CRC for
Water Sensitive Cities

Integrated Research Project 5 Knowledge based water sensitive solutions for development in high groundwater environments

Stage 1 Report
Prepared by GHD, Water Technology and the University of Western Australia

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Integrated Research Project 5 Knowledge based water sensitive solutions for development in high groundwater environments
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Executive summary

The CRC for Water Sensitive Cities' Integrated Research Project 5 (IRP5, Knowledge-based water sensitive city solutions for groundwater impacted developments) aims to better understand the impact of urban development in groundwater impacted environments. Project outputs will include guidelines and innovative solutions that achieve more effective, water sensitive outcomes for groundwater impacted developments.

Stage 1 was a scoping study, conducted by GHD, Water Technology and the University of Western Australia. Its objectives were to:

- Collate and critically evaluate the current state of knowledge locally (WA/Australia) and globally in the design and implementation of urban (residential) development and water management approaches in areas with high and variable groundwater tables, focused on addressing priorities directed by the Project Steering Committee (PSC)
- Identify contested or unknown design and implementation parameters and methodologies for such developments and urban water management systems that could be further investigated (at full scale) in the follow-up project phase (Stage 2)
- Investigate alternative building/construction and land development methods and their performance in high groundwater environments from a national and international perspective
- Develop an action and research plan to address key knowledge gaps, with a focus on applications to inform water sensitive development at the Brabham research case study site.

The study examined the available state of knowledge about topics on development in groundwater affected areas and then classified each topic into one of four categories:

Evidenced: That which is evidenced through scientific methods with negligible disagreement among experts.

Agreed: That which is generally agreed among experts or practitioners, with little deviation. This category includes practices that are agreed but lack a scientific basis.

Contested or uncertain: That which is contested between experts or practitioners, or subject to a wide range of understanding.

Unknown: That which is largely or completely unknown.

The state of knowledge for each topic was obtained from written sources (industry guidelines, policies, standards, technical reports and scientific literature) and interviews with key stakeholders and experts.

Altogether, the study investigated 82 knowledge items under four headings:

- Pre-existing development
- Impact of development on water resources and environment
- Impacts of high groundwater on infrastructure
- Impacts of high groundwater on liveability.

Most knowledge gaps related to pre- and post-development water balances

The study identified 27 contested knowledge areas and six unknown knowledge areas (see chapter 6). These contested and unknown knowledge areas are clustered around the broader knowledge areas of pre- and post-development water balance of the superficial aquifer:

- infiltration and recharge rates

- evapotranspiration rates
- groundwater fluxes
- groundwater levels

Without understanding the pre-development water balance, it is difficult to maintain and protect pre-development hydrologic and nutrient cycles. Just as importantly, poor understanding of the post-development water balances means hydrologic models include a broad range of parameterisation, increasing the risk that a development will underperform, affecting infrastructure, property and receiving environments. It also makes it difficult for practitioners to select, size and configure stormwater treatment train, storage and attenuation measures, and design measures to control groundwater levels or achieve separation distances. Regulators are similarly ill-equipped to assess and approve the proposed water management solutions.

Perhaps reflecting this poor understanding of water balances, the study categorised knowledge areas relating to the effectiveness of water sensitive urban design (WSUD) in high groundwater environments as contested, and those relating to the impact of WSUD on subsurface hydrology and nutrient cycling as unknown.

Other knowledge gaps related to pollutant pathways and nutrient cycles in high groundwater environments, which leads to ill-informed decisions about pollutant capture and treatment.

Research priorities address fundamental water balance and water quality gaps

Given the importance of understanding pre- and post-development water balances, the study recommends prioritising knowledge gaps that related to the pre- and post- development water balance of the superficial aquifer. Deriving answers to some contested or unknown areas will be straightforward. For example, post-development groundwater levels without groundwater controls can be estimated simply once practitioners understand the superficial aquifer water balance.

By contrast, closing some knowledge gaps will require substantive research. The study identified the following priorities for further research:

- pre- and post-development infiltration and recharge rates
- pre- and post-development evapotranspiration rates
- post-development pollutant pathways and nutrient cycles.

A large number of variables exist within these research priorities, such as aquifer properties; soil types; rainfall intensity, frequency and duration; vegetation species and density; temporal effects of vegetation growth; WSUD types and configurations; and pervious and impervious fractions and connectivity.

The study proposed using case studies of pre- and post-development groundwater and surface water in urban developments with high groundwater to address the knowledge gaps. Case studies should monitor all aspects of the water balance (all water inputs and outputs of a system). Case study sites must also be selected carefully, to ensure the widest application of research outputs for future development.

1 Introduction

1.1 Purpose and scope

GHD, Water Technology and the University of Western Australia were engaged by the CRC for Water Sensitive Cities (CRCWSC) to undertake Stage 1 of Integrated Research Project 5 (IRP5)—*Knowledge-based water sensitive city solutions for groundwater impacted developments*. IRP5 aims to better understand the impact of urban development in groundwater impacted environments and will generate water sensitive solutions for areas with high groundwater tables. The outputs from the project will include guidelines and innovative solutions that achieve effective water sensitive outcomes for groundwater impacted developments. The project will focus on a research case study located at Brabham, in the Swan Region of Western Australia, jointly with WA Dept of Communities.

1.2 Study Objectives and Context within the IRP5 Project

Stage 1 of IRP5 is a scoping study, which involved collating existing knowledge and then coordinating a Research Action Plan for Stage 2. The objectives of Stage 1 were to:

- Collate and critically evaluate the current state of knowledge locally (WA/Australia) and globally in the design and implementation of urban (residential) development and water management approaches in areas with high and variable groundwater tables, focused on addressing priorities directed by the Project Steering Committee (PSC)

- Identify contested or unknown design and implementation parameters and methodologies for such developments and urban water management systems that could be further investigated (at full scale) in the follow-up project phase (Stage 2)

- Investigate alternative building/construction and land development methods and their performance in high groundwater environments from a national and international perspective

- Develop an action and research plan to address key knowledge gaps, with a focus on applications to inform water sensitive development at the Brabham research case study site.

1.3 Definitions

This project uses the following definitions:

High groundwater: When the water table is within 4 m of the natural ground surface. Includes regional unconfined aquifers and local seasonally (perched) water tables. Also referred to as “shallow groundwater” or “near-surface groundwater” throughout this report.
Superficial aquifer: is the aquifer nearest the surface, having no overlying confining layer (the unconfined aquifer).

The state of knowledge of the topics this report investigated falls on a spectrum ranging from unknown to known. This report assesses the topics’ position on the spectrum by presenting the available information, classifying the topic into one of four categories:

- **Evidenced**: That which is evidenced through scientific methods with negligible disagreement among experts.

- **Agreed**: That which is generally agreed among experts or practitioners, with little deviation. This category includes practices that are agreed but lack a scientific basis.

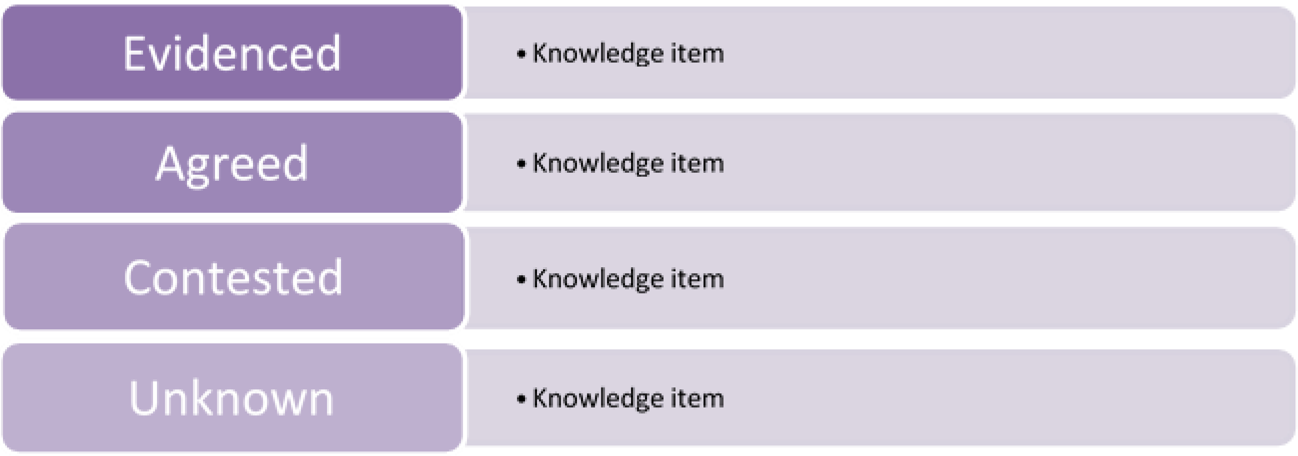
- **Contested or uncertain**: That which is contested between experts or practitioners, or subject to a wide range of understanding.

- **Unknown**: That which is largely or completely unknown.

1.4 Report style

1.4.1 State-of-Knowledge Summary

Summaries of the state of knowledge are provided at key junctures in this report using the following style.



Evidenced	• Knowledge item
Agreed	• Knowledge item
Contested	• Knowledge item
Unknown	• Knowledge item

1.4.2 Interview quotations

Quotations from interviewees are provided either in paragraph or stylised as follows.

Unsaturated zones are not at all well known

1.5 Methodology

The methodology adopted for this project is broadly to:

- Evaluate current academic literature on the above topics (noting that a literature review was available from the previous CRCWSC Research Project B2.4 (<u>Hydrology and nutrient transport processes in groundwater/surface water systems</u>)
- Investigate grey literature and industry expertise and sources locally and globally on the topics described in the Objectives section (Chapter 1.2).
- Summarise and critically evaluate the current literature on the aforementioned topics, including areas:
    - where evidence is available and appears to be sound
    - where there is generally shared agreement and alignment in professional judgement, or
    - where there is disagreement or uncertainty e.g. quantify the range in criteria or parameters used in urban hydrology or hydraulic modelling.
- Conduct structured interviews with key stakeholders and experts locally and globally (identified in cooperation with the Project Steering Committee, PSC) and compare the results of these interviews with findings from the literature review.
- Identify key design and implementation parameters that are contested or unknown and could be further investigated in Stage 2.
- Conduct a joint workshop with key stakeholders to discuss, evaluate and consolidate the identified key design and implementation parameters and methodologies that need further investigation through practical research activities.
- Integrate and summarise findings from the above key activities in a "State-of-knowledge" document as a

final report from the study, which includes:

  - Preliminary best practice recommendations, supported by robust evidence where available, that industry can use to guide water sensitive development in high groundwater environments, with a focus on solutions that can be applied or trialled at Brabham
  - Recommendations with respect to what is required to change practice and achieve more water sensitive developments in high groundwater environments, and
  - An outline of key knowledge gaps that need to be addressed to improve industry capacity to achieve water sensitive developments in high groundwater environments, with a focus on those gaps that need to be addressed to achieve an exemplar water sensitive development at Brabham.

- Facilitate/coordinate the development of a Research Plan for Stage 2 that is focused on the Brabham case study, with input from the Project Steering Committee, UWA, Dept of Community and the Dept of Water and Environmental Regulation.

1.6 Sources of Information

1.6.1 Written sources

Written sources include International and National industry guidelines, policies, standards, technical reports and scientific literature. Technical reports include water management strategies and plans developed under the Western Australian Better Urban Water Management framework (Western Australian Planning Commission, 2008) and local government technical reports. Information sources are cited throughout the document and listed in Chapter 7.

1.6.2 Expert Interviews

Practitioner and stakeholder interviews were undertaken to capture knowledge and experience from practitioners familiar with the challenges posed by urban development in high groundwater environments. The practitioners were selected by the PSC based on the following criteria:

- Balance of urban development, government, water utility and research personnel, with an emphasis on those with the requisite technical knowledge to answer the interview questions
- Geographic spread, both nationally and internationally
- One from each organisation
- Availability and willingness to participate.

In total, 20 practitioners and stakeholders were interviewed. The interview questions are provided in Appendix 1. The information obtained from the interviews is cited throughout the document, using named sources where consent was given, or anonymous sources where it was not.

2 Background and setting

2.1 Pre-development environment

The pre-development environment as defined in this chapter refers to the environmental setting immediately prior to urban development, whether this is an undisturbed natural environment, or a disturbed environment such as an area of agricultural land use.

Understanding the pre-development environment is essential to undertaking urban development in order to set a water balance and quality baseline.

2.1.1 Water balance

The water balance of a pre-development environment is a product of the relationship between rainfall, runoff, infiltration and evaporation characteristics and the unique environmental characteristics of a site and its catchment (soils, vegetation and topography). Water also enters and leaves the superficial aquifer and the deep (confined) aquifer. The conceptual water balance model illustrated in Figure 1 is evidenced by numerous studies.

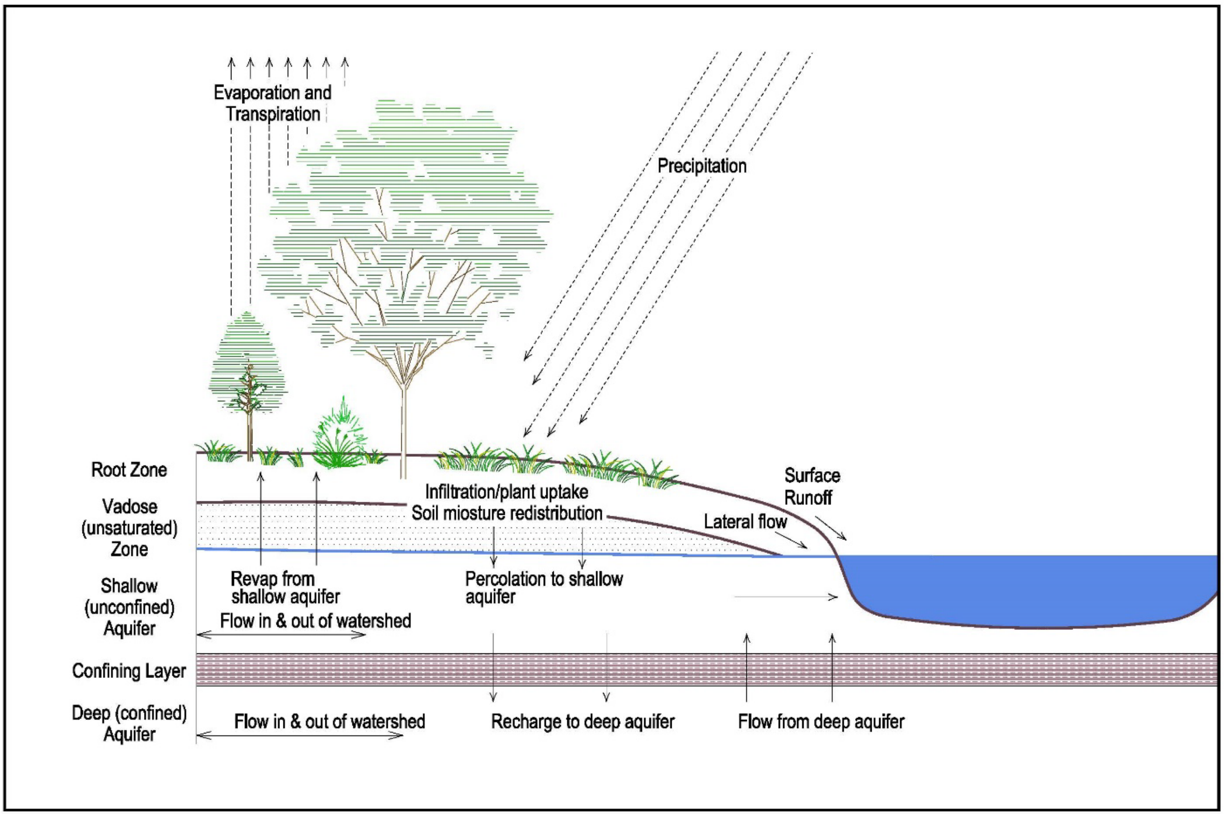


Figure 1: Pre-development water balance

2.1.1.1 Precipitation

Precipitation depths, intensities, seasonality, and temporal patterns are well understood in Australia through a network of public and private rainfall gauging stations and detailed analyses by the Bureau of Meteorology. Methods for predicting the impacts of climate change on rainfall intensity are provided by Australian Rainfall and Runoff (Ball et al., 2016), while seasonal and annual changes in rainfall depth due to climate change are also provided by the CSIRO and Bureau of Meteorology (Clarke et al., 2011).

2.1.1.2 Interception

Interception of precipitation by leaves, branches and groundcovers is a loss from the system. Characteristics such as trees/ha, branch angle, the uniformity or lack of uniformity in crown height, the nature and thickness of the bark layer, leaf shape and inclination, and leaf area index will all influence interception. External factors such as rainfall intensity and wind strength also influence interception rates. While it is difficult to draw general conclusions about interception losses by particular forest types, carefully conducted event-based studies can quantify the influence of a number of the variables (Crockford et al., 2000). High groundwater levels do not directly influence interception losses. Interception losses are therefore categorised as agreed.

Given that interception rates for eucalypt species have been measured at up to 11% of the annual rainfall depth (Crockford et al., 1990) and 30% per annum for pine plantations (Silberstein et al., 2012), they can be a significant component of a site's water balance.

2.1.1.3 Surface water runoff

Surface water runoff is a function of precipitation (spatial and temporal), topography, surface roughness, infiltration and, to a lesser extent, interception. Considerable research has been undertaken to understand catchment runoff rates and volumes over broad temporal and spatial scales. Different interpretations of variables by practitioners invariably lead to a range of runoff estimates, however the processes and parameters for a given catchment are generally agreed with little deviation, where groundwater levels are low.

Where groundwater levels are at or near the surface, runoff rates and volumes are not well predicted - largely due to significant variations in infiltration loss parameterisation. This is particularly the case for event based hydrology rather than seasonal or long term hydrology, where rainfall intensity exceeds the saturated hydraulic conductivity of the soil. Runoff can also be generated where groundwater rises above the ground surface, or where groundwater is intercepted by a waterway or drain, in addition to event based runoff.

2.1.1.4 Evapotranspiration

Evapotranspiration (ET) includes canopy evaporation, vegetation transpiration, ground surface evaporation, and soil evaporation from both the saturated and unsaturated zones. Canopy evaporation, vegetation transpiration, and surface water evaporation are all well researched. Within the root zone, evaporation and plant uptake rates are also well researched. However, research associated with evaporation rates in high groundwater environments is limited. Recharge rates can be used as an indicator of ET rates, and are discussed in Chapter 2.1.1.6.

Areas with sparse vegetation, an abundance of bare soil, shallow groundwater and dry climatic conditions are prone to substantial groundwater evaporation, particularly during long dry seasons (Balugani et al., 2017) Conversely, in a wet climate, soil water plays a negligible role in evapotranspiration at depths greater than 0.75m (Wilson et al., 2001).

In the presence of trees, Carter et al. (2010) report that a plantation of trees can be more effective than a pump in maintaining a deep water table and thereby controlling waterlogging and associated salinity. Farrington et. al. (1989) identified a positive correlation between increasing groundwater depth and evapotranspiration rates among native vegetation, however the correlation was weak, of moderate confidence (R^2=0.6), and only applied to groundwater depths between 5m and 12m. Conversely, Barron et. al. (2012) found that evapotranspiration rates are lower with a diminishing access to groundwater. While ET in high groundwater environments is energy limited, the number of contributing variables and range of literature findings leads to the conclusion that evapotranspiration fluxes in high groundwater environments are contested.

2.1.1.5 Lateral Flow

Lateral flow within the root and vadose zones is a function of the continuity of the soil and perching horizons, storage capacity of the soil, soil permeability, and slope of the soil and perching horizons. Literature for simple homogeneous systems is common, however the variability of these factors in natural environments results in uncertainty in real world applications.

Soil moisture content thresholds to initiate flow, recharge reaching the water table and their rates, and the need to overcome water storage thresholds for lateral flow initiation in the landscape become critical. There is common agreement in the scientific community that this is a knowledge gap which has significant need for improved parameter estimation in existing models, for both base flow and storm flow. Lateral flow is therefore considered a contested topic.

Unsaturated zones are not at all well known

2.1.1.6 Infiltration and Recharge

After losses to ET, runoff and lateral flow, infiltration rates of remaining soil water are determined by:

- Soil characteristics including ease of entry, storage capacity, and transmission rate through the soil
- Vegetation type, particularly root characteristics, and
- Antecedent moisture conditions.

Pre-development infiltration rates are estimated by practitioners using a variety of methods. Shukla (2003) analysed ten infiltration models including Green-Ampt and Horton's models, using double-ring infiltrometer tests, and reported that Horton's model gave the best results for most land use conditions.

In areas of very high groundwater, where the vadose zone is saturated, surface water runoff rates are higher.

Following infiltration, recharge into the aquifer is subject to additional geotechnical and hydrogeological factors. In the Perth region, in locations of Bassendean soil where groundwater is within 4m of the surface, recharge rates are estimated using groundwater models to be between -35% to +32% of annual rainfall for pine plantations, between +6% to +39% of annual rainfall for banksia forests, and +45% of annual rainfall for pasture (Xu et al., 2009).

Understanding and quantifying pre-development infiltration and recharge rates is essential for urban development, where practitioners seek to maintain pre-development hydrology. If infiltration rates are under- estimated, practitioners may overdesign post-development infiltration measures, increasing groundwater levels and reducing surface water runoff. Conversely, the over-estimation of pre-development infiltration rates may under-design post-development infiltration measures, leading to excess post-development runoff.

2.1.1.7 Groundwater Flow

The theory to describe the movement of water in a shallow unconfined aquifer and its interaction with a surface water body (stream, wetland, lakes and drains) is well understood and agreed (see (Pinder et al., 2006)). The theoretical hillslope shown in Figure 2 presents lines of equal hydraulic head (fluid potential) that drive the groundwater flow in three different areas: the upland (F), mid-slope (E) and near-stream (D) riparian zones.

The water table elevation corresponds to the value of the fluid potential (i.e. the contour value) at the point where it intersects the water table (shown as horizontal dashed lines in A,B,C). The flow field at each landscape region (denoted by F,E,D) in Figure 2 shows downward movement in region F, horizontal flow in region E (where potential lines are vertical), and finally upward flow in region D (where potential increases with depth) indicating the discharge point into a stream or above ground (spring). This theoretical flow dynamic corresponds to homogenous-isotropic media, under a given recharge rate to the water table via the unsaturated zone (vertical arrows in Figure 2) and in absence of vegetation and/or pumping extractions.

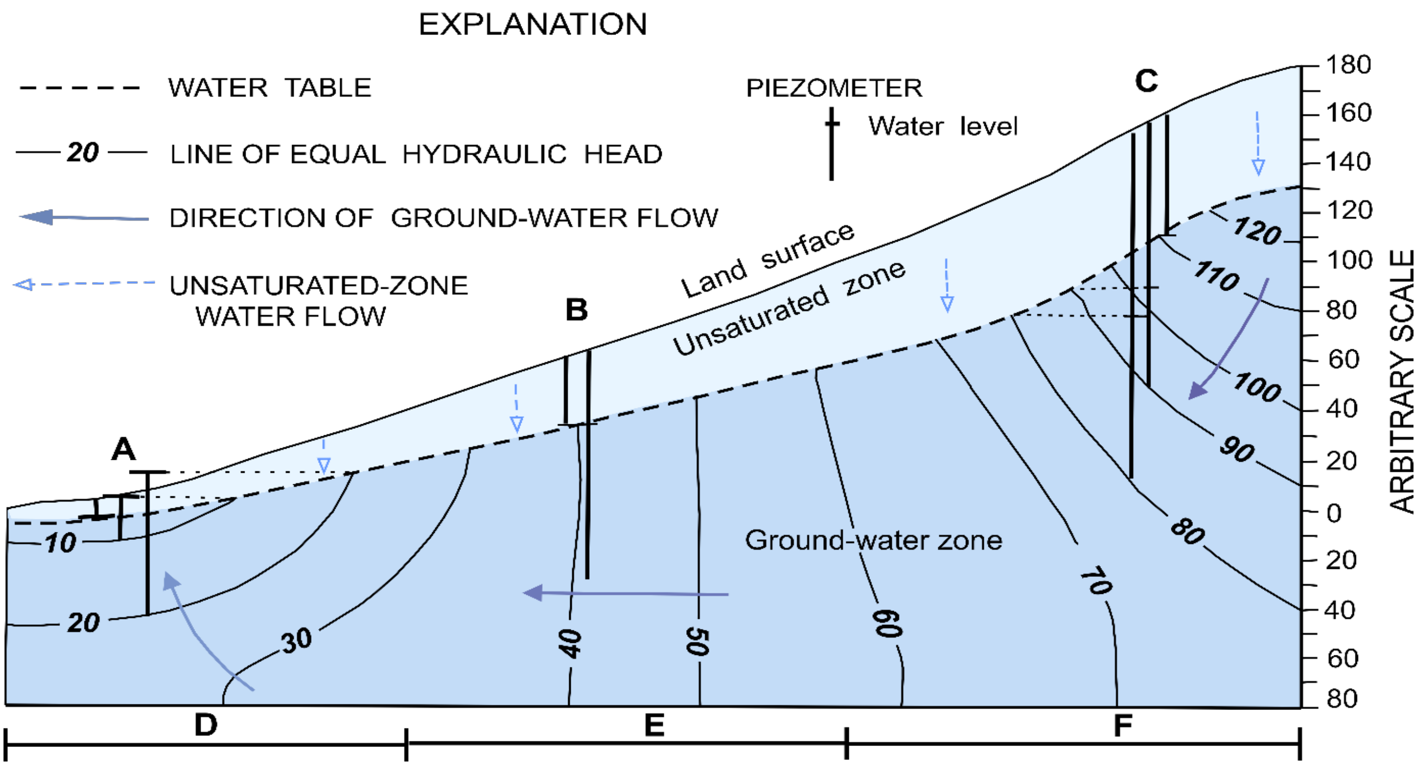


Figure 2: Superficial groundwater flow in the near-stream environment (Winter et al., 1998)

Numerical groundwater models currently available reproduce these dynamics and it can be concluded that this is not an area of contested knowledge. Models are used for surface-groundwater interactions (Fleckenstein et al., 2010), assessing the impact of climate change on these interactions (Saha et al., 2017), and the assessment of management strategies in near stream zones for vegetation health (Doody et al., 2009) and pollutant dynamics. However, the difficulties in transferring understanding of these processes across varying spatial-temporal scales need to be understood (Fleckenstein et al., 2010).

Predicting water table levels along the landscape in natural systems also presents difficulties due to processes governing water flow and pathways in the unsaturated zone, which ultimately affect recharge to the water table. This has been the focus of research on hillslope hydrology over the past three decades and it relates to the questions: How does the water from a rainfall, or irrigation event reach the stream, drains, and subsoil drains over the course of an event? And how does the water table develop in space and time affecting groundwater discharge to streams?

Difficulties in practical applications are often associated with assumptions of unsaturated zone hydrology and soil physics as well as a lack of information to properly characterize the subsurface environment and most importantly the depth of the impending or impervious layer along the landscape. A more realistic view of water table elevation in Figure 2 requires an understanding of how recharge rates change along different zones of the landscape.

Lateral flow in the subsurface occurs mainly as shallow throughflow saturated path (upper soil layers) and saturated flow from the unconfined aquifer. Both water sources have been identified to be dominant on runoff and pollutant generation pathways from forested and agricultural landscapes (Vidon & Hill, 2004). Significant research in headwater catchments has demonstrated the linkage between the hydrology of near stream zones and its upland landscape and their role on the catchment water balance and hydrochemistry. The size of the upland aquifer (unconfined) has been shown to impact on the magnitude and seasonality of subsurface flow inputs to lowland areas (Devito & Hill, 1998); while the depth and permeability of saturated sediments overlaying a confining layer influences flow paths, water residence times and water-vegetation interactions (Hill, 1996) (Correll et al.,1997). Topography plays an important role in local infiltration and recharge processes impacting on the hydraulic gradient of the water table towards lowland and near stream areas (Devito et al., 2000).

Hydrological connectivity, defined as the ability to transfer water from one part of a landscape to another (Ocampo et al., 2006) (Bracken & Croke, 2007), has proven to allow the integration of several complex processes into patterns that reflect the transfer of a mass of water and solutes across different portions of the landscape. Shallow subsurface flow connectivity has been shown to impact on dissolved organic carbon (McGlynn et al., 2003), runoff generation and nitrate dynamics (Ocampo et al., 2006) and overall catchment scale runoff response (Jensco et al., 2010). In a forested environment, Jencso et al. (2010) demonstrated that the magnitude and timing of water and solute concentrations at the catchment outlet was controlled by the size (water storage in saturated zone), spatial arrangement of uplands and near stream zones along a stream network, and by the timing and duration of shallow groundwater connectivity between these areas. Such concepts have led to the development of a new generation of hydrological models capable of predicting water storage, levels, discharge volumes and solute pathways from a catchment (Smith et al., 2012) (Tetzlaff et al., 2014).

It is recognised that a sound analysis of groundwater flows and hydrological connectivity is essential to understand the movement of water and physical, chemical and biological transformations of solutes through the landscape in low order streams and headwater catchments. There is a need for research into how continuous flow fields develop under sets of different environmental conditions to assist managers to know when and where to intervene in a catchment (Bracken et al., 2013).

Evidenced	• Pre-development evapotranspiration rates • Precipitation intensity, duration and temporal patterns
Agreed	• Pre-development infiltration rates • Interception rates
Contested	• Pre-development infiltration rates in high groundwater • Lateral flow and fluxes to surface water • Fluxes to the superficial and confined aquifers • Evapotranspiration rates in high groundwater
Unknown	

Figure 3: Pre-development water balance state of knowledge

2.1.2 Groundwater Levels

Determination of pre-development groundwater levels and their fluctuation is a critical component of urban design, planning and management.

The following information is required for design and construction works in areas with shallow groundwater tables:

- Maximum groundwater levels over the life of structures or urban areas
- Maximum and minimum groundwater levels during construction and development
- Historical minimum groundwater levels (for acid sulfate soil assessment)
- Groundwater level response to urbanisation.

DoW (2012) recommends up to two full years of groundwater level monitoring with at least monthly frequency, but it states that the monitoring duration for specific projects would depend on their potential risks and, therefore, can differ from the recommended duration. DoW (2012) provides little guidance on the spatial density and placement of bores. However, bore construction requirements are reasonably well addressed by guidelines in a number of Australian Local and State Government jurisdictions, usually in relation to contaminated site investigations.

A review of pre-development groundwater monitoring programs undertaken in Western Australia indicated little consistency in bore densities in high groundwater areas. Given the range of variables affecting groundwater levels and flows, monitoring programs need to be suitable for individual site conditions. Pre-development monitoring frequencies in Western Australian studies typically range from 15-minute to monthly. Sub-daily groundwater level response times suggest that monthly water level monitoring is likely to underestimate extremes.

There is also no standard (or agreed) methodology to determine pre-development groundwater levels. For different projects, different approaches are taken and those are often driven not by technical requirements, but by project budgets and schedules. While DoW (2013a) explains water resource factors that are impacting controlled groundwater levels, it doesn't recommend a methodology to determine maximum groundwater levels. A number of existing industry approaches are presented in Chapter 2.1.2.2.

The following sections summarise existing methodologies in research and industry to determine pre-development groundwater levels. Traditionally, although with some exceptions, researchers are using 3-D numerical models, while practitioners are applying 1-D numerical models or more simplified calculation methods. Limitations of the existing methodologies are described below, noting that these are widely recognised by most industry practitioners.

2.1.2.1 Sources of Information

The Perth Groundwater Atlas (Department of Water, 2004) presents an interpolated groundwater surface constructed for May 2003 (seasonal minimum water levels) and a historical maximum groundwater surface that is based on measured maximum water levels in monitoring boreholes. As all boreholes have different record periods, the reported maximum groundwater surface is not related to any particular time and should therefore be considered “indicative only”. Atlas explanatory notes state that the primary objective of the Perth Groundwater Atlas is to provide information to assist in the installation of groundwater abstraction bores and “because of changes in groundwater and natural surface levels that can occur over time … Department of Water is not in a position to guarantee the accuracy of the data”.

Department of Water WIR system and other state and national databases (Department of Water and Environmental Regulation, 2017). The WIR database contains historical water level monitoring records and stores data from bores, surface water and rainfall sites for Western Australia. This database is normally used to determine minimum and maximum groundwater table levels and seasonal variations on a site (subject to the availability of monitoring records) or in the site’s proximity. The database monitoring records are also used to calculate AAMGL as explained below, which it is noted is not recommended for design purposes. There are other databases that were collated by DWER for specific projects and regions (e.g. Swan Coastal Plain). These databases are not available online but can be obtained on request from DWER.

All States of Australia have their own water management information systems (see for example http://data.water.vic.gov.au/monitoring.html for Victoria) that contain groundwater level observations. Based on the experience gained through several MSc research projects at the University of Western Australia, other than in WA these water information systems contain a limited number of measurements that provide any real assistance in understanding regional maximum groundwater levels. The Western Australia water information databases however (i.e. WIR system and more local databases) have good spatial coverage and a fair number of bores with measurements, though to be included the data require significant time and resource investment for updates and quality checks. This is why much of the groundwater level measurements that have been conducted for various State infrastructure projects, such as Gateway WA or Forrestfield Airport Link, have not been included in WIR database**.**

Project-specific water level monitoring data varies widely, both in spatial density and temporal frequency and duration.

2.1.2.2 Methodologies to determine pre-development groundwater levels

Use of Perth Groundwater Atlas

Despite known inaccuracies of the atlas (up to 3m (Zirakbash et al., 2018)), it is often used for screening purposes (i.e. to determine whether a high groundwater table may cause risk and therefore needs to be investigated). DoW (2013a) clearly states that the Perth Groundwater Atlas “is not intended to define the groundwater regime for urban development”. Despite the above statement, some practitioners also use the Perth Groundwater Atlas for urban design purposes.

Average Annual Maximum Groundwater Level (AAMGL)

Even though the AAMGL approach is not mentioned in DoW (2013a), it is a widely used concept in Western Australia for the determination of maximum groundwater levels for groundwater dependant ecosystems, and subsequently for subdivision, road construction and, in particular, for pavement design. IPWEA (2016) mentions AAMGL in relation to selecting the invert discharge level of subsoil drains.

To estimate the pre-development AAMGL, annual groundwater peaks are averaged over several years. The peaks can either be measured locally on site or obtained from the WIR database. The Department of Water and Environmental Regulation has no guidelines in respect to calculating AAMGL (Davies et al., 2004). The concept was criticised by practitioners over the last decade with major concerns related to the following (Davies et al., 2004):

- Not accounting for existing drainage systems (e.g. deep surface drains) that are controlling the local groundwater table
- Periods of averaging are not defined, this results in different periods of data being used by different practitioners or by the same practitioner on different occasions
- Further, the method does not account for long term trends in groundwater levels.

Further to their review of the AAMGL concept, Davies et al. (2004) proposed a Controlled Groundwater Level (CGL) be used in existing drainage systems. CGL is the invert level of groundwater controlling infrastructure (IPWEA, 2016).

Back-calculation of recent measurements towards historical maximums

After seasonal maximum groundwater tables are established locally, current practice is to estimate local maximum groundwater levels based on the closest monitoring borehole from the WIR database with a long term record. Using local maximum data, design groundwater levels are typically established by adding a value corresponding to the:

- Difference between the maximum historical and seasonal groundwater levels at a borehole with long term records
- Difference between the estimated maximum and the seasonal maximum groundwater level at a borehole with long term records. Estimated maximums can be higher or lower than historical maximums and they aim to balance the high additional costs associated with conservatism and the risk that these estimated groundwater levels will be exceeded (see Boronina et al. (2014) for Australian case study and Socolow et al. (1994) for USA case study).
- Difference between the AAMGL and the seasonal maximum groundwater level at a borehole withlong- term records.
- Seasonal variations of the groundwater table for a future construction period are usually assumed to be the same as those during the monitoring period. Historical minimum groundwater levels are estimated based on long term records in a similar way to the estimation of maximum groundwater levels.

2.1.2.3 Mathematical Models

Time-series correlation analysis

Several research studies (e.g. Almedeij & Al-Ruwaih, 2006; Chen et al., 2002) have attempted to predict groundwater level fluctuations using established correlations with climatic variables. Even though some of the correlations demonstrate good matches between measured and calculated groundwater hydrographs, the applications of this method for most cases are limited because it does not explain how to determine:

- Maximum groundwater levels at key locations where no long term hydrographs are available.
- Climatic parameters that will be associated with maximum groundwater levels.

Further, time series analyses have a clear disadvantage of a lack of consideration of physical concepts in the analysis approach due to the inherent structure of the equations (Bidwell, 2005). Moreover, statistical and stochastic approaches of time series analysis cannot consider spatial variations of the hydraulic properties of an aquifer, land use, soil type and slope in areas of investigation. The above parameters are often important to consider for the determination of maximum groundwater levels.

Lumped-parameter models

Other studies (e.g. Upton & Jackson, 2011) have applied lumped parameter models to predict groundwater levels. Although these models may correctly represent concepts of groundwater flow and interactions of its components, they are usually not able to estimate groundwater table elevations at the level of accuracy and reliability required for urban development in areas with shallow groundwater tables.

Numerical models

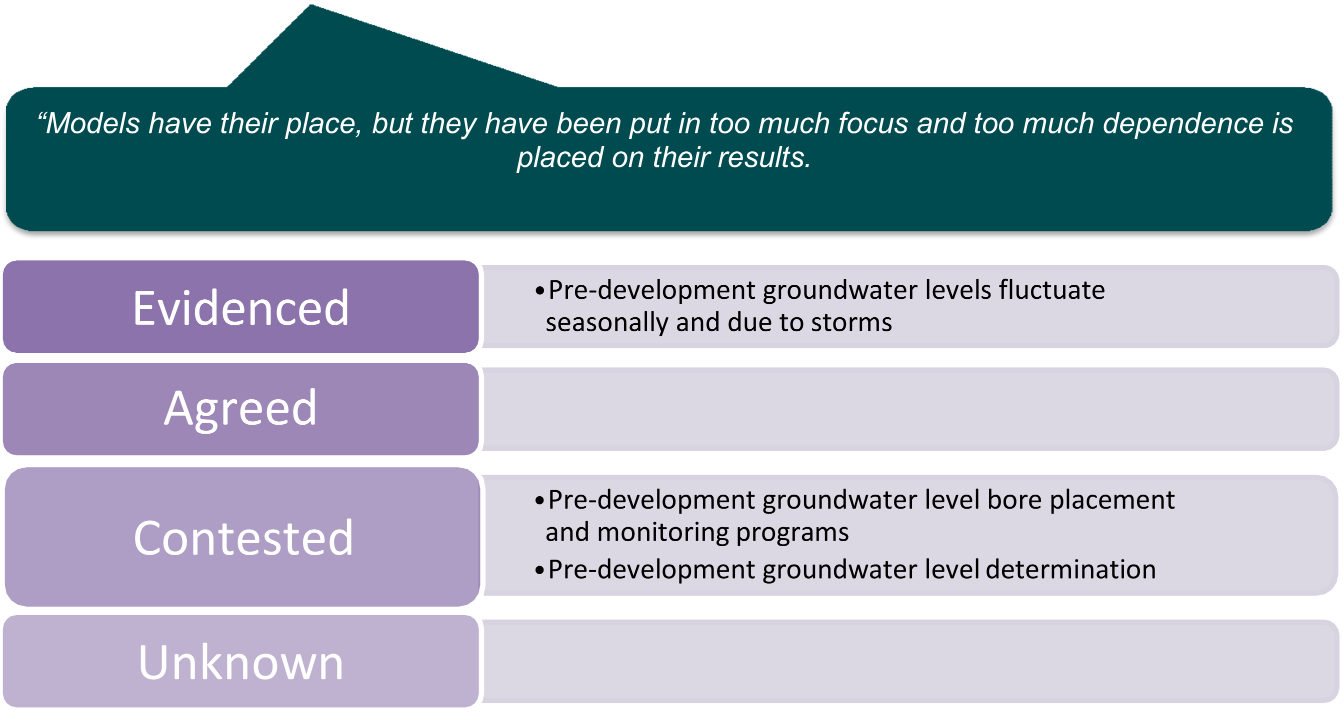
A common view of practitioners is that if reliable estimates of groundwater levels are required, a complex 3-dimensional groundwater flow numerical model needs to be developed. Such a model would have to be calibrated using local and regional data sets and parameterised in such a way that it will be able to predict either maximum or minimum groundwater levels as required. Though DoW (2013a) does not infer that groundwater modelling is required to calculate maximum groundwater levels, the document does encourage the use of numerical groundwater flow models for these purposes.

Recent project experience by the authors has suggested that, over recent years, no numerical model developed by industry or university researchers has been able to predict maximum groundwater levels with the reliability or accuracy required for urban development design purposes. Although most reviewed models were developed according to the Australian Groundwater Modelling Guidelines (Barnett et al., 2008) and were deemed to be acceptable for descriptions of *regional* groundwater flows and *regional* environmental impacts, they have typically failed *local* validations and were not able to reliably predict maximum groundwater levels at *specific locations* (e.g. road alignments).

Using numerical models for the determination of the Design Groundwater Level (DGWL) may look appealing given the possibility to account for the inherent, and often significant, complexity of physical processes (e.g. surface-groundwater interactions near compensating basins) and the heterogeneity of aquifers (Barnett et al., 2008). However, most regional models have uncertainties of 2-10 metres in the prediction of hydraulic heads. This uncertainty is acceptable for regional models; however, it is excessive for civil structure design that may be influenced by groundwater level changes. In many cases, it is not possible to reduce the predictive uncertainty for regional models because it is controlled by parameters that are either difficult to measure (e.g. spatially- distributed Specific Yield) or their complex behaviour requires significant simplification. For example, natural (pre- development) recharge cannot be measured and it is controlled by several factors including rainfall, vegetation cover, land slope etc. In most groundwater models, the recharge value is just a “professional guess” that is based on general concepts, while exact numbers are usually not able to be justified.

Other uncertainties in modelling maximum groundwater levels are related to parameters for specific prediction periods. For example, even if predicted maximum rainfall is deemed reliable, its conversion into recharge rates as a percentage of daily rainfall (a common approach among practitioners) remains over-simplified, as in reality recharge rates depend on numerous factors as highlighted earlier.

While the importance of accurate determinations of maximum groundwater levels is widely recognised by practitioners, there is currently no standard and agreed methodology or even recommendation on what approach needs to be used.



“Models have their place, but they have been put in too much focus and too much dependence is placed on their results.

Evidenced
- Pre-development groundwater levels fluctuate seasonally and due to storms

Agreed

Contested
- Pre-development groundwater level bore placement and monitoring programs
- Pre-development groundwater level determination

Unknown

Figure 4: Pre-development groundwater levels state of knowledge

2.1.3 Water Quality

2.1.3.1 Variability

The surface and groundwater quality of a pre-development environment is the product of the environmental characteristics of a site and its catchment (hydrology, soils, vegetation and topography) and pre-development land use (undisturbed or disturbed). Pre-development land use is a key consideration in identifying water quality pollutants and potential impacts on water resources and receiving environments within a catchment.

Nitrogen (N) and phosphorus (P) export from catchments commonly reflect 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 from agricultural and forested environments (Creed et al., 1996) (Aubert et al., 2013) and some researchers have investigated transformations of mobile nutrients along specific flow pathways (Ocampo et al., 2006). The N and P 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.

Greenfield urban expansion areas typically comprise rural or semi-rural properties and associated land uses. These broadscale land use types typically result in diffuse sources of water quality pollutants. On the Swan Coastal Plain, the introduction of trace element fertilisers in the 1950s led to widespread land clearing for the expansion of agricultural production (Kelsey et al., 2011). In some areas, the long term application of these fertilisers has resulted in the accumulation of nutrients within the shallow soil profile, while in other areas the remnants of wetlands of the Swan Coastal Plain have resulted in elevated organic nutrient concentrations in the soil profile (Chapter 3.2.2). Land clearing may also result in increased salinity and the disturbance of acid sulfate soils within a catchment.

Urban fringe and rural land use localities are also likely to contain effective ‘point source’ polluting land use types such as intensive agricultural practices (e.g. intensive animal industry, horticulture).

2.1.3.2 Monitoring

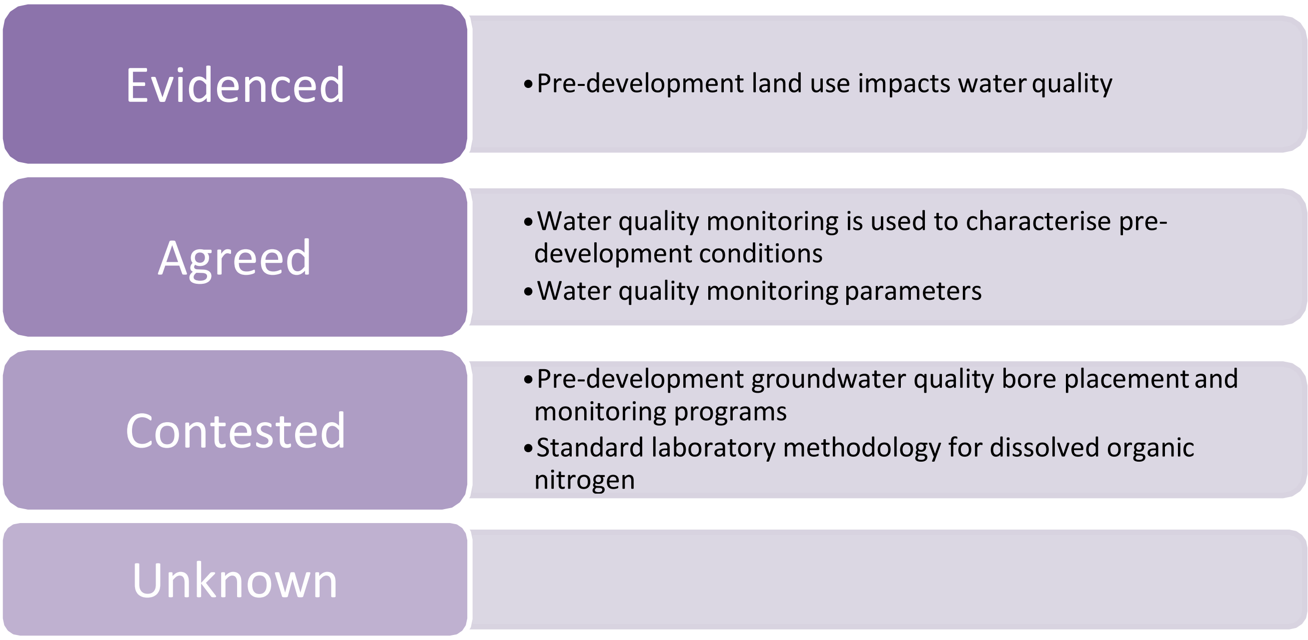
Determination of pre-development water quality is important to assist with identifying issues that need to be addressed as part of the land development process, and to reduce the risk to both water resources and the development. Pre-development water quality is characterised by monitoring of site surface water and groundwater resources. The recommended standard timeframe for pre-development monitoring in greenfield areas of Western Australia is two full years before site works begin, where no historic monitoring record exists (Department of Water, 2012). In practice this is often interpreted as monitoring of water quality for two full winter groundwater level peaks, although different pre-development water quality monitoring approaches are often applied for different projects, with similar drivers to the pre-development groundwater level determination (these being project budgets and schedules). The duration of pre-development monitoring programs reported in reviewed water management plans ranged from reporting of a single monitoring event through to three years of monitoring, with varying frequencies of monitoring also reported.

In addition to variations in the duration of pre-development monitoring programs, other key issues include the spatial density and placement of bores to adequately characterise the pre-development environment, in particular groundwater monitoring where there is variation in subsurface conditions across the site. These decisions are generally made based on desktop assessments of site conditions, prior to geotechnical surveys of the site.

Water monitoring guidelines for better urban water management strategies and plans (Department of Water, 2012) recommends water quality parameters for monitoring at sites proposed for urban development, including general physiochemical parameters and nutrient forms. Organic nutrients are not considered in the guideline nutrient suite, with practitioners noting that the key parameter missing was total filtered nitrogen, which is used to determine dissolved organic nitrogen. It was further noted that a standard methodology for dissolved organic nitrogen should be specified in the guidelines as laboratories use different approaches.

A review of water management plans has identified that most pre-development water quality monitoring programs considered the nutrient suite recommended by the guidelines, with some also reporting dissolved organic nitrogen.

Practitioners also noted that pre-development monitoring programs should consider all potential water uses (e.g. managed aquifer recharge, or MAR) and receiving water bodies at the pre-development stage and not be limited to background water quality characterisation of water resources. Strategic planning at the regional scale may be required to support this.



Evidenced	• Pre-development land use impacts water quality
Agreed	• Water quality monitoring is used to characterise pre-development conditions • Water quality monitoring parameters
Contested	• Pre-development groundwater quality bore placement and monitoring programs • Standard laboratory methodology for dissolved organic nitrogen
Unknown	

Figure 5: Pre-development water quality state of knowledge

3 Impact of development on water resources and environment

Urban systems impact on water resources and the environment in areas with high groundwater. Current practices attempt to minimise this impact; however, an incomplete understanding of pre- and post-development surface water and groundwater systems can result in residual impacts described in this chapter. Impacts are described both before and after implementation of current management measures, given the variability in current management measures, and the potential for these to change in future.

3.1 Water Balance

Several hydrological changes occur when a catchment is urbanised, primarily through alteration of the proportions of overland, subsurface and groundwater flows. This is illustrated in Figure 6, where SCS is an abbreviation of Source Control Systems.

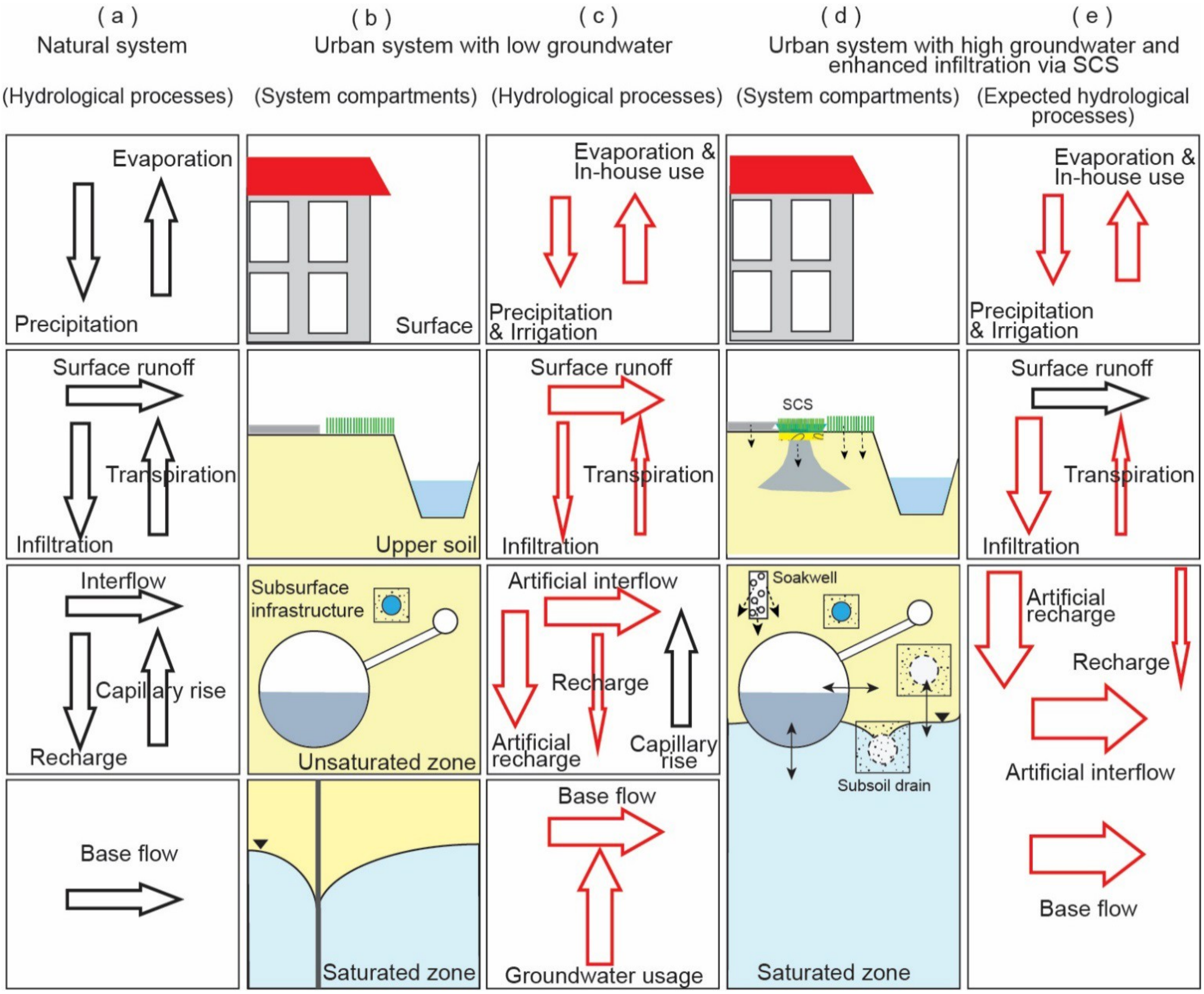


Figure 6: Conceptual model of perturbation of the urban water balance. Red arrows represent water flow that has been modified or introduced by urbanisation and proposed urbanisation in high groundwater environment with SCS. Modified after Schirmer et al. (2013) and Ocampo (2017).

3.1.1 Vegetation and Evapotranspiration

Urbanisation alters vegetation types and coverage, and therefore transpiration rates. Vegetation also changes over time, with newer developments exhibiting less tree canopy cover and shallower root depth when compared to older developments. Urbanisation alters soil and ground surfaces, and therefore evaporation rates. Barron et al. (2013) showed that urbanisation diminished evapotranspiration losses, which is supported by Hall et. al. (2010a) and Marillier et. al. (2012)

Evapotranspiration rates can be measured or estimated using a variety of methods, including catchment water balance, energy balance, remote sensing, and eddy covariance. The CSIRO WAVES integrated energy and water balance model can predict evapotranspiration. This model was found to be sensitive to rainfall, Leaf Area Index, light extinction, and maximum vegetation rooting depth (Xu et al., 2009). While WAVES is suitable for use at the development scale, it requires detailed vegetation data that may not be available at the planning stage.

There is no evidence that WAVES has been used by industry to predict evapotranspiration at this scale. A review of published and unpublished water management strategies and plans in Western Australia indicated a range of post-development methods for estimating evapotranspiration, including:

- Nil, as a conservative assumption for groundwater level prediction;

- Bureau of Meteorology monthly potential evapotranspiration rates;
- Bureau of Meteorology monthly pan evaporation rates;
- Engineering estimates; and
- Estimates incorporated into irrigation demands.

> *“Development reduces evapotranspiration and increases groundwater recharge, particularly into imported sand fill”*

> *“you can use Penman Eq. to get a rough evapotranspiration estimate”*

Figure 7: Post development water resources: vegetation and evapotranspiration state of knowledge

3.1.2 Groundwater table

Urbanisation often causes increases in groundwater levels due to higher post-development net recharge rates (Appleyard, 1995; Davies et al., 2014; Silberstein et al., 2009; Xu et al., 2009). The higher net recharge is associated with a decrease in evapotranspiration (Barron et al., 2013) and, in Western Australia, an increase in runoff infiltration from impervious surfaces due to the provision of infiltration measures (e.g. soakwells, biofiltration, rain gardens).

In developing countries, increases in groundwater levels also occur due to leakage from water distribution networks and exfiltration from sewage systems and wastewater disposal pools (Abu-Rizaiza, 1999; Al Sefry & Sen, 2006).

Other studies, outside of WA, suggest that urbanisation can lower groundwater tables due to decreased groundwater recharge over the areas with impervious surface cover (Leopold, 1968; Ferguson & Suckling, 1990; Rose & Peters, 2001; Konrad et al., 2005; Hardison et al., 2009). The difference can be attributed to differences in urban water management practices (i.e. no soakwells) and varying hydrogeological conditions between regions.

Groundwater levels may also rise or fall in response to the construction of underground structures (e.g. published case study by Bob et al. (2015). The impact of underground structures on groundwater flows and levels was reviewed by Attard et al. (2016). This review concludes that underground structures can:

- Impede the natural flow of the groundwater, which may result in rising water levels upstream and falling water levels downstream of the underground structure.
- Disturb the groundwater flow system, which may result in additional drainage and consequently lowering the groundwater table.

Despite evidence of the variety and complexity of responses of groundwater tables to urbanisation, little guidance exists on how to predict the impact of urbanisation on groundwater balance and water levels for specific cases. This gap in research and methodology is stated by (Bhaskar et al., 2016).

Numerous academic and some industry studies use numerical models (see Davies et al. (2014) for a case study in Western Australia and Gattinoni & Scesi, (2017) and Goebel et al. (2004) for case studies in Europe (Italy and Germany) or other types of mathematical models (e.g. 1D analytical equations - Serafini et al. (2014) to assess the impact of urbanisation on groundwater tables. Modelling approaches for urban catchment hydrogeology are listed and explained in Table 2 of (Salvadore et al., 2015). Most of the listed models include water level predictions as parts of their algorithms.

As explained in Chapter 2.1.2.3, the application of mathematical models, even for pre-development conditions, faces challenges of predicting groundwater levels at local scales, when a local feature (e.g. a clay lens or constructed feature) can impact model outcomes more than the regional properties that are determined during model calibration.

Predicting groundwater flows and levels for post-development conditions is associated with additional challenges that are summarised in detail by Salvadore et al. (2015) and Van de Ven (1990). In urban catchments, groundwater flow components interact with each other in multiple ways and at various temporal and spatial scales. These interactions are very difficult to impossible to quantify or sometimes even determine conceptually for water balance. In particular, urban recharge is a crucial water balance component in urban catchments.

However, the determination of such recharge usually has high uncertainty, both, spatial and temporal. Vazquez-Sune et al. (2005) contains a good summary of the sources of such uncertainty in the determination of urban recharge rates and also describes methods of recharge quantification. The latter review states that the most reliable methods of recharge quantification involve the calibration of mass-balance models by chemical species associated with known sources. While this approach would bring the most reliable recharge rates and, consequently, predicted post-development groundwater levels, it requires time, skills and funds that are rarely available for practical applications. Further, not every site may be associated with chemical tracers that help estimate recharge rates.

Calculating groundwater levels for post-development conditions generally focuses on two aspects:

1) How much will the groundwater level rise due to the extra recharge from urban areas or other post-development changes (e.g. cutting pine plantations), and at what stage do we need to start thinking about using subsoil drains to control groundwater levels; and

2) How water levels will be impacted by subsoil drains if they are constructed; this will help guide fill requirements

The IPWEA (2016) guideline methodology only really addresses the second aspect of post-development water levels. It states that modelling is required for designing groundwater drainage systems that must predict the performance of the system and provide average and peak discharges through the system. The required models may vary from steady state, spreadsheet-based, models to numerical 1, 2 or 3-dimensional models, however there is little guidance on model selection and the required level of complexity. While drawdown and mounding effects can be reasonably well estimated by 1D models for most hydrogeological conditions, absolute water table levels at distances from a drain (i.e. near a model boundary) will remain inaccurate. IPWEA (2016) recommends setting up local boundaries based on publicly available regional models (i.e. Perth Regional Aquifer Modelling System (PRAMS) (2009a), Peel Harvey Aquifer Modelling System (PHRAMS) or South West Aquifer Modelling System (SWAMS)). However, the referenced models, as reported in their explanatory notes, may have predictive uncertainties of up to 10 m or even higher. This uncertainty may or may not impact drainage systems predictions.

IPWEA (2016) doesn’t provide any qualitative or quantitative criteria of model performance or requirements to address model uncertainty. The document also contains recommended recharge rates; however, the base or justification of the selected recharge rates is not explained.

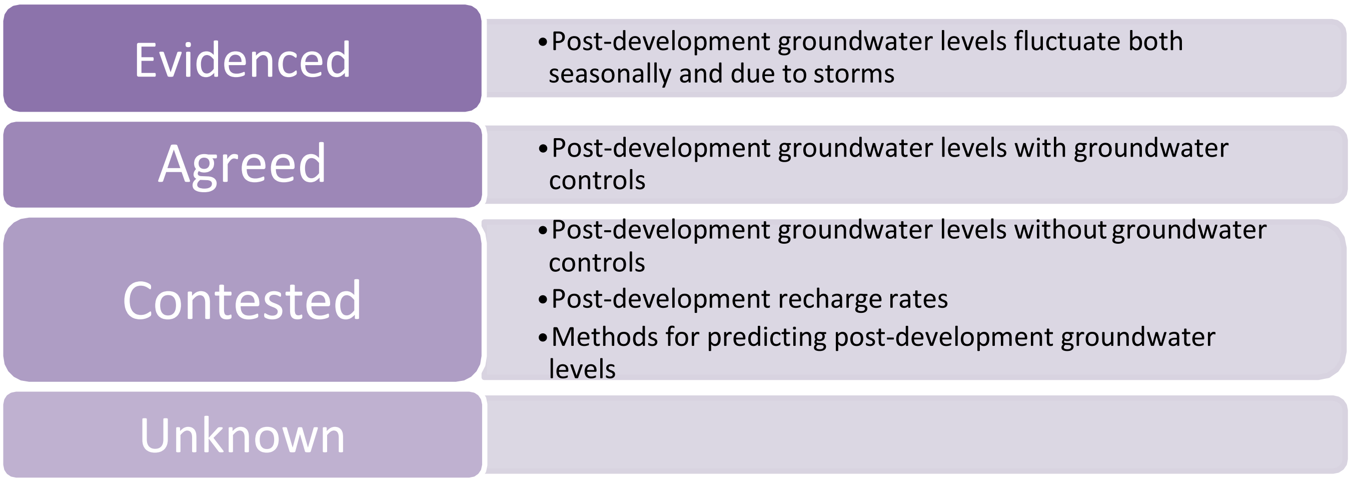
Numerous studies (e.g. Schirmer et al., 2013) recognise the low reliability of predictions of groundwater flow and levels in urban catchments. Schirmer et al. (2013) state that “the high level of complexity and parameter uncertainty as well as structural uncertainty remains a major problem of coupled and integrated model applications”. Rather than using numerical models in a standard way, i.e. trying to model a real system with all its features, as described in Australian Groundwater Modelling Guidelines (Barnett et al., 2012), numerical models could be used in a more holistic way with particular focus on better conceptualisation and quantification of the most important site-specific processes and parameters. Model objectives would have to be stated more specifically beforehand to explain what models are expected to achieve and what wouldn’t be achieved.

Probabilistic modelling approaches can help to better account for parameter uncertainty.

Where groundwater controls are proposed, such as those described in Chapter 4.3.3, maximum groundwater levels are generally agreed. While drain spacing is known and hydraulic conductivity generally agreed, infiltration and recharge rates can be a source of uncertainty.

> *“For post-development, we work on 60-70% [recharge] of rainfall total”*

> *“One study used 35% [recharge] for both pre and post development”*



Evidenced	Post-development groundwater levels fluctuate both seasonally and due to storms
Agreed	Post-development groundwater levels with groundwater controls
Contested	Post-development groundwater levels without groundwater controls Post-development recharge rates Methods for predicting post-development groundwater levels
Unknown	

Figure 8: Post development water resources: groundwater levels state of knowledge

3.1.3 Water and Sewer

Potable water used for garden irrigation and other outdoor water has the potential to increase the recharge of groundwater and therefore water table levels. For Perth, annual outdoor water use for single residential houses is 707 L/house per day, compared to multi residential use of 389 L/house/day (Water Corporation, 2003). More recent estimates of 605 ML/annum have been made, which equates to 552 L/house/day (GHD Pty Ltd, 2008). It is noted that demands in both estimates don’t distinguish between water sources, whether potable water, garden bores, or rainwater tanks. Further, there are uncertainties related to how much water is consumed by vegetation, evaporated, or recharged.

Sewerage systems can both leak into groundwater and also receive groundwater inflows. In a high groundwater environment, the hydraulic head difference increases the potential for groundwater inflow into sewer systems, although there are several variables related to the age and condition of pipe, pipe material and joints, relative groundwater levels, soil properties, and the presence of tree roots that make quantification of this process difficult. Where sewers are located above the groundwater, leakage from sewers into groundwater is more likely.

> *“10% of metro Adelaide groundwater levels are controlled by the sewers”*

Leakage from water pipes in Melbourne and Perth is estimated at 8% and 7% respectively of the urban water supplied (Bureau of Meteorology, 2012). This leakage adds to the groundwater balance, increasing groundwater levels.

Evidenced	• Potable water used for irrigation adds to groundwater balance • Potable water leakage adds to groundwater balance
Agreed	• Gravity sewer systems remove water from groundwater balance in high groundwater environments
Contested	
Unknown	

Figure 9: Post development water resources: water and sewer state of knowledge

3.1.4 Water Dependent Ecosystems

Water dependent ecosystems (WDE) are reliant on specific water regimes to maintain their ecological values, including species composition and ecological processes, as well as their economic, social and cultural values. Where urban development occurs in proximity to water dependent ecosystems, it has the potential to alter the pre-development site water balance, and therefore the water dependent ecosystem water regime (e.g. water quantity, level, period of inundation) outside the range of normal seasonal/climatic variability.

Urban development has the potential to alter a site water balance via several means including:

- Increasing recharge to groundwater (e.g. localised infiltration as outlined in Chapter 3.1.7; loss of deep rooted vegetation; irrigation of POS and private household irrigation via reticulated/scheme water).
- Localised decline in pre-development groundwater levels (e.g. drawdown associated with local groundwater use for irrigation of POS and private household demand via bores).
- Decline in groundwater levels and recharge (e.g. through groundwater controls as outlined in Chapter 3.1.8).

Landform modification (e.g. cut to fill) also has the potential to alter the local water balance through alterations of the local catchment hydrology and therefore the water regime of water dependent ecosystems (Monk, 2006; Department of Water, 2010 b). The effect of this was modelled for selected wetlands in the Murray region (Dep0b) however it is uncertain if impacts have been measured in the field.

Urban development also has the potential to degrade water quality levels in water dependent ecosystems through the mobilisation of accumulated stored nutrients (Chapter 3.2.2), the introduction of pollutants (Chapter 3.2.1) and adverse impacts associated with acid sulfate soils (Chapter 3.2.3).

Evidenced	
Agreed	• Change in water balance impacts water dependent ecosystem water regime
Contested	• Horizontal separation required to reduce impacts on water dependent ecosystems
Unknown	• Impact of land form modification on water dependent ecosystems

Figure 10: Post development water resources: water dependant ecosystems state of knowledge

3.1.5 Impervious surface

Impervious surfaces can be divided into (Ball et al., 2016)

- Directly Connected Areas, defined as impervious areas (e.g. roofs and paved areas) which are directly connected to the drainage system – referred to as Directly Connected Impervious Areas (DCIA); and
- Indirectly Connected Areas, defined as:
    - Impervious areas which are not directly connected, runoff from which flows over pervious surfaces before reaching the drainage system (e.g. a roof that discharges onto a lawn) – referred to as Indirectly Connected Impervious Areas (ICIA); or
    - Pervious areas that interact with Indirectly Connected Impervious Areas, such as nature strips, garden areas next to paved patios, etc.

Urbanisation results in impervious surfaces replacing vegetated landscapes and this (Ball et al., 2016):

- Decreases the storage of water within soil profiles and on the ground surface and so increases the proportion of rain that runs off;
- Increases the velocity of overland flow; and
- Reduces the amount of rainfall that recharges groundwater.

Prior to current practices of runoff attenuation, urbanisation causes up to a 10-fold increase in peak flows of floods in the range of 1 to 4 Exceedances per Year (EY), with diminishing impacts on larger floods (Tholin & Keifer, 1959; McPherson, 1974; Hollis, 1975; Cordery, 1976; Ferguson & Suckling, 1990)

Initial losses for gauged, traditionally designed, urban catchments in Australia are concentrated near 0mm, while gauged rural Australian catchments have a mean initial loss of 32mm, as illustrated in Figure 11. Continuing losses for DCIA can be assumed to be zero (Ball et al., 2016). This is in contrast to double ring infiltrometer measurements of infiltration through impervious surfaces, which led the authors to conclude that within the study catchment, impervious surfaces infiltrate 21% of annual rainfall (Wiles & Sharp, 2008). However, the link between pavement fracture, hydraulic conductivity and catchment scale infiltration rates is weak, so the findings are discounted.

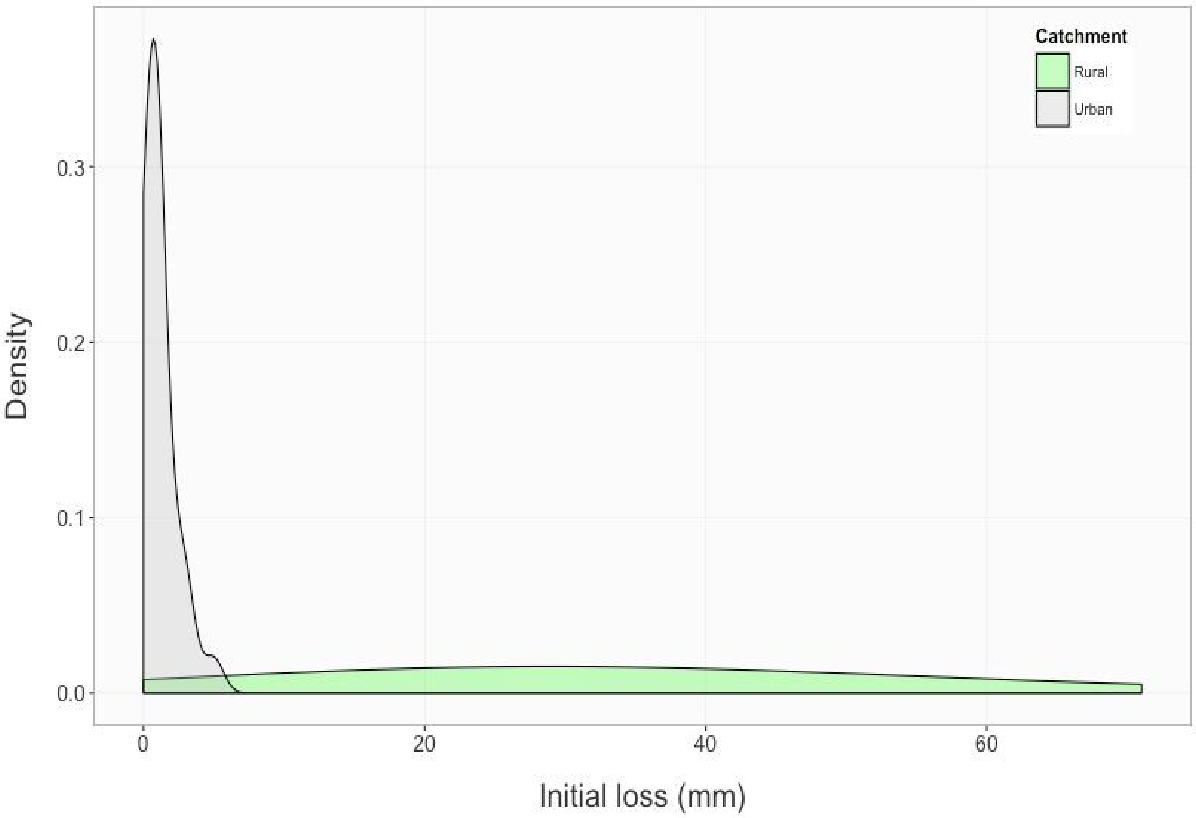


Figure 11: Comparison of Initial Loss in Urban and Rural Catchments (Ball et al., 2016)

Runoff rates and volumes from indirectly connected impervious surfaces are evidenced to lie between rural catchment rates and connected impervious urban catchment rates. Initial and continuing losses of 40% to 80% of recommended rural catchment losses are recommended by AR&R (Ball et al., 2016). AR&R does not publish rates for high groundwater environments.

In contemporary Australian urban developments, management measures such as on-site-detention and infiltration are implemented in the majority of cases. Thus, findings by Wills & Davies (2015) conclude that management measures and the use of indirectly connected impervious surfaces can produce zero surface water runoff at the lot scale. Specific factors such as whether the driveway slopes to the road or to the lot can make the difference between a connected and indirectly connected impervious catchment.

Impervious surfaces significantly reduce recharge and increase runoff, in the absence of other urbanisation factors such as changes in evapotranspiration and stormwater disposal methods. However, where groundwater levels (saturated zone) are at or very close to the surface, runoff rates are already high, so impervious surfaces are concluded to have a lower impact on runoff and recharge rates. There is a lack of literature specifically addressing surface water runoff rates in urban areas with high groundwater, particularly where groundwater causes seasonal inundation, and how this changes because of impervious surfaces.

Evidenced	• Impervious surface impacts on water balance in low groundwater environments
Agreed	
Contested	• Impervious surface impact on water balance in high groundwater environments • Runoff coefficients • Continuing losses in high groundwater environments
Unknown	

Figure 12: Post development water resources: impervious surfaces state of knowledge

3.1.6 Rainwater tanks

Rainwater tanks are known to reduce surface water runoff volumes by capturing roof runoff and storing the water for indoor or outdoor uses. Indoor use of rainwater diverts the water to the sewer system, reducing either runoff volumes or groundwater recharge volumes. Outdoor use of rainwater returns the water to the environment, either as runoff, infiltration or evapotranspiration, usually long after the rainfall event. Due to the variability of roof sizes, tank sizes, beneficial uses, and associated temporal demands, the potential beneficial impact of rainwater tanks on the groundwater balance is considered contested. Some researchers are strongly in favour of these devices while others are less so. It is safe to conclude that further work (primarily appropriately configured and monitored test cases) is required to quantify the benefits of rainwater tanks on groundwater levels in high groundwater environments.

Practitioners usually ignore the effects of stormflow attenuation offered by rainwater tanks, on the basis that they are assumed to be full prior to a stormflow event. This is documented in the Queensland Urban Drainage Manual (Department of Energy and Water Supply, 2013), however the literature to support this practice is lacking.

Evidenced	
Agreed	
Conteste	• Rainwater tanks impact on water balance
Unknown	• Rainwater tanks impact on stormflow

Figure 13: Post development water resources: rainwater tanks state of knowledge

3.1.7 Localised infiltration

Infiltration systems capture and store stormwater runoff prior to infiltrating into the soil. The storage can be located at the surface, such as in basins and swales, or underground, such as in tanks, trenches, and soakwells. In all systems, infiltration rates are a factor of soil permeability, hydraulic head, groundwater levels, antecedent moisture conditions and device specific aspects such as the dimensions of the soil-water interface and blockage considerations. Storage volumes are a factor of infiltration rates, starting water levels and the volume and shape of the storm hydrograph.

Infiltration is used to counteract the effects of impervious surfaces on recharge. It is evidenced that the use of infiltration devices causes local increases in groundwater levels (Machusick et al., 2011). The duration and extent of this mounding is dependent on the inflow hydrograph, infiltration device geometry and soil and groundwater conditions (Endreny & Collins, 2009). Practitioners have attempted to estimate such mounding using either (IPWEA, 2016):

- Steady state calculations, typically using variations of the Houghoudt equation
- Dynamic 1-dimensional models; or
- Detailed 2-dimensional or 3-dimensional models.
- Groundwater modelling, as discussed in Chapter 2.1.2.2.

If infiltration is likely to be a stormwater disposal method, practitioners usually undertake pre-development infiltration testing using one of the following methods:

- In-situ constant head or falling head permeameter tests.
- Laboratory constant head or falling head saturated hydraulic conductivity.
- Auger hole slug tests to estimate saturated hydraulic conductivity.
- Estimations of saturated hydraulic conductivity based on particle size distribution.

The difference between hydraulic conductivity and infiltration rates is an important distinction, with practitioners applying a variety of adjustments to hydraulic conductivity to estimate infiltration rates, such as the factors proposed by Argue (2005) and Coffey (2010).

Infiltration devices are at risk of blockage from debris and fines transported from runoff. Best practice is to provide pre-treatment prior to discharge into the infiltration device, particularly those with restricted access for maintenance. Open basins are frequently configured without pre-treatment, but with a maintenance schedule to remove sediment and debris build-up. Vegetation in basins, biofilters and other devices helps maintain the infiltration capacity and prevent clogging (Payne et al., 2014).

There are few published reports on the accrual rates and characteristics of blockage material from urban catchments, probably due to the wide range of contributing factors, such as vegetation density and type, topsoil characteristics, seasonal factors, gross pollutant generation rates and associated land uses, and frequency of street sweeping. There are anecdotal reports of infiltration device failures due to blockage.

A review of published and unpublished Urban Water Management Plans in Western Australia reveals inconsistency among practitioners on methods for estimating blockage. Cocks (2007) proposes a calculation based on a clogged base layer, while practitioners have applied reductions to the measured infiltration rate to account for blockage. Blockage processes and rates are therefore considered contested.

Evidenced	• Concentrated infiltration causes local increases in groundwater level
Agreed	
Contested	• Infiltration device infiltration rates • Infiltration device blockage rates
Unknown	

Figure 14: Post development water resources: infiltration measures state of knowledge

3.1.8 Importation of fill and groundwater controls

Fill is often imported in areas of high groundwater for the geotechnical reasons discussed in Chapter 4.3.1. Fill increases the available groundwater storage and head, although the ability of groundwater levels and volumes to increase depends on how the water balance changes post-development. Subject to fill properties and pore size, increased fill can also generate capillary rise. In the greater Perth region, fill is typically a granular material imported to site from an external borrow pit. Granular, non-hydrophobic, materials have a high infiltration potential, for both pervious precipitation losses and stormwater disposal. Subject to the method and configuration of stormwater disposal via infiltration, and changes to vegetation, importation of fill has the potential to increase recharge into superficial aquifers.

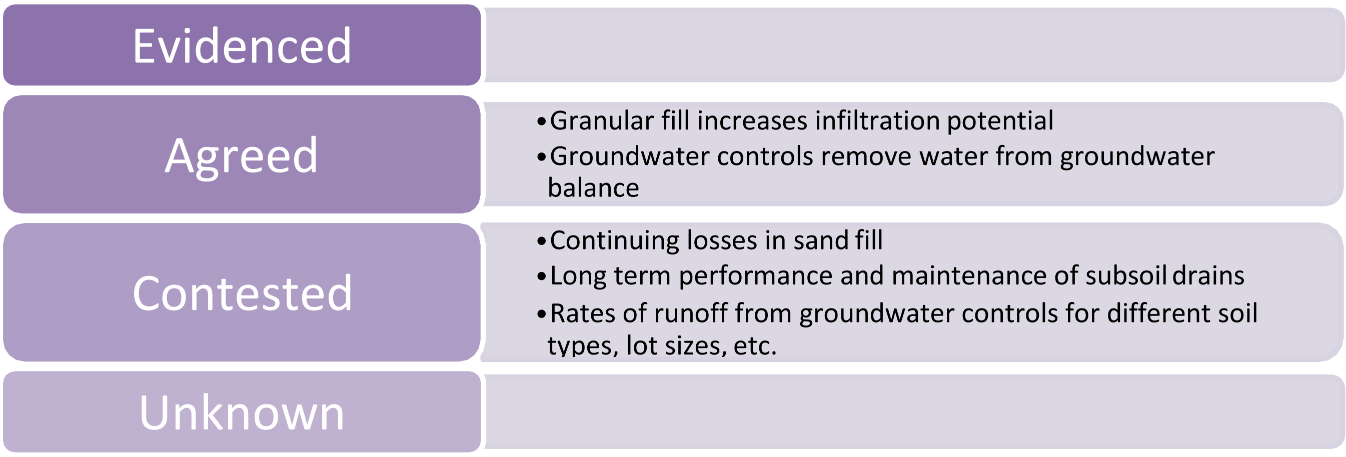
Groundwater controls such as subsoil drains, pumping systems and open drains lower or control groundwater levels by removing water from an aquifer and discharging it to surface water systems or making it available for other uses.

Regional and district scale estimates for subsoil drainage yields have been modelled within the Murray region of Western Australia. Catchment modelling (considering a range of climate and development scenarios) estimated between 12 and 23 GL of subsoil drainage water would be available for harvesting in the Murray Drainage Water Management Plan area (Hall et al. 2010b), with 2.1 to 3.5 GL within the Nambeelup Industrial area (Marillier 2012).

Groundwater levels fluctuate daily and seasonally as discussed in Chapter 2.1.2. When groundwater controls are constructed below the maximum recorded or predicted groundwater level, they act to limit or control groundwater fluctuations. When installed below the minimum recorded or predicted groundwater level, they lower groundwater levels.

Practitioners set the spacing and hydraulic capacity of subsoil drains, pumping spears, and open drains using the methods outlined in Chapter 4.3.3. Groundwater level fluctuations still occur during recharge events, however the change in the phreatic surface is significantly dampened by the controls. Groundwater controls increase surface water discharge and decrease aquifer storage.

Groundwater controls used in combination with imported fill will increase surface water discharge and decrease aquifer storage if the groundwater controls are installed below the pre-development maximum groundwater level but have negligible impact on aquifer storage if installed above the pre-development maximum groundwater level.



Evidenced	
Agreed	• Granular fill increases infiltration potential • Groundwater controls remove water from groundwater balance
Contested	• Continuing losses in sand fill • Long term performance and maintenance of subsoil drains • Rates of runoff from groundwater controls for different soil types, lot sizes, etc.
Unknown	

Figure 15: Post development water resources: imported fill and subsoil drainage state of knowledge

3.1.9 Managed Aquifer Recharge (MAR)

Managed aquifer recharge is the intentional recharge of water to suitable aquifers for either subsequent recovery and reuse or to achieve environmental benefits (Standards Australia, 2011) (Department of Water and Environmental Regulation, 2015). When used primarily for recovery, this technique is also often referred to as Aquifer Storage and Recovery (ASR) or Aquifer Storage Treatment and Recovery (ASTR).

Sources of water for MAR and ASR/ASTR include:

- Stormwater;
- Wastewater; and
- Subsoil drainage (less common).

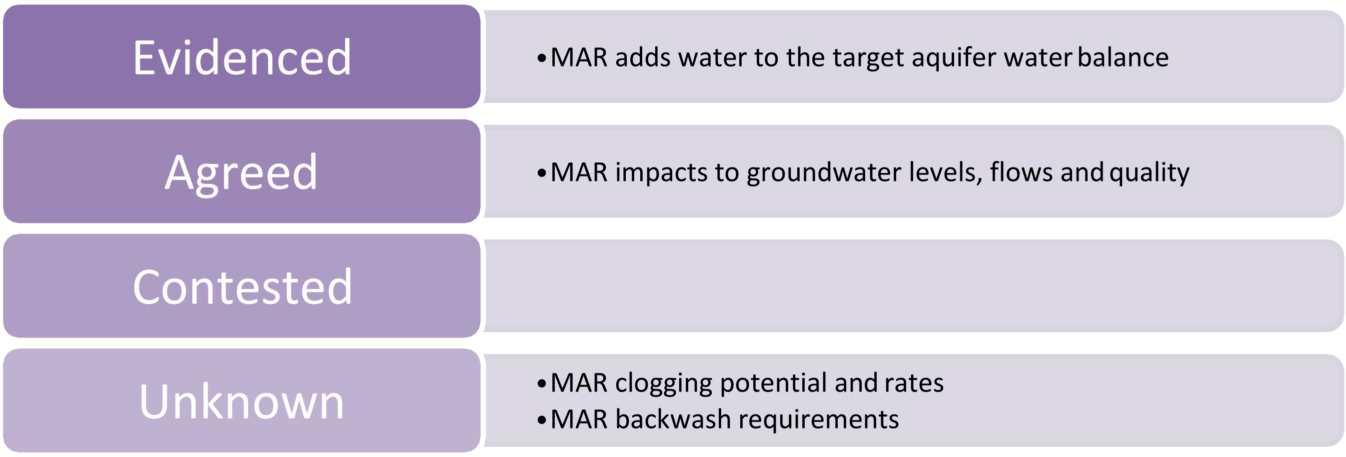
Water may be stored in superficial or deep aquifers. Subject to health, environmental and operation considerations, the quality of the source water, and the intended use of the water, a range of treatment measures may be required.

Once the source water flow rates and qualities are known, impacts on groundwater levels, flows and quality are generally agreed, and usually demonstrated through groundwater models.

There is a lack of literature on the water quality requirements for long term injector well operations. GHD (2016) suggested tertiary treatment is required to maintain feed water suspended solids to concentrations below 5 mg/L. Further, injector well backwash requirements are also unknown. Department of Water (2016) identified the risk of clogging due to chemical reactions.

In shallow groundwater environments, superficial aquifers can be used for both disposal of stormwater and extraction for beneficial use, such as irrigation, when the water quality is fit-for-purpose. Aquifer recharge of superficial aquifers is typically undertaken through infiltration and can also be via injection wells. The impacts of infiltration on groundwater levels and water balance is discussed in Chapter 3.1.5.

Methods employed by practitioners to quantify recharge rates are subject to the limitations of runoff predictions described in Chapter 3.1.5, together with the limitations of predicting the infiltration rate and the capacity of the aquifer to accept the recharge volume and rate. Following a slug test, the capacity of the aquifer is usually predicted using numerical models, with the limitations and uncertainties of these described in Chapter 2.1.2.3. Aquifer recovery rates are usually predicted using numerical and demand modelling.



Evidenced	• MAR adds water to the target aquifer water balance
Agreed	• MAR impacts to groundwater levels, flows and quality
Contested	
Unknown	• MAR clogging potential and rates • MAR backwash requirements

Figure 16: Post development water resources: MAR state of knowledge

3.2 Water Quality

3.2.1 Pollutant sources and transport mechanisms

Urbanisation introduces a range of new pollutant sources to a catchment and, when combined with higher runoff volumes, has the potential to increase pollutant loadings to surface and groundwater resources. The *Survey of nutrient inputs on the Swan Coastal Plain*, completed by the Department of Water in 2006, quantified nutrient inputs for urban residential land in metropolitan Perth and regional centres. The survey found that key nitrogen inputs were from gardens (70%), lawns (21%) and pets (9%), with similar findings for phosphorus with key inputs from gardens (81%), lawns (12%) and pets (7%). The survey further found that medium sized lots (601-730 m^2) had statistically greater nutrient inputs than both smaller and larger lots, with new homes applying significantly more nutrients than older homes (Kelsey et al., 2010).

Barron et al. (2010) identified key nutrient sources within urban catchments of the greater Perth region as wet and dry atmospheric deposition (e.g. rain and dry fallout), inorganic and organic fertilisers in private gardens and public open spaces, and vegetation decomposition.

These findings are supported by recent research of sources and mechanisms controlling nutrient transport in medium to high density residential catchments in Tampa Bay (Florida, USA) (Yang et al., 2017). The study concluded that 50% of nitrate was contributed by atmospheric deposition, 33% by fertilizer, and that primary phosphate sources were desorption from natural sediments and the degradation of organic materials (leaves, grass).

While overall contribution of nutrients from urbans areas can be small on a catchment basis, the intensity of fertilisation in urban areas creates far higher nutrient loads per unit area when compared to the agricultural land uses (such as cattle grazing, cropping or mixed grazing) that urban development typically displaces (Kelsey et al., 2010; Hall, 2010; Department of Water 2010a). It is suggested that reducing urban lot sizes will reduce householder fertiliser application and nutrient export on a lot basis (Bowman Bishaw Gorham, 2002) (Kelsey et al., 2010), with broad practitioner agreement. There is also potential for water quality to improve with a change in land use, particularly where the pre-development land use is an intensive animal industry (e.g. piggery or poultry farm) or contaminated site.

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 associated with urban development (i.e. at-source infiltration, leakage from sewer and mains drainage, septic tanks, fertilisation and the irrigation of private gardens and parks) (Ocampo, 2017). Within an urban environment, elevated recharge rates result in a higher water table, a decline in travel time from nutrient source to water table and shorter travel times in the unsaturated zone (Ocampo, 2017).

Unconfined aquifers are more vulnerable to contamination by urban development, particularly where their vadose zone is thin and their water table is shallow (Foster et al., 1998). Rising groundwater levels associated with urbanisation may mobilise nutrients in the soil profile making receiving water resources more vulnerable to contamination by human disturbances. Introduced fill has the potential to increase travel time to groundwater compared to pre-development conditions, however water movement through soils with high hydraulic conductivity or macropores can also result in short travel times that do not allow sufficient time for nutrient interaction with the soil matrix, constraining biologically mediated processes in the unsaturated zone. Where groundwater controls are installed these also reduce the travel time in the saturated zone, and therefore the potential for nutrient attenuation in the aquifer (Chapter 3.1.8).

Where groundwater abstraction results in major changes to the hydraulic head distribution within an aquifer, this may result in the reversal of groundwater flow directions, leading to potential seawater intrusion and water quality deterioration. The effect of saline intrusion is quasi-irreversible, with salinity diffused into pore-water taking decades or potentially longer to elute (Foster et al., 1998).

The impacts of urban development on post-development water quality is measured through water quality monitoring. In Western Australia, the recommended timeframe for post-development monitoring of each stage of subdivision (following completion of the last lot) is three full years depending on the level of risk (Department of Water, 2012). Actual post-development monitoring periods vary depending on local government handover requirements, resources (financial and personnel) as well as delays in completion of subdivision. With regard to post-development monitoring, local practitioners noted that:

- Three-year monitoring periods are insufficient to assess the impact of development and the nutrient retention efficacy of WSUD elements in areas of shallow groundwater.

- Better use of existing post-development monitoring data would assist in assessing modelling predictions of the impacts of urban development, as well as to evaluate if WSUD works in areas of high groundwater. This would require strategic coordination (the CRC could be well placed to help in this regard).

The limited availability of post-development water quality data in Western Australia has been acknowledged as a constraint to assessing the potential use of subsurface drainage water for MAR (Kretschmer et al., 2011).

3.2.2 Pre-development nutrients

Areas on the urban fringe that are landmarked for future urban development in the greater Perth region typically comprise rural or semi-rural properties and associated land uses. Pre-development water quality monitoring (Chapter 2.1.3.2) within these urban fringe areas frequently identifies high total nutrient concentrations (primarily total nitrogen) within the shallow soil profile. Barron et al. (2010) note that in areas of shallow groundwater, nutrient concentrations are frequently dominated by organic forms, with inorganic species typically removed through nutrient transformations (nitrification, denitrification) and plant uptake associated with higher groundwater residence times.

These high concentrations are often attributed to nutrient accumulation due to historic agricultural land use practices (referred to as legacy nutrients) however there is emerging research that indicates that the high pre-development nutrient concentrations may be linked to broader characteristics of the Swan Coastal Plain.

Petrone et al. (2009) examined dissolved organic nitrogen (DON) concentrations in ten major sub-catchments of the Swan Coastal Plain from a mix of forest, agricultural and urban land uses, finding high proportions of DON in both agricultural and urban catchments. This research is supported by a recent groundwater sampling survey of 108 groundwater bores distributed across diverse land use, soil and vegetation complexes of the Swan Coastal Plain. The survey found that in more than two-thirds of the 108 bores, the total nitrogen concentration was made up predominantly of DON (Sobia Ahmed pers. comm., PhD student University of Western Australia).

An alternate suggestion to the legacy nutrient terminology is that the broad spatial distribution of wetlands on the Swan Coastal Plain (existing and destroyed/degraded) and the disturbance of historic wetland sediment nutrient stores because of land development may be a cause of elevated pre-development nutrients. Wetlands comprise more than 25% of the land surface of the Swan Coastal Plain, playing an important role in nutrient cycling for connected groundwater and surface water resources, with wetland sediments considered to be a major long term store of nutrients.

Balla (1994) estimated that 80% of the wetlands of the Swan Coastal Plain have been lost or severely degraded. Many areas on the urban fringe of the Swan Coastal Plain are also areas of high groundwater, which historically comprised a series of shallow wetlands occurring as seasonally waterlogged flats or basins. Further research is required to assess the link between historic land use practices, historic wetland distributions and elevated pre-development groundwater nutrient concentrations. The source of elevated pre-development nutrients is therefore considered contested.

> *"It would be good if we could move past the terminology of legacy nutrients….reference to pre-development nutrients also infers a link to land use, whereas it's just the groundwater conditions"*

Regardless of the source of high nutrient concentrations in pre-development groundwater, the urban fringe of metropolitan Perth predominantly comprises areas of high groundwater, which may once have featured seasonally inundated wetlands - but now consist of rural or semi-rural land uses. As a result, there are a number of potential future urban development sites within areas of high groundwater that are likely subject to elevated pre-development nutrient conditions. While uncertainty about the risk that organic nutrients pose to receiving environments has been reported (Barron et al., 2010), research has identified labile DON concentrations greater than dissolved inorganic nitrogen concentrations in major sub-catchments of the Swan Coastal Plain, highlighting its importance as a readily available source of nitrogen for in-stream and estuarine primary production in urbanising coastal catchments (Petrone et al., 2009).

The dominance of organic forms of nutrients is identified as a concern for design of WSUD elements, which are typically designed to target inorganic and particulate forms of nutrients. In particular, unlined WSUD elements do not provide redox conditions and residence times to allow nutrient transformation to occur.

In shallow groundwater environments, it is generally agreed that improvement of site drainage through localised infiltration (Chapter 3.1.7) and groundwater controls (Chapter 3.1.8) have the potential to mobilise nutrients by reducing travel times and opportunities for nutrient transformation. De-watering activities associated with development may also mobilise pre-development nutrients.

3.2.3 Acid Sulfate Soils

Acid sulfate soils form when soils naturally containing sulfide minerals are oxidised, forming sulfuric acid. Oxidation can occur when soils are exposed to the air following excavation or draining, or by the lowering of water table levels. In areas of high groundwater, urban development activities which may disturb acid sulfate soils include estate and underground infrastructure development (including the installation of sewage pipework and pump station infrastructure), construction at depths at and beyond the standing water table, developments involving disturbance to wetlands, lakes and waterways, dewatering operations (including those of minor scale), compacting saturated soils or sediments, drainage works, groundwater pumping, artificial deepening of lakes, waterways and wetlands, de-sludging or otherwise cleaning open drains, displacing previously saturated sediment resulting in groundwater extrusion and aeration of ASS (Department of Environment Regulation, 2015).

A number of practitioners also noted that underground structures, such as retaining walls, may also impede the natural flow of groundwater resulting in increased upstream water levels and decreased downstream water levels - leading to the potential exposure of acid sulfate soils.

Resulting acid can release other substances, including heavy metals, from the soil and into the surrounding environment leading to range of environmental consequences including (Degens, 2009); (Department of Water, 2012); (Queensland Government, 2016):

- Soil, waterway and wetland acidification.
- Reduction of soil stability and fertility.
- Degradation of wetlands, water dependent ecosystems and ecosystem services.
- Loss of habitat ecosystem complexity and biodiversity through impacts such as fish kills, harm to other aquatic organisms and vegetation deaths.

Acid sulfate soils are widespread around coastal areas of Australia. Prior to 2000, acid sulfate soils were not identified as a significant issue in the greater Perth region (Water and Rivers Commission and Department of Environmental Protection, 2002; Degens, 2009). Subsequent acid sulfate soil planning policy development for Western Australia identified particular areas of concern, including areas with high water tables on the Swan Coastal Plain (areas where the highest known water table level is within three metres of the surface) (Department of Water, 2012).

Acid sulfate soil risk mapping of the Swan Coastal Plain (and other parts of Australia) is required by practitioners as a screening tool to assess the level of risk of acid sulfate soils for broad scale planning purposes. Further site- specific investigations are then required to determine if acid sulfate soils are actually present and whether they may pose a risk to the environment.

For areas of particular concern of acid sulfate soils occurrence, detailed site investigations and the preparation of acid sulfate soil management plans may be required as part of special planning controls or approvals in relation to development area or site works. There are currently no requirements for detailed site investigations and acid sulfate soil management plans for the purpose of long term management of groundwater levels in areas of high risk of acid sulfate soils.

Evidenced	•Urban development may disturb acid sulfate soils •Acid sulfate soils impact receiving ecosystems
Agreed	•Acid sulfate soil risk mapping used for broadscale planning •Areas of Swan Coastal Plain with high groundwater (<3 m) have high risk of acid sulfate soils •Detailed site investigations completed for site works where risk of acid sulfate soils is high •Underground structures may expose acid sulfate soils
Contested	
Unknown	

Figure 17: Post development water resources: acid sulfate soils state of knowledge

3.3 Management Measures

3.3.1 Measures to maintain pre-development water balance

Decreases in groundwater recharge and subsequent increases in surface water runoff are frequently managed through the use of infiltration measures, including:

- Surface infiltration devices such as basins or swales.
- Underground infiltration devices such as tanks and soakwells.
- Disconnecting impervious surface or creating ICIA's.

As discussed in Chapter 3.1.7, the effectiveness of such devices is subject to a number of variables and uncertainties related to runoff generation and aquifer characteristics.

3.3.2 Vegetation to control groundwater levels

Vegetation used to control groundwater levels is well researched in agricultural areas for salinity control. In the presence of trees, Carter et al. (2010) report that a plantation of trees can be more effective than a pump in maintaining a deep water table and thereby controlling waterlogging and associated salinity. While there is sufficient evidence on the effect of plantations and forests on groundwater levels, there is less evidence in urban settings, where there is a variety of species, and complicated spatial land use distributions associated with roads, public open space and gardens. Further discussion is provided in Chapter 4.3.8.

3.3.3 Water Dependant Ecosystems water regime

Maintenance of the pre-development water balance is important to protect the ecological values and ecosystem functions of water dependent ecosystems (WDE). Where a high value, water dependent, ecosystem may be impacted by a change in land use to urban development, practitioners are generally required to identify the level of risk to WDEs.

For urban development within Western Australia, practitioners are required to maintain or improve pre- development conditions, or where changes to pre-development conditions will occur they must demonstrate that the changes will not result in unacceptable adverse effects on WDEs (Department of Water, 2013b). For WDEs with defined high ecological values, the sensitivity of the ecosystem to changes in site water balance may need to be defined through site specific assessments, and determinations of the ecological water requirements or site water balance.

Western Australian planning guidance notes that proposals for planning scheme amendment for urban use should include an assessment of approaches to form land modification (e.g. cut to fill, filling) that reduce impacts on WDEs (Western Australian Planning Commission, 2008).

Adaptive management of urban drainage may be implemented to manage or improve environmental outcomes. For example, drainage infrastructure constructed in the 1990s to enable urban development of the groundwater constrained South Jandakot region of Perth diverted drainage water away from the Beeliar wetlands. Following rainfall decline in the southwest of Australia and reduced wetland water levels, key stakeholders initiated a water supplementation program to protect the Ramsar listed Thomsons Lake, supported by an appropriate monitoring regime (Department of Conservation and Land Management, 2006).

Buffers may be used to minimise risks associated with human disturbance in the vicinity of a WDE. A hydrological buffer means that potential impacts to water regimes due to drainage design and groundwater controls are not permitted within the buffer zone, although development can occur within the buffer (Department of Water, 2010b). Ecological buffers generally mean that no disturbance or development is allowed within the buffer zone.

Special planning controls or conditions may also accompany local planning policy where planning applications may present a risk to a WDE or receiving waterbody. For example, the City of Swan Local Planning Scheme 17 identifies special conditions in response to the environmental attributes and values of different development areas. For the Albion development zone (including the potential Brabham development area), the Special Use conditions specify the preparation of a range of management plans to protect significant environmental features, including Wetland Management Plans, Bushland Management Plans and Threatened Ecological Community Management Plans.

Internationally, the Florida Springs Task Force (established in 1999) developed a range of strategies and action steps to protect and restore Florida’s springs. These included outreach (community education), information (monitoring programs, research), management (coordinated land use planning, best management practices, acquisition of land), regulation (legal protection of water sources and values) and funding strategies (Florida Springs Task Force, 2000). Action steps to achieve the strategies are reported to include the development of protocols for spring protection during revision of land use zoning, the identification of vulnerable spring recharge areas and provision of enhanced protection of groundwater aquifers under existing Florida legislature including Strategic Regional Policy Plans.

3.3.4 Measures to capture or treat pollutants

An important aspect of water sensitive urban design (WSUD) is applying best practice management measures to capture and treat pollutants. Best practice management measures include structural and non-structural controls, with practitioners typically implementing these in a treatment train targeted at the pollutants of concern at different stages of the design (Figure 20).

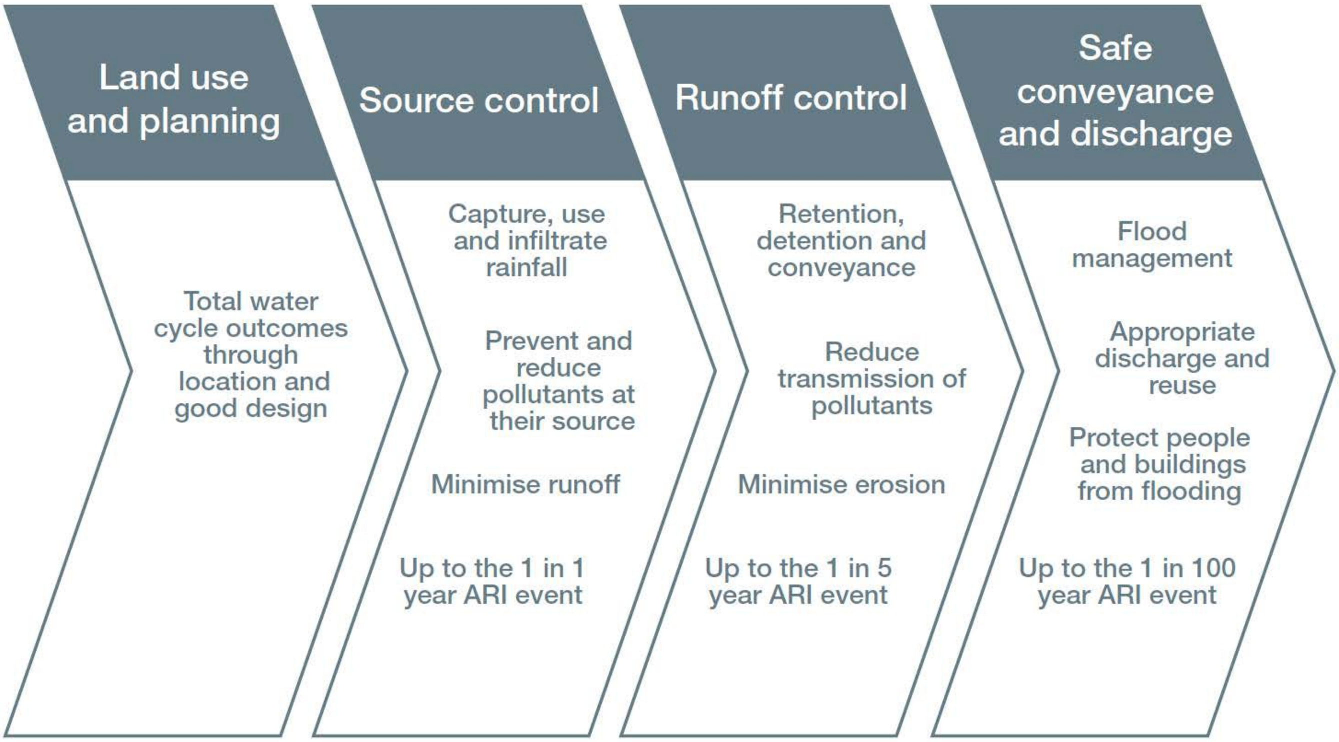


Figure 18: Water sensitive urban design treatment train (Department of Water, 2011a)

Structural controls are engineered devices implemented to manage stormwater drainage quality and quantity, while non-structural controls are institutional practices designed to prevent or minimise pollutants from entering stormwater drainage (Department of Water, 2009b). Source control is identified as the most effective means of reducing pollutant export from a development area, based on the premise that it is easier to control pollution at the source rather than treating it within the drainage system (ARMCANZ and ANZECC, 2000).

Barron et al. (2010) reviewed the most effective WSUD elements to target nutrient forms in Perth urban drains that intercept shallow groundwater. They note that there are limited options for in-situ groundwater treatment and organic nutrient forms, and while no single WSUD element will treat all nutrient forms, vegetated elements are more effective in nutrient control than non-vegetated elements. Key recommendations were for non-structural controls that prevent nutrient input (fertiliser control, soil amendment) and structural water quality control measures (lining of infiltration elements with soil amendment, bioretention systems, drain maintenance) that remove nutrients from the conveyed waters.

The Urban Nutrient Decision Outcomes (UNDO) tool (Department of Water, 2016) was developed to evaluate the nutrient reductions that could be achieved by the conceptual design of structural WSUD elements for urban development in Western Australia. It is intended to be used at the planning stage of development to assist developers to select best practice WSUD elements based on nutrient export rates and structural WSUD element efficacy based on local data (Department of Water, 2016). UNDO does not consider pre-development (or legacy nutrients), identifying that elevated nutrient concentrations in groundwater may need to be managed concurrently (Department of Water, 2016). Elsewhere in Australia, the MUSIC modelling tool (eWater, 2013) is widely used for such purposes.

A key regulatory concern is the lack of validation of the efficacy of structural controls, such as bioretention WSUD elements, within high groundwater environments (Ocampo et al., 2017 and Hunt et al., 2017). Practitioners are also uncertain of the effectiveness of WSUD elements in areas of high groundwater, with some Western Australian practitioners noting that the water quality performance of bioretention elements was reduced due to interaction with groundwater, while others noted that with shallow groundwater being the predominant nutrient source, that unlined WSUD elements were designed to enable treatment of intercepted groundwater. Guidelines have recently been prepared to assist the development of monitoring programs to assess the performance of WSUD elements in areas of high groundwater (Hunt et al., 2017).

Ocampo et al. (2017) assessed the performance of two biofilters (a raingarden and a bioretention basin) in areas that experience seasonally high groundwater on the Swan Coastal Plain, finding that both the hydrological performance and nutrient attenuation were impacted. Based on the key findings, the study recommended that a treatment train approach should be applied across a catchment that provides a range of redox conditions (i.e. alternating surface and subsurface elements), is designed to extend subsurface travel times through filter media and considers placement of biofilters spatially across the catchment (including upland areas as a means of source control) to increase infiltration, subsurface travel times and nutrient attenuation. The importance of dissolved oxygen dynamics/redox conditions on nitrogen concentrations in shallow groundwater beneath infiltration type WSUD elements (trench, basin, bioretention, raingarden and swale) has also been identified in several local (Appleyard, 1993) and international studies (Fischer et al., 2003; Datry et al., 2004; O'Reilly et al., 2012).

Over the last two decades, there has been a concerted effort to restore urban streams around the world, particularly in new urban developments. These works aim 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 been undertaken for nutrient removal purposes. The nutrient retention effectiveness of these engineered systems, particularly in areas with high groundwater levels, remains unclear due to changes in the complex subsurface hydrology under urbanisation that in most cases changes the depth to the water table and affects groundwater quality (Groffman et al., 2002).

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. Short travel times can result from water moving through soils with high hydraulic conductivity or macropores, and do not allow sufficient time for nutrient interaction with the soil matrix and may constrain biologically mediated processes in the unsaturated zone. This can also lead to shallow groundwater contamination.

While groundwater interception/contribution to WSUD elements is acknowledged among practitioners, the design of these systems is typically targeted at inorganic nutrient species. The dominance of organic nutrient forms in some high groundwater areas (Chapter 3.2.2) may compromise the nutrient removal performance of a typical bioretention WSUD element designed to treat inorganic nutrient species (Barron et al., 2010; Ocampo et al., 2013).

Key practitioner comments around the design of WSUD elements included:

- Maintaining a balance between nutrient adsorption of soil amendment materials and required permeability of the media (e.g. fill or infiltration media) used in WSUD elements is an issue.
- Flat topography in areas of shallow groundwater is a key constraint to the effective design of biofilter WSUD elements.
- National guidelines (Payne et al., 2015) are used to inform biofilter design where there is sufficient head, however many biofilters installed in areas of shallow groundwater do not have adequate clearance from groundwater to provide appropriate treatment.
- Economics are typically a key driver in biofilter design. Where specified biofilter media (e.g. FAWB, 2009) is used, this has cost implications which may impact other parts of the development (e.g. POS amenity).
- Some local practitioners have a preference for the design of unlined bioretention basins underlain with subsoil drainage.
- WSUD element maintenance by local government is an emerging issue. Operations and maintenance issues can constrain implementation.
- Better standards of construction and a more consistent language around what constitutes a biofilter is required.
- One interstate practitioner noted that requirements for WSUD elements for small developments (>6 lots) have created piecemeal devices with associated regional management issues, with another noting that large projects can be more cost-effective than small projects.
- Nationally the integration of coastal tidal exchange into WSUD treatment trains is encouraged in some areas, however practitioners have noted vegetation deaths due to tidal inundation.

There was strong agreement from practitioners in Western Australia that the design of WSUD elements is typically driven by local government maintenance requirements or particular design preferences, and not specific water quality outcomes. Concern was expressed that in some instances, the WSUD element design specified in the urban water management plan supporting a subdivision was different to the final constructed element due to subsequent changes to the design during construction at the request of local government. Further, it was noted that the treatment media or soil amendments specified for use in accordance with guidelines e.g. (FAWB, 2009) may not be installed during construction/landscaping due to local availability or cost implications.

Design of WSUD elements is typically driven by local government maintenance requirements or particular design preference and not water quality outcomes.

Soil amendments are typically used to treat pollutants at the source, through the improvement of a soil or media's nutrient retention ability. Work completed by the Chemical Centre and Department of Agriculture in the 1980s and 1990s identified that a lack of iron/aluminium hydroxide minerals in the sandy soils of the Swan Coastal Plain was largely responsible for their poor phosphate adsorption (Allen et al. 2001). After this research, many local governments and approving authorities recommended that sandy soils be amended or blended with clays or loams to improve their phosphate adsorption capacity (i.e. phosphorus retention index (PRI), (Allen & Jeffery, 1991).

Some examples of soil amendment materials for phosphate retention that are used in Western Australia include sands high in iron (e.g. yellow Spearwood sands), calcareous or lime-rich sands (e.g. Karrakatta soils), brown loams (foothill slope soils which may be blended with sands), and Iron Man Gypsum (IMG), previously known as neutralised used acid (Wendling & Douglas, 2009; Wendling et al. 2009; Wendling et al. 2010) identified its potential use for removing dissolved phosphorus and organic nitrogen in surface water, and has been demonstrated to achieve similar improvements in water quality in trials under field conditions (Douglas Partners, 2012; Degens & Shackleton, 2016). The longest monitored trial to date has shown reductions in phosphate and dissolved organic nitrogen concentrations sustained over more than 4 years (Degens, 2018). Importation of sand fill to provide groundwater separation is also identified as a water quality buffer, with the fill providing some adsorption of phosphorus. Few soil amendment options for targeting nitrogen species are reported.

Nationally, Moreton Bay Regional Council requires testing of all biofilter media to ensure it complies with required nutrient retention and permeability specifications, a practice which is not consistent across all local governments. This is identified as a subject of contention as there are limited market providers, resulting in potential monopoly pricing.

Groundwater controls installed at or close to the pre-development maximum groundwater level are generally considered to minimise the drainage of shallow groundwater and associated pre-development nutrients to a brief period corresponding with seasonal high groundwater tables, reducing the risk to receiving water sources and sensitive ecosystems. However, this is contested due to the potential for increased recharge following urban development and requires further investigation.

Where groundwater is controlled at a site, regulatory guidance typically recommends the installation of bioretention WSUD elements with soil amendment at subsoil drain outlets to provide water quality treatment prior to conveyance from the site. Practitioners noted that the integration of water quality treatment where groundwater is controlled is difficult due to the generally flat topography of these areas. More recent approaches have recommended lining of subsoil drainage with a soil amendment targeted at the pollutant of concern (Degens et al., 2016; The Civil Group, 2015; Calibre, 2017), particularly where groundwater control is proposed within an area with pre-existing water quality concerns (e.g. elevated pre-development nutrients).

Planning controls are a key non-structural practice to manage the risk of pollutants in areas of high groundwater. It was noted that state planning policies for urban development should take a risk-based approach with regard to management requirements depending on the local conditions. One interstate practitioner noted that the concept of

Neutral or Beneficial Impact (NORBI) was a key management requirement for any development that may affect key groundwater resources.

While it is agreed that non-structural practices are key elements for the management of nutrient and pollutants associated with urban development, the effectiveness of community education and awareness programs to achieve behaviour changes is uncertain. Engagement fatigue is identified as a potential issue and there is uncertainty regarding uptake rate and effectiveness of programs. However, driving attitudinal change is identified as an ongoing process with one practitioner noting:

> *"… you can't do it for a while then drop it without the benefits deteriorating. "*

Policy provisions implemented by Local Governments may provide a more effective means of delivering outcomes through Environmental Planning Policy, Public Open Space and Landscaping Policy, or requirement for site specific Nutrient Management Plans for areas of concern.

Provision of residential landscaping packages by developers can ensure that appropriate soil amendments are used to target residential gardens, or alternatively they could include native gardens and minimum lawn allocation to reduce nutrient application requirements for gardens and lawns. Based on the UNDO tool Residential Factsheet, the nutrient input rates for native gardens in small residential lots (400-500 m2) is 28 kg/ha/year for nitrogen and 0.9 kg/ha/year for phosphorus, compared to 384 kg/ha/year and 115 kg/ha/year for traditional garden areas (Department of Water, 2016).

It has been suggested that reducing urban lot sizes, and consequently the area of garden established within each lot, will reduce householder fertiliser application and nutrient export on a lot basis (Bowman Bishaw Gorham, 2002; Kelsey et al., 2010). This has broad agreement from practitioners, with comments including:

> *"The denser the urban development (smaller lots, less gardens)...better from a water quality perspective as there is less opportunity for fertilisation"*

3.3.5 Acid sulfate soils

As noted in Chapter 3.2.3 detailed site investigations and preparation of acid sulfate soil management plans may be required to manage risks in areas of particular concern of acid sulfate soils occurrence. These requirements typically relate only in relation to development proposals or site works and there is currently no requirement for detailed site investigations and acid sulfate soil management plans for the purpose of long term management of groundwater levels in areas of high risk of acid sulfate soils.

Special planning controls or conditions may also accompany local planning policy in response to the environmental attributes and values of different development areas (as per Chapter 3.3.3). Examples include the City of Swan Local Planning Scheme 17 Special Use conditions for the Albion development area (including the proposed Brabham development). Avoiding the disturbance of acid sulfate soils through the preservation of the soil structure and hydrologic regime is the preferred strategy to minimise potential impacts (Department of Water, 2012), however this may compromise developable land. Where acid sulfate soils are identified, detailed site investigations should be completed to determine the extent of affected land and the most appropriate management strategy for a site.

Alternative management options may include:

- Strategic reburial
- Stable containment

- Direct neutralisation.

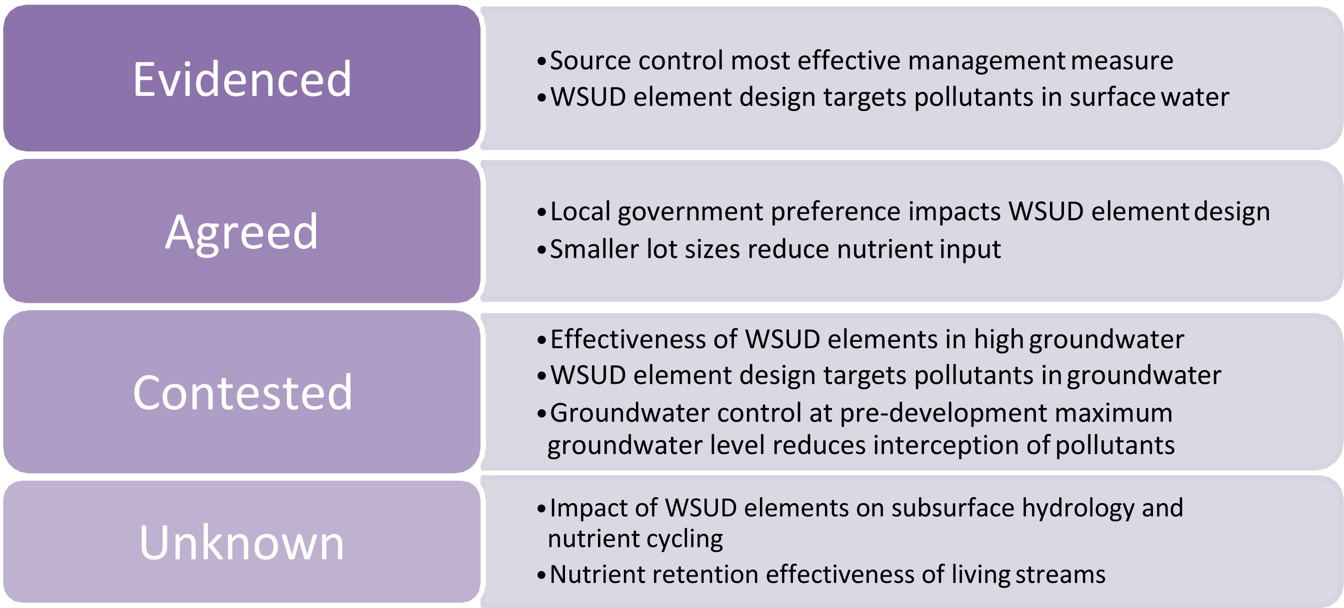


Figure 19: Post development water resources: management measures state of knowledge

4 Impacts of high groundwater on infrastructure

4.1 Water balance

4.1.1 Buildings

Groundwater table rise may cause several impacts on infrastructure and buildings. Among those are the following (Abu-Rizaiza, 1999):

- A reduction of soil bearing capacities. This may result in considerable differential settlement in buildings and consequently cracks in columns, beams, and walls;
- When parts of buildings or bridges lie below the groundwater table or even within its capillary fringe, the strength of concrete and masonry may be impaired due to exposure to polluted groundwater. During wet periods, the structures are exposed to moisture, while during dry periods evaporation creates salt crystals that can exert pressure within the pores of the masonry units or the joining mortar. The salt crystals dissolve during humid periods and recrystallize upon subsequent drying. Repeated cycles of wetting and drying can eventually cause cracking and concrete disintegration.

Lowering of initial groundwater levels may cause subsidence of various scales that may affect utility pipes, roads and basements. This effect can take place not only during dewatering and construction but also in the long term, as a result of the construction of underground structures which can act as drains or barriers (Marinos et al., 1998).

4.1.2 Roads

When a road is constructed below the groundwater level, the bath structures and the pavements are the two most significant road structures that may be influenced by the design water level (Dawson, 2008). Design of these structures requires the determination of maximum groundwater table (or Design Groundwater Levels).

4.1.2.1 *Bath Structures*

Bath structures are concrete structures used to protect pavement and infrastructure where road design intercepts natural groundwater levels and environmental consideration prevent permanent lowering of groundwater. Groundwater level influences the length and height of the side retaining walls to the bath structures and in turn the height of earth batters. The risk of the water level exceeding the design water level may lead to water seeping from the earth batters and overtopping the walls - leading to immersion of the pavement.

The bath structures will need to be reinforced to control leakage which may occur in the event of a failure of the waterproof membrane. Design water levels will impact the height of the structures that require reinforcement.

4.1.2.2 *Pavement Structures*

The immersion of asphalt pavement in water during even short periods of seasonal groundwater level rise can lead to saturation, risk of bitumen stripping (loss of bitumen from the asphalt mix), consequent loss of strength and eventual pavement failure. As the stripping is likely to occur in the lower layers of the pavement, total reconstruction would be required to rectify the problem.

According to McRobert and Foley (1999) around 230 km of main roads and many more kilometres of local roads in the southwest of Western Australia were damaged because seasonal or long term groundwater level rise was not correctly accounted for in the road design.

Alternative pavements such as concrete and water bound macadam pavements can tolerate immersion, but at a considerably higher cost than traditional pavements. The decision of whether to use traditional or alternative pavements is largely based on if water levels are expected to create a risk of pavement saturation.

4.1.3 Utilities

During the construction of utilities, open trenches that intercept groundwater require dewatering. Without management measures, dewatering has the potential to generate numerous impacts both locally and to the receiving environment.

Underground gas, water, electricity and telecommunications infrastructure is largely inconsequential to high groundwater environments during the operational phase, unless excavations are required. Above ground electrical infrastructure (e.g. service pillars, LV frames, HV switchgear) usually requires a 300 mm to 500 mm freeboard above the 1:100 Annual Exceedance Probability (AEP) surface water flood level, and a 500 mm vertical separation to groundwater in the case of substations (Western Power, 2013).

As discussed in Chapter 3.1.3, high groundwater has the potential to infiltrate into sewer systems, increasing loads on sewage treatment plants.

Evidenced	• High groundwater levels reduce structural bearing capacity and can weaken and damage pavements
Agreed	• High groundwater impacts utility construction methods • High groundwater has negligible impact on most utilities in the long term • High groundwater can infiltrate into sewer systems • High groundwater requires special measures for electrical substations
Contested	
Unknown	

Figure 20: Post development infrastructure: water balance state of knowledge

4.2 Water Quality

Australian Standard AS2159 identifies that site investigations should test soil and groundwater for aggressive agents that may impact the durability of footings and foundations. The aggressive agents that are targeted include sulfate, pH and chloride.

4.2.1 Acid Sulfate Soils

Disturbance of acid sulfate soils, and the subsequent potential for soil and water acidification, can lead to a range of infrastructure impacts (Queensland Government, 2016); (Department of Water, 2012):

- Risk of long term infrastructure damage (e.g. culverts, bridge structures, underground structures) through acidic water corroding concrete and steel structures.
- Blistering and cracking of asphalt surfaces, damaging roads and foundations.
- Blocking of reticulation systems, small pipe systems and subsoil drains with iron precipitates and calcium salts.
- Costs associated with maintenance of affected infrastructure.

Areas with high water tables on the Swan Coastal Plain are identified as of particular concern for acid sulfate soils within Western Australia (Department of Water, 2012). Therefore, the management of proposed urban development in these areas requires detailed investigations to determine appropriate management strategies.

4.2.3 Salinity

Where high salt concentrations are identified in the soil profile under pre-development conditions, there is potential for urban salinity hazard to develop because of rising groundwater. Land development and land use practices in an urban environment that have the potential to contribute to urban salinity include the removal of deep rooted vegetation, changes to landform that alter site drainage, siting of infrastructure and services (e.g. retaining walls), changes to local recharge patterns and the importation of salt in water applied at a site (e.g. with grey water).

The risk of urban salinity may also result from capillary action of soils drawing salt to the surface, and as such the importation of clean fill over saline areas may not be an effective long term solution (Cement, Concrete and Aggregates Australia, 2005).

Localised dryland salinity is reported to be evident on the Swan Coastal Plain wherever a shallow water table coincides with clay-dominated sediments (Smith et al., 2002).

As noted previously (Chapter 3.2.1), potential seawater intrusion and water quality deterioration may occur where groundwater abstraction results in major changes to the hydraulic head distribution within an aquifer. The effect of saline intrusion is quasi-irreversible, with salinity diffused into pore-water taking decades or longer to elute (Foster et al., 1998).

Key impacts associated with urban salinity include financial costs from damage to, and shortened lifespan, of buildings and other concrete structures (retaining walls, paths, driveways), as well as additional maintenance of underground infrastructure and services (stormwater and sewerage systems, underground gas and power) and other infrastructure such as roads, bridges, railways, power poles and water storages. Salinity impact on infrastructure can occur as a result of both chemical and physical damage, with the extent of the impact dependent on the concentrations and particular types of salts present, and the composition of the building material (Department of Environment and Climate Change NSW, 2008).

Within Western Australia, the impact of urban salinity has largely been confined to rural townsites and associated infrastructure, with the State Government implementing a program to manage townsite salinity in 1997 (Rural Towns Program) involving 38 towns and communities during the mid-2000s (Commonwealth of Australia, 2006). Impacts of salinity on road assets in southwestern Western Australia have been reported (McRobert et al., 1999). Dames and Moore (2001) report that the damage to housing from townsite salinity was relative to both the depth of the water table and the type of construction, with no economic costs incurred with water table depths of greater than 1.5m. Where saline water tables were within 0.5m of the ground surface, brick houses were reported to have escalated maintenance and drainage repair costs when compared to houses elevated on stumps (Dames and Moore, 2001).

4.2.3 Nitrate

In locations where there is infiltration of water with high nitrate concentrations coincident with poorly buffered soils and shallow aquifers, there is the potential for nitrate reduction and coupled oxidation of sulfides (Department of Water, 2011b). This may result in acidification of the shallow aquifer and associated problems with metal mobilisation and damage to buried infrastructure etc (Chapter 3.2.3).

Evidenced	•Acid sulfate soils and salinity impact on infrastructure
Agree	•Detailed site investigations completed to quantify risk from site works where risk of acid sulfate soils is high •High groundwater areas (< 3 m) of Swan Coastal Plain have high risk of acid sulfate soils •Potential for urban salinity to develop where high salt concentrations in soil profile or groundwater •Fill not an effective solution to salinity due to capillary action •Some groundwater has high NOx potential
Contested	
Unknown	

Figure 21: Post development infrastructure: water quality state of knowledge

4.3 Management measures

4.3.1 Buildings

Management measures to deal with high groundwater are a requirement of the Building Code of Australia (BCA), and are addressed by Australian Standards. The BCA (2016) specifies that a building is to:

- be constructed to provide resistance to moisture from the outside and moisture rising from the ground
- perform adequately under all reasonably expected design actions; and
- withstand extreme or frequently repeated design action, where groundwater and rainwater are specified actions.

Australian Standard AS 2870-2011 (SAI 2011) establishes performance requirements and specific designs for common foundation conditions as well as providing guidance on the design of footing systems using engineering principles. Sites are classified into one of seven categories, ranging from Class A “Little or no ground movement” to Class E “Extremely reactive”. In greater Perth markets, Class A sites attract a higher sale price and are preferred for slab-on-ground footings. In areas of high groundwater in the greater Perth region, unmodified sites do not achieve Class A classification without either the importation of fill, the provision of groundwater controls, or a combination of both.

4.3.2 Imported fill

Fill material is a management measure used to:

- Meet BCA requirements using simple foundations.
- Achieve certain AS2870 site classifications.
- Protect road pavements.
- Achieve local requirements for on-site disposal of stormwater (e.g. soakwells).
- Achieve local requirements for separation distances.

- Avoid waterlogging of soils, particularly in POS (Chapter 0).
- Achieve minimum grades for surface water drainage.

Free draining fill material is required to achieve many of the above objectives, however practitioners report combinations of poorer quality material placed at depth, overlaid by free draining material, can still function efficiently.

4.3.3 Groundwater controls

Groundwater controls are a management measure used to lower or control groundwater levels, to achieve many of the same objectives as imported fill. Groundwater can be drained using either:

- Subsoil drains, such as:
    - Perforated pipes surrounded by aggregate and geotextile, also known as a French drain.
    - Curtain drains, with or without a perforated pipe, finishing at or near surface.
- Open drains, such as swales, channels and ditches.
- Pumping systems, typically using a network of spears, sumps, or other options that are connected to a subsoil drainage network.

Practitioners in Australia provided anecdotal evidence that pumping systems are not used in Australia, except as a temporary measure or for basement sump drainage. They also report that subsoil drainage has been known to fail through blockage or soil variability, however subsoil drains and open drains are a preferred method in Australia. United States practitioners also report using subsoil drainage and open drainage, and pumping, for similar purposes.

4.3.4 Managed Aquifer Recharge

MAR is reported by practitioners in Australia as both a potential groundwater control measure, and an unsuitable groundwater control measure. MAR is not strictly classified by the authors as a management measure for groundwater levels, rather it is the collecting or pumping of subsoil drainage water that is the management measure, for another beneficial use such as MAR. Collecting and pumping groundwater is addressed above in Chapter 4.3.3.

4.3.5 Building materials and construction methods

The preference for thin building slabs appears to be a Perth industry preference, with practitioners from South Australia and the Eastern seaboard reporting the use of piles and other construction methods in areas of high groundwater.

4.3.6 Alternate urban form/land development methods

As with the management of acid sulfate soils (e.g. (Department of Water, 2012) or salinity impacted land (e.g. (Commonwealth of Australia, 2006) avoidance strategies may be applied to minimise potential impacts associated with urban development in groundwater constrained areas. SKM (2007) identify the adoption of passive land uses over highly constrained sites (e.g. retention of deep vegetation) to minimise the requirement for any intervention to manage groundwater.

A Federal review of the extent and economic impact of salinity in Australia identified urban planning and regulation as a key concern, finding there was little regard for the long term implications of urban salinity when rezoning land for urban development (Commonwealth of Australia, 2006). Similar concerns may be applied to rezoning of groundwater constrained land due to the potential for wide ranging impacts.

In response to the identification of shallow groundwater conditions in an urban investigation area in the City of Casey, southeast of Melbourne, it was recommended that planning guidelines for the appropriate construction of buildings, roads and services should be followed, and development should avoid land uses and land management activities that could promote or create shallow water table conditions (Planning Casey, 2009). Similarly, it was identified that highly groundwater constrained areas in Cranbourne West in Victoria may require special planning considerations (SKM, 2007).

4.3.7 Roads

Bath structures and alternative pavements described in Chapter 4.1.2 are a means to protect road infrastructure from the impacts of high groundwater.

4.7.8 Trees

While trees are known to lower groundwater levels through evapotranspiration, and the removal of trees is known to cause groundwater levels to rise, only a small number of practitioners reported the potential for trees to be used as a management measure. Practitioners report challenges with retaining trees and providing fill to achieve minimum groundwater clearance requirements. There are also challenges and unknowns in the temporal and spatial distribution of trees, and how this can impact groundwater levels. For example, new developments are likely to feature immature trees that will be ineffective for groundwater level control. The spatial distribution and density of trees also varies across a development, with more trees likely in POS areas and on the verge. Whether this distribution and density is sufficient for groundwater control is unknown.

> *“Yes, trees can pump water but we have not seen such an approach here”*

Trees are an existing management measure for rising salinity, predominantly in rural towns. A bulletin published by the former Department of Agriculture and Food (2001) asserts that trees planted near roads can be an effective method of preventing the ground beneath the road pavement becoming saturated.

> *“In the road reserve is actually no room to put trees”*

4.3.9 Salinity

Key management measures to reduce the impact of urban salinity include avoidance of development in potential salinity hazard areas. Where development is proposed within areas that have the potential to develop a salinity hazard, management measures are focussed around the following key measures:

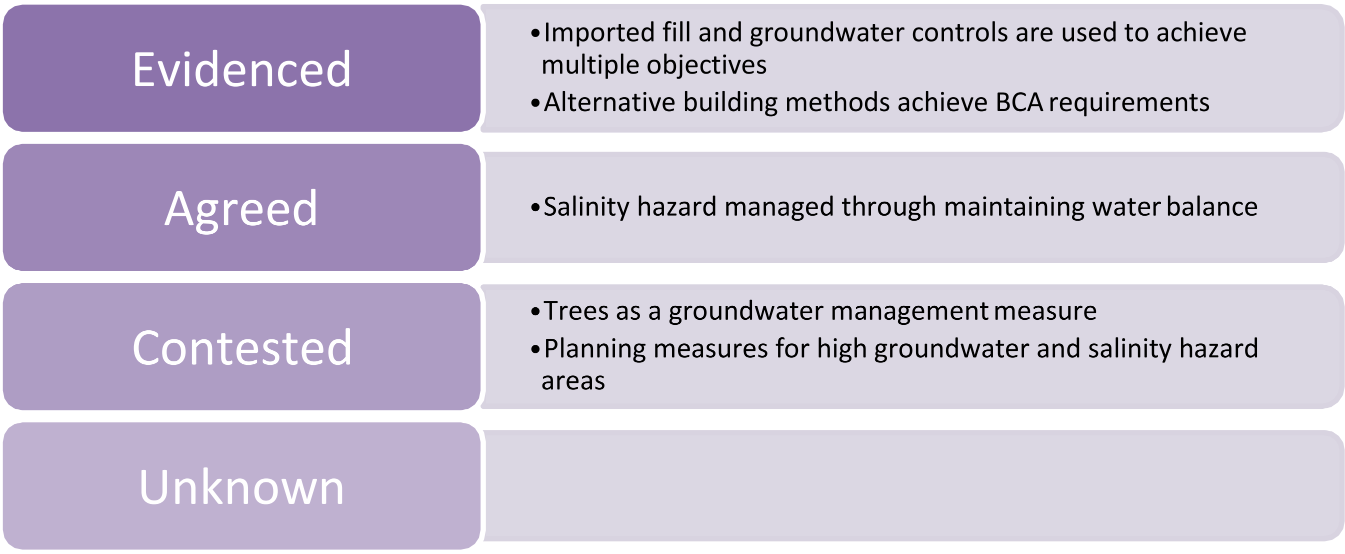
- Maintain existing site water balance (evapotranspiration and water table levels).
- Avoid disturbance of sensitive soils.
- Retain or maintain native vegetation.
- Implement building controls.

Due to the dynamic nature of salinity, it is recommended that where a site has the potential to develop a salinity hazard, impacts may be reduced through consideration of building design and construction types that are suited to the prevailing conditions (Cement, Concrete and Aggregates Australia, 2005; Buckland et al., 2005). The Building Code of Australia further requires that construction uses more damage-resistant materials, while Australian Standards (AS2159) identifies concrete and steel classifications under various exposure conditions (acid sulfate soil and salinity) and soil conditions.

The Department of Environment and Climate Change NSW (2008) identifies the use of exposure class bricks, or alternatively using a brick with a low initial salt content, as further precaution in potential salinity hazard areas.

For sites that have existing salinity hazard, or the potential to develop urban salinity, the use of fill may not be an effective long term solution as there is potential for capillary action to draw salts to the surface (Cement, Concrete and Aggregates Australia, 2005).

Buckland and McGhie (2005) identify a wide range of strategies for managing urban salinity in areas where an existing issue is identified, including lowering of the water table, onsite management of imported water, designing and constructing salinity-resistant infrastructure, supply of fresh water where possible, and abandoning or relocating infrastructure.



Evidenced	• Imported fill and groundwater controls are used to achieve multiple objectives • Alternative building methods achieve BCA requirements
Agreed	• Salinity hazard managed through maintaining water balance
Contested	• Trees as a groundwater management measure • Planning measures for high groundwater and salinity hazard areas
Unknown	

Figure 22: Post development infrastructure: management measures state of knowledge

5 Impacts of high groundwater on liveability

5.1 Water balance

In cases where urban areas do not have ASS, nutrients, and salinity issues but high groundwater, a few practitioners indicated that the baseflow generated by high groundwater is beneficial for living streams and associated amenities.

5.1.1 Disposal methods of stormwater and associated liveability impacts

Disposal of surface water is typically via:

- Underground detention storage, where stormwater is stored underground and slowly released to the downstream stormwater network.
- Underground infiltration storage, where stormwater is infiltrated into a superficial aquifer. Typical products used in Australia include soakwells (Western Australia), infiltration trenches, and infiltration tanks.
- Surface detention storage, where stormwater is stored in a basin and slowly released to the downstream stormwater network.
- Surface infiltration storage, where stormwater is infiltrated into a superficial aquifer via basins, swales, or biofilters.

Other disposal methods, such as MAR and stormwater harvesting, also require temporary storage. MAR is widely used in South Australia and stormwater harvesting is widely used on the Eastern seaboard.

Disposal of stormwater via infiltration and surface flow attenuation affects liveability through:

- Consumption of land for surface-based infiltration measures. Surface based infiltration measures are preferred in areas of high groundwater due to low vertical separation distances favouring such measures. Where vertical separation distances are low, storage depth is constrained, and therefore storage areas are expanded to achieve the target storage volume. Further, low vertical separation also decreases infiltration rates as described in Chapter 2.1.1, therefore increasing storage volumes and required areas.

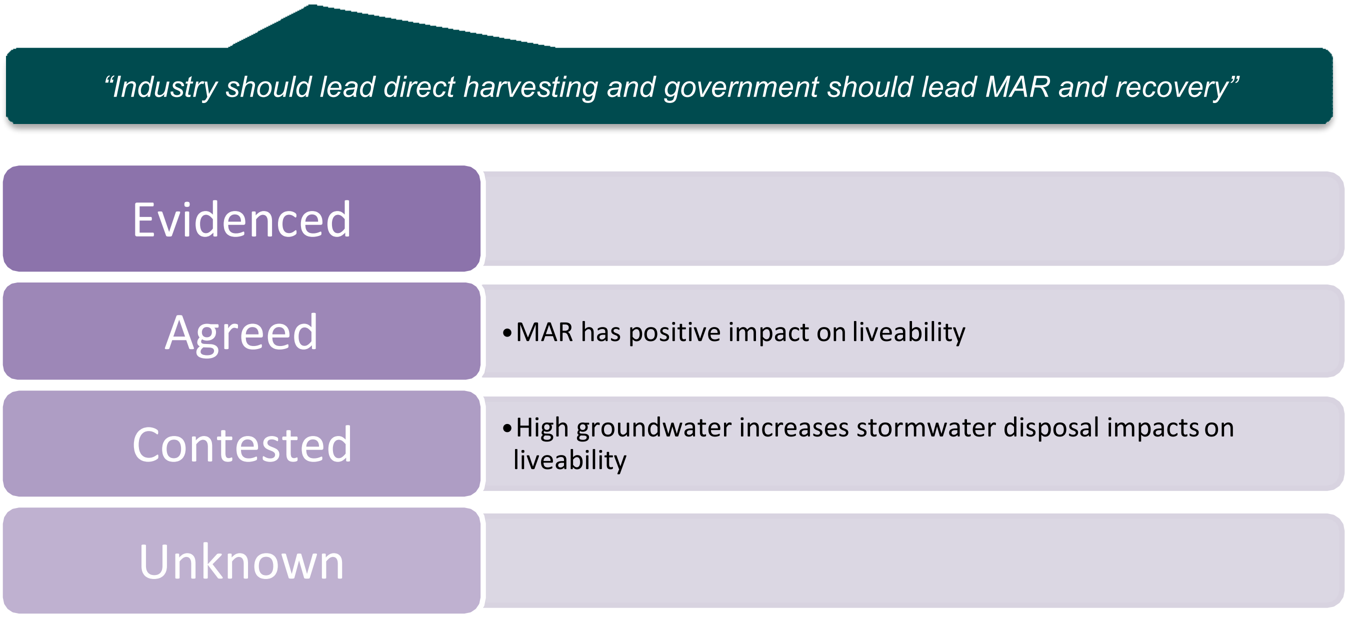
- Seasonal or event-based waterlogging of soils, either in gardens or Public Open Space due to local and temporal increases in phreatic surface as described in Chapter 3.1.7.
- Seasonal or event-based ponding, exceeding 96-hour durations at certain times of the year (Department of Water, 2011c), are a mosquito breeding risk, as well as restricting public access. Extended ponding can have further public amenity risks associated with algal blooms, pests, and odour.
- Flooding caused by insufficient storage requirements due to the underestimation of post- development groundwater rise.

Disposal of stormwater to groundwater has some benefits to liveability, including:

- Reduced downstream surface water infrastructure and land take, due to lower runoff rates and volumes, particularly open channels and basins.
- Urban heat island mitigation
- Increased open space amenity (e.g. increased house prices associated with views to restored waterways and other water bodies (Polyakov et al., 2017).
- Water storage for irrigation through MAR (Chapter 5.1.2).

5.1.2 Managed aquifer recharge

In many jurisdictions Australia wide, potable water resources are highly constrained and increasing in cost. MAR can offer a fit-for-purpose water resource for irrigation and other uses. Practitioners consider MAR to be unsuitable in areas of high groundwater, unless the target aquifer is not the superficial aquifer. MAR is usually considered in WA where there is no groundwater allocation for a development, therefore providing a positive liveability outcome due to the ability to irrigate gardens and/or POS. While MAR has positive liveability outcomes, practitioners cite treatment and approval challenges for pumped injection projects. Costs and risks associated with such projects are ultimately borne by the community.



“Industry should lead direct harvesting and government should lead MAR and recovery”

Evidenced	
Agreed	• MAR has positive impact on liveability
Contested	• High groundwater increases stormwater disposal impacts on liveability
Unknown	

Figure 23: Post development liveability: water balance state of knowledge

5.2 Water quality

5.2.1 ASS, nutrients (midge/mosquito, algal blooms), salinity

Degradation of water quality because of urban development in areas of high groundwater may occur as a result of disturbance and mobilisation of acid sulfate soils, export of nutrients in site drainage and potential development of urban salinity.

Disturbance of acid sulfate soils, and the subsequent potential for soil and water acidification, can lead to a range of human health and amenity impacts (Queensland Government, 2012; Department of Water, 2012):

- Increased mosquito breeding due to acidification of waterbodies, which may increase the prevalence of mosquito-borne diseases such as Ross River virus.
- Loss of visual amenity caused by rust coloured stains, scums and slimes from iron precipitates.
- Loss of amenity due to loss of habitat and vegetation deaths as described in Chapter 3.2.3.
- Damage to public infrastructure as described in Chapter 4.2.1.

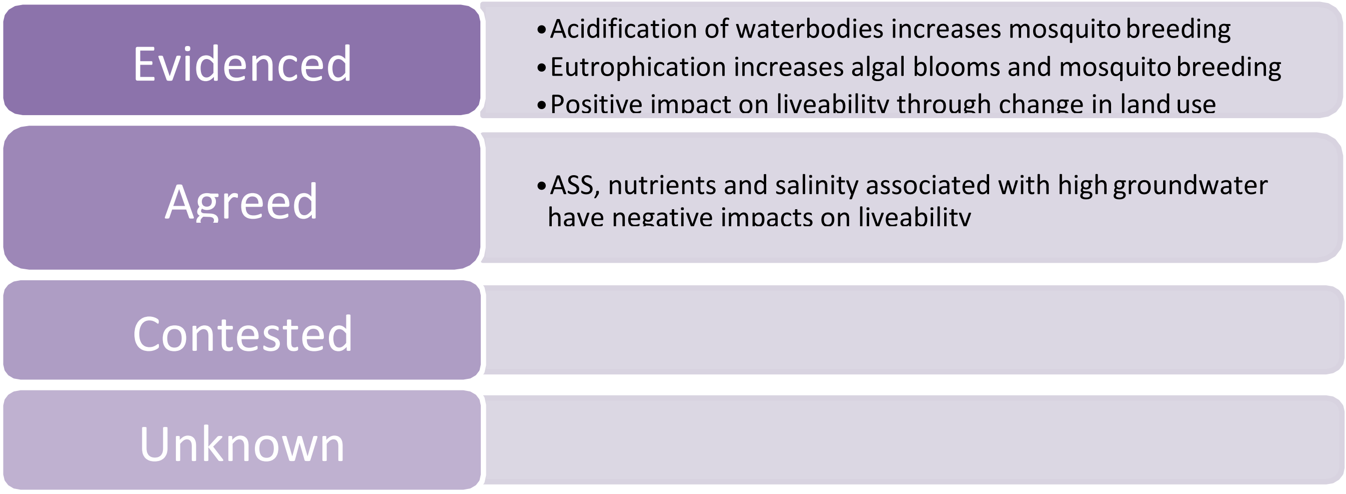
Urban development in areas of high groundwater may transport excessive nutrients into receiving waterbodies (rivers, wetlands or estuaries) where it can lead to several amenity impacts including:

- Excessive and unbalanced growth of plants and algae (eutrophication), which may also present a direct public health risk and have associated foul smells.
- Potential for increased breeding of mosquito and midges in eutrophic waterbodies, with associated public health risks and nuisance impacts.

Urban salinity has the potential to impact urban amenity through damage and increased repair and maintenance requirements to public infrastructure (e.g. footpaths, playing fields, parks, gardens and trees) as described in Chapter 4.2.2. A decline in the amenity and biodiversity of high value freshwater water dependent ecosystems may result from urban salinity impacts. Further impacts include the potential degradation of the cultural and spiritual values of important heritage sites.

As noted in Chapter 3.2.1, there is also potential for water quality to improve with a change in land use, particularly where the pre-development land use is an intensive animal industry (e.g. piggery, poultry farm) or a contaminated site. Reduced pollutant inputs and/or site remediation will result in positive impacts on liveability, however improvements in water quality may take some time to be realised due to groundwater residence times.

Trees were reported by a few practitioners as a measure to improve groundwater quality. This is supported by Nidzgorski and Hobbie (2016). There is limited empirical evidence that trees can improve the performance of WSUD facilities. Few studies have recently provided evidence that hydrologic performance of bioswales was enhanced by transpiration that accounted for 46-72% of water outputs (Scharenbroch et al., 2016). It was also found that good health trees where in areas interacting with infiltration based stormwater control infrastructure, and nutrient concentration reduction in water leaching from systems having trees on it (Denman et al., 2016).



Evidenced	• Acidification of waterbodies increases mosquito breeding • Eutrophication increases algal blooms and mosquito breeding • Positive impact on liveability through change in land use
Agreed	• ASS, nutrients and salinity associated with high groundwater have negative impacts on liveability
Contested	
Unknown	

Figure 24: Post development liveability: water quality state of knowledge

5.3 Management measures

Management measures for liveability are covered by management measures for water balance and infrastructure, in Chapters 3.3 and 4.3.

6 Research summary

This study evaluated academic and non-academic research, and "grey" literature, from both Australian and international sources to define the state of knowledge for urban development in areas of high groundwater. Structured interviews were also conducted with over 20 practitioners, regulators, researchers and academics located nationally and internationally.

Preliminary findings were discussed with the Project Steering Committee in a workshop to evaluate and consolidate the identified key design and implementation parameters and methodologies for research. Key outcomes of the workshop discussions, including knowledge gaps and additional literature, were incorporated into the subsequent drafting of the state of knowledge for urban development in areas of high groundwater.

6.1 Knowledge gaps and contested areas

This report has identified 27 contested knowledge areas and six unknown knowledge areas (Table 1). (Appendix 2 summarises all knowledge areas.)

Table 1: State-of-knowledge summary

	Contested knowledge items	**Unknown knowledge items**
Pre-development environment	**Water balance** • Pre-development infiltration rates in high groundwater • Lateral flow and fluxes to surface water • Fluxes to the superficial and confined aquifers • Evapotranspiration rates in high groundwater **Groundwater levels** • Pre-development groundwater level bore placement and monitoring programs • Pre-development groundwater level determination **Water quality** • Pre-development groundwater quality bore placement and monitoring programs • Standard laboratory methodology for dissolved	

	organic nitrogen	
Impact of development on water resources and environment	**Water balance** - Post-development groundwater levels without groundwater controls - Post-development recharge rates - Methods for predicting post-development groundwater levels - Horizontal separation required to reduce impacts on water dependent ecosystems - Impervious surface impact on water balance in high groundwater environments - Runoff coefficients - Continuing losses in high groundwater environments - Rainwater tanks impact on water balance - Infiltration device infiltration rates - Infiltration device blockage rates - Continuing losses in sand fill - Long term performance and maintenance of subsoil drains - Rates of runoff from groundwater controls for different soil types, lot sizes etc. **Management measures** - Effectiveness of WSUD elements in high groundwater - WSUD element design targets pollutants in groundwater - Groundwater control at pre-development maximum groundwater level reduces interception of pollutants	**Water balance** - Impact of land form modification on water dependent systems - Rainwater tanks impact on stormflow - MAR clogging potential and rates - MAR backwash requirements **Management measures** - Impact of WSUD elements on subsurface hydrology and nutrient cycling - Nutrient retention effectiveness of living streams
Impacts of high groundwater on	**Management measures** - Trees as a groundwater management measure	

infrastructure	• Planning measures for high groundwater and salinity hazard areas	
Impacts of high groundwater on liveability	**Water balance** • High groundwater increases stormwater disposal impacts on liveability	

These knowledge areas are clustered around the broader knowledge areas of pre- and post- development water balance, particularly:

- Infiltration and recharge rates
- Evapotranspiration rates
- Groundwater fluxes
- Groundwater levels.

Without understanding the pre-development water balance, urban development practitioners are in a weak position to maintain and protect pre-development hydrologic and nutrient cycles. Poor understanding of post- development water balances is reported by practitioners to result in a broad range of parameterisation in hydrologic models, increasing the risk that a development will under-perform, impacting on infrastructure, property, and receiving environments. Further, this poor understanding impacts on practitioners' ability to select, size and configure the stormwater treatment train, storage and attenuation measures, and design measures to control groundwater levels or achieve separation distances. Regulators are similarly ill-equipped to assess and approve the proposed water management solutions.

Potentially as a consequence of the poor understanding of the water balance, knowledge areas such as WSUD effectiveness in high groundwater environments and the impact of WSUD on subsurface hydrology and nutrient cycling are also categorised as contested and unknown knowledge areas respectively. Although the impacts of development on water quality are generally agreed, a lack of knowledge on pollutant pathways and nutrient cycles in high groundwater environments leads to ill-informed decisions regarding pollutant capture and treatment. WSUD designs that work well in low groundwater environments and are adopted without modification for high groundwater environments may perform poorly or fail. Understanding WSUD water balance and nutrient cycling is essential to the design of appropriate WSUD measures in high groundwater environments.

Priority knowledge gaps that, if addressed, will be of greatest benefit to those planning, designing or regulating urban development are therefore those related to the pre- and post-development water balance of the superficial aquifer.

6.2 Closing the knowledge gaps

Prioritising research to those findings that have wide application and can address a broad spectrum of unknown or contested areas offers the greatest benefit. Deriving answers to some contested or unknown areas will be straightforward. For example, the contested aspect "post-development groundwater levels without groundwater controls" has substantial impact on site levels and drainage and can be estimated simply once the superficial aquifer water balance is understood.

Conversely, addressing some findings may involve substantive research efforts or require long periods of time to evaluate, with little bearing on development and environmental outcomes. For example, a longitudinal study on infiltration device blockage may take many years of data collection, with the outcome having a larger bearing on maintenance scheduling rather than design of future urban developments.

Based on feedback received by the authors at the Project Steering Committee workshop and meetings, the priority contested, and unknown findings are those that relate to water balance, infiltration, and recharge in high groundwater environments, both before and after development, effective treatment measures, and alternative building designs and urban form. Stage 2 research should address the fundamental water balance and water quality aspects common to many of the priority knowledge gaps:

- Pre- and post-development infiltration and recharge rates
- Pre- and post-development evapotranspiration rates
- Post-development pollutant pathways and nutrient cycles.

Within these research priorities exist a large number of variables, such as such as aquifer properties; soil types; rainfall intensity, frequency and duration; vegetation species and density; temporal effects of vegetation growth; WSUD types and configurations; and pervious and impervious fractions and connectivity.

Data to address many of the contested and unknown aspects identified in this report may be provided through case studies completed in urban development areas in high groundwater environment. For example, targeted pre- and post-development groundwater and surface water monitoring of urban development case studies in areas of high groundwater will provide data to assist in addressing several key contested and unknown knowledge areas around the water balance. It is critical that case studies monitor all aspects of the water balance (all water inputs and outputs of a system), as recommended by CRCWSC Project B2.4 (Hydrology and nutrient transport processes in groundwater/surface water systems).

It is also important to select sites for case studies carefully, to ensure the widest application of research outputs for future development. The knowledge generated from these case studies may be extrapolated across broader urban development in areas of high groundwater, and for different urban forms, and assist with broader understanding and adaptation by practitioners, developers and regulators.

Where data is not available, the research project must define the data collection program, preferably in support of the case studies.

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Appendix 1 – Interview documentation

Interview Questions

General

1. What has been your experience working in areas of near-surface groundwater? What is your role?

Water Balance

2. How does [stormwater drainage/ vegetation/ impervious surfaces/ soakwells/ rainwater tanks/ imported fill/ climate change] impact site water balance? Please consider surface water flows and volumes and near-surface groundwater levels. What evidence do you have to support this?
   Did you need to assess these impacts? If Yes, what methods did you use?

Water Quality

3. What happens to [nutrients/ other pollutants/ ASS] as a result of development? Consider concentrations, load, species, etc. What evidence do you have to support this?
4. How does [stormwater drainage/ vegetation/ impervious surfaces/ soakwells/ rainwater tanks/ imported fill/ climate change] impact water quality? Please consider surface and near-surface groundwater quality. What evidence do you have to support this?
5. How WSUD treatment elements (e.g. biofilters) perform in high groundwater environments? What evidence do you have to support this?
6. Where WSUD treatment elements (e.g. biofilters) have been incorporated in an urban area with near-surface groundwater conditions have these been constructed and installed in accordance with nationally approved guidelines? (e.g. Adoption Guidelines for Stormwater Biofiltration Systems, Payne et al. 2015).
7. Where WSUD treatment elements have been installed in an urban area with near-surface groundwater conditions, did the design of the WSUD element consider potential interaction with near-surface groundwater? If Yes, how did the design accommodate near-surface groundwater inputs?
8. Where WSUD treatment elements have been installed were any design modifications made due to availability of locally sourced materials or due to local conditions? For example did the treatment media meet FAWB guideline specifications? Were the WSUD treatment elements unlined or lined?
9. Are the methodologies and/or lack of available water quality data impediments for your WSUD projects approval? Please consider surface and near-surface groundwater quality.
   Are there any other issues?

Flood Risk

10. What method do you use to calculate water losses (abstraction) for flood prediction under post- development scenario? Would the method apply under high groundwater conditions? Is there a better method? Is there an industry used method you strongly disagree with?
11. What catchment antecedent moisture conditions are considered for flood risk analysis under post- development scenario? Are water losses considered constant or transient during flood modelling?
12. How many infiltration sources and rates do you consider for flood modelling under post-

development scenario?

13. Have you considered the impact of groundwater interaction with stormwater infrastructure for flood prediction under post- development scenario? If Yes, what criteria do you agree and disagree with?

Groundwater levels

14. How do near-surface groundwater levels change in response to urban development? What evidence do you have to support this?
15. Did you need to estimate this response quantitatively? If Yes, what methods did you use?
16. What measures have you used to control groundwater or increase clearance to groundwater (e.g. subsoil/subsurface drains, open drains, pumping, imported fill)? How does groundwater respond to these measures? What evidence do you have to support this?
17. Which sources of information do you use to define soil profile characteristics and depths and depth to impervious/confining layer for assessment of pre- and post- development groundwater levels? Please provide a few of them with the first being your preferable source.
18. How many sources/types of infiltration processes do you consider in a post- development scenario to assess groundwater levels?
19. What methods and parameters do you use to calculate pre- and post-development groundwater levels?
20. What recharge values do you use to calculate pre- and post-development groundwater levels? Which method do you feel confident with and which do you strongly disagree with? Is there a need for recommended values in areas with high groundwater?
21. Do you think the current approaches to determine pre- and post-development groundwater levels are adequate for their purposes? If yes, what is needed to address this?

Groundwater levels risk

22. Would you expect groundwater interaction with underground stormwater drainage infrastructure even though measures to increase clearance to groundwater were in place in areas with high groundwater? If Yes, what evidence do you have to support this?
23. Are you required to or have you considered the effect of groundwater interaction on reducing water conveyance of the stormwater infrastructure for different ARI-design flood events? If Yes, which criteria do you use and which one do you disagree with?

Ground water levels benefit

24. Other than sustaining groundwater dependent ecosystems in high groundwater areas, do you see benefits to liveability by undertaking a more natural-engineered approach to control high groundwater if innovative built forms allow the development of such environments? Please consider what it would be for winter and summer scenarios for your region.

Groundwater quality

25. What measures have you used to treat pollutants in near-surface groundwater? How effective was the measure? What evidence do you have to support this?
26. What methods and parameters do you use to calculate pre- and post-development

groundwater quality?

27. Are the methodologies and/or lack of available water quality data impediments for your WSUD projects approval? Are there any other issues?

Surface water flows

28. How do surface water flows change in response to urban development? Please consider changes in flow regime (i.e. stormflow and baseflow). What evidence do you have to support this?
29. What measures have you used to manage surface water flow rates and volumes (e.g. forms of detention or retention storage and/or enhanced infiltration facilities)? How does surface water respond to these measures? What evidence do you have to support this?
30. What methods and parameters do you use to calculate pre- and post-development surface water flows? Do parameters change according to catchment discretization size (e.g. catchment scale dependent)?

Surface water quality

31. What measures have you used to treat pollutants in surface water? How effective was the measure? What evidence do you have to support this?
32. What methods and parameters do you use to calculate pre- and post-development surface water quality?

Harvesting and Managed Aquifer Recharge

33. Have you considered groundwater harvesting and/or MAR in areas of high groundwater?
34. What are the conditions (e.g. inter-annual variability, site, source, treatment, use, allocation) for successful groundwater harvesting and/or MAR projects in high groundwater environments?
35. Is groundwater harvesting and/or MAR a practical, local-scale solution for management of high groundwater?

Development

36. Can you identify any alternative building or construction methods that have been implemented in areas of high groundwater?
37. Can you provide examples of building or construction methods/groundwater controls/storage that haven't worked?

General

38. In your experience working in areas of near-surface groundwater what are the key impediments facing developers and their consultants in getting their WSUD projects approved?
39. What do you think are the key contested areas when undertaking urban development in areas of near-surface groundwater?
40. Who else should we speak with? In particular anyone who disagrees with you?

Appendix 2 – State-of-knowledge summary

The following tables summarise the state of knowledge about topics on development in groundwater affected areas.

Table A2.1: State-of-knowledge summary — Pre-development environment

	Evidenced	Agreed	Contested	Unknown
Water balance	• Pre-development evapotranspiration rates • Precipitation intensity	• Pre-development infiltration rates • Interception rates	• Pre-development infiltration rates in high groundwater • Lateral flow and fluxes to surface water • Fluxes to the superficial and confined aquifers • Evapotranspiration rates in high groundwater	
Groundwater levels	• Pre-development groundwater levels fluctuate seasonally and due to storms		• Pre-development groundwater level bore placement and monitoring programs • Pre-development groundwater level determination	
Water quality	• Pre-development land use impacts water quality	• Water quality monitoring is used to characterise pre-development conditions • Water quality monitoring parameters	• Pre-development groundwater quality bore placement and monitoring programs • Standard laboratory methodology for dissolved organic nitrogen	

Table A2.2: State-of-knowledge summary — Impact of development on water resources and environment

	Evidenced	Agreed	Contested	Unknown
Water balance	• Post-development groundwater levels fluctuate	• Post-development groundwater levels with	• Post-development groundwater levels without	• Impact of land form modification on water

	seasonally and due to storms • Potable water used for irrigation adds to groundwater balance • Potable water leakage adds to groundwater balance • Impervious surface impacts on water balance in low groundwater environments • Concentrated infiltration causes local increases in groundwater level • MAR adds water to the target aquifer water balance	groundwater controls • Gravity sewer systems remove water from groundwater balance in high groundwater environments • Change in water balance impacts water dependent ecosystem water regime • Granular fill increases infiltration potential • Groundwater controls remove water from groundwater balance • MAR impacts to groundwater levels, flows and quality	groundwater controls • Post-development recharge rates • Methods for predicting post-development groundwater levels • Horizontal separation required to reduce impacts on water dependent ecosystems • Impervious surface impact on water balance in high groundwater environments • Runoff coefficients • Continuing losses in high groundwater environments • Rainwater tanks impact on water balance • Infiltration device infiltration rates • Infiltration device blockage rates • Continuing losses in sand fill • Long term performance and maintenance of subsoil drains • Rates of runoff from groundwater controls for different soil	dependent ecosystems • Rainwater tanks impact on stormflow • MAR clogging potential and rates • MAR backwash requirements

			types, lot sizes etc.	
Water quality	- Urban development may disturb acid sulfate soils - Acid sulfate soils impact receiving ecosystems	- Acid sulfate soil risk mapping used for broadscale planning - Areas of Swan Coastal Plain with high groundwater (<3 m) have high risk of acid sulfate soils - Detailed site investigations completed for site works where risk of acid sulfate soils is high - Underground structures may expose acid sulfate soils		
Management measures	- Source control most effective management measure - WSUD element design targets pollutants in surface water	- Local government preference impacts WSUD element design - Smaller lot sizes reduce nutrient input	- Effectiveness of WSUD elements in high groundwater - WSUD element design targets pollutants in groundwater - Groundwater control at pre-development maximum groundwater level reduces interception of pollutants	- Impact of WSUD elements on subsurface hydrology and nutrient cycling - Nutrient retention effectiveness of living streams

Table A2.3: State-of-knowledge summary — Impacts of high groundwater on infrastructure

	Evidenced	Agreed	Contested	Unknown
Water balance	- High groundwater levels reduce	- High groundwater impacts utility		

	structural bearing capacity and can weaken and damage pavements	construction methods • High groundwater has negligible impact on most utilities in the long term • High groundwater can infiltrate into sewer systems • High groundwater requires special measures for electrical substations		
Water quality	• Acid sulfate soils and salinity impact on infrastructure	• Detailed site investigations completed to quantify risk from site works where risk of acid sulfate soils is high • High groundwater areas (<3m) of Swan Coastal Plain have high risk of acid sulfate soils • Potential for urban salinity to develop where high salt concentrations in soil profile or groundwater • Fill not an effective solution to salinity due to capillary action • Some groundwater has high NOx potential		
Management measures	• Imported fill and groundwater controls are used to achieve multiple objectives	Salinity hazard managed through maintaining water balance	• Trees as a groundwater management measure • Planning measures for high	

	- Alternative building methods achieve BCA requirements		groundwater and salinity hazard areas	

Table A2.4: State-of-knowledge summary — Impacts of high groundwater on liveability

	Evidenced	Agreed	Contested	Unknown
Water balance	- Acidification of waterbodies increases mosquito breeding - Eutrophication increases algal blooms and mosquito breeding - Positive impact on liveability through change in land use	- MAR has positive impact on liveability	- High groundwater increases stormwater disposal impacts on liveability	
Water quality		- ASS, nutrients and salinity associated with high groundwater have negative impacts on liveability		
Management measures				

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