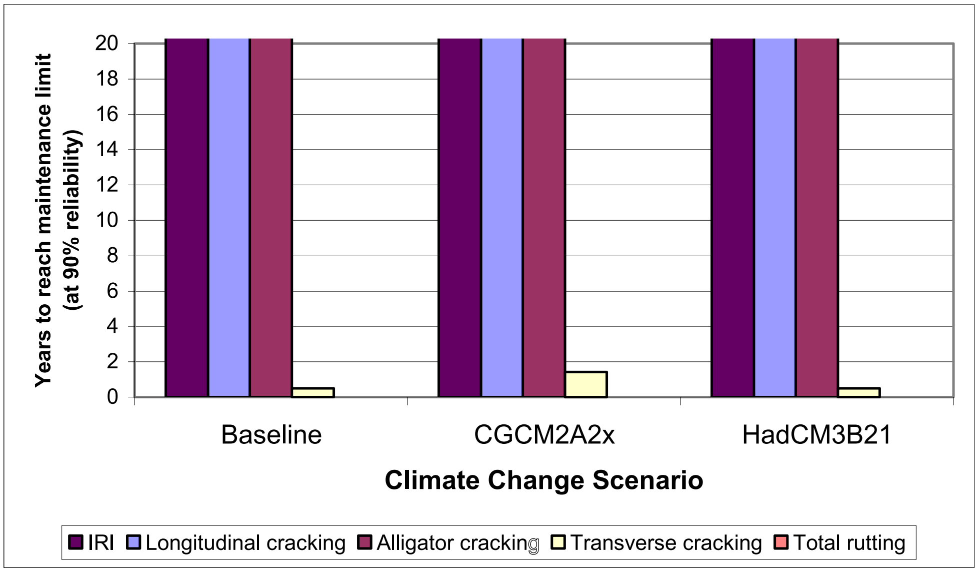
*values greater than 20 years indicate parameter limits not reached during design life

Figure 32b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Quebec site (Montreal)



*values greater than 20 years indicate parameter limits not reached during design life

Figure 33a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Newfoundland site (St. John's)



*values greater than 20 years indicate parameter limits not reached during design life

Figure 33b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Newfoundland site (St. John's)

Influence of Pavement Structure and Baseline Traffic

In addition to showing the relative impact of the climate change scenarios, the results from Table 11 suggest that other variables, especially pavement structure and baseline traffic, may be significant factors shaping pavement deterioration. To better understand the role of structural and baseline traffic assumptions, all of the structures represented in the case study were run through MEPDG under the same baseline climate and CGCM2A2x climate change scenario (Winnipeg, Manitoba). Terminal deterioration results for IRI, longitudinal cracking, alligator cracking, AC rutting, and total rutting indicators are presented in Figures 34-38. The most striking observation is that relative differences between various structure and traffic situations, as represented among the set of sites in the study, are much greater than those associated with changes in climate at the Winnipeg site. In particular, longitudinal and alligator cracking seem insensitive to changes in climate relative to variations in structure and traffic levels while AC rutting appears to be the most sensitive to shifts in climate among the indicators studied. Both the magnitude and direction of change are influenced by structural and traffic assumptions. For example, while the CGCM2A2x results for AC rutting were consistently higher than the baseline climate for all structures, relative rutting increased more for the Alberta structure (36 percent) than for the Newfoundland structure (18 percent). Changes in IRI, total rutting, and longitudinal cracking between the baseline climate and CGCM2A2x scenario were inconsistent across the structure types, increasing in some instances (e.g., IRI for Alberta, Manitoba and Ontario structures) and decreasing in others (e.g., IRI for British Columbia, Quebec and Newfoundland structures).

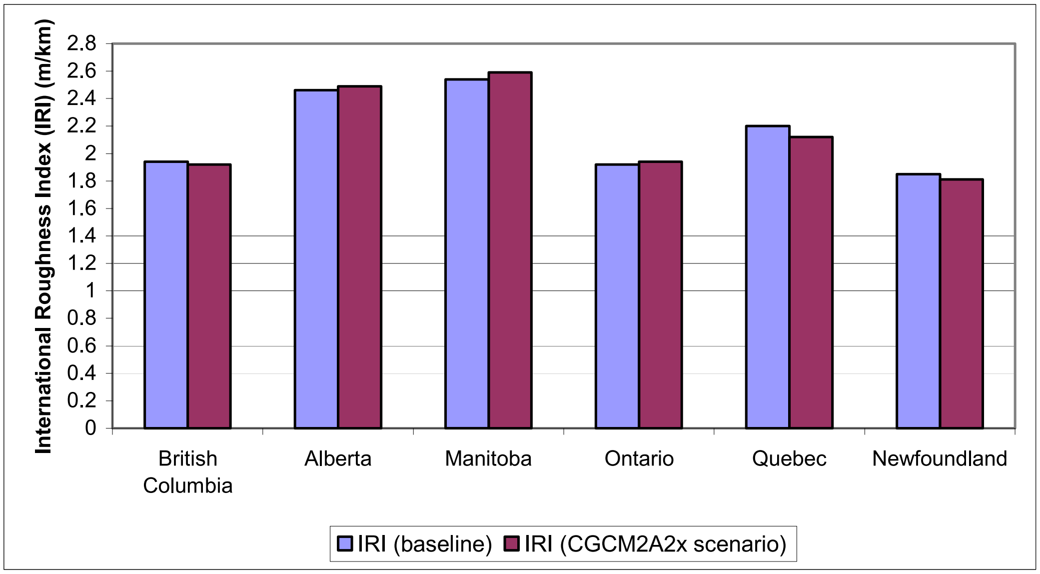


Figure 34. Changes in IRI resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

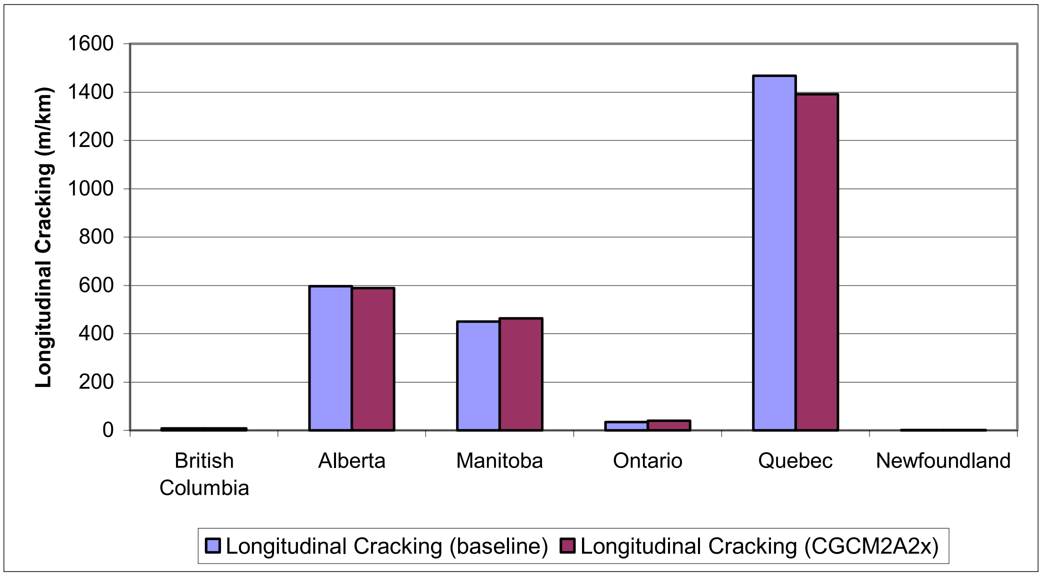


Figure 35. Changes in longitudinal cracking resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

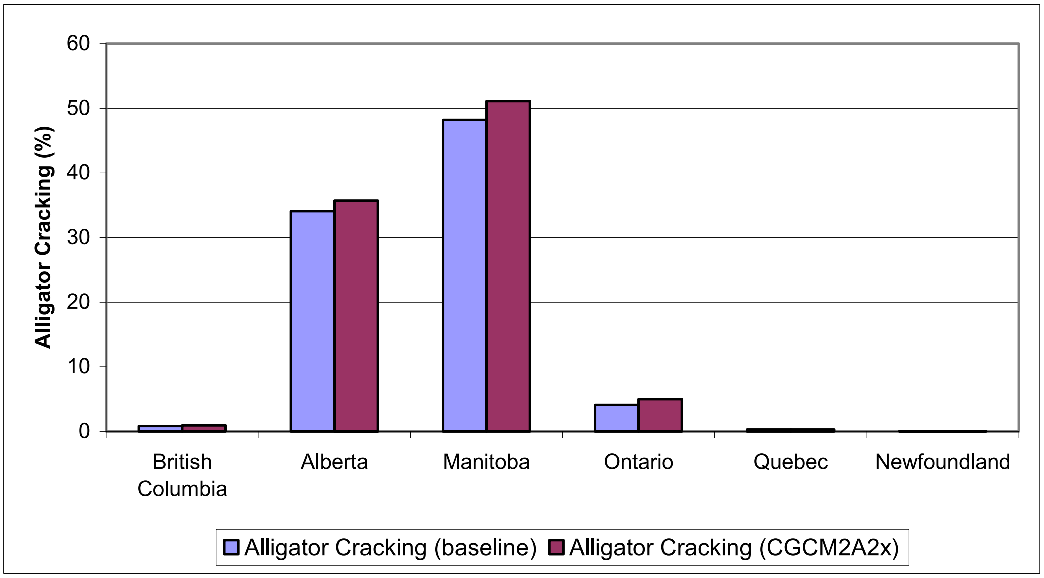


Figure 36. Changes in alligator cracking resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

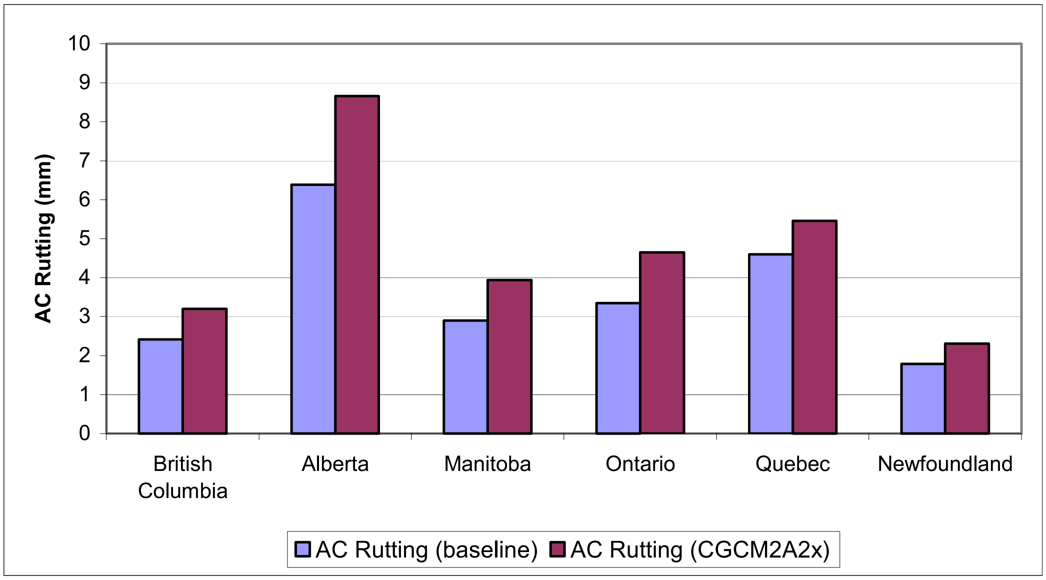


Figure 37. Changes in AC rutting resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

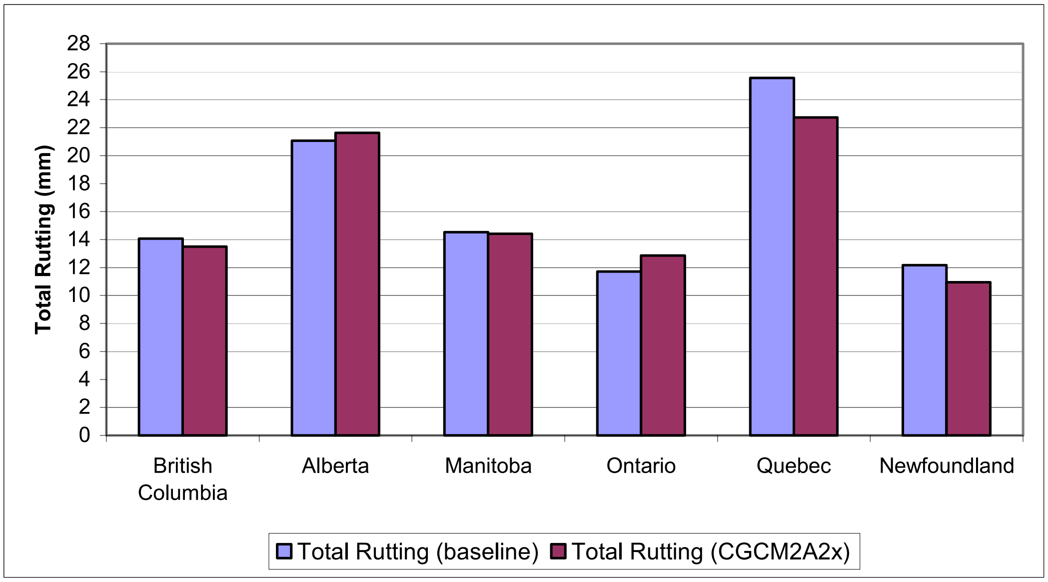


Figure 38. Changes in total rutting resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

Combined Influence of Climate Change and Traffic Growth

While many structural factors or assumptions remain constant throughout the pavement design life, the amount of traffic does not. Loads in most regions of southern Canada are likely to increase through time in conjunction with trends in population and economic growth. In order to understand the effect of increasing traffic on baseline results, the MEPDG control data sets for each site were run again assuming a 4 percent per annum compound growth in Average Annual Daily Truck Traffic (AADTT). Four percent is a best practice value and is suitable for estimating AADTT growth over a 20-year design life. The resulting cumulative growth in heavy trucks for each site is illustrated in Figures 39-40.

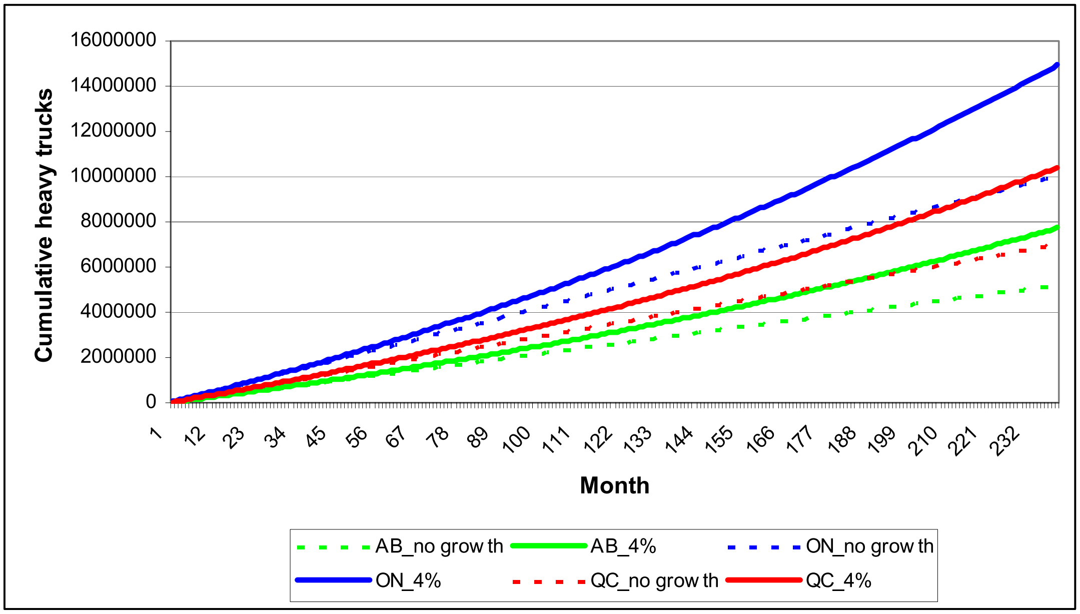


Figure 39. Changes in cumulative heavy trucks for no growth and 4 percent annual compound growth scenarios at Alberta, Ontario, and Manitoba sites

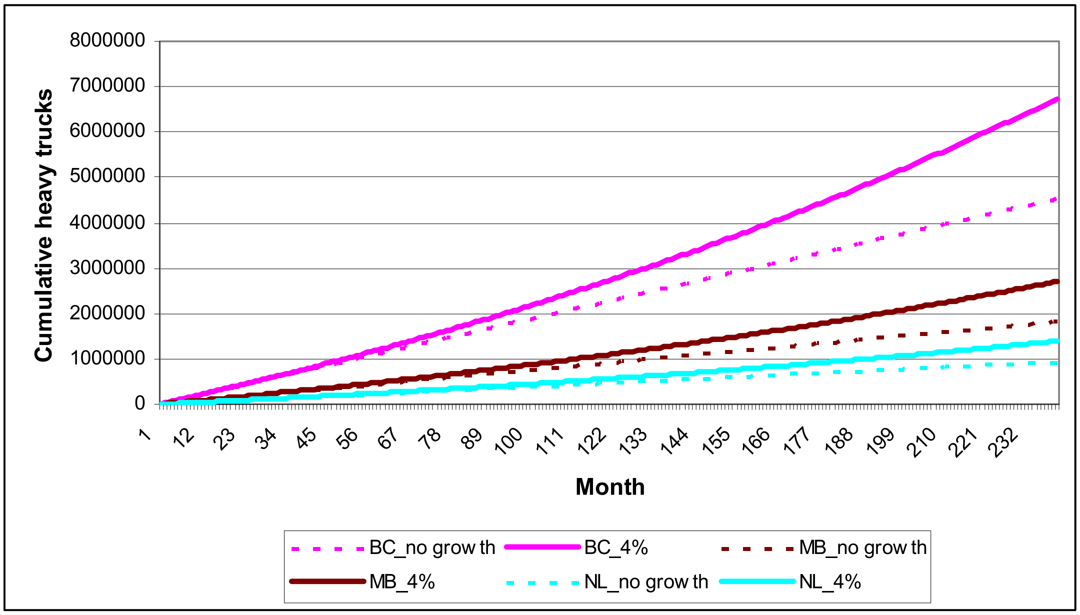


Figure 40. Changes in cumulative heavy trucks for no growth and 4 percent annual compound growth scenarios at Alberta, Ontario, and Manitoba sites

Results for both the static no growth and annual 4 percent growth scenarios, under baseline climate and climate change conditions, are presented in Tables 12-17. The tables are organized by performance parameter and include estimates of terminal deterioration and the timing of achieving maintenance-related thresholds. Terminal deterioration is expressed in absolute terms and as a relative percent of the control (no traffic growth, baseline climate) for each scenario combination. The timing of reaching critical thresholds is specified for both 50 and 90 percent reliability levels as determined by MEPDG.

As expected, greater loads induced greater terminal deterioration and earlier achievement of maintenance-related thresholds for all pavement distress indicators except for transverse cracking which is influenced primarily by climatic and material factors. Relative increases in AC and total rutting were consistent across all sites although somewhat less than the relative increase in terminal truck growth (49 percent). Increases in IRI and especially longitudinal and alligator cracking exhibited more variability across the sites. This observation is likely a function of the variability in pavement structures and baseline traffic volumes that was previously discussed.

The impacts of the CGCM2A2x and HadCM3B21 climate change scenarios relative to the no growth baseline that were described in detail for the first set of MEPDG analyses were generally unaffected by the application of a 4 percent per annum growth in traffic. While higher traffic loads increased the absolute deterioration and resulted in earlier achievement of maintenance-related thresholds, the relative changes from the CGCM2A2x or HadCM3B21 scenario to respective no growth and 4 percent growth traffic baseline climate scenarios did not deviate by more than 3 percent. This suggests that there is no significant synergistic effect between climate and traffic growth, as simulated through MEPDG.

Table 12. IRI performance results for all sites and scenarios

Case Study Site	International Roughness Index (IRI) m/km	Change relative to control (%)*	Years to 2.7 m/km maintenance threshold (50/90% reliability)* **
British Columbia			
CONTROL: Baseline climate + no traffic growth	1.55	-	nr/nr
CGCM2A2x + no traffic growth	1.54	-0.7	nr/nr
HadCM3B21 + no traffic growth	1.58	1.9	nr/nr
Baseline climate + 4% annual AADTT growth	1.58	1.9	nr/nr
CGCM2A2x + 4% annual AADTT growth	1.57	1.3	nr/nr
HadCM3B21 + 4% annual AADTT growth	1.61	3.9	nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	2.34	-	nr/14.3
CGCM2A2x + no traffic growth	2.37	1.3	nr/13.9
HadCM3B21 + no traffic growth	2.38	1.7	nr/13.8
Baseline climate + 4% annual AADTT growth	2.53	8.1	nr/12.9
CGCM2A2x + 4% annual AADTT growth	2.59	10.7	nr/12.3
HadCM3B21 + 4% annual AADTT growth	2.60	11.1	nr/12.1
Manitoba			
CONTROL: Baseline climate + no traffic growth	2.54	-	nr/12.4
CGCM2A2x + no traffic growth	2.59	2.0	nr/12.0
HadCM3B21 + no traffic growth	2.60	2.4	nr/11.9
Baseline climate + 4% annual AADTT growth	2.85	12.2	18.9/11.0
CGCM2A2x + 4% annual AADTT growth	2.92	15.0	18.2/10.8
HadCM3B21 + 4% annual AADTT growth	2.95	16.1	18.1/10.8
Ontario			
CONTROL: Baseline climate + no traffic growth	1.92	-	nr/nr
CGCM2A2x + no traffic growth	1.94	1.0	nr/nr
HadCM3B21 + no traffic growth	1.95	1.6	nr/nr
Baseline climate + 4% annual AADTT growth	1.97	2.6	nr/nr
CGCM2A2x + 4% annual AADTT growth	1.99	3.7	nr/nr
HadCM3B21 + 4% annual AADTT growth	2.01	4.7	nr/nr
Quebec			
CONTROL: Baseline climate + no traffic growth	2.12	-	nr/17.8
CGCM2A2x + no traffic growth	2.10	-0.9	nr/18.3
HadCM3B21 + no traffic growth	2.11	-0.5	nr/17.9
Baseline climate + 4% annual AADTT growth	2.19	3.3	nr/16.8
CGCM2A2x + 4% annual AADTT growth	2.16	1.9	nr/17.1
HadCM3B21 + 4% annual AADTT growth	2.18	2.8	nr/16.8
Newfoundland			
CONTROL: Baseline climate + no traffic growth	1.79	-	nr/nr
CGCM2A2x + no traffic growth	1.77	-1.1	nr/nr
HadCM3B21 + no traffic growth	1.78	-0.6	nr/nr
Baseline climate + 4% annual AADTT growth	1.81	1.1	nr/nr
CGCM2A2x + 4% annual AADTT growth	1.79	0.0	nr/nr
HadCM3B21 + 4% annual AADTT growth	1.80	0.6	nr/nr

*results rounded to one decimal place
**nr (not reached during 20-year design life)

Table 13. Longitudinal cracking performance results for all sites and scenarios

Case Study Site	**Longitudinal Cracking***		
	m/km	**Change relative to control (%)**	**Years to 378.8 m/km maintenance threshold (50/90% reliability)****
British Columbia			
CONTROL: Baseline climate + no traffic growth	6.8	-	nr/nr
CGCM2A2x + no traffic growth	6.7	-1.9	nr/nr
HadCM3B21 + no traffic growth	6.8	0.0	nr/nr
Baseline climate + 4% annual AADTT growth	12.0	76.3	nr/nr
CGCM2A2x + 4% annual AADTT growth	11.7	72.9	nr/nr
HadCM3B21 + 4% annual AADTT growth	12.0	76.8	nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	551.1	-	14.8/1.8
CGCM2A2x + no traffic growth	602.3	9.3	13.7/1.0
HadCM3B21 + no traffic growth	583.3	5.8	13.8/1.7
Baseline climate + 4% annual AADTT growth	818.2	48.5	11.8/1.8
CGCM2A2x + 4% annual AADTT growth	873.1	58.4	10.8/1.0
HadCM3B21 + 4% annual AADTT growth	854.2	55.0	11.1/1.7
Manitoba			
CONTROL: Baseline climate + no traffic growth	450.8	-	17.1/1.8
CGCM2A2x + no traffic growth	464.0	2.9	16.8/1.8
HadCM3B21 + no traffic growth	464.0	2.9	16.9/1.8
Baseline climate + 4% annual AADTT growth	683.7	51.7	13.1/1.8
CGCM2A2x + 4% annual AADTT growth	697.0	54.6	12.9/1.8
HadCM3B21 + 4% annual AADTT growth	698.9	55.0	12.9/1.8
Ontario			
CONTROL: Baseline climate + no traffic growth	33.3	-	nr/11.8
CGCM2A2x + no traffic growth	33.9	1.7	nr/11.5
HadCM3B21 + no traffic growth	35.2	5.7	nr/11.1
Baseline climate + 4% annual AADTT growth	58.9	76.7	nr/9.8
CGCM2A2x + 4% annual AADTT growth	59.7	79.0	nr/9.4
HadCM3B21 + 4% annual AADTT growth	61.9	85.8	nr/9.2
Quebec			
CONTROL: Baseline climate + no traffic growth	1647.7	-	2.8/0.7
CGCM2A2x + no traffic growth	1647.7	0.0	3.0/0.6
HadCM3B21 + no traffic growth	1636.4	-0.7	3.0/0.6
Baseline climate + 4% annual AADTT growth	1789.8	8.6	2.8/0.7
CGCM2A2x + 4% annual AADTT growth	1789.8	8.6	2.9/0.6
HadCM3B21 + 4% annual AADTT growth	1784.1	8.3	2.9/0.6
Newfoundland			
CONTROL: Baseline climate + no traffic growth	5.3	-	nr/nr
CGCM2A2x + no traffic growth	5.6	5.4	nr/nr
HadCM3B21 + no traffic growth	5.6	4.3	nr/nr
Baseline climate + 4% annual AADTT growth	9.7	81.7	nr/nr
CGCM2A2x + 4% annual AADTT growth	10.2	91.2	nr/nr
HadCM3B21 + 4% annual AADTT growth	10.1	88.8	nr/nr

*results rounded to one decimal place

**nr (not reached during 20-year design life)

Table 14. Alligator cracking performance results for all sites and scenarios

Case Study Site	Alligator Cracking (%)*		
	Coverage (%)	Change relative to control (%)	Years to 25% coverage maintenance threshold (50/90% reliability)**
British Columbia			
CONTROL: Baseline climate + no traffic growth	0.7	-	Nr/nr
CGCM2A2x + no traffic growth	0.7	7.5	Nr/nr
HadCM3B21 + no traffic growth	0.7	10.5	Nr/nr
Baseline climate + 4% annual AADTT growth	1.1	61.2	Nr/nr
CGCM2A2x + 4% annual AADTT growth	1.2	73.1	Nr/nr
HadCM3B21 + 4% annual AADTT growth	1.2	79.1	Nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	28.9	-	17.0/5.2
CGCM2A2x + no traffic growth	32.2	11.4	15.1/4.8
HadCM3B21 + no traffic growth	31.0	7.3	15.9/4.9
Baseline climate + 4% annual AADTT growth	40.5	40.1	13.8/4.9
CGCM2A2x + 4% annual AADTT growth	44.0	52.3	12.0/4.1
HadCM3B21 + 4% annual AADTT growth	42.9	48.4	12.8/4.8
Manitoba			
CONTROL: Baseline climate + no traffic growth	48.2	-	17.1/1.8
CGCM2A2x + no traffic growth	51.1	6.0	16.8/1.8
HadCM3B21 + no traffic growth	51.0	5.8	16.9/1.8
Baseline climate + 4% annual AADTT growth	59.8	24.1	7.1/2.1
CGCM2A2x + 4% annual AADTT growth	62.4	29.5	6.8/1.9
HadCM3B21 + 4% annual AADTT growth	62.4	29.5	6.8/2.0
Ontario			
CONTROL: Baseline climate + no traffic growth	4.6	-	nr/nr
CGCM2A2x + no traffic growth	5.1	10.5	nr/nr
HadCM3B21 + no traffic growth	5.2	13.1	nr/nr
Baseline climate + 4% annual AADTT growth	6.9	50.7	nr/20.0
CGCM2A2x + 4% annual AADTT growth	7.6	65.9	nr/18.9
HadCM3B21 + 4% annual AADTT growth	7.8	69.7	nr/18.5
Quebec			
CONTROL: Baseline climate + no traffic growth	0.5	-	nr/nr
CGCM2A2x + no traffic growth	0.5	4.4	nr/nr
HadCM3B21 + no traffic growth	0.5	2.2	nr/nr
Baseline climate + 4% annual AADTT growth	0.9	97.8	nr/nr
CGCM2A2x + 4% annual AADTT growth	0.9	104.4	nr/nr
HadCM3B21 + 4% annual AADTT growth	0.9	100.0	nr/nr
Newfoundland			
CONTROL: Baseline climate + no traffic growth	0.1	-	nr/nr
CGCM2A2x + no traffic growth	0.1	14.3	nr/nr
HadCM3B21 + no traffic growth	0.1	14.3	nr/nr
Baseline climate + 4% annual AADTT growth	0.1	71.4	nr/nr
CGCM2A2x + 4% annual AADTT growth	0.1	100.0	nr/nr
HadCM3B21 + 4% annual AADTT growth	0.1	100.0	nr/nr

*results rounded to one decimal place

**nr (not reached during 20-year design life)

Table 15. Transverse cracking performance results for all sites and scenarios

Case Study Site	Transverse Cracking*		
	m/km	Change relative to control (%)	Years to 189.4 m/km maintenance threshold (50/90% reliability)**
British Columbia			
CONTROL: Baseline climate + no traffic growth	19.1	-	nr/nr
CGCM2A2x + no traffic growth	0.6	-96.9	nr/nr
HadCM3B21 + no traffic growth	35.8	87.1	nr/nr
Baseline climate + 4% annual AADTT growth	19.1	0.0	nr/nr
CGCM2A2x + 4% annual AADTT growth	0.6	-96.9	nr/nr
HadCM3B21 + 4% annual AADTT growth	35.8	87.1	nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.3/0.3
CGCM2A2x + no traffic growth	399.6	0.0	0.3/0.3
HadCM3B21 + no traffic growth	399.6	0.0	0.3/0.3
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.3/0.3
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	0.3/0.3
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.3/0.3
Manitoba			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.3/0.3
CGCM2A2x + no traffic growth	399.6	0.0	0.4/0.3
HadCM3B21 + no traffic growth	399.6	0.0	0.4/0.4
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.3/0.3
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	0.4/0.3
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.4/0.4
Ontario			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.5/0.5
CGCM2A2x + no traffic growth	399.6	0.0	1.5/1.4
HadCM3B21 + no traffic growth	399.6	0.0	0.5/0.5
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.5/0.5
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	1.5/1.4
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.5/0.5
Quebec			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.4/0.4
CGCM2A2x + no traffic growth	399.6	0.0	0.4/0.4
HadCM3B21 + no traffic growth	399.6	0.0	0.5/0.5
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.4/0.4
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	0.4/0.4
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.5/0.4
Newfoundland			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.5/0.5
CGCM2A2x + no traffic growth	399.6	0.0	1.6/1.4
HadCM3B21 + no traffic growth	399.6	0.0	0.6/0.5
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.5/0.5
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	1.6/1.4
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.6/0.5

*results rounded to one decimal place

**nr (not reached during 20-year design life)

Table 16. AC rutting performance results for all sites and scenarios

Case Study Site	Asphalt Concrete (AC) Rutting* mm	Change relative to control (%)	Years to 6.4 mm maintenance threshold (50% reliability)**
British Columbia			
CONTROL: Baseline climate + no traffic growth	2.1	-	nr
CGCM2A2x + no traffic growth	2.5	16.9	nr
HadCM3B21 + no traffic growth	2.5	19.3	nr
Baseline climate + 4% annual AADTT growth	2.6	21.6	nr
CGCM2A2x + 4% annual AADTT growth	3.0	40.9	nr
HadCM3B21 + 4% annual AADTT growth	3.1	44.1	nr
Alberta			
CONTROL: Baseline climate + no traffic growth	5.5	-	nr
CGCM2A2x + no traffic growth	6.8	22.7	17.1
HadCM3B21 + no traffic growth	7.3	31.8	14.9
Baseline climate + 4% annual AADTT growth	6.6	20.3	19.0
CGCM2A2x + 4% annual AADTT growth	8.1	47.0	13.1
HadCM3B21 + 4% annual AADTT growth	8.7	58.1	11.9
Manitoba			
CONTROL: Baseline climate + no traffic growth	2.9	-	nr
CGCM2A2x + no traffic growth	3.9	35.9	nr
HadCM3B21 + no traffic growth	3.9	34.1	nr
Baseline climate + 4% annual AADTT growth	3.5	21.0	nr
CGCM2A2x + 4% annual AADTT growth	4.7	62.8	nr
HadCM3B21 + 4% annual AADTT growth	4.7	60.3	nr
Ontario			
CONTROL: Baseline climate + no traffic growth	4.2	-	nr
CGCM2A2x + no traffic growth	5.4	27.0	nr
HadCM3B21 + no traffic growth	5.4	28.9	nr
Baseline climate + 4% annual AADTT growth	5.1	21.1	nr
CGCM2A2x + 4% annual AADTT growth	6.5	52.8	19.1
HadCM3B21 + 4% annual AADTT growth	6.6	55.2	19.0
Quebec			
CONTROL: Baseline climate + no traffic growth	5.3	-	nr
CGCM2A2x + no traffic growth	6.1	13.9	nr
HadCM3B21 + no traffic growth	6.2	16.8	nr
Baseline climate + 4% annual AADTT growth	6.5	21.5	19.9
CGCM2A2x + 4% annual AADTT growth	7.3	37.9	16.1
HadCM3B21 + 4% annual AADTT growth	7.5	41.1	15.8
Newfoundland			
CONTROL: Baseline climate + no traffic growth	1.2	-	nr
CGCM2A2x + no traffic growth	1.5	21.9	nr
HadCM3B21 + no traffic growth	1.5	21.9	nr
Baseline climate + 4% annual AADTT growth	1.4	19.3	nr
CGCM2A2x + 4% annual AADTT growth	1.8	47.1	nr
HadCM3B21 + 4% annual AADTT growth	1.8	47.1	nr

*results rounded to one decimal place

**nr (not reached during 20-year design life)

Table 17. Total rutting performance results for all sites and scenarios

Case Study Site	Total Rutting (all layers)* mm	Change relative to control (%)	Years to 19.1 mm maintenance threshold (50/90% reliability)**
British Columbia			
CONTROL: Baseline climate + no traffic growth	10.7	-	nr/nr
CGCM2A2x + no traffic growth	11.1	3.8	nr/nr
HadCM3B21 + no traffic growth	11.2	4.8	nr/nr
Baseline climate + 4% annual AADTT growth	11.6	8.5	nr/nr
CGCM2A2x + 4% annual AADTT growth	12.0	12.8	nr/nr
HadCM3B21 + 4% annual AADTT growth	12.1	13.8	nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	19.0	-	nr/8.0
CGCM2A2x + no traffic growth	18.9	-0.5	nr/8.8
HadCM3B21 + no traffic growth	19.9	4.7	16.7/7.0
Baseline climate + 4% annual AADTT growth	20.8	9.3	14.9/7.0
CGCM2A2x + 4% annual AADTT growth	20.9	9.6	15.1/7.8
HadCM3B21 + 4% annual AADTT growth	22.0	15.7	12.9/6.8
Manitoba			
CONTROL: Baseline climate + no traffic growth	14.5	-	nr/nr
CGCM2A2x + no traffic growth	14.4	-0.9	nr/nr
HadCM3B21 + no traffic growth	14.9	2.3	nr/nr
Baseline climate + 4% annual AADTT growth	15.8	8.5	nr/nr
CGCM2A2x + 4% annual AADTT growth	15.8	8.7	nr/20.0
HadCM3B21 + 4% annual AADTT growth	16.3	12.0	nr/18.8
Ontario			
CONTROL: Baseline climate + no traffic growth	12.1	-	nr/nr
CGCM2A2x + no traffic growth	13.2	9.0	nr/nr
HadCM3B21 + no traffic growth	13.3	10.3	nr/nr
Baseline climate + 4% annual AADTT growth	13.3	10.3	nr/nr
CGCM2A2x + 4% annual AADTT growth	14.6	21.0	nr/nr
HadCM3B21 + 4% annual AADTT growth	14.8	22.7	nr/nr
Quebec			
CONTROL: Baseline climate + no traffic growth	21.8	-	10.9/4.3
CGCM2A2x + no traffic growth	21.1	-3.2	13.0/5.1
HadCM3B21 + no traffic growth	21.6	-0.8	11.9/4.8
Baseline climate + 4% annual AADTT growth	23.9	9.3	8.9/3.8
CGCM2A2x + 4% annual AADTT growth	23.2	6.1	10.8/4.9
HadCM3B21 + 4% annual AADTT growth	23.8	8.9	9.8/4.3
Newfoundland			
CONTROL: Baseline climate + no traffic growth	9.1	-	nr/nr
CGCM2A2x + no traffic growth	9.0	-1.1	nr/nr
HadCM3B21 + no traffic growth	9.1	0.6	nr/nr
Baseline climate + 4% annual AADTT growth	9.8	8.1	nr/nr
CGCM2A2x + 4% annual AADTT growth	9.7	7.0	nr/nr
HadCM3B21 + 4% annual AADTT growth	9.9	9.0	nr/nr

*results rounded to one decimal place

**nr (not reached during 20-year design life)

3.3 Discussion and Limitations

As with other forms of infrastructure, the fundamental concern related to a changing climate in pavement design and management is the potential for premature design failure. Current and past designs generally assume a static climate whose variability can be adequately determined from records of weather conditions which normally span less than 30 years and often less than 10 years. The notion of anthropogenic climate change challenges this assumption and raises the possibility that the frequency, duration or severity of thermal cracking, rutting, frost heave and thaw weakening may be altered leading to premature deterioration as indicated by trends in one or more of the performance indicators described earlier. The case studies provided empirical evidence to support this contention for several sites in Canada. The analysis of deterioration-relevant climate indicators at 17 sites suggests that, over the next 50 years, low temperature cracking will become less problematic; structures will freeze later and thaw earlier with correspondingly shorter freeze season lengths; and higher extreme in-service pavement temperatures will raise the potential for rutting. Evidence from the 6 sites examined in the MEPDG analysis was not as universal but nonetheless suggests that rutting (AC and total) and cracking (longitudinal and alligator) issues will be exacerbated by climate change with transverse cracking becoming less of a problem. In general, maintenance, rehabilitation or reconstruction will be required earlier in the design life. As important, the MEPDG analysis indicates that the absolute impacts of climate change are intimately tied to the type of structure, materials, and traffic conditions experienced at a particular site—to such an extent that a formal aggregate analysis of economic impacts was beyond the scope of the current investigation.

The results of this study are dependent on many assumptions, particularly those concerning representativeness of sites and manipulation of climate scenarios. Site selection for both case studies was driven by data availability (e.g., LTPP, Environment Canada) and engineering expertise. Every effort was made to select sections that were representative of climates typically experienced in southern Canada. Additional sites that capture an even broader range of climates and pavement structures found within Canada could have been analyzed and a greater number of climate change scenarios, and alternative or more sophisticated means of downscaling scenario data, could have been incorporated into the research—with concomitant increases in costs. While such additions would no doubt contribute to greater confidence in the results, it is likely that the general findings would not change significantly.

Accordingly, the discussion turns to an interpretation of results into practical recommendations for adaptation—the final steps in the climate impact assessment model proposed by Carter *et al*. (1999). The literature review and stakeholder discussions confirmed that technologies already exist to adequately manage any of the impacts uncovered in this study. By purposely applying design tools or thresholds presently used in pavement engineering research and practice (e.g., PGAC, freeze-thaw indices, MEPDG) to assess impacts, the authors also confirmed their efficacy at detecting changes associated with climate. None of the potential impacts suggested through this study fall beyond the range of conditions presently experienced in North America—analogous pavement structures and environmental and traffic situations abound among the agencies represented in the LTPP database. PG ratings and other material properties can be adjusted and structural designs can be strengthened for new asphalt pavements. Maintenance schedules can be advanced (or deferred) and systems can be put in place to monitor and predict freezing and thawing effects on pavement strength and restrict traffic accordingly.

For large, well-funded road authorities that manage much of the primary paved road network in Canada, the key adaptation issues will surround not how to deal with potential impacts but rather when to modify current design and maintenance practices. The basis for such decisions often falls back to an assessment of relative costs (between status quo and various designs or interventions) borne by the public, road users and, to the extent permitted in contractual agreements, by private sector construction and maintenance providers. As introduced in the literature review, pavement management systems and tools such as Life Cycle Cost Analysis (LCCA) are available to determine when a particular maintenance (e.g., crack sealing, patching, etc.), rehabilitation (e.g., AC overlay, cold in place recycling, etc.) or reconstruction activity should be implemented for a given network and section. The addition of climate change scenarios to typical 20+ year design evaluations into the LCCA process—essentially an extension of the MEPDG applications used in the current study—could be readily used to support future decisions. Regardless of future climate change, the reliability of such design evaluations could be improved by considering longer time series of climatic data to capture more variability.

Unfortunately, not all road authorities are equal in terms of the financial resources, technical expertise, and monitoring and information infrastructure available to implement and sustain a modern pavement management system. This concern may apply to secondary and tertiary low volume road networks that receive lower priority in larger agencies but is likely most relevant to rural and small urban local or municipal agencies where monitoring and modeling capacity may be limited and where engineering judgement is the basis for most decisions. Municipal partnerships and associations (e.g., Ontario Good Roads Association) and less formal collaborations will be critical in ensuring that these important elements of the road transportation system become aware of, monitor, and manage potential climate change impacts through emerging best practices.