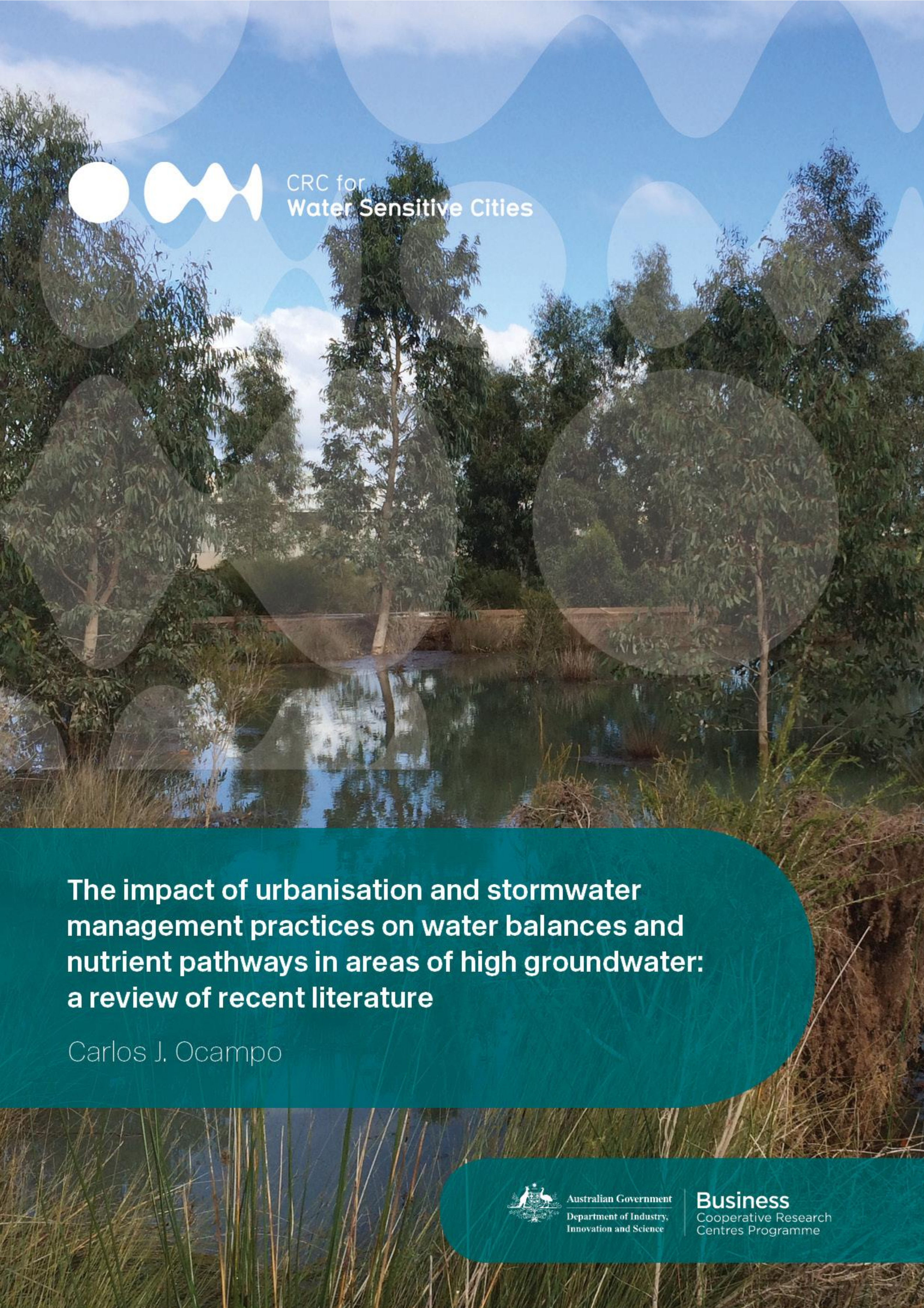

CRC for
Water Sensitive Cities

The impact of urbanisation and stormwater management practices on water balances and nutrient pathways in areas of high groundwater: a review of recent literature

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The impact of urbanisation and stormwater management practices on water balances and nutrient pathways in areas of high groundwater: a review of recent literature
Hydrology and nutrient transport processes in groundwater/surface water systems (Project B2.4)
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Executive summary

The need to understand the impact of urbanisation and changing land use on water and solute mass balances in the groundwater underlying urban areas has been increasingly recognised over the past 25 years. Groundwater resources are now included, for example, as part of integrated urban water management (IUWM). Conceptual models for IUWM have recently included:

- the impact of urbanisation on the water balance
- the impact of urban stream restoration on groundwater supplied baseflow
- the potential to reduce groundwater supplied nutrients and pollutant loadings to receiving water bodies.

Globally, the implementation of water sensitive urban design (WSUD) technologies such as at source control systems (SCSs) has been strongly recommended to offset the impact of urbanisation on surface hydrology, nutrients, and pollutant export. However, we don't properly understand how such systems affect shallow water tables, how artificially enhanced infiltrated water travels via the complex urban subsurface hydrology (known as urban karst), and how the altered subsurface hydrology affects nutrient discharge to water bodies.

The dynamics of the urban subsurface hydrology are complex. They are the result of the intricate conveyance system (which alters the pre-development soil properties), a variety of artificial recharge sources, and poorly characterised localised sources that were traditionally believed to be impervious (such as pavements, via cracks and joints). This complexity of the urban subsurface hydrology is acute in catchments with significant groundwater-surface water interactions, and it has implications for nutrient fate and transport. Yet, while recent literature reviews recognise these issues as key knowledge gaps and challenges, the issues have received little attention in areas with high groundwater.

In 2014, the Cooperative Research Centre for Water Sensitive Cities (CRCWSC) established research project B2.4 'Hydrology and nutrient transport processes in groundwater/surface water systems'. The project aimed to assess the performance of selected SCSs (for example, infiltration basins, living streams and raingardens) in areas impacted by high groundwater. The team undertook an intensive field assessment of SCS performance across the Perth coastal plain in areas where the depth to groundwater seasonally ranged from 0 metres to 3 metres. Adyel et al. (2015), Ruibal-Conti et al. (2015) and Ocampo et al. (2017) detailed the assessment results. Hunt et al. (2017) is a guide to the monitoring protocols for assessing the performance of SCSs impacted by high groundwater.

In parallel with the SCSs performance assessment, the B2.4 project team identified other regions of the world where urban development in high groundwater areas created specific challenges. The team also reviewed published literature on water and nutrient balances in urban areas with high groundwater and significant groundwater-surface water interaction. This report summarises that review and highlights that Australia's key knowledge and data gaps are common across the world. The objective was to compile and synthesise relevant literature on:

1. the effects of urbanisation and stormwater practices on the water balance and hydrological processes of the urban subsurface

2. the implication of these processes for the fate and transport of nutrients along subsurface pathways in areas with high groundwater.

The knowledge gained from the literature review has been synthesised into a conceptual model specific to Perth's high groundwater conditions and urbanisation processes. Knowledge gaps have been identified, and recommendations made about how to address these gaps. Further, we suggest how new knowledge could assist design and planning of urban development in these areas of high groundwater.

The summarised research literature used case studies that span spatial scales from a few square metres (an individual SCS) to hundreds of square kilometres (catchment scale). All case studies focus on specific processes affecting unsaturated zone hydrology and the shallow, unconfined groundwater balance, over short time scales (a few days to weeks). They include variability at seasonal scale (that is, infiltration, recharge, water table response, and interflow), and the biogeochemical processes controlling nutrient transport under conditions relevant to Perth. We also included literature that involved *similarities* to Perth conditions in one or more aspects, such as soil characteristics (texture), rainfall (annual total and seasonality), and the prevalence of a shallow water table (depth of less than 5 metres). However, the case studies do not cover groundwater water balance outputs of evapotranspiration and groundwater extractions (such as pumping from bores from depths greater than 10 metres).

The literature review confirmed fundamental knowledge gaps remain:

- How do water balances operate in the unsaturated zone beneath urban areas?
- How do water table dynamics determine the characteristics of infiltrating/exfiltrating water into soil water storage? And, therefore, how do they affect recharge to and discharge from groundwater via underground stormwater infrastructure (urban karst)?
- What are the relative contributions of different infiltration sources and groundwater to interflow? And what is the contribution of interflow to runoff in the urban karst?
- How do all of the above affect environmental conditions and exposure times along different subsurface pathways? And how do they ultimately impact on nutrient transformations?

These knowledge gaps have consistently been identified in the literature, using empirical evidence (comprehensive data sets), simple mass balances involving tracers, and state-of-the-art three-dimensional numerical models. Given these knowledge gaps, it is hard to couple the well-developed areas of stormflow modelling (surface hydrology) and groundwater modelling (hydrogeology). The accurate prediction of changing water balances and nutrient export under urbanisation thus remains extremely challenging.

Below, we summarise the conclusions from the literature review, with a focus on water fluxes in and out of the urban unsaturated zone; implications for shallow water table dynamics; and the impact of the water fluxes on nutrient transformations.

Infiltration in the urban mosaic

In the coupled groundwater–surface water models that urban water balances frequently use, the representation of infiltration neglects important aspects of the process. These aspects are transient in nature and recover over time. Transient infiltration rates at the onset of an event can be up to three orders of magnitude larger than steady state infiltration rates, and they can be extremely important for short duration rainfall events. Infiltration estimated from 24 hour total rainfall that is typically used in coupled groundwater–surface water models can result in this water flux being underestimated.

Infiltration does occur from hard impervious areas (roads, parking lots etc.) via cracks and joints. Its magnitude and timing depend on the runoff from impervious areas, not rainfall. Urban water balances do not currently account for this infiltration, yet measured infiltration rates from these ‘impervious’ areas are comparable to infiltration in sandy soils (estimated to be up to 21 per cent of annual rainfall). The literature suggests up to 50 per cent of impervious areas should be considered as pervious, although we lack sufficient supporting data. Large uncertainties remain about ‘losses modelling’ in urban environments, particularly about the proper quantification of water volumes entering the subsurface environment.

Recharge of groundwater from rainfall events

Only a few studies compared recharge rates for SCSs and irrigated lawn areas. The results showed the SCSs produced 10 times more recharge than did lawns (including irrigation). Studies reported recharge rates of up to 40 per cent more than previously estimated for SCSs. Recharge values were reported as a percentage of infiltrated water at a depth of 2 metres (seepage) below the SCS bed, in a range of 60–80 per cent of the infiltrated water.

Large discrepancies are evident in the reported recharge in urban areas with shallow water tables, reflecting the studies' different methods and spatial scales. A general view in the literature is that 'improved estimates of recharge rates, based on recent mass balances and datasets, are larger than previously thought'. This outcome could be the result of previous water balance attempts not properly considering infiltration rates and total flux.

Recharge rate estimates at the urban catchment scale have been commonly reported after calibration of the coupled groundwater–surface water models. In the Perth context, previous recharge values ranged from 21 per cent to 37 per cent of the mean annual rainfall, while more recent estimates for areas with shallow water tables and infiltration practices reached 41–48 per cent of the annual rainfall. Several recent modelling studies agreed recharge accounted for approximately 60 per cent of total annual infiltration.

Improved estimates of recharge in the urban mosaic and landscape are needed, and mass balances of the unsaturated zone provide a valid approach. Analytical tools for recharge estimates are freely available, but they lack comprehensive datasets to adequately encompass local conditions.

Interflow processes and delivery mechanisms

The increasing number of scientific publications on this topic in 2016–17 shows we need to better understand the fate of infiltrated water and its pathways in urban areas. Research efforts in this area are underway in the United States, Europe and Australia (Melbourne).

At the scale of individual SCSs and small catchments with SCSs, both numerical modelling and field data have confirmed water mounding in areas with shallow water tables occurs during an event. Important to the mound's relaxation (the water table's return to pre-event levels) are the density of SCSs (that is, the number of SCS elements per area of catchment), their position in the landscape, and the hydraulic conductivity of the subsurface material. The time that relaxation takes should provide insight into the fate of the recharging water. Modelling results suggest mounding from isolated SCSs can dissipate within 48 hours in sandy soils, but can take up to 40 days in finer material. Only a few empirical studies confirmed dissipation times in sandy soils after the inflow of runoff to SCSs. A shorter recovery time, or departure from the hypothetical mound height or shape, could be attributed to temporary interactions with fill trenches from utilities, subsoil pipes to control groundwater, or stormwater drainage pipes. Unfortunately, no datasets have been reported or used to address this issue.

At the catchment scale, numerical models and recent field studies of urban areas with infiltration practices and mixed land uses provided evidence of altered hydrology across the unsaturated zone. These studies showed water that recharges the shallow aquifer returns to the stream, affecting its hydrology, hydrochemistry, and nutrient export. Mass balances and multi-technique approaches are cost-effective ways to examine how infiltration sources contribute to interflow and affect nutrient export. This knowledge is essential to:

- improve existing tools for urban planning, SCS individual design, and SCS spatial allocation in the catchment
- understand SCSs impact on the water table
- properly assess nutrient removal efficiency
- manage the impact of urbanisation on receiving water bodies.

Nutrient cycling along subsurface flow pathways in urban areas

This review found no comprehensive study reporting nutrient transformations along the subsurface pathway in urban environments (that is, from infiltration sources to recharge of the water table, and via subsurface transport to final discharge to the receiving waters). Only recent literature in tiled agricultural landscapes addressed how infiltration partitioned into the soil matrix, macropores water flow components, and shallow water table recharge, during rainfall events, impacting nutrient export from subsoil drains.

The studies concluded, given the rapid response of different flow components (peak flows within 45 minutes to 6 hours) and that up to 50 per cent of the total outflow bypasses the soil matrix, there is little opportunity for nutrient attenuation/processing within the shallow unsaturated zone before nutrients reach the subsoil pipes. But, in an agricultural context, the literature consistently reports nutrient attenuation (that is, nitrate) in the shallow groundwater beneath riparian zones when favourable conditions for the supply of carbon source and nitrate are found in a slow movement saturated flow field.

Whether the above findings apply to the unsaturated and saturated zones under urbanised areas is debatable, given (a) the complex subsurface of urban environments, and (b) the acceleration of different flow processes shortening the time scales for nutrient processing. No published study has documented how water pathways along the subsurface media (both unsaturated and saturated zones) in urban areas affect nutrient transport and transformations. A rare numerical modelling study in Perth explored the problem, assuming non-reactive transport of nutrients along different subsurface pathways. It provided insights into nutrient storage in the shallow groundwater, and nutrient discharge over time after urbanisation. Recent work in the United States supported some model findings, but highlighted that nutrients transform along the pathways (that is, they are not conserved).

Early studies of SCSs or at the whole urban catchment scale provided basic data for assessing potential contamination of groundwater and surface water resources. But these studies were inadequate for understanding nutrient transformation processes. The fate of dissolved oxygen (DO) introduced by infiltrating water along the subsurface pathway, and then the transport of DO into the shallow aquifer, depends on the amount of dissolved organic carbon (DOC) transported with the infiltrating water or available in the shallow sediments or filter material, and the transit time along this pathway. The amount of DO remaining (after DOC processing) controls oxic-anoxic conditions in the subsurface environment, in turn affecting nutrient transformation and availability.

Sandy soils consistently experience oxic conditions during infiltration, leading to little nutrient attenuation along the infiltration pathway. By contrast, fine textured subsurface soils (up to 41 per cent silt and clay) allow increased travel time, resulting in anoxic conditions at 2 metres depth and thus up to 90 per cent attenuation of inorganic nitrogen. Some literature reported DO recovery and increased nitrate concentrations along the shallow groundwater pathway away from the SCS locations. It found SCSs can act as local hotspots of nitrogen cycling, but the downstream fate and transport of nitrogen is unknown. Phosphorus dynamics along subsurface pathways were rarely reported.

Travel time along the subsurface pathway is an important consideration in addressing nutrient transformations. Infiltration from a large SCS with a travel time of 15 hours over 4 metres is not sufficient to achieve inorganic nitrogen reduction under steady infiltration conditions. The travel time concept may not be suitable, however, to address nutrient transformations for a small SCS where rapid shifts in filter media DO concentrations have been reported, with anoxic conditions present for up to two days after inflow events, then returning to oxic conditions as the water content decreases. Under such conditions, an exposure time scale (τ_E) approach may be better suited to exploring nutrient transformations.

Infiltrated water in urban areas with high groundwater experiences very short pathways, determined by a thinner, unsaturated zone (less than 4 metres) and the upper layer of the water table being impacted by infiltration. Unfortunately, no published research reported nutrient transformation along pathways within the shallow water table before its discharge via stormwater pipes (if intersected) or diffuse discharge (via bank and bed) to urban drains and streams.

Conceptual model to guide future work, and recommendations

We synthesised the literature findings as a conceptual model to guide future work on nutrient fate and transport along subsurface pathways in urban areas of high groundwater. This work will be important for helping to improve design aspects of SCSs, the spatial allocation of SCSs in catchments in relation to groundwater dynamics, and the overall effectiveness of SCSs for nutrient attenuation.

The model reflects current built forms and stormwater management practices in Perth, and incorporates different states of hydrological isolation and connection for:

- individual SCS elements (at rainfall event scale)
- local mounding (at event and seasonal scales)
- shallow water table dynamics (at seasonal scale).

It also provides the expected τ_E for nutrient processing, plus a qualitative description of interflow composition as the catchment transitions from dry summer to wet winter conditions. The conceptual model highlights that τ_E values remain unknown for interflow components within imported fill and the high groundwater during times of hydrological connectivity. These time scales correspond to significant knowledge gaps identified from the literature.

It is imperative to address infiltration rates, recharge rates, and the relative magnitude of water sources contributing to interflow within the urban mosaic and individual SCS elements. The conceptual model guides the spatial scale at which the following recommended activities should be implemented, to allow site comparisons and the extrapolation of results for different urban forms:

- Estimate infiltration/exfiltration rates from SCSs using hydrograph recession analysis. Measure the hydrograph at the surface water storage or filter media storage via continuous water level recordings.
- Compute recharge rates and amounts, and report them at a standard depth of 2 metres below ground level, using soil moisture sensors and shallow bore hydrograph analysis. Collect data under hard surfaces (such as streets and parking lots), under housing built on imported fill (isolated and close to subsoil drains), and under green areas on both imported fill and natural soils.
- Undertake interflow monitoring via a combination of hydrometric and environmental tracers to identify the source of infiltration and to quantify groundwater discharge. Conduct monitoring along stormwater drainage pipes to ensure a proper mass balance approach.
- Use a mass balance approach along the high groundwater pathway, following control planes and using an integrative mass flux concept, with budget regions including areas where interflow monitoring is undertaken. Locate control planes from highland to lowland areas to quantify τ_E and nutrient transformations.

1 Introduction

Balancing water and solute masses in groundwater beneath urban areas has gained momentum over the past 25 years. Groundwater resources are now included as part of integrated urban water management (IUWM) (Schirmer et al., 2013). Urban hydrogeology has become an area of active research among hydrogeologists looking at the impact of urbanisation on water and solute balances in aquifers (shallow and deep) under urban environments. This research is covering a wide range of spatial (from small precincts or neighbourhoods to entire metropolitan areas) and temporal (from annual to century) scales.

Under the IUWM holistic approach, water supply, drainage, and sewage systems are all part of an integrated physical system operating under an organisational framework within a natural landscape (Mitchell, 2006). Mitigating the environmental impacts of urban development on surface water resources dominated the adoption of IUWM, with groundwater management remaining in a very incipient stage (Mitchell, 2006). The recent focus on urban groundwater management for consumptive potable and non-potable uses, and for environmental requirements, demands a quantification—using multi-technique approaches—of how urbanisation affects water fluxes, pollutants and micro-pollutants in and out of the urban groundwater system (Schirmer et al., 2013).

Recent conceptual models for IUWM included the impact of urbanisation on the water balance (Schirmer et al., 2013), stormflow management to restore urban stream baseflow (Hamel et al., 2013), and a decision support framework for assessing impact on baseflow (Bhaskar et al., 2016). Often, such conceptual models and assessment tools closely follow hydrological model structures, by driving water flow partitioning and fluxes (quantitatively in models and qualitatively in tools) through different hydrological components of the urban environment.

A simplified conceptual model, for example, divided the urban environment into four compartments or regions, with corresponding hydrological processes and fluxes: the surface, the upper soil, the unsaturated, and the groundwater saturated zones (Schirmer et al., 2013). While imperviousness in the surface and upper soil zones reduces infiltration and transpiration, and thus causes greater surface runoff, the outflow (or artificial interflow) from the unsaturated zone also increases. This increase mainly results from the import of water via mains, the irrigation of green spaces (parks, yards), and the interception of some stormwater infiltrated during events that are efficiently conveyed by sewage and stormflow drainage infrastructure (Lerner, 2002). Finally, some of the artificial recharge or indirect local recharge (linear in pipes or localised in infiltration ponds) reaches the water table (the saturated zone) and increases the water table interaction with pipes and urban streams as baseflow.

A large body of research worldwide recommended the implementation of water sensitive urban design (WSUD) or low impact development (LID) technologies, to moderate the negative impact of urbanisation on surface hydrology (that is, the surface and soil compartments of IUWM) and water quality. This recommendation applies for both existing and new urban areas. Subsequently, at source control systems (SCSs) such as infiltration–filtration systems (trench, basin, bioretention, raingarden, and swale) and harvesting systems (which divert runoff from impervious areas) have been extensively assessed for their hydrological efficiency and their reduction of pollutant concentrations (Davis et al., 2009; Roy-Poirier et al., 2010; Ahiablame et al., 2012; Kidmose et al., 2015). While most literature has focused on the need to improve efficiency in pollutant reduction, and discussed the potential accumulation of pollutants in such systems, few studies have looked to better understand how infiltration from SCSs affects water table level dynamics over space and time (Endreny and Collins, 2009).

Endreny and Collins (2009) highlighted the research community’s growing interest beyond source control and pollutant removal. They noted a move to assess how SCS infiltration may affect water table responses and mounding (Göbel et al., 2004; Endreny and Collins, 2009; Kebler et al., 2012), water fluxes, and shallow interflow in the subsurface media (DeBusk et al., 2011), and the potential use of infiltrated stormwater to restore baseflow regime of urban waterways (Hamel et al., 2013; Li et al., 2017). Linking these hydrological processes is difficult because infiltrated water’s pathway and contribution to baseflow are catchment specific and not straightforward; further, they are catchment scale dependent (Hamel et al., 2013; Bonneau et al., 2017).

The complex dynamics of the urban subsurface hydrology, or ‘urban karst’ (Sharp et al., 2001), result from the combination of:

- an intricate conveyance system (trenches, tunnels, pipes) that alters the pre-development porosity and permeability of the soil

- a variety of artificial recharge sources (linear and point sources), direct recharge sources (infiltration from undisturbed land), and unknown localised sources from paths traditionally believed to be impervious (carparks, driveways, low permeability areas) and directly connected to drainage infrastructure (Lerner, 2002).

Important advances have been made in quantifying artificial linear recharge (leakage) from sewer systems, and the interaction of sewer systems with the water table (Wolf et al., 2006; Rieckermann et al., 2007). But the effect of localised infiltration from SCS elements remains unclear. Infiltration occurs at much faster rates under transient conditions, and additional complexity arises from properly quantifying interflow in the time domain (Blasch et al., 2006).

The comprehensive literature review conducted by Schirmer et al. (2013) focused on information needed to assess urban water balance and water quality. It reviewed recent literature on adaptive methods and holistic modelling approaches; that review will not be repeated here. The authors identified future research needs for determining water balances and water flow, and highlighted key gaps and challenges:

1. recharge estimation in time and space

2. the identification of infiltration from paved areas or disconnected sealed surfaces

3. the quantification of water flow in the urban unsaturated zone

4. the use of holistic approaches to examine the complex urban recharge, interflow and discharge processes.

New datasets, field techniques, and multi-technique approaches (including coupled groundwater–surface water interaction models) presented in recent years could provide valuable insights into how to create a more robust conceptual model for predicting the impact of urbanisation on the urban groundwater systems by first balancing water, then extending the work to pollutant dynamics (Schirmer et al., 2013; Hamel et al., 2013).

A detailed literature review (Carey et al., 2013) assessed the impacts of urbanisation on catchment nutrient (nitrogen and phosphorus) pathways, and identified research gaps and challenges. It noted substantial advances in the identification and management of point and non-point sources. But it also found a lack of knowledge about nutrient fate and transport within urban catchments in general, and specifically how different water sources contribute to nutrient discharge at catchment outlets. This knowledge gap is acute in catchments with significant groundwater–surface water interactions. Yet such understanding is fundamental for the design of more effective control measurements and strategies to mitigate the potential negative impacts of new urban developments.

Our objective for this report was to compile and synthesise recent literature, specific to the gaps in and challenges for quantifying:

- the effects of urbanisation and stormwater practices on the water balance, recharge processes, and subsurface hydrology

- the fate and transport of nutrients and pollutants in areas with high groundwater.

To the best of our knowledge, only a few studies have addressed these matters. This important knowledge gap must be addressed if we are to better assess the impact of urbanisation and stormwater management in the areas of high groundwater (less than 5 metres to the water table) found in the Perth coastal plain in Western Australia, Australia. Starting to tackle this knowledge gap was a focus of the Cooperative Research Centre for Water Sensitive Cities' (CRCWSC) Project B2.4 'Hydrology and nutrient transport processes in groundwater/surface water systems'. This literature review thus aimed to:

- identify both agreed and contentious understandings of the impact of urbanisation and the implementation of best management practices on water balances in areas of high groundwater
- help close gaps in understanding of the urban surface hydrology and the urban hydrogeology, to improve our modelling capabilities for urban stormwater design and planning, and for the prediction of the fate and transport of nutrients and pollutants
- contribute to the use of multi-technique approaches to gather the new information needed to resolve the above issues.

2 Effect of urbanisation on water balances

A wealth of urban groundwater research has assessed the impact of urbanisation on the water balance. Much of the research has focused on groundwater yields, the effect of changed land uses on recharge, and the artificial recharge from water supply and sewer pipes (Schirmer et al., 2013). Figure 1 illustrates a simplified conceptual model of an urban water balance, highlighting the natural and modified water fluxes, and new pathways introduced by urbanisation (columns a, b and c).

The comprehensive literature review by Schirmer et al. (2013) focused on information needed to assess urban water balances and water quality problems. It extensively reviewed recent literature on adaptive methods and holistic modelling approaches, and is not repeated here. The literature shows cities in the developed world have become importers of water from remote sources, and the exploitation of groundwater beneath urban areas has declined in response to associated environmental problems (for example, land subsidence, and salt water intrusion in coastal cities). Given the reduction in abstraction volumes, groundwater levels are rising again. The research has stressed the shift of groundwater recharge sources as cities develop, with minor change in net recharge values.

Long term urban water balances studies (20–150 years) have been undertaken in Beijing, China (Zhang and Kennedy, 2006); Leipzig, Germany (Haase, 2009); Birmingham, England (Thomas and Tellam, 2006); Barcelona, Spain (Vazquez-Sune et al., 2010); and Copenhagen, Denmark (Jeppesen et al., 2011), to name just a few. The researchers followed a holistic approach using complex numerical tools (coupling surface hydrology, unsaturated zone hydrology, groundwater flow models, and hydrochemical tracers) and geographic information systems (GISs) to quantify the overall water balance and the relative importance of water fluxes and hydrological processes.

In Beijing, a water balance conducted to estimate the sustainable yield of the city aquifer (~50 per cent of water supply via groundwater) indicated wastewater sources provided 30–60 per cent of the water, with increasing concern about the groundwater resources quality. In Leipzig, the results of a water balance using empirical methods (without data validation) showed urban spread largely increased surface runoff, with a slightly decrease in net recharge to groundwater due to surface sealing and reduced evapotranspiration. More sophisticated modelling tools to address recharge to groundwater were used in both Birmingham and Copenhagen:

- The Birmingham study stressed the potential relevance of groundwater recharge from paved areas due to lack of evapotranspiration. But it did not validate all the recharge estimations with measurements.

- The Copenhagen study showed an increase in groundwater recharge due to an increase in precipitation that balanced the urbanisation effect. It also highlighted that water main leaks made up 50 per cent of total recharge by the 1950s, then pipe renovations reduced those leaks.

Hydrochemical approaches used in the Barcelona study accounted for eight different recharge sources, and showed 50 per cent of aquifer water originated from the water supply and sewage network. In this case, stormwater had a major impact locally on the water resources. (We refer the reader to Schirmer et al. [2013] for further details on water balance applications.)

A similar approach was followed in studies of the Perth coastal plain, Western Australia, with Barron et al. (2013a) and Locatelli et al. (2017) undertaking water balances in an urbanised area with high groundwater. Figure 1 (columns d and e) show the resulting urban water balance, modified water fluxes and introduced pathways.

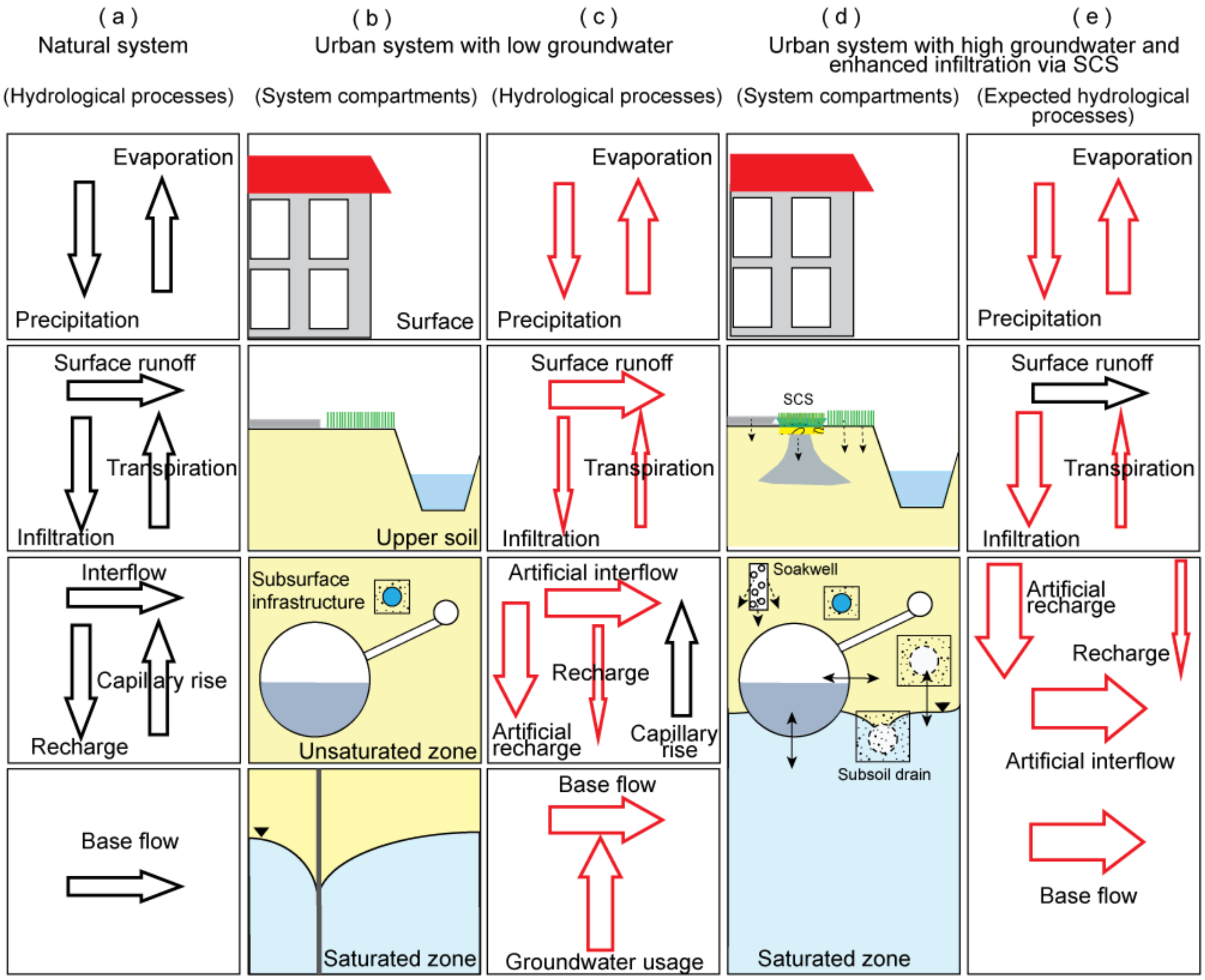

Figure 1: Conceptual model of perturbation of the urban water balance. The red arrows represent water flow that has been modified or newly introduced by urbanisation and proposed urbanisation in a high groundwater environment with source control systems (SCSs). Modified from Schirmer et al. (2013)

2.1 Recharge in urban environments: mounding and rapid water table responses

The holistic approaches mentioned above (coupling urban hydrology processes with unsaturated zone and groundwater flow models of different complexities) have been applied at different urban catchment scales:

- large scale, which is greater than 10 km^2 (Göbel et al., 2004; Miller, 2006; Barr and Barron, 2009; Barron et al., 2013a; Locatelli et al., 2017)
- small scale, which is 1–10 km^2 (Endreny and Collins, 2009)
- individual SCS scale (Carleton, 2010; Newcomer et al., 2014).

These studies focused on the implementation of best stormwater management practices, and assessed the impact on infiltration and recharge to groundwater, and on subsurface hydrology. Specifically, they looked at the overall water balance at catchment scale, as well as the local mounding and response of the shallow water table.

Barr and Barron (2009) and Barron et al. (2013a) explored the effect of urbanisation in the Southern River catchment (150 km^2), which contained 30 km^2 of urban areas and incorporated current best management practices for urban developments in areas of high groundwater. These practices included direct infiltration from roof and road runoff (via soakwells), and groundwater level control by subsoil drainage. The novel work by Locattelli et al. (2017) expanded the above study, and investigated the effect of extensive infiltration via soakwells in a smaller area within the Southern River catchment. Both modelling approaches coupled urban surface hydrology processes with unsaturated zone and groundwater aquifer dynamics, using modified standard models—namely, a variation of MODFLOW called MODHMS (Barr and Barron, 2009), and commercially available tools such as MIKE SHE and MIKE URBAN (Locatelli et al., 2017).

Barron et al. (2013a) showed urbanisation and stormwater management practices affected the water balance of the area. They attributed the increase in the catchment scale runoff coefficient (from 1 per cent to 40 per cent) and the changes in streamflow regime from ephemeral to perennial (duration of flow) to changes in the hydrology of the shallow unsaturated zone. Recharge occurred at higher rates than found before urbanisation, evapotranspiration losses diminished, and the groundwater discharge to stream increased via subsoil drains (a common practice in areas with high groundwater). Both annual gross recharge (the amount of water reaching the water table) and net recharge (the difference between infiltrated water minus evaporation from model subsurface layers) increased after urbanisation, from 29 per cent to 41 per cent (~60 per cent of total infiltration) of annual rainfall for gross recharge and from 1 per cent to 8 per cent of annual rainfall for net recharge from direct infiltration practices.

Locatelli et al. (2017) advanced and refined the previous modelling work by:

- explicitly coupling soakwell infiltration with groundwater levels (soakwell performance can be impacted)
- increasing spatial resolution (to 70 × 70 metre grid) and reducing the time step to a 10 minute interval
- spatially aggregating soakwells over a housing block of 100 × 400 metres
- exploring changes in long term water balances over 40 years.

Over an urbanised subcatchment, the study showed soakwell infiltration increased from less than 5 per cent of the annual rainfall in 1974 to 21 per cent by 2012. The increase was a response to the spread in urban areas from 8 per cent to 88 per cent respectively. Over the whole catchment, net recharge values for 2009–14 was 19 per cent of annual rainfall, with values ranging from 0 in undeveloped areas to 48 per cent in urbanised areas. Despite significant differences in their modelling tools and hydrological processes representation used, both studies agreed urbanisation with implemented SCSs and groundwater control via subsoil pipes will lead to increased recharge, increased baseflow to rivers, and increased net recharge to groundwater (recharge less evapotranspiration).

Small catchment scale studies have focused on quantifying the magnitude of local water table mounding that results from infiltration from individual SCSs, and their spatial distribution and density within an urban catchment. As the water exfiltrates the SCS, it needs to travel in the unsaturated zone until it reaches the water table to become effective recharge. The term ‘seepage’ is commonly used in numerical modelling of the unsaturated zone, and it refers to the water leaving the numerical domain at approximately 2 metres depth in the soil profile beneath SCSs (Miller, 2006; Newcomer et al., 2014). These studies showed 56 per cent and 89 per cent of exfiltration from SCSs will become recharge for dry and wet years respectively.

Higher rates of recharge lead to a higher water table. As a result, the length of the water path (from the SCS bed to the water table) rapidly declines, the travel time in the unsaturated zone shortens, and the water table and mounding respond more dynamically. Few studies have specifically investigated these characteristics in small urban areas (from a few hectares up to 10 km^2) with 2–5 metre depth to the water table. One, two and three dimensional groundwater flow modelling (Göbel et al., 2004; Miller, 2006; Endreny and Collins, 2009) and water balances driven by flow data (Keblel et al., 2012) are some of the very few examples.

These studies provided strong evidence that 'recharge rates' and the 'spatial distribution' of SCSs are more important for the water table dynamics and mounding than are the degree of imperviousness and size of development. In one study, recharge accounted for 60–80 per cent of the annual rainfall from swales and trenches, and resulted in water table mounding of up to 2.3 metres (Göbel et al., 2004). In another, mounding in sag areas (low elevation points in the catchment) was found to be up to 1 metre, when considering different spatial configurations of biofilters under frequent rainfall events (two year average recurrence interval [ARI] of 24 hours) (Endreny and Collins, 2009). That study also demonstrated that a decrease in permeability in the subsurface media substantially increased mounding duration (that is, the time for the water table to return to pre-mounding level) from two to seven days, to 40 days under wet weather conditions. This time is longer than intra-event periods, and it could result in an overlap of mounding events and, ultimately, a higher water table.

The progressive development of water mounding was observed in a perched water table beneath infiltration ponds in an arid environment (~330 millimetres of annual rainfall) in New Mexico (United States) with sandy soil (3 metre depth) overlying a clayed layer (Miller, 2006; Stephens et al., 2012). Both studies demonstrated that recharge values in the area increased to 40 per cent of the annual rainfall, and were much larger than previous estimates of 1 per cent (3 millimetres per year). Pond infiltrating areas represented 12 per cent of the catchment areas.

Despite their successful calibration of groundwater models with water level data, it is important to note that these studies used transient or variable recharge rates over seasonal and inter-annual scales, but a constant recharge rate over the duration of rainfall period. Further, results from the complex modelling tools are often questioned, given uncertainties in the modelled parameter values, processes representation, and spatial scale issues associated with hydrological systems. But these tools are still used to quantify the overall impact of urbanisation on a water balance, and the relative magnitude of changes in water pathways within the system. The question remains whether future empirical evidence will support these modelled findings.

Field data has demonstrated the rapid and direct response of a shallow water table to inflow into infiltration basins on a 40 hectare urban catchment of the headwater Brettenbach River (Trier-Petrisberg, Germany). In the catchment, SCSs were used to enhance infiltration for flood control (Kebler et al., 2012). Although the SCSs were implemented in areas not suitable for infiltration under local guidelines (sandy loam soils receiving an annual rainfall of 784 millimetres), the water table was found at a depth of 1–3 metres, and it showed no significant increase over time due to the low density of implemented SCSs in the area.

2.2 Observations on the dynamics of the water table, subsurface pathways, and recharge sources in surficial sandy aquifers in Perth (Western Australia)

Most studies undertaken in the Perth coastal plain area have focused on sustainable aquifer functioning for water consumptive uses and allocation. Using the numerical model PRAMS, Davidson and Yu (2008) focused on the Gnangara and Jandakot mounds, which both contribute to Perth's drinking water supply and support groundwater dependent ecosystems. Also a concern, the effect of urbanisation on high groundwater quality has been investigated at SCS or local scales, and at larger scales comprising the surficial aquifer (Appleyard, 1993; Appleyard, 1995; Salmon et al., 2014). Here, we review research findings from Bassendean and Spearwood sands and the Guilford formations, where most existing and new urban development occurs.

Rapid fluctuations of the water table were commonly observed in response to rainfall events at the onset of the wet season in May. They were found at local or point scale infiltration basins (Appleyard, 1993), at field scale in light industrial and residential areas (Benker et al., 1997), and at larger scale such as the surficial aquifer mounding under non-urban land uses (Salama et al., 2005):

- Appleyard (1993) reported recharge from infiltration basins (600 m^2) over stormflow events in areas with shallow water tables (~2.5 metres below ground). The water table responded within minutes to the inflow to the basin, and peaked within six hours, with water level increases of 0.5–2.5 metres depending on the season.

- Benker et al. (1996) also observed rapid increases in the water table at monitoring bores that were 300–400 metres from basins where stormwater was infiltrating, influencing the groundwater flow patterns across the site. Storm-induced infiltration from such facilities in urban areas clearly has an effect on infiltration rates and recharge. For non-urban land uses, however, such responses should be associated with soil texture characteristics and soil moisture antecedent conditions.

- Salama et al. (2005) investigated sub-surface flow pathways in representative soils (Bassendean and Spearwood sands) using infiltration tests and in-situ dye experiments under non-urban land uses. They showed infiltrated water followed different pathways under dry (fingering) and wet (uniform) soil moisture conditions. But the moisture front reached similar depths (more than 1.5 metres) during a 40 millimetre irrigation event of one hour. Rapid infiltration occurred, and these results are relevant for considering the time scale of recharge processes in areas of high groundwater (that is, less than 5 metres).

All studies consistently documented the seasonal pattern of the water table level variability. This annual fluctuation ranged from 0.3 metres to 2.5 metres, depending primarily on the depth to water table and land uses. The water table usually reaches a maximum value between mid-August and the end of September, with the timing strongly depending on rainfall distribution and the depth to water table. Both urban and cleared areas displayed a slow rise in the water table in late June and July months.

The magnitude and seasonal variability of the water table hydraulic gradient in urban areas in Perth were found to be consistent across study sites under different urban typologies (built forms on different soil types and with different water table depths). High gradients of up to 0.004 m/m were found at high ground elevation in the Gnangara mound and close to the Upper Swan River valley north of Perth (Salama et al., 2005; McHugh et al., 2011). Low mean gradient values of 0.0018 m/m were reported close to light industrial and/or old residential areas in suburban Jolimont (Benker et al., 1996). Despite consistency in the observed hydraulic gradients across studies, few studies reported the effect of local recharge by infiltration facilities on hydraulic gradients and flow direction. Benker et al. (1996) suggested such infiltration influences the horizontal direction of the groundwater flow by 3 per cent, but also increases the local vertical spread of a contaminant plume. As Appleyard (1993; 1995) noted, these basins are responsible for spatial variability in recharge rates, and they influence the hydrochemistry of the shallow water table.

Although reported water table fluctuations and hydraulic gradients were consistent across these field studies and spatial scales, the literature shows large discrepancies in reported recharge values. Cargeeg et al. (1987) estimated recharge values for sewered urban areas in Perth at approximately 21 per cent of the mean annual rainfall, and they used these values in the Perth regional aquifer modelling. The need to improve groundwater modelling predictions guided the research effort to reduce uncertainties for recharge estimates under different land uses. Appleyard (1995) also investigated the impact of sewered urban development on recharge and groundwater quality, using groundwater data at three levels of urban development: uncleared, new residential (less than 20 years old), and old residential (more than 60 years old). Appleyard estimated recharge in the new urban area was about 37 per cent of the average annual rainfall (~800 millimetres), noting this value was greater than previously estimated recharge for sewered urban areas, and probably larger than in undeveloped areas.

Recharge estimates for other land uses were reported by means of water balance approaches (Salmon et al., 2014). Xu et al. (2009) proposed recharge values of 30 per cent and 40 per cent of the average annual rainfall for low density pine plantations and market gardens respectively. These estimates were higher than earlier respective estimates of 25 per cent and 17 per cent using seasonal water table fluctuation levels (Salama et al., 2005). The later work also estimated recharge rates for urban areas at approximately 11 per cent of the average annual rainfall. Such low values were later attributed to a lack of representativeness of the selected specific yield value for the aquifer. Surprisingly, one monitoring site (bore l80c) located close to a new urban development over high groundwater (Ellenbrook, Western Australia) presented a remarkable seasonal variation of approximately 5 metres in water level; further, its estimated recharge value exceeded the average annual rainfall by 25 per cent. We discuss this unusual value in the context of urbanisation's impact on water table levels in section 2.4.

2.3 Interflow processes in urban areas: the link to baseflow and surface water flow regimes

The numerical modelling by Barron et al. (2013a) and Locatelli et al. (2017) establishes that the increase in groundwater discharge from the catchment relates to changes in the unsaturated zone water balance and water flow pathways that increased the interflow component. Interflow—that is, the infiltrated water moving through the shallow saturated subsurface media—is relevant to runoff generation and water pathways in rural and forested catchments where a shallow impeding layer exists in the subsoil (McGlynn et al., 2002; McGlynn and McDonnell, 2003). However, as Bonneau et al. (2017) noted, little is known about the interflow process in urban catchments; its connection to local exfiltration sources of SCSs and their flow regimes; its interaction with shallow water tables; or its discharge into stormflow drainage systems.

Hamel et al. (2013) discussed several analytical techniques to identify the interflow process, which are based mainly in stormflow hydrographs at catchment outlets (the recession limb of the hydrograph). The sharp falling limb of stormflow hydrographs in urban areas, particularly in small catchments, limits current approaches that use runoff hydrographs with data collected at hourly or daily time scales.

Difficulties in addressing interflow (and, for example, its connection to SCSs) stem from the available observations at the catchment scale outlet. That outlet integrates several water pathways: directly connected surface pathways, surface and subsurface pathways via drainage pipes, and pathways via the shallow water table. DeBusk et al. (2011) compared flow regimes resulting from a SCS (a bioretention basin with a subsurface pipe outflow) and ephemeral streams from non-urban catchments, to assess how well they mimic shallow water table recharge (interflow) during inter-event periods (after events). The study found no statistical differences in both systems' flow rates and total volumes over the first 24 hours and over slightly longer periods respectively. It concluded that a SCS flow regime behaves like a natural catchment. However, the observations were conducted in natural catchments characterised by low soil permeability (silty loam and clay) where interflow may be limited.

Mass balance approaches (using either hydrometric data alone or in combination with tracers) for nested stations along drainage pipes have been shown to be suitable for quantifying different inflow and infiltration sources in urban areas (Schirmer et al., 2013). These approaches can quantify interflow volumes and the time scales of different infiltration processes, and they could improve our understanding of the urban karst dynamics (Sharp et al., 2001; Bonneau et al., 2017).

V&A (2010) used hydrometric flow data from nested monitoring stations along pipes in the City of Ukiah (California, United States), which has ~889 mm average annual rainfall, and strong seasonality in rainfall. They captured the hydrological responses of all flow components in the sewer: frequent rainfall events (ARI less than two years, one hour to one day duration), infiltration sources, and dry weather flows (water use). They proposed an index series based on characteristic hydrologic responses (peak flow and time scales) for inflow (stormflow) and infiltration sources (water table, rainfall dependent infiltration, and rapid interflow via trenches) to classify urban catchment responses to rainfall (Figure 2).

V&A (2010) defined the ‘inflow’ as stormwater discharged into the sewer system. The sources included private sewer laterals, direct connections (downspouts), backyard drains, and holes in manholes, and all were easily identified from the sharp increase in water levels with rainfall. The infiltration included three different pathways but all pathways entered the sewer system in a similar way—that is, via defective pipes, joints, manhole walls, and cracks resulting from root intrusion points and broken pipes. The pathway ‘rainfall responsive infiltration’ (intercepting shallow infrastructure trenches) differed from other ‘rainfall dependent infiltration’ in the timing of their appearance in the sewer pipes: the later took 24 hours or slightly longer. The third pathway corresponded to water table (or groundwater) infiltration. It was driven by its depth above the sewer pipe, and by the degree of the pipe submergence. This infiltration component (or recharge) was detectable by the disruption of typical diurnal cycles (frequency and amplitude in flow rates) of the dry weather flows in the sewer or baseflow.

The relevance of this work is that it proposed ways to normalise the data based on water source volumetric contributions and physical characteristics of the sewer systems (pipe length/dimensions, catchment areas, and dry weather flow regime). Further, the work allows for comparing and ranking relevant water pathways for management purposes. This framework can be easily expanded to contaminant transport in the catchment, by providing fundamental times scales for the hydrological processes involved.

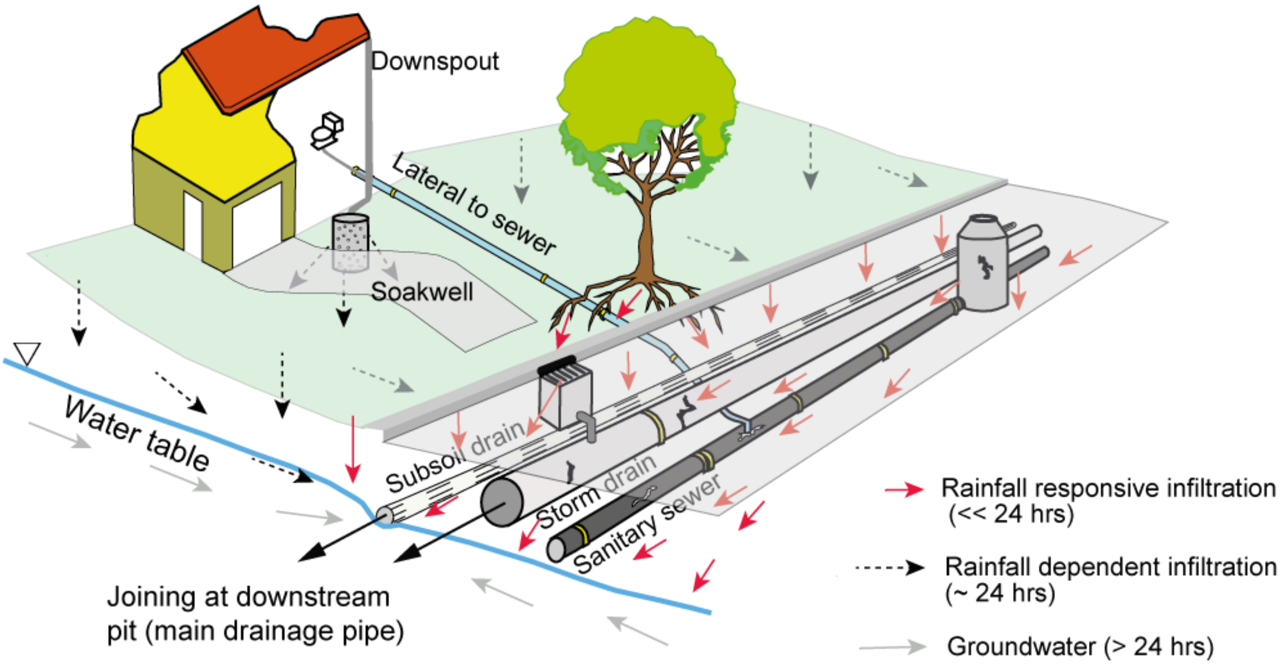

Figure 2: Different sources of infiltration in the urban karst. Modified from V&A Consulting (2010)

Mass balances approaches, and chemical and isotopic tracers have been used to assess recharge through rapid subsurface flow pathways, and to determine the role of subsurface storage beneath urban catchments in runoff generation (Meriano et al., 2011; Bhaskar and Welty, 2015). Meriano et al. (2011) used this approach in a small, highly urbanised catchment (87 per cent) in Pine Creek (Canada) with a shallow water table at 2 metres depth. They showed recharge effectively took place over a 38 hour period and represented 6 per cent of the total rainfall in a small event (5.8 millimetres) during summer, after dry antecedent conditions.

Predictions of flow discharge from catchments in hydrology have been commonly based on storage–discharge relationships (Beven, 2006). But how urban development (with its impervious cover, fill and pipes) affects the subsurface storage and its discharge is unknown. Using numerical modelling and tracers (stable isotopes), Bhaskar and Welty (2015) examined how existing water stored in the subsurface contributed to stormflow in urbanised areas. Although rainfall depth was identified as a primary control on volumetric contributions of pre-event water (shallow groundwater) to the outflow, mismatches between numerical model predictions and observations could be the result of subsurface pipes and drainage not being sufficiently represented in the model. The large proportion of pre-event water was particularly surprising for an urban watershed, where groundwater–surface water interactions are commonly assumed to be more limited than in other catchment settings. The large proportion of pre-event water was explained by the size of the subsurface storage—that is, the storage may be small and, therefore, is almost always filled by any precipitation event before this water discharges (spilling). However, the authors did not consider the possibility that local mounding of the water table could intercept sewer and drainage pipes, delivering close to pre-event signals to the catchment outlet.

All the above findings highlight the impact of urbanisation on the subsurface hydrology (referred to as *karstification* of the water table): not only does the spatial variability of the recharge increase, but the pathway and timing of infiltrating water, and the hydrological response of the water table change too.

2.4 Empirical evidence of recharge and interflow in urban areas with high groundwater

Using hydrometric data for streamflow at the Bayswater Main Drain catchment outlet (Perth), and baseflow separation techniques (digital filter), Barron et al. (2010) demonstrated that baseflow in the drains increased in late August and peaked in October. This finding indicated a substantial contribution of groundwater via stormwater infrastructure. Unfortunately, the data did not allow quantification of groundwater discharge, nor provide conclusive evidence of the interflow pathway.

A seepage face may be considered the surface expression of groundwater discharge. Its temporal dynamics can be directly linked to the local groundwater storage and recharge of the immediately upstream surface catchment, particularly when the seepage is a surface expression of the local water table. An investigation of the Egerton seepage, located immediately downstream of The Vale development (approved by Ministerial condition November 2004), assessed the impact of urbanisation on the hydrology and water quality of the seepage (McHugh et al., 2011). This study was part of a research program on Perth high groundwater systems, undertaken by the WA Department of Water over 2007–10. Shallow bores (EGT_C less than 5 metres depth) at the seepage were monitored: these bores were situated next to the existing bore B25, previously set by Ministerial condition as a reference point to assess the long-term impact of urban development on local groundwater hydrology.

McHugh et al. (2011) showed evidence of an increasing water table level since 2000, by approximately 1 metre (compared with pre-development data from 1996-97). The trend was confirmed by historical data from bore B25 that also displayed an increase in water levels and seasonal amplitude by approximately 0.5 metres since 2004. The study concluded the hydrology of the seepage was influenced by urban development activities, and by local recharge and runoff from the new developed areas. The seepage dried out in summer 1999-2000, given dewatering for road construction work at The Vale (even though good rainfall was recorded in previous years), but flowed strongly after development (the end of 2005 and 2007) despite lower than average rainfall years.

The study also confirmed the earlier unusual findings by Salama et al. (2005) that the seasonal water table fluctuation was 5 metres at bore l80c, and resulted in annual recharge estimates that were larger than the average annual rainfall in the area. Additionally, low values of electrical conductivity (200–300 μS/cm) and oxidising environmental conditions (positive redox potential values, although low levels of dissolved oxygen in the water) in the shallow water table highlighted the strong influence of rainfall recharge. This study is one of the few that has qualitatively demonstrated the impact of urbanisation on shallow water table recharge and subsequent discharge from the seepage.

In relation to SCSs for stormwater, and their interaction with high groundwater, a recent field study on an urban development in Perth (Ocampo and Oldham, 2017) documented that interaction with groundwater affected the hydrologic performance of a bioretention system. The study also quantified the discharge of groundwater from underdrain pipes. It showed a reduction in volumetric control by the bioretention basin, the establishment of baseflow conditions, and an increase in the outflow water's salinity coincided with a high water table intercepting the underdrain outflow pipes of the system. A mass balance approach using a passive tracer quantified (a) the volumetric contribution of groundwater at 25 per cent of the outflow volume during rainfall events and (b) the increased export of inorganic nitrogen forms (Ocampo et al., 2017). The study highlighted that the duration of groundwater interactions, along with the subsequent increase in groundwater contribution to the baseflow in the system, relates to the average annual rainfall.

Although these studies are constrained to specific sites, their findings are consistent with the numerical modelling results of Barron et al. (2013a) and Locatelli et al. (2017). All highlight the increase in recharge and interflow volumes (infiltrated water plus groundwater) to the surface water, under urbanisation. However, we still need to account for all relevant subsurface pathways leading to water table recharge, mounding and its interaction with underground water infrastructure, and to properly quantify infiltration sources, volumes and rates.

2.5 Infiltration volume and rates from source control systems: new insights

Traditionally, the effectiveness of SCSs has been assessed by stormflow peak discharge and runoff volume reductions. Studies have accounted for infiltration into amended media and underlying soils, and for exfiltration from filter media and/or lateral walls, as a water loss (Figure 3).

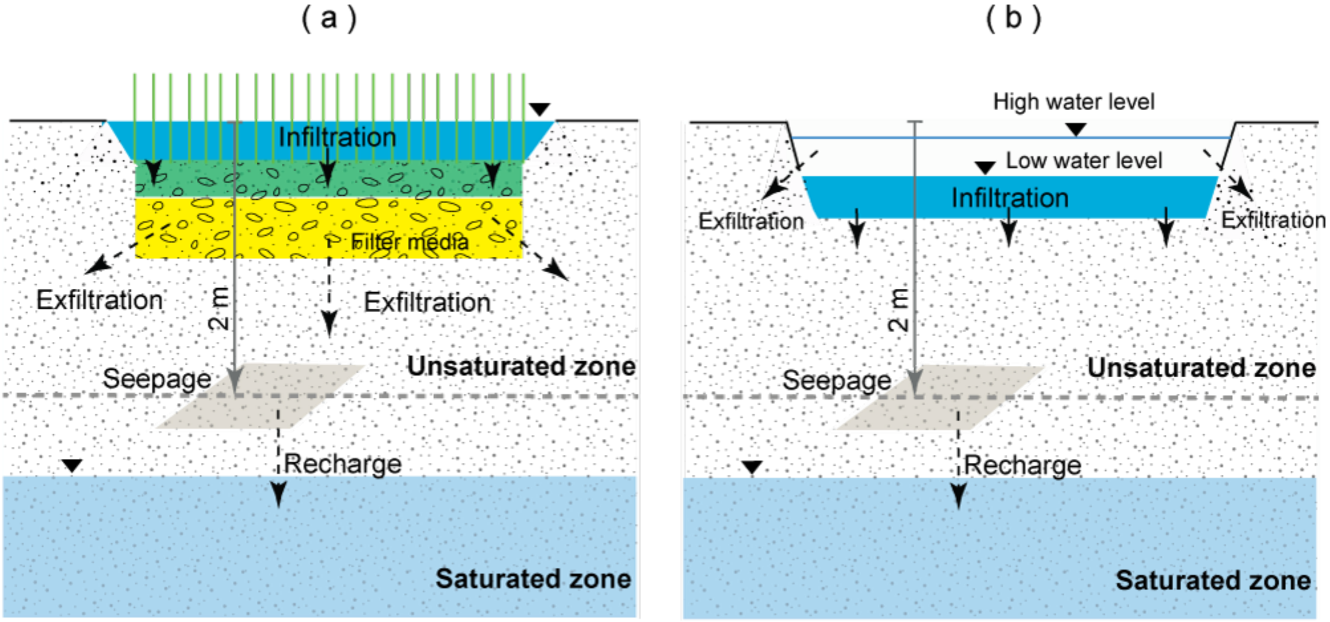

Figure 3. Conceptual model of hydrological processes in the unsaturated zone beneath SCSs: (a) small size (area smaller than 50 m^2) and (b) large size (area greater than 300 m^2) Notes: 1. Large size SCSs do not present engineered filter media. 2. The seepage flux plane is located 2 metres below the ground surface. 3. The horizontal dimension in (a) and (b) is not to scale.

A water balance metric commonly used in the SCS literature is the recharge efficiency (as a percentage), defined as the percentage of total water inputs to SCSs that becomes recharge:

$$\text{Recharge efficiency (\%)} = \left(\frac{\text{Inflows} - \text{Outflows}}{\text{Inflows}}\right) \text{ x } 100 \qquad (1)$$

where inflows are from precipitation and runoff, and outflows include evaporation and overflows such as bypass and surface discharge. (To avoid confusion, we clarify that the literature's use of 'recharge efficiency' is different from recharge to groundwater as previously presented in this document.) The definition of outflows in (1) depend on the type of system and the control volume selected for the water balance. Infiltration rates and their temporal dynamics have rarely been measured at field scale.

As local sources of recharge, SCSs have proven to be very efficient in increasing the volume, rate, and timing of infiltration processes. But Lerner (2002) highlighted the mismatch between design considerations and field operational conditions. Lewellyn et al. (2015) showed SCSs achieved greater than designed volume removal during large or infrequent events. They concluded the performance measurement based on surface and subsurface storage of SCSs underestimates the real performance, because infiltration is a continual process, and constantly recovers its capacity during storm events.

Recent work has focused on quantifying the recharge rates from SCSs of different sizes, and their impact on the shallow water table. Schlea et al. (2014), for example, studied the performance of raingardens (18.5–26.5 m^2) for runoff volume control. They documented the formation of a shallow perched water table under the SCS, sitting above a low permeability material (mostly clay). They found the recharge efficiency (as percolation into the surrounding soils and gravel bed beneath the road) was an average 37–42 per cent, and greater than the volume stored in the raingardens. The study attributed the observed rapid response of the water table level during rising and falling limbs to the subsurface media's hydraulic connectivity to stormwater drainage pipes and preferential flow paths. Percolation from the saturated zone was occurring more than three times faster than that expected as a result of the saturated hydraulic conductivity (Ks) of the soil media.

A comprehensive multi-approach study was conducted in San Francisco (United States) on the effective recharge to a shallow perched water table (2.1 metre depth) under both an infiltration trench (area of 11 m^2) and an urban lawn (Newcomer et al., 2014). It used data from a field monitoring program to compare four alternative methods for estimating recharge (including two dimensional numerical modelling). The authors demonstrated that recharge rates under the infiltration trench were one order of magnitude greater than beneath the lawn, and approximately 40 per cent greater than previously estimated for induced or local recharge in the area. High recharge was enhanced by the large volumes of water directed to SCSs, with recharge efficiencies of 58–79 per cent.

Since the late 1990s, large stormwater retention (or detention) basins have been commonly used to reinstate the water storage capacity of a catchment affected by urbanisation. Such large basins (from 300 to 30,000 m^2) were originally designed to minimise infiltration. But, while recharge was found likely to occur at a rate higher than ambient recharge, research has historically focused on:

- the loading of urban pollutants from such SCSs into the high groundwater in sandy coastal plain areas (Appleyard, 1993; Fisher et al., 2003)

- understanding pathways to aquifers of contaminants of emerging concern (Laws et al., 2011).

The literature has rarely reported recharge rates from such large SCSs. Recharge rates from these SCSs are commonly estimated from water balances as a residual value from the coupling of infiltration (for example, the one dimensional Richard's equation) and groundwater models, matching few water table observations (Miller, 2006). For the above studies, the common basin setting incorporated a 3 metre sandy layer overlying a finer material, a perched water table, and seepage at depths of 2 metres beneath the pond beds, accounting (on average) for 80 per cent of the infiltrated water and 60 per cent of the annual rainfall infiltrated.

Early work by Appleyard (1993) reported water table responses to recharge from infiltration basins in Perth across three different sites. The water table was 2–3.5 metres beneath the basin floors. Rapid water table response to rainfall resulted in mounding that returned to initial levels three days after the rainfall event (31.6 millimetres over two days). Water infiltrated at a variable rate: initially low (at 3.33 centimetres per hour) when the water table was high, and increasing (to 8.33 centimetres per hour) as the mounding relaxed and the water table dropped to approximately 50 centimetres below the basin. Infiltration rates of 3.75 centimetres per hour were also found from a larger basin (~2023 m^2) in southern California (US Geological Survey, 2003; Laws et al., 2011) with a sandy soil over a clay lens, and a water table 2.5 metres below ground. The infiltration rate of a 1400 m^2 basin in Mandurah (Perth) demonstrated seasonal variability because it responded to changing water table depths (Wood, 2014): it fell by 30 per cent as the water table reached the basin bed level.

2.6 Infiltration rates from urban pavements

While the literature largely ignores infiltration through impermeable pavements, it has recognised that a proportion of the impermeable area (up to 50 per cent) should be treated as pervious (Lerner, 2002). Wiles (2007) challenged concepts originating from a surface water balance perspective in urban areas, leading to the ‘recharge misconception’ that the observed increase in surface flows under urbanisation implies a reduction in precipitation-based recharge.

Impervious pavements enhance surface runoff, but fractures, joints and rivulets also infiltrate water to become localised recharge. Wiles and Sharp (2008) investigated the infiltration mechanism via pavement fractures and joints (in parking lots, roads, and concrete curb gutters) in Austin, Texas (United States). They estimated localised recharge from impervious surfaces accounted for 21 per cent of the annual precipitation (with average annual rainfall of 809 millimetres). Infiltration occurred largely via fractures (aperture range of 0.1–10 millimetres) in asphalt pavements, and resulted in equivalent hydraulic conductivities of 0.29–7.6 centimetres per hour. Concrete curb gutters with fractures enhanced infiltration at higher equivalent hydraulic conductivities of 0.1–240 centimetres per hour (aperture range of 0.25–9 millimetres). The study found the average equivalent hydraulic conductivity for pavements converted to an infiltration rate of 0.21 centimetres per hour, which can lead to a high recharge equivalent to that of fine sands, sandstones and silty loam soils. It highlighted that urban utility trench fill has an important effect on near-surface permeability, because the fill creates a network of interconnected conduits for infiltrated water to either travel laterally (in natural fractures or preferential pathways) or infiltrate the low permeability matrix material (as the water ponds).

Research has also investigated infiltration through permeable pavements with infiltration trenches, to assess the potential effect of clogging in reducing trench infiltration from the surface, as well as exfiltration to surrounding base soils (Emerson et al., 2010; Brown and Borst, 2015). After three years of trench operation, measured recession rates fell from 100 to 10 centimetres per hour (Emerson et al., 2010) for trenches in loamy sandy soils (hydraulic conductivity of 7.1 centimetres per hour) with a depth to the water table of 5 metres, indicating a reduction in exfiltration rates. The initial infiltration rates meant the trench emptied in just less than a day; by the end of the study period, the trench took up to eight days to empty. The authors did not consider higher groundwater in the area beneath the trench (mounding) as a possible explanation for the decrease in the recession rate.

More recently, Brown and Borst (2015) used shallow piezometers along the length of two trenches (~18 metres and 36 metres). They monitored the formation of a shallow water table from the upstream to the downstream edges of the trench. As in previous studies, they computed exfiltration rates using drawdown water levels. The infiltration rate to deep soil (4 metres) in the area was 4.3 centimetres per hour (sandier material, with a porosity of 0.43). The study found, under low water levels (0.2 metres) in the trench media, the drawdown rates were closely related to the infiltration rate of the surrounding soil, but sharply increased for high water levels (greater than 1.8 metres).

This increase in infiltration rate corresponded to the presence of fill material (sand pack) surrounding nearby water mains pipes. During storm events, sensors’ lack of response to infiltrating water identified the uneven accumulation of water in the trench (on the uphill edge) and the progression of clogging in downhill bores. The authors concluded drawdown rates were faster than expected from infiltration rates measured at the bottom of the trench, highlighting the role of side wall exposure.

2.7 The use of transient and constant infiltration rates to assess recharge from SCSs

Studies assessing infiltration rates from SCSs have highlighted the lack of applicability of one dimensional infiltration theory, because exfiltration through the trench walls plays a critical role. Also, simple modelling that uses constant infiltration rates at the bottom of SCSs, plus constant exfiltration rates across the wetted side walls, does not account for the pathways by which water exits such systems. Alternative data analysis based on the recession rates of the falling limb of event hydrographs in SCSs (at different trench ponding conditions, for example) may be useful to address this issue (Emerson et al., 2010; Brown and Borst, 2015).

Stormflow runoff captured by SCSs and converted into infiltration must be considered a dynamic process that transitions between transient and steady state conditions. In this way, it is similar to the ephemeral streamflow in semi-arid and arid environments. Only limited research has investigated this dynamic process, particularly at field scale. In a rare study of a two-layer textured soil with high permeability in the upper layer (as commonly used in SCSs), Blasch et al. (2006) investigated the relative contribution of transient and steady state infiltration rates on cumulative infiltration. The comprehensive study found, on average, transient infiltration rates at the onset of an event were two to three orders of magnitude larger than steady state infiltration rates. The use of steady state rates to estimate cumulative infiltration underestimated the total infiltration by 26 per cent for long duration events, but this underestimate increased to 90 per cent for short duration rainfall events. The authors highlighted the need to consider transient infiltration to improve estimates of recharge to water tables.

3 Coupling of surface water and groundwater nutrient transport processes in urban areas with shallow groundwater

At the catchment scale, state-of-art numerical tools are used to assess the effect of urbanisation on water and nutrient balances, and their pathways. For high groundwater environments, they are also used to account for groundwater–surface water interactions. Over-parameterisation of such models, along with the lack of nutrient data to support the modelling effort (for example, spatial and temporal coverage for pre and post development), is the fundamental barrier to scientific publication of results. For this reason, only a few studies have been reported (Barron et al., 2013b). However, numerical tools are still useful for providing insights into catchment responses to land use changes. They are also useful for testing hypotheses on expected trends in key hydrological and nutrient processes, and the relative importance of those processes for catchment discharges.

Following the above philosophy, Barron et al. (2013b) investigated whether mobilisation of stored (or legacy) nutrients in the shallow groundwater occurs as a result of hydrological changes in the subsurface environment due to urbanisation. The study applied detailed numerical modelling tools over a small scale (1 km^2) in a catchment on the Swan coastal plain in Perth. It used a modified version of the MODFLOW 2000 groundwater model (WUWsol) coupled to a solute transport model (MT3DMS package), assuming:

- all nutrients behave conservatively along pathways (with only mixing and transport causing concentration changes)
- nutrient concentrations (carbon, nitrogen and phosphorus) in the groundwater under pre-development conditions (from available data)
- an exponential decay in nutrient concentration with depth.

Under these assumptions, groundwater nutrients would be flushed out via subsoil pipe drains, with no biogeochemical processes occurring. This would be the case even in winter when higher nitrate concentrations occurred due to fast flow in surface water drains, and in summer when mineralised nitrogen was mobilised. Leaching of nutrients would increase in winter as a result of recharge, and decrease in summer as a result of the downward movement of groundwater to deeper layers. The model predicted an increase in nutrient mass over five years after urbanisation, followed by a more stable pattern. The study suggested the full impact of urbanisation on water quality would take up to five years, which has implications for post development monitoring programs.

Of course, nitrogen and phosphorus concentrations would likely change along subsurface pathways, depending on environmental conditions in the unsaturated zone and the shallow water table. These transformations would occur at different spatial and temporal scales, would alter nutrient fluxes, and would change nutrients' availability for transport towards the catchment outlet.

Also important is the source of nutrients in urban catchments. Yang and Toor (2017) reported on the nutrient sources of, and mechanisms controlling nutrient transport from, six medium to high density residential catchments in Tampa Bay, Florida (United States). They used stable nitrogen isotope data to determine the nutrient sources (atmospheric, fertiliser and soil organic sources) in road runoff during 21 rainfall events. Total nitrogen (TN) concentrations varied significantly across rainfall, roof and road runoff, but nitrate concentrations remained relatively consistent. The study concluded atmospheric deposition contributed 50 per cent of nitrate, and fertiliser contributed 33 per cent. It found phosphate sources were the desorption from natural sediments, and the degradation of organic materials (leaves and grass). These findings identified different nutrient sources in the surface water pathway (stormflow runoff), supporting the minimisation of nutrient impact on receiving urban water bodies.

3.1 The time scales of infiltration and recharge processes, and their effect on nutrient cycling

Given infiltration and exfiltration from SCSs seem to occur at higher rates than in surrounding soils, the use of rates based on just soil properties (such as Ks) is questionable for predicting nutrient transport and transformations along the pathway to the water table. Short travel times can result from water moving through soils with high hydraulic conductivity or macropores: they do not allow for nutrient interaction with the soil matrix, and they constrain biologically mediated processes in the unsaturated zone. Shallow groundwater contamination can result.

Critical environmental conditions in the subsoil environment—such as soil moisture content, dissolved oxygen (DO) concentrations, pH conditions, and oxidation-reduction potentials— are controls on nutrient fluxes through the unsaturated zone. The delicate balance between the supply and consumption of DO (related to dissolved organic carbon [DOC] degradation) under infiltration basins' engineered filter media and sediments in the unsaturated and saturated zones is important to the fate of nutrients (Datry et al., 2004; Mermillod-Blondin et. al, 2015). In turn, the travel times of the water supplying oxygen and DOC affect this balance.

To better characterise these travel times, we may need to consider both transient and steady state infiltration rates. This issue has practical implications for monitoring shallow water table dynamics and water quality. Generally, this monitoring is conducted at fortnightly or monthly intervals, and assumes the water table responds slowly to rainfall and infiltration under natural recharge conditions. The travel time of exfiltration from large SCSs to the water table has been investigated since the early nineties, when contaminant attenuation beneath retention/detention ponds was assessed to help manage stormwater runoff and improve aquifer recharge practices (Beganskas and Fisher, 2017). These considerations have only recently been reported for small scale SCSs such as infiltration trenches and raingardens (Newcomer et al., 2014; Danfoura and Gurdak, 2016). But government research organisations have undertaken a large body of work without necessarily releasing the results via journal literature. This work commonly used water quality and tracer data, and covered seasonal scales (under transient conditions) and short-term control experiments (close to steady state). We discuss it in more detail below.

3.2 Biogeochemical investigations in subsurface pathways of large SCSs

Although not specifically targeted for stormwater management, the work by Laws et al. (2011) estimated travel time and resulting nutrient concentrations for nearly steady conditions from an infiltration basin (area of 2023 m^2) in California (United States). At the site, shallow water table (depth ~2.4 metres) had developed in sandy soil over clay lenses. Average saturated hydraulic conductivities beneath the basin were 9.1 metres per day and 9.7 metres per day for the vertical and horizontal directions respectively, with water infiltrating the basin bed at a rate of 0.9 metres per day. Travel times were estimated, using diurnal temperature data, at 15 hours and 51 hours at a depth of 3.7 metres and 7.8 metres respectively. The study showed fast moving water in the unsaturated zone slowed as it reached the water table, impacting DO dynamics and nitrogen transformations, and resulting in high nitrate concentrations (greater than1 milligram per litre) at 7 metres beneath the basin.

Using 16 detention basins constructed in a new urban development, Fischer et al. (2003) measured infiltration of water to the shallow water table (depth ~3 metres) in a coastal plain area of New Jersey (United States). Infiltration rates varied by an order of magnitude of 7.2–88 metres per day. The study showed low oxygen concentrations in shallow groundwater beneath the basin, but more oxygenated water in the groundwater, with oxidised forms of nitrogen (include nitrite and nitrate) being consistently high.

Datry et al. (2004) investigated how infiltration affected water quality beneath an infiltration basin in Lyon (France). The authors highlighted the need to determine the 'thickness of the groundwater layer physio-chemically affected by stormwater inputs'. The shallow perched water table was at 1.2 metres beneath the infiltration basin in rainfall events, and up to 2.5 metres in the dry season. The authors reported that infiltrated stormwater influenced the first

1 metre of the water table, but did not penetrate more than 3 metres into the water table. The oxygen dynamics during infiltration events showed short pulses (less than two days) of modified DO concentrations (2 milligrams per litre), but the authors concluded the transit time of the infiltrating water was too short to allow re-oxygenation. They suggested the strong oxygen deficit in the shallow groundwater was due to the input of already low oxygen water from the infiltration bed, rather than the biodegradation of DOC in infiltrating rainwater. The authors concluded elevated concentrations of DOC and phosphate in the high groundwater resulted from mineralisation of organic sediment in the basin. In relation to nitrogen, ammonium was the dominant species in the infiltration bed in the dry season, but it was oxidised to nitrate beneath the basin bed (ammonium was not present in the groundwater). This process can occur only in the presence of appreciable concentrations of oxygen. The dynamics of DO and DOC are temperature dependent, so seasonal scale variability is expected.

O'Reilly et al. (2012) analysed DO and nitrate dynamics in soils below two infiltration basins in Florida (United States) with different soil textural characteristics (98 per cent and 59 per cent sand respectively) in areas with shallow water tables (3 metres and 2 metres depth for the sandy and clayed soils respectively). During rainfall events in the wet season, the water table remained 0.6 metres below the basin bed at the sandy site, but reached the ground level (and above) at the clayed site. As a result, the soil moisture content was more stable and higher in the clayed site. The authors showed oxic conditions (DO greater than 5 milligrams per litre) and high nitrate concentrations (1.3–3.3 milligrams per litre) found in the sandy soils contrasted with the more clayed soils, which exhibited DO reduction (anoxic at 2 metres soil depth) and a 99 per cent reduction in nitrate concentrations. The abundance of DO in the sandier soils led to almost conservative transport of nitrate to the water table.

Similar results were found by Appleyard (1993) in an infiltration basin in Perth (Australia) in areas with a shallow water table (depth less than 2.5 metres). He found shallow bores (depth ~6 metres) responded within minutes to inflow to the basin, and peaked 6–24 hours after ponding water occurred, lowering the depth to water table by 0.5–2.5 metres, depending on the season. Although limited to seasonal scale water quality sampling, the study demonstrated the water table presented characteristics similar to those of the infiltrated water, with low salinity, high DO, and TN dominated by nitrate.

The forms of biodegradable and refractory DOC, and their concentration dynamics during infiltration, for three basins used for aquifer recharge were reported by Mermillod-Blondin et al. (2015) in Lyon (France). Basins collected runoff from urban residential, commercial and industrial land uses in areas with shallow water tables (less than 4 metres depth). The results indicated a sharp reduction in DOC concentrations (75 per cent biodegradable DOC), and highlighted the high retention of DOC in the unsaturated zone, over a thickness of 1.7–3.2 metres. However, the remaining flux of DOC (without affecting its biodegradable percentage) led to an increase in DOC in the water table, far exceeding its background DOC. The study highlighted the enrichment in DOC in the shallow groundwater pathways that can drive biogeochemical processes. The authors noted the need for further studies on DOC transfer to the water table.

3.3 Biogeochemical investigations in subsurface pathways of small SCSs

So far, we have summarised research investigating biogeochemical processes along the subsurface pathways beneath infiltration/retention basins. Other common stormwater management practices are small raingardens and infiltration trenches. In these systems, the small stormflow volumes and shorter time scales of the infiltration do not allow suitable environmental conditions for nutrient processing and removal to establish. There is a paucity of reported studies on this issue. Design considerations that influence the biogeochemical processes in the unsaturated zone under small-scale SCSs also require investigation, but little data are available to support this work.

In a rare study, Danfoura and Gurdak (2016) reported on DO concentrations and redox conditions in water infiltrating from a small trench, in an area with a shallow water table. This study built on previous research by Newcomer et al. (2014). Danfoura and Gurdak (2016) found anoxic conditions were present in the subsurface filter media of the trench within hours of the onset of a rainfall event, and continued for up to two days. They suggested this finding indicated microbial respiration under saturated conditions in the filter media. Average DO reduction rates were found to be two to five orders of magnitude higher than those previously reported in groundwater, and they were attributed to the pulse of oxygenated and DOC-rich stormwater runoff. The filter media rapidly returned to oxic conditions after two days, coincident with saturation levels decreasing in the filter media. However, the authors suggested anoxic conditions persisted longer in the unsaturated zone beneath the filter media. Findings from this work have implications for the design of filter media to achieve suitable redox conditions. Manipulating the area-to-depth ratio of the filter gravel media may achieve the travel times necessary to sustain appropriate redox conditions and minimise water table nutrient contamination.

3.4 Nutrient export patterns from urban catchments with significant groundwater–surface water interactions

Nitrogen and phosphorus export from catchments commonly reflects the relative contribution (proportion) and location (spatial distribution) of their sources, which are related to catchment land uses (Carey et al., 2013). Patterns of nutrient export have been extensively studied and reported for agricultural and forested environments (Creed et al., 1996; Aubert et al., 2013), and some studies have investigated transformations of mobile nutrients along specific flow pathways (Cey et al., 1999; Ocampo et al., 2006; Jensen et al., 2017). The nitrogen and phosphorus export patterns also reflect the different runoff generation mechanisms that control both water pathways and nutrient availability for transport. These mobile nutrient species are subject to physical and biogeochemical transformation during transport along the pathways. Research efforts over the past two decades in agricultural contexts focused on nutrient losses via subsoils drainage used to lower water table and increase subsurface water movement. That work specifically demonstrated how mechanisms of flow generation of tile drained systems affect pathways for pollutant mobilisation, and how to control groundwater discharge for environmental benefits. The studied landscapes are of particular interest for urbanisation in high groundwater areas because they present substantial groundwater–surface water interaction, along with changes in interflow water composition over rainfall events and across seasons.

Tiled landscapes in both fine textured and sandy loam soils have been investigated under different climates, from humid continental climates in Canada and the United States (Sanchez Valero et al., 2007; Cuadra and Vidon, 2011; Smith et al., 2015; Lam et al., 2016), to those with marked seasonality in rainfall and evaporation in Italy and Sweden (Bonaiti and Borin, 2010; Wesström et al., 2014). Nitrate usually represented more than 70 per cent of the nitrogen flux during rainfall events (Cuadra and Vidon, 2011; Smith et al., 2015), with groundwater levels impacting runoff generation but not significantly solute export. As much as 98 per cent of annual phosphorus export occurred in the non-growing season, coinciding with high flows (Lam et al., 2016). Since early 2000, research has highlighted the agronomic and environmental advantages of implementing water table management systems that can provide subsoil drainage controls and subirrigation, or simply drainage control in tiled landscapes (Wesström et al., 2014). Such systems have been tested, with reported reductions of up to 77 per cent of flow and 70 per cent of nitrate via retention of groundwater discharge for a few days.

Urbanisation results in altered water quality characteristics and temporal variability in the receiving surface waters, due to changes in runoff generation processes, pathways, and the spatial distribution of nutrients in the urban mosaic (namely, septic tanks, lawn fertilisers, at-source infiltration, parks, and leaks from sewer and mains). Implementation of SCSs within urban catchments has been effective at restoring pre-development surface runoff production (Ahiablame et al., 2012; Chui and Trinh, 2016; Kong et al., 2017). Also, it has the potential for nutrient attenuation and reduced export (Davis et al., 2009; Roy-Poirier, 2010; Ahiablame et al., 2012; Bell et al., 2017). However, SCSs' impact on the subsurface hydrology and nutrient cycling remains poorly understood. These systems could modify interactions between the shallow water table and receiving surface waters by incorporating shorter travel pathways (via stormwater pipes) compared with pre-development's more diffuse pathways (along banks and beds of permeable drains and natural channels).

Surface runoff from impervious surfaces has increased the nutrient export from urban areas during high flow, less frequent events (Shields et al., 2008; Petrone, 2010), and the directly connected impervious area has been found to impact the magnitude of both first-flush runoff and nutrient export (Harper and Baker, 2007). Consequently, management strategies have targeted the disconnection of impervious surfaces from runoff pathways (Schiff and Benoit, 2007), and the implementation of SCSs. Bell et al. (2017) reported reduced nitrogen, phosphorus and DOC concentrations in the outlet of catchments with SCSs, under different urban and suburban types in Charlotte, North Carolina (United States). Where SCSs were implemented across significant portions of the urban catchments, reductions in nutrient concentrations were observed in receiving streams. However, the authors cautioned that the extent of nutrient reduction may be influenced by the type, location and extent of SCS implementation in the urban catchment.

We noted earlier that the complexity of the urban subsurface drainage network has a more profound effect on the water quality of catchment discharge than does the relatively more uniform surface landform. Some studies have reported that urbanisation increased solute concentrations in baseflow (that is, flows through the drain network between rainfall events), and increased nutrient export from urban catchments (Rose, 2007; Barron et al., 2010; Janke et al., 2014; Gabor et al., 2017). These nutrient exports have been attributed to increases in groundwater discharge and possible effluent from old septic tanks within the catchment. However, other studies have stressed the poor understanding of mechanisms controlling nutrient export via subsurface pathways in urban catchments; they found no significant differences between baseflow and stormflow nutrient concentrations and loads (Taylor et al., 2005; Shields et al., 2008).

Interest in the relationship between nutrient export and baseflow from urban catchments has gained momentum in recent years, with studies investigating groundwater connectivity with the urban drainage network. This work is of particular interest in areas with high groundwater, because such connectivity could rapidly mobilise dissolved nutrient species. Barron et al. (2010) showed, in urbanised and light industrial areas in Perth, urban drains conveyed baseflow all year round and comprised 40–80 per cent of the annual discharge, and up to 80 per cent of the annual nutrient load, with nutrient forms (organic and inorganic) displaying a clear seasonal pattern.

Janke et al. (2014) reported contrasting export patterns for nitrogen and phosphorus, which were explained by the differences in flow paths from six urban catchments in St Paul, Minnesota (United States). Coarse sandy material underlaid all catchments, which presented shallow water tables that intersected stormflow drains. Flow paths were identified from hydrometric data and environmental tracers. They showed phosphorus was mobilised and delivered during stormflow, with significant differences in phosphorus export between stormflow and baseflow conditions. But they found the opposite for nitrogen export. Baseflow was seasonally dominated by groundwater inputs (May to October) and characterised by high concentrations of inorganic dissolved nitrogen. By contrast, high concentrations of organic nitrogen occurred during stormflows. The authors suggested high nitrogen export during baseflow was linked to widespread manipulated infiltration of stormwater in the catchment that subsequently discharged (as shallow groundwater) to the drains. For the same catchments, Hobbie et al. (2017) calculated nutrient mass balances to confirm the contrasting pathways for phosphorus and nitrogen export. They highlighted the need for different management strategies along the surface and subsurface pathways.

A more recent study was done by Gabor et al. (2017) along a stream reach of the Red Buttle Creek in Salt Lake, Utah (United States). It confirmed the stream hydrology and biogeochemistry were driven by ‘urban recharge returning to the stream’ via a spring discharge and also groundwater upwelling to the stream. The carbon and nitrogen dynamics indicated the urban aquifer was acting as a biogeochemical reactor, and the authors noted the importance of assessing the appropriate time scales (thought to be one month to years) required for nutrients to transform before discharging to the stream.

Over the past two decades, there has been a concerted effort to restore urban streams around the world, particularly in new urban developments. The aim has been to mimic pre-development conditions, slow stormflows, reinstate ecosystem functionality, and improve amenity for residents (McGrane, 2016). Riparian zone management and the re-engineering of urban drains into living streams have also aimed for nutrient removal. However, the nutrient retention effectiveness of these engineered systems, particularly in areas with high groundwater, remains unclear. This lack of understanding is due to changes in the complex subsurface hydrology under urbanisation, which (in most cases) changes the depth to water table and impacts groundwater quality (Groffman et al., 2002).

The altered temporal dynamics of groundwater–surface water interactions under urbanisation can impact mechanisms affecting nitrogen and phosphorus export, and the extent of nutrient attenuation:

- Investigating nitrate dynamics along subsurface pathways in a degraded urban stream in Baltimore, Maryland (United States), Mayer et al. (2010) showed wet conditions resulted—for a few days after storm events—in high connectivity between the water table and the stream, and high nitrate fluxes out of the catchment. They suggested suitable conditions for nitrate attenuation during such times could be encouraged by increasing residence times within riparian zones (that is, channel banks) and providing DOC sources.

- Recent work highlighted that transport mechanisms within restored living streams can themselves result in contrasting patterns for nitrogen and phosphorus attenuation. Singh and Oldham (2017) investigated this attenuation under high baseflow conditions in an urban stream situated in a catchment with high groundwater. They found uptake at a rooted bank drove a reduction in dissolved inorganic nitrogen export, but not in filterable reactive phosphorus (FRP). They suggested FRP is at biogeochemical steady state within the 40 metres study reach. In this case, upstream groundwater interactions resulted in high baseflow conditions in the living stream, which promoted contact between stream water and the rooted bank.

- More complex nutrient dynamics from decadal to diel time scales were recently reported by Adyel et al. (2017) for a living stream, re-engineered from a compensation basin, in a light industrial and residential area in Perth. Nutrient cycling mechanisms were complex and affected by the discharge of anoxic groundwater and strong diurnal cycles of DOC in the surface water. The study measured oxic to anoxic transitions in the stream water within a 24 hour cycle.

These three studies provide new insights into how groundwater–surface water interactions in urban areas with high groundwater can affect nutrient cycling and nutrient export. Our modelling capabilities must, therefore, incorporate these interactions.

4 Monitoring strategies for the fate of infiltrating stormwater and subsurface pathways

This literature review highlights that the water balance of the unsaturated zone, along with its discharge to the shallow water table, is critical for nutrient pathways. It also highlights that these processes are significantly impacted by urbanisation and current stormwater management practices in areas with a shallow water table. Measurement of key hydrological variables in the unsaturated zone, and of their connection to sources of infiltrating water in the urban subsurface environment, is essential for better quantifying the impact of urbanisation on catchment hydrology and nutrient pathways. But such measurements remain challenging. Below, we recommend monitoring methods.

Initially, focused measurements are needed to determine the transient and rapid nature of hydrological processes in urban catchments (at parcel, streetscape, precinct and catchment scales—see Bonneau et al., 2017). This high frequency dynamic impacts on the magnitude of water fluxes (that is, infiltration from source control systems [SCSs], and interflow via pipes), and on shallow water table dynamics, at both event and seasonal time scales. Its monitoring should include interactions between the water table and underground infrastructure (for example, subsoil pipes controlling groundwater) that lead to increased interflow in the 'urban karst' (Bonneau et al., 2017). Understanding these links will allow us to identify water pathways and their time scales, and predict contaminant fate and transport within urban subsurface environments. Given the lack of such data, appropriate urbanisation policy and planning are problematic in areas with shallow water tables (Barron et al., 2010; Bonneau et al., 2017).

4.1 Unsaturated zone hydrological monitoring techniques in urban areas

Soil moisture measurements allow quantification and prediction of key state variables within the unsaturated zone, and can be related to media parameters (hydraulic properties) and water fluxes (evapotranspiration, recharge, and plant water uptake). Robinson et al. (2008) and Vereecken et al. (2008) reviewed state-of-art technologies and analytical tools available for soil moisture measurements at different spatial scales (from point to catchment), while Rivett et al. (2011) presented a comprehensive review of methods for monitoring the fate and transport of complex contaminants in the unsaturated zone. This section contains an overview of the different methods, followed by more detailed examples of the use of such methods in urban environments.

Among the different technologies currently available for soil moisture measurements (contact and non-contact with soil media), time domain reflectometry has been used and reported in the literature for urban applications (Stander et al., 2013; Newcomer et al., 2014; Brown and Borst, 2015; Wiesner et al., 2016). This method allows for acquiring high temporal frequency data at point scale, and soil profile measurements compatible with the rapid and transient characteristics of water movement in urban areas.

Soil hydraulic properties at field scale during infiltration can be inversely obtained from soil moisture measurements. However, they need to be combined with other measurements (namely, a knowledge of soil properties and matric potential). The combined methods have been successfully used for steady state infiltration, but only Ritter et al. (2003) have estimated the effective hydraulic properties under natural field conditions. One promising approach to link point scale observations to catchment scales involves using wireless sensor networks, as presented by Cardell-Oliver et al. (2005).

Alternative techniques involving heat transfer are increasingly used to determine unsaturated zone infiltration (Constantz et al., 2003) and groundwater–surface water interactions (Kalbus et al., 2006). These techniques require high temporal resolution temperature data obtained at different depths of the soil profile; water fluxes can then be computed via analytical tools (Gordon et al., 2012).

4.2 Soil moisture and temperature data to address infiltration and recharge from SCSs and urban soils

Soil moisture data using time domain reflectometry sensors have been used to quantify infiltration from SCSs, and the effect of clogging on infiltration. More recently, they have been used to investigate spatial and temporal hydrological variability in urban soils impacted by a shallow water table. Soil moisture measurements are always supported by simultaneous monitoring of water levels in the surface storage, in the subsoil media (that is, the formation of a perched water table), and in nearby shallow bores, to map the water table beneath the SCS. These measurements are all required for a full water balance of the SCS.

Studies by Stander et al. (2013), Newcomer et al. (2014), and Brown and Borst (2015) demonstrated the use of time domain reflectometry sensors to quantify infiltration and exfiltration processes from several SCSs (trenches under permeable pavement strips, raingardens, urban lawns) and a full water balance assessment (including recharge) in different climate scenarios (Newcomer et al., 2014). High frequency temporal data were collected at different locations in the SCSs, and specific sensor arrangement depended on the SCS physical size (the length of the trenches, and at several depths for raingardens). This technique has been widely used in laboratory soil column experiments, supporting numerical model development and testing of infiltration systems (Browne et al., 2013). A recent study by Wiesner et al. (2016) used continuous soils moisture data to characterise hydrological responses and water fluxes of urban soils in Hamburg (Germany). It found local site factors (for example, modified soil characteristics due to fill material) affected the short-term hydrological regime, including the shallow water table dynamics.

The use of heat as a tracer to compute point-specific infiltration rates and travel time of water infiltrating the subsurface was also reported as most suitable for large retention/detention basins. The study by Laws et al. (2011), for example, estimated travel time by using diurnal temperature cycles under close to steady state flow conditions in the field. A recent study by Beganskas and Fisher (2017) also estimated infiltration rates from temperature time series analysis; it compared those rates with basin averaged rates (mass balance) for a large stormflow detention basin. The authors indicated the techniques are suitable for long duration events (wet conditions over four to five days), given infiltration from the basin seems to be limited by inflow volumes.

O’Reilly et al. (2012) presented an example of a comprehensive monitoring network to quantify water balances in unsaturated zones and shallow water tables under infiltration basins, and their implications for nutrient and contaminant fate and transport. The monitoring network combined all the above techniques, and allowed data collection for a full water balance computation (including travel time along different pathways).

As we noted earlier, these examples can be used to guide monitoring programs designed to quantify the unsaturated zone hydrology beneath SCSs. Such programs should be used in conjunction with existing guidelines for SCS performance assessment in areas with high groundwater (Hunt et al., 2017).

4.3 Quantifying contributions of infiltration sources, interflow, sewer, and groundwater interactions: multi-technique approaches to characterise urban karst subsurface hydrology

Multi-technique approaches are required to quantify:

- the impact of urbanisation and stormwater management practices at the catchment scale on the urban karst subsurface hydrology
- how these impacts change water pathways (Schirmer et al., 2013; Li et al., 2017).

Such approaches need to combine high frequency hydrometric records with passive tracers such as temperature, electrical conductivity, or environmental tracers such stable isotopes (Bonneau et al., 2017).

Hydrometric data (water level and flow discharge) at high frequency (2–5 minutes) can be used to map different infiltration sources and water pathways, based on the time response of the runoff hydrograph to rainfall. Successfully used in California (V&A, 2010), this approach requires substantial instrumentation of nested stations along the drainage network (pipes) to the catchment outlet.

Traditional hydrograph separation techniques have been used to identify two source components, using stable isotopes to map runoff from catchments (Meriano et al., 2011; Gabor et al., 2017) and using electrical conductivity to map water pathways within SCSs (Ocampo et al., 2017). When undertaking such monitoring, it is important to note that any baseflow (or slow flow) component in the stormflow network could contain water sources from shallow groundwater discharge and leakage from main and sewage networks. Techniques to address this issue usually combine tracers and hydrometric data (Wolf et al., 2006; Rieckermann et al., 2007; Gabor et al., 2017). Or, they may use high resolution hydrometric data alone, as shown by the V&A (2010) study, which identified discharge of groundwater from the disruption of diurnal flow cycles in the sewer pipes.

Herfort et al. (1999) defined control planes and used the integrative mass flux concept to quantify water and solute budgets in a high groundwater, industrial urban area. They extended the viable and easy-to-use integrative method for balances in the urban subsurface environment, using concentration values and basic aquifer parameters (Shciedek et al., 2007). The method defines upstream and downstream control planes, and uses normalised fluxes between them for each mass balance zone along the flowpath. The contaminant concentration is measured in individual wells located to represent each mass balance zone boundary. To account for leakage rates of water mains and sewers, and leaching from road salting and infiltration, these factors need to be represented as mass balance zones or combinations of zones. A positive solute budget indicates areas where sources reach the groundwater, while a negative budget generally reflects plumes and degradation. This method must be used to design locations for shallow groundwater monitoring across the urban area of interest: it ensures each mass balance zone accounts for areas containing SCSs, water table mounding, and interactions with stormwater underground pipes.

4.4 Monitoring water quality in the filter media and subsurface sediment of infiltration element

Tedoldi et al. (2016) reviewed state-of-art monitoring and experimental techniques, and numerical modelling of the fate and transport of heavy metals and organic pollutants (polycyclic aromatic hydrocarbons) in the soil and filter media of SCSs (which the authors called sustainable urban drainage systems). Their comprehensive review of a variety of systems provided important information on the depth of different compounds' migration into the filter media—information that can assist with instrument and sensors deployment. The authors concluded there was a lack of established metrics to assess performance of soil/media removal capacity, and they highlighted the importance of characterising the hydraulic behaviour of infiltration and flow paths (particularly the downward fluxes of pollutants to the water table) from hotspot areas not retained by the soil/filter matrix.

Detailed sampling strategies for water quality parameters and nutrients from the unsaturated zone (lysimeters, suction cups) and shallow water table (multi-port wells) beneath infiltration basins and SCSs can be found in Datry et al. (2004), Laws et al. (2011), O'Reilly et al. (2012), and Danfoura and Gurdak (2016).

5 Conclusions

This literature review was limited to research investigating the impact of urbanisation and stormflow management practices on the water and nutrient balances in areas with high groundwater, and where significant groundwater–surface water interactions are expected. The summarised research spanned spatial scales from a few square meters (an individual source control system [SCS]) to hundreds of square kilometres (catchment scale). All case studies focused on unsaturated and saturated zone hydrology and biogeochemical processes related to nutrient transport under conditions relevant to Perth. That is, the reviewed literature covers studies with similarities in one or more aspects, such as soil characteristics (texture), rainfall (annual total and seasonality), and/or shallow water table (depth of less than 5 metres).

This literature review confirmed fundamental knowledge gaps about how the water balance operates in the unsaturated zone beneath urban areas, and how the water table dynamics (the lower boundary of the unsaturated zone) determine the characteristics of infiltrating/exfiltrating water into soil water storage, and thus affect recharge to and discharge from groundwater. Most of the questions relate to the time scales of water fluxes in and out of the unsaturated zone—that is, how does rapidly infiltrating water, which is dumped into the unsaturated zone, become rapid recharge to the shallow water table, and then discharge via stormflow pipes during rain events?

The mechanisms of runoff generation from the unsaturated zone in ‘urban karst’ are unknown. Without this knowledge, the coupling of well-developed areas of stormflow modelling (surface hydrology) and groundwater modelling (hydrogeology) remains challenging. Our understanding of the knowledge gaps is supported by empirical evidence (comprehensive data sets), simple mass balances using tracers, and application of state-of-the-art, three-dimensional numerical models.

Below, we summarise our conclusions from the literature review, with a focus on water fluxes in and out of the urban unsaturated zone, and their impact on nutrient transformations. Based on these conclusions, we present a conceptual model for urban developments in areas of high groundwater, and recommend the monitoring needed to address the knowledge gaps.

5.1 Infiltration in the urban mosaic

5.1.1 Rapid runoff response

Runoff peaks and volumes from impervious areas are a function of rainfall intensity and duration and the time of concentration of the catchment. Experimental work at field scale properly captures runoff generation (as rainfall and flow measured in minutes); however, coupled groundwater–surface water numerical model applications in an urban context, it uses 24 hour total rainfall and, consequently, neglects the rapid runoff response to rainfall. This approach is questionable, and it has implications for the adequate capture of infiltration processes (which are the key water flux input to the unsaturated zone).

5.1.2 Infiltration from impervious areas

Contrary to common assumption, infiltration from hard impervious areas (roads, parking lots etc.) does occur, and its magnitude and timing depend on the runoff amount from impervious areas (not rainfall). Called the secondary permeability of hard surfaces (concrete and asphalt), it enhances infiltration via cracks and joints, at rates comparable to those in sandy soils. The more surface runoff produced from hard surfaces, the larger is the infiltration amount. The amount of infiltration can be parameterised as a function of overland flow quantity and duration. Urban water balances do not currently account for this infiltration, which has been estimated to be up to 21 per cent of annual rainfall. The literature suggests up to 50 per cent of impervious areas should be considered as pervious, but data to support this suggestion is insufficient.

5.1.3 Transient and higher infiltration from SCSs

Infiltration processes are ‘transient in nature and recover over time’, particularly in well-drained soils and in the fill material commonly used in urban developments in Western Australia. The recovery of infiltration capacity is also enhanced by the presence in the urban subsurface of buried shallow infrastructure pipes and fill. Transient infiltration rates at the onset of an event can be up to three orders of magnitude larger than steady state infiltration rates. They can be extremely important, therefore, for short duration rainfall events. Major rainfall events in Perth consist of short duration rainfall bursts of up to 15 millimetres separated by few hours, allowing infiltration capacity to recover over time. The SCS literature highlights remarkable volumetric control by infiltration trenches during large, infrequent events. They attributed that control to a measured infiltration capacity that was larger than design values. Infiltration/exfiltration rates from large SCSs are volume runoff limited; they are more likely to be influenced by water table mounding at event or seasonal time scales (and to decrease when the water table is within 0.5 metres of the bed). Recent literature using multi-techniques and mass balance approaches reported infiltration rates higher than expected.

5.1.4 Hydrological modelling of infiltration

Finally, we stress that all the above processes occur at short time scales, from minutes to less than 24 hours. A parameterisation of urban infiltration processes is required, at the time scales used by coupled groundwater–surface water models. Urban flood models account for aspects of these infiltration processes by means of transient infiltration algorithms for single rainfall events, and they have been shown to be suitable for surface runoff prediction. However, based on the above literature review, large uncertainties remain about ‘losses modelling’ in urban environments, particularly the proper quantification of water volumes entering the subsurface. But this knowledge is critical for us to understand the fate of infiltrated water, and its optimal management in urban areas. The most recent scientific literature highlighted this issue, which research efforts around the world reflect.

5.2 Recharge of groundwater from rainfall events

5.2.1 Discrepancies in recharge estimates

The literature review identified large discrepancies in recharge estimates from urban areas with shallow water tables. The discrepancies relate to mainly methods and spatial scales of the study, but the literature generally considers improved estimates of recharge rates based on recent mass balances and datasets are larger than previously thought. This view might have arisen because previous water balance attempts did not properly consider infiltration rates and totals in the unsaturated zone, and underestimated the infiltration process.

5.2.2 Recharge up to 50 per cent of annual rainfall

Studies have commonly reported recharge rates and totals (both gross and effective) at the urban catchment scale after calibrating groundwater models against available water level data from bores, and then report them as a percentage of the annual rainfall (or in millimetres per year). The estimate allows for quantifying the relative importance of recharge in the water balance, but it has little use in addressing the fate of infiltrated water into a thinner unsaturated zone in areas with high groundwater. In the Perth context, previous recharge values range from 21 per cent to 37 per cent of the mean annual rainfall, with more recent estimates in areas with a shallow water table and infiltration practices reaching 41–48 per cent of the annual rainfall. All modelling studies reported in this literature review indicated recharge accounted for approximately 60 per cent of total annual infiltration.

5.2.3 Higher recharge volumes beneath SCSs

Recharge beneath SCSs has been reported as a percentage of infiltrated water at 2 metres (seepage) below the SCS bed. Reported values were 60–80 per cent of the infiltrated water, with the higher value corresponding to large SCSs. In this context, recharge is no longer reported as a function of the rainfall amount, but rather on infiltration amount, because it is inflow volume limited.

Only a few studies compared recharge rates for SCSs and irrigated lawn areas. Results showed SCSs produce 10 times more recharge than lawns (including irrigation). Studies reported recharge rates up to 40 per cent more than previously estimated for SCSs.

5.2.4 Measurement of recharge

Recharge rate estimates from SCSs were consistent across different methods, when comprehensive datasets were available and allowed the development of a rigorous mass balance. In-situ methods using data (1D-Darcy and drain gauge) were more suitable for individual recharge events, while calibrated two dimensional models provided recharge event information with spatial resolution and allowed long-term simulation under different scenarios. However, reported recharge differed when estimated using both bore hydrographs and aquifer specific yields. The differences can be attributed to depth to water table (the thickness of the unsaturated zone) and physical bore characteristics. This method is highly suitable for shallow water table areas with semi-arid environments, because water table dynamics respond to individual events. But hydrometric data and the use of bore hydrographs and specific yields in such conditions for urban areas have not been reported yet in the literature.

Better estimates of recharge in the urban mosaic and landscape are needed, and mass balance of the unsaturated zone provides a valid approach. Analytical tools for recharge estimates are freely available, but we lack comprehensive datasets to adequately encompass local conditions.

5.3 Interflow processes and delivery mechanisms

The increasing number of scientific publications on this topic in 2016–17 highlighted the need for improved understanding of the fate of infiltrated water and its pathways in urban areas. Research efforts in this area are underway in United States, Europe and Australia (Melbourne).

5.3.1 Water mounding and SCS density

At the scale of individual SCSs and small catchments with SCSs, both numerical modelling and field data confirmed water mounding in areas with shallow water tables occurs during an event. The mounding reaches a peak level within hours of the inflow to the SCS. The density of SCSs in an urban area (the number of SCSs per area of catchment), their position in the landscape, and the hydraulic conductivity of the subsurface material play an important role in the mound’s relaxation (that is, the return of the water table to pre-event levels). The time that relaxation takes should provide insight into the fate of the recharging water.

5.3.2 Timescales of mounding

Modelling results suggest mounding from isolated SCSs can dissipate within 48 hours in sandy soils but take up to 40 days in finer material. Progressive mounding occurs from isolated SCSs in fine textured soils (over a seasonal scale), and no long-term trend in increasing water table levels has been reported. Mounding relaxation over a shorter time, or departure from its hypothetical height or shape, could be attributed to temporary interactions with fill trenches from utilities, subsoil pipes to control groundwater, or stormwater drainage pipes. No reported datasets specifically address this issue.

5.3.3 Increased discharge to drains and streams

At the catchment scale, numerical models and recent field studies of urban areas with infiltration practices and mixed land uses provide evidence of altered hydrology across the unsaturated zone. These studies showed water from rapid infiltration sources percolates to the subsoil and increases water tables that intercept stormwater pipes and then convey groundwater to the stream. Water that recharges the shallow aquifer returns to the stream, impacting its hydrology, hydrochemistry, and nutrient export.

Recent studies demonstrated how water and chemical mass balances and multi-technique approaches are cost-effective ways to address knowledge gaps on the impact of ‘urban karst’ hydrology on nutrient export. This knowledge is essential for improving the tools available for urban planning and design, and managing the impact of urbanisation in receiving water bodies.

5.4 Nutrient cycling along subsurface flow paths

5.4.1 Paucity of data

This review found no comprehensive study that reported on nutrient transformations along these three subsurface pathways in urban environments: infiltration, recharge of the water table, and subsurface transport to the receiving waters. A rare numerical modelling study in Perth explored the problem, assuming conservative transport of nutrients along different subsurface pathways. It provided insights into nutrient storage in the shallow groundwater, nutrient discharge over time after urbanisation, and the timeframe (~five years) to achieve steady concentrations in the groundwater). Recent US work supported some of the model findings, but highlighted that nutrients transform along the transport pathways—that is, they are not conservative. We can explore the use of recent nutrient management practices in tiled agricultural landscapes (for example, via structural controls on discharge from subsoil drains) into the urban context. These management practices include damming of groundwater and control discharge to enhance biogeochemical processes that naturally occur in restored riparian zones subject to flooding (Jensen et al., 2017).

Early studies on SCSs, or at the whole urban catchment scale, provided basic data for assessing potential contamination of groundwater and surface water resources. But they were inadequate for understanding nutrient transformation processes. Nevertheless, findings on the dominant environmental conditions during infiltration and transport within the shallow groundwater can help to formulate a conceptual model of nutrient transformation. They can also guide future research efforts to improve understanding of this critical area.

5.4.2 Transport of oxygen along subsurface pathways

The fate of DO introduced by infiltrating water along the subsurface pathway, and its transport into the shallow aquifer, depends on the amount of DOC transported with the infiltrating water or available in the shallow sediments or filter material, and the transit time along this pathway. These factors control the oxic-anoxic conditions in the subsurface environment, which affect nutrient transformation and availability.

Sandy soils experience oxic conditions during infiltration, leading to little nutrient attenuation along the infiltration pathway. When sufficient DOC is available along the subsurface pathway, decreases in DO can trigger attenuation of inorganic nitrogen; limited information on the fate of phosphorous has been reported. Fine textured subsurface soils (up to 41 per cent silt and clay) increase travel time and result in anoxic conditions at a 2 metre depth, leading to up to 90 per cent attenuation of inorganic nitrogen. Some literature reported DO recovery and increased nitrate concentrations on the shallow groundwater pathway away from the SCS locations. SCSs can act as hotspots of nitrogen cycling, but the downstream fate and transport of nitrogen are unknown. Field scale experiments in tiled landscapes in the agricultural context provided evidence that damming the shallow groundwater can result in nitrate export reduction via controlled flow discharge and nitrate concentration reduction within the water table (maintenance of anoxic conditions).

5.4.3 Impact of travel time

Travel time along the subsurface pathway is an important factor in considering nutrient transformations reported for agricultural and natural landscapes (Ocampo et al., 2006; Jensen et al., 2017). The travel time concept may not be suitable for examining nutrient transformations in systems that experience stages of isolation or disconnections along a subsurface water pathway. Rather, an appropriate characteristic time scale could be the exposure time, τ_{E}, proposed by Oldham et al. (2013) for hydrological systems—that is, a measure of the time available for processing nutrients during transient water storage and under environmental conditions that promote that processing. Infiltration from large SCSs with travel times of 15 hours over a 4 metre travel path was not sufficient to achieve inorganic nitrogen reduction under steady infiltration conditions (Laws et al., 2011). For small SCSs, the exposure time concept could be applied, because a rapid shift in filter media oxygen concentration has been reported under field conditions, with anoxic conditions present for up to two days after inflow events, then returning rapidly to oxic conditions as the water content decreases. Strategies tailored for nutrient removal over such short timeframes will require design changes (the manipulation of physical dimensions) and possibly additional supply of DOC sources.

Infiltrated water in urban areas with shallow groundwater experiences very short pathways, determined by a thinner unsaturated zone (less than 4 metres) and the upper top layer of the water table being impacted by infiltration. Unfortunately, no published research reports nutrient transformation along pathways within the shallow water table before its discharge via stormwater pipes (if intersected) or diffuse discharge (via bank and bed) to urban drains and streams. Only recent research work in tiled landscapes has provided insights into nutrient mobilisation mechanisms, and reported how damming of the shallow groundwater via structural controls achieved nutrient export reduction by increasing exposure times and intensifying biogeochemical processing. Although promising, no such approach has been tested in urban areas.

5.5 The need to assess nutrient transformations in urban areas with high groundwater in Perth

Our findings from this literature review were synthesised into a conceptual model (Figure 4) to guide future work on nutrient fate and transport along subsurface pathways in urban areas with high groundwater. The model reflects current built form (for example, imported fill for higher footing soil class, and subsoil drains for groundwater control) and stormwater management practices (for example, water sensitive urban design SCSs for treatment) currently used in Perth. It covers spatial scales from a few hundred meters to 1 kilometre, which are typical of new precincts (Figure 4a). The conceptual model identifies the key water pathways and time scales required to address nutrient transformations; these are needed to guide better SCS design and monitor their effectiveness. It also highlights the unknown exposure time scales in groundwater under urban areas, and identifies where potential solutions implemented in other landscape settings could be introduced to address nutrient export in urban areas.

The model incorporates different states of hydrological isolation and connection for SCSs (at rainfall event scale, Figure 4b), local mounding (at event and seasonal scales, Figure 4a), and shallow water table dynamics (at seasonal scale, Figure 4a). It provides expected exposure time scales (τ_E) for nutrient processing (Figure 4a and b). The exposure time scales estimated for SCSs and local mounding during isolation states reflect the duration of anoxic conditions, when nitrogen transformation and phosphorous release occur. These are important considerations when designing and assessing SCSs for nutrient reduction and their impact on receiving waterways.

The model also shows a qualitative description of interflow composition, as the catchment transitions from dry summer to wet winter conditions. Sources of water for interflow are reported as a proportion of infiltration sources within the urban mosaic and groundwater interactions (Figure 4c). Interflow composition is based on results from CRCWSC Project B2.4 research, and from literature on water pathways in tiled landscapes. Currently, regulatory agencies and industry do not consider water sources contributing to interflow either during SCS design to achieve nutrient attenuation, or during standard monitoring to assess SCS effectiveness (such as water sample collection). The proposed model should guide monitoring activities to account for seasonal variability of the water sources, particularly when groundwater is interacting with SCSs and the drainage network.

Two τ_E values remain unknown, and they correspond to interflow components in the imported fill and high groundwater during times of hydrological connectivity, when lateral flow pathways dominate transport. These time scales correspond to significant knowledge gaps identified from the literature: natural nutrient attenuation capacity of the fill; minimum pathway length in the groundwater to achieve guideline concentration triggers before interception by subsoil or drainage pipes; and a better subsoil drainage design (depth and separation) that controls both water table elevation and its water quality. Damming of the groundwater in tiled landscapes has been shown to be a viable solution to increase exposure time scale and enhance suitable conditions for nutrient processing (for example, exposure to anoxic conditions) to treat groundwater at source. Such an approach could be suitable for implementing in new imported fill tiled urban landscapes such as Figure 4, whereby a complete disconnection from the stormwater drainage system is properly designed and implemented (for example, there is no groundwater contribution to stormwater runoff drainage).

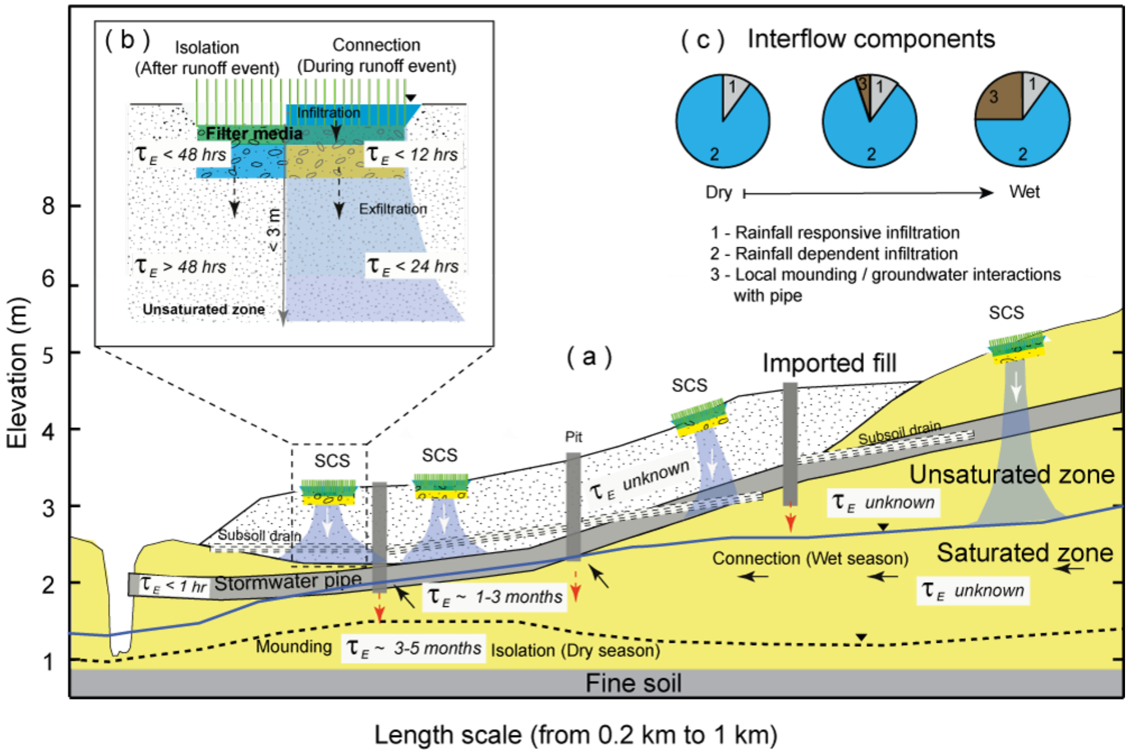

Figure 4. Conceptual model of hydrological processes and relevant τ_E values for nutrient processing in the urban karst, in areas with high groundwater: (a) landscape representation of current built forms and stormwater management practices, (b) individual SCSs, and (c) variation of interflow components over seasonal scales

5.6 Recommendations to address knowledge gaps for water and nutrient balances in urban areas with high groundwater

It is imperative to quantify infiltration rates, recharge rates, and the relative magnitude of water sources contributing to interflow, within the urban mosaic and for individual SCSs. They all directly affect subsurface water pathways, stages of connection and isolation, the exposure time scale for nutrient processing and attenuation, and the overall performance of SCS elements and treatment trains in existing and new developments. Yet neither the design process nor post construction assessment of SCS performance account for any of these factors. Using the above conceptual model (Figure 4) for any urban area with high groundwater conditions would guide the spatial scale at which the monitoring activities (recommended below) should be implemented.

Site inter-comparisons, extrapolation of results for different urban forms, and ultimately the establishment of hydrological typologies for different groundwater conditions will be possible only if consistent methods are used. The developed conceptual model should facilitate this standardisation of methods. For this reason, we recommend:

1. Estimate infiltration/exfiltration rates from SCSs using hydrograph recession analysis. These hydrographs should be measured at the surface water storage or filter media storage via continuous water levels recording for small, minor, and major runoff events. Monitoring of major events will account for the effect of antecedent moisture conditions in the catchment. The data will improve our estimates of water mass transfer to the subsurface, and facilitate numerical model testing, to overcome uncertainty about transient infiltration and the recovery of infiltration capacity processes. As a result, industry and regulators facilitating the SCS adoption pathway should be able to agree on common methods.

2. Compute and report recharge rates and amounts at a standard 2 metres below ground level (including for SCSs, as shown in Figure 3) using two soil moisture sensors. The estimate should be cross-checked with a shallow bore hydrograph analysis by recording water table level variations to a depth of less than 4 metres. Data must be collected from areas under hard surfaces (such as streets and parking lots), under housing over imported fill (isolated and close to subsoil drains), and under green areas over both imported fill and natural soils. This information is crucial to tackle knowledge gaps related to the main water input to the groundwater system, and to the exposure time scale for pollutant transformation/attenuation. Within the Perth context, the extent of the former process is not agreed on, while the latter concept is not well understood, let alone quantified, by industry practitioners, regulators and researchers.

3. Use the above data and suggested analytical techniques (Carleton, 2010) to quantify mounding characteristics (height and extension) and time of relaxation. This information will support researchers' and industry practitioners' use of numerical tools to account for impact on groundwater by SCS spatial allocation during the design phase (Zhang and Chui, 2018).

4. Undertake interflow monitoring using a combination of hydrometric and environmental tracers, to quantify the relative contributions of infiltration and groundwater discharge. Monitoring should be conducted along stormwater drainage pipes to ensure a proper mass balance approach. These data will assist in design practices for SCS sizing and treatment performance in areas of high groundwater, given design does not currently account for interflow volumetric composition and the water quality characteristics (for example, nutrient concentration of infiltration and groundwater) of each water source entering, interacting and/or leaving the SCS. This knowledge gap constrains our ability to identify processes leading to removal and/or attenuation within the SCS, and ways to implement innovative designs. We recommend an adaptive water sampling strategy and tailored cost-effective program to target specific hydrological conditions and nutrient processes—for example, the use of the exposure time scale from Figure 4 for planning and targeting parameters and analytical determinations.

5. Apply a mass balance approach in the high groundwater, following the control planes and integrative mass flux concept reported in the literature. Water and solute budget regions must include those areas where interflow monitoring is undertaken. Control planes along the shallow groundwater pathways should extend from highland to lowland areas of the urban development, to quantify τ_E controlling nutrient transformations. Knowledge about the exposure time for pollutant transport and processing in the groundwater will allow testing and use of current numerical tools to assess natural attenuation in the groundwater, and to evaluate engineering solutions that enhance nutrient processing. A field scale damming of groundwater in a new fill tiled urban precinct could allow the generation of different on-ground scenarios via manipulation of groundwater levels and discharge. It would be an excellent opportunity to address knowledge gaps, determine the robustness of the mass balance approach, and trial field techniques.

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