COMPARISON OF WELLHEAD PROTECTION DELINEATION METHODS WITH RESPECT TO NONPOINT POLLUTION SOURCES

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Final Report 1993 WWRC-93-09

Final Report

Submitted to

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State of Wyoming
Herschler Building
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June 1993

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COMPARISON OF WELLHEAD PROTECTION DELINEATION METHODS WITH RESPECT TO NONPOINT POLLUTION SOURCES

FINAL REPORT

This final report contains a listing of the tasks to be performed by the project followed by the results obtained from the project in terms of these tasks.

The purpose of this project was to evaluate the different methods used to delineate wellhead protection areas using EPA guidelines and the several suggested analytical and numerical models for defining wellhead protection areas for unconfined and confined aquifers typical of Wyoming. The specific tasks identified for this project are detailed below:

Task One: Analysis of Delineation Techniques and Collection of Data

The specific objectives under Task 1 were: (1) examination of the EPA defined analytical and numerical models for defining wellhead protection areas to determine the type and quantity of data required for each models application; (2) collect required data for model evaluation for a confined aquifer (Casper Formation near and surrounding Laramie) and an unconfined aquifer (alluvial aquifer near and surrounding Torrington); and (3) evaluate the modeling techniques developed and tested at Laramie and the publications of EPA on "Wellhead protection strategies for confined-aquifer settings" and "Delineation of wellhead protection areas in fractured rocks" to suggest methods which would be most applicable for wellhead protection delineation for different geological settings which exist in Wyoming.

Task Two: Modeling, Calibration and Comparison

The specific objectives under Task 2 were: (1) to evaluate each of the models for wellhead protection delineation using the data obtained on the confined (Casper Formation aquifer) and unconfined (Torrington area aquifer) aquifers; and (2) develop a calculated fixed radius evaluation method and provide relevant information to be included in a wellhead protection plan for small community water supply systems who could utilize this technique.

Task Three: Comparison of Determined Protection Areas to Overall Protection Goals.

The specific objective under Task 3 was to take the wellhead protection areas determined from each model under Task 2 and evaluate them in light of the three levels of protection goals outlined by EPA.

RESULTS OF THE PROJECT BY TASK:

Task 1 Results:

Deliverable 1:

A Plan B paper (Appendix A) by Barry McConnery entitled "Wellhead Protection for Confined Aquifers" was developed as a part of this project and details several suggested methods of wellhead delineation. The methods detailed (Appendix A: Pages 19 - 44) are (1) arbitrary fixed radii; (2) calculated fixed radii; (3) simplified variable shapes; (4) analytical methods; (5) hydrogeologic mapping; and (6) numerical flow/transport models. The paper indicates advantages and disadvantages of each method along with requirements for the use of the method. A discussion of the wellhead protection methods and how they apply to confined aquifers is discussed and the differences associated with confined and unconfined aquifer analysis is also included in the report (Appendix A: Pages 45 - 51). A detailed discussion on the use of EPA Wellhead Protection Area (WHPA) semi-analytical groundwater flow models (Version 2) is presented in Appendix D with the delineation of the affected areas for wellhead protection of the Town of Torrington municipal wells. The flow models compared were GPTRAC, RESSQC, MWCAP and Montec.

Deliverable 2:

A description of the geologic setting and groundwater properties of the Casper Formation aquifer around Laramie are contained in Appendix A (Pages 8 - 18) in the Plan B paper by McConnery. Lundy (1978) developed a finite difference numerical model for the Casper Formation aquifer at Laramie which was used along with other data from the City of Laramie to obtain the groundwater hydraulic properties of the aquifer (Reference is cited under the Plan B paper by McConnery). These properties are further detailed in Appendix C as a part of the wellhead delineation for the City of Laramie.

A description of the alluvial setting of the aquifer in and surrounding Torrington is detailed in the M.S. thesis by Parks (1991). The groundwater hydraulic properties determined for the alluvial aquifer at Torrington are contained in Appendix B.

Reference:

Parks, Gary D. 1991. "Numerical Simulation of Groundwater Flow and Contaminant Transport in an Alluvial Aquifer" M.S. Thesis, University of Wyoming, Laramie, Wyoming 165p.

Deliverable 3:

The report on this particular element is contained in Appendix C and gives results of the wellhead delineation on several of the City of Laramie wells (Turner/City Springs and Pope Springs wells) and methods used for analyzing confined aquifers in fractured media for use with respect to fractured rock areas within Wyoming.

Task 2 Results:

Deliverable 1:

The more simple delineation analysis methods were performed on the Casper Formation aquifer in and surrounding Laramie using the calculated fixed radii, analytical methods and hydrogeologic mapping associated with calculated fixed radii in fault zones and is contained as part of the Plan B paper by McConnery in Appendix A (Pages 45 - 61). The paper also discusses why some methods were not used as a part of the analysis.

Appendix C gives more detailed results for several of the Laramie well fields using the results of Lundy (1978) and the EPA semi-analytical groundwater flow models. The City of Laramie is presently updating these results for all of their well fields using the same methodology and more hydraulic property values that they have obtained that were not available to this project. Our information and results were all given to Western Water Consultants who is doing the update work for the City of Laramie.

The evaluation of the wellhead protection areas for the Torrington municipal wells were completed using the numerical simulation model developed by Parks (1991) and the methods available for modeling through the EPA semi-analytical groundwater flow model computer programs. The evaluation by the EPA model GPTRAC using the results of the numerical model developed 3, 5, and 10 year delineation areas for the Torrington area are contained in Appendix D. Appendix D also contains a comparison of GPTRAC, RESSQC, MWCAP and Montec and why GPTRAC was selected for use at Torrington.

Deliverable 2:

A report (Appendix E) was developed which should assist small communities in Wyoming in their WHPA delineation efforts because it compiled hydraulic properties for principal water bearing strata throughout Wyoming. The report utilizes these hydraulic properties to estimate protection areas for specific times of travel and pumping rates in an effort to give small communities a feel for what they will actually be dealing with in terms of a WHPA.

Task 3 Results:

Deliverable:

WHPA's are evaluated in terms of three levels of protection goals by EPA. These are:

1. Reaction Time, to provide a remedial action zone to protect wells from unexpected contaminant releases.

2. Attenuation of Contaminants, to attenuate the concentrations of specific contaminants to desired levels at the time they reach the wellhead.

3. Protection of All or Part of the Zone of Contribution, to provide a well field management zone in all or a major portion of a well's existing or potential recharge area.

The evaluation of the Casper Formation aquifer in and surrounding the City of Laramie by several different methods (Appendix A and C) pointed out the fact that significant areas will be excluded from the reaction time zone as well as including areas which need not be protected because they are down gradient and are confined from the aquifer. These analyses indicate that for larger communities the need for more detailed analysis is definitely the approach to undertake unless the community decides to use larger than necessary reaction times with the simpler methods (fixed radii, etc).

The evaluation done on the Torrington alluvial aquifer pointed out the fact that it will be very difficult to provide large reaction times to contaminant spills because the movement of groundwater is at significant levels throughout most of the aquifer. The widespread problem of nitrate points to the fact that the entire area must be under best management type practices in order to control and manage the aquifer to the benefit of all users in the area. It will require monitoring wells in the source areas of the aquifer feeding the municipal wells to allow time to provide cleanup or reallocation of well usage by Torrington.

In both the Laramie and Torrington situations, it will require changing zoning requirements and other measures of public information to better protect their well fields from future contamination.

APPENDIX A

Wellhead Protection for Confined Aquifers

by

Barry James M^{c}Connery

A Plan B Paper
Submitted to the
Department of Civil and Architectural Engineering
of the University of Wyoming
in Partial Fulfillment of Requirements
for the Degree of
Masters of Science

University of Wyoming
Laramie, Wyoming
July, 1991

Acknowledgements

The author wishes to express his sincere thanks to the members of his graduate committee for the time and interest which they expressed in this study: Victor Hasfurther for his support, inspiration and guidance throughout my graduate program; Thomas Edgar for his support and interest in my graduate program; Jack Evers for his time and practical subjectivity. The author wishes to express sincere appreciation to the Range Management and Petroleum Engineering Departments for the use of their facilities.

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Introduction

Groundwater supplies roughly 25 percent of all the fresh water used in the United States. This nation has a large appetite for groundwater which is indicated by the fact that in 1980 it consumed approximately 89,000 million gallons per day (mgd). Of this total, agriculture is the greatest user, devouring roughly 68% of the total or 61,200 mgd. Industrial uses and power generation account for another 15% or 12,500 mgd and the remaining 17% or 15,000 mgd are for human consumption. In rural areas, roughly 96% of all drinking water originates from groundwater sources. (Jaffe, 1987)

In 1972, the government of the United States passed the Clean Water Act (CWA). The goal of the CWA was to make the nation's waters fishable and swimmable by 1983 and to end the discharge of toxic chemicals into surface waters by 1985. In December of 1974, the Safe Drinking Water Act (SDWA) was signed into law, this gave the EPA power to set and enforce standards for hazardous substances that occur in drinking water. This legislation was designed to clean up all the nations surface waters, but still nothing was mentioned about the nation's vast unprotected groundwater supplies. Large amounts of contaminates were allowed to enter the nation's groundwater supplies through underground storage tanks, landfills, and other types of pits and ponds.

It was not until the 1986 Amendments to the SDWA that the nation's groundwater sources were to be protected from contamination. The amendments authorized two new provisions for groundwater protection in the SDWA, the first was the Wellhead Protection (WHP) program and the second was the Sole Source Aquifer Demonstration (SSAD) program. These amendments were the first of a nationwide program to protect groundwater resources used for public water supplies from a wide range of potential threats. Both of these programs are designed to support the development of State and local efforts to protect their groundwater resources.

The WHP program is designed to assist States in protecting areas surrounding wells within their jurisdiction against contaminants that may have adverse effects on human health. These zones, denoted as Wellhead Protection Areas (WHPA's), are defined in the SDWA as "the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or field." (U.S. EPA, 1987).

The SSAD program is designed to protect critical aquifer protection areas located within areas designated as sole or principal source aquifers. A sole or principal source aquifer is defined as "an area having an aquifer which is the sole or principal drinking water source for the area and which, if contaminated, would create a significant hazard to public health." (Calabrese, 1989).

The wellhead protection areas are needed to safe guard against contamination from three general divisions of threats. The first is the direct introduction of contaminants to the area immediately contiguous to the well through improper casing, road runoff, spills, and accidents. A second basic threat is from microbial contaminants such as bacteria and viruses. The third major threat is from the broad range of chemical contaminants, including inorganic and naturally occurring or synthetically-derived organic chemicals.

The Environmental Protection Agency (EPA) has outlined six methods to produce a delineation of the area that should be protected around a well. The methods are listed below in order of increasing technical sophistication and cost:

- Arbitrary fixed radii
- Calculated fixed radii
- Simplified variable shapes
- Analytical methods
- Hydrogeologic mapping
- Numerical flow/transport models.

The above methods range from simple and economical methods to highly complex and expensive ones.

The purpose of this paper is to discuss how these delineation methods can be used to help define the WHPA for a confined aquifer. The Casper aquifer in the area surrounding the City of Laramie, Wyoming will be used as an example of how to delineate and protect a group of confined aquifer well fields from potential contamination. The study area around Laramie, Wyoming encompasses 192 mi^2 within T. 14 N through T. 17 N. and R. 72 W. through R. 73 W. Figure 1 shows the location of the study area and sites that will be mentioned in the paper.

The Casper aquifer in the area of Laramie, Wyoming includes the Casper and Fountain Formations, which have a combined thickness that ranges from 0 to 750 feet in the area. The Casper Formation is of Pennsylvanian-Permian age and the Fountain Formation is of Pennsylvanian age. The Casper Formation is comprised of a series of interbedded sandstones and limestones. The sandstones are rather thin and quite permeable, while the limestones possess very little permeability. The Fountain Formation is comprised of permeable arkosic sandstones and lenses of sandy shale. As the formations head northward into the Laramie Basin, the Casper limestone replaces the sandstone, and the Fountain Formation slowly thins and eventually disappears. The two

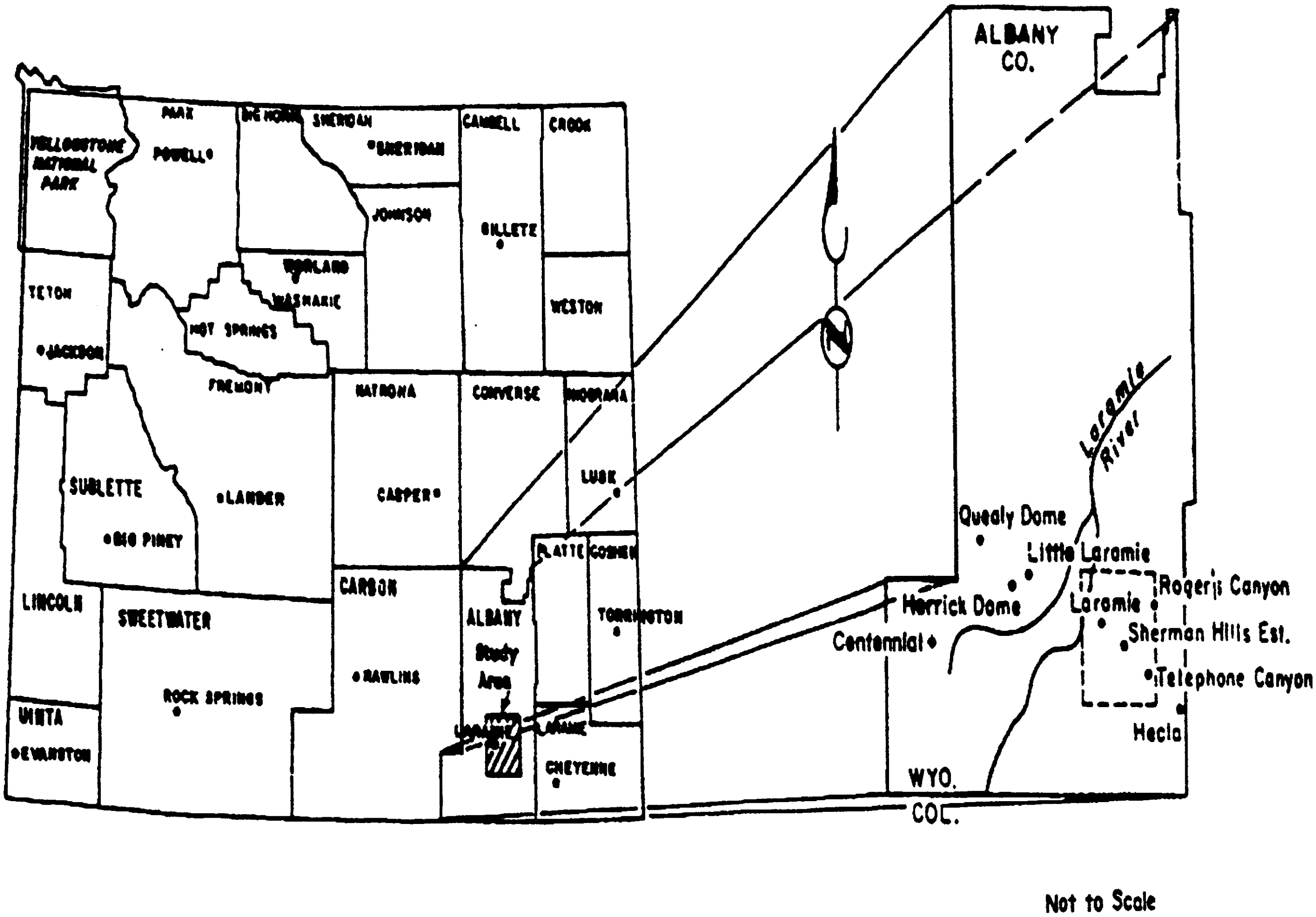


Figure 1. Location of study area in Albany County, Wyo. including localities mentioned in the text. (Lundy, 1978)

formations are confined by underlying pre-Cambrian rock and overlying Satanka Shale.

The Casper and Fountain Formations are the major sources of potable water in the Laramie area. In 1976 the City of Laramie obtained approximately 70 percent of its water, $3.0\text{x}10^6$ gallons per day (gpd) from two springs and one well field that discharged from these two formations (Lundy, 1987). Today the city has two well fields and one spring which can produce approximately $10.5\text{x}10^6$ gpd from the Casper aquifer. The two well fields are comprised of 6 wells. There are 2 wells in the Turner field, capable of pumping $4.32\text{x}10^6$ gpd. The remaining 4 wells are located in the Pope field and are designed to pump $4.45\text{x}10^6$ gpd. The spring is located at Simpson Springs and can produce roughly $1.7\text{x}10^6$ gpd. The Turner well field is located near the City Springs area, and is intersected by a number of faults. The Pope well field is located along the Pope Fault. Water is also pumped from the Casper aquifer for various domestic, industrial and institutional purposes in the area surrounding the City of Laramie.

To the west of the study area, roughly 20 miles, can be founded the following oil fields:

- Quealy Dome
- Little Laramie
- Herrick Dome.

All three of these oil fields produce from the upper portion of the Casper Formation. The oil produced in the Casper Formation in this area is sour, containing over 3 percent sulphur, and have API gravities ranging from 23° to 27° (West, 1953a, 1953b).

As can be seen, the City of Laramie and the surrounding area uses the Casper and Fountain Formations to obtain potable drinking water. Improper management of contaminated sites and chemical applications, resulting from human activities, often allows these pollutants to come in contact with groundwater supplies. One solution to this problem is to prevent contaminated groundwater from coming in contact with the wells and springs of the area by establishing areas of protection which restrict certain type of activities around them.

The approach used to delineate WHPA's will be discussed on the following pages by first describing the geological setting, the aquifer properties associated with the Casper aquifer, details of the methods for delineating WHPA's and then describing the use of these delineation techniques for a confined aquifer with Laramie, Wyoming as an example.

Geological Setting

Stratigraphy

The Laramie Basin is underlain by sedimentary rocks ranging in age from Pennsylvania to Quaternary. Underlying these rocks is an igneous and metamorphic basement complex of pre-Cambrian age.

The main water bearing formations that the City of Laramie uses are the Casper, Pennsylvanian-Permian age, and Fountain, Pennsylvanian age, Formations. The Casper Formation overlies and interfingers with the Fountain Formation. The Casper Formation consists of a series of shales, limestones, and sandstones. The sandstones are generally fine grained, poorly graded subarkoses that are well-cemented in decreasing abundance with: calcite, clay, silica, and hematite (Kirn, 1972), whereas the Fountain Formation is generally a well graded arkose and is easily distinguished from the Casper sandstones. The lower parts of the Fountain Formation contain thick beds of arkosic sandstone and conglomerates, while the Casper limestones are usually microcrystalline and fossiliferous. As these formations move northward in the Laramie Basin, the Casper sandstone is gradually replaced by limestone, and the Fountain Formation thins and eventually disappears, as shown in Figure 2.

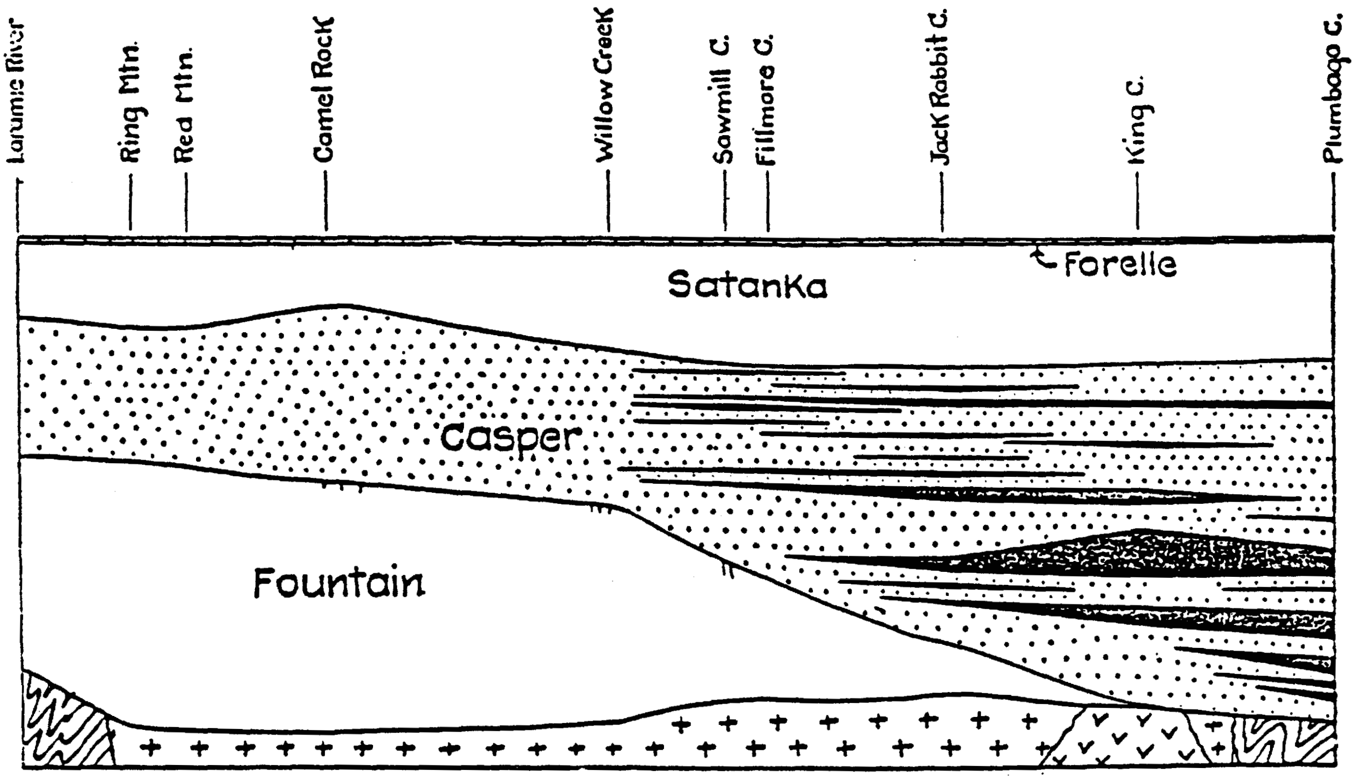


Figure 2. Cross-section from southwest to northeast across the Laramie Basin. The black represents limestones in the Casper. (Knight, 1929)

In the area of interest, the Casper Formation ranges from about 500 to 720 feet in thickness. Benniran (1970) reported the thickness of the Casper Formation in Telephone Canyon as 687 feet. Lundy (1978) reported thickness of the Casper and Fountain Formations near Telegraph Canyon as 712 and 38 feet, respectively. The reported combined thicknesses of the Casper and Fountain Formations at City and Pope Springs are 650 and 700 feet.

The Casper Formation outcrops in an area west of the Laramie Mountains, elevations of about 8900 feet, to the City Springs area, as shown in Figure 3. At City Springs, the Casper Formation begins to curve downward beneath the City of Laramie where it becomes buried by the Permian Satanka Shale, Forelle Limestone, and the Chugwater Formations. They dip westward at angles between 2° and 8° and strike approximately north-south (Lundy, 1978). By the time the Casper and Fountain Formations reach the center of the Laramie Basin, they have become deeply buried by the overlaying formations.

These overlaying formations contain thick (approximately 1,000 feet) impermeable shale beds which act as confining layers and help create the artesian conditions in the underlying Casper and Fountain Formations. These formations contain layers of red siltstone, mudstone, and shale which is subordinated by laterally extensive thin

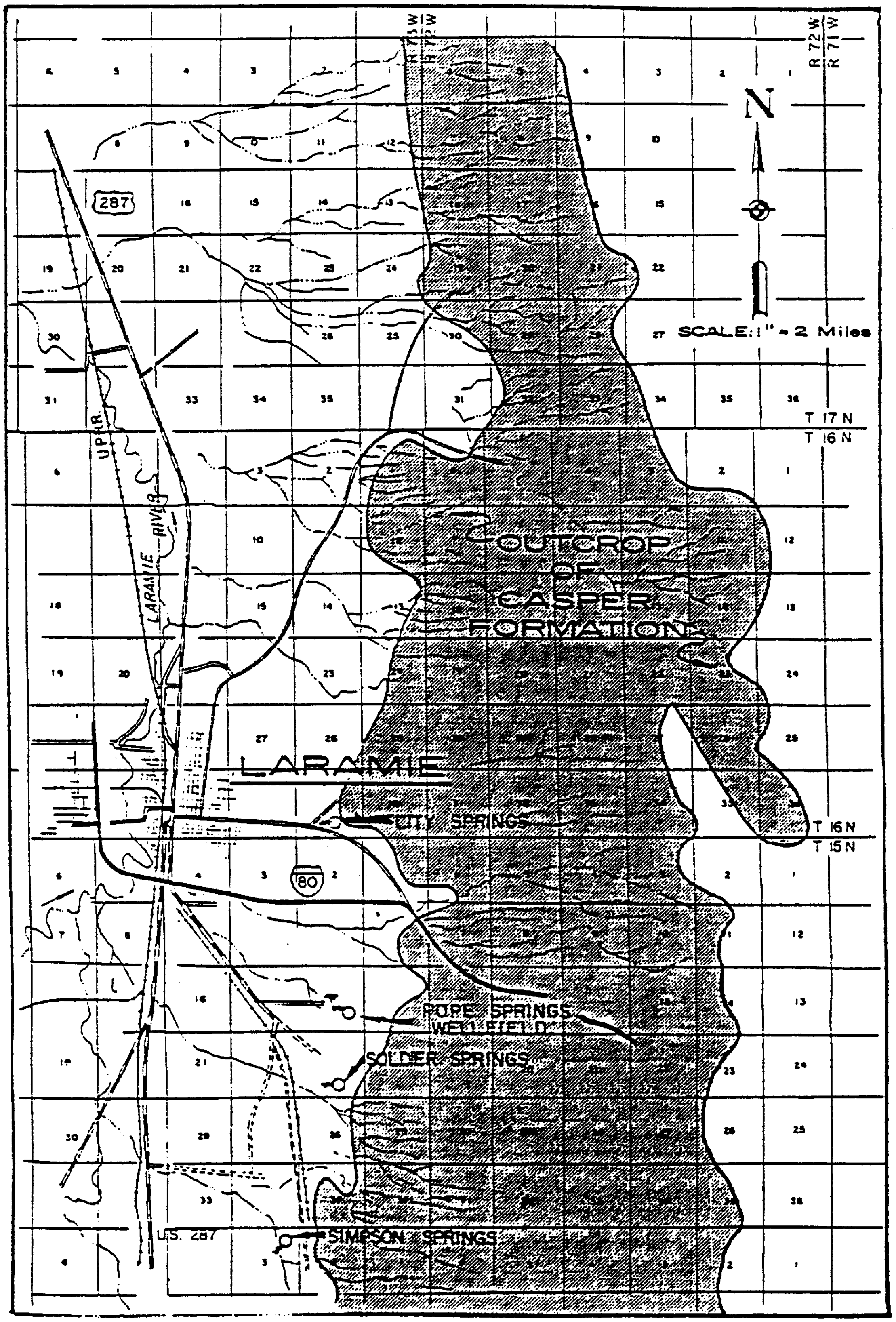


Figure 3. Casper Formation Outcrop area in the vicinity of Laramie, Albany Co., Wyo. (Banner,1978)

limestone, dolomite, and gypsum beds (Lundy, 1987).

The Fountain Formation lies unconformably upon rocks of pre-Cambrian age. This underlying pre-Cambrian basement is composed of granite gneiss, anorthosite, and gabbro. Figure 4 illustrates a typical geological cross section of the pre-Cambrian basement to the Triassic overburden.

Structural Geology

There are two types of faults that occur in the Laramie area. One group of faults is the Laramide reverse faults and associated monoclines, and the other set of faults is a group of normal faults and associated folds (Lundy, 1987). This faulting and folding allows vertical flow to occur from the Casper and Satanka Shale Formations in the vicinity of Laramie. These faults and fracture zones not only act as vertical flow paths, but also function as collector structures and conduits for groundwater flow to the many springs near the Casper-Satanka contact.

City Springs is intersected by four faults, the Jackrabbit fault and monocline, Spur, City Springs, and Quarry faults. The Pope well field is located along the Pope fault, and Soldier Springs is along the Soldier fault. The Spur, City Springs, Jackrabbit, Quarry, Sherman Hills, Pope, and Solider faults are all major normal faults. The

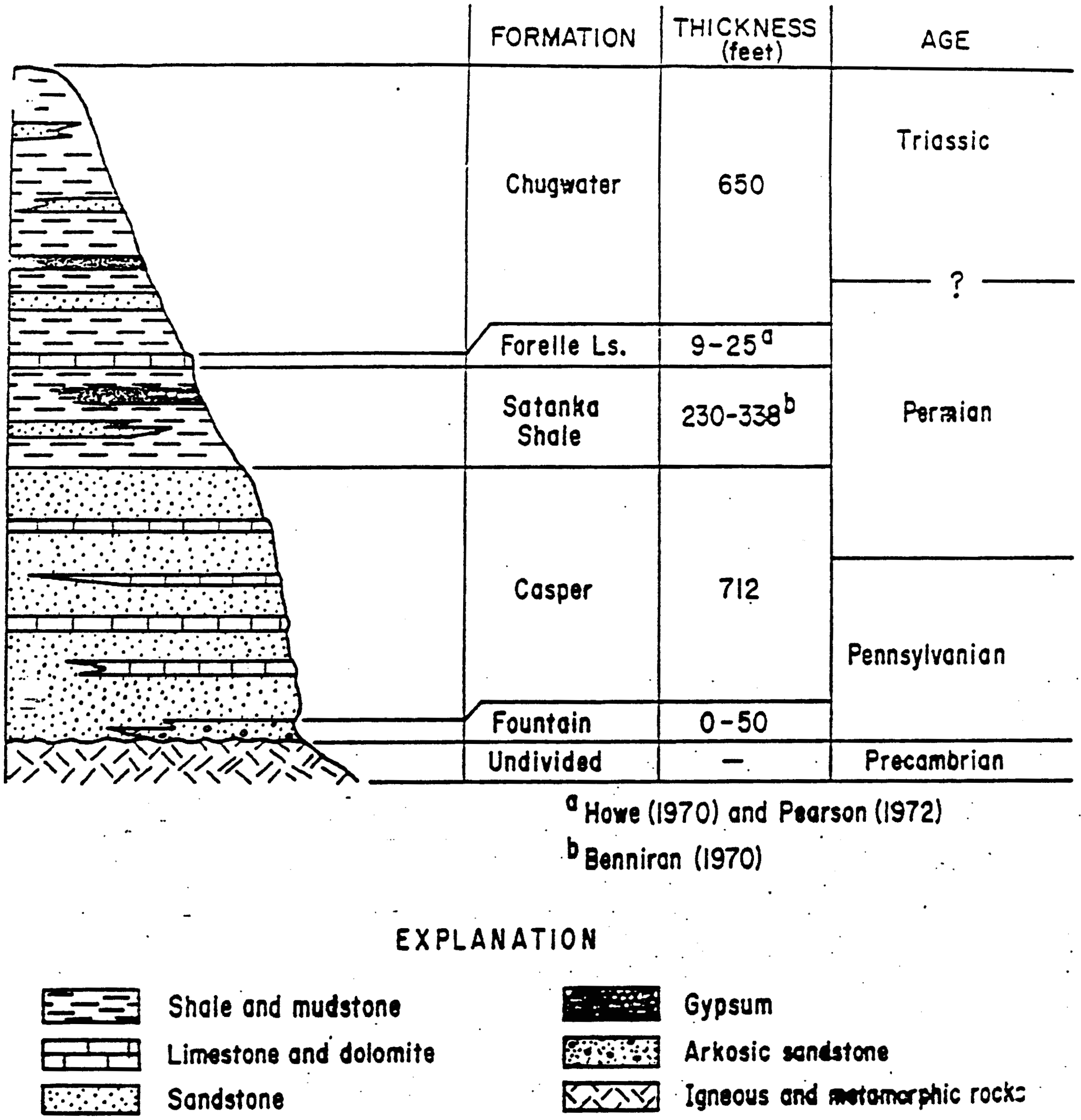


Figure 4. Cross section of pre-Cambrian through Triassic rocks in the vicinity of Laramie, Albany Co., Wyo. (Lundy, 1978)

locations of these tectonic structures is shown in Figure 5. Displacements across the faults are as great as 200 ft and the dip of the fault planes range from 60° to 80° (Lundy, 1978). The Sherman Hills, Quarry, and Jackrabbit faults all reach the surface around the City Springs area. The Soldier and Pope faults also reach the surface around their respective well fields. There is approximately 40 feet of stratigraphic displacement from the Soldier fault, whereas the Sherman Hills and Quarry faults have 65 and 60 feet of displacement, respectively. Some areas along the Spur fault have displacements as great as 200 feet, and as little as 50 feet. The Springs fault has a displacement of approximately 20 feet.

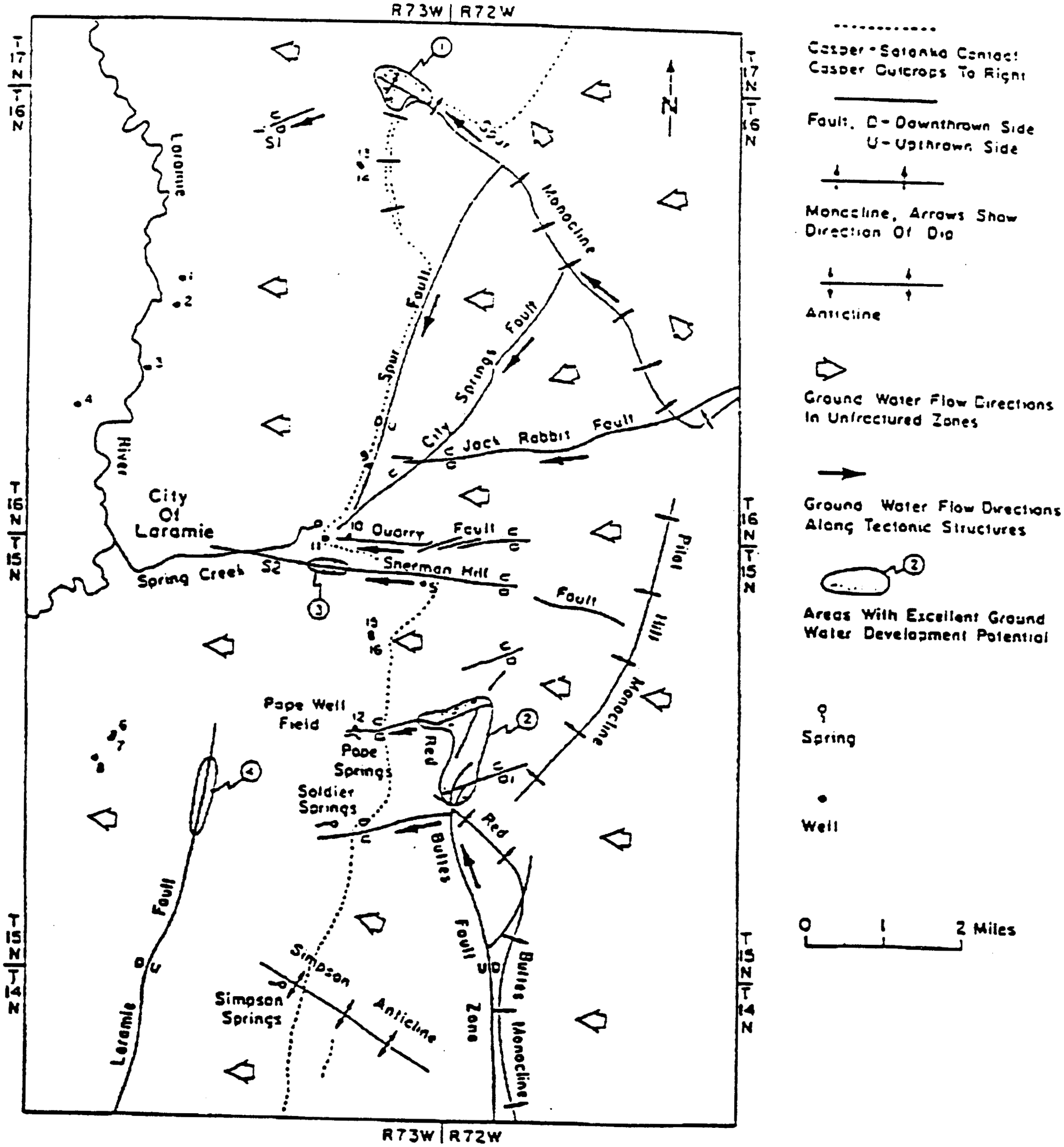


Figure 5. Locations of tectonic structures, selected well and springs and groundwater flow direction. (US EPA, 1988)

Groundwater Hydrology

The regional groundwater flow in the Casper aquifer is westward from the outcrop area, in the Laramie Mountains, toward the Laramie Basin.

Hydraulic Properties of the Rock Units

Limited data is available on the porosities and hydraulic conductivities of the Casper and Fountain Formations in the vicinity of Laramie. Porosity is defined as the ratio of the volume of voids in the rock to the total volume of the rock. Davis (Lundy,1978) determined that the porosity of the Casper Formation in the Laramie area was approximately 24 percent, however, Evers (Lundy, 1978) found 15 to 30 percent porosity in the upper 60 feet of the Casper Formation in a well to the west of City Springs. West (1953a, 1953b) found average porosities of the upper 125 feet of the Casper Formation at Little Laramie, Herrick Dome, and Quealy Dome fields of 23, 20, and 14 percent, respectively. Kirn (1972) believed that the matrix and cement in the Casper sandstones only comprise a small percentage of the total rock volume, resulting in the intergranular porosity being quite small. The intergranular porosity of one well-cemented Casper sandstone was reported by Goodrich (Lundy, 1978) to be 22 percent.

Transmissivities and hydraulic conductivities have been calculated for various locations around the Laramie region. Transmissivity is defined as the ease with which water passes through an aquifer under a given pressure and hydraulic conductivity is defined as the capacity of a porous medium to transmit water. West (1953a) determined hydraulic conductivities of 2.2 and 4.3 feet/day for the Herrick Dome and Little Laramie fields, respectively. Morgan (Lundy, 1978) calculated transmissivity and hydraulic conductivity for the City Springs area using the Theim solution as 18,000 feet^2/day and 28 feet/day. Wester (1976) determined transmissivity and hydraulic conductivity for the Pope well field as 18,000 feet^2/day and 26 feet/day using the Theim solution and 23,000 feet^2/day and 33 feet/day using specific capacity. Banner (1978) reported transmissivities for the Pope Springs and the City Springs areas as 20,000 feet^2/day and 21,400 to 22,700 feet^2/day, respectively.

Coefficient of storage or storage coefficient is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in piezometric head. Wester (1976) reported a storage coefficient for the Pope Springs area of $6x10^{-3}$.

Morgan (Lundy, 1978) reported a storage coefficient for the City Spring area of $1x10^{-3}$. Banner (1978) also reported storage coefficients of $1x10^{-3}$ and $5x10^{-4}$ for the Pope Springs and the City Springs area, respectively.

The driving force that causes water to flow may be represented by a quantity known as the hydraulic gradient. Hydraulic gradient is define as the rate of change in total head per unit of distance of flow in a given direction. Hydraulic gradients can be calculated by using a potentiometric surface map. With the use of a generalized potentiometric surface map created by Lundy (1978), a hydraulic gradient of 0.059 was calculated for the Casper aquifer in the area surround Laramie, Wyoming.

Wellhead Protection Methods

Natural groundwater flow patterns are modified by pumping wells. A cone of depression within the water table or piezometric level of a confined aquifer is created by each of these pumping wells. These depressions tend to draw surrounding groundwater into the well. If contaminates, whether chemical or biological, are present in this area of depression there is a chance that they will reach the well bore at sometime in the future. Thus protection areas around wells or well fields need to be developed to guard these important groundwater resources from such contamination.

If an aquifer is protected by an overlaying impermeable unit that provides sufficient protection from contaminant releases at the surface, then the area surrounding the well would not require any areas to be delineated for protection beyond the first 100 feet or so directly surrounding the wellhead. A confined aquifer that is deeper than 300 feet and does not have any fractures or other conduits present in the confining unit, also does not require any WHPA delineated at the wellhead but should indicate where the surface recharge area for the confined aquifer is located (US EPA, 1987).

There are many examples of wellhead protection programs both here in the United States of America and abroad. The States of Florida, Massachusetts, and Nebraska all use the arbitrary fixed radii method of delineating WHPA's. Vermont, Texas, and also Florida have used the calculated fixed radii methods for determining WHPA's. West Sussex, in the southern part of England, has implemented an aquifer protection policy utilizing simplified variable shapes for describing WHPA's. Holland, West Germany and the State of Massachusetts are using analytical methods in outlining WHPA's. While the States of Vermont, Connecticut, and Massachusetts use hydrogeologic mapping to define WHPA's. Finally, Massachusetts and parts of Southern Florida employ numerical flow and transport models to delineate WHPA's.

The city of Kennedale, Texas uses the time of travel criteria to determine a calculated fixed radii WHPA. Whereas the County of Palm Beach, Florida is a little more sophisticated and uses both the time of travel and drawdown criteria to determine WHPA's by the use of numerical flow and numerical transport models. Franklin, Massachusetts applies three WHPA delineation methods, fixed radii, numerical model and hydrogeological mapping based on only two criteria of distance and flow boundaries to protect its recharge areas.

As mentioned earlier there are six primary methods used to delineated WHPA's. They are listed in Table 1 in order of increasing technical complexity and amount of expertise required to implement each method. All six delineation methods can be used to define a protection area around a well or a spring in either an unconfined or confined porous-media aquifer.

Table 1. Delineation Methods of various WHPA including amount of expertise.

Method	Level of Expertise
Arbitrary fixed radii	Non-technical
Calculated fixed radii	Junior Hydrogeologist/Geologist
Simplified variable shapes	Junior Hydrogeologist/Geologist
Analytical methods	Mid-level Hydrogeologist/Modeler
Hydrogeologic mapping	Mid-level Hydrogeologist/Modeler
Numerical flow/transport models.	Senior Hydrogeologist/Modeler

These methods will be discussed in the pages to follow, along with the advantages and disadvantages of each method.

Arbitrary Fixed Radii

Delineation of a protection area using this method involves drawing a circle of a specified radius around a well or well field that is to be protected (Figure 6). This radius may be based on scientific data or professional

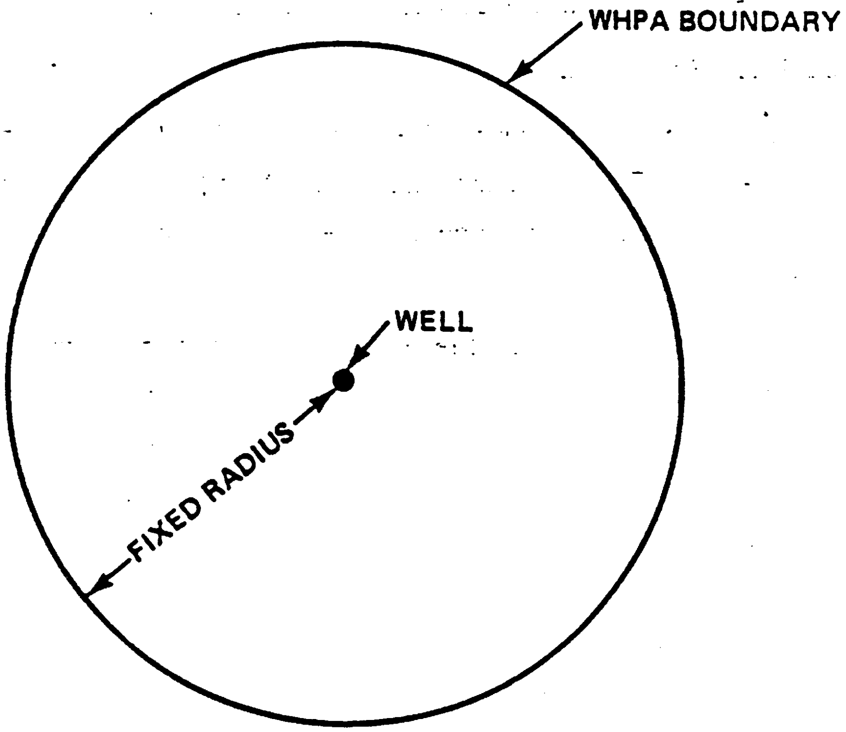


Figure 6. WHPA Delineation using the Arbitrary Fixed Radius Method. (US EPA, 1987)

judgement along with some very general hydrogeological considerations. For example, the State of Massachusetts uses an area delineated by a 400 foot radius around public supply wells. This distance has been established as the critical recharge area to the well. This value was selected based on the relatively effective attenuation of microbial contaminants in the groundwater environment over short distances. However, recent studies have shown that some chemical contaminates are able to travel much further than the 400 feet being used by Massachusetts. The method is best suited for use in aquifers that have relatively flat piezometric surfaces or water tables.

Advantages. The arbitrary fixed radii method is an easy technique for applying a distance criteria to a wellhead protection area. This method can be economical and requires relatively little technical expertise. If a well field is to be protected, the method can be used to delineate a large number of wells in a short period, or the method can be used to initially define protection areas until a more complex method can be implemented. It is also a good method for a small town to use, that does not have the technical expertise or funds to do an indepth hydrogeological study to obtain the necessary data to delineate a protection area using a more sophisticated method.

Disadvantages. This method may be inexpensive and easy to implement, but it has its drawbacks. Since there is no scientific basis for the criteria threshold values, there is also a high degree of uncertainty associated with the use of this method. As stated earlier, this can be an economical method to implement but if the area delineated is under or over protected, this could add costs to purchasing or controlling land in the area where protection is not required. Recharge areas may lay outside the radius and also outside the area of protection offered by this method.

Calculated Fixed Radii

This delineation method is based upon calculating a radius of a circle for a specified time of travel (TOT), as shown in Figure 7. A radius is determined using a volumetric flow equation that is based on a volume of water that will be drawn to a well in a specified time. The volumetric flow equation is defined as

$$r=\sqrt{\frac{Qt}{\pi n H}} \tag{1}$$

where

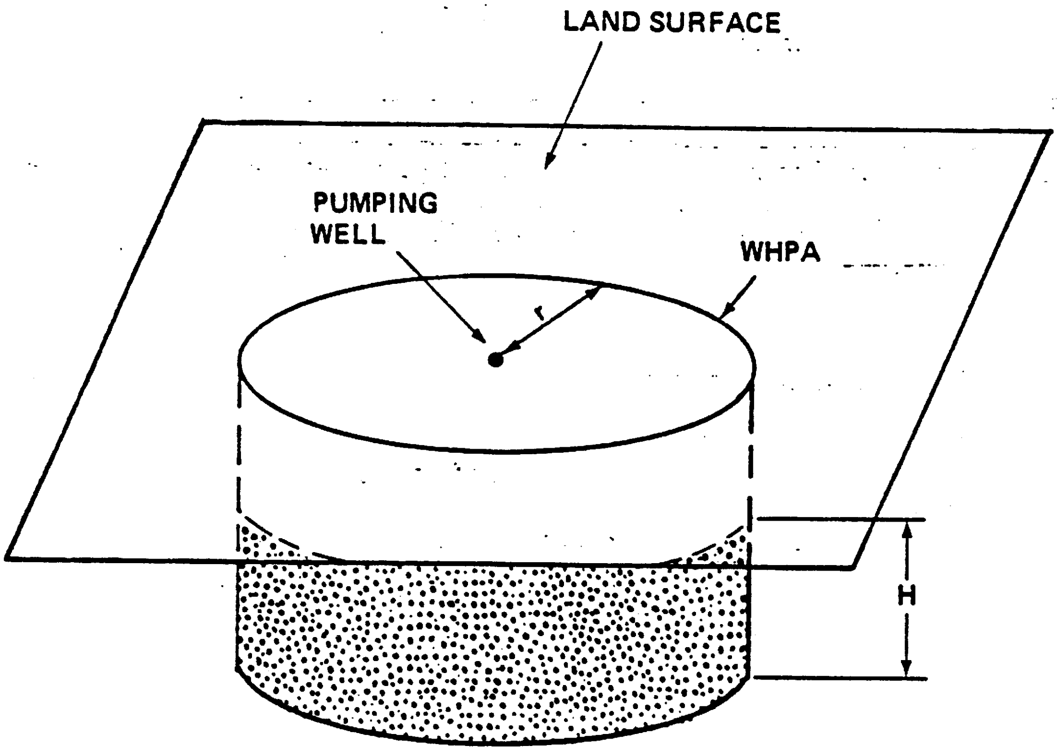
r = Radius of protection

Q = Pumping rate of well

n = Aquifer porosity

H = Open interval or length of well screen

t = Travel time to well.



-Radius (r) is calculated using a simple equation that incorporates well pumping rate and basic hydrogeologic parameters.

-Radius determines a volume of water that would be pumped from well in a specified time period.

H = Open interval or length of well screen.

Figure 7. WHPA Delineation using the Calculated Fixed Radius Method. (US EPA, 1987)

The amount of time is based on the amount of time considered adequate to allow clean up of the groundwater contamination before it reaches the well or the time to allow adequate dilution or dispersion of the contaminant. The above equation assumes that the porosity is constant throughout the aquifer. If the aquifer porosity does change, then the volume of water contained in the cylinder will be wrong causing the calculated radius of protection to be incorrect.

Advantages. This method is quite easy to implement and is relatively inexpensive, although it does require a small amount of technical background. Since very little technical experience is required to run this method, small towns with the help of a consultant can utilize this method. The consultant would just be used to determine the formation parameters of the aquifer, if they were not presently available to the town. After all the needed information is made available a number of wells can be delineated, with more accuracy then offered by the previous method, in a short period of time. The same degree of accuracy is obtained from this method in unconfined or confined aquifers.

Disadvantage. This method is slightly more expensive than the arbitrary fixed radii method, because it requires determining some hydrogeological properties from around the well site or field, because it is more accurate than the arbitrary fixed radii. However, this method does not take into account many of the factors that influence contaminant transport. This effect is present when the aquifer is in an area of heterogeneous and nonisotropic hydrogeology or where there are significant hydraulic flow boundaries.

Simplified Variable Shapes

This delineation method involves the use of "standardized forms", that are generated with analytical models. The standardized forms are developed using data from different sets of hydrogeologic parameters with varying pumping rates, hydraulic gradients, storativities, and aquifer thicknesses. Figure 8 shows some of the standardized forms that the Southern Water Authority in West Sussex, Great Britain. uses to delineate WHPA's. When a WHPA is to be delineated for a certain well, the standardized form that most closely matches the pumping rate and parameters at the well is chosen. This standardized form is then drawn over the well in the direction of the groundwater flow.

Standardized forms for different criteria are calculated for different sets of hydrogeologic conditions. The different standardized shapes are calculated by first determining the down gradient and lateral extent of the groundwater flow boundaries around the pumping well, and

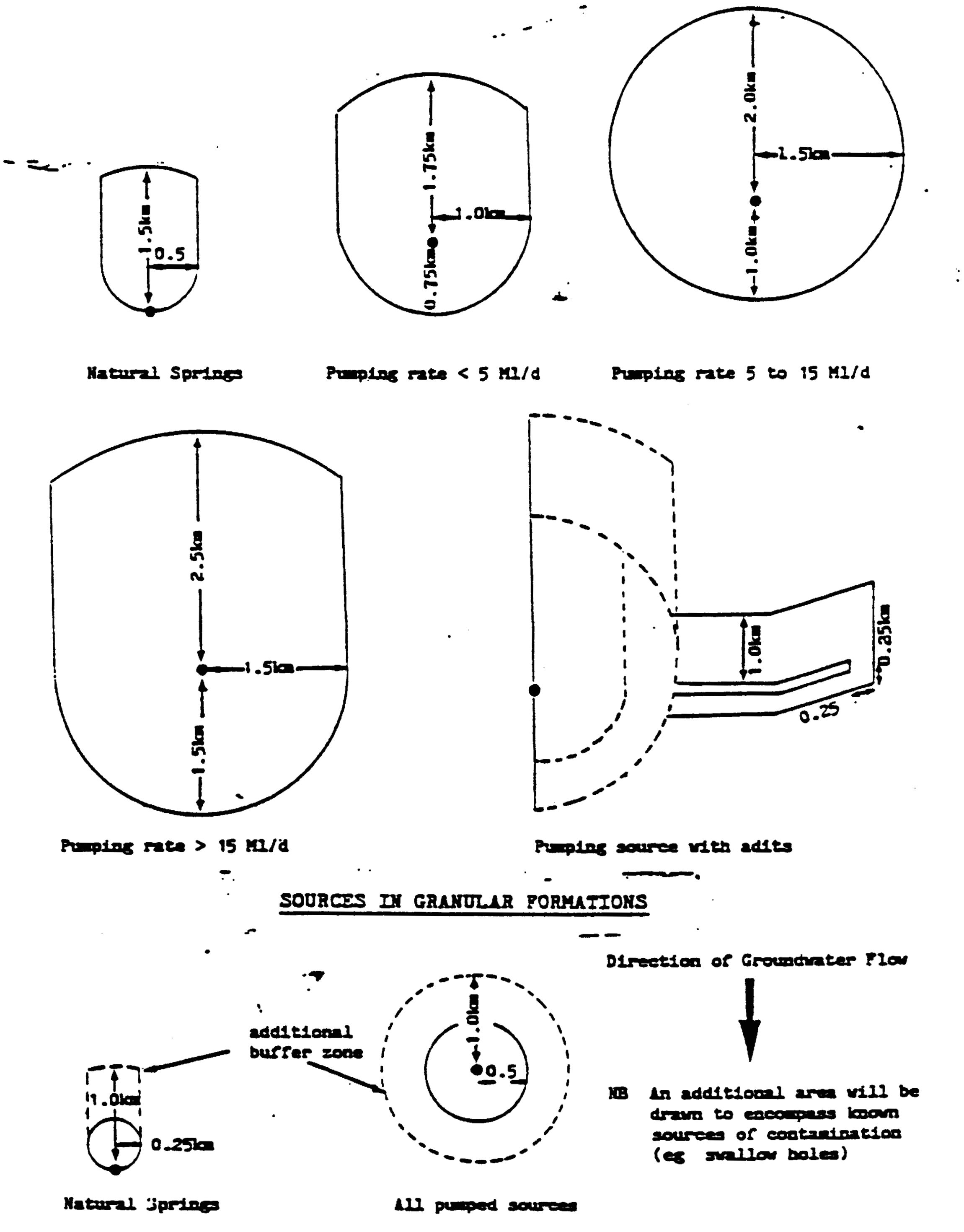
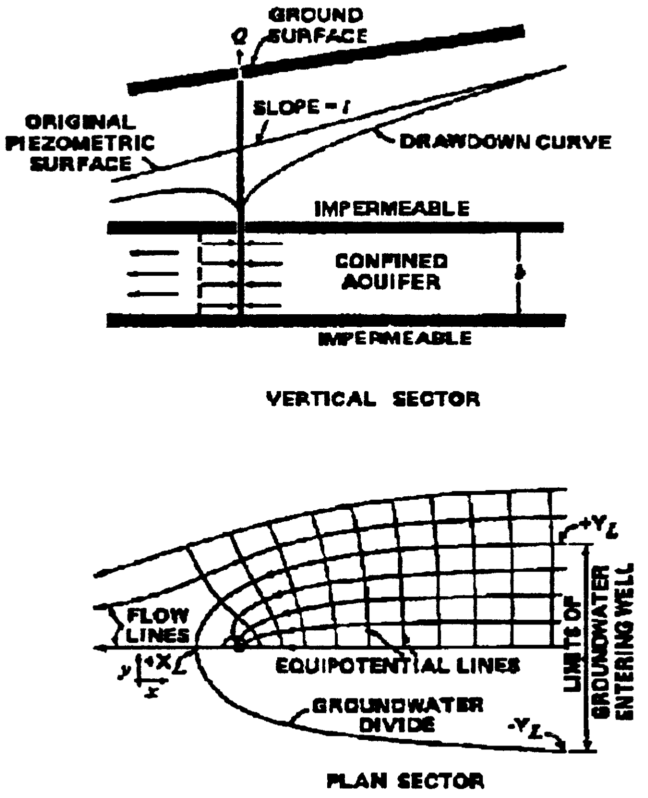


Figure 8. Standardized forms used by the Southern Water Authority. (Southern Water Authority, 1985)

then using a TOT equation to determine the up gradient extent of the protection area. A uniform flow equation is most commonly used to determine the down gradient and lateral boundaries for a well. The uniform flow equation as defined by D.K. Todd (US EPA, 1987) is show in Figure 9. The uniform flow equation presented in Figure 9 is for a confined aquifer. The equation can also be used in an unconfined aquifer if b is replaced by the uniform saturated aquifer thickness h_0, provided that the drawdown is small in relation to the aquifer thickness. The same assumptions that apply to the Dupuit solution, also apply to the uniform flow equation.

Advantages. Once the standardized shapes for an area are determined, any well within the surrounding area can have its WHPA easily delineated within a short period of time. The method requires only a small amount of field data to determine the standardized shapes. Once these shapes are determined the only information required to delineate a WHPA is the pumping rate, material type, and the direction of groundwater flow. This method may be used by a small town with the help of a consultant who determines the hydrogeologic parameters needed to calculate the shapes. The method is more refined than the fixed radius method, and only has a moderate increase in cost.



VERTICAL SECTOR

PLAN SECTOR

$$-\frac{Y}{X}=\tan\left(\frac{2\pi Kbi}{Q}Y\right) \qquad (2)$$

where

X = The distance along the centroidal axis, with the well located at the origin
Y = The distance outwards from the centroidal axis
Q = Well pumping rate
K = Hydraulic conductivity
b = Saturated thickness or screen length
i = Hydraulic gradient
π = 3.1416

(Note units are consistent)

Figure 9. Uniform Flow Equation (Todd, 1980).

Disadvantages. There may be a large expense in obtaining enough field data to determine the hydrogeological properties in an area. Also the method may not be accurate in areas where there are geologic heterogeneities and hydrologic boundaries, and where the groundwater flow direction is uncertain.

Analytical Methods

This is the most common type of delineation method used in areas where the hydrogeologic setting is complex and a greater accuracy is needed than can be obtained from any of the above methods. WHPA's are delineated with the use of equations that can define the groundwater flow and contaminant transport. Usually a uniform flow equation is used in conjunction with either a TOT or flow boundary criteria to determine the protection area. Limited hydrogeologic data is required to run the models, however, these parameters are necessary for each well for which the method is applied. The hydrogeologic parameters usually include transmissivity, porosity, hydraulic gradient, hydraulic conductivity, and saturated thickness of the aquifer.

The uniform flow equation is used to determine the null or stagnation point down gradient from the well and the TOT or flow boundary criteria are used to determine the up gradient extent of the protection area. Computers are usually used to help calculate the limits of these protection areas. Figure 10 shows an area that has been delineated using the analytical method. The up gradient and down gradient null points are also shown in the figure.

Advantages. Most hydrologists and engineers should be able to understand the methods and equations involved, and should be able to apply them to the proper situation. The method does take into account the site specific hydrogeologic parameters, thus providing a more accurate representation of the actual hydrogeologic setting than any of the previous methods mentioned.

Disadvantages. This method would be hard for a small town or city to implement, since they probably would not have the technical expertise to understand and use the equations correctly, however, a larger city with a engineering department should have no problems delineating WHPA's using this method. The methods use models that generally do not take into account hydrologic boundaries, aquifer heterogeneities, and non-uniform rainfall or evapotranspiration. The costs of using the analytical methods to delineate WHPA's is relatively low, however, the implementation costs can be high if site specific hydrogeologic data must be determined for each area to be protected. Site studies or field exploration may be needed

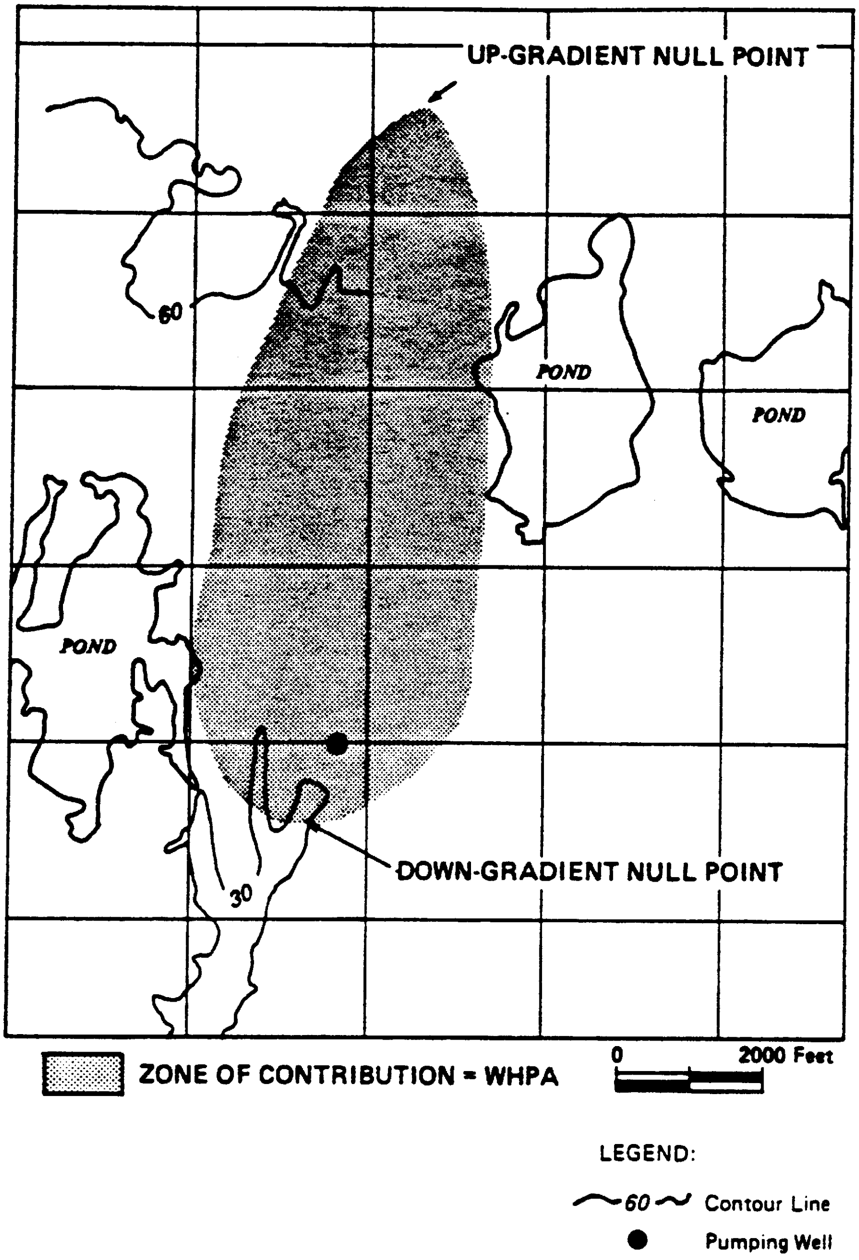


Figure 10. WHPA Delineated Using Analytical Models. (US EPA, 1987)

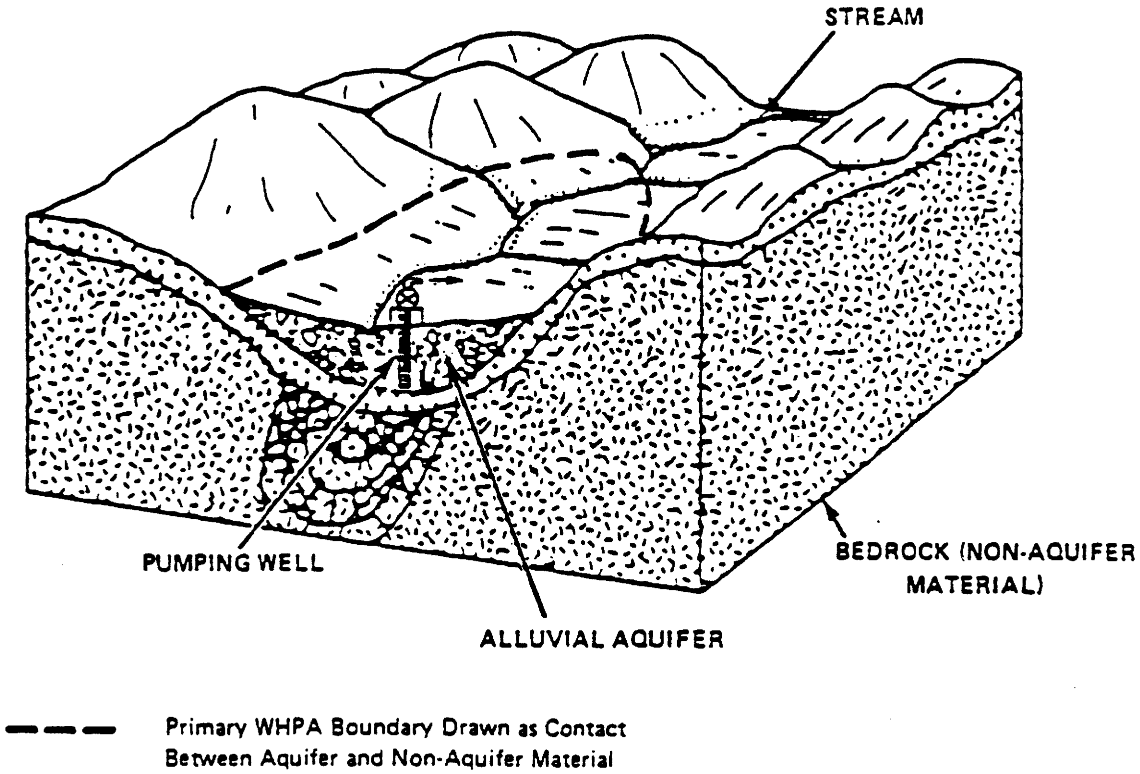
to determine the required information.

Hydrogeological mapping

In many hydrogeologic settings, hydrogeological mapping can be used to map flow boundaries and time of travel criteria through the use of geological, geomorphic, geophysical, and dye tracing methods. Geologic observations may provide surface indications of lithology changes, which will correlate with WHPA boundaries, as shown in Figure 11. Surface geophysical data can be used to map the spatial extent or thickness of unconfined aquifers. Hydrogeologic mapping may also include mapping of groundwater levels in order to identify groundwater drainage divides, as shown in Figure 12. The method is particularly appropriate in some types of aquifers, such as upland carbonate aquifers that recharge into conduit karst during storm events.

Surface geophysics can be used to delineate WHPA's, by mapping subsurface boundaries in unconfined aquifer systems. The most commonly used geophysical technique for delineating WHPA's is seismic refraction and electrical resistivity, with gravity and magnetic methods having only secondary applications.

Dye tracing can be used to map underground conduits by injecting dyes or tracers into the groundwater system. The dye is introduced at a sink hole or stream that flows into



NOTE: A secondary protection zone could be delineated based on the larger area of recharge derived from surface runoff, and inferred from topography and basin boundaries.

Figure 11. WHPA Delineated using Hydrogeologic Mapping with Geologic Contacts. (US EPA, 1987)

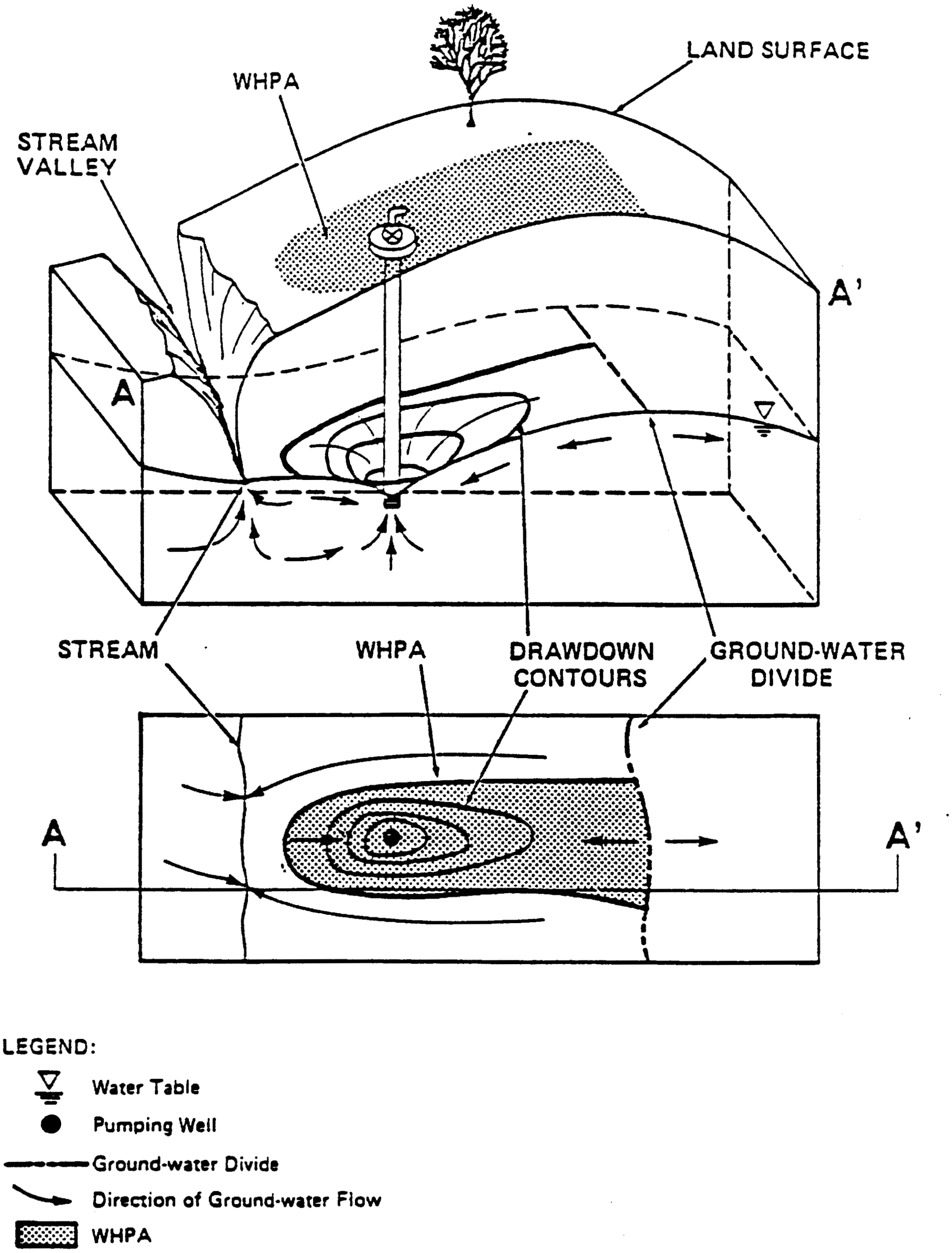


Figure 12. WHPA Delineated using Hydrogeologic Mapping with Groundwater divides. (US EPA, 1987)

the groundwater which is suspected to flow to the area which is to be included in the delineated WHPA. Water from the supply well or stream is then monitored and/or observed for a period of time that is adequate for the tracer to reach the supply. If the tracer is detected in the supply, the source from which the tracer was injected becomes part of the WHPA.

Using hydrogeological mapping to delineate a WHP program can be either inexpensive or expensive. It depends on the type of method used and the amount of hydrogeological data that is present for the area being delineated. Geophysical techniques are generally the most expensive, followed by mapping of geologic contacts, dye tracing, regional water level mapping, and basin delineation using topographic mapping.

Advantages. This type of delineation method is well suited to hydrogeologic settings dominated by near surface flow boundaries, as are found in many glacial and alluvial aquifers with high flow velocities, and also highly anisotropic aquifers, such as fractured bedrock and conduit flow karst.

Disadvantages. The method requires specialized expertise in geologic and geomorphic mapping, plus significant judgement on what constitutes likely flow boundaries. This method is less suited to delineating WHPA's in large or deep aquifers, however, the method can be used to determine the flow boundaries for these types of aquifers.

Numerical Flow/Transport Models

Numerical flow/transport models are particularly useful for delineating WHPA's where the boundary and hydrogeologic conditions are quite complex. Computers are usually used to simulate groundwater flow and/or contaminate transport using mathematical approximations in computer programs. Input data for these programs may include such hydrogeologic variables as permeability, porosity, specific yield, saturated thickness, recharge rates, aquifer geometries, and the location of hydrologic boundaries. Solute transport parameters such as dispersivity, diffusion, and half lives may also be incorporated into these models. A wide variety of numerical models are presently available both commercially and through organizations and universities.

Numerical modeling methods can be used to map criteria such as TOT, flow boundaries, and drawdown. This is typically performed by using a two-step procedure with a flow model being used to generate a hydraulic head field, and then a particle tracking or solute-transport program used to aid in outlining the WHPA. Figure 13 outlines the delineation of a well in the Cape Cod area using the numerical model, analytical model, and the calculated fixed radius equation.

Advantages. These models offer possibly the most accurate delineations, though at a considerable cost. The models can be applied to nearly all types of hydrogeological settings, and can simulate dynamic aspects of the hydrogeologic system that affect WHPA size and shape.

Disadvantages. Costs for this method are usually higher than for the other methods, and considerable technical expertise in hydrogeology and modeling is required by this method. The higher costs may be warranted where a higher degree of accuracy is required. Since higher technical skills are required to run a numerical model, it would be difficult for a small town to implement such a program without the help for a large consulting company and funding from State or Federal agencies. However, in larger cities that have large engineering departments that have some experience with modelling and have larger budgets, they should have few problems in delineating WHPA's using numerical modeling methods.

Confined Aquifer Situations vs Unconfined

Water can exist below the land surface in two completely different physical conditions. The two physical conditions are either a confined or unconfined aquifer.

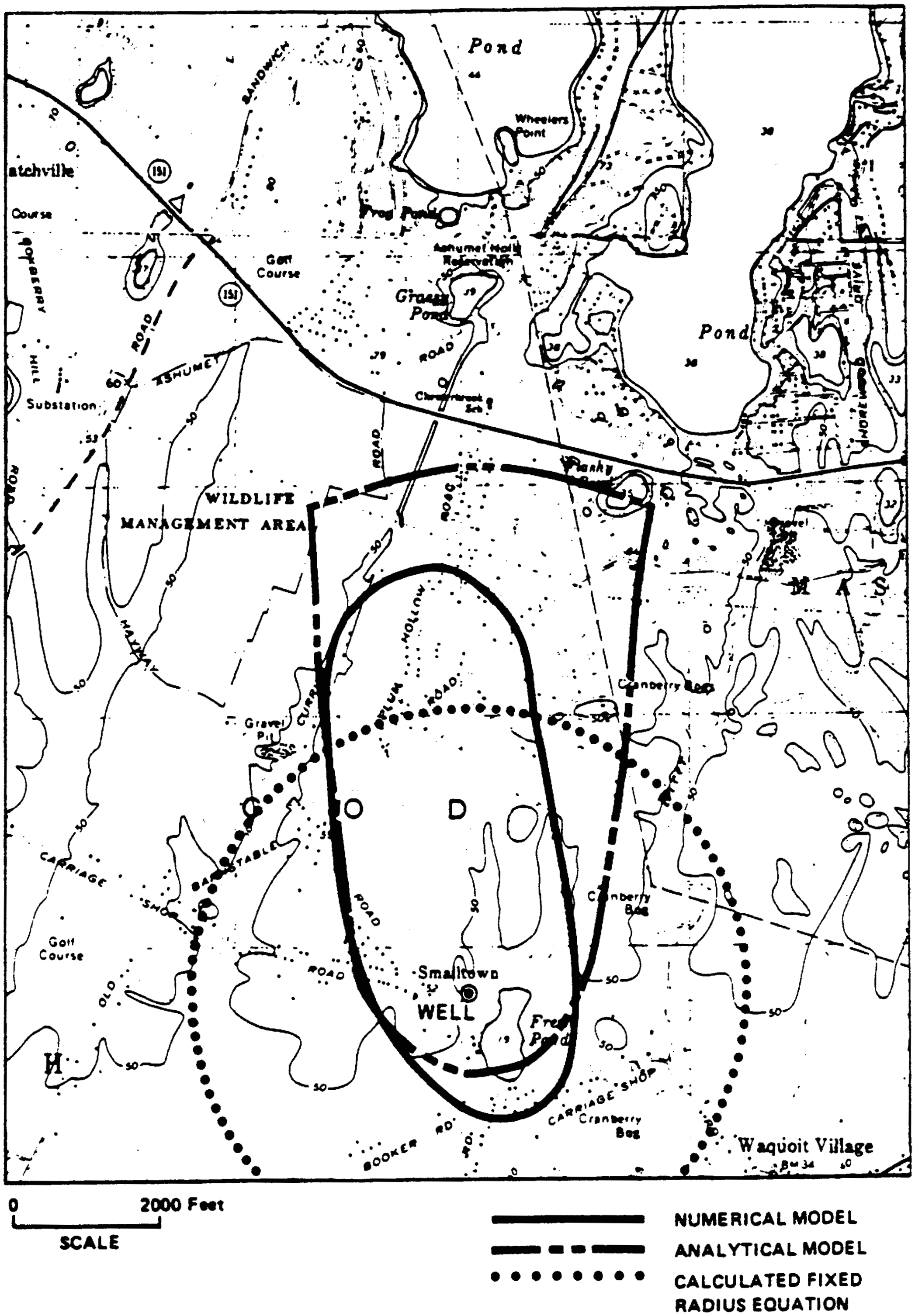


Figure 13. Delineated Protection Areas for Cape Cod, MA. (US EPA, 1987)

An unconfined aquifer is one in which the water table forms the upper boundary to the aquifer. A confined aquifer is defined as an aquifer bounded from above and below by confining layers that are of a distinctly lower permeability than that of the aquifer. These two distinct aquifer types require different methods of wellhead protection in order to protect the groundwater system from possible contamination. Figure 14 shows the two types of aquifers.

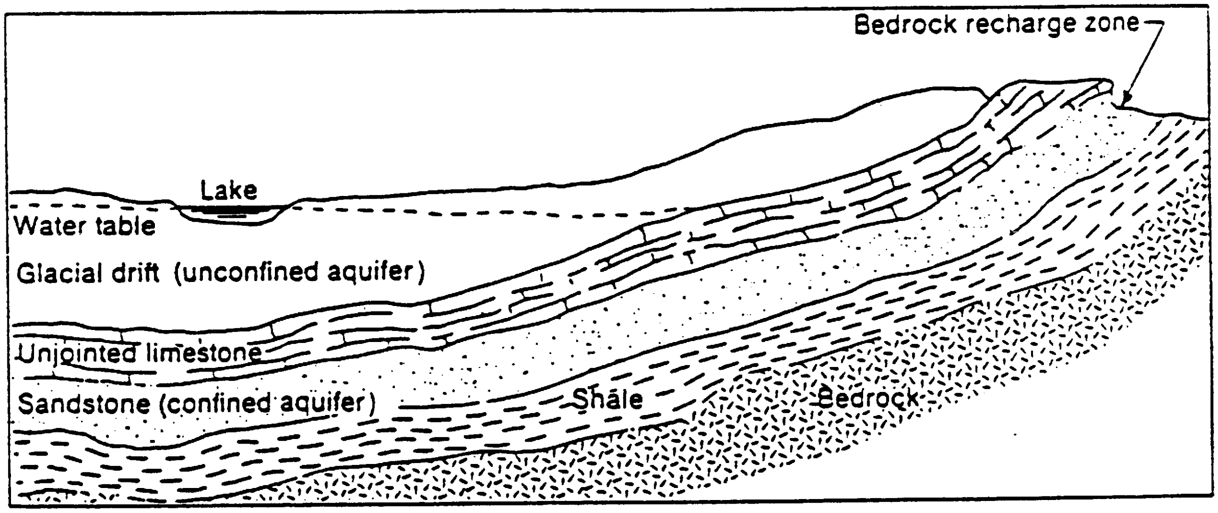


Figure 14. Diagram of confined and unconfined aquifers. (Driscoll, 1986)

The unconfined aquifer is the most commonly contaminated aquifer, this is because it does not have a protective or confining layer between the water table and land surface.

In the unconfined aquifer the entire area up gradient from the well or well field, including the area directly around the well to the recharge area, is susceptible to groundwater contamination and thus the area surrounding the well for some distance from the well requires protection from contamination. The reason for this amount of protection is the unconfined aquifer does not have an impermeable layer between the surface and the water table, to protect it from contaminates that are spilled or placed in or on the surface of the land.

Conversely, a confined aquifer requires protection from contamination only in the areas directly surrounding the wellhead and the recharge area. If faults are found in the subsurface or abandoned or improperly cased wells that penetrate into the confined aquifer are present in an area encompassing the up gradient area of a well or well field to the recharge area of the confined aquifer, these areas need to be addressed as possible sites for groundwater contamination.

All six delineation methods could be employed in defining the wellhead protection area for an unconfined aquifer. The fixed radii methods are best implemented in piezometric surfaces that are almost flat. The more complex methods are usually used in areas where the piezometric surface is sloping a significant amount, causing the down gradient null point to move closer to the well. The previous delineation methods can be used when different types of regions need to be delineated or when the required delineation area does not need to be that accurate, but still offer the aquifer some sort of protection from contaminates that originate from above or below the soil surface.

Since a confined aquifer has an overlying impermeable layer above and below, this probably provides adequate protection from contaminate spills from both above and below the soil surface. Thus, the only area requiring protection is the recharge area and the area immediately surrounding the well bore is to be protected. Exceptions to this would be in areas where there are fractures or other conduits present in the confining layers. Depending on the amount of protection required, the simplest methods, such as the fixed radius method, may be used to protect areas where there are fractures or conduits in the confining layer and in the area near the well bore. More exotic methods, such as analytical flow equations or numerical models, may be chosen if a greater amount of accuracy is required in these special areas. If the recharge area is at a great distance, a distance great enough to allow for sufficient attenuation of the chemical contaminates to levels that are acceptable, away from the well then this area may not need to be protected from contamination. However, if the recharge area is in close proximity to the well, then this area may need some sort of protection. Depending on the degree of protection required, hydrogeological mapping, analytical flow equations, or numerical modelling may be used to delineate the area for groundwater protection.

WHPA Delineation for a Confined Aquifer

There are many examples of wellhead protection programs here in the United States and Europe. The structure and scope of these programs vary and reflect the differing demographic, political, and hydrogeologic conditions present at the site. Some states and municipalities have developed wellhead protection as part of their overall groundwater protection programs. The main focus of these programs is the delineation of wellhead protection areas that impose land use controls to protect the public water supply wells. This paper will use the Casper Aquifer in the area surrounding the City of Laramie, Wyoming as an example of how to delineate wellhead protection areas for confined aquifers. The wells that are to be delineated belong to the city and are operated by the city.

As mentioned earlier, the City of Laramie and the surrounding area uses the Casper aquifer to obtain potable water. The City of Laramie, presently, has not implemented any WHPA's to be delineated for its two well fields and one spring, since it does have an alternative surface water source, the Laramie River, for obtaining its drinking water. Even though the City of Laramie does have that can be uses as an alternative source of potable water, a WHP program should be set up to protect the Casper aquifer in the area surrounding the city. This program should offer protection to the aquifer from three general threats. The first threat is the direct introduction of contaminants to the area immediately surrounding the well through improper casing, road runoff, spills, and accidents. The second basic threat is from microbial contaminants and the third is from a broad range of naturally occurring or man-made chemical contaminants.

In order to accomplish the goal of protecting the Casper aquifer from the above threats, a series of protection areas should be outlined. The first area would encompass the area directly around the well, this would protect the aquifer from the first threat. A second area would be required to protect the recharge area. This would also include the zone of contribution to the well. Finally, the area around faults which could cause flow to the well would need to be protected, since these act as conduits for groundwater flow which can move contaminants directly to the wellhead.

The WHPA delineation methods used in this example include (1) a calculated fixed radius method and (2) an analytical method (using the uniform flow equation). An arbitrary fixed radius (AFR) method is to be used to delineate the areas around faults that outcrop up gradient from the wells in the recharge area. A comparative analyses of the delineated areas will be done for the two well fields and the one spring.

Selection criteria for Methods used in Delineation

A time of travel (TOT) criteria based on ease of application was used because of the degree of accuracy that this criteria can obtain in this type of geologic setting. The rationale used in choosing the time values used for determining the WHPA's was based on the assumption that the time allotted would allow for sufficient attenuation of chemical contaminates to levels that would allow for the contaminant to meet safe drinking water standards or to allow enough time to clean up the contaminate before it reaches the well as well as cleaning up the contaminated area.

The numerical flow/transport model was not used in delineating the City of Laramie well fields, because the analytical method was felt to accurately define the protection area. Also the numerical flow/transport model was considered to be beyond the scope of this study.

The methods were chosen based on the ease of determining and implementing the WHPA methods.

Calculated Fixed Radius.

The calculated fixed radius (CFR) method uses a volumetric flow equation to determine the radius of the protection area. The WHPA will be delineated with the CFR method using a TOT criteria of 10, 25, and 50 years.

Analytical Method.

The analytical method that will be used is based on the uniform flow equation developed by Todd (US EPA, 1987). The model determines the stagnation or null point for a well and also how wide the WHPA is to be to give adequate protection to the recharge area. The up gradient boundary is determined by using 10, 25, and 50 year TOT criteria and a travel time equation to calculate the distances.

The area calculated by the analytical method differs from the area determined by the calculated fixed radius. The reason for this difference is because the two flow velocities at the protection boundaries are different, this results in a different time of travel for each method.

Fault Delineation Method.

The faults are to be delineated using the Arbitrary Fixed Radius (AFR) method. This method will be modified so that the area surrounding faults which lead to wells are protected by a buffer zone. This buffer zone would encompass an area of 400 feet on each side of the fault along the fault plane. This buffer zone will extend up gradient and down gradient from the well a distance approximately 4600 feet along the fault plane. The area outlined in Figure 17 should be enclosed by a fence. This would prevent the possibility of any contaminates coming in contact with the exposed fault. If a spill was to occur near the fence off area, it should be cleaned up quickly and the fault plane should be grouted near the surface. In fact it may be justified to grout the faults from the land surface to the confining layer at the well casing area initially. The reason to grout the area around the fault, is to prevent any contaminate from entering the aquifer along the fault and traveling down the fault plane to the well.

The boundary width was picked on the basis that microbiologic contaminates that are found in a groundwater environment are effectively attenuated over short distances. Recent studies have shown, however, that some chemical contaminates are able to travel much further than the 400 feet. The lateral extent of the boundaries were based on the 50 year travel time to the well using the aquifer parameters calculated in Table 2.

Data Requirements.

Hydrogeologic data used in calculating the WHPA by the CFR and analytical method are shown in Tables 2 and 3. The values for hydrogeologic properties around the well fields were determined from a report done by Banner (1978) and values for the Casper aquifer in areas away from the well fields were determined by Lundy (1978) using Huntoon well #1. The hydrogeologic data from Huntoon well #1 is only an approximation of the spatially varying parameters in the aquifer.

Calculations and Comparisons of Resulting WHPA's.

Tables 2 and 3 show the calculations for the two well fields and the one spring. The equations used to determine the WHPA's are given in Table 4.

Figures 15 through 18 show the delineated WHPA's for the well fields, spring, and faults using the CFR and analytical methods. The CFR provided the largest area of coverage for the 10, 25, and 50 years. However, the analytical method protects more of the recharge area for each well then does the CFR method. The CFR may over protect the aquifer down gradient, and under protect the aquifer in the recharge area above the well.

The analytical method offers less up gradient protection for the 10 year time of travel criteria. For the

25 year TOT both methods give equal up gradient protection for each well field, however, the up gradient protection area for Simpson Springs is larger when calculated by the analytical method. The up gradient protection area calculated by the analytical method using the 50 year TOT criteria encompasses more area up gradient, than does the CFR method.

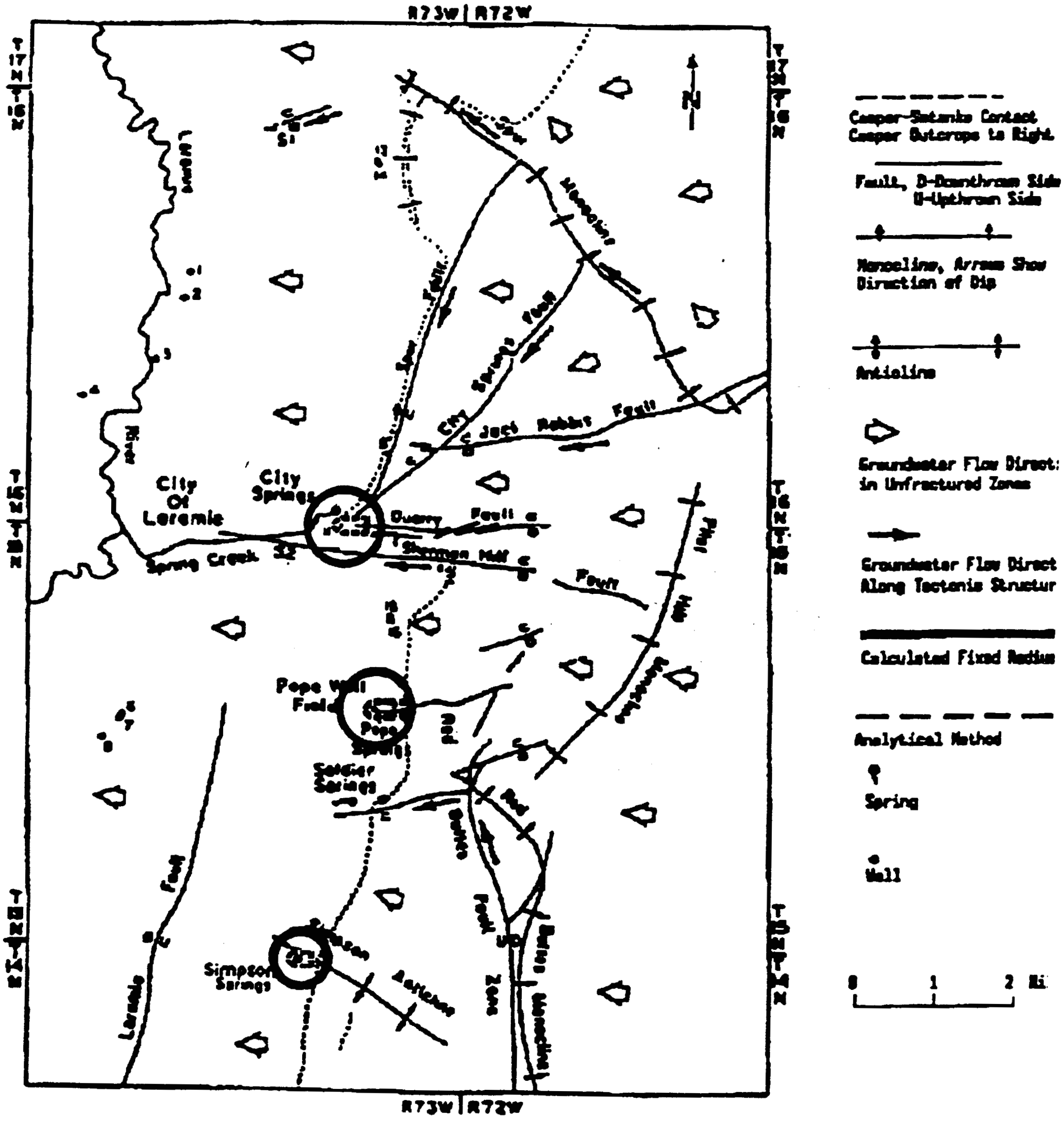


Figure 15. WHPA Analysis for Laramie Example (10 yr TOT). (US EPA, 1988)

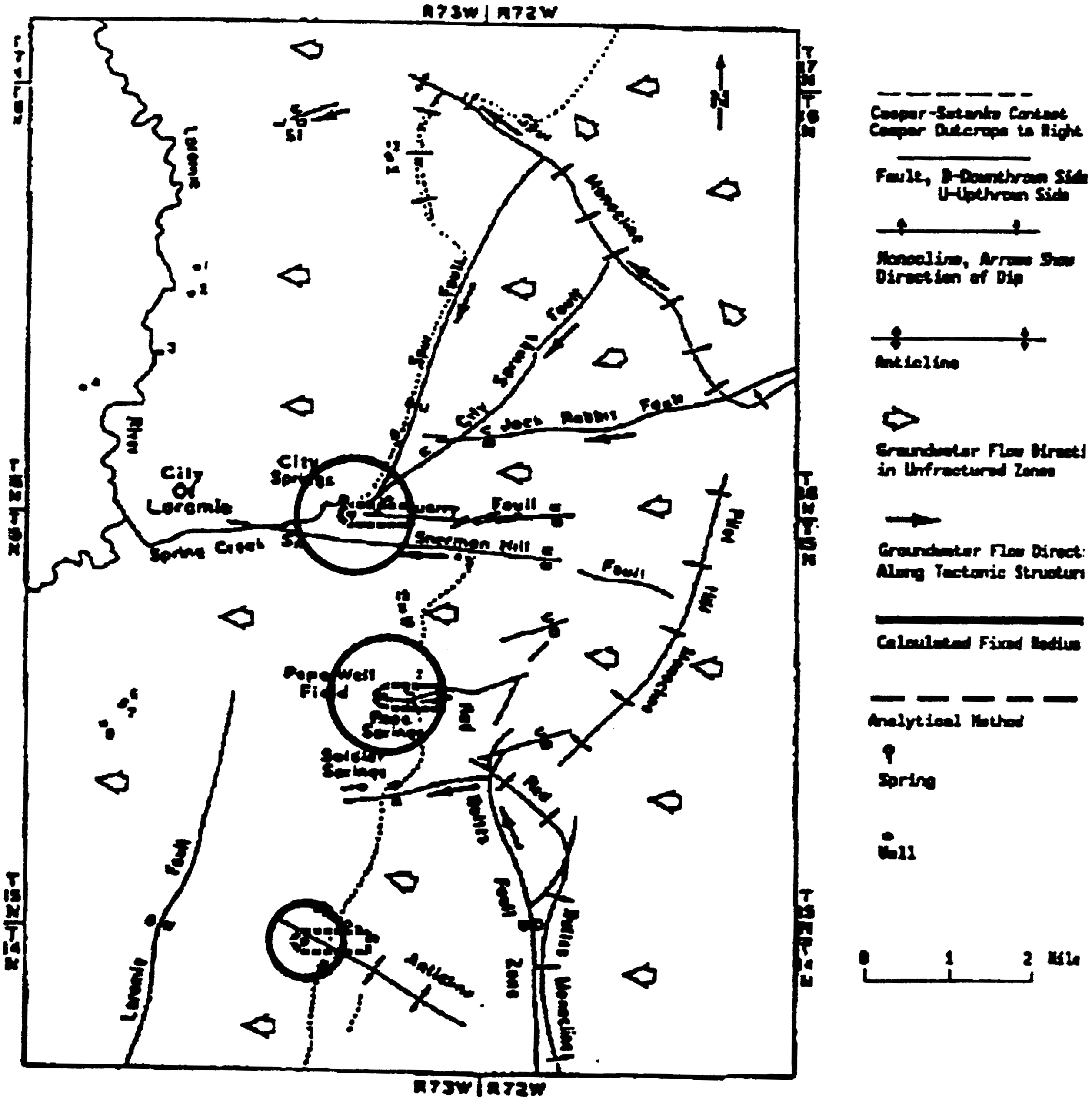


Figure 16. WHPA Analysis for Laramie Example (25 yr TOT).
(US EPA, 1988)

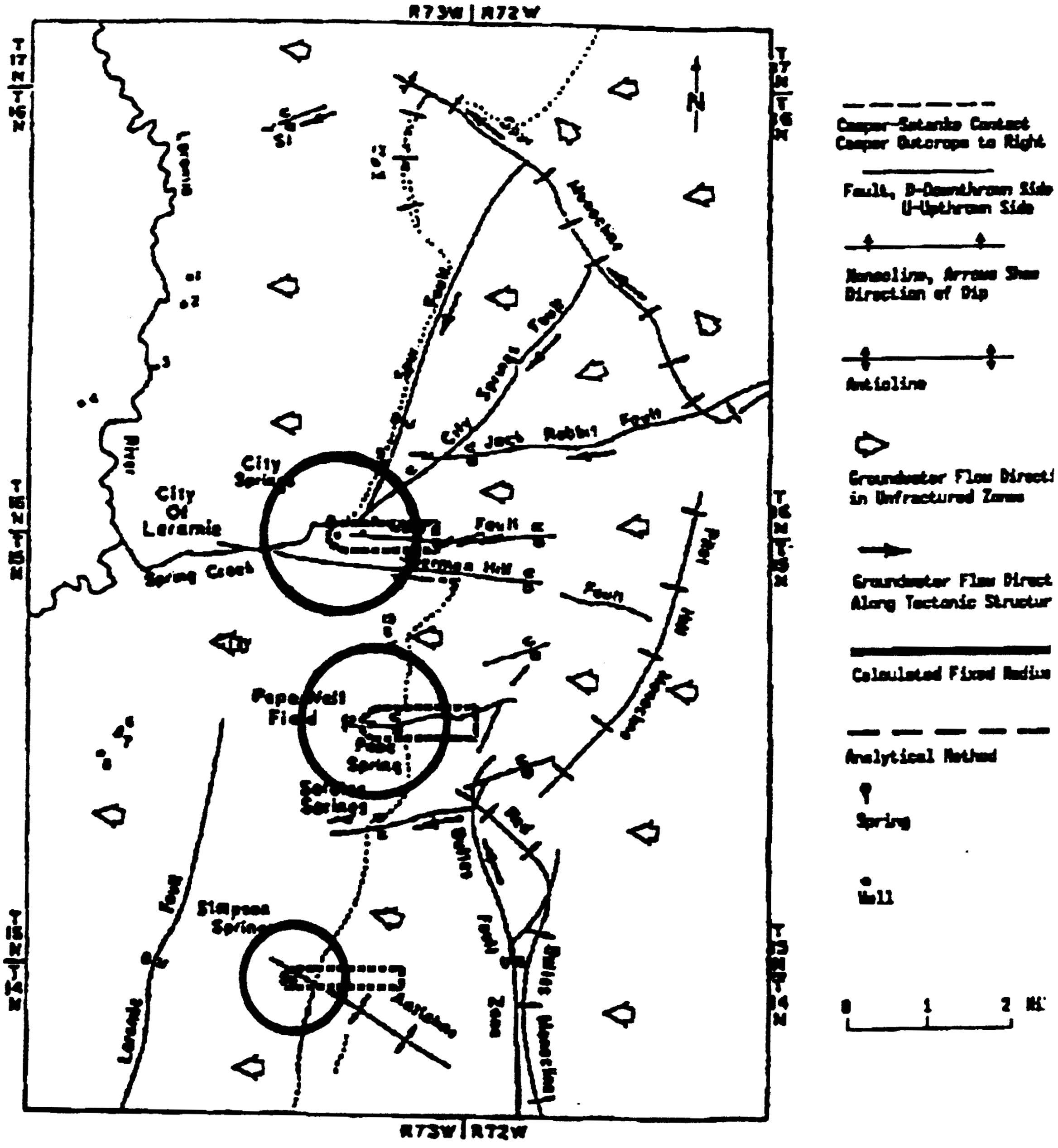


Figure 17. WHPA Analysis for Laramie Example (50 yr TOT). (US EPA, 1988)

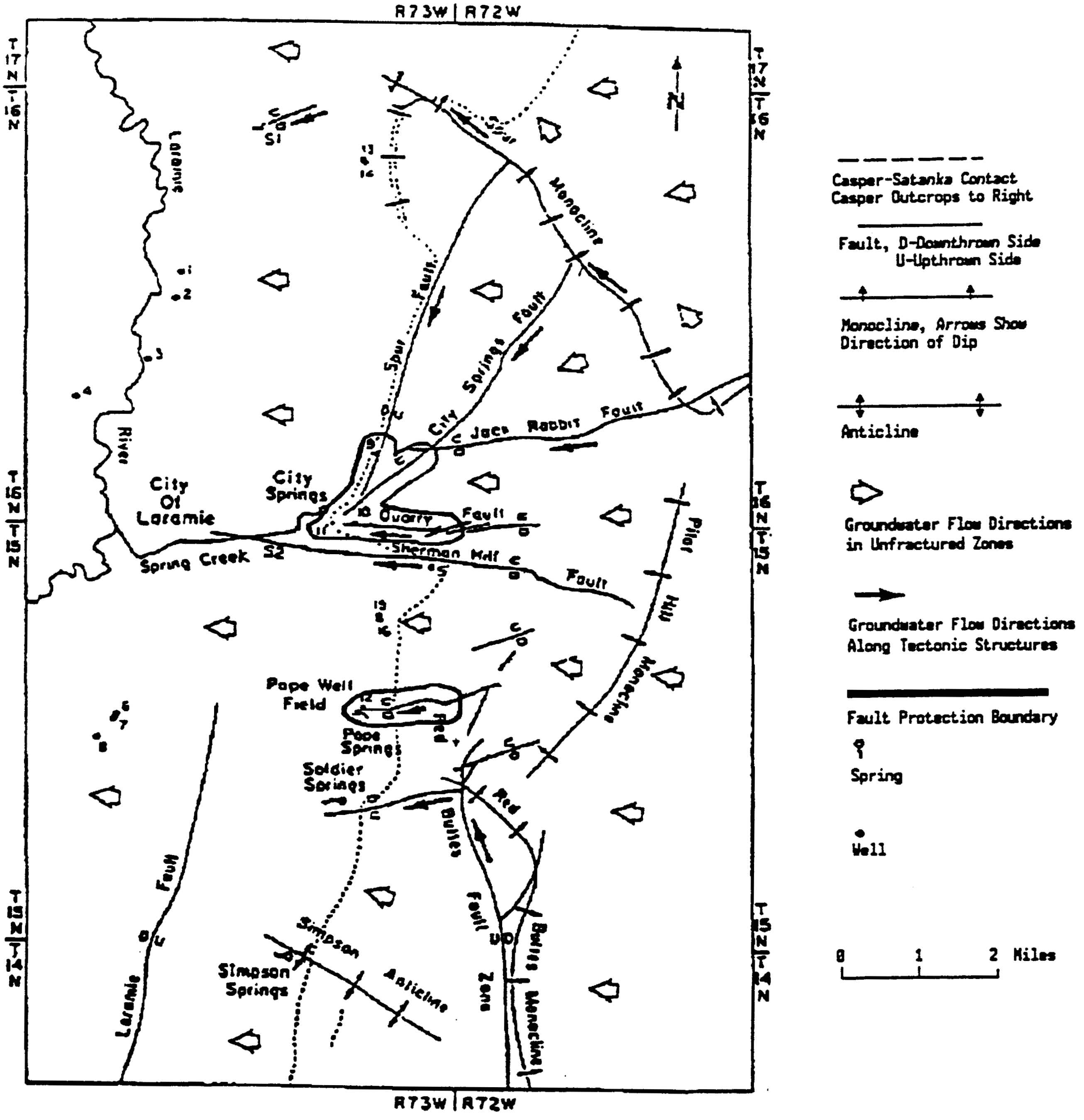


Figure 18. Delineation of Fault areas.
(US EPA, 1988)

Table 2. CFR Delineation Areas for Each Well Field.

City Springs area

Porosity = 24%
Open interval = 650 ft
Flow rate = 210787500 ft^3/yr

Travel time to well (yr)	Radius of WHPA (ft)
10	2075
25	3280
50	4640

Pope Springs area

Porosity = 24%
Open interval = 700 ft
Flow rate = 2171750000 ft^3/yr

Travel time to well (yr)	Radius of WHPA (ft)
10	2030
25	3210
50	4535

Simpson Springs area

Porosity = 24%
Open interval = 700 ft
Flow rate = 82946250 ft^3/yr

Travel time to well (yr)	Radius of WHPA (ft)
10	1250
25	1980
50	2800

Table 3. Analytical Method Delineation Areas for Each Well Field.

Hydrogeologic parameters in the Casper Aquifer[a]

$i = 0.0594$
$K = 1.5$ ft/d
Porosity = 24%

Flow velocity in aquifer = 0.37 ft/d

Distance to 10-year TOT line:	1355	ft (0.25 mi)
Distance to 25-year TOT line:	3390	ft (0.65 mi)
Distance to 50-year TOT line:	6775	ft (1.28 mi)

Pope Springs area

$T = 20500$ ft^2/d
Open interval=700.00 ft
Flow rate = 595000 ft^3/d

Boundary limit for water entering well:$Y_L = \pm 245$ ft
Distance to down gradient null point:$X_L = - 80$ ft

City Springs area

$T = 17250$ ft^2/d
Open interval = 650.00 ft
Flow rate = 577500 ft^3/d

Boundary limit for water enter well	± 280 ft
Distance to down gradient null point	- 90 ft

Simpson Springs area

$T = 17250$ ft^2/d
Open interval = 700 ft
Flow rate = 227250 ft^3/d

Boundary limit for water enter well	110 ft
Distance to down gradient null point	-35 ft

Note a: Value is for Casper aquifer in the vicinity of Huntoon #1.

Table 4. Calculations Used In Determining WHPA's.

CFR Method

Volumetric Flow Equation: $r=\sqrt{\frac{Qt}{\pi nH}}$

Analytical Method

Flow velocity in aquifer: $K\frac{i}{n}$

Distance to TOT line equation: (v)(t)

Boundary limit for water entering well:

$$Y_L=\pm\frac{Q}{2Ti}$$

Distance to down gradient null point:

$$X_L=-\frac{Q}{2\pi Ti}$$

Where:

Q = Pumping rate of Well
n = Aquifer porosity
H = Open interval or length of well screen
t = Travel time to well
T = Transmissivity
i = Hydraulic gradient
v = Flow velocity
π = 3.1416

Summary

Groundwater is a valuable source of potable drinking water, because of its availability and quality. In rural areas 96% of all drinking water originates from groundwater supplies. It is easily accessible in most parts of the country. Also it is usually a safe source for drinking water, since it is not subject to extremes in temperatures, nor generally to changes in quality, and it is buffeted from floods and droughts that may have an affect on surface water supplies.

Since it is usually found in the upper regions of the subsurface, it can be more economical to produce than building a facility to process surface water. But, if this source of pure drinking water is not protected in some manner, it can become contaminated and than it can be very costly and a time consuming problem to rectify. It is much easier and reasonably inexpensive to delineate a protection area around a well or well field, than it is to try to clean up a groundwater supply after it has been contaminated. Thus it is important to set up protection areas to guard groundwater supplies from possible contamination from surface or subsurface pollution before it is too late.

Unconfined aquifers are plentiful through out the country, however, they are most often the aquifers to become contaminated from chemical and biological sources. This is because the unconfined aquifer does not have a protective shield between the ground and water surface and they are exposed to the atmosphere, so they can become easily contaminated.

Unlike the unconfined aquifer, the confined aquifer has a confining layer between the ground surface and the water. Even with this protective layer, confined aquifers can still become contaminated. Critical areas where confined aquifers may become contaminated from chemical or biological pollutants are around recharge areas, and the area directly surrounding the well. Also if the confining layer is faulted or disjoined, there is a possibility that these areas could act as possible conduits for contaminates to travel along and eventually pollute the groundwater supply. Therefore these areas should also be protected from both chemical and biological contamination.

Every city should have some sort of wellhead protection program operating to protect its groundwater supplies whether those supplies are in confined or unconfined aquifers . The delineation method may be a simple arbitrary fixed radius method or a complex numerical flow/transport model, but some sort of program should be in operation. It can be as easy as choosing a radius for the arbitrary fixed radius method or as difficult and time consuming as gathering data for the simplified shape method or hydrogeological mapping.

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APPENDIX B

TORDATA2.XLS

OTHER ID	WELL NUMBER	MAP I.D. NUMBER	EASTING (FT)	NORTHING (FT)	PUMPING RATE (FT^3/DAY)	SATURATED THICKNESS (FT)	HYDRAULIC GRADIENT	DARCY'S K (FT/DAY)	TRANS (FT^2/DAY)
CITY 05	1	2	10500	11600	4226	160	0.001263	960	153600
CITY 14	2	13	6200	10800	8100	160	0.001263	960	153600
CITY 13	3	20	10100	20300	35500	65	0.014610	390	25350
CITY 15	4	25	10700	10200	49000	160	0.001263	960	153600
CITY 12	5	27	14600	11400	20000	30	0.001263	180	5400
CITY 07	6	36	13600	15000	24000	90	0.001263	540	48600
CITY 09	7	41	11000	10200	4812	160	0.001263	960	153600
CITY 11	8	42	12800	17500	2200	50	0.014610	300	15000
CITY 06	9	51	11800	17200	42000	50	0.014610	300	15000
CITY 04	10	56	13200	12800	128500	40	0.001263	240	9600
			CITY WELL AVG.	=	37200				
IRRIGATION									
24—61—2CB	11	102	15900	17700	16900	65	0.014610	390	25350
	12	103	13000	18800	16900	65	0.014610	390	25350
	13	104	12100	19200	16900	40	0.014610	240	9600
	14	A	16000	15300	16900	50	0.001263	300	15000
	15	B	13600	9700	16900	160	0.001263	960	153600
	16	C	12800	9400	16900	160	0.001263	960	153600
24—61—10C	17	D	11900	10800	16900	160	0.001263	960	153600
	18	E	10600	19800	16900	65	0.014610	390	25350
	19	F	8800	19900	16900	50	0.014610	300	15000
					AVERAGE =	94	0.006883	562	68937
		39	3200	9300	16900	160	0.001263	960	153600
		64	3100	9800	16900	160	0.001263	960	153600
24—61—5CB1			1000	18100					
24—61—15CC1			10800	5900					
CITY 08			9300	13800					

APPENDIX C

Delineation of Well Head Protection Area (WHPA) at Laramie Basin of The Casper Aquifer

Introduction

In my previous reports (report 1 dated 06/25/92 and report 2 dated 07/29/92), the well head protection areas (WHPAs) with respect to Turner and Pope well fields were delineated based on two well discharge values obtained from Laramie Water Treatment Plant and State Engineer's Office (Cheynne) respectively. Also, in report 2, it was stated that WHPAs for Turner1 and Turner2 for 3, 5 and 10 years do not change much. The maps attached with the present report contains WHPAs with reasonable shapes and sizes with the same discharge values presented in report 2. The only difference between the current study and the previous one (report 2) is that the area of each of zones 1 and 2 used for modeling was shortened in north-south direction so that each zone of the aquifer can be considered more like an Equivalent Porous Midium (EPM). The transmissivity values were also taken to be less than what was considered in earlier studies because once the aquifer was assumed as a porous medium, the equivalent transmissivity must be less than those at fault locations. In the previous delineations the transmissivity at fault location was considered to be same as that of the whole aquifer. For the respective values of transmissivity, porosity and well locations, see tables 1 and 2 in the next section.

In this report a brief discussion about various methods available for delineating WHPAs in fractured rocks is included. Also, the criteria for considering a fractured rock medium as an

Equivalent Porous Medium (EPM) is described.

Delineation of WHPAs at Laramie Basin

The GPTRAC code needs the number of zones and their respective locations based on transmissivity and porosity values. Therefore, in this study, the aquifer was divided into two zones. (see figures 1, 2 and 3). Zone 1 includes all the wells and most of the fractures in the forms of faults surrounding the wells. The transmissivities at fault locations range from 18000 ft^2/day to 23000 ft^2/day (Lundi, 1978). Therefore, the equivalent transmissivity for the whole of zone 1 was taken to be 15000 ft^2/day. Thus the EPM approach was utilized. Next, each zone was discretized into various cells each having a hydraulic head value. The hydraulic heads were obtained by interpolating the values given in the potentiometric map of Lundi (1978)

Zone 2 is situated near the downstream end of ground water flow. There is no municipal well situated in this zone and the presence of faults is minimal in this zone. The transmissivity and porosity values for this zone were taken to be 1000 ft^2/day and 0.03 respectively. These values were assumed from past experience of WHPA delineation at Torrington which was purly a porous medium aquifer.

From the geological sections given with Lundi's equipotential map (figure 8 in Lundi's Thesis), it is evident that thickness of the aquifer is greater in the west than that in the east. The thickness in the west was given as 700 ft by Lundi and hence the thickness in the east was considered to be 650 ft. Thus the thickness of zone 1 was taken to be 700 ft. and that of zone 2 was taken to be 650 ft.

Zone 1, thickness = 700 ft.

Well	Coordinates		Discharge	Transmissivity		Porosity
	x(ft)	y(ft)	ft^3/d	x(ft^2/d)	y(ft^2/d)	
Turner1	8184	16922	336924	15000	1000	.01
Turner2	5322	16922	240660	15000	1000	.01
Pope	7920	2640	1155168	15000	1000	.01

Table 1: Transmissivity, Porosity and Well locations in zone 1.

Zone 2, thickness = 650 ft.
(No municipal well situated)

Transmissivity		Porosity
x(ft^2/d)	y(ft^2/d)	
1000	1000	.03

Table 2: Transmissivity and Porosity of the aquifer in zone 2.

Methods for delineating WHPAs in fractured rocks

In this report, the methods which were used for delineation of WHPAs (EPA, June 1991) at the village of Junction City (central Wisconsin) and at the town of Sevastopol (north eastern Wisconsin) will be described. In those sites the aquifer medium was fractured dolomite and for Laramie basin it is fractured sandstone with occasional intrusion of fractured limestone and dolomite (see figure 4).

The methods tested in order of increasing complexity at Wisconsin sites are given below.

1) Arbitrary fixed radius
2) Calculated fixed radius
3) Vulnerability mapping
4) Flow-system mapping,
    - with TOT criterion
    - with analytical equations
5) Residence time approach and
6) Numerical flow/transport models.

The first two methods are not particularly suitable for the accurate delineation of WHPAs in fractured rocks. The arbitrary fixed radius method does not incorporate any hydrogeologic or contaminant transport considerations, and can best be used as a first-step approach. When the radius is large enough, the true ZOC will be included within the WHPA delineated by methods 1 and 2 and will be protected. However, large areas outside the ZOC will also be protected. The application of analytical flow equations to calculate a fixed radius brings an improvement over

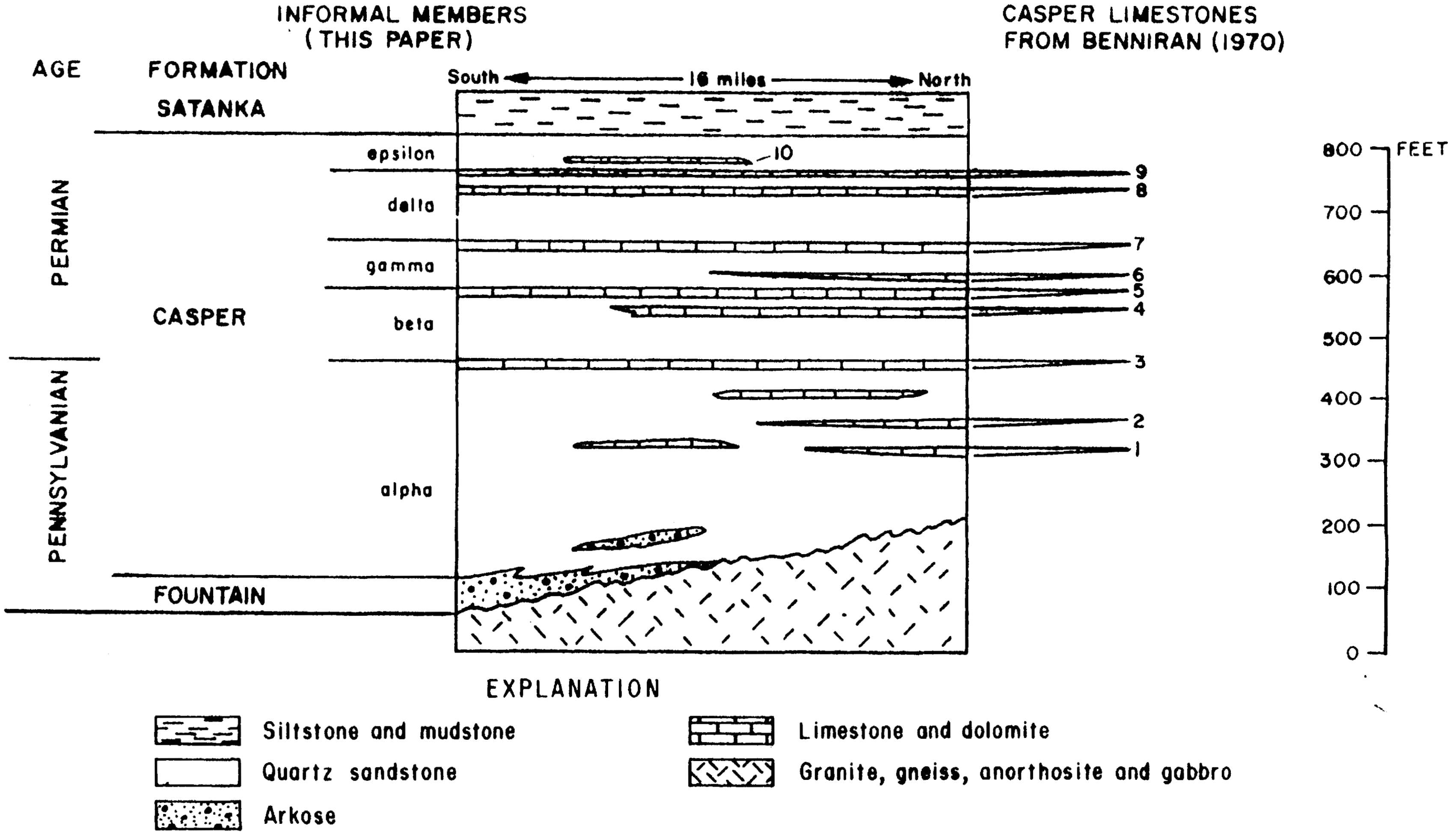

Figure-4: Cross section of the Aquifer at Laramie basin.

the arbitrary fixed radius method, but may not give acceptable results in unconfined fractured rock settings because it fails to account for heterogeneity, anisotropy, groundwater recharge, and vertical components of flow all of which can occur in fractured rock settings.

The three methods - flow system mapping and flow system mapping combined with TOT criterion or with analytical equations, the residence time approach, and numerical modeling were found suitable for ZOC delineation in unconfined fractured rocks that behave as a porous media at the WHPA scale.

Four WHPA delineation approaches were suggested for unconfined fractured-rock aquifers that do not behave as porous media. These methods include vulnerability mapping combined with the arbitrary fixed radius method or the simplified variable shapes method, hydrogeologic mapping, the residence time approach, and numerical ground water flow/ transport modeling. The following sections describe each of these methods in detail.

Vulnerability mapping uses geologic maps, soils maps, water table maps, aerial photographs, and mapping of surficial features to identify areas of landscapes particularly vulnerable to ground water contamination. Vulnerability mapping does not produce a ZOC for a given well; however, it does identify significant fractures near the well that may contribute to ground water contamination. Vulnerability mapping combined with the arbitrary fixed radius method or the simplified variable shapes method (U.S EPA, 1987) can be used to delineate a WHPA in fractured rocks that do not approximate a porous media.

Advantages of vulnerability mapping

1) The assumption of uniform porous medium is not necessary.

2) The method does not require detailed measurement of aquifer parameters.

3) The method uses a variety of data, ranging from office available maps to field measured surface features.

Disadvantages of vulnerability mapping

1) The method does not delineate a ZOC for the well.

2) The results are somewhat subjective.

Flow-System Mapping

Description:

Hydrogeologic mapping (U.S. EPA, 1987) identifies the physical and hydrologic features that control ground-water flow. Physical boundaries to ground-water flow can include the geologic contacts that form the limits of the aquifer, structural features such as fault-block walls or zones of fracturing, and topographic features that may function as ground water divides. Hydrologic features, including rivers, canals and lakes, can function as flow-system boundaries. The flow system mapping method, a subset of the hydrogeologic mapping method, uses ground water divides and flow system boundaries derived from a water-table map to delineate the ZOC for a given well.

Flow-system mapping assumes that hydrogeologic boundaries, particularly potentiometric boundaries, are stationary through time. In aquifers where water levels fluctuate seasonally or where drawdowns approach potentiometric divides, caution must be used when delineating boundaries for ZOC analysis.

Flow-system mapping assumes that hydrogeologic boundaries, particularly potentiometric boundaries, are stationary through time. In aquifers where water levels fluctuate seasonally or where well drawdowns approach potentiometric divides, caution must be used when delineating boundaries for ZOC analysis.

Flow-system mapping requires detailed mapping of the configuration of the water table. Ideally, investigators should use field measurements in properly constructed monitoring wells and nested piezometers for construction of such maps. In practice, funding and time considerations can rule out such detailed field work. In some situations, available office data, in the form of water levels on well constructors' reports, previous hydrogeologic studies, and surface-water features on topographic maps, can produce acceptable water table maps (Blanchard and Bradbury, 1987). Field measurements of water levels in existing domestic and industrial wells can supplement these data.

Once a water-table map is constructed, flow lines are drawn perpendicular to the water-table elevation lines. These flow lines begin at the well and extend upgradient to the ground-water divide. Using a water-table map to determine ground water flow lines assumes an isotropic aquifer, which is not always the case in fractured rock settings. In simple hydrogeologic settings (without major faults, facies changes, etc.), the ZOC delineated by the flow system mapping method takes into account the ground-water flow system geometry. It neither includes downgradient areas that do not contribute water to the well nor excludes upgradient areas that do contribute water to the well. This method tends to be conservative in the sense that it usually overestimates the true ZOC for a given well.

Advantages of the flow system mapping method are

1) The method is simple and requires only limited training in hydrogeology;

2) The methods can be used with various types of data ranging from office data to detailed field data;

3) The method uses mappable hydrogeologic boundaries.

Disadvantages of flow system mapping method are

1) The method assumes a uniform, two dimensional aquifer that approximates a uniform porous medium.

2) The method can produce unacceptably large ZOC estimates if the protected well is located far from a ground-water divide;

3) Errors in the water-table map can cause large errors in ZOC delineation.

Flow-System Mapping with Time of Travel Calculations

A water-table map can be used to estimate the horizontal hydraulic gradient. Using the gradient in combination with estimates of hydraulic conductivity and aquifer porosity, ground-water velocity can be calculated according to:

$$v = Ki/n \text{ .... } (1)$$

where v is the average linear velocity of the ground water, K is the horizontal hydraulic conductivity, i is the horizontal hydraulic gradient, and n is the porosity. The velocity, in combination with a specified time of travel, can be used to limit the WHPA to that portion of the ZOC that will contribute water to the well within a specified amount of time. Determination of the position of the TOT line incorporates the assumption that contaminants in ground water will move in the same direction and at the same velocity as the ground water.

Calculation of the TOT boundary is based on:

$$d = vt \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where d is the upgradient distance from the well to the TOT line, v is the average linear velocity across the ZOC (calculated using equation 1 above), and t is the desired time of travel. Note that the hydraulic gradient, i, in equation 1, is calculated as the total change in water table elevation from the upgradient ZOC boundary to the well divided by the horizontal distance from the upgradient ZOC boundary to the well. This is clearly a simplification of reality because, in most cases, i will not be uniform over the basin. However, in most cases, the error in the location of the TOT line will be small.

<u>Advantages of combining flow-system mapping with the TOT criterion are</u>

1) The TOT criterion provides a way to limit the WHPA in areas where the ZOC delineated from flow-system boundaries is unacceptably large;

2) Adding the TOT criterion requires little additional work once the flow-system method has been completed;

3) The method requires only elementary mathematics.

<u>Disadvantages of combining flow-system mapping with the TOT criterion are</u>

1) Errors in estimates of porosity or hydraulic conductivity

can cause large errors in the TOT calculation and thus in WHPA delineation;

2) The method assumes a uniform, two dimensional aquifer that approximates a uniform porous medium;

3) The presence of a highly conductive fracture zone could cause very large errors in the TOT calculation and in the resulting WHPA.

Flow-System Mapping with Uniform Flow Equation

Description:

The construction of a water-table map allows the application of the uniform flow equation (Todd, 1980) to define the ZOC to a pumping well in a sloping water table. The input requirements are the same as for combining flow-system mapping with the TOT criterion. The uniform flow equation assumes a uniform porous medium and can be expressed as:

$$-Y/X = \tan(2\pi KbiY/Q) \ldots\ldots \quad (3)$$

where Y is the distance from the well parallel to the pre-pumping equipotential lines, K is the hydraulic conductivity, b is the saturated thickness of an aquifer, i is the pre-pumping hydraulic gradient, and Q is the well pumping rate. This equation leads to two equations that delineate the ZOC of a well:

$$X_1 = -Q/(2\pi Kbi) \ldots\ldots\ldots \quad (4)$$

and

$$Y_1 = \pm Q/(2Kbi) \ldots\ldots\ldots \quad (5)$$

where X_1 is the distance from the well to the pre-pumping downgradient null or stagnation point, and Y_1 is the distance to the transverse boundary limits from the upgradient boundary center.

Advantages of this method are

1) The method accounts for some of the effects of pumping on the ZOC without detailed mapping of a cone of depression, which reduces the amount of required field work,

2) The method is simple and requires only limited training in hydrogeology;

3) The method uses data derived from a water-table map.

Disadvantages of this method are

1) The method assumes a uniform, two-dimensional aquifer that approximates a uniform porous medium;

2) The method ignores the effects of hydrologic boundaries (except ground-water divides), aquifer heterogeneities, and non-uniform recharge;

3) The method can produce unacceptably large ZOC estimates if the protected well is located far from the ground-water divide;

4) Errors in the water-table map or in estimates of porosity or hydraulic conductivity can cause large errors in ZOC delineation.

Residence-Time Approach

Description:

The residence-time approach utilizes water chemistry and isotopes to identify ground-water travel paths and flow rates. Geochemical parameters (for example mineral concentrations and saturation indices) can help indicate the source area of ground water. Environmental isotopes (tritium, oxygen-18) in ground water can be used to estimate a minimum age of water produced by a well. Such analyses are relevant to ZOC and TOT analyses in three ways. First, relative age determinations can provide a check on travel time estimates obtained by the hydraulic approaches described above. Second, in areas where the water produced by a well can be shown to be hundreds or thousands of years old, the potential ZOC of a well might be so large that local well Head Protection might not be appropriate or effective. Third, in areas where the geochemical or isotopic signatures of ground-water vary radically from place to place, these variations can be used to differentiate zones of rapid recharge from zones of less rapid recharge. For example, a well located near a river that produces water having geochemical and isotopic contents similar to the river water might be directly connected to the river through the fracture network; a well adjacent to a river that produces water with a different geochemical and isotopic content might not be directly connected to the river.

Tritium (^3H) is a radioactive isotope of hydrogen that is naturally present at low levels in the earth's atmosphere, but tritium in the atmosphere increased dramatically following atmospheric atomic weapons testing from 1952 to the mid-1960s. During this time, all recharging ground-water was enriched with tritium, and ground water was enriched with tritium, and ground water that has entered aquifer since 1952 generally contains elevated tritium levels. The half life of tritium (12.3 years) is relatively short, making it an excellent indicator of recent ground water recharge and relative ground water age (Egboka and others, 1983; Knott and Olimpio, 1986), where age is defined as the time since the water was in contact with the atmosphere. Hendry (1988) summarized the general qualitative interpretations of ground-water age on the basis of tritium in ground water. Tritium analyses are reported in tritium units- a ratio of tritium atoms (^3H) to the much more common (^1H) atoms. One tritium unit, or TU, represents one tritium atom per 10^18 hydrogen atoms.

<u>Advantages of the residence-time approach are</u>

1) The assumption of a uniform porous medium is not necessary;

2) The method can give information about relative ground-water age, which can be useful in determining the appropriateness of WHPA delineation;

3) The method helps confirm TOT estimates made by other techniques;

4) The method does not require detailed measurements of aquifer parameters, although knowledge of such parameters increases the method's usefulness.

<u>Disadvantages of the residence-time approach are</u>

1) The method requires skill and experience in geochemical and isotopic interpretation;

2) The method is not applicable to all settings, and results are sometimes ambiguous;

3) Geochemical and isotopic analyses can be expensive;

4) The method may not produce a mappable ZOC, but it can help confirm a ZOC and TOTs delineated by some other method.

Numerical Flow/Transport Models

Description:

A WHPA can be delineated using computer models that approximate ground-water and/or solute transport equations numerically. Such delineation is usually a two-step process: simulating a flow system followed by calculation of contaminant flow paths within that system. Where the hydrogeologic setting is complex, models can be particularly useful because they allow simulation of a wide variety of conditions and ground-water flow boundaries. Modeling of a flow system involves discretization of either a two or three dimensional problem domain into nodes. Such discretization can account for spatial variability of aquifer parameters, thus enabling the inclusion of aquifer heterogeneity and anisotropy in the model simulation. Most ground water flow models also allow for temporal variation of many parameters. The flexibility of computer models allows for variation of recharge rates, pumping rates, thickness of aquifer layers, storativity, and hydraulic conductivity. Models such as widely used U.S. Geological Survey (USGS) Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (McDonald and Harbaugh, 1988) are able to simulate pumping wells, rivers, drains, recharge, and evapotranspiration.

Most numerical models in the public domain at the present time (1989) simulate ground water flow using the governing equations of porous-media flow. Such models are adequate for well head protection studies in fractured rock aquifers if the aquifer behaves as a porous medium at the scale of the study. Although models that can simulate flow through fracture networks using the governing equations for fracture flow exist, few, if any, such models are currently in the public domain. In addition, the enormous data requirements for such models limit their use to very sophisticated studies.

Once a flow-system model is calibrated so that the simulated head distribution approximates the field heads, transport computer programs can simulate the probable flow paths that contaminants may follow and the TOTs of these contaminants. A ZOC can be delineated by starting these paths at various locations within the flow system and noting which flow paths terminate at the pumping well. Model-produced TOTs along these travel paths can further refine the ZOC using the TOT criterion.

Model simulations are only as reliable as their input parameter values. The cost and technical expertise needed for adequate data collection can be quite high and such collection can require substantial field investigations. Input parameters requiring some degree of field measurement can include aquifer transmissivity, porosity, and the thickness of various layers. Characterization of these layers requires a high degree of geological background and skill. Building, running, and calibrating the model are also complex tasks requiring skilled personnel and a large time investment. In general, if the modeled system is an accurate portrayal of the real system, the resulting ZOC represents the most accurate delineation possible.

Changes in the ZOC delineation resulting from natural or man-made effects can also be predicted. The accuracy and adaptability of the model to so many types of hydrogeologic settings make this method desirable, but it is usually the most costly method to implement in terms of time, money, and personnel. Numerical modeling is probably best applicable to those situations where the accuracy required or flow system complexities warrant such a costly approach.

Advantages of numerical simulation are

1) Commonly available numerical models can simulate aquifers in three dimensions and can include most of the inhomogeneity, anisotropy, and transient behavior observed in the field;

2) If properly discretized, numerical models can simulate discrete fracture zones;

3) Because numerical models give an integrated solution over the model domain, ground water flow paths and travel travel times can be determined with much greater precision than with other methods;

4) Adequate numerical codes are widely available.

Disadvantages of numerical solution are

1) Most practical models require a porous-medium assumption at some scale;

2) Models require significant amounts of data for proper calibration, verification, and prediction;

3) Modeling is often very expensive and time consuming because it requires substantial amounts of data and expertise.

WHPA Delineation Methods for Fractured Rocks That Do Not Behave

As Porous Media

Fractured-rock aquifers that do not behave as porous-media aquifers generally fall into two categories. The first category includes aquifers with numerous interconnected fractures. These aquifers contain discrete zones or regions of intense fracturing, large fracture apertures or fractures widened by solution that are significantly more permeable than the surrounding fractured rock. The second category of fractured-rock aquifers that do not behave as porous-media includes rocks with very sparse and poorly connected fractures in a low permeability matrix. Such situations are probably most common in structurally homogeneous igneous and metamorphic rocks such as granite and quartzite. In such aquifers obtaining adequate yield for production wells can be difficult and usually involves completing the well to intersect one or two major water-bearing fractures that act as conduits and storage reservoirs for ground water.

In both cases, ZOCs based on well hydraulics or the uniform flow equation will be incorrect because they ignore the system heterogeneity. However, porous-media based numerical models may be able to simulate some of these systems by treating the permeable fractured zones as permeable model layers or a series of nodes in a less permeable matrix.

Khaleel (1987) described the criterion for assuming a fractured rock medium as an Equivalent Porous Medium (EPM). This paper deals with the columbia river basalt as the fractured medium. In this case, four possible flow situations were considered, such as, a) flow through open unfilled fracture with uniform aperture of .23mm, b) flow through open unfilled fracture with lognormal distribution of apertures, c) clay-filled fracture with a uniform aperture of .23mm and d) clay filled fracture of lognormal aperture distribution.

Criteria

A polar plot of $1/\sqrt{k_j}$ vs. α must result in an ellipse when the equivalent media can be considered as homogeneous, anisotropic or a circle when the equivalent media can be considered as homogeneous isotropic.

What is k_j and α and how to make a polar plot:

k_j is the hydraulic conductivity in the j direction and α is the angle of the plane along which the flow takes place.

How to make the polar plot

In evaluating an EPM approximation for fluid flow through fractured basalts, a two dimensional generation region is first selected and fracture patterns are produced according to postulated description of real fracture systems. Within a generation region, a flow region is selected for discrete fracture flow analysis. Boundary conditions are applied to the flow region so that material inside the flow region would experience a relatively constant hydraulic head as if it were a homogeneous anisotropic continuum (Long, 1985). A hydraulic head of 1.0 is assigned to all points where fractures intersect the inflow side, whereas a head of zero is assigned to the opposite outflow side. The other two sides are assigned no flux boundaries. Steady flux into the flow region in the direction of the applied hydraulic gradient is calculated using a Galerkin finite element program (Baca et al., 1984, England et al., 1985). The basalt rock matrix is assumed to be impermeable. By rotating the boundaries of the flow region α degrees and thereby rotating the direction of the gradient, the fluid fluxes can be calculated for various directions. The hydraulic conductivity, k_j, in the direction of the grdient can be calculated from j, the magnitude of the gradient applied across the flow region, and Q_j, the total outflow from the flow region in the direction of the gradient, i.e.,

$$k_j = Q_j/(A_j \cdot j)$$

where A_j is the area perpendicular to the applied gradient.

Thus, the values of various k_j and α are obtained. When these values are plotted the resulting graph may be a circle or an ellipse which indicates the validity of the assumption of equivalent porous medium (EPM). If the resulting plot does not result in a circle or an ellipse, then EPM approach is not valid and the delineation of WHPA msy be done by some other method.

Subjective criteria for determining whether fractured rock can be treated as a porous medium for the purposes of well head protection include pumping test responses, configuration of the water-table surface, the ratio of fracture scale to problem scale, distribution of hydraulic conductivity, and variations in water chemistry and water quality.

Long and others (1982) provide theoretical criteria for determining when fractured systems behave as porous media. They suggest that "fracture systems behave more like porous media when (1) fracture density is increased, (2) apertures are constant rather than distributed, (3) orientations are distributed rather than constant, and (4) larger sample sizes are tested".

Methods for delineation of WHPA in aquifers that do not behave as Porous medium

Once the aquifer is considered as equivalent porous medium, the numerical modeling can be used for WHPA delineation. If it is considered as EPM then Vulnerability mapping and hydrogeologic mapping can also be used. Vulnerability mapping may be used to identify areas particularly vulnerable to ground-water contamination, and these areas could form the basis for the delineation of a WHPA using the arbitrary fixed radius method or the simplified variable shapes method (U.S. EPA, 1987). Hydrogeologic mapping (U.S. EPA, 1987) uses geologic contacts, structural features, and water table maps to determine ground-water basin boundaries. In some cases, the ground water basin may function as the ZOC for a given well; in cases where the basin is small enough, the entire basin could be delineated as the WHPA.

The residence-time approach is useful in settings where the porous medium assumption doen not hold. This approach can be used to establish the age and geochemical origin of water produced by the well to be protected. The residence-time approach alone cannot be used to determine a WHPA and it should be used in combination with the hydrogeologic mapping method or the vulnerability mapping method.

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6/25/92 Report

INTRODUCTION

The Well Head Protection (WHP) program seeks to accomplish the goal of protecting groundwater sources from potential contamination. One of the major elements of WHP-program is the determination of zones within which contaminant source assessment and management will be addressed. These zones, called Well Head Protection Areas (WHPA's), are defined in the Safe Drinking Water Act (SDWA) as "the surface and subsurface area surrounding a water well or wellfield, supplying a public water system through which contaminants are reasonably likely to move toward and reach such water well or wellfield". There are some methods developed by USEPA for the delineation of WHPA. These methods are developed to assist State and Private agencies engaged in WHPA-delineation and these are available in various EPA publications. The method which was used here for the delineation of WHPA for Laramie-basin area of the Casper Aquifer is known as "General Particle Tracking Module (GPTRAC)" which is one of the four methods described in the manual "USEPA WHPA"-version 1.0, prepared by Blandford and Huyakorn of Hydrogeologic Inc., for the USEPA.

The GPTRAC has two options, one semianalytical and the other numerical. In this case, the numerical option was used because it is accurate and easy to handle.

The assumptions used in the GPTRAC are as follows:

1. Flow in the aquifer is at steady state
2. Flow in the aquifer is horizontal (two dimensional in areal view).

The first assumption implies that the aquifer is under equilibrium conditions, and therefore temporal variations in sources and sinks (including pumping) are not considered. This model is therefore most applicable to continuously used water supply wells. The second assumption implies that for both confined and unconfined aquifers if the drawdown to initial saturated thickness ratio is small (less than approximately 0.1), vertical flow of water can be ignored.

Hydrogeologic Characteristics of the Aquifer

To facilitate the hydrogeologic conditions, figures 1 and 2 may be seen. Figure 1 shows the map of equipotential lines of ground water flow of the aquifer. It may be noted that there are several faults passing through the sub-surface rocks and these faults act as conduits where the transmissivity values are very high (Lundy, 1978). There are three municipal wells which are the main sources of discharge from this aquifer. These three wells are Turner 1, Turner 2 and Pope wells. The locations and respective discharge are given in Table 1. Only these three wells were used for the delineation of WHPA and all other wells shown in figure 1 are domestic wells of very low discharge capacities. Therefore, all these domestic wells were excluded for the delineation of WHPA. From this map it is evident that ground water flow takes place from east to west. The equipotential lines represented by firm lines indicate outcrop area which is at higher elevation than the area consisting of equipotential lines represented by dashed lines (Lundi, 1978).

Figure 2 shows the geologic formation of the area (Lundi, 1978). Most of the aquifer rock consists of sand-stone and the depth of the aquifer varies from 600 to 700 ft. For GPTRAC model, depth = 700ft was used. The porosity of sand-stone may vary from 5 to 30 percent (Freeze and Cherry, 1979). For running the model it was observed that for porosity greater than 0.05, the model could not delineate the WHPA. Therefore porosity = 0.05 was accepted for sand-stone. It must be remembered that this porosity was found to work well when the transmissivity was taken to be 18000 - 23000 ft^2/day (Lundi, 1978). The reason for these high values of transmissivity is the presence of numerous faults in and around the well locations. For

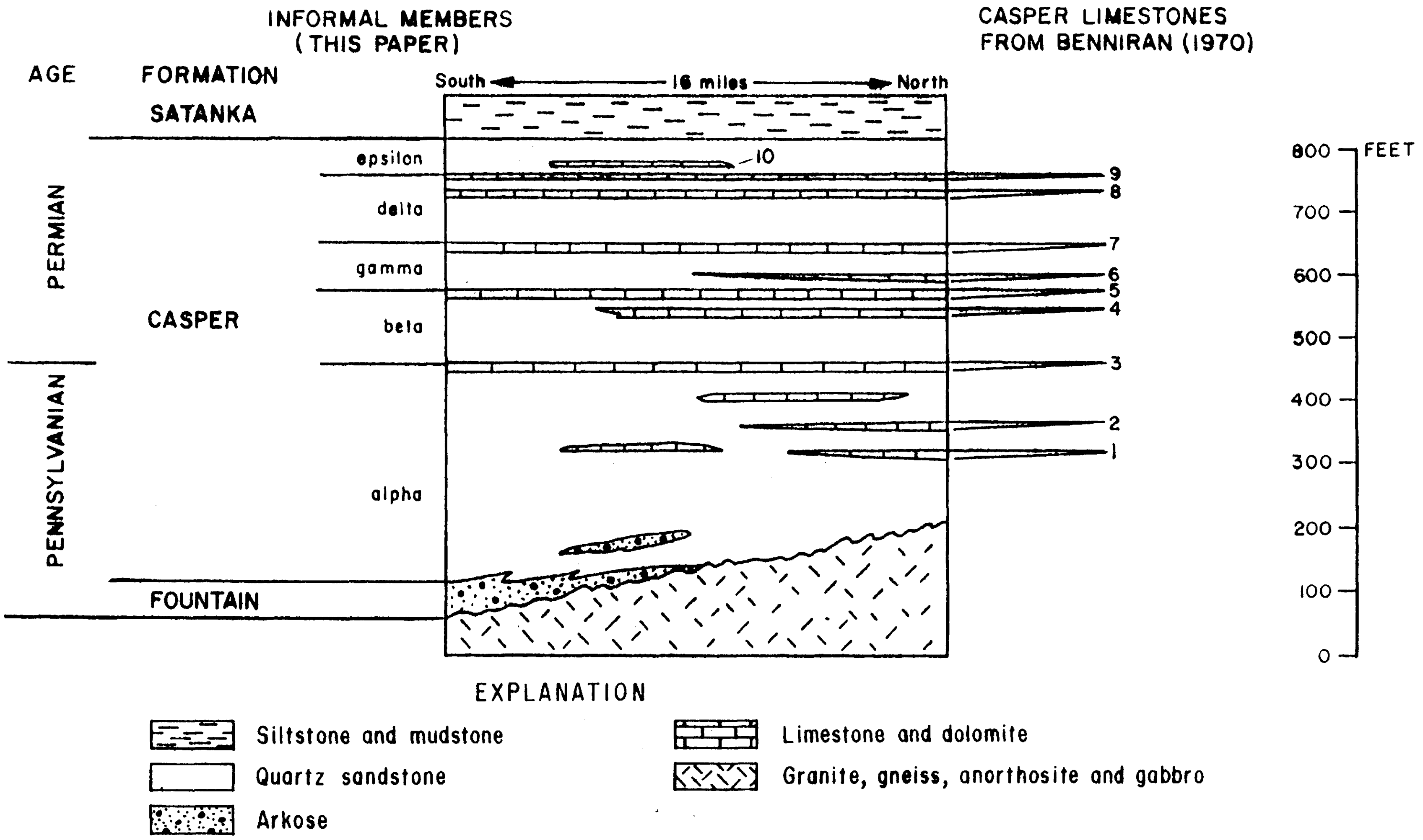

Figure 2 : Geologic formation of the rocks of Laramie Basin of the Casper Aquifer.

WHPA's see figures 3, 4 and 5 for time of capture = 8, 10 and 20 years respectively.

Use of the Model

The GPTRAC numerical program is a very user friendly Fortran program which mainly requires (1) Number of zones (2) Head at different cells (3) porosity, transmissivity and thickness of aquifer at each zone (4) number of pathlines for delineating the capture zone which is same as well head protection area (5) Inputs regarding the positions of wells, discharge rates, etc.

The whole Laramie basin was divided into two zones depending on the nature and number of faults. The southern part contains faults which are mostly oriented in a horizontal (east - west) direction. However, there are a few vertical (north-south) faults also. Therefore, both horizontal and vertical transmissivity values were considered in the model. The transmissivity value = 23,000 ft^2/day (Lundi, 1978) was used for both the directions. Zone 2 contains faults which are slightly slanted (oriented in northeast to southwest) and transmissivity for this zone was taken to be 18,000 ft^2/day for both the directions (Lundi, 1978). It was found that WHPA for 8 years in zone 1 became reversed and that in zone 2 became very small. It means that the model failed to calculate the WHPA for zone 1 for 8 year and that for zone 2 for less than 8 uears. However, it could delineate protection area for more than 8 years and figures 4 and 5 show the WHPA's for 10 and 20 years.

The discharge of each well was taken from the Water Treatment Plant, City of Laramie and their names, positions and transmissivities in the vicinity of the wells are given in Table-1 below.

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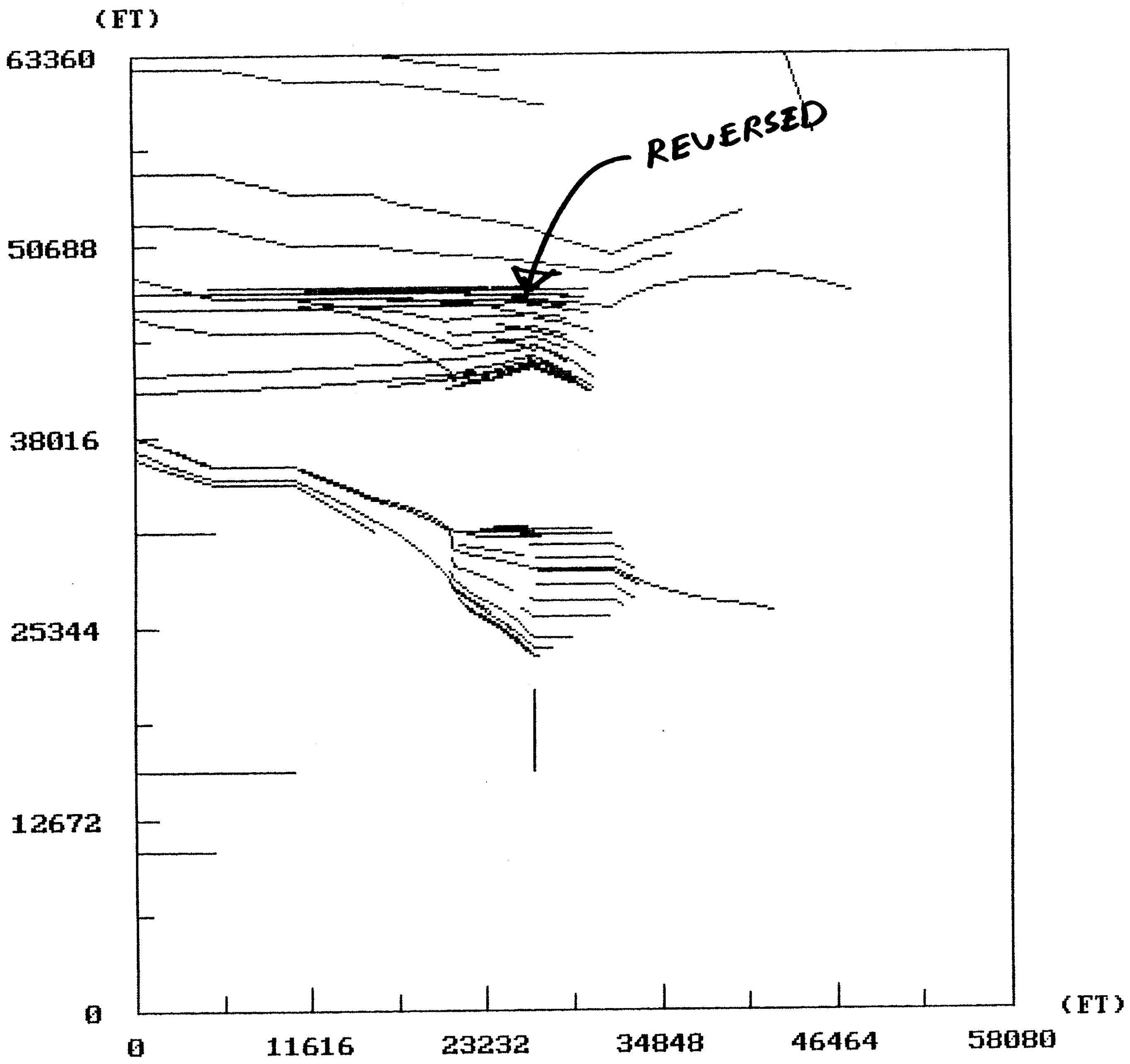


FIGURE-3 : WHPA FOR 8 YEARS

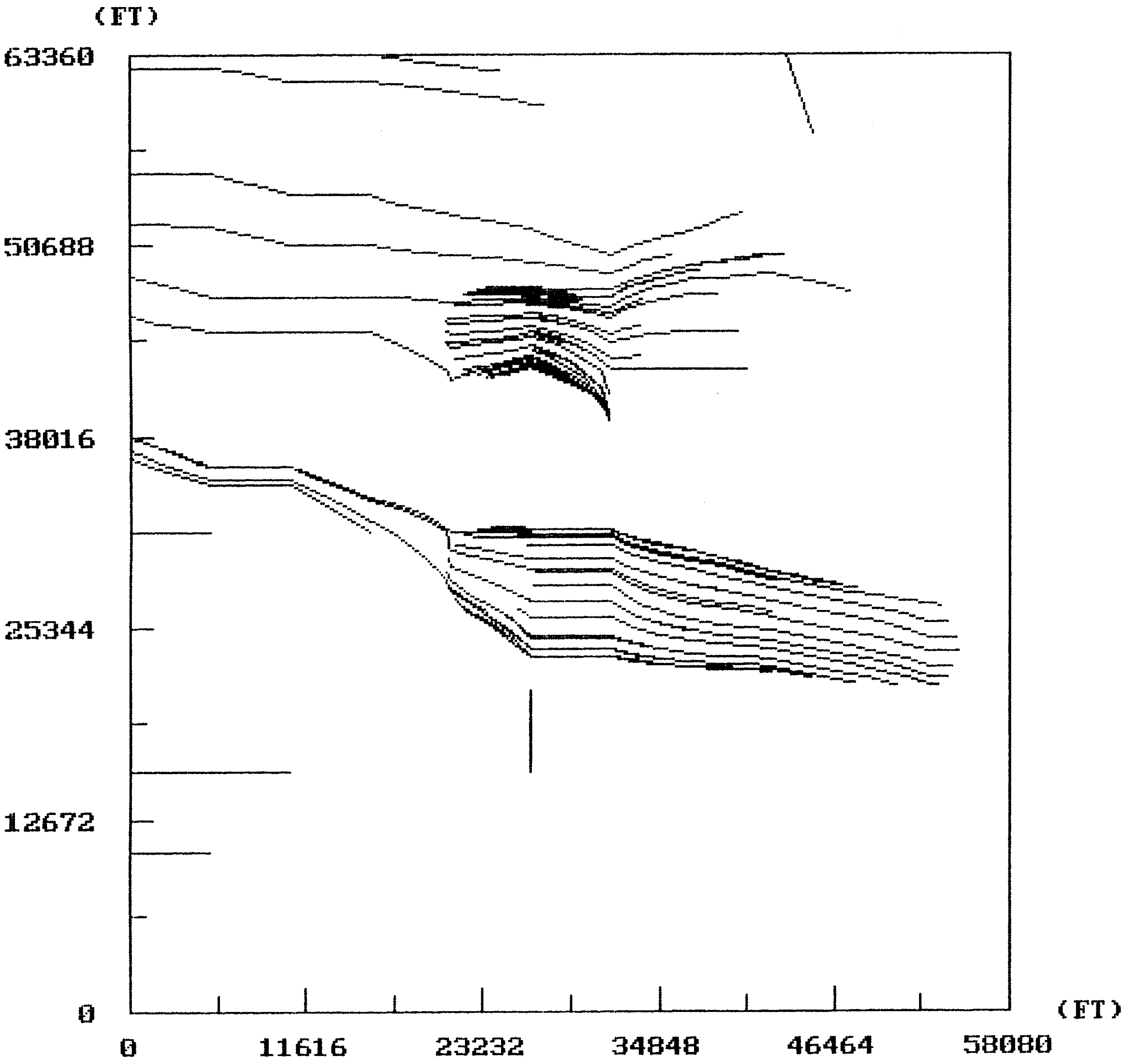


FIGURE-4: WHPA FOR 10 YEARS

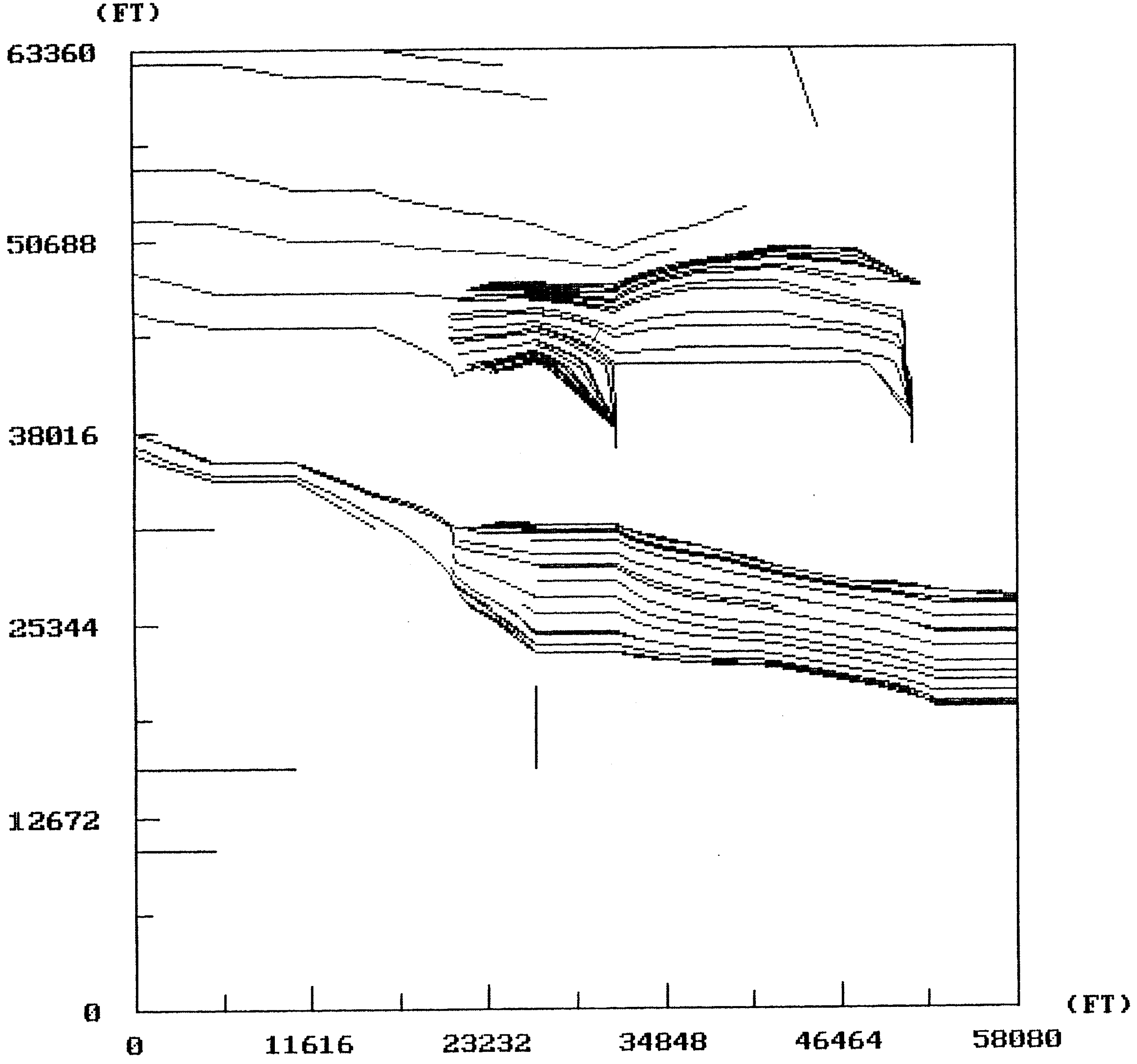


FIGURE-5 : WHPA FOR 20 YEARS

Well	Coordinates		Discharge	Transmissivity	
	X ft.	Y ft.	ft^3/day	X ft^2/day	Y ft^2/day
Turner1	24024	43322	401100	18000	18000
Turner2	21162	43322	307510	18000	18000
Pope well field	23443	29110	401100	23000	23000

Table 1 : Location of wells and their discharge values.

Conclusion

While running the model, it was observed that porosity and transmissivity are the two most sensitive parameters for the delineation of WHPA. The transmissivities of 18,000 ft^2/day for zone 2 and 23,000 ft^2/day for zone 1 were taken from data presented from Lundi (1978) and could be nearly accurate. Porosity less than 0.05 will make the WHPA greater for corresponding time period. For porosity greater than 0.05, the WHPA will be highly reduced and therefore we may not be worried about that.

References:

1. Blandford T. N and Huyakorn P. S. "USEPA WHPA". United States Environmental Protection Agency, Office of Ground Water Protection, February, 1990.
2. Freeze and Cherry. "Ground Water". Prectice Hall, New Jersey, 1979.
3. Lundi Don A. "Hydrology and Geochemistry of the Casper Aquifer in the vicinity of Laramie, Albany County, Wyoming". M.S Thesis submitted to the

Graduate School of University of Wyoming, December, 1978.

APPENDIX D

Introduction

WHPA, version 2, is a semi-analytical groundwater flow model that consists of four computational modules designed to delineate wellhead protection areas (WHPA's). This model was developed for the EPA Office of Groundwater Protection.

The WHPA model was utilized to determine WHPA's for existing municipal wells in and surrounding Torrington, Wyoming. WHPA is thought to be an appropriate technique for this situation because the contaminant of interest (nitrate) is conservative. In other words, groundwater flow approximates solute movement in this unconfined, shallow aquifer. The overall capture zone, otherwise known as the zone of contribution, for the Torrington well field represents that portion of the aquifer supplying groundwater to the wells for a specified period of time.

Each module will be discussed individually; but to summarize, three of the modules calculate capture zones for two-dimensional, steady state groundwater flow. The fourth module, called Monte Carlo, performs an uncertainty analysis of the delineated capture zone. The four modules are: (1) RESSQC, (2) the Multiple Well Capture Zone module (MWCAP), (3) the General Particle Tracking module (GPTRAC), and (4) the Monte Carlo module (Montec).

Background

A recent numerical simulation (Parks, 1991) of the alluvial aquifer surrounding Torrington, using Modflow, has provided the basis for this report. From this simulation, the aquifer flow system was characterized. Specifically, the potentiometric surface map, flow boundaries, porosity, hydraulic conductivity, and saturated thickness were either compiled or determined in the referenced study. Municipal well pumping capacities were determined from historical data from the Torrington Department of Public Works.

It is apparent from this study that a unique flow system exists. The most important features that influence the shape and size of WHPA's are the bedrock outcrops immediately north of Torrington. The potentiometric contour map also reflects these features. The darkened areas shown on Figure 1 represent the bedrock outcrops and their influence on the flow system. The outcrops appear to restrict flow (i.e., impermeable) and redirect it toward the breach. The bedrock outcrops are separated by a breach that behaves as a spillway, in which, groundwater flows from terrace deposits into the floodplain aquifer. Groundwater flow velocity increases within the breach because of the steep hydraulic gradient and converging streamlines. This results in long and narrow WHPA's. However, the primary impact on WHPA delineation is that the groundwater flow direction changes above and below the breach. This makes the task of WHPA delineation much more difficult. The approximate coordinates locating Torrington on Figure 1 are x=14 and y=4.

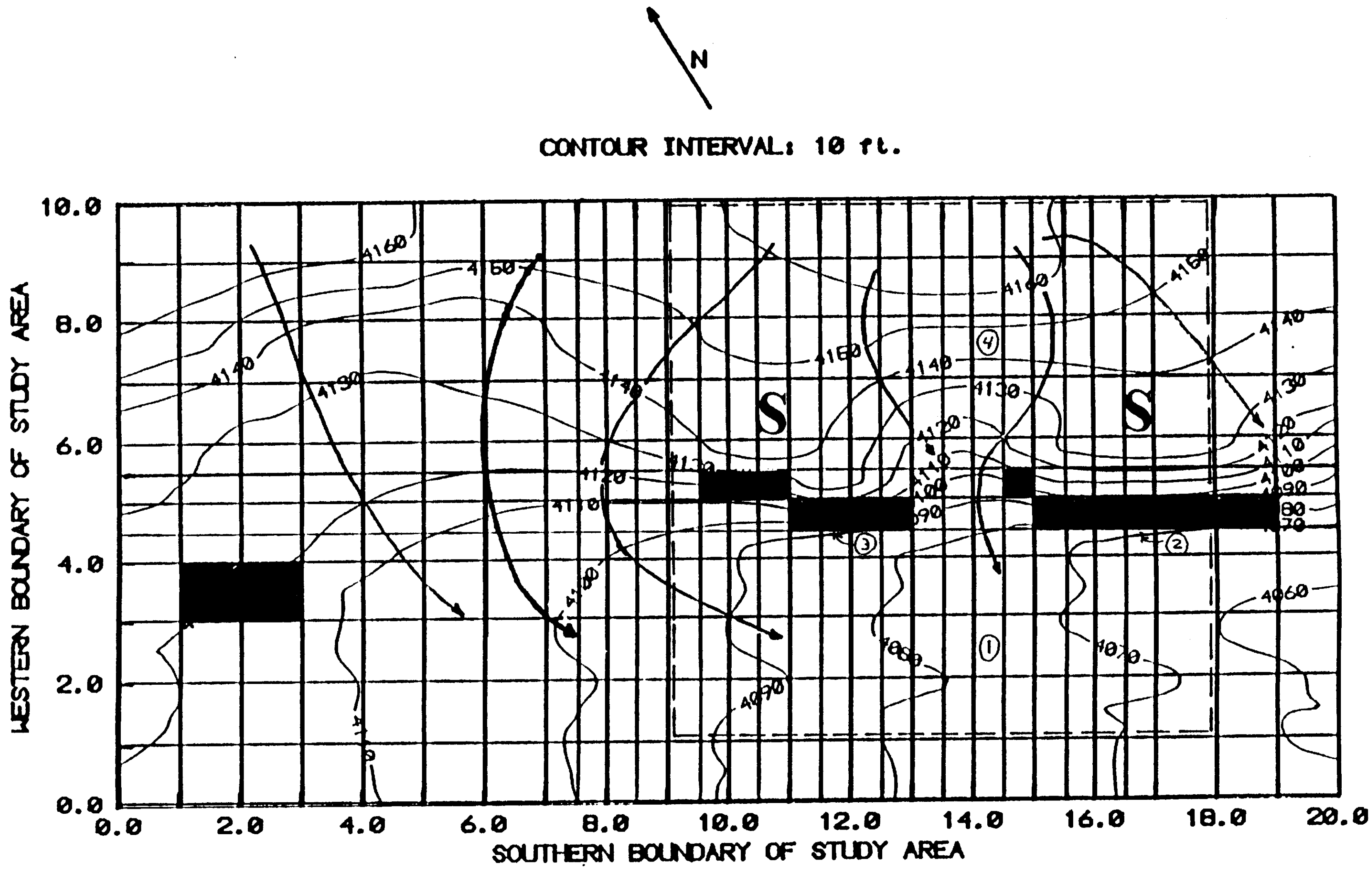


Figure 1. Areas of Stagnation (S) and Direction of Flow (arrows) in the Aquifer. (Parks, 1991)

Results and Evaluation

All four modules were evaluated for their applicability, and most were found to be inadequate or inappropriate for this groundwater flow system. In fact, the numerical option of the General Particle Tracking module is the only method for which results are presented.

GPTRAC

Numerical Option. The General Particle Tracking module contains two components, a semi-analytical and a numerical option. The numerical option is designed to be used as a postprocessor for numerical groundwater flow models. This option requires as input the hydraulic heads at nodes of the rectangular grid system. The head information is utilized to calculate x and y direction velocity components of groundwater flow at the edges of each grid block. Numerical integration of velocity components with respect to time and space is then applied to describe capture zones and streamlines.

The primary advantage of the numerical option is that a heterogeneous aquifer with complex boundary conditions can be considered. This method allows the aquifer to be divided into many zones with varying porosity, saturated thickness, and transmissivity in both the x and y directions.

For this investigation, the study area outlined in Figure 1 by the dashed line is divided into four zones. The zones are described as follows: (1) the floodplain aquifer, (2) the eastern bedrock outcrop, (3) the western outcrop, and (4) the terrace aquifer. Zones 2 and 3, the bedrock outcrops, are treated as impermeable zones with transmissivities substantially less than terrace and floodplain deposits. The North Platte river is not represented in this study. It is thought that this is a more conservative approach resulting in larger WHPA's.

The numerical option delineates capture zones around pumping wells for steady state groundwater flow. Consequently, some assumptions were necessary as to the average daily pumping rates of municipal wells. These wells were assumed to operate half of the time. In other words, the rated pumping capacities were halved and input as steady state pumping rates. Domestic wells were not considered.

The results of the numerical option applied to the study area are presented in Figures 2, 3, and 4. Figures 2, 3 and 4 represent the overall capture zones for the municipal well field for travel times of 3, 5 and 10 years, respectively. From these Figures, the locations of the bedrock outcrops and the breach are readily apparent. However, the capture zones for individual wells are not so easily recognized because of the close proximity of adjacent wells and the converging and diverging groundwater flow at the entrance and exit of the breach.

Figure 5, the transparency of the Torrington area, is provided as an overlay to get a sense of the actual WHPA sizes. The dark circles indicate municipal well locations. The map image was distorted by the numerous reducing steps so locations on the map should not be considered as exact.

Figure 2. Overall Capture Zone (Three-Year Simulation)

Figure 3. Overall Capture Zone (Five-Year Simulation)

Figure 4. Overall Capture Zone (Ten-Year Simulation)

The yellow lines shown on Figures 2, 3 and 4 indicate forward-tracked pathlines of individual particles over a five year period. Forward tracking is normally used to determine if a pollution source will contaminate a pumping well. The red pathlines delineate time-related capture zones of 3, 5, or 10 years.

One shortcoming of this module is that it failed to produce reasonable results for smaller time-related capture zones. For simulation times less than three years, the capture zone pathlines did not conform to the regional hydraulic gradient. Initially, the three-year simulation illustrated this problem. Capture zone pathlines originated at the well and proceeded downgradient instead of upgradient as expected. The upgradient portion of the capture zone, however, appeared to be reasonable. This was overcome by dividing the floodplain aquifer into finer grid blocks. Hydraulic head values for new and smaller grid blocks were estimated by linear interpolation between known heads in a north-south fashion. A much finer grid system would be necessary to delineate a one-year WHPA.

The EPA Office of Groundwater Protection recommends time periods of 10 to 25 years when determining time-related capture zones. It was necessary to balance, when considering the lengths of simulation periods, the limited size of the study area and constraints of the model. 3, 5, and 10 year simulation periods were selected simply because that appears to be the lower limit which still yields reasonable results. However, these simulation times resulted in capture zones that approach or exceed the size of the study area to the north where hydraulic heads are unknown. Results of the three-year simulation did not extend beyond the northern boundary of the study area.

Several irrigation wells (5) located in the terrace aquifer were considered for their impact on the size of the overall capture zone. Irrigation well pumping rates were varied significantly without any noticeable effect on capture zone width. The effect on upgradient length was not determinable.

In conclusion, the GPTRAC numerical module appears to be the most versatile method. It is capable of delineating WHPA's for a heterogeneous aquifer(s) with a complex flow system. This module is limited only by the numerical model used to obtain the potentiometric head map.

Semi-Analytical Option. This option assumes a system of pumping and injection wells that fully penetrate a homogeneous aquifer under steady state conditions. A constant-head or no-flow boundary can be specified along any edge of the study area. Well interferences are accounted for by superposition of solutions. Specifically, the input requirements include: (1) the regional hydraulic gradient, (2) the direction of groundwater flow, (3) porosity, (4) saturated thickness, and (5) transmissivity, etc. From the input information, it is evident that this module is best suited for a one-directional, homogeneous flow system with simple boundary conditions and a constant hydraulic gradient. Referring back to Figure 1, it is noticeable that both the flow direction and gradient fluctuate greatly with location. WHPA's delineated by this method would be straight, and would not reflect the convergence of streamlines at the entrance to the breach. Consequently, this module was thought to be inadequate for delineation of WHPA's for the Torrington flow system.

RESSQC

RESSQC is used to delineate time-related capture zones for a steady-state flow system including both injection and pumping wells in a homogeneous aquifer. Stream and barrier boundaries can be implemented using image well theory. Well interferences arising in a multiple well system are determined by superposition.

The primary disadvantage of this method is that aquifer flow parameters such as, hydraulic gradient and flow direction, are held as constants. The impermeable zones in the study area could have been simulated with image wells, but again the resulting WHPA's would have been straight. Portions of WHPA's on the terrace aquifer generated by this method would be seriously undersized because an average flow direction is assumed. The convergence of groundwater flow in terrace deposits at the entrance to the breach could not be simulated.

MWCAP

The Multiple Well Capture Zone module is designed to delineate time-related capture zones for steady-state pumping wells in a homogeneous aquifer. Streams or boundaries can be simulated and are assumed to be linear and fully penetrating.

Well interferences are neglected; each well is assumed to operate independently.

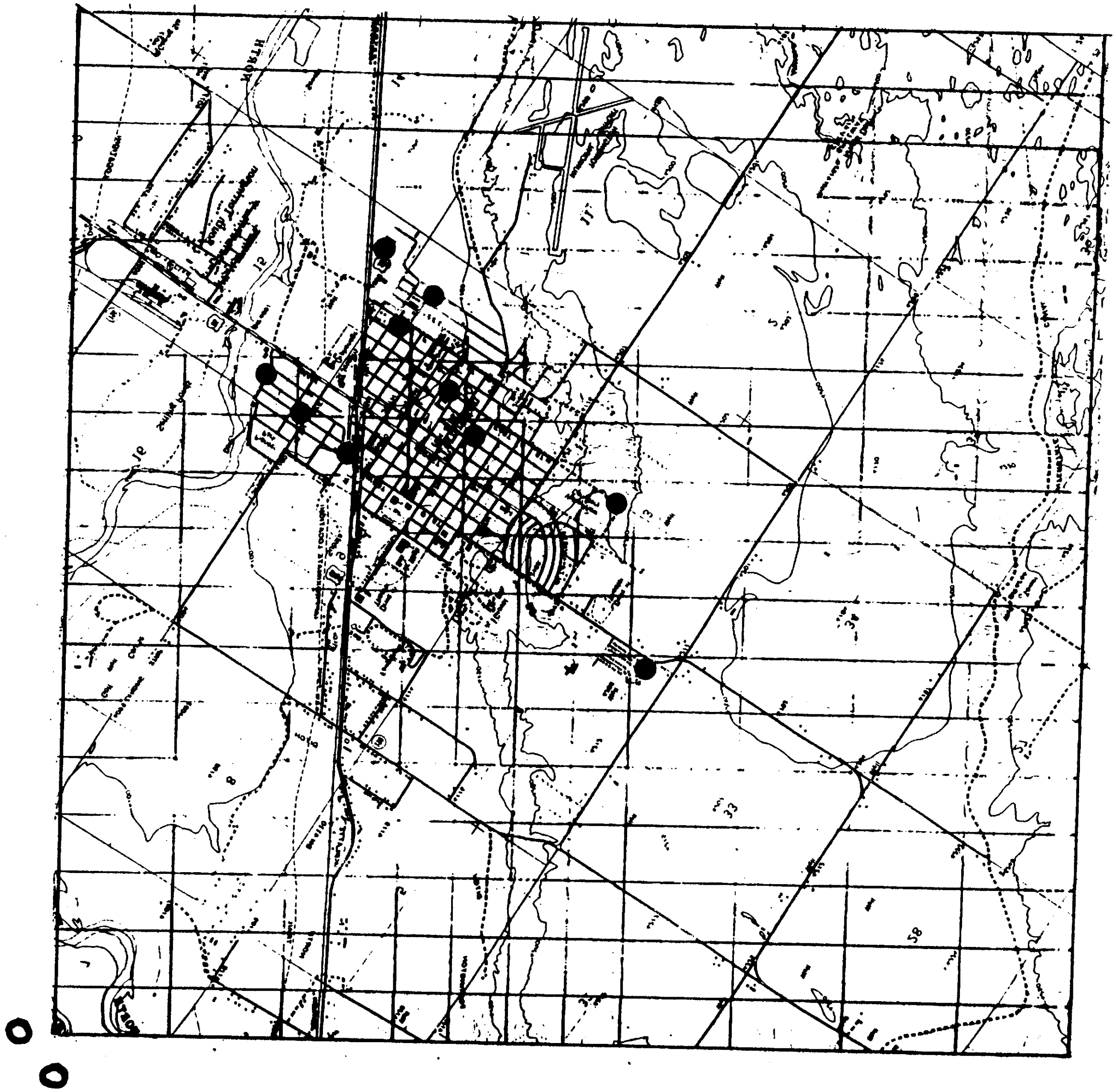
This module provides a little more flexibility, in some ways, than the RESSQC module discussed previously. Input parameters can be specified for each well rather than for the entire aquifer. Input requirements for each well include: (1) regional hydraulic gradient, (2) flow direction, (3) conductivity, (4) saturated thickness, (5) porosity, and (6) the boundary type and the perpendicular distance from the well.

As was mentioned previously for the RESSQC and the GPTRAC Semi-Analytical modules, the convergence of groundwater flow in terrace deposits toward the breach can not be simulated by this method either. These modules can not account for changes in direction as groundwater flows around a barrier. Consequently, results from this method were omitted as well.

References

Blandford, T. N. and P. S. Huyakorn. WHPA-A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas. Feb., 1990. EPA-Office of Groundwater Protection.

Parks, Gary D. Numerical Simulation of Groundwater Flow and Contaminant Transport in an Alluvial Aquifer. Dec., 1991.



APPENDIX E

The objective of this report is to assist small communities in their Wellhead Protection Area (WHPA) delineation efforts by compiling hydraulic properties of principal water bearing strata in Wyoming. Hydraulic properties, or ranges of properties, were then utilized to estimate protection areas for specified times of travel and pumping rates.

Increasingly, irreplaceable ground water resources are threatened by contamination originating from surface activities. Ground water contamination is of particular concern for two reasons. First of all, contamination is difficult to detect until it appears in the potable water supply. Secondly, by the time the contamination is detected, it is often too late for remedial actions to be effective (Freeze and Cherry, 1979). Establishing a WHPA is an inexpensive alternative in preventing contamination of a municipal ground water supply.

This report is intended to provide only general information useful in developing rough estimates of protection areas, and to illustrate the use of a few simple delineation methods. To correctly size protection areas, avoiding overprotection or underprotection, site-specific information is required which is beyond the scope of this study.

Approach

For the purposes of this report, the state was divided up according to structural features, with each basin and uplift considered separately. Structural basins examined were the Wind River, Bighorn, Laramie, Hanna, Shirley, Powder River, Great

Divide, Washakie, Denver-Julesburg, and Green River basins. Additional regions considered include the Overthrust belt and various uplifts. Figure 1 is a structural feature map of Wyoming showing the areas of this report. Formations underlying these features were assessed for pollution vulnerability and the quantity of groundwater present. Hydraulic properties of formations suitable for development as municipal water supplies and susceptable to contamination were compiled.

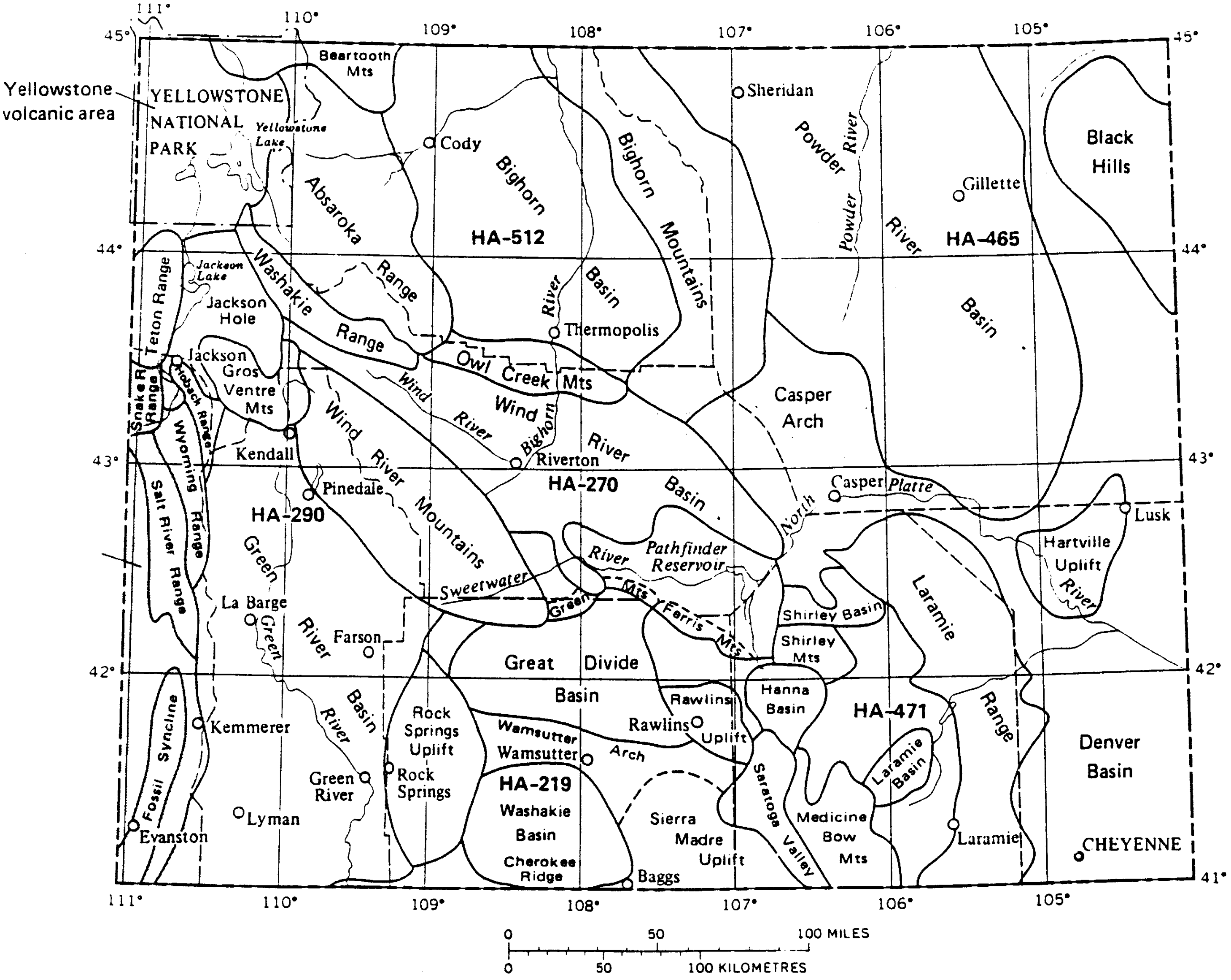


Figure 1 Structural feature map of Wyoming (From HA-539).

In general, aquifers present at shallow depths are more likely to be threatened by contamination. Consequently, alluvium and terrace deposits are included in this report although they are sometimes limited in extent and saturated thickness. Hydraulic properties and protection areas are included regardless, since they are the most vulnerable and the least expensive to develop. Ground water flow in alluvium is assumed to conform to the topography of the land.

Sufficient hydraulic information is provided so that a choice between a few WHPA delineation methods is possible. The delineation methods utilized herein are the Calculated Fixed Radius and two analytical methods, Time of Travel and Zone of Contribution.

Much of the background information for this study was obtained from a series of reports entitled, "Occurrence and Characteristics of Ground Water in Wyoming," which were prepared by the Water Resources Research Center at the University of Wyoming. These reports describe the availability and quality of ground water for each basin. The reader is referred to these reports for additional information.

The WHPA's estimated in this report actually indicate the time (i.e., time of travel) required for water to travel from the WHPA boundary to a pumping well. A nonreactive contaminant will have essentially the same time of travel as water since advection is the primary transport mechanism. However, movement of some contaminants may be retarded due to low solubility or an affinity for the solid phase. In this case of a reactive contaminant, WHPA's may be significantly oversized.

WHPA Delineation Methods

All structural basins generally exhibit similar ground water flow systems. Recharge areas are present at uplifted basin flanks where the water bearing formation outcrops. Hydraulic gradients develop and direct groundwater toward the basin; from recharge areas where precipitation infiltrates and flows to the center of the basin and areas of discharge. Basins usually contain surface waters that accept discharge from underlying strata due to upward leakage of ground water. A variation of this flow system is possible when ground water divides are present.

With the typical hydrogeological configuration of a basin in mind, the next step in establishing protection areas is to characterize the flow system. The requisite aquifer properties to define the flow system and satisfy the three delineation methods are: hydraulic conductivity (k), regional hydraulic gradient (i), porosity (n), and the production interval (H) or saturated thickness (b). Pumping rates (Q) and times of travel (t) were assumed based on the capability of the aquifer to supply water and standard delineation practices, respectively. Delineation methods are discussed individually in the following sections.

Hydraulic properties of the water bearing strata vary greatly throughout a basin: strata thickness and composition vary because of diverse depositional environments, zone of intense fracturing may occur at basin edges resulting in enhanced permeability, and porosity is likely to be lower at a greater depth. Therefore, an effort was made to determine averages, ranges of values, or typical values of hydraulic properties for each formation under consideration. This averaging of hydraulic properties fulfills the underlying assumptions of homogeneity and isotropy.

Additionally, many assumptions were necessary in estimating hydraulic properties. Porosity and the regional hydraulic gradient presented particular problems. When available, potentiometric surface maps were utilized to estimate the hydraulic gradient. In a large number of instances, however, these maps were not available. Values of regional hydraulic gradient were determined from elevation contour maps. This technique assumes that the hydraulic grade line is parallel to the slope of the formation. Alluvial aquifers were treated in a similar manner; the groundwater surface was assumed to conform to the local topography. Likewise, porosity values were not always available. Rough estimates were assumed from lithologic decriptions and the depths of burial.

Calculated Fixed Radius Method

The calculated-fixed-radius method estimates a circular protection area as illustrated by the following equation:

$$Qt = n\pi HR^2$$

where Q is the pumping rate of the well, n is the aquifer porosity, H is the production interval, R is the radius of the protection area, and t is the time of travel. In this form, the left-hand side equals the volume pumped in a specified period of time, while the term on the right is the volume of water contained in a cylinder of porous media with radius R, height H, and porosity n.

Solving the above equation for R yields:

$$R = (Qt/\pi nH)^{1/2}$$

This technique is most applicable for aquifers with a nearly horizontal potentiometric surface.

Analytical Methods

Because structural basins are the dominant geological feature of Wyoming, two analytical delineation methods were chosen for their suitability to sloping aquifers. These techniques, the time-of-travel and zone-of-contribution methods, when utilized together, are useful in predicting protection areas for sloping aquifers. However, for a groundwater flow system in which the potentiometric surface is approximately horizontal, analytical methods become inappropriate. This should be kept in mind when reviewing protection area dimensions tabulated in the following sections. At the basin's margins, analytical results are more valid, whereas the calculated fixed radius approach is best for basin centers.

Time of Travel. The time-of-travel (TOT) method utilizes Darcy's law and the regional hydraulic gradient to determine the distance upgradient to the WHPA boundary. The following equations illustrate this method:

$$x = vt = kit/n$$

where v = pore water velocity, n = porosity, t = time of travel, i = regional hydraulic gradient, x = distance, and k = the hydraulic conductivity. The effect of the pumping well is ignored in this technique.

This method was utilized to determine the upgradient length of the WHPA. The following ZOC method estimates protection area size near the pumping well.

Zone of Contribution. The analytical zone-of-contribution (ZOC) method assumes steady state flow conditions. This method predicts the dimensions of the ground water divide that sets-up around a pumping well. All streamlines that intersect this boundary indicate groundwater that will enter the well. Down gradient from the well a culmination point forms at a distance X_o, as determined from the equation:

$$X_o = Q/(2\pi kHi)$$

where Q is the well pumping rate, H is the saturated thickness, k is the hydraulic conductivity, and i is the regional hydraulic gradient. The width, F, of the zone of contribution perpendicular to the flow direction was calculated from the equation:

$$F = Q/kHi$$

This method was utilized to determine the size of the zone of contribution down gradient and near the well.

Laramie, Hanna, and Shirley Basins

Three principal aquifer aquifers have been identified by

Richter (1981) in the Laramie, Shirley, and Hanna basins. These are the Tertiary, Cloverly, and Casper-Tensleep aquifers. The Tertiary aquifer consists of the North Park, Browns Park, White River, Wind River, Hanna, and Ferris formations. The locations, at shallow depths, of the principal aquifers are: (1) Casper-Tensleep and Cloverly formations in the eastern Laramie and Shirley basins, (2) the Hanna and Ferris formations in the Hanna, Carbon, and northern Laramie basins, (3) Browns Park, North Park, and Wind River in the northern Laramie basin and the Saratoga valley. Water production in the Saratoga valley is primarily from the Browns Park and North Park formations. The Wind River and White River formations are the primary water bearing units in the Shirley basin.

Unconsolidated alluvium of Quaternary age underlies the floodplains of the Laramie, Little Laramie, North Platte, Rock Creek, Encampment, Medicine Bow, and Little Medicine rivers (Richter, 1981). Saturated thickness varies from 1 to 60 feet.

Table 1 contains aquifer hydraulic parameters and protection area dimensions for the Laramie, Shirley, and Hanna basins. For the analytical methods, TOT and ZOC, approximate ground water flow directions may be assumed from Figure 2. Gradients for Casper and Cloverly formations were measured at the eastern edge of the study area.

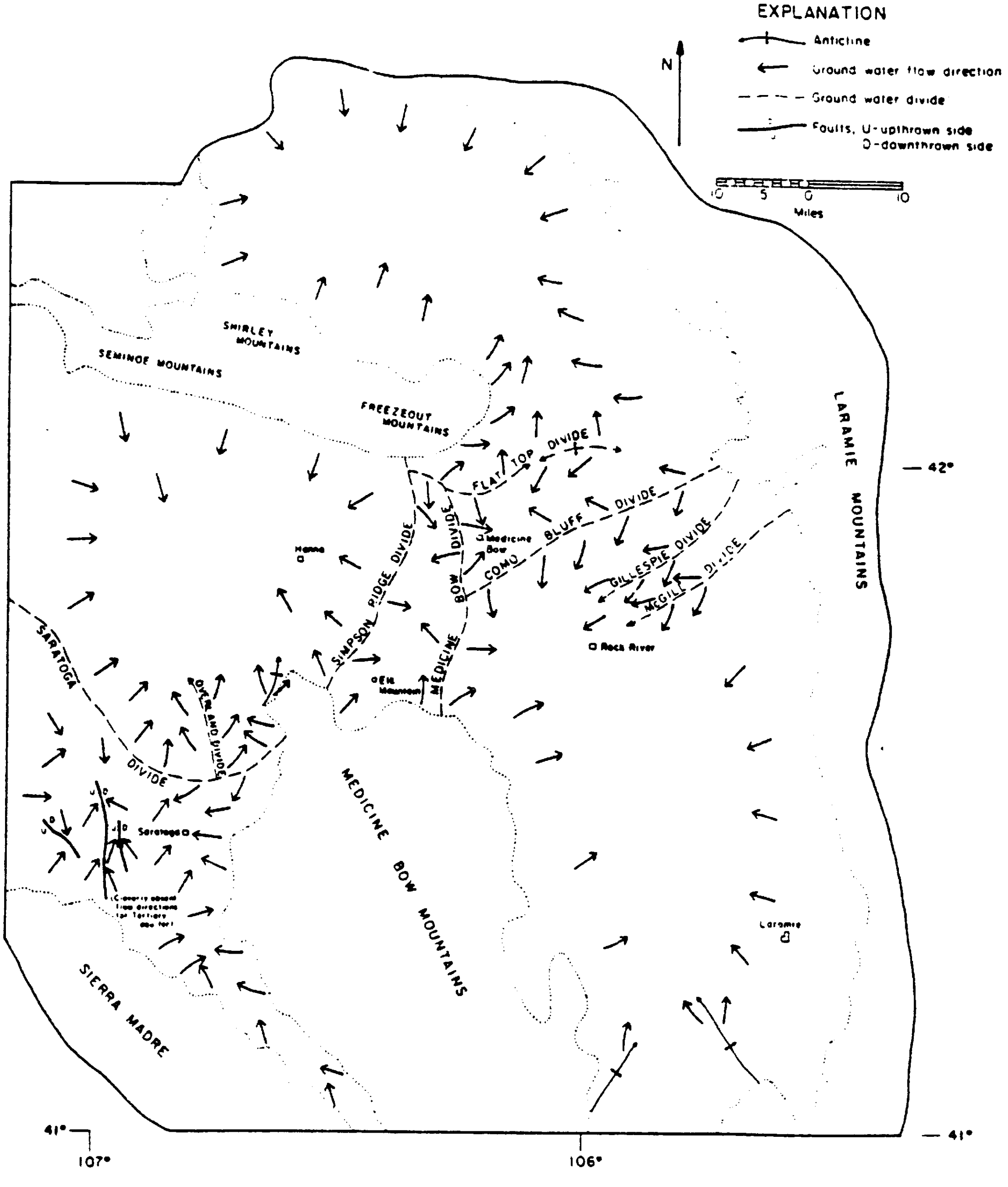


Figure 2 Generalized ground water flow directions in the cretaceous rocks in the Laramie, Shirley, and Hanna basins, Wyoming. (From Richter, H.R., 1981)

Aquifer Hydraulic Properties -- Laramie, Shirley, and Hanna Basins

Period	Fm	Production Interval (H) feet	Hyd. Cond. (k) ft/day	Porosity (n)	Gradient (i)	Assumed Flowrate Q (gpm)
Pennsyl.	Casper	350	12	0.15	.03-.08	500
Cretac.	Cloverly	50	2	0.15	.07-.11	100
Tertiary	Ferris	20	35	.15-.20	.05-.10	100
	Hanna	20	25	.15-.20	.05-.10	100
	Wind Riv.	175	12	.15-.20	.05-.10	500
	White R.	185	12	.15-.20	.05-.10	500
	Browns Pk	115	20	.15-.20	.05-.10	500
	N. Park	140	14	.15-.20	.05-.10	500
Quaternary	Alluvium	50	45	0.23	.002-.02	100

Protection Area Dimensions - Laramie, Shirley, Hanna Basins

Fm	CFR	R (ft) (1)	ZOC	(2)	TOT	x (ft) (3)
	t=5 yrs.	t=10yrs.	Xo (ft)	F (ft)	t=5 yrs.	t=10 yrs
Casper	1032	1460	46	286	11680	23360
Cloverly	1221	1727	279	1750	2677	5354
Ferris	1931/1672	2730/2365	44	275	42583	85167
Hanna	1931/1672	2730/2365	61	385	30417	60833
Wind Riv.	1460/1264	2064/1788	73	458	14600	29200
White R.	1420/1229	2008/1739	69	434	24333	48667
Browns Pk	1800/1559	2546/2205	67	419	24333	48667
N. Park	1632/1413	2308/1999	78	491	17033	34067
Alluvium	986	1395	68	428	7141	14282

(1) Radius, R=((Q*t/n*H)*22367)^.5. (R at minimum n / R at max. n)
(2) For ZOC: Xo=Q*30.64/kHi, at maximum i. F = 2*Pi*Xo.
(3) x=kit*365/n, using minimum n and Maximum gradient i.

Table 1

Green River Basin and Overthrust Belt

The Green River basin and Overthrust belt of southwestern Wyoming exhibit vastly different hydrogeologocal configurations. This is due to different structural features. The Green River basin has a typical basin flow system with recharge along the basin's flanks and flow toward the Green river. The Overthrust belt, on the other hand, contains many fault zones. Stratigraphic displacements have resulted in areas of disrupted ground water circulation. High recharge and large fracture permeability suggest that the Overthrust belt has a high potential for ground water development. However, these same characteristics make delineation of protection areas more difficult.

Overthrust Belt. The important water-bearing strata of the Overthrust belt are largely of Tertiary and Quaternary age. The exception is the Madison, which is an important water source in the northern Overthrust belt. The Tertiary aquifers of interest are the Evanston, Wasatch, Green River, and Bridger formations. In the southern part of the study area, the Evanston and Wasatch aquifers are capable of yielding moderate to large quantities of water to wells. The most productive Quaternary aquifers are found in the valleys of the Snake, Salt, and Bear rivers. Alluvium and terrace deposits are often more than 100 feet thick and approach 400 feet at a few locations in the Bear River valley.

Green River Basin. The most productive formations are again Tertiary and Quaternary deposits. The principal Tertiary aquifers are the Wasatch formation, the Bridger formation, and the Laney member of the Green River formation. The locations where aquifers are present at shallow depths are: (1) the Wasatch in the northern Green River basin and at basin flanks, (2) the Laney member in eastern Green River basin, and (3) the Bridger formation in the south-central Green River basin. Quaternary deposits overlie Tertiary sediments in the valleys of the Green river and its major tributaries and along the southwestern flank of the Wind River mountains. Gradients are generally similar to the local topography.

For the formations mentioned above, hydraulic properties and protection area dimensions are shown in Table 2. Figures 3, 4, and 5 are potentiometric surface maps of the Green River basin and Overthrust belt. Orientation of protection areas may be inferred from these figures; flow is perpendicular to potentiometric contour lines. In this instance, flow is generally to the south and toward the Green river drainage

Aquifer Hydraulic Properties -- Green River Basin and Overthrust Belt

Period	Fm	Production Interval (H) feet	Hyd. Cond. (k) ft/day	Porosity (n)	Gradient (i)	Assumed Flowrate Q (gpm)
Overthrust Belt:						
Tertiary	Madison	200	5	.12-.17	.05-.15	600
	Evanston	50	5	.15-.2	.05-.15	100
	Wasatch	150	1	.2-.25	.008-.01	300
	Green R.	150	3	.15-.2	.007-.012	400
	Bridger	50	5	.15-.2	0.014	150
Quaternary	Alluvium	150	16	0.23	.002-.02	300
Green River Basin						
Tertiary	Green R. (Laney Member)	150	40	.15-.2	.004-.009	400
	Wasatch	150	1	.20-.25	.004-.02	300
	Bridger	50	5	.15-.20	.003-.012	150
Quaternary	Alluv.	60	16	0.23	.002-.02	150

Protection Area Dimensions

Fm	CFR R (ft) (1)		ZOC	(2)	TOT x (ft) (3)	
	t=5 yrs.	t=10yrs.	Xo (ft)	F (ft)	t=5 yrs.	t=10 yrs
Overthrust Belt						
Madison	1672/1180	3344/2361	123	770	11406	22812
Evanston	1221/916	2442/1832	82	513	9125	18250
Wasatch	1058/846	2116/1632	6128	38503	91	182
Green R.	1410/1058	2320/2115	2270	14261	438	376
Bridger	1496/1122	2992/2243	1313	8251	852	1703
Alluvium	986	1394	192	1203	2539	5078
Green River Basin						
Green R.	1410/1058	2820/2115	227	1426	4381	8761
Wasatch	1058/846	2116/1692	3064	19252	183	366
Bridger	1496/1122	2992/2243	1532	9626	730	1460
Alluvium	1103	1559	239	1504	2539	5078

(1) Radius, R=((Q*t/n*H)*22367)^.5. (R at minimum n / R at max. n)

(2) For ZOC: Xo=Q*30.64/kHi, at maximum i. F = 2*Pi*Xo.

(3) x=kit*365/n, using minimum n and maximum gradient i.

Table 2

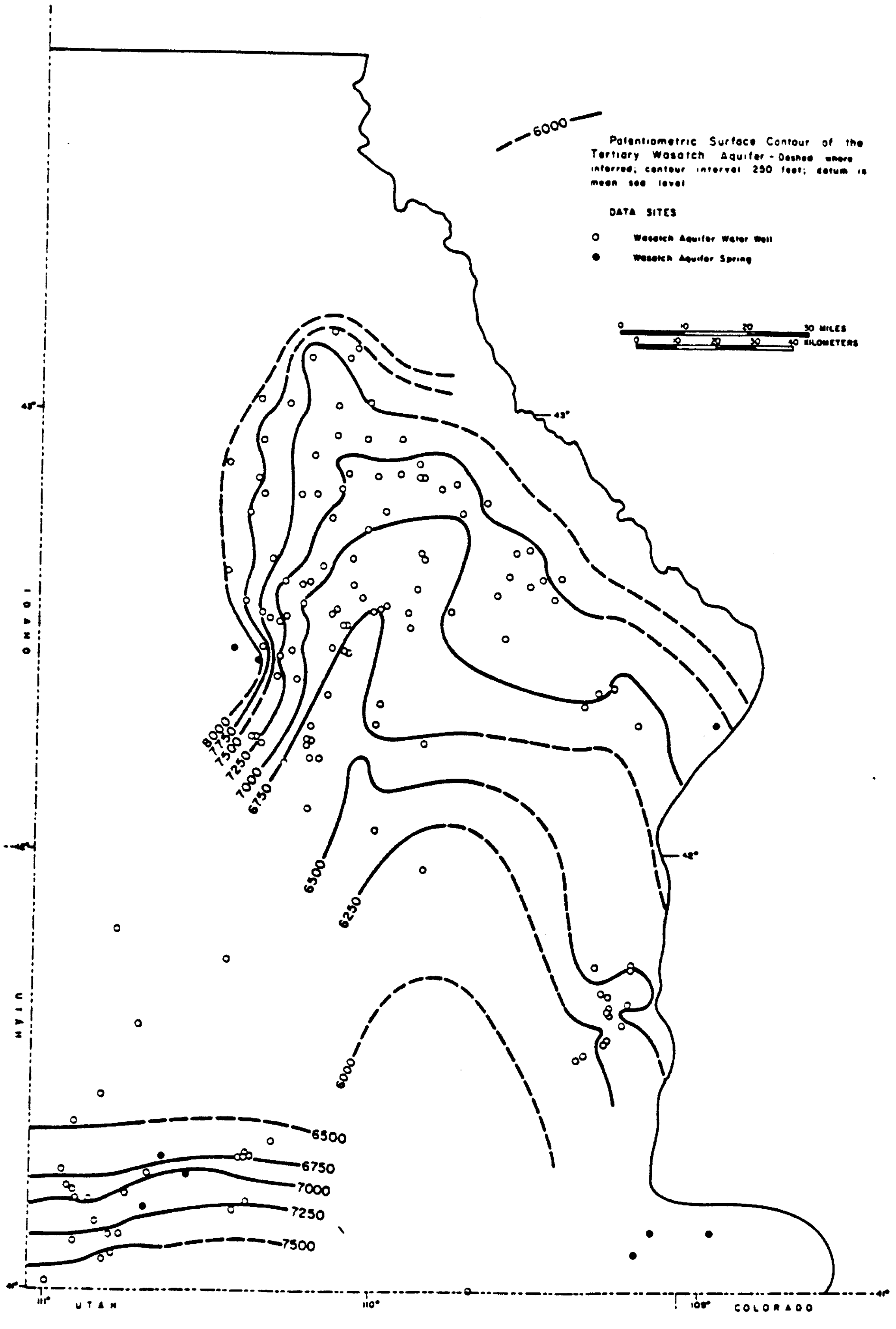


Figure 3 Potentiometric surface map of the Tertiary Wasatch aquifer, Green River basin and Overthrust belt (From Ahern, J. et al., 1981).

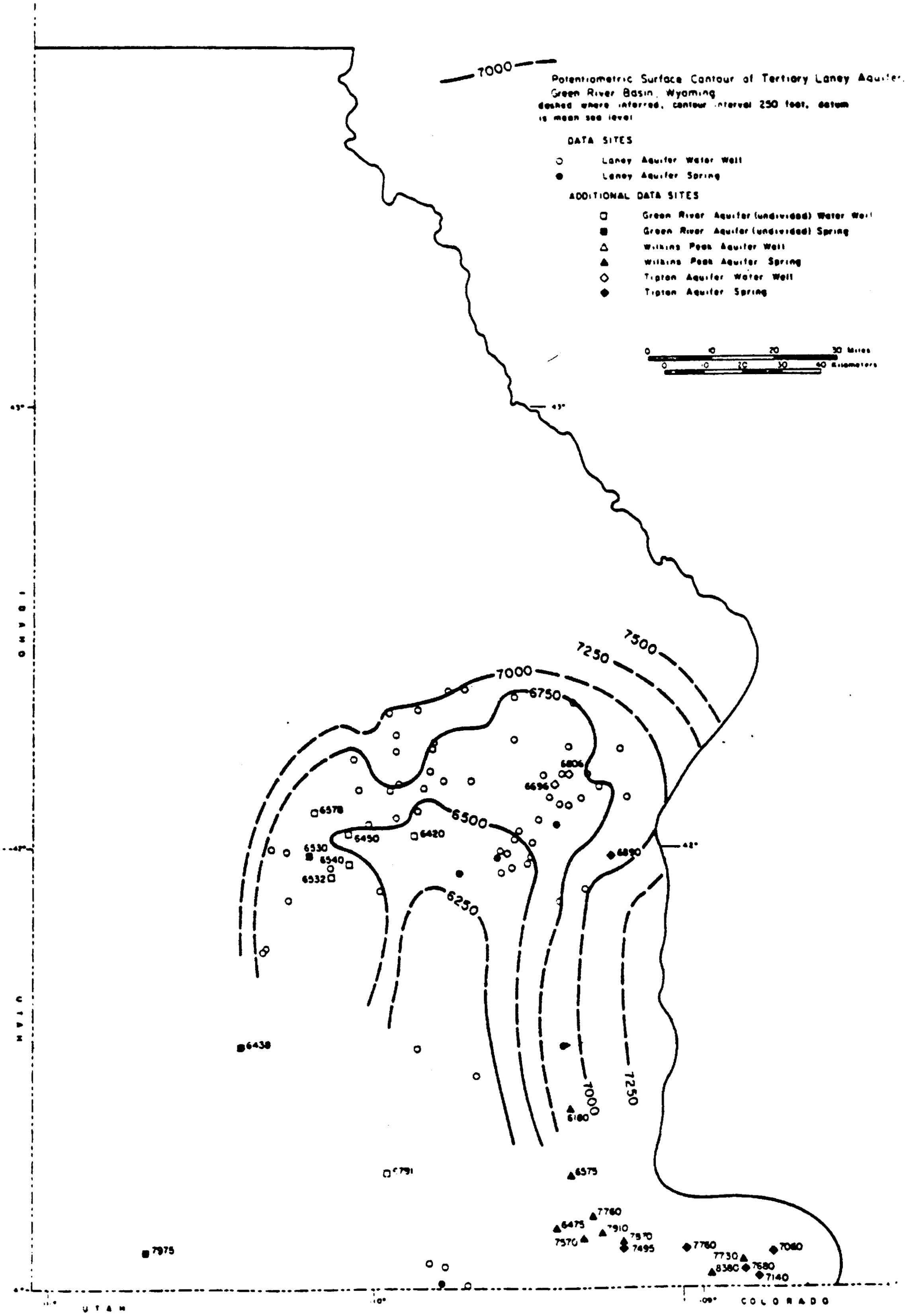


Figure 4 Potentiometric surface map of the Tertiary Laney aquifer in the Green River basin (From Ahern, J. et al., 1981).

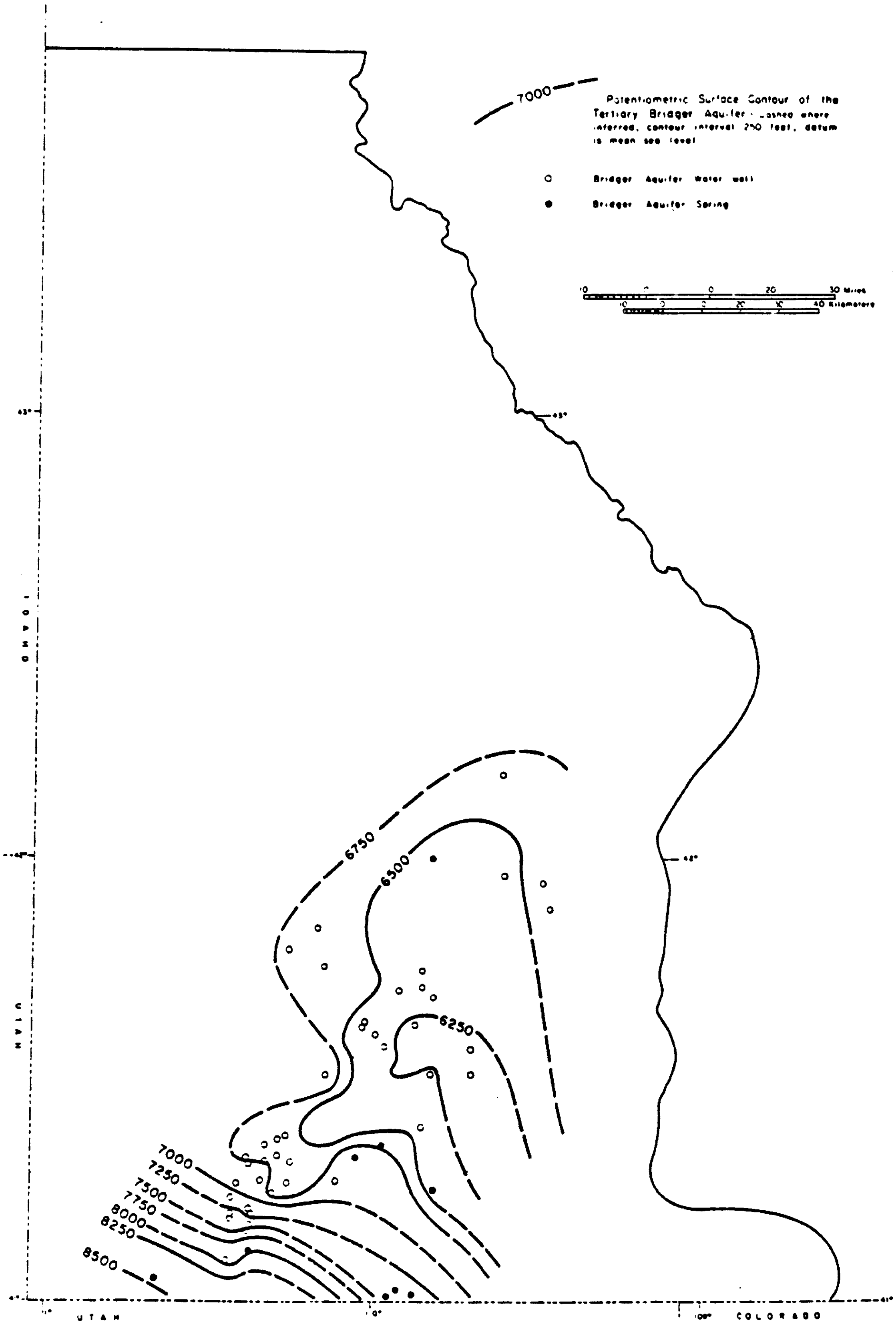


Figure 5 Potentiometric surface map of the Tertiary Bridger aquifer in the Green River basin and Overthrust belt (Ahern, J. et al., 1981).

Great Divide and Washakie Basins

The most utilized aquifers in the Great Divide and Washakie basins are the Battle Springs formation in the northern and eastern Great Divide basin, the Ericson formation and Bishop Conglomerate near the Rock Springs uplift, the Laney member of the Green River formation in the western Washakie basin, the Wasatch formatiom on the Wamsutter arch and the Great Divide basin, the North Park formation in the Sierra Madre uplift, and Quaternary deposits of wind-blown sand and alluvium near the Ferris mountains and the Little Snake River valley. With the exception of the unconsolidated Quaternary deposits and the Ericson formation (Cretaceous), these are all Tertiary formations These aquifers are present at shallow depths and therefore, vulnerable to contamination.

Table 3 lists aquifer hydraulic properties and the sizes of protection areas for the calculated-fixed-radius method. Other WHPA methods were not considered due to the extremely low gradients within the basins. Flow directions and gradients for analytical methods were assumed from Figures 6 and 7.

Aquifer Hydraulic Properties -- Great Divide and Washakie Basins

Period	Fm	Production Interval (H) feet	Hyd. Cond. (k) ft/day	Porosity (n)	Gradient (i)	Assumed Flowrate Q (gpm)
Quaternary	Deposits	40	9	0.23	.002-.02	25
Upper-Tertiary	N. Park	70	3	.15-.25	.004-.008	400
	Browns Pk	60	2	.15-.25	.004-.008	300
	Bishop	40	2	.12-.18	.004-.008	50
	Green R. (Laney)	60	2	.15-.25	.004-.008	200
	Wasatch	50	7	.16-.38	.004-.008	300
Tertiary						
	Battle Spg	100	3	.15-.25	.004-.008	600
	Fort Union	30	7	.15-.39	.004-.008	300
Cretac.	Ericson	30	7	.08-.26	.003-.013	150

Protection Area Dimensions - Great Divide and Washakie Basins

		CFR R (ft) (1)	
Period	Fm	t=5 yrs.	t=10yrs.
Quatern.	Deposits	551	779
Upper Tertiary	N. Park	2064/1599	2919/2261
	Browns Pk	1931/1496	2731/2115
	Bishop	1079/881	1526/1246
Tertiary	Green R. (Laney)	1576/1221	2228/1727
	Wasatch	2048/1329	2896/1879
	Battle Spg	2115/1638	2991/2317
	Fort Union	2731/1693	3862/2394
Cretac.	Ericson	2644/1467	3738/2074

(1) Radius, R=((Q*t/n*H)*22367)^.5. (R at minimum n / R at max. n)

Table 3

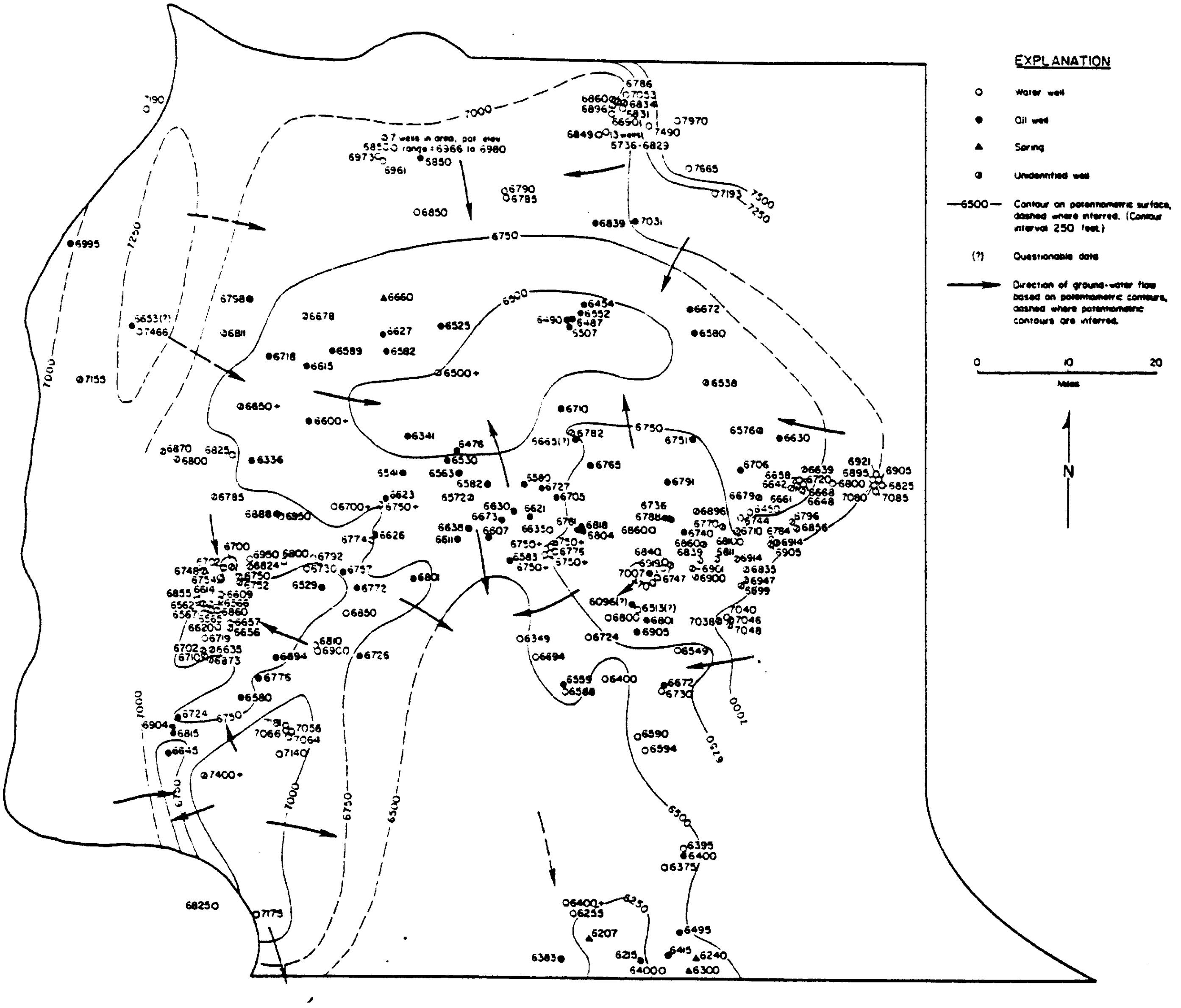


Figure 6 Potentiometric surface map, Tertiary aquifer system (Collentine, M. et al., 1981).

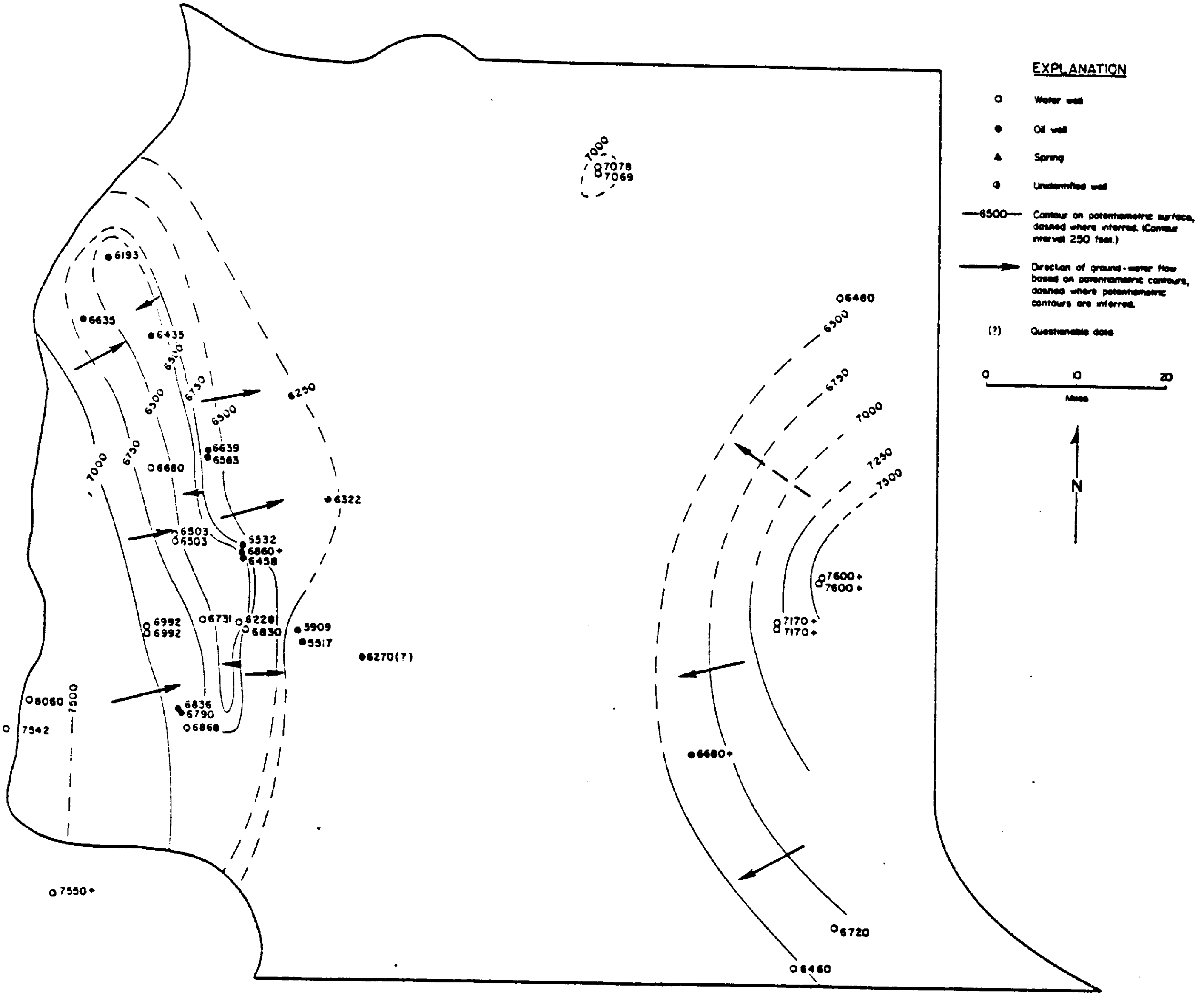


Figure 7 Potentiometric surface map, Mesaverde aquifer. (From Collentine, M. et al., 1981.)

Bighorn Basin

Municipal water supplies within the basin are provided primarily from Quaternary deposits, the Madison Limestone, and the upper Cretaceous-Tertiary aquifer systems. However, the Madison formation is at great depth throughout most of the basin and therefore, not susceptible to contaimination. Non-municipal public drinking water supplies tap Quaternary and upper Cretaceous-Tertiary aquifer systems. Of the near-surface aquifers, only the Quaternary deposits are considered as major aquifers. The upper Cretaceous-Tertiary aquifer system is capable of delivering only small quantities of water. Formations comprising this system are largely discontinuous and lenticular; therefore, potentiometric surface data is not available.

Most wells and municipalities are located along major drainages, which include the North and South Forks of the Shoshone river, the Greybull, Bighorn, and Clark's Fork (Yellowstone) rivers and their tributaries. Quaternary deposits of varying thickness underlie the floodplains of these rivers, with flow generally in the downstream direction.

Upper Cretaceous and lower Tertiary deposits are the shallowest bedrock in the basin. Water can usually be obtained at depths less than 500 feet. However, sandstone aquifers within these formations are discontinuous; the quantity of available water will vary greatly. Formations in this grouping are the Willwood, Fort Union, Lance, Meeteetse, and the Mesaverde.

Table 4 contains aquifer properties and protection area dimensions for the Bighorn basin. However, because of a lack of potentiometric data for the upper Cretaceous-Tertiary aquifers, only the calculated fixed radius method was utilized.

Aquifer Hydraulic Properties -- Bighorn Basin

Period	Fm	Production Interval(H) feet	Hyd. Cond. (k) ft/day	Porosity (n)	Gradient (i)	Assumed Flowrate, Q (gpm)
Quat	Alluvium	35	31	.2-.25	.002-.02	100
	Terrace	20	53	.2-.25	.002-.02	50
U. Cret.-	Willwood	30	NA	.12-.25	NA	50
Tertiary	Ft. Union	30	NA	.12-.25	NA	50
	Lance	20	NA	.12-.25	NA	50
	Meeteetse	20	NA	.12-.25	NA	50
	Mesaverde	40	NA	.12-.25	NA	50

NA=Not Available

Protection Area Dimensions - Bighorn Basin

Fm	CFR	R (ft) (1)	ZOC	(2)	TOT	x (ft) (3)
	t=5 yrs.	t=10yrs.	Xo (ft)	F (ft)	t=5 yrs.	t=10 yrs.
Alluvium	1264/1131	1788/1599	141	887	5658	11315
Terrace	1182/1058	1672/1496	72	454	9673	19345
Willwood	1246/863	1763/1221	NA	NA	NA	NA
Ft. Union	1246/863	1763/1221	NA	NA	NA	NA
Lance	1526/1058	2159/1495	NA	NA	NA	NA
Meeteetse	1526/1058	2159/1495	NA	NA	NA	NA
Mesaverd	1079/748	1526/1057	NA	NA	NA	NA

(1) Radius, R=((Q*t/n*H)*22367)^.5. (R at minimum n / R at max. n)

Table 4

Wind River Basin

Principal aquifers in the Wind River basin that are vulnerable to contamination are Quaternary deposits, and the Wind River and Arikaree formations of Tertiary age. Most wells in the basin tap these three aquifer systems. The Arikaree formation is the principal source of water in the southeastern part of the basin where it is present at the surface. The Arikaree aquifer is comprised of the Moonstone, Arikaree, and White River formations. Quaternary deposits throughout the basin are concentrated along major surface drainages. These are the Wind, Little Wind, Popo Agie, and Sweetwater rivers. The Wind River formation underlies the entire basin but is most productive in the western part of the basin.

Table 5 lists aquifer parameters and protection area dimensions for the Wind River basin. In order to properly orient protection areas, Figure 8 indicates the general ground water flow directions in the basin. Notice that the groundwater flow direction is approximately basinward. Quaternary deposits and the Arikaree aquifer are exceptions to this. Ground water flow in Quaternary deposits is generally toward surface drainages, while flow is toward Pathfinder and Alcova reservoirs in the Granite Mountains (Arikaree aquifer) area.

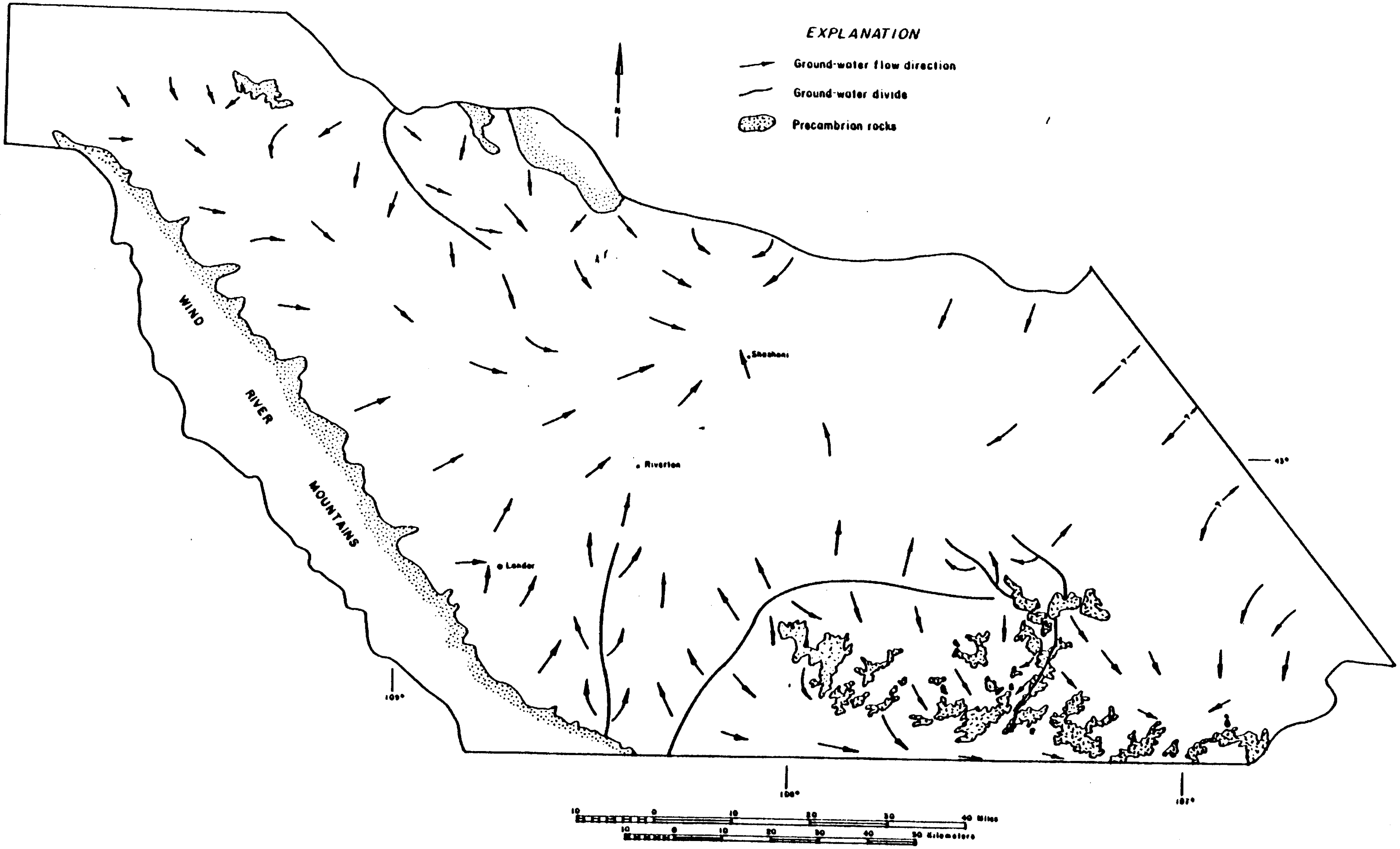


Figure 8 Generalized ground water flow directions in the Lower Cretaceous rocks, Wind River basin. (From Richter, H.R., 1981.)

Aquifer Hydraulic Properties -- Wind River Basin

Period	Fm	Production Interval(H) feet	Hyd. Cond. (k) ft/day	Porosity (n)	Gradient (i)	Assumed Flowrate, Q (gpm)
Quaternary	Alluvium	50	20	.2-.25	.002-.02	300
	Terrace	30	20	.2-.25	.002-.02	100
Tertiary	Moonstone	50	1	.14-.25	.01-.1	100
	Arikaree	100	23	.14-.25	.01-.1	200
	White R.	100	1	.12-.2	.01-.1	150
	Wind R.	200	3	.12-.2	.01-.019	300

Protection Area Dimensions - Wind River Basin

Fm	CFR R (ft) (1)		ZOC	(2)	TOT x (ft) (3)	
	t=5 yrs.	t=10yrs.	Xo (ft)	F (ft)	t=5 yrs.	t=10 yrs.
Alluvium	1832/1638	2590/2317	460	2888	3650	7300
Terrace	2365/2115	3344/2991	255	1604	3650	7300
Moonston	1264/946	1788/1338	613	3850	3910	7821
Arikaree	1264/946	1788/1338	27	84	29982	59964
White R.	1182/916	1671/1295	460	2889	4562	9125
Wind R.	1182/916	1671/1295	806	2533	1156	2312

(1) Radius, R=((Q*t/n*H)*22367)^.5. (R at minimum n / R at max. n)
(2) For ZOC: Xo=Q*30.64/kHi, at maximum i. F = 2*Pi*Xo.
(3) x=kit*365/n, using minimum n and maximum gradient i.

Table 5

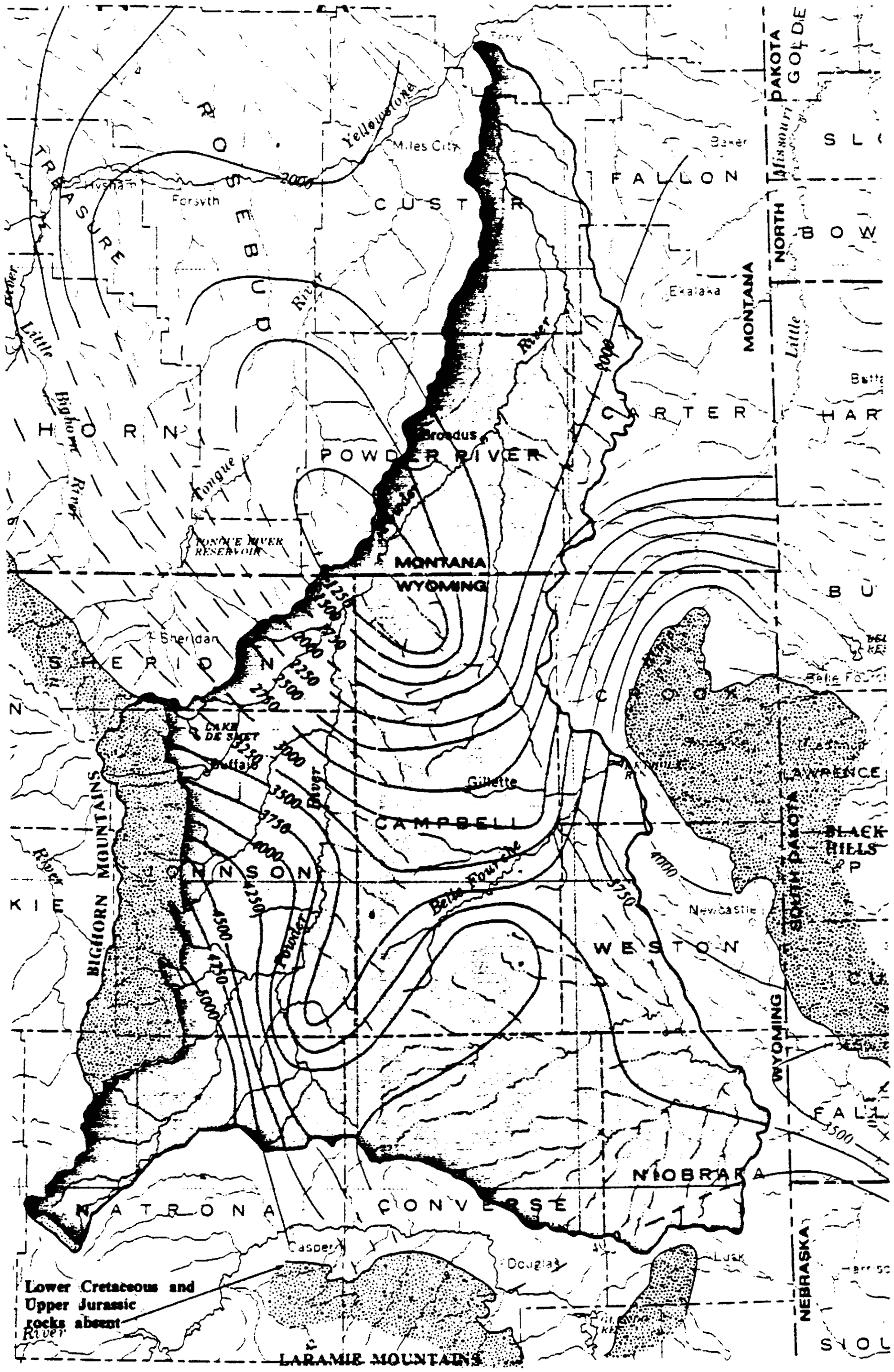
Powder River Basin

Principal aquifer systems present at shallow depth in the Powder River basin are Quaternary deposits, the Arikaree, White River, Wasatch, Fort Union, and the Fox Hill/Lance formations. The Wasatch and Fort Union are the shallowest bedrock formations in the central basin. The Arikaree is the major source of groundwater in the extreme southeastern part of the basin; whereas, the Lance is the surficial bedrock formation at the basin's southeastern and southwestern margins.

Narrow strips of alluvium underlie surface drainage valleys in the area. Important alluvial deposits are located along the North Platte, Powder, Little Powder, Belle Fourche, Cheyenne rivers, and Lance, Crazy Woman, and Clear creeks. Other Quaternary deposits include glacial deposits in the Bighorn mountains and wind-blown sand near Casper. Only alluvial deposits are significant sources of ground water.

Most municipal wells in the basin withdraw ground water from the Madison and Wasatch/Fort Union aquifer systems. To a lesser extent, alluvium and the Fox Hill/Lance aquifer systems, at the basin margins, are also utilized for municipal drinking water.

Hydraulic properties and protection area dimensions are listed in Table 6. Figure 9 is a generalized potentiometric surface of the region. The flow direction, which is roughly perpendicular to equipotential lines, is generally to the north. Because of low hydraulic gradients in the central basin, results for analytical mehtods are not particularly meaningful.



Hydrology from D.T. Hoxie and K.C. Glover (written commun., 1983).

EXPLANATION

For All Figures

—*4500*—— **GENERALIZED POTENTIOMETRIC CONTOUR** – Shows altitude of equivalent fresh-water head in well completed in the formation mapped. Dashed where approximately located. Contour interval, in feet, varies. Datum is sea level

Figure 9 Potentiometric surface map in the Lower Cretaceous aquifer, Powder River basin. (From Lowry, M. et al., 1983.)

Aquifer Hydraulic Properties -- Powder River Basin

Period	Fm	Production Interval (H) feet	Hyd. Cond. (k) ft/day	Porosity (n)	Gradient (i)	Assumed Flowrate Q (gpm)
Quatern.	Alluvium	40	10	.38-.45	.002-.02	400
Tertiary	Arikaree	50	3	.1-.5	.002-.01	300
	White R	50	2	.15-.4	.002-.01	50
	Wasatch/ Ft Union	60	2	.28-.3	.002-.01	100
	Fox Hill/ Lance	40	3	.2-.3	.01-.03	100

Protection Area Dimensions - Powder River Basin

Fm	CFR R (ft) (1)		ZOC	(2)	TOT x (ft) (3)	
	t=5 yrs.	t=10yrs.	Xo (ft)	F (ft)	t=5 yrs.	t=10 yrs
Alluvium	1716/1576	2426/2229	1532	9626	960	1920
Arikaree	2590/1158	3663/1638	6128	38503	548	1096
White R	863/529	1221/748	1532	9626	243	487
Wasatch/ Ft. Union	999/965	1413/1365	3830	24065	130	260
Lance/ Fox Hills	1182/965	1672/1365	851	5348	821	1642

(1) Radius, R=((Q*t/n*H)*22367)^.5. (R at minimum n / R at max. n)
(2) For ZOC: Xo=Q*30.64/kHi, at maximum i. F = 2*Pi*Xo.
(3) x=kit*365/n, using minimum n and maximum gradient i.

Table 6

Denver-Julesburg Basin

The most important aquifer systems for the purposes of this report are the Quaternary alluvial aquifers, the Tertiary aquifer, and the Fox Hill/Lance aquifer. The Tertiary aquifer system, consisting of the White River group, Arikaree, and Ogallala formations, is the most productive in the basin. Significant yields have also been obtained from Quaternary deposits along the North Platte and its tributaries, the Wheatland Flats, and the Pine Bluff Lowland. The Lance/Fox Hills aquifer system exhibits lower yields. This aquifer system has been developed primarily in the east-central part of the basin.

Figure 10 indicates that the general ground water flow pattern is from west to east and converging toward the North Platte river. Table 7 contains aquifer hydraulic properties and protection area dimensions.

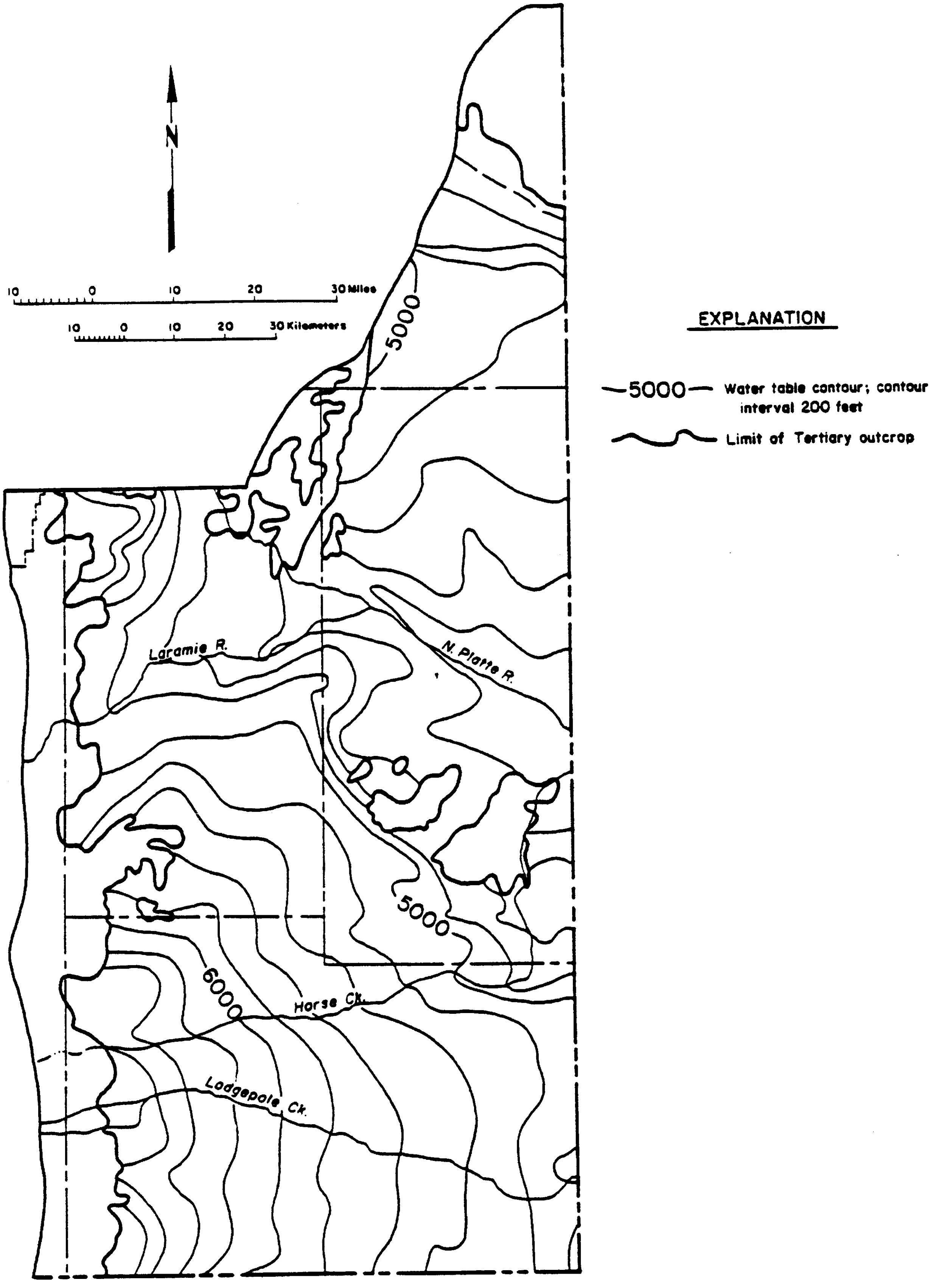


Figure 10 Water table map of the Tertiary aquifer system, Denver-Julesburg basin. (From Gutentag and Weeks, 1980.)

Aquifer Hydraulic Properties -- Denver-Julesburg Basin

Period	Fm	Production Interval (H) feet	Hyd. Cond. (k) ft/day	Porosity (n)	Gradient (i)	Assumed Flowrate Q (gpm)
Quatern.	Alluvium	120	110	.2-.35	.002-.02	750
	Terrace	50	100	.2-.35	.002-.02	300
Tertiary	Ogallala	60	44	.1-.3	.004-.007	400
	Arikaree	90	18	.2-.4	.004-.007	400
	White R.	50	8	.1-.25	.004-.007	200
Cretac.	Lance/ Fox Hills	80	3	.1-.2	.004-.007	100

Protection Area Dimensions - Denver-Julesburg Basin

Fm	CFR R (ft) (1) t=5 yrs.	t=10yrs.	ZOC Xo (ft)	(2) F (ft)	TOT t=5 yrs.	x (ft) (3) t=10 yrs
Alluvium	1869/1413	2643/1998	87	547	20075	40150
Terrace	1832/1385	2590/1958	92	578	18250	36500
Ogallala	2731/1576	3861/2229	663	4167	5621	11242
Arikaree	1576/1115	2229/1576	1081	6791	1150	2300
White R.	2115/1338	2991/1891	2189	13751	1022	2044
Lance/ Fox Hills	1182/836	1672/1182	1824	11459	383	767

(1) Radius, R=((Q*t/n*H)*22367)^.5. (R at minimum n / R at max. n)
(2) For ZOC: Xo=Q*30.64/kHi, at maximum i. F = 2*Pi*Xo.
(3) x=kit*365/n, using minimum n and maximum gradient, i.

Table 7

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