CRC for
Water Sensitive Cities

Guiding urban water management in areas that experience high seasonal groundwater: Expert Panel report

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Guiding urban water management in areas that experience high seasonal groundwater: Expert Panel report
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Executive summary

The Cooperative Research Centre for Water Sensitive Cities (CRCWSC), in collaboration with research and industry partners, has been progressing Integrated Research Project 5 (IRP5) – *Knowledge-based water sensitive solutions for development in high groundwater environments*) (CRCWSC 2017). As part of Stage 2 of IRP5—*Guiding urban water management in areas of the Swan Coastal Plain that experience high seasonal groundwater*—the CRCWSC established an Expert Panel in September 2019 to prepare two main products:

1. Technical guidance for planning and designing urban developments in high groundwater areas, building on practitioners' and researchers' experience and knowledge of the Swan Coastal Plain in Western Australia

2. Recommendations for further research, data and information collection and/or methods that may improve the guidance over time.

The Expert Panel comprised Associate Professor Dr Sally Thompson from The University of Western Australia (UWA), Dr Margaret Shanafield from the National Centre for Groundwater Research and Training (Flinders University, Adelaide), and Greg Claydon (Chair, and CRCWSC Board Director), assisted by Research Associate Dr Ana Manero (UWA, Perth).

The Panel has produced this report based on site visits, detailed discussions, and feedback on an earlier draft report from a range of Western Australia based urban development industry practitioners and consultants, local and state government officials and researchers, and in consultation with the Urban Development Industry Association's (UDIA) Water Committee for WA, the multi-stakeholder Land Development in Groundwater Constrained Environments Steering Group (convened by the Institute of Public Works Engineering Australasia (IPWEA) WA branch) and the Western Australian Local Governments Association (WALGA)), the CRCWSC's Western Region Advisory Panel, and Perth's Water Sensitive Transition Network. This report also draws on relevant previous work by the CRCWSC and the Expert Panel's own tacit knowledge and experiences.

Note: We have used the term 'high groundwater' throughout this report, recognising that this is the standard terminology used by the CRCWSC for IRP5. But we recognise the term 'shallow groundwater' is also used in the literature and by some practitioners and researchers, perhaps to help illustrate the importance of surface water and groundwater interactions and what happens in the unsaturated zone between the two, and recognising that, in groundwater management generally, groundwater levels may be relatively 'high' (e.g. after relatively higher rainfall periods) but not 'shallow'.

Key findings

[1] <u>Changes to the status quo can bring benefits</u> – The status quo for predicting and mitigating the impacts of high groundwater on urban development is generating harm in several areas of urban development and sensitive environments within the Swan Coastal Plain of Western Australia. Uncertainties in the status quo approaches have, in some instances, led to using excessive amounts of onsite sand-based fill, which add to urban development costs and impact on housing affordability. In other instances, insufficient mitigation of high groundwater has led to nuisance flooding, damage to public and private infrastructure, water quality deterioration and changes to groundwater dependent ecosystems. This means that adopting best practices or changes in the development methods could present a win-win-win opportunity for the public, the environment, and land development interests.

[2] There is a need for better technical guidance on and understanding of the urban water balance – Currently, limited sector-wide technical guidance exists to predict the impact of urbanisation on water balances and water quality in specific areas constrained by high groundwater, although industry practitioners have been working together over recent years to identify and fill knowledge gaps and promote best practices. The success of these efforts has been hampered by a lack of data and information, and process, regulatory and capacity barriers.

[3] Earlier decision making in planning and approval processes can mitigate cumulative adverse impacts – Land development in high groundwater areas may have cumulative environmental impacts; for example, on flooding, water quality and/or on the health of groundwater dependent ecosystems (GDEs). Such cumulative impacts need to be identified and managed early in the planning and approval processes. Early identification and management are more often than not at odds with the current timing and scale of detailed hydrological site assessments, which typically occur at subdivision scale, in the framework of a local water management plan, and *after* regional and district planning decisions have been taken.

[4] Different approaches are required for different levels of groundwater risk – In developing local water management plans and subdivision scale engineering designs, the appropriate level of site investigation, modelling and design varies with site-specific groundwater 'risk'. Consequently, depending on the site risk, there may be differences in the extent of monitoring needed to inform modelling for planning and design, the types of assumptions that should be made in modelling and design, and the extent and transparency of the information used to prepare reports for approval.

[5] Technical demands on local governments are significant – The demands in terms of time and personnel on local governments imposed by the review and approval of technical hydrological/hydrogeological/engineering investigations and designs are significant. Maximising local governments' abilities to meet these demands is a key opportunity to improve development outcomes in high groundwater environments across the Swan Coastal Plain.

[6] Lack of clarity around governance responsibilities can present barriers to good technical results – Breaks in the chain of responsibility within the planning, design and construction process contribute to failures to achieve best practice outcomes. These can be exacerbated by:

- separation of responsibilities within state and local government departments
- lack of clear and open channels of communication between local government decision makers and advisory state departmental bodies
- inconsistent requirements for assessing proposals across municipalities.

[7] Several other barriers need to be overcome to satisfy the appetite for greater innovation – Diverse stakeholders are calling for greater innovation in construction methods/materials, stormwater management, allocation of responsibility between private and public entities, and in the planning process more broadly. Roadblocks hindering such innovation include:

- lack of timely post-development monitoring
- lack of guidance informing how to implement innovations and consider trade-offs
- lack of well-monitored demonstration sites
- legal ambiguity around the status of and responsibility for drainage infrastructure, particularly on private lots

- fragmented and incomplete legal frameworks around surface and sub-surface drainage management
- late introduction of detailed hydrological assessments within the planning and approval processes (particularly problematic for cumulative impact mitigation), despite the existence of the Better Urban Water Management framework (WAPC 2008).

[8] Better use can be made of existing and future monitoring information – Improving the timeliness of post-development monitoring, and making better use of the information generated by such monitoring, will have several benefits:

- creating opportunities for adaptive management (given that the development cycle for a given subdivision may proceed over one to two decades, earlier monitoring would create an opportunity to rectify any design flaws)
- greatly adding to the data, information and knowledge available about the spatial and temporal impacts of urban development on water balances, levels and qualities in locations subject to high groundwater
- better informing future planning and design and improving long-term outcomes for the industry, community and the environment.

There are positive opportunities for industry, regulators and academia to work closely together towards this additional knowledge building. While the Expert Panel acknowledges that some of the above findings are arguably outside of the scope of our Terms of Reference (Appendix A), we nevertheless see them as important and there is a need for progress to be made in addressing them.

Key guidance

[1] A risk-based framework – Guidance is provided for adopting a consistent, risk-based framework to determine the level of pre-development site investigation, modelling and design evaluation that is appropriate for locations impacted by high groundwater. This framework is based on evaluation of the annual exceedance probabilities (AEPs) for the level of the phreatic surface and includes:

- the use of simplified (and potentially further improved) Controlled Groundwater Level (CGL) methods for low risk sites
- one-dimensional modelling methods (e.g. those based on the Hooghoudt equation) with enhancements for moderate risk sites
- two- or three-dimensional modelling methods (as the default without very strong justifications otherwise) for high risk sites.

These levels of risk are based on factors such as pre-development groundwater level (depth), pre-development land use/water quality, pre-development groundwater abstraction, soil type, receiving environments and other environmental constraints. Note that (i) this framework is intended to provide guidance only, and should be subject to site-specific consideration of appropriate levels of assessment, developed between regulators and proponents, and (ii) the use of the term 'annual exceedance probability' in this context does not refer to storm event AEPs, but to AEPs developed based on long-term monitoring or modelling of water table levels.

[2] Consistent and coherent modelling approaches – In using the risk-based framework, consistency is required in modelling work and assumptions across the various planning levels and stages, with appropriate sensitivity analyses undertaken, and controls in place to ensure the assumptions and results can be followed through to implementation. Guidance is provided for a limited number of key influencing parameters, including for assisting

initial ‘sense’ checks, while recognising the importance of appropriate site-based and case-based methodologies. Where deviations in modelling or assumptions, including parameter values, from earlier work are to occur or have occurred, justifications should be coherent, transparent and supported, with any associated additional risks and cumulative impacts clearly identified.

[3] Demonstration of robust and resilient design and construction approaches – An alternative approach to further refining modelling is to adopt lot/sub-division/precinct/drainage designs that can accommodate modelling error and/or other uncertainties. Various approaches are available and are being used or considered by experienced practitioners in Western Australia. These should be the subject of further demonstration and monitoring to evaluate their performance.

[4] Development and use of helpful technical assessment tools – Local governments should adopt tools to facilitate their approval and compliance roles. These could include adopting existing or new/updated guidelines/approaches or parts thereof, checklists, identifying ‘red flags’ that indicate potential modelling or design problems, or numerical tools. State regulators should be involved in developing and adopting these tools to ensure consistency and coherence, and the urban development industry and their consultants should be involved in preparing them and assisting in their dissemination.

Key recommendations for future research

Research and/or other work should be undertaken to:

[1] Improve understanding of recharge dynamics of the pre- and post-development landscape at a range of scales by:

- measuring (and parameterising models to predict) evaporation and transpiration from undeveloped landscapes with high groundwater (and making these models available to stakeholders, including consultants, developers, agencies, and local governments for prediction purposes)
- measuring gross recharge associated with different components of the urban landscape (including lot rears, soakwells and paved areas), under different soil and depth-to-water conditions
- developing methods to predict gross and net recharge across the range of urban landscape components, soil types and depths-to-water
- further considering future climate impacts on recharge dynamics
- further considering water quality impacts
- considering research that would develop/assess new and innovative technologies/methods to measure aspects of the urban water balance, that are more accurate, more practical, cheaper, more reliable, and/or more suited to urban systems than currently exist.

We acknowledge that while the above priority knowledge gaps should be progressed, research in this area will be of limited benefit if it is not well understood how changes to the local hydrology (including water quality) will impact on the receiving environments or adjacent environmental assets. This underlying need is fundamental to protecting Western Australia’s assets and should be a consideration in all stages of research, modelling, legislative approvals and development.

[2] Improve the understanding of the risks associated with common modelling assumptions, particularly those associated with using steady state models such as the Hooghoudt equation. Issues to be addressed include:

- viability of replacing steady state models with quasi-steady models and the errors in AEP computation associated with such replacement
- techniques to select appropriate cross-sections on which to apply a Hooghoudt equation when subsoil drains are graded and the perpendicular length scale is an underestimate of actual flow path length
- assessment of whether parameter values for recharge and saturated hydraulic conductivity in the Hooghoudt equation introduce larger uncertainties than the actual physical setting of the subsoil drains.

[3] Develop tools to facilitate the technical assessment of proposals by local governments and provide education and training in using those tools, up-to-date guidance materials and other matters relevant to building industry and regulator capacity, institutional strengthening and capability.

[4] Proceed towards creating and evaluating demonstration projects on topics including:

- alternative construction methodologies and urban and built forms appropriate to high groundwater environments
- the performance of a variety of precinct, sub-division, and on-lot stormwater management strategies
- the feasibility of rear-of-lot directly connected drainage of the local groundwater mound
- landscaping approaches that are compatible with high groundwater in lot rears and in public open spaces.

[5] Expand on the work of this project to cooperatively develop a comprehensive technical guidance note, supported by the urban development industry and regulators, for planning and designing urban developments in high groundwater areas. Such guidance could be incorporated into existing processes and documents, such as those associated with *Australian rainfall and runoff 2019* (ARR), and/or build on those of the IPWEA, noting, for example, that IPWEAWA has produced a *Specification for separation distances for groundwater-controlled urban developments 2016*. The guidance note could usefully include a short series of case studies and worked examples to help explain a methodology and why it is reasonable in each case. Such a guidance note could also be used to inform and, for relevant parts, be incorporated into initiatives such as Design WA, currently being developed by the Western Australian Planning Commission (WAPC).

While this priority list can sensibly be undertaken in the order presented, it can also be progressed iteratively as resources and circumstances permit. It is not a comprehensive list of all technically related research needs, nor does it cover specific improvements in commercial, legal and planning frameworks surrounding urban development in high groundwater environments, which were beyond the brief for the Expert Panel. We encourage stakeholders to explore the policy issues and options identified in this report, including greater legislative clarity, to reduce or remove barriers to the implementation of otherwise sensible technical solutions. It is the Panel's considered view that addressing the policy, regulatory and governance issues identified in this report will lead to better informed decision making, mitigation of unacceptable risks and better environmental, economic and liveability outcomes.

Without progress in the above areas of research and further work, and the development and following of improved guidance, we believe that impacts of high groundwater will continue to generate harm in several areas of urban development and sensitive environments within the Swan Coastal Plain. These harms include (i) the use of excessive amounts of onsite sand-based fill, which adds to urban development costs, impacts housing affordability, and creates environmental impacts including quarrying, transport/carbon costs, sedimentation/erosion risks, and long-term changes in the landscape profile; and (ii) insufficient management of the risks posed by groundwater which can lead to nuisance flooding, public health risks (e.g. mosquito breeding), and damage to public and private infrastructure in at-risk locations.

Although challenges remain in managing development in high groundwater environments, the Expert Panel was tremendously impressed and heartened by the commitment, goodwill and engagement of a very broad group of stakeholders in addressing these challenges. We hope this report is a useful contribution to minimising risks to the built and natural environments, and to maximising the opportunities for innovation, resource recovery and creativity that the challenge of high groundwater also provides.

1. Background

1.1 Reason for this Expert Panel project

Western Australia established a process in 2008 to consider water resources as part of the planning and development approvals system (WAPC 2008). When managing high groundwater, a local structure plan requires estimation of current and future groundwater levels, as well as the potential for the development to mobilise groundwater nutrients and contaminants. To date, particular guidance has been provided for developing district water management strategies, local water management strategies and urban water management plans (Figure 1; Department of Water 2008), and for controlling groundwater levels (Department of Water 2013).

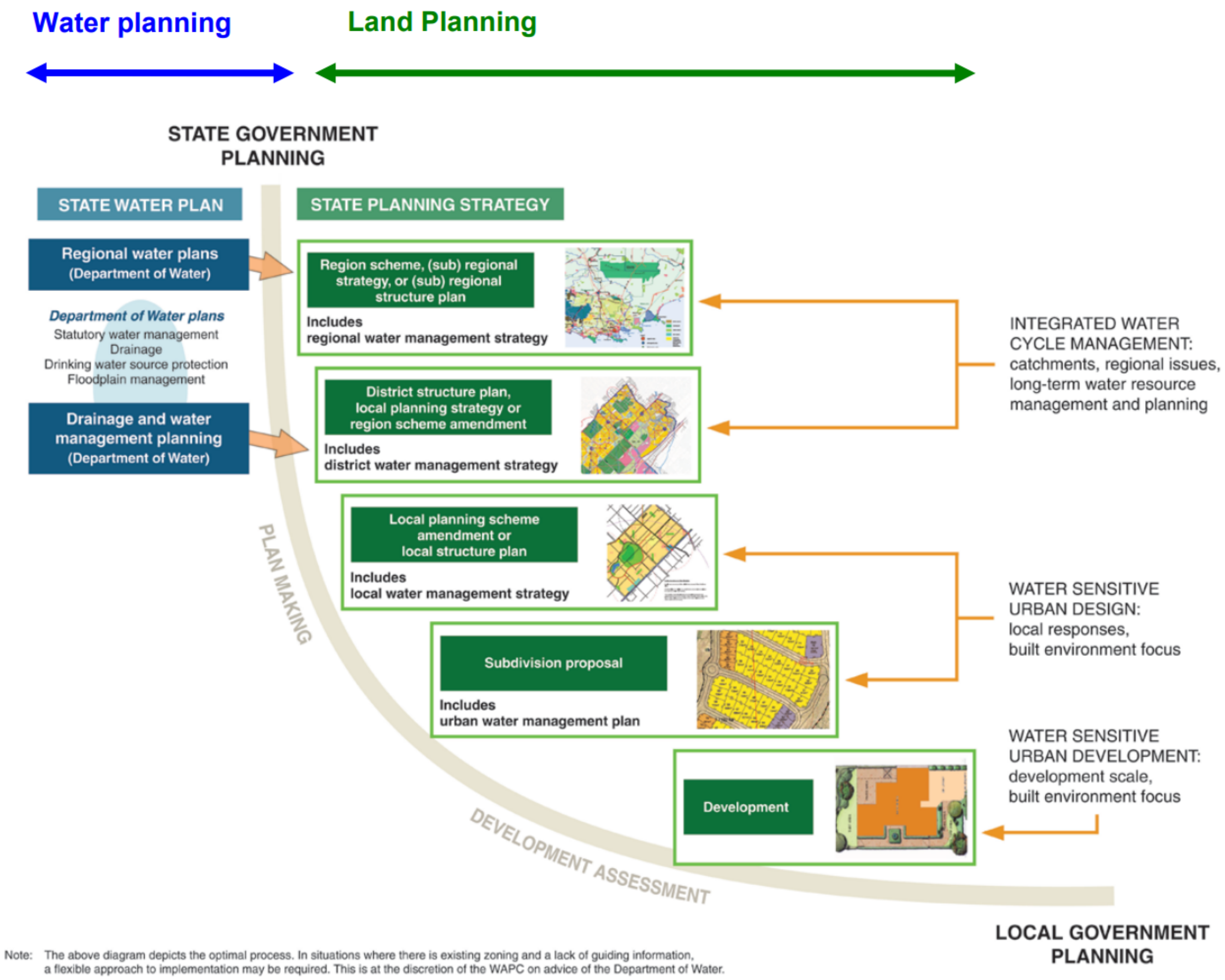

Figure 1: Integration of land and water planning in better urban water management
Source: Department of Water (2008)

In response to these requirements, the practitioners in Western Australia make assumptions to predict:

- changes to groundwater levels post-development
- runoff and recharge rates under different conditions for stormwater management
- interactions between surface water and groundwater.

Currently, these predictions are based on available guidelines, including those in ARR 2019 (Ball et al. 2019) and the Institute of Public Works Engineering Australasia (IPWEA 2016). Despite significant scientific advances in the area of urban developments in locations impacted by high groundwater (Barron et al. 2013; Ocampo et al. 2017; Ocampo 2018), there is still debate among Western Australian water management practitioners about the accuracy of certain approaches and assumptions for modelling and managing high groundwater environments in the Swan Coastal Plain. This has implications for achieving best practice urban development in such environments, now and in the future. As a result, we need a consistent approach in the Swan Coastal Plain to determine appropriate water management strategies for urban development in such environments.

In response to such a need, the Cooperative Research Centre for Water Sensitive Cities (CRWSC) established two projects. The first one (2014–18), *Hydrology and nutrient transport processes in groundwater/surface water systems – Project B2.4*, aimed to assess the performance of source control systems (SCSs) in areas impacted by high groundwater (CRCWSC 2019). The second project, in 2017, was *Knowledge-based water sensitive city solutions for groundwater impacted developments*—also referred to as Integrated Research Project 5 (IRP5) (CRCWSC 2017).

IRP5 consists of two stages. The aim of Stage 1 (conducted mostly in 2018) was to better understand the impact of urban development in areas of high groundwater, with a focus on the Swan Coastal Plain. Following a review of the literature and stakeholder interviews, the Stage 1 report (GHD 2018) identified over 30 specific questions where current understanding is lacking or inconsistent among experts and practitioners. These questions were grouped into four key areas of knowledge regarding pre- and post-development water balance: 1) infiltration and recharge rates; 2) evapotranspiration rates; 3) groundwater fluxes; and 4) groundwater levels. Areas (1) and (2), together with post-development pollutant pathways and nutrient cycles, were prioritised to be addressed in Stage 2 of IRP5.

Thus, Stage 2 was commissioned in 2019 to address the knowledge gaps identified in Stage 1. Stage 2 is structured in two activities: an Expert Panel guidance note, and field validation of recharge parameters. The Expert Panel was established to formulate guidance for the concept planning and design approach to be applied when developing water management strategies for urban development in high seasonal groundwater environments (see Appendix A for the Expert Panel's Terms of Reference). The principal objective of the guidance is to provide a consistent methodology for designing urban developments in areas subject to high seasonal groundwater tables.

This report synthesises the Expert Panel's understanding about best practice methodology for technical assessment and management of high groundwater in urban development sites and provides guidance on how this best practice could be standardised.

1.2 Methodology

The understanding and guidance provided in this report is based largely on site visits and information provided by academic, industry and government representatives through presentations to and discussions with the Expert Panel in November and December 2019 and February 2020. Participants were asked to present about the details of site assessment, modelling and design undertaken in one or more projects in which high groundwater was an important technical constraint on urban development. A detailed description of the methodology is presented in Appendix B. Participants were provided with a list of technical questions (Appendix C) by the Expert Panel, noting that not all the listed questions were relevant in every instance. Following the presentations, the Expert Panel undertook semi-structured discussions with the presenters.

The Expert Panel also drew on relevant literature from Australia and overseas and previous work by the CRCWSC, together with its own tacit knowledge and experience.

Additionally, some or all of the Expert Panel members consulted on an earlier draft report with several relevant stakeholder groups, including the Urban Development Institute of Australia (UDIA) Water Committee for WA, the multi-stakeholder Land Development in Groundwater Constrained Environments Steering Group (convened by the Institute of Public Works Engineering Australasia (IPWEA) WA branch and the Western Australian Local Governments Association (WALGA)), the CRCWSC's Western Region Advisory Panel and Perth's Water Sensitive Transition Network, and reported to the CRCWSC's IRP5 Project Steering Committee.

1.3 Scope of the report

The Expert Panel's role is to provide guidance and recommendations for future work pertaining to best practice around technical issues: for example, those relating to fundamental scientific uncertainty, uncertainties derived from model representation of hydrological processes in areas impacted by high groundwater on the Swan Coastal Plain and within corresponding areas of urban development, and uncertainties associated with the parameterisation of such models. Policy, governance and planning questions that pertain to the ability of developers and their consultants to undertake best practice technical site assessment, water related modelling and associated engineering design, and of decision makers to approve, modify or reject corresponding technical elements of proposed development plans, were treated as lying within the scope of the Expert Panel.

The Expert Panel recognises that many stakeholders see a very broad scope for improvements in the commercial, legal and planning frameworks surrounding urban development in Western Australia and likely elsewhere. These broader topics, however, lie beyond the brief of the Expert Panel. We have attempted to reflect and recognise these issues as they were raised (see Appendix F for a summary of inputs from practitioners), but do not provide specific guidance relating to these broader topics.

The Expert Panel's review was limited to the material and information with which we were presented and the related discussions. This also constrains our ability to offer guidance on all pertinent topics. For example, where only a single participant addressed a topic, we may have lacked enough evidence to elucidate what 'best practice' would comprise. The guidance we provide in these topics is necessarily high level, even though several of these topics are of great urgency and importance. Further, several issues we considered important were not raised by any participants (likely due to the relevant people not engaging with the process). In these cases, we identify technical concerns about these topics do exist, but we generally refrain from providing specific guidance, even though, again, these topics may be of urgent importance.

2. Introduction

2.1 What is high groundwater?

For the purposes of this report, the Expert Panel has adopted high groundwater regions as those in which the top of a perched water table or an unconfined aquifer (the water table or phreatic surface) regularly approaches the land surface (e.g. groundwater within 0.9 m of the surface) (Minnesota Pollution Control Agency 2019), or within 4 m of the surface in IRP5 Stage 1. For consistency with IRP5 Stage 1, if the phreatic surface is within 4 m of the land surface, we are saying the location has 'high groundwater'. (We have used the term 'high groundwater' throughout this report, recognising that this is the standard terminology used by the CRCWSC for IRP5. But we recognise that 'shallow groundwater' is also used in the literature and by some practitioners and researchers, perhaps to help illustrate the importance of surface water and groundwater interactions and what happens in the unsaturated zone between the two, and recognising that, in groundwater management generally, groundwater levels may be relatively 'high' (e.g. after relatively higher rainfall periods) but not 'shallow'.)

High groundwater regions occur worldwide, including in regions with shallow confining layers, montane and piedmont areas, floodplains, deltaic environments and lowlands more generally (see Figures D1 and D2 in Appendix D). In Australia, high groundwater environments are prevalent in the south west of the country, along the foothills of the Great Dividing Range, in parts of the interior, and along river floodplains (Fan et al. 2013). This report focuses on high groundwater on the Swan Coastal Plain that surrounds and contains the Perth metropolitan area. Figures D3 and D4 (in Appendix D) illustrate the spatial distribution of depth to groundwater in the Swan Coastal Plain and its overlap with planned future urban growth.

2.2 Why can high groundwater be a problem?

Urban development moving into areas impacted by high groundwater results in challenges for industry, planners, regulators, the general community and the environment.

High groundwater has the potential to cause several impacts (GHD et al 2018; New WAter Ways 2019) including:

- damage to infrastructure, including concrete foundations and bitumen roads, with possible structural failure
- compromised performance of water (and 'wastewater') control systems
- loss of amenity in public and private open spaces, with seasonal or event-based waterlogging preventing pedestrian or vehicular traffic; and/or restricting sustainable plant growth or health; and/or potentially creating conditions for mosquito and nuisance midge breeding
- increased amounts of poor quality water entering receiving waterways and wetlands.

Nevertheless, high groundwater can also present opportunities. For example, there is a focus on increasing urban tree canopy in the Perth metropolitan area for multiple benefits, including urban cooling and enhanced liveability. Access to groundwater provides a source for establishing vegetation and reducing irrigation requirements. The opportunity of using high groundwater as a supply source is discussed later in this report.

2.3 Understanding high groundwater: the pre- and post-urban development water balances

Determining and understanding pre-development groundwater levels and their fluctuations is a critical component of urban planning, design and management (New WAter Ways 2019). The pre-development water balance is influenced by rainfall, interception, evapotranspiration, infiltration and runoff characteristics, while geotechnical and hydrogeological factors also influence recharge into an aquifer (see Figure 2).

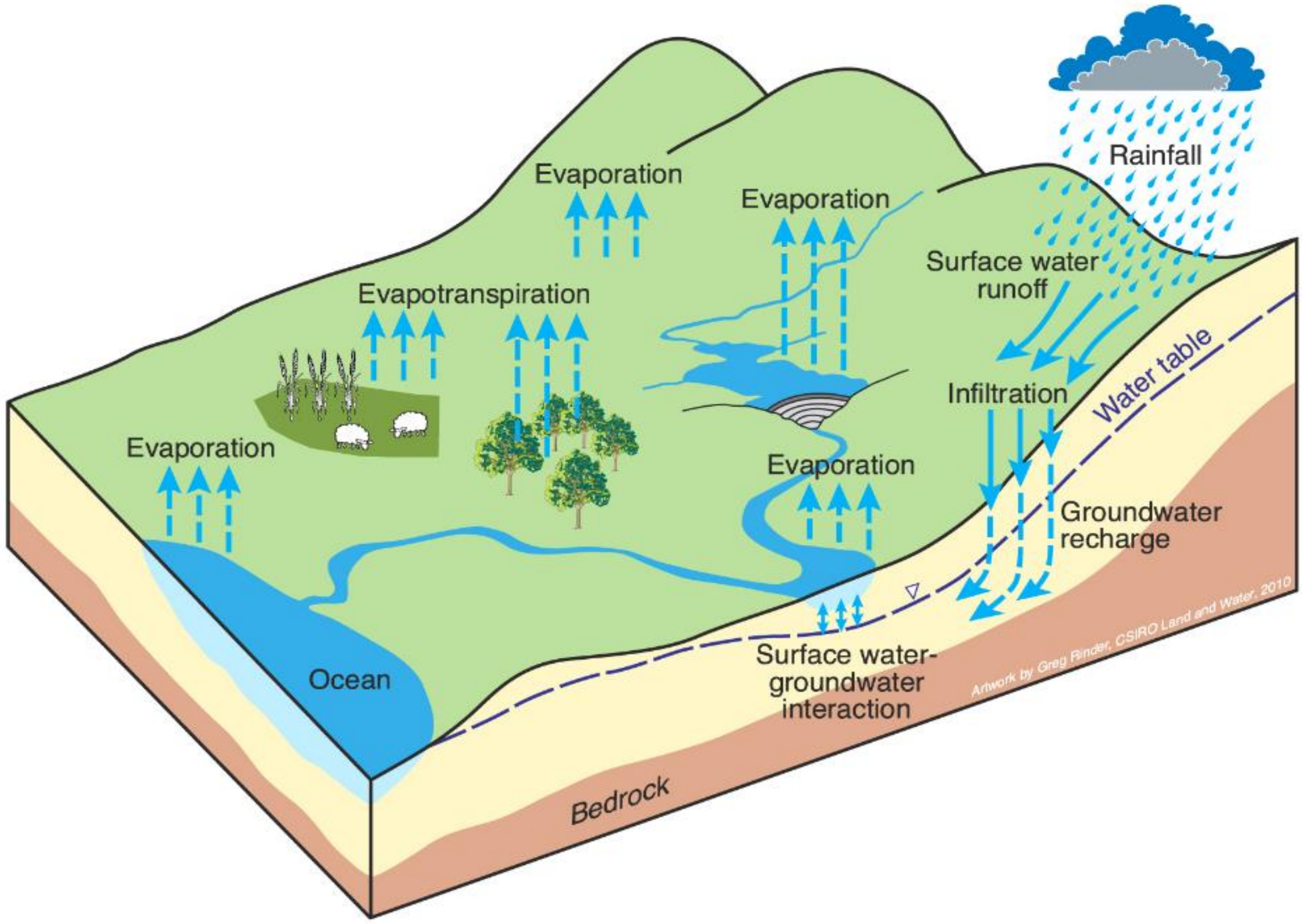

Figure 2. Simplified conceptual pre-urban development water balance factors
Source: www.ewater.org.au (2012)

Understanding the conceptual water balance helps to predict the impacts of urban development and the design of suitable water management measures. Urban development alters the pre-development water balance, potentially impacting on water resources, infrastructure, amenity and the environment. Hydrological changes occur when a catchment is developed, and surface (overland), unsaturated sub-subsurface and groundwater flows may be altered. Without specific management controls, urban development in the Swan Coastal Plain may result in increases in groundwater levels due to higher post-development net recharge, through the reduction of transpiration from the loss of vegetation, and/or use of artificial rainfall/runoff infiltration systems (rain gardens, soakwells, trenches and the like), and/or the use of imported water for site irrigation (see Figure 3). High groundwater may also limit volumes of water that can otherwise be recharged.

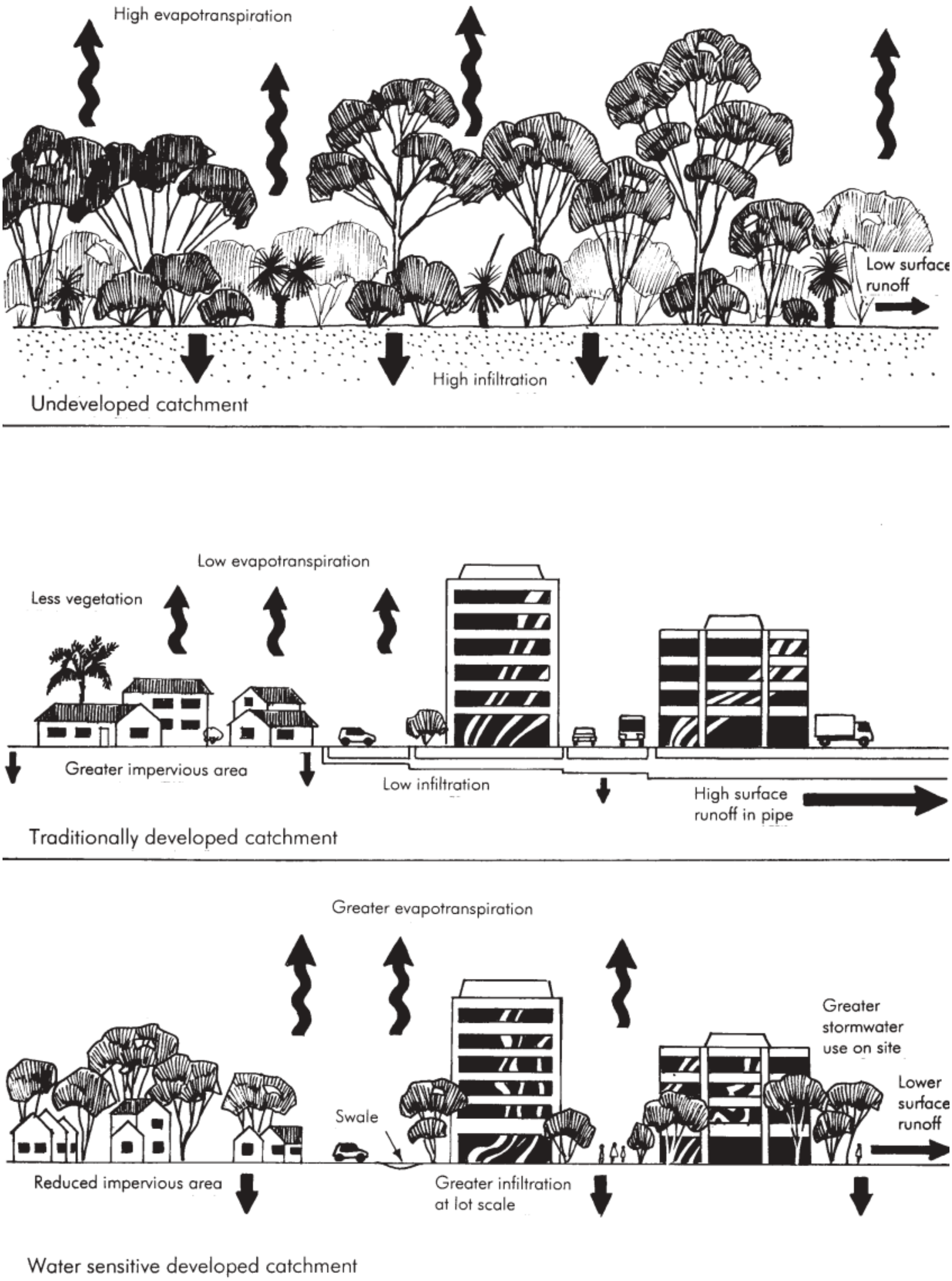

Figure 3. Simplified conceptual post-urban development water balance factors
Source: Stormwater Management Manual for Western Australia, Department of Water (2007)

Previous work by the CRCWSC and others (Barron et al. 2013; Baskar 2016; Ocampo et al. 2017; Locatelli et al. 2017; Ocampo 2018; CRCWSC 2019) has increased our understanding of these processes, though several knowledge gaps remain as outlined in Appendix D which summarises existing literature.

2.4 Current development responses to high groundwater and their implication

In the Swan Coastal Plain, imported sand fill is typically used in areas of high groundwater to separate urban development infrastructure and landforms and the groundwater table. Specific infrastructure, such as wastewater management systems and road and rail alignments, and/or creating a 'Class-A' site that minimises the required thickness of the concrete slab necessary for most housing construction methods, may require sand fill. (Demand for double-brick houses substantially drives the residential development market.)

Using fill in groundwater constrained sites on the Swan Coastal Plain is controlled by both 'upstream' and 'downstream' needs to elevate development above the natural land surface.

Upstream requirements relate primarily to achieving prescribed separation distances between the phreatic surface of the groundwater and urban infrastructure, including road bases, foundation slabs, and vegetated surfaces (turf, back yards, public open space). To achieve such conditions in high groundwater sites, developers rely on either importing fill to achieve a specified level of clearance above the water table, or using subsoil drains to lower the water table, or both.

These strategies can effectively manage groundwater, but they have disadvantages that can be quite significant and must be weighed against the potential gains. For example, an increasingly risk adverse approach to managing groundwater risks can lead to increasing use of fill. The cost of fill is high (often at $30 per cubic metre or more, with some presenters mentioning that fill can contribute more than 30 per cent to lot development costs). This means that if more fill is used than is really needed to provide an adequate buffer to groundwater, it can result in:

- unnecessary additional costs to developers and thus homebuyers, decreasing the affordability of new housing
- unnecessary clearing/mortality of vegetation at fill sources
- carbon emission and transportation impacts from importing fill (trucking etc.)
- large changes in the elevation and relief of the built environment, potentially leading to:
    - large grade separation between neighbouring developments, which can be unsightly and cause privacy issues
    - large grade separation between developments and neighbouring natural land surfaces, with increased erosion and other risks
    - loss of floodplain storage, contributing to elevated regional/catchment flood risks in some areas
    - changes in the direction and rate of groundwater flow, with potential offsite impacts, including to neighbouring groundwater dependent ecosystems and watercourses

- difficulties in retaining natural vegetation within land development sites (due to grade separations).

Conversely, where fill levels are not enough to manage groundwater (due to cost cutting, poor design, etc.), there can be significant difficulties associated with groundwater expression. These costs are typically incurred by private landholders or local governments, and include:

- damage to public infrastructure (e.g. anecdotally ~ $1 million for road replacement in one example shown to the Expert Panel)
- damage to private property
- exposure to increased regional, catchment and local flood hazards
- loss of amenity (soggy backyards, flooded public open spaces, mosquito breeding etc.)
- exposure of local governments to claims for liability associated with these risks.

These examples of ‘upstream’ controls illustrate that difficulties in groundwater management in these sites are highly visible, leading to resident complaints and requiring remedial action.

On the other hand, ‘downstream’ requirements of groundwater management are related to the disposal or use of drained water. In many sites across the Swan Coastal Plain, groundwater contains elevated nitrogen and phosphorus concentrations, meaning this drainage water must be treated before discharge offsite. This treatment requirement can itself be an important driver of the use of fill to elevate the surface of the urban environment. Treatment options such as bioretention basins or vegetated swales require specified vertical separation distances from both the outlet (to a drain or waterway) and from the site drainage network (due to required grades on the drains and pipes). In practice these requirements, which govern the hydrological function of the treatment and discharge systems, often impose significant demands for fill.

As illustrated in Figure 4, standard treatment options can require 1–1.5 m of fill over the land surface to achieve their hydrological functionality.

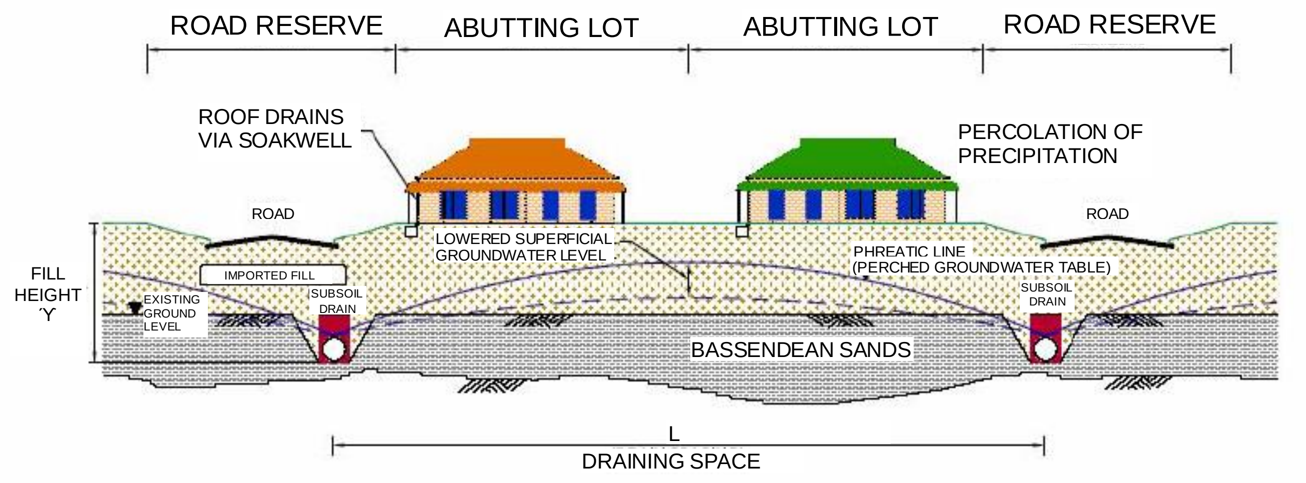

Figure 4. Typical layout of drainage water treatment systems and impacts on fill requirements
Source: Peel Development Commission (2006)

Thus, although downstream demands for fill are often less visible to residents, they represent the opportunity to address a large driver of the demand for fill. This has two consequences:

1. **Industry is aware of this large demand for fill**. In a context where fill is expensive and is not itself environmentally benign, there is a need for an evidence basis to maintain industry 'buy-in' regarding current 'end-of-pipe' treatment practices. Recent findings that 'end-of-pipe' treatment via bioretention basins and raingardens in the Swan Coastal Plain achieved excellent phosphorus removal but inconsistent nitrogen removal, add to the ambiguity around the cost–benefit of 'end-of-pipe' water sensitive urban design (WSUD) (Ocampo et al. 2017). Inconsistent performance may be due to these systems not being designed, built and maintained to best practice, and/or the systems intercepting groundwater when not designed to manage groundwater.

2. **Opportunities to innovate around the treatment or onsite reuse of drained subsurface water also represent opportunities for fill reduction**. Interestingly, unlike several other parts of the world (see Appendix E for examples of international approaches to managing high groundwater in urban areas), very little use is made of groundwater pumping on the Swan Coastal Plain to control groundwater levels in urban development areas. The implications of actively managing groundwater via pumping include the interactions of such pumping with the demands for groundwater abstractions and the ecological health of groundwater dependent ecosystems on the Swan Coastal Plain, and suggest that this option would require careful analysis if implemented. Other options such as in-pipe treatment methods, retaining water onsite, reclaiming water for alternative uses (e.g. via managed aquifer recharge (MAR) and distributing a range of smaller treatment types throughout subdivisions (Ocampo et al. 2017)) have considerable potential to reduce fill requirements. Participants in this project indicated some of these practices are already in place across the Swan Coastal Plain (in some cases having been required precisely because 'end-of-pipe' treatment was ineffective). While adopting these options in a remedial sense can be costly for local government, their cost-effectiveness if designed upfront bears examination.

In summary, the costs associated with both 'over-design' or 'under-design' of groundwater management and treatment strategies suggests opportunities to find more optimal or 'win-win' approaches to groundwater management that benefit private, public, corporate and environmental interests. For example, one participant estimated an approximate 10:1 payoff for developers by improving site characterisation and modelling upfront (advising of corresponding costs in the order of tens of thousands of dollars) and consequently reducing fill costs (saving in the order of hundreds of thousands of dollars' worth of fill).

Overall, improved practice surrounding management of development on high groundwater on the Swan Coastal Plain represents an opportunity for Western Australia. It may also provide an opportunity to showcase and innovate approaches that could lead to national or global uptake.

3. Terminology

Urban development and hydrological dynamics in regions with high groundwater interface with a broad range of scientific and engineering disciplines, each of which uses different terminology and makes different assumptions. The Expert Panel experienced several situations where different participants used the same term for quite different purposes. The most evident example of this was the term ‘infiltration’, which was used variously to mean:

- the process by which water enters the soil
- the maximum rate at which water could enter the soil (i.e., infiltration capacity)
- the rate at which water enters the soil (i.e., infiltration rate)
- the rate at which water replenishes groundwater (i.e., net recharge)
- a volume of water that can be held within the soil (i.e., a cumulative infiltration volume).

While the term ‘infiltration’ is appropriate to all these contexts, its quantitative interpretation is quite different among them. Participants also used the term ‘recharge’ quite differently. It is the Expert Panel’s opinion that casual use of terminology represents a potential source of misinterpretation, confusion and error, and we recommend practitioners attempt to be explicit and adopt a consistent glossary of terms to avoid such problems (see Appendix G for the glossary used in this report).

Additionally, people working on the problem of land development in the Swan Coastal Plain appear to have developed several colloquial terms of practice, not all of which were familiar to all members of the Expert Panel. While we, in practice, enjoyed the colour that terms like ‘shandy-ing’ bring to the otherwise dry problem of groundwater and surface water mixing in a given environment, we were concerned that such terms might also cause confusion, particularly in the context of an international and diverse workplace. We recommend practitioners reconsider using colloquial terms that describe technical outcomes and, if not avoiding these completely, at least ensure such language is adequately explained and does not become a barrier to good communication.

4. Guidance

This section is based primarily on matters raised during discussions the Expert Panel had with participants and during meetings with multi-stakeholder groups (as well as feedback on an earlier draft report). The topics and comments are also informed to various extents by the Expert Panel's knowledge of available literature and the experience and observations of the Expert Panel's members.

Therefore, the contents are not necessarily fully comprehensive nor do they necessarily cover all the most significant issues that may be faced. For example, while high groundwater conditions are often associated with acid sulfate soil risks on the Swan Coastal Plain, these matters were not routinely raised with the Expert Panel. We are also aware there is already a considerable body of guidance material for identifying and managing acid sulfate soil risks (Department of Environment Regulation (2015a and 2015b)), so this report does not include guidance on managing acid sulfate soils.

Similarly, this report does not provide further commentary several important considerations for surface water or flood modelling, such as the selection of so-called 'runoff coefficients, because the multi-stakeholder Land Development in Groundwater Constrained Environments Steering Group is quite actively considering such matters and we do not wish to cut across those discussions.

Given these factors, the Expert Panel offers the following observations, findings and guidance, to assist practitioners and regulators in considering best practices and dealing with technical uncertainties. Not all the content is purely technical in nature (and may arguably be outside the Expert Panel's terms of reference), but it may influence technical considerations and implementation of otherwise sensible technical solutions that the Expert Panel would support.

4.1 Cumulative impacts of development

Urban development in areas of high groundwater can have important cumulative environmental and natural hazard impacts. Specifically, urban development over high groundwater may impact:

(a) Regional and catchment flood behaviour

Areas of high groundwater often coincide with low-lying, flat environments, including several major floodplain areas along the Swan Coastal Plain. Therefore, development in these areas can impact on regional and catchment flood risks.

The processes by which urban development interacts with regional and catchment flood behaviour varies depending on the severity of the flood.

For larger events (greater than 10 per cent AEP), loss of available storage (or connectivity to available storage) on the floodplain associated with land levelling and filling is a major process of concern, potentially exacerbating the severity and extent of regional and catchment flooding. This warrants careful consideration. Loss of connectivity can be threshold-like in nature: for example, the final development in a floodplain area may sever connectivity between a channel and available storage in the floodplain. This nonlinearity may cause large inequities in risk, cost and mitigation requirements between otherwise comparable developments in the same floodplain area.

Changes in land surface characteristics and stormwater management, and the interaction of these processes with groundwater in urban areas, may also exacerbate flood inundation risks but are most important for 'nuisance' flooding (i.e., less than 50 per cent AEP). Nuisance flooding, although rarely responsible for loss of life, can nonetheless be extremely costly (Moftakhari et al., 2017).

The processes responsible for altering flood risk for intermediate events (up to 10 per cent AEP) in urbanised areas over high groundwater remain poorly explained and we recommend further research and investigative effort and guidance on these matters.

(b) Changes in the local direction, volume and timing of groundwater flow, and impacts on sensitive environments

Elevating the land surface using fill has the potential to alter the phreatic surface throughout the developed site relative to a pre-development condition, and to create new gradients in the water table surface. These gradients can result in changes to the local direction of groundwater flow, which are compounded by changes in the timing and availability of groundwater (e.g. a reduction in seasonal variation due to irrigation of public open space and gardens).

In addition, there may not be a clear understanding about how more localised seasonal perched water table systems interact with broader scale surficial unconfined aquifers. Ecosystems may depend on perched aquifers, which can provide a source of water as a surface or subsurface expression of groundwater. Recognising that a groundwater body is potentially perched is necessary for appropriate groundwater management since groundwater flow pathways in a perched system may differ significantly from those in the underlying flow systems. Conceptualising a perched aquifer setting requires careful consideration (and investigation) of the potential hydraulic connection between a perched aquifer and an underlying aquifer (Richardson et al, 2011).

There are also locations around the greater Perth metropolitan area where potentially sensitive environments are surrounded by urban developments that use fill (e.g. Figure 5A). The implications of the cumulative impacts of such developments, either in terms of alterations to hydrology or how these alterations may impact on ecosystems, represent, in our view, a potentially significant environmental impact of urban development in high groundwater sites and one that would be most appropriately assessed at regional, district and catchment scales to allow the evaluation of cumulative impacts.

(A)  (B) 

Figure 5A. An area in Perth surrounded by multiple urban developments, many of which use fill to elevate the land surface. The implications of this local elevation of the land surface on the local regional groundwater dynamics, and of any such hydrological changes on the ecology of the nature reserve, are unclear.

Figure 5B. A lake in the greater Perth metropolitan region showing the tell-tale green tint of an algal bloom. Eutrophication in the lake is primarily driven by groundwater inflows and became problematic approximately 15–20 years following urbanisation of the surrounding area.
Source: NearMap

(c) Regional, district and catchment nutrient loads to sensitive environments

Urban development can result in the mobilisation of groundwater with high nutrient concentrations, through subsoil drainage or through changes in the local elevation and gradient of the phreatic surface. Although regulations can and do address managing nutrient levels within discharge from the subsoil drainage system, managing nutrient export to sensitive environments via groundwater flow paths (and managing its alteration by land development) was not widely discussed with the Expert Panel. But anecdotally, several examples exist of sensitive environments that have been adversely impacted by nutrients in groundwater drainage following urban development. For example, Figure 5B shows evidence of a blue–green algal bloom event in a lake in the greater Perth metropolitan area in 2017. Current management of the lake, which has successfully reduced blue–green algae impacts, is to actively pump groundwater upstream of the lake, reducing groundwater inputs to the lake, which are the source of most of the nutrients fuelling the algal bloom. Reportedly, these nutrient issues began approximately 15–20 years after urbanisation, but it is unclear what drove that delay.

Urbanisation therefore has the potential to exacerbate flood hazards, and to change local hydrology and local water quality with broadly unknown impacts on sensitive neighbouring environments. Most of these impacts arise as the cumulative outcome of land development at regional and district scales. Current planning practices, in which detailed water management plans are typically developed and evaluated for individual land packages (i.e., at the local structure plan approval phase), make it difficult to address these cumulative impacts. Additionally, given the diversity of authorities responsible for different water bodies, ecosystems and development, the potential for these cumulative environmental impacts suggests it would be beneficial to consolidate communication and the exchange of advice between local governments, relevant state government agencies and other authorities with statutory oversight of cumulative impacts.

Further, there is an opportunity for the relevant state government agencies, in partnership with industry and local governments, to develop regional, district and catchment modelling frameworks and undertake increased modelling at regional, district and catchment scales. This practice is undertaken in other parts of Australia and warrants further consideration on its applicability to Western Australia. In this way, there will be a better opportunity to more clearly understand where subsurface drainage will go, how it will impact GDEs, how water quality will be affected, how its abstraction will impact regional and local groundwater levels, who will bear the costs for offsite management and remediation of poor quality water, and the like. This can also be a further area of research, recognising that multidisciplinary research, which more broadly considers these impacts, will help decision makers to identify suitable urban development.

4.2 Site-based risk assessment

Despite the potential for cumulative impacts of development noted above, the Expert Panel heard that, for most locations, the pertinent scale for undertaking technical groundwater assessments and modelling is an individual development parcel.

The risks associated with the presence of high groundwater (to either the development itself or to sensitive neighbouring environments) are not uniform across all sites, and this lack of uniformity means that the appropriate level of site investigation, modelling and design/management should also be tailored to the level of risk.

Therefore, we recommend the first assessment that developers and consultants should undertake is a risk assessment to classify the land parcel into one of three broad categories of risk. Further, adopting a consistent agreement about this classification and its consequences with planners and regulators across municipalities would streamline expectations for developers and become an initial evaluation approach for local governments.

The three risk categories below are presented in initial qualitative rather than quantitative terms, and then summarised in a risk matrix that attempts to identify indicators of risk. In general, the risk attached to a site should be the highest risk level flagged by the presence of any individual indicator suggested below and in Table 1.

The Expert Panel recognises the details for these risk categories may be improved over time as more information becomes available and local understanding grows. We recommend that the guidance be updated from time to time accordingly.

We also recognise the risks associated with urban development in high groundwater areas often fall within a spectrum, rather that always fitting neatly into a low, medium or high category. In addition, there is likely to be a 'step change' in the level of monitoring, investigations, modelling and assessments required (and corresponding time and financial resources) as one moves from low to medium risk, and medium to high risk, sites. Consequently, the choice of approach needs to be considered carefully, justified transparently and preferably agreed early between the proponent and the regulator. Providing guidance around risk levels is intended as a basis for such discussions, not a prescriptive requirement.

Low risk:

Low risk sites are those where:

- 'high' groundwater is nonetheless deep enough (e.g. greater than 2 m below the surface in sandy soils) to accommodate subsurface infrastructure between the water table and the land surface in all likely events
- there is unlikely to be a large change in net recharge (i.e., recharge minus evaporation from the water table) between pre- and post-development conditions
- soils are homogeneous, permeable and well characterised
- any subsoil drainage water would be retained on site or consumptively used off site
- neighbouring land parcels do not contain sensitive environments (GDEs, streams, or other high value natural environments)
- pre-development land use is unlikely to have created legacy nutrients or other groundwater contamination.

In these sites, although the water table may be within 4 m of the land surface, it is nonetheless unlikely to interact with urban infrastructure, to be greatly changed in its level by urbanisation, or to present a water quality threat. Moreover, these sites are well understood in terms of their geotechnical and soil behaviour. They might therefore be considered relatively ***low risk***.

Moderate risk:

Moderate risk sites are those where:

- 'high' groundwater lies approximately 2 m below the land surface, or will be controlled at around that level via the use of subsurface drainage
- there is potential for some moderate change in net recharge (i.e., recharge minus evaporation from the water table) between pre- and post-development conditions

- soils exhibit some heterogeneity and are more challenging to characterise
- drainage water requires offsite disposal, but the site is unlikely to have significant legacy nutrients.

These sites are likely to employ engineering techniques, specifically subsoil drains, to control the phreatic surface. This level of control may successfully manage risks associated with high groundwater, provided the drains are appropriately designed. In sites where there is confidence in soil properties and post-development changes to net recharge, this design can focus on the question of drain sizing, grade and spacing, without requiring complex modelling. Therefore, such sites might be considered relatively ***moderate risk***. Even in sites using subsoil drainage for groundwater control, the presence of legacy nutrients, nearby sensitive environments, or the potential for large changes in net recharge associated with land cover change could elevate risk.

High risk:

High risk sites are those where any of the following may apply, individually or collectively:

- the pre-development water table approaches or intersects the land surface
- large changes in net recharge (i.e., recharge minus evaporation from the water table) are expected to occur between pre- and post-development conditions
- regional groundwater conditions tend to drive water into the site (e.g. sites located within a regional groundwater col; i.e., at the convergence of flow paths)
- soils are heterogenous, containing significant clay or limestone, and/or are poorly characterised
- neighbouring land parcels contain sensitive environments (GDEs, streams, or other high value natural environments)
- pre-development land use is likely to have created legacy nutrients or resulted in other forms of groundwater contamination
- the site is the ‘last’ in a series of regional or district scale development projects, such that it could generate threshold changes in connectivity and flow paths (surface or subsurface) in a catchment or sub-catchment.

These sites are likely to need detailed investigations, assessments, engineering design and three dimensional groundwater modelling (or very strong justifications provided as to why they would not be needed), to understand and manage the impacts of urban development on groundwater flow, water quality and, in some cases, regional or district scale land use change impacts (e.g. regional and catchment flooding). These sites are likely to be complex and require a higher investment in characterisation than lower risk sites. They may exhibit greater uncertainty about the direction and magnitude of future changes in recharge, and thus in both the level of the phreatic surface and the volumes of drainage water produced. Therefore, they might be considered relatively ***high risk*** sites.

Table 1. Risk matrix relating site indicators to risk classifications

	Low risk	Moderate risk	High risk
Pre-development groundwater level (depth)	>> 2 m	~ 2 m or > 2 m (with subsurface drainage controls installed)	< 2 m or groundwater col (where mounds intersect)
Pre-development groundwater abstraction	Cleared, pastured land (no groundwater abstraction)	Some tree cover (likely some groundwater abstraction)	Dense tree cover Previous irrigation allocation (likely high groundwater abstraction)
Soil type	Sand only	Sand with clay lensing	Significant clay areas, or complex heterogeneous soils
Receiving environments	Waters retained onsite or used consumptively	Waters discharged offsite (e.g. into surface drains)	Sensitive receiving environments
Other environmental constraints	Not located near floodplains, GDEs or other sensitive environments Isolated from other development		Proximity to GDEs Location in floodplain 'Last' development (cumulative impact)
Pre-development land use/water quality	Low legacy nutrients (e.g. native bush sites)		High legacy nutrient burden (e.g. agricultural sites, wetland sites) Other contamination (e.g. brownfield sites)
Minimum modelling tools required	Controlled groundwater level with steady state or dynamic 1-D model	Two-dimensional groundwater drainage model (or 1-D assessments with cautions)	Three-dimensional groundwater model (as the default without very strong justifications otherwise)

(Note: Meeting any one of the high risk criteria can trigger a high risk classification. Meeting any of these criteria should therefore trigger a deliberate groundwater risk assessment, but it is also possible that a high risk criterion could be met without the site being high risk overall; for example, dense tree cover is unlikely to be problematic at a site where pre-development groundwater levels are very deep. For this reason, these criteria represent guidelines that can be used to shape specific risk assessment and evaluation conditions between regulators and proponents on a site-by-site basis).

4.2.1 Guidance on controlled groundwater level (CGL) assessment

The Expert Panel is aware that guidance has been previously provided about water resource considerations when controlling groundwater levels in urban developments in Western Australia (Department of Water, 2013) and about specifying separation distances for groundwater controlled urban development (IPWEA, 2016). We broadly support these approaches and we were informed that the development industry and regulators support them too.

The controlled groundwater level (CGL) has been defined as the invert level of groundwater controlling infrastructure. But the Expert Panel heard more technical work is required so that the existing guidance can include more advice about determining ecological water requirements, particularly for sensitive environments. More information about additional technical work that could be expected to inform future guidance is in section 5.

Interestingly, some participants outlined how they use the average annual maximum groundwater level (AAMGL), which reflects the long-term peak groundwater behaviour at a site under pre-development land conditions. It may be suitable for characterising potential groundwater dynamics in low risk sites, but is not well suited to use in medium or higher risk sites because:

- it is not risk-based (so the probability of an exceedance event is not characterised by this method)
- it does not account for prospective changes in net recharge following urbanisation.

Consistent with Department of Water (2013) and IPWEA (2016), industry best practice for determining the CGL at a given site requires:

- two years of onsite monitoring
- identifying the nearest appropriate long-term monitoring well/s
- bias-correcting the monitoring well data (e.g. by applying a simple additive correction factor) to match the observed onsite monitoring data over this two-year period
- using the bias corrected groundwater monitoring data to identify the groundwater level behaviour over the past 30 years
- using this information to determine the level/s against which clearances are developed.

We have supported using a 30-year period to: (i) avoid problems with small sample sizes (likely to arise for shorter records), and (ii) to reduce the difficulties associated with non-stationary climate in Western Australia, which will be more pronounced for longer averaging periods. Future climate projections may also be considered with cautions. The aim of the analysis of historical groundwater levels should be to obtain an adequate understanding of the groundwater behaviour, recognising the quality of the available data, trends observed or expected, risks to be managed, and outcomes to be achieved.

In applying this method, it is important that monitoring data are used directly, and that regional groundwater maps such as the Perth Groundwater Atlas should *not* be used to compute the CGL. This methodology should also involve careful consideration of the selected bores used (e.g. to ascertain whether they are relevant to the development site in terms of geology, groundwater connectivity, and proximity), and scrutiny of the monitoring well data behaviour relative to onsite monitoring. Very large differences in groundwater levels, very large differences in seasonal or event-based responses, or differences in the sign of any trends over that two-year period may indicate very different processes occurring between the development and the long-term monitoring bore locations. These features indicate the selected bore is a poor proxy for the development site.

Limited periods of record, sparse bore networks, or changes in climate, geology, and hydrologic connectivity of the groundwater between bores and development sites can all make the recommendation to use 30 years of groundwater monitoring data as a proxy unachievable or inappropriate. In these circumstances, using a shorter period for analysis may be reasonable, or using alternative proxies for long-term groundwater fluctuations, such as rainfall records, could drive bias correction instead. Further research could focus on developing worked examples and standard methodologies for these options.

Further, with the extent of urban development related groundwater monitoring that has been and will be undertaken, it would seem highly desirable that a groundwater information repository be built, into which pre- and post-development monitoring data, collected to some agreed protocols and standards, could be deposited for the development industry and all agencies involved in regulating and facilitating development to use. This would address the lack of use of these data, by putting them in a georeferenced, searchable system, and would certainly start to increase the density of 'ever monitored' locations across the Swan Coastal Plain.

4.2.2 Guidance on one-dimensional groundwater model assessments

One-dimensional (1-D) assessments aim to estimate the height of the groundwater mound created by recharge within a landscape in which groundwater controls operate (e.g. subsoil drainage).

The most widely adopted method for these assessments is a steady state solution for flow in an unconfined aquifer between two drains—typically, Hooghoudt's equation. But using steady state, one-dimensional equations has several limitations:

- The optimal averaging process by which to assess appropriate recharge values for sizing fill levels is unclear; supporting data and local observations may be lacking; and the steady state solution is especially sensitive to the choice of recharge values and changes in groundwater levels.

- Steady state techniques preclude developing a risk-based metric (so this method cannot characterise the probability of specific exceedance events).

- 'Typical' solutions to Hooghoudt's equation consider spatially uniform recharge, which is unlikely to occur in urbanised sites.

These issues are taken up in the IPWEA (2016) guidelines, which recommend an approach to using the Hooghoudt equation, in which the 72-hour, 50 per cent AEP rainfall is recommended for design purposes if the Hooghoudt equation is used. While this is appropriate from the perspective of reducing the risk of undersizing fill, this approach doesn't optimise fill use.

Additionally, using one-dimensional models has some challenges:

- <u>Site characterisation</u> – This is particularly due to heterogeneity of site soils. Take particular care to delineate areas of clay lensing or limestone, and note models run separately for different soil types within a site.

- <u>Model parameterisation</u> – Two major sources of model parameter uncertainty are relevant to the one-dimensional models: K_{sat} and its variability, and net recharge under pre- and post- construction environments, considering that rainfall events may present large temporal variability, affecting infiltration rates and allowing recovery of infiltration capacity over time.

  K_{sat} estimates should consider a realistic range of values for sensitivity analysis. The range in K_{sat} for fill sand quoted to the Expert Panel was 1 m/day–10 m/day, with a typical design assumption of 5 m/day, and it would be sensible to understand the sensitivity of proposed designs to this range of variability. Any current practice that involves a sensitivity analysis of only +/- 10 per cent is insufficient to capture this potential range of variability. Because fill regularly fails to exhibit the design K_{sat} value, failure to adequately characterise post-construction fill and/or test design robustness to the feasible range of fill conductivities poses a risk. It is also important to note that, in site characterisation, K_{sat} should be measured at the relevant depth for the model and not just at the land surface.

When considering net recharge behaviour, it is worth noting that, in terms of spatial averages, the total volume of infiltrated water is likely to be similar pre- and post-development (particularly under sites that rely on using soakwells to infiltrate impervious surface runoff; while sites where these areas are directly connected to the stormwater system could reduce infiltration volumes more substantially). But abstraction, transpiration from the unsaturated and saturated zones, and evaporation from water tables are likely to be lower following urbanisation, and recharge is likely to be more concentrated spatially in urbanised sites. These issues should be addressed separately. To assess net recharge under vegetated conditions, an unsaturated zone water balance model can be used. The common current industry practice of estimating net recharge and/or evapotranspiration as a fraction of precipitation is non-physical and particularly inappropriate if non-stationary climate conditions are to be considered. Characterisation of gross recharge beneath different components of the urban landscape remains a major uncertainty that requires further research (Ocampo 2018).

- Conceptualisation – Frequently, the Hooghoudt equation is applied along a transect perpendicular to the orientation of two parallel drains. This transect is not appropriate if the drains slope downhill, because the direction of the steepest slope of the water table will then also be slanted downhill. This will effectively extend the distance over which groundwater flows. Thus, the transect distance may need to be increased. Alternatively, the site could be engineered to minimise the groundwater flow path distances between drains (e.g. by grading the subsoil clay).

  Additionally, spatial heterogeneity in net recharge across different elements of the urban landscape (e.g. soakwells versus roads versus paving versus houses) may have a significant influence on the overall shape of the groundwater mound, as can the efficiency of the drains in removing water from the soil locally.

Software is available to address—at least partially—difficulties associated with steady state recharge assumptions and difficulties associated with the heterogeneity of recharge, by using the Hooghoudt equation in a pseudo-steady fashion and solving it piecewise for locations of different recharge. This approach is promising, although subject to the remaining uncertainties regarding flow path length, appropriate estimates for gross recharge underneath different forms of urban landscape, and the importance of transient conditions for creating groundwater mounding. It may be possible to use AEP methods where such pseudo-steady models are used, although the correspondence between AEPs estimated from pseudo-steady solutions and AEPs estimated for fully transient models under otherwise identical conditions should be explored before doing so.

Therefore, we suggest that best practice for using 1-D groundwater models involves:

- characterising in detail the post-development land surface or sensitivity analyses for K_{sat} that explore the full feasible range of values for fill
- running models under different climate scenarios to estimate pre-development net recharge rates
- adopting the assumption that infiltration volumes remain unchanged but evapotranspiration is greatly reduced (potentially to nothing) to estimate post-development, spatially averaged net recharge values
- using pseudo-steady, spatially variable recharge tools to solve the Hooghoudt equation, including estimates of AEP.

But future research is required to provide confidence in this approach and potentially to determine suitable correction factors, specifically:

- developing a simple methodology to correct the drain spacing to account for additional flow path lengths for graded subsoil drains
- measuring and characterising gross recharge rates beneath different components of urban infrastructure
- characterising AEP error associated with using pseudo-steady rather than fully transient models.

4.2.3 Guidance on 2D and 3D groundwater assessments

Two- and three-dimensional groundwater assessments require running a distributed groundwater model. Consultants widely use several packages, which broadly represent the best practice tools. These packages are generally necessary for high risk sites, complex designs, and in situations where developers aim to minimise the use of fill.

There are several advantages to adopting a two- or three- dimensional modelling methodology. The first is that these models are fully transient. This makes it feasible to use climate time-series to force the model. The results of long time-series or Monte Carlo runs can then be evaluated in terms of exceedance probabilities related to different peak levels of the phreatic surface, and thus used in an annual exceedance probability (AEP) framework. We recommend that practitioners follow ARR 2019 (Book 3, chapter 2) methods for estimating events per year or annual exceedance probabilities from a time-series, but that they develop such time-series using long-term (at least 30 year) model runs. Selecting an appropriate forcing time-series is problematic: the longer the time-series, the greater the confidence in the resulting AEP behaviour, but long time-series cannot be obtained from historical weather data due to the non-stationarity in the climate. In this context, it may be appropriate to use stochastic weather generators to create time-series for Monte Carlo simulation. The AEP behaviour discussed here relates to the groundwater response probability and *not* the rainfall event probability. The aim is to understand the long-term groundwater level behaviour from the observations and the modelling.

Using a more complex model does not alleviate the characterisation and uncertainty challenges relevant to one-dimensional models and, again, care must be taken in site characterisation, sensitivity analysis, and estimating net recharge behaviour.

Using both two- and three-dimensional models requires calibration and sense checking. Calibration should be undertaken to the bore levels and fluctuations in the pre-development model. Sense checks (e.g. ensuring that the model indicates groundwater at the surface during winter in areas of a wetland/lake) can provide better spatial insight across sites than purely relying on monitoring bores.

4.2.4 Inherent limits of model certainty

In the context where minimisation of fill is a goal, it is unknown whether modelling can ever provide a sufficiently precise prediction to control risks associated with groundwater.

In general, the uncertainty in soil parameters, recharge rates, and model ‘correctness’ are not well understood, meaning that the margins of error to be expected around model results are also poorly constrained. There is a need to more closely examine current approaches to infiltration modelling and consider the findings reported in Ocampo 2018 (summarised in Appendix D) and CRCWSC 2019.

Options could be to invest in either better modelling and better understanding of uncertainty, or to consider design methodologies that are more robust with respect to the relevant uncertainties.

4.3 Design to minimise fill and/or waterlogging risks

The extent to which improved parameterisation, model sophistication and modelling expertise can reduce the uncertainty around performance of groundwater management systems and thus give confidence about post-development groundwater levels, even in sites with groundwater controls installed, remains unknown. This means that at present, and for the foreseeable future, there is a degree of risk associated with engineering design to control groundwater.

Broadly, there are three options for managing this:

(i) ‘conservative’ (i.e., more rather than less) use of fill under all circumstances

(ii) fill minimisation plus design to mitigate against high groundwater

(iii) accept that some things will not work out and ‘correct’ them after problems emerge.

At present, many authorities are opting for option (i). But, as previously noted, conservative use of fill has many economic and environmental downsides.

Situations that seek less conservative use of fill could employ a range of designs to mitigate high groundwater at lot rears, which may be appropriate to consider given the limitations of modelling and design. These include:

- landscape designs that accommodate periodic waterlogging in gardens – examples could include developing rain gardens/winter gardens (Harlow and Coate 2004) or using raised garden beds/lawns to provide clearance to *only* the components of the yard that need protection from wet soils. Appropriate education for the homeowner, new buyer and/or community could support these approaches

- drainage designs that provide additional subsurface drainage from the rear of lots – for example, short and directly connected (to stormwater) subsoil drains could be installed in the expected location of the groundwater mound in the rear of each lot. Although this would create an element of drainage infrastructure that homeowners would need to manage (again, supported with appropriate education), responsibility for maintenance could be similar to that for on-lot sewerage. Demonstration sites to show the feasibility of this approach would also be beneficial

- drainage designs that enhance drainage from the rear of lots – for example, by grading any underlying clay towards roadside subsoil drains. This option has proven successful, but can only be used where there is underlying clay

- surface drainage from lots – which should also be considered in locations where high groundwater may impact lot rears, by grading the lot so that any surface flooding that does occur has a viable surface flow pathway to the street and the stormwater drains.

Additionally, fill depths may be reduced if pipe grades can be made shallower, reducing the fall needed across the pipe length. This could reduce the need for fill. While the United States has experience with shallower pipe falls, and the ASCE recommends a minimum 1:1000 grade for stormwater pipes, a grade of 1:500 is more common in Western Australia. Some local governments reported blockages in 1:1000 grade pipes.

4.4 Assessing performance

The performance of existing groundwater management designs, and of urban stormwater infrastructure in high groundwater areas, is not well understood. Broadly, there would be value in understanding:

- whether systems function as designed (e.g. location and height of phreatic crests relative to predictions, volumes and timing of subsoil drainage water relative to predictions)

- how system function changes over time (e.g. does the efficiency of subsoil drains vary over their life, how is performance impacted by maintenance schedules, what is the functional lifespan of in-situ water treatment methods?)

- whether the presence of high groundwater alters system functionality (e.g. how does soakwell performance vary with depth to groundwater, and how does WSUD performance vary with increasing contributions of groundwater to surface water runoff?).

Developing this understanding is challenged by the requirements of post-development monitoring. Often, monitoring is not initiated until the final stage of a multi-stage development (which may be rolled out over a 10–20 year period). This gap represents a lost opportunity for adaptive management when problems do arise. Also, the required 2-year period for post-development monitoring may not be long enough to assess changes in system performance with age.

4.5 Available guidelines

Practitioners can access many sources of guidance. Broadly, we recommend that practitioners attempt to achieve site characterisation, modelling, design and approval with:

1. the IPWEA WA draft *Specification for separation distances for groundwater controlled urban development* (2016) and its references. During the consultation process we spoke with several stakeholders who remain concerned that some clearances in this document (lot rears and playing fields, particularly) may not be sufficient to reduce risks to acceptable levels. But it is not clear whether the waterlogging reported at such locations is actually due to insufficient clearance or whether there were confounding factors such as poor design, poor parameterisation (K_{sat} etc.), lack of maintenance, blockages in the designed system, or unforeseen outlet controls. These specific levels and clearances should be subject to ongoing discussion

2. ARR 2019. This represents a national consensus on best practice in numerous areas of urban stormwater management. We recommend that local governments and state government agencies adopt (and publicise their adoption of) ARR requirements as updated in 2019. Designs or analyses that use outdated methods or that attempt to mix and match methods from different iterations of ARR cannot be considered best practice.

While only a few participants in this project mentioned them, we also recognise and support using documents such as the Australian groundwater modelling guidelines (Barnett et al. 2012), the Australian GDE assessment framework (Richardson et al. 2011), the Western Australian local government guidelines for subdivisional development (IPWEA 2017), and several documents by the Department of Water (2007, 2008, 2013) to support WSUD and the Better Urban Water Management (BUWM) framework (WAPC 2008).

4.6 Approaches to standardise aspects of modelling and design review

Local governments are key decision makers in urban water management plans, and they also frequently incur liabilities associated with failure to adequately manage groundwater/surface water in urban developments. Local government agencies are acutely aware of these responsibilities and concerned about their skill, time and financial capacities to fulfill them in increasingly complex development environments, including those impacted by high groundwater.

In this context, approaches that can simplify, streamline and support local government decision makers would be valuable. One such approach is to develop checklists that local governments can use to rapidly 'sense check' modelling for individual sites. For example, local government could require that consultants supply them with models of the pre-development water table level, a pre-development LIDAR surface (if available), pre-development aerial photography, and post-development land elevations and modelled water table levels. With these data (particularly if they could be dynamically overlaid with each other), it should be possible for local government to identify some basic questions about the coherence between models of groundwater behaviour and observations. For example, local government authorities could check that:

1. surface water features such as lakes and wetlands in the site are consistent with the predicted groundwater surface (the difference between the land surface and the water table height should be >0 at these locations)

2. the post-development surface provides enough clearance to the modelled groundwater levels (which could allow authorities to determine whether the design is robust to any errors/uncertainties/assumptions identified in groundwater modelling)

3. high groundwater locations (and any errors/uncertainties associated with estimating the phreatic surface in those locations) will not have problematic implications, such as on the functioning of public open space or other aspects of liveability.

At present, a key limitation to employing such approaches may be software and access to geospatial tools, resources and skills. Developing open source and accessible graphical user interfaces (GUIs) to automate these tasks for local government authorities could greatly facilitate these kinds of checks.

4.7 Capacity building and advice

Not all local governments have appropriate capacity to assess technical, hydrology, hydrogeology and/or engineering information, including modelling. There are two major difficulties: (i) the lack of a funding model to support time investment in such assessments, and (ii) whether local governments can employ personnel with sufficient technical expertise to perform them. In addition to the points raised in sub-section 4.6, further institutional changes could potentially create such capacity.

Several participants indicated that a centralised technical review/advice hub (hosted by, for example, regional councils or a collection of local governments) could provide a way to consolidate this role with appropriate specialists. Professional representative bodies such as IPWEA, Engineers Australia, the Australian Water Association and others, and local initiatives such as New WAter Ways, can also help in this space via training, peer support, mentoring, networks and so on. For example, industry and regulator capacity could be bolstered by further education and training programs, especially for early and mid-career professionals, building on up-to-date guidance materials and those delivered by New WAter Ways, the National Centre for Groundwater Research and Training, and others.

4.8 Legal frameworks

Some legal frameworks for managing and having responsibility for drainage infrastructure are unclear in Western Australia (and elsewhere). More specifically:

- Responsibility for groundwater drainage infrastructure housed within private lots is not well understood, which has implications if this approach is otherwise technically sound. It also has implications for maintenance in particular, and without appropriate maintenance, the lot (and more broadly) can be adversely affected.

- Drainage, especially that which is relevant to managing water in areas subject to high groundwater, is not subject to specific legislation, although the *Local Government Act 1995* and the Common Law both address some aspects of drainage. Issues such as infrastructure on private land which needs to be maintained to achieve public good (e.g. subsoil drainage systems) falls into a legal grey area and may subvert otherwise sensible technical solutions.

While it is not within the Expert Panel's terms of reference to suggest improvements to legal frameworks relevant to urban developments and drainage in high groundwater environments in the Swan Coastal Plain, we certainly encourage stakeholders to further explore the policy issues and options, including greater legislative clarity, to reduce or remove barriers to implementing otherwise sensible technical solutions.

4.9 Changing building practice and behaviour

Many participants who spoke with the Expert Panel indicated frustration with the lack of innovation around building methodologies and urban and built form and how these intersect with water management. Demonstration projects would provide important certainty around innovation in this space, which could encourage greater experimentation and confidence in a broader range of building and urban development strategies. Types of demonstration project that may be particularly valuable in locations subject to high groundwater risks include:

- projects using 'novel' house construction methodologies other than concrete slab on ground and double brick exterior walls (e.g. projects using so-called 'lightweight construction')

- projects that innovate with on-lot and/or whole-of-development water detention (versus infiltration/disposal)

- projects that implement on-lot mound drainage

- projects that innovate around garden or other landscape design for high groundwater in yards and public open spaces.

4.10 Changing the planning, building and construction approval processes

The Expert Panel heard that, under current planning and approval frameworks, it is challenging to achieve consistency between environmental design, civil design, and the 'as built' nature of developments. Since it is desirable to seek to optimise designs around groundwater management (for instance, by requiring the use of certain soakwell specifications and locations to achieve appropriate groundwater clearance), this challenge may need to be confronted. Separation of responsibilities under different pieces of legislation and within many local government departments exacerbates the challenge.

4.11 Recovery of groundwater drainage flows

The recovery of groundwater from subsoil drainage systems represents a potentially valuable water supply option. This is an exciting and important opportunity for development to synergise with improved water sustainability. Other than work by Davies et al. (2018), research in this topic remains fairly preliminary (e.g. in locations where existing groundwater use entitlements are fully allocated and/or fully used, but unmet water demands still exist or are increasing), and some stakeholders are scrutinising it, including water resource management and regulatory agencies. The Water Corporation and the Department of Water and Environmental Regulation, in partnership with other stakeholders, have been undertaking a feasibility of a subsoil MAR trial, which will help address some of the issues. This project can provide more information about recovery of groundwater drainage waters. The Expert Panel considers it too soon to offer guidance on how to undertake such recovery, but strongly supports ongoing investigations into realising the benefits of this potential water source, while also ensuring acceptable water quality and ecological impacts from use and reuse of groundwater from subsoil drainage systems.

4.12 Performance of WSUD in high groundwater environments

The presence of high groundwater can impact on the performance of numerous WSUD technologies. It can alter conditions in the unsaturated zone and thus change infiltration rates and detention times, or if groundwater discharge is downstream of WSUD infrastructure, it can re-introduce high nutrient water following treatment (e.g. see Ocampo 2018 and other previous work by the CRCWSC). The Expert Panel saw several cases where WSUD infrastructure had been designed and/or constructed inappropriately for the high groundwater conditions and so was not performing well. We also saw cases of poor or no maintenance leading to ineffective performance of the WSUD infrastructure.

In general, WSUD design should be able to accommodate high groundwater *if* the design is undertaken with an awareness of the presence, behaviour and quality of groundwater, and is optimised to treat groundwater or to account for the implications of groundwater on the hydraulics of WSUD elements. Thus, in these environments, WSUD should be deliberately designed with the hydraulic and water quality implications of groundwater dynamics incorporated into it.

4.13 Off-site impacts of fill on hydrology, hydroperiod and ecology

Many interview participants agreed that it is probable that extensive urbanisation and widespread use of fill in proximity to sensitive natural environments (particularly GDEs) will alter the hydrology and hydroperiod of these environments. But the Expert Panel did not hear much discussion about this issue requiring management through subdivision drainage design, and no-one we spoke with was aware of specific monitoring to document this issue. The Expert Panel is aware that this may reflect a gap in the range of stakeholders interviewed, but there was some commentary that significant groundwater quality impacts, including biogeochemical impacts, on some parts of the Swan Coastal Plain have arisen as a result of urban developments and modification of groundwater levels in recent decades. Nonetheless, there appears to be a need to determine the impacts of the extensive use of fill and the resulting grade separations between natural land surfaces and urbanised land surfaces on hydrology and hydroperiod in sensitive environments.

4.14 Clarity of geotechnical investigations and options

On several occasions, the Expert Panel heard of the challenges that modellers, design engineers and assessment staff face while interpreting and evaluating the results of geotechnical investigations, especially in highly complex and heterogeneous sites and with different methods being used to measure parameters, including basic ones such as hydraulic conductivity. Hydraulic conductivity can be measured in the field or in the laboratory using several standard methods. We heard that at least five different methods are commonly used in the Perth region, althought the estimates (typically of saturated hydraulic conductivity) are not necessarily comparable between these methods. Practitioners need to adopt a standard approach for consistency and added to procedural guidelines.

It is important that there is not a mismatch between the geotechnical information and what the hydrologists are trying to do with it. The two professions should liaise closely as investigations and assessments are undertaken. This includes geotechnical investigations both at the development site and for any fill materials that may be imported. Participants reported they had observed significant differences in fill geotechnical and hydraulic properties, even at lot scales. This emphasised the importance of post-development/post-compaction tests.

In addition, some participants commented about the lack of clarity in the hydraulic performance (imperviousness or lack thereof) of peat, especially in circumstances where it is not removed from the site and replaced with imported fill, with such removal and replacement being the more common practice for residential development on the Swan Coastal Plain. We were not made aware of any work that would prove performance under a range of circumstances. So, this could be investigated further, recognising there may be potential for groundwater acidification, increased underground fire risk, carbon dioxide emissions, and impacts on the surface and subsurface flora and fauna that such soils sustain.

4.15 Transparency and coherence in technical reports

As mentioned, the Expert Panel knows about other guidance on preparing district and local water management strategies and urban water management plans under Western Australia's Better Urban Water Management framework (e.g. see the Department of Water and Environmental Regulation here or here). But several participants indicated that further guidance is desirable and better practices are required for transparency and to justify the modelling parameters and assumptions used to support those strategies and plans. This includes demonstrating consistency and coherence in modelling across the various scales of planning and design, justifying any changes made, conducting sensitivity testing, and handling uncertainties.

This report goes only a small way to providing such additional guidance, and we support further development of it over time as new data, information and knowledge become available.

5. Recommendations for future research or other work

The Expert Panel was advised of numerous areas where additional research is needed. We have identified some of those needs and described ways to address them in earlier sections. In this section, we focus on the priority technical knowledge gaps and needs for new tools associated with development practices in high groundwater environments on the Swan Coastal Plain. It is not a comprehensive list of technically related research needs, nor does it cover specific improvements in commercial, legal and planning frameworks surrounding urban development, which were beyond our brief. Despite this, we certainly encourage stakeholders to further explore the policy issues and options, including greater legislative clarity, to reduce or remove barriers to implementing otherwise sensible technical solutions.

The priority knowledge gaps identified here are to:

(i) improve understanding of recharge dynamics of the pre- and post-development landscape

(ii) improve understanding of the risks associated with common modelling assumptions

(iii) develop tools to help local governments assess proposals.

Further longer term work includes establishing, monitoring and evaluating demonstration projects as discussed in sub-section 4.9 and below, to extend proof-of-concept ideas into reality and achieve practice change under Western Australian conditions.

We acknowledge that while stakeholders should progress these priority knowledge gaps, research in this area will be of limited benefit if practitioners don't understand how changes to the local hydrology (including water quality) will impact on the receiving environments or adjacent environmental assets. We support the research underway to better identify and understand impacts of urban development on estuaries, and would like stakeholders to consider similar research for terrestrial ecosystems. For example, what are the ecological water requirements and what are the tolerable changes to groundwater levels and quality such that key groundwater dependent ecosystems are protected? This underlying need is fundamental to protecting Western Australia's environmental assets, and should be a consideration in all stages of research, modelling, legislative approvals and development.

While the priority list above can be sensibly undertaken in the order in which it's presented here, it could also be progressed iteratively as resources and circumstances permit. The Expert Panel believes that undertaking this further work will improve informed decision making, mitigate unacceptable risks, and achieve better environmental, economic and liveability outcomes.

We believe that progress in these research areas and further work, plus developing and following improved guidance, is imperative. Without it, the impacts of high groundwater will continue to generate harm in several areas of urban development and sensitive environments within the Swan Coastal Plain; result in the use of excessive amounts of onsite sand-based fill, which add to urban development costs and impact housing affordability; and lead to nuisance flooding and damage to public and private infrastructure in at-risk locations.

5.1 Improve understanding of recharge dynamics of the pre- and post-development landscapes at a range of scales

Despite many years of groundwater level monitoring (and in many cases the available data not being analysed) and the considerable detailed work in regional scale groundwater assessment and modelling (Department of Water 2009), the evaporation and transpiration dynamics of pre-development high groundwater landscapes across the range of relevant scales are poorly understood.

In addition, past work recognises that recharge is more sensitive to water level change when the water table is close to the surface. For example, Barr and Barron (2009) simulated that the average monthly ratio of infiltration to rainfall has a subtle maximum in June and then slowly decreases for the rest of the wet winter period. This is because the water table reaches the surface in the low-lying areas, either stopping the infiltration altogether or reducing the infiltration rate to the same rate as leakage to the deeper parts of the aquifer. They classified this as a ‘rejected recharge’, which may offer opportunities as a consumptive water source. They also simulated that the monthly ratio of recharge to rainfall has a minimum in late autumn (May) and then increases through the winter–spring period. The gradual increase in the recharge occurs because infiltration associated with the early winter rain takes time to infiltrate through the soil profile to recharge the deeper water table areas, and because the rise in the water table during winter reduces the time it takes for the infiltration to reach the water table.

Of course, recharge dynamics are much more variable than even monthly changes would indicate, and such changes are important to the planning and design of urban developments. This means that characterising recharge in pre-development landscapes is difficult. It is also difficult to understand likely net recharge changes post-development, which are often driven less by increases in the volume of water infiltrating and percolating through the unsaturated zone following land cover change, and more driven by changes in water uptake from the unsaturated zone/capillary fringe following removal of pre-development vegetation.

In the context of the post-development landscape, recharge is likely to be highly spatially variable depending on the installation of subsurface infrastructure (e.g. soakwells, drains) and land cover features (e.g. roads versus paving). There has been very little research to quantify these differences which can be quite influential on the spatial pattern of the phreatic surface (according to models). Measuring recharge across the range of these infrastructure types, ideally under different conditions (e.g. soakwells with large, small or no clearance to the phreatic surface, or on sands or in fill above clay), is important to better understand the performance of infrastructure and site-level water table dynamics. Such performance may well change over time, so targeted long-term drainage and related water table control infrastructure performance monitoring, assessment and evaluation are also matters for further research, as outlined in sub-section 4.4.

Building on the findings and recommendations of previous projects by the CRCWSC (Ocampo et al. 2017; Ocampo 2018; CRCWSC 2019), this work should be the essential ingredient of the subsequent phase of IRP5 that commenced in early 2020. The research can also be augmented over time by appropriate analyses and evaluation of pre- and post-development monitoring already (or to be) undertaken by developers and/or their consultants, and by incorporating water quality and future climate impacts. There are considerable opportunities for the urban development industry, regulatory agencies and academia to work together to improve the knowledge base and so improve best practice guidance over time. Stakeholders should also consider research to develop/assess new and innovative technologies/methods to measure aspects of the urban water balance which are more accurate and practical, cheaper, more reliable, and/or more suited to urban systems than current options.

5.2 Improve understanding of the risks associated with common modelling assumptions

One of the most common simplifications associated with modelling is using steady state equations to describe the phreatic surface. By neglecting transient conditions, these equations may over- or under-state the risks of the water table crossing defined thresholds. Transient modelling of comparable scenarios (e.g. comparing Hydrus 2D models to SammEE) across multiple winter storm realisations and for different soil/infrastructure conditions would give insight into the risks from using steady state approaches and whether these risks are reasonable or not.

Additionally, using three-dimensional models to explore steady state flow paths between inclined drains could help develop guidance on the appropriate selection of a transect along which to apply 2D flow equations.

5.3 Develop tools to facilitate local government assessment of proposals

Consultation with practitioners identified several low cost and sensible immediate checks that local government could make to ‘sense check’ consultant modelling. But many of them require some level of GIS expertise, which is not available in all local governments. Developing tools that help local governments to assess via these methods (e.g. which are based on open-source software and provide a user-friendly GUI) would be a very useful step forward. Bolstering local government capacity and capability to provide good assessment would provide a very useful check against problems in the design phase. Industry and regulator capacity and capability could also be bolstered with further education and training programs, especially for early and mid-career professionals, building on up-to-date guidance materials and those delivered by New WAter Ways, the National Centre for Groundwater Research and Training, and others.

5.4 Proceed towards creating demonstration projects

We, and many participants, believe we need more demonstration projects to address many of the issues raised in this report, to extend proof-of-concept ideas into reality, and to achieve practice change under Western Australian conditions. It was suggested to the Expert Panel that there are two forces at play to effect ‘change to the status quo’: (i) change to/within the development industry and (ii) change to consumer demand/expectations/behaviour. If this recommendation is prioritised to proceed in the next phase, it may be necessary to consider how demonstrations will change both development industry and consumer demand. Suggested topics include:

- alternative construction methodologies and urban and built forms appropriate to high groundwater environments
- the performance of a variety of precinct, sub-division, and on-lot stormwater management strategies
- the feasibility of rear-of-lot directly connected drainage of the local groundwater mound
- landscaping approaches that are compatible with high groundwater in lot rears and public open spaces.

5.5 Cooperatively develop further guidance

The Expert Panel was very impressed by the passion, enthusiasm and commitment of the practitioners and researchers who participated in its project, and the very supportive nature of the multi-stakeholder groups. Consequently, we strongly suggest expanding on the work of this project to cooperatively develop a more comprehensive guidance note, supported by the urban development industry and regulators, for planning and designing urban developments in high groundwater areas. Such guidance could be incorporated into existing processes and documents, such as those associated with ARR 2019 and/or build on those of the IPWEA, noting for example that IPWEA WA has produced the *Specification for separation distances for groundwater-controlled urban developments 2016*. The guidance note could usefully include a short series of case studies and worked examples to help explain a methodology and why it is reasonable in each case. The guidance note could also be used to inform and (for relevant parts) be incorporated into initiatives such as Design WA, being developed by the Western Australian Planning Commission.

6. Summary and conclusions

Improving the methods used to mitigate the presence of high groundwater in urban developments offers the potential to dramatically improve the status quo for developers, residents, local government, and the natural environment. It is worth working to improve processes and outcomes in this arena.

High groundwater sites vary in the risks they pose to residents, local government or the natural environment following urban development. These risks provide a framework for selecting groundwater investigation, modelling and assessment methodologies. The higher the risk, the more sophisticated the methodology should be.

Regardless of model sophistication, there are pervasive uncertainties around model parameterisation, particularly that pre-development evaporation and transpiration are poorly understood (the Expert Panel is aware of one measurement site on the Swan Coastal Plain), and post-development gross recharge rates are also not well understood. In the absence of better understanding of these processes—which force all models—there will be uncertainty associated with all modelling output. This is particularly true for models attempting to make forecasts under future climatic conditions.

Therefore, additional research is needed to better understand gross recharge in urbanised environments and evaporation and transpiration in pre-development locations. This research should be coupled with design innovations that can reduce the risks of groundwater flooding and provide robustness to model uncertainty.

Although challenges remain in managing development in high groundwater environments, the Expert Panel was tremendously impressed and heartened by the commitment, goodwill and engagement of a very broad group of stakeholders in addressing these challenges. We hope this report usefully contributes to minimising risks to the built and natural environments, and to maximising the opportunities for innovation, resource recovery and creativity that the challenge of high groundwater also provides.

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Appendices

Appendix A. Expert Panel Terms of Reference

Aims

- Formulate guidance for a process and methodology for urban water management in developments in areas subject to seasonal high groundwater in the Swan Coastal Plain. This will be undertaken through an industry consultation process, drawing on the experience and knowledge of practitioners and researchers working in the region.

- Review relevant research and industry activities (e.g. CRCWSC Project B2.4 literature review; CRCWSC Integrated Research Project 5 (IRP5) Stage 1 report and literature review; Western Australia's GW Steering Group and SW Runoff Co-efficient Workshop outcomes) and a number of case studies to identify the technical and/or process barriers that needed to be overcome and the level of certainty behind the selection of modelling assumptions. Modelling assumptions to be considered are to include, but not necessarily be limited to, annual and event-based runoff rates and recharge rates at different scales, evapotranspiration rates and their application in water balance modelling, and stormwater management system (including groundwater impacts) modelling.

- Set the framework for transparency around modelling parameters (e.g. where the assumptions lie; range in assumptions), including implications for policy.

- Recommend a way forward to move from subjective to quantitative assessment and reduce margins of error. This can be incorporated into policy and guidelines which are currently under review (provided it is completed within the State Planning Policy review timeframe).

Background

In the absence of some fundamental science, there is some debate among Western Australian water management practitioners about whether at least some of the current approaches and assumptions being used for the modelling and management of high groundwater environments in the Swan Coastal Plain are justifiable. This has implications for achieving best practice urban development in such environments, now and in the future. As a result, there is a need for a consistent approach in the Swan Coastal Plain to determining appropriate water management strategies for urban development in such environments.

It is proposed that an independent Expert Panel be established to formulate guidance for the concept planning and design approach to be applied when developing water management strategies for urban development in high seasonal groundwater environments. This guidance will be based around the concept of integrated urban water management. The principal objective of the guidance is to provide consistent methodology and parameters for designing urban developments in areas subject to seasonal high groundwater tables. The guidelines will reflect a consensus approach among key stakeholders, moderated by the Expert Panel. It will be based on diagnostics of case studies, drawing on the expertise and tacit knowledge of the Expert Panel.

Statement of intent

The Expert Panel will consist of a variety of experts, including those with technical knowledge of surface and groundwater interactions, systems and processes, and/or an understanding of the specific high groundwater and urban development issues that are prevalent in WA. Expert Panel members will be independent of and not hold a conflict of interest—whether real or perceived—with urban developments and related decisions in WA.

The Expert Panel will have a combination of policy, modelling and science expertise to ensure the guidance that is formulated meets both scientific and practical policy needs. Individually and collectively the members will have the ability (be it knowledge, networks, authority, legitimacy) to inform decision making and best practice and be able to understand and influence the complex system change processes that are needed to address the existing debates and uncertainties within the Western Australian technical and policy environment.

Activities of the Expert Panel

The Expert Panel will undertake activities including:

- review past work and seek submissions and/or hold local 'hearings' including site visits on various priority topics/approaches/assumptions that were contested or unclear in Stage 1 of the CRCWSC's IRP5 to identify matters for further investigation by the Panel
- further explore these topics/approaches/assumptions through a review of local case studies to, where possible, test sensitivity, verify assumptions and validate approaches to support best practice
- deliberate areas they are able to resolve and communicate this through a draft document that will be circulated for stakeholder comment
- document uncertainties and, where appropriate, recommend an interim range of values for key modelling parameters, together with a process for reducing uncertainty in the future (including providing guidance on any relevant field validation program), and seek stakeholder comment through collaborative processes
- consider stakeholder comments and prepare an updated guidance document for consideration and publication by the CRCWSC
- attend Expert Panel meetings as follows:
    - Meetings to be held on an as needed basis at the discretion of the Chair of the Expert Panel, excluding any local 'hearings'; this is likely to be monthly.
    - The duration of the Panel will be limited to eight months, unless agreed otherwise by the CRCWSC.
    - Meetings and/or teleconferences of the Expert Panel will be coordinated by the CRCWSC Executive and will include updates and reports to the IRP5 Project Steering Committee (PSC).
    - It is proposed that Greg Claydon be the independent Chair of the Expert Panel.
- Guide the development of the field validation program as part of Work Packages 2 and 3 of Stage 2 of IRP5.

Appendix B. Expert Panel methodology

The analysis conducted by the Expert Panel consisted of two distinct phases. First, a review of the recent literature and available guidance aimed at identifying the *status quo* and current knowledge gaps. The review focused on topics/approaches/assumptions that were contested or unclear in Stage 1 of the CRCWSC's IRP5 Scoping Study. The documents reviewed and key findings are reported in Appendix D.

The second phase of the Expert Panel's approach consisted of a series of qualitative case studies to identify the technical and/or process barriers and build an understating of current practices across the industry. Given the in-depth, qualitative nature of the research, we used non-probability sampling methods, which are most appropriate for exploratory studies. In particular, we employed purposeful sampling to identify individuals and organisations who are patricianly knowledgeable about high groundwater in urban areas across the Swan Coastal Plain. We selected participants based on their ability and willingness to voluntarily and anonymously participate and communicate in an effective, articulate manner (Palinkas et al. 2015).

It is understood that the accuracy and quality of practitioners' work in relation to urban planning and impact varies widely, which was reflected in the sampling process. Hence, we selected case studies in three broad categories: (i) examples of industry best practices that could serve to inform the guidance note to be developed by the Expert Panel; (ii) examples of most commonly applied practices across the industry; and (iii) examples of practices that can be improved. Further, to understand the perspective of various stakeholder groups, we conducted case studies with the following participants: regulators and resource managers, local government authorities (i.e., cities and shires), consultants to the urban development industry, and research academics.

Prior to considering the case studies, we notified participants of the questions to be discussed, which allowed them to prepare the materials to be presented. Questions are detailed in Appendix C, and all questions did not necessarily apply to all case studies and all participants.

We generally carried out the case studies in the format of presentations by participants, followed by semi-structured interviews. The open-ended nature of the questions enabled participants to provide narrative answers, and thus provide new insights, which the Expert Panel may not have previously identified. We collected data in the form of presentation transcripts and notes on specific questions. We also collected written materials, such as reports and presentations. We analysed descriptive data using a qualitative approach. First, we classified narratives into common themes, following thematic analysis (Braun and Clarke 2012). Second, we reviewed participants' responses to identify information to fill the existing knowledge gaps and identify questions that warrant further research.

References for Appendix B

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Appendix C. List of questions for participants

Additional information to guide participant presentations

Scope of presentation and discussion

The Expert Panel requests that participants make a presentation that covers in detail one urbanisation project in an area impacted by high groundwater, preferably, but not necessarily, a project that has already received planning/environmental approval (i.e. a 'success' story). By doing a 'deep dive' on these projects as case studies, we hope to augment the more general picture provided to the CRCWSC during previous consultations.

The Expert Panel requests that the participants use their presentation to describe in detail the technical approaches used to assess and/or predict the impacts of the proposed development on the site water balance and related topics (e.g. water resources, flood/waterlogging risks, nutrient pathways if relevant, impacts on sensitive environments etc.).

The Expert Panel is interested to learn about the overall methodology, as well as such details as the conceptual and numerical models used, their parameterisation, calibration and testing or validation, as well as major sources of uncertainty and how they were addressed.

Following the presentations, the Expert Panel will facilitate a technical discussion based on the information that participants offer in their presentations and aim to clarify and deepen the Panel's understanding of the methods used by the participants.

Guide for the presentation

The Expert Panel requests that participants cover the following topics in their presentations (although the list below is not intended to be exhaustive, and we recognise that not all topics will be relevant to all projects/participants):

Project background:

- Type, purpose of project/case study
- Its status
- Special features (e.g. 'routine' or 'innovative' – how and why, scrutiny from planners/regulators/industry/community, other features of particular note)
- Reason for presenting this project

Physical and environmental context:

- Description of the project site – catchment areas and condition, topography, soils, vegetation, land and water uses, groundwater levels, infrastructure and other physical features considered relevant pre- and for post-development
- Prior availability of data and information relevant to water management, nutrient management, and other environmental management factors
- Nature of the high groundwater challenges faced in the project (e.g. water disposal, water supply, proximity to sensitive environments like wetlands) and how those challenges influenced the approach taken to the project

Overall project methodology:

- Overall technical approach used to assess and/or predict the impacts of the proposed development and reasons for selecting it
- Alternative approaches considered and reasons for not selecting them

Modelling approach:

- Modelling approach used in the project and reasons for selecting it
- Alternative approaches considered and reasons for not selecting them

Model structure:

- Components of the model (or other predictive tools used) – what physical and biological processes does it capture, and how does it describe them?
- Description of how the model represents space (e.g. gridded, semi-distributed, lumped); heterogeneity (e.g. in land cover, soil/aquifer properties, plant water uptake, etc.); specific urban infrastructure and processes (e.g. pipelines, rainwater tanks, infiltration galleries, building foundations, pumping for irrigation, etc.)
- Hydrological processes that were difficult but important to represent in the model and any work-arounds adopted to cope with them

Model parameters:

- Variables that required parameterisation
- Variables that were most important to get right for good results
- Approach taken for each parameter (e.g. use of default values, use of literature values, use of values based on expert knowledge, use of calibration, use of other ‘evidence’)
- Where relevant, description of the calibration approach used (e.g. observation(s) calibrated to, and parameters allowed to vary in the calibration)

Model predictions:

- Methods used to characterise uncertainty in model predictions and the extent and results of any sensitivity testing undertaken
- Modelling processes that were particularly influential to the hydrology of the project
- Overall confidence in the modelling results and reasons for that level of confidence

Model satisfaction/improvements:

- Reflections on the suitability of the modelling platform used, and the modelling methodology employed
- Suggestions for improvement to the modelling platform and the modelling methodology
- Suggestions for additional measurements to be available for model forcing/testing/calibration for this project
- Suggestions for the most important factors for the Expert Panel to provide guidance and recommendations on

Appendix D. Summary of literature

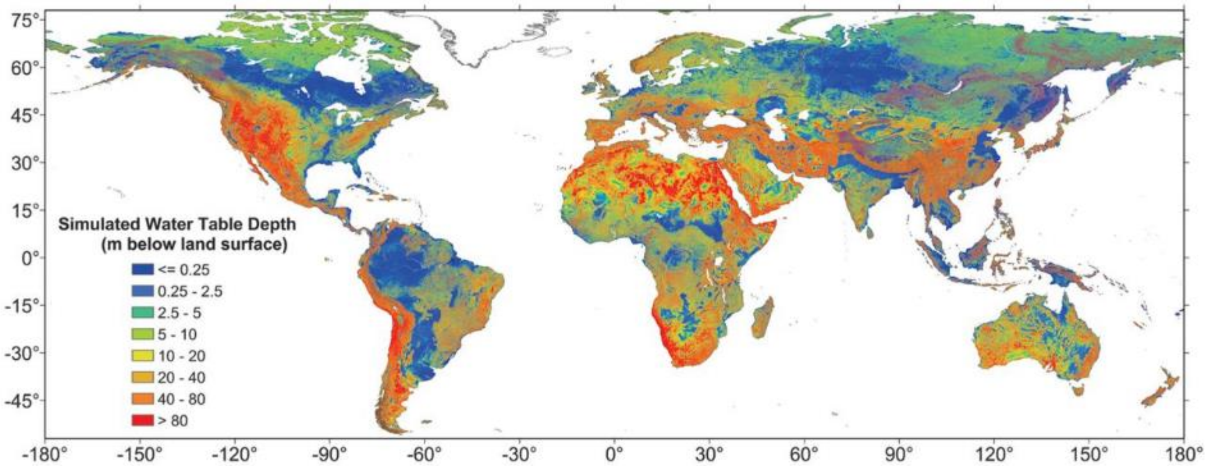

Figure D1. Global simulated depth to groundwater
Source: Fan et al. (2013)

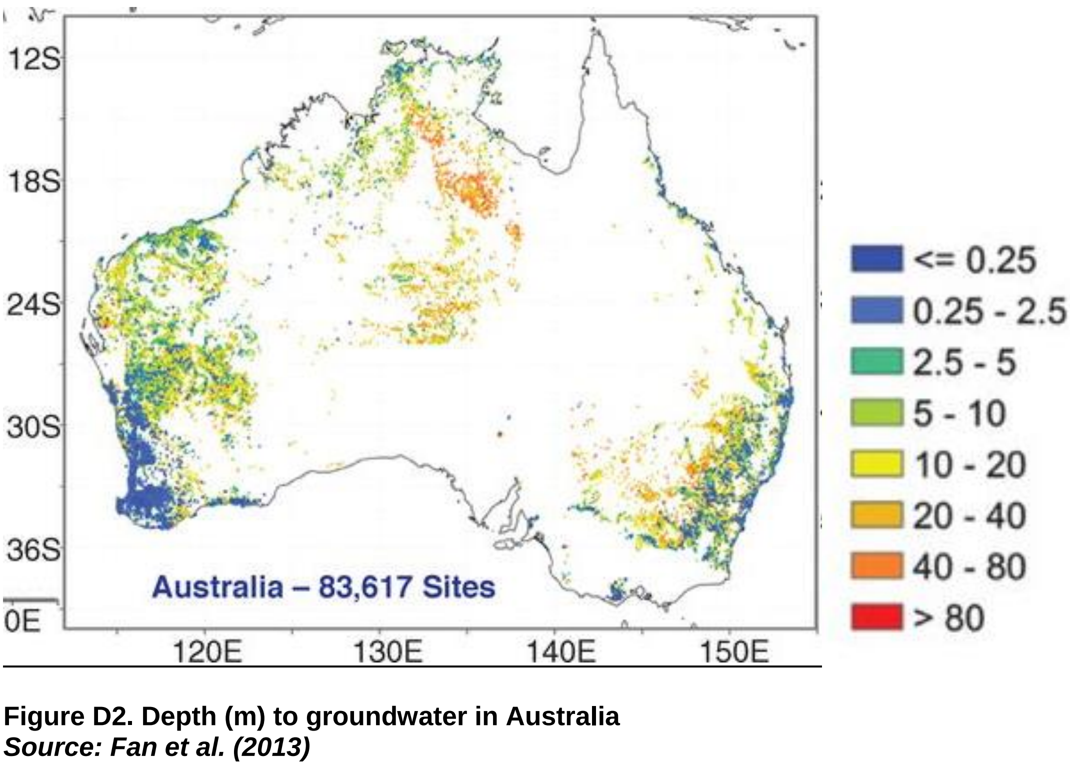

Figure D2. Depth (m) to groundwater in Australia
Source: Fan et al. (2013)

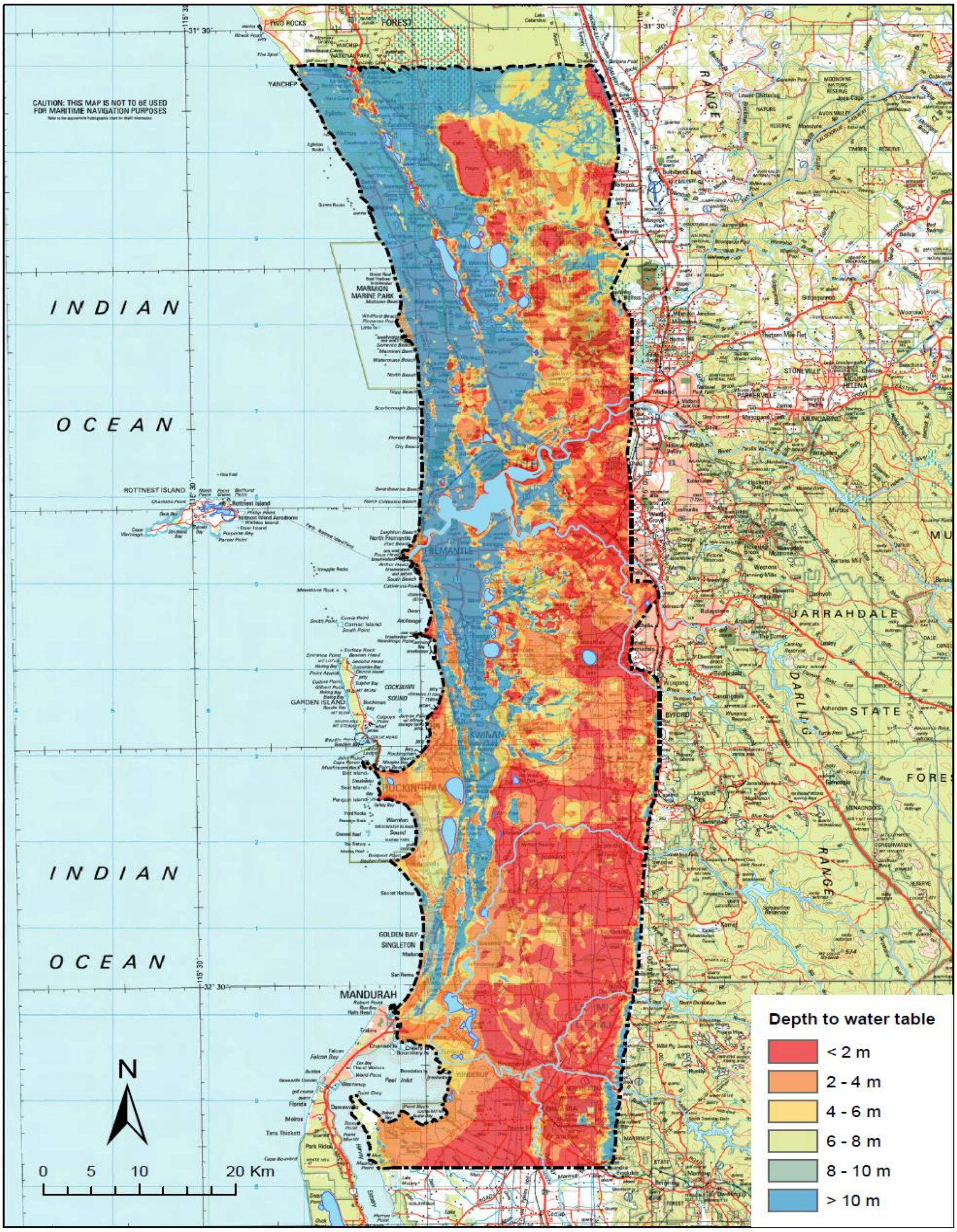

Figure D3. Depth to groundwater across the Swan Coastal Plain
Source: Modified from Wang et al. (2018)

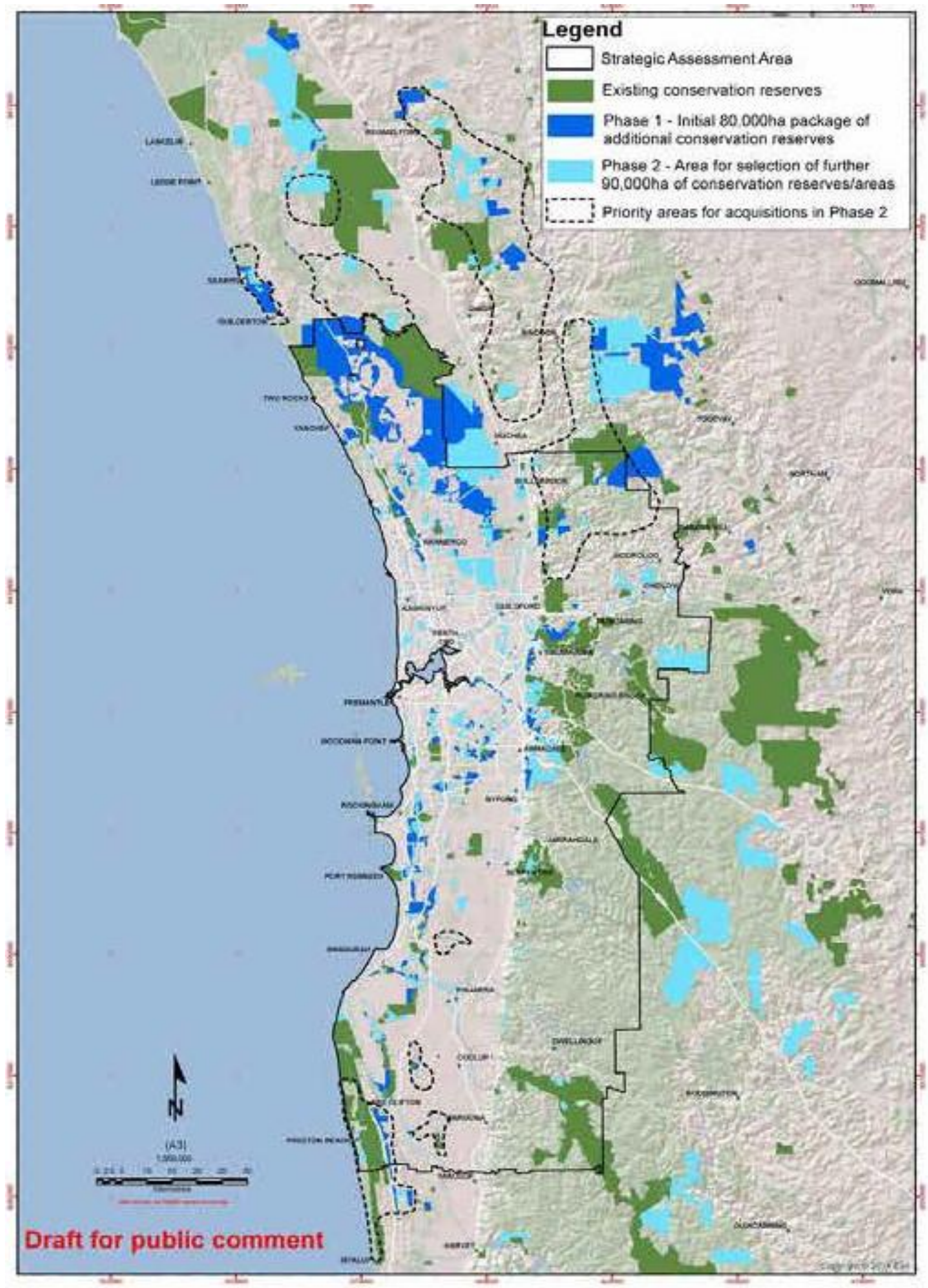

Figure D4. Intersection of future urban growth with areas of high groundwater on the Swan Coastal Plain
Source: Perth and Peel Green Growth Plan for 3.5 million summary document (2015), Department of Premier and Cabinet

The impact of urbanisation on water balances and nutrient pathways in areas of high groundwater: A review of recent literature

As part of Project B2.4: *Hydrology and nutrient transport processes in groundwater/surface water systems* (CRCWSC 2019), a comprehensive literature review was carried out (Ocampo 2018). This examined over 100 journal articles on water and nutrient balances in urban areas with high (shallow) groundwater and significant groundwater–surface water interaction. While water sensitive urban design (WSUD) is often recommended to offset the impact of urbanisation, in areas of high groundwater, it is still not well understood how such systems impact high water tables, how additional infiltrated water travels underground and how these processes impact nutrient loads in water bodies. Thus, the purpose of the literature review was to gain an understanding of the current status of the knowledge and remaining gaps on two key questions:

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

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

The review focused on case studies with processes specifically affecting unsaturated zone hydrology and the high, unconfined groundwater balance, over short time scales (a few days to weeks). The studies included cases sharing certain similarities with Perth (e.g. soil, rainfall and high water table (less than 4 m deep)).

The literature concludes that, while the areas of stormflow modelling (surface hydrology) and groundwater modelling (hydrogeology) are well developed, the lack of understanding around surface–groundwater interactions hinders accurate predictions of changing water balances and nutrient export under urbanisation. The review identified four key knowledge gaps, as described:

- **Infiltration in the urban mosaic**. Typically, coupled groundwater–surface water models estimate infiltration rates from 24-hour totals, which can be much lower than transient rates at the onset of an event. Thus, infiltration is often underestimated, particularly for short duration rainfall events. Further, urban water balances often do not account for infiltration through cracks and joints in hard impervious areas. The literature suggests up to 50 per cent of impervious areas should be considered as pervious, although there is insufficient supporting data.

- **Recharge of groundwater from rainfall events.** Large discrepancies exist in the recharge in urban areas with high water tables, with recent improved estimates being larger than previously thought. In particular, lawns produced 10 times less recharge that source control systems (SCSs), whose recharge rates are up to 40 per cent more than previously estimated.

- **Interflow processes and delivery mechanisms.** In areas with high water tables where SCSs are used, it was found that density, location and materials of SCSs affected water mounding and its relaxation (return to pre-event levels). Further, water that recharges the high aquifer returns to the stream, affecting its hydrology, hydrochemistry, and nutrient export. Mass balances and multi-technique approaches are cost-effective ways to examine how infiltration sources contribute to interflow and affect nutrient export.

- **Nutrient cycling along subsurface flow pathways in urban areas.** The review found no comprehensive study reporting nutrient transformations along the subsurface pathway in urban environments. Only studies in tiled agricultural landscapes were found, but the dynamics can be different to those in urbanised areas given the complexity of the subsurface and shorter time scales for nutrient processing.

Based on its findings, the literature review provides **a conceptual model to guide future work in Perth**. This includes:

- **Estimate infiltration/exfiltration rates from SCSs** using hydrograph recession analysis. Measure the hydrograph at the surface water storage or filter media storage via continuous water level recordings.
- **Compute recharge rates** and amounts and report them at a standard depth of 2 metres below ground level. Collect data under hard surfaces, housing built on imported fill and green areas.
- **Undertake interflow monitoring** via hydrometric and environmental tracers to identify the source of infiltration and to quantify groundwater discharge. Conduct monitoring along stormwater drainage pipes to ensure a proper mass balance approach.
- **Use a mass balance approach** along the high groundwater pathway, following control planes and using an integrative mass flux concept. Locate control planes from highland to lowland areas to quantify exposure time and nutrient transformations.

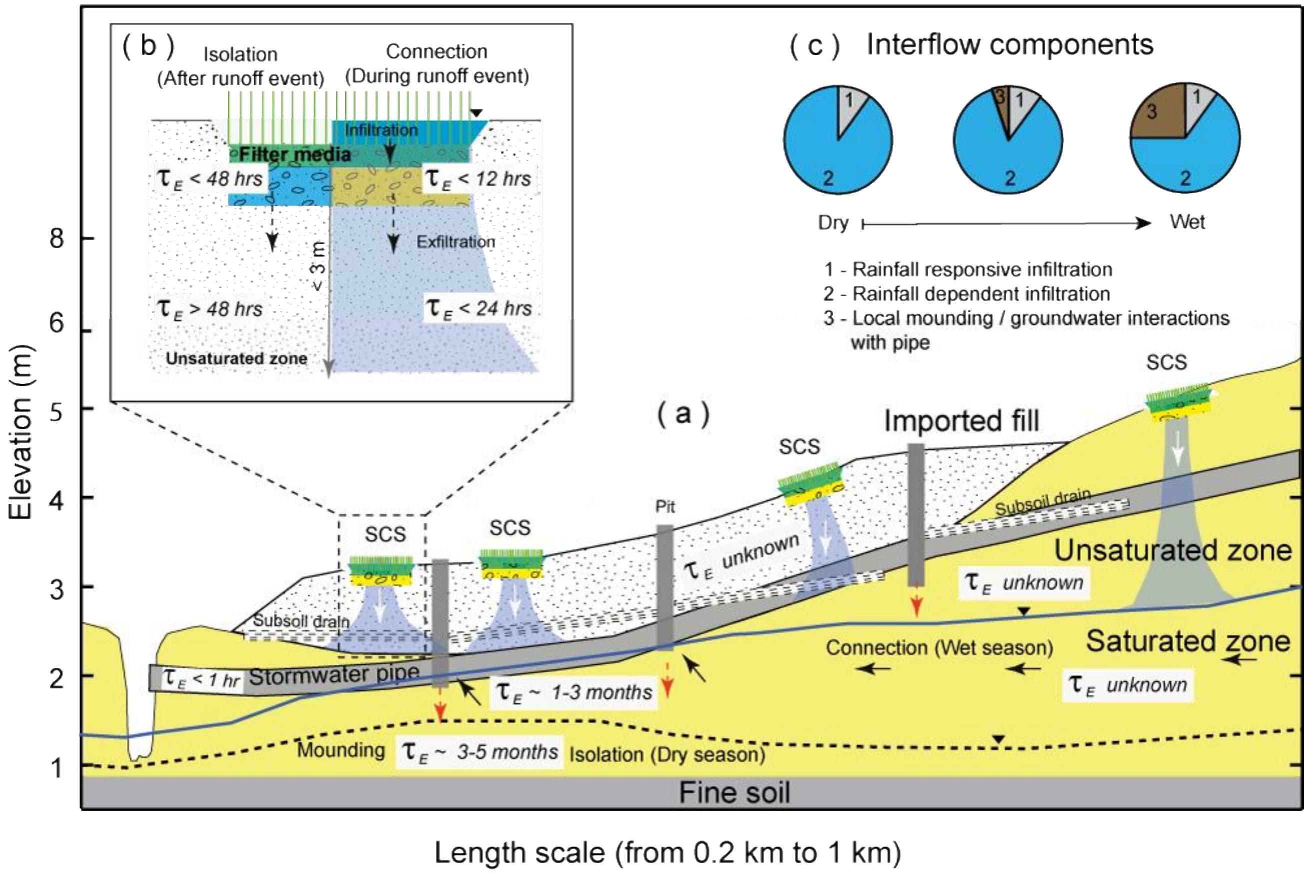

Figure D5. Conceptual model of hydrological processes and relevant τE values for nutrient processing in the urban karst, in areas with high groundwater: (a) landscape representation of current built forms and stormwater management practices; (b) individual SCSs; (c) variation of interflow components over seasonal scales*. Source: Ocampo (2018) and (CRCWSC 2019)*

In addition to the literature review summarised above, other studies in Western Australia have found that urbanisation with stormwater infiltration increases recharge and lowers evapotranspiration (Locatelli et al. 2017). As a result, the water table tends to rise and, thus, the probability of groundwater seepage above terrain increases. A comparative study in Perth (WA) and Baltimore (Maryland), developed a decision-support framework to help predict the likelihood and direction of changes in baseflow (Bhaskar et al. 2016). The study (p. 293) found how pre-development water table height, climate, geology and urban infrastructure interacted such that urbanisation led to a rise in Perth's baseflow, yet a fall in the case of Baltimore. Further, a modelling study in the Southern River catchment in Western Australia showed how urbanisation can significantly reduce evaporation and evapotranspiration (Barron et al. 2013). Because of direct infiltration of roof and road runoff, groundwater recharge rates increase, thus leading to greater discharge flows into the urban drainage system.

Integrated Research Project 5 Stage 1 report – 2018

In 2018, GHD, Water Technology and the University of Western Australia carried out Integrated Research Project 5 (IRP5) Stage 1: *Knowledge-based water sensitive city solutions for groundwater impacted developments.* The project had four key objectives:

1. Review current state of knowledge
2. Identify knowledge gaps in urban development design and methodologies
3. Investigate alternative building/construction/development methods
4. Develop an action and research plan to address key knowledge gaps.

The project's methodologies included literature review, structured interviews with stakeholders and experts, and a stakeholder workshop. The resulting report (CRCWSC 2019) provides a summary of the findings of Stage 1 of IRP5.

The report highlights the lack of a consistent methodology for determining pre-development groundwater levels within the Swan Coastal Plain. Methods applied vary widely across researchers and practitioners and include the use of:

- *Perth groundwater atlas* (Department of Environment 2004)
- average annual maximum groundwater level (AAMGL) – although this is not endorsed by the Department of Water (Department of Water 2013)
- back-calculation of recent measurements towards historical maximums.

Further, numerical models for estimating groundwater levels typically fail at the local levels, because they entail uncertainties of 2–10 m in hydraulic levels. While such uncertainty may be acceptable for regional models, it is excessive for civil structure design. Uncertainties commonly originate from parameters that are difficult to measure (e.g. spatially very variable), or processes whose complex behaviour requires simplification.

To illustrate water balances pre- and post-development, the IRP5 Stage 1 report provides a diagram sourced from Ocampo (2018) (Figure D5 in this report). It is understood that, in Western Australia, urbanisation often causes increases in groundwater levels due to higher post-development net recharge rates. This can be a result from decreased evapotranspiration and increase in infiltration through the provision of soakwells, biofiltration or rain gardens. Post-development groundwater levels can also rise or fall in response to the construction of underground structures (e.g. subsoil drains). Importantly, urban development has the potential to impact water dependent ecosystems through changes in water levels, mobilisation of nutrients, or introduction of pollutants.

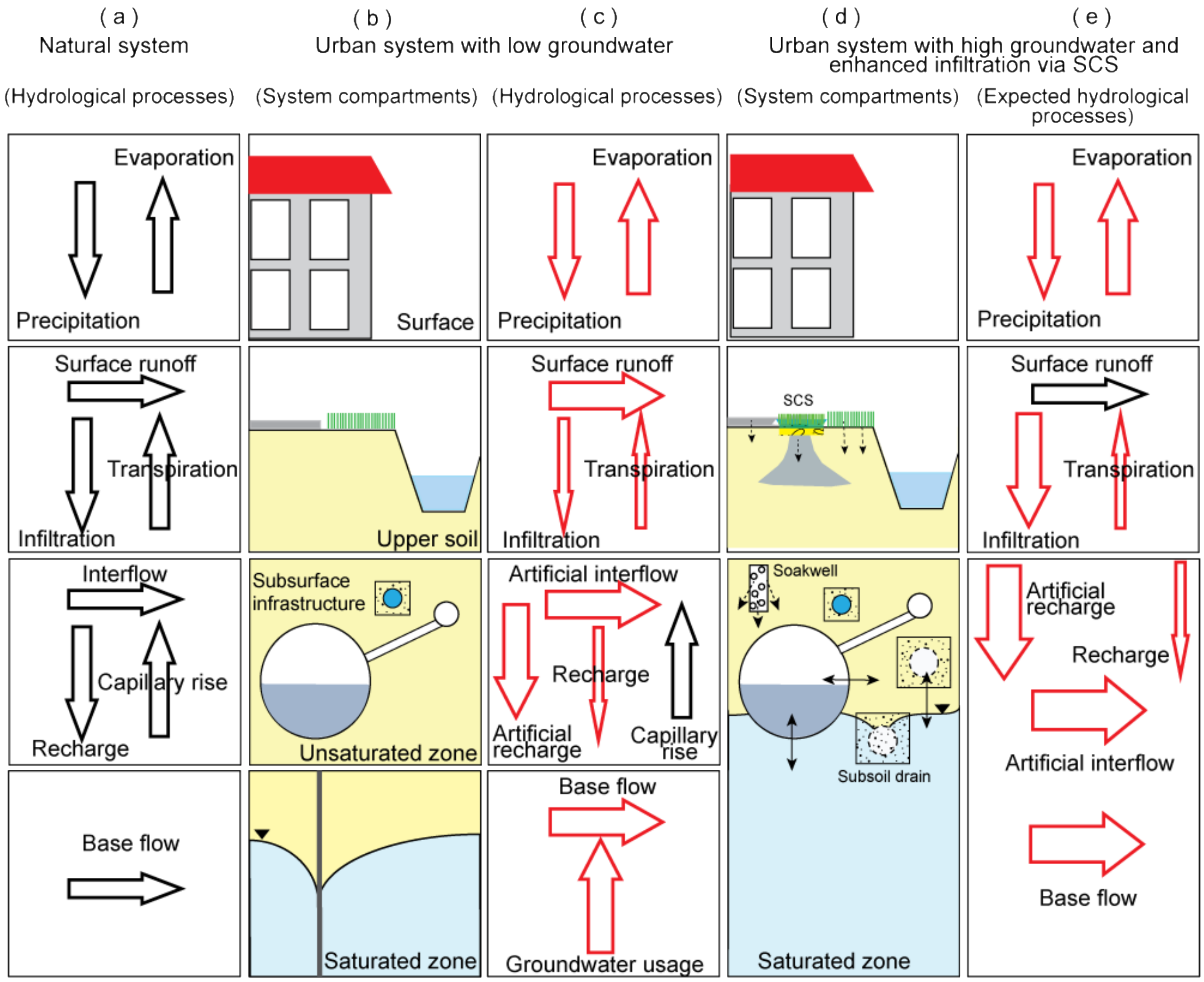

Figure D6. Conceptual model of perturbation of the urban water balance. Red arrows represent water flow that has been modified or introduced by urbanisation or proposed urbanisation in high groundwater environments with SCSs
Source: Ocampo (2018)

Groundwater table rise may cause several impacts on infrastructure and buildings, including reduction of soil bearing capacities and strength of concrete, damage to pavement and other structures, as well as infiltration into sewage systems. Hence, management measures to deal with high groundwater are a requirement of the National Construction Code (Australian Building Codes Board 2019) and are addressed by Australian Standard AS 2870-2011. In addition, fill material, drainage and alternative construction methods can be used to manage adverse impacts of high groundwater.

This report identified 27 contested and six unknown knowledge areas, clustered around infiltration and recharge rates; evapotranspiration rates, groundwater fluxes; and groundwater levels. Poor understanding of pre-and post-development water balance results in impeded ability to protect current hydrologic cycles and a risk of the development negatively impacting infrastructure, property and the receiving environment. As a result, the IRP5

Stage 1 report concludes that Stage 2 research should address the following fundamental water balance and water quality knowledge gaps:

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

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Appendix E. Examples of international approaches for managing high groundwater in urban areas

This section was developed with supporting information provided by Carl Davies, as part of the PhD Thesis 'Subsurface drainage for sustainable urban development' (Davies, in preparation).

Constructed wetlands and wet ponds

Constructed wetlands and wet ponds are a common practice to management of stormwater in coastal plain urban communities across the United States (Chesapeake Stormwater Network 2009). A key advantage is that excavated materials on site can be used as fill to elevate the terrain, where the development will be built. However, in areas of high groundwater, wet ponds can be strongly impacted by the water table and have limited capacity for nutrient removal (Sønderup et al. 2015). In fact, without adequate maintenance, wetlands and ponds designed to manage stormwater can result in poor water quality conditions, such as algae blooms, mosquito breeding and odours (EPA 2009). Two examples of the use of constructed wetlands and wet ponds in the United States are urban areas in south east Florida and the Chesapeake Bay Watershed, on the east coast.

South east Florida

South east Florida is characterised by low-lying terrain and a high groundwater table, which rises rapidly in response to heavy rainfall (Czajkowski et al. 2018). Occasionally, in preparation for large storm events, groundwater levels are lowered to increase the unsaturated zone storage. However, due to the risk of sea water intrusion, a continuous management strategy is to control canal water levels to maintain a positive gradient that recharges the aquifer with freshwater. The dual risk of flooding and seawater intrusion is especially significant in urban areas of south Florida's east coast, such as Miami, Palm Beach and Broward (Sukop et al. 2018). Importantly, many residents of south east Florida depend on a highly transmissive superficial aquifer as their main source of drinking and irrigation water (Czajkowski et al. 2018). Further, the area is home to environmentally sensitive areas, especially the Everglades wetlands.

Traditionally, south east Florida has relied on detentions systems, as one of the key strategies for stormwater and flood risk management (Peluso & Marshall 2002). These include wet or dry detention ponds and constructed wetlands. Dry ponds remain usually dry between rainfall events and are considered effective in removing suspended solids, but not for the treatment of nutrients. In addition, they are not recommended for wetlands, floodplains or very large drainage areas (> 100 ha). Wet detention ponds maintain a permanent pool of water and store urban runoff for hours or days, before controlled release. Nutrients can be partially removed through biological activity in the vegetation, yet a risk of algae blooms and mosquito breeding remains. Constructed wetlands, such as the one in Lake Okeechobee (Guardo et al. 1995), typically provide a higher level of treatment, although they require periodic maintenance (Peluso & Marshall 2002). A recent study (Garcia et al. 2020) shows that, in addition to large hydraulic retention times and effective nutrient removal, constructed wetlands can provide multiple environmental benefits, such as carbon sequestration or habitat provisioning. Figure E-1 illustrates a flow equalisation basin in Palm Beach County—a reservoir with a 74 Hm^3 holding capacity, which temporarily stores stormwater runoff for release to the Everglades stormwater treatment areas (SFWMD n.d. a)

Figure E-1. Flow equalisation basin in Palm Beach County, Florida, flowing into a contributed wetland
Source: SFWMD (n.d. a)

Chesapeake Bay Watershed

The Chesapeake Bay Watershed covers an area of 166,530 km^2 across the states of Virginia, Maryland, West Virginia, Delaware, Pennsylvania, New York and Washington, DC. The coastal plan is characterised by its flat terrain, high water table and highly altered drainage system (Chesapeake Stormwater Network 2009). Historically, stormwater management in the coastal plan had been designed following the principles applied in the nearby Piedmont plateau, without being adapted to the different hydrological and hydrogeological characteristics. The flat terrain in the Coastal Plain lacks enough head to effectively move water out of the conveyance system (Chesapeake Stormwater Network 2009). More recently, human activities in the Chesapeake Bay Watershed have resulted in further challenges for storm and groundwater management, including the extensive use of drinking water wells and septic systems, and urban development over areas where (previously) animal manure had been widely applied.

Wet ponds—permanent pools of standing water—are one of the oldest and most widespread forms of stormwater management in the Chesapeake Bay coastal plain (Chesapeake Stormwater Network 2018). One of the main reasons is the advantage of obtaining sediments from onsite excavations, which can then be used as fill elsewhere in the development site. The resulting excavation can be built into a pond to temporarily store floodwater. However, given that most ponds are excavated below the water table, they become influenced by groundwater. This results in diminished nutrient removal capability, limited runoff reduction and frequent nuisances from stagnant water (Chesapeake Stormwater Network 2009 p. 6).

Figure E2. Wet pond in Virginia, within the Chesapeake Bay Watershed
Source: Chesapeake Stormwater Network (2018)

While wet ponds are commonly used, the Chesapeake Bay Watershed (Chesapeake Stormwater Network 2009) identified a wide range of potential stormwater management practices. These are grounded into three categories, based on their suitability. First, *preferred* practices are those that are feasible at most developments in the coastal plain and have high flow and/or nutrient management capacity. Preferred practices include constructed wetlands, bioretention, rain tanks, wet swales (except for residential areas), dry swales, rooftop disconnection (lots < 557 sqm), permeable pavement and filter strips. Second, *acceptable* practices are those that are widely applicable, yet require major design adaptations and/or have reduced capability to reduce pollutants. Acceptable practices comprise filtering, urban bioretention, small scale infiltration, compost amendments, green roofs and wet ponds. Finally, *restricted* practices have limited feasibility and poor pollutant removal capacity. These include extended retention ponds, grass channels and large scale infiltration.

Combined surface and groundwater management

The Netherlands is a highly urbanised country, with 95 per cent of its population living within 50 km from the coast (EuroStat 2013). Two-thirds of the land lies below the sea level, while many urban and agricultural areas have been reclaimed from swamps and lakes, thus resulting in severe changes to the natural hydrological environment (Yu et al. 2018). Across the eastern (coastal) half of the country, the groundwater is at surface, and excess precipitation (300 mm/a) is discharged through artificial drainage systems (de Vries 2007). Every year, close to 2 Hm^3 of fresh groundwater is extracted, 60 per cent of which is used for public water supply.

A traditional water management strategy in areas of high groundwater in the Netherlands, including the greater Amsterdam city area, consists of diking and draining lakes through small regulated catchments, referred to as *polders* (Yu et al. 2018). The water level within *polders* is controlled by pumping water into regional drainage canals, called *boezem*s, which in turn can drain into outlets or ditches. Within the regulated catchments (*polders*), water can be purposely managed in one direction or another, alternating with wet and dry conditions. In times of high water demand, water is let to flow from the *boezems*, into the *polder* ditches by gravity, as shown in

Figure E3 (a). Conversely, during periods of precipitation excess, water can be pumped from within the small catchment and into the *boezem* Figure E3 (b). Importantly, draining of *polders* has led to ground subsidence, resulting in higher groundwater seepage rates, which, in turn, requires higher pumping rates to maintain the water level within the *polder.* Further, groundwater seepage substantially affects surface water quality through the introduction of brackish, alkaline, and nutrient-rich water (Yu et al. 2018).

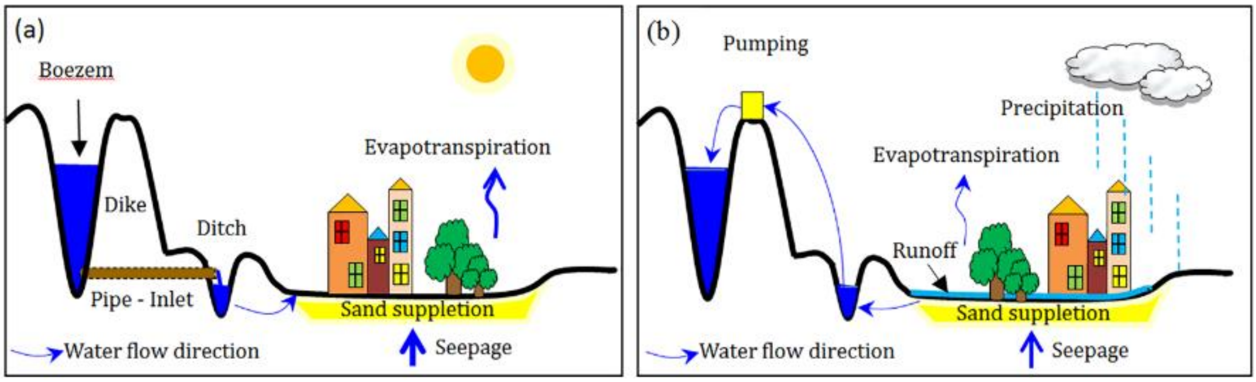

Figure E3. Conceptual model of water management in a *polder* during periods of water deficiency (a) and surplus (b)

Source: Yu et al. (2018)

An enhanced approach to the *polder* system consists of the use of subsurface drainage systems that collect storm and groundwater, to be then discharged into the ditches. This system helps prevent wet cellars or flooding of residential areas (Yu et al. 2019), and reduces the need for fill to elevate new developments (Davies in preparation). An example is polder Geuzenveld, located in the western part of Amsterdam (Yu et al. 2019), as shown in Figure E 4.

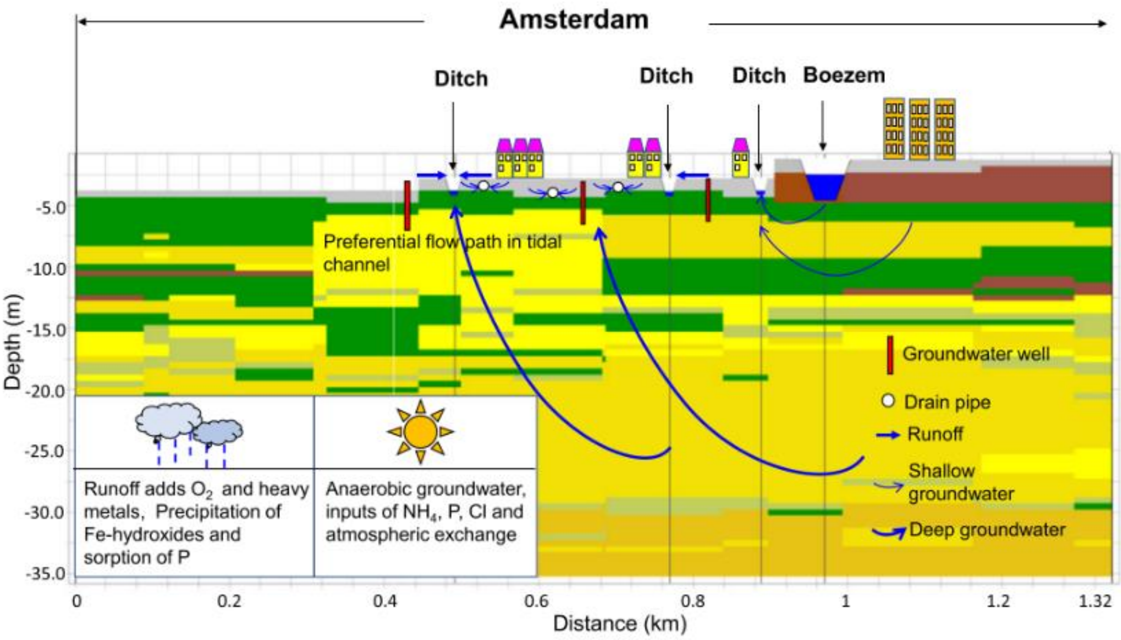

Figure E4. Conceptual model of water fluxes in a *polder* system with subsurface drainage
Source: Yu et al. (2019)

Subsurface drainage and pumping

South Dunedin, New Zealand

South Dunedin urban area (New Zealand) is located in a low-lying area, which had been reclaimed from coastal dunes and marshes (Rekker 2012). The high-water table (0.3–0.7 m below the ground level) currently poses a risk of restricted drainage (Goldsmith & Hornblow 2016), surface ponding and even liquefaction (Barrell et al. 2014). An important factor resulting in rapid, high rises in the water table is heavy rainfall (Fordyce 2014). Importantly, the groundwater level is also impacted by the water level in the adjacent ocean, both of which have raised circa 20 cm over the last 150 years. Because the aquifer is not used as a source for drinking water, it has not been thoroughly investigated (Fordyce 2014). Recognizing the knowledge gap and high groundwater-associated risks, Otago Regional Council (2019) has launched a comprehensive groundwater monitoring program across the Dunedin area.

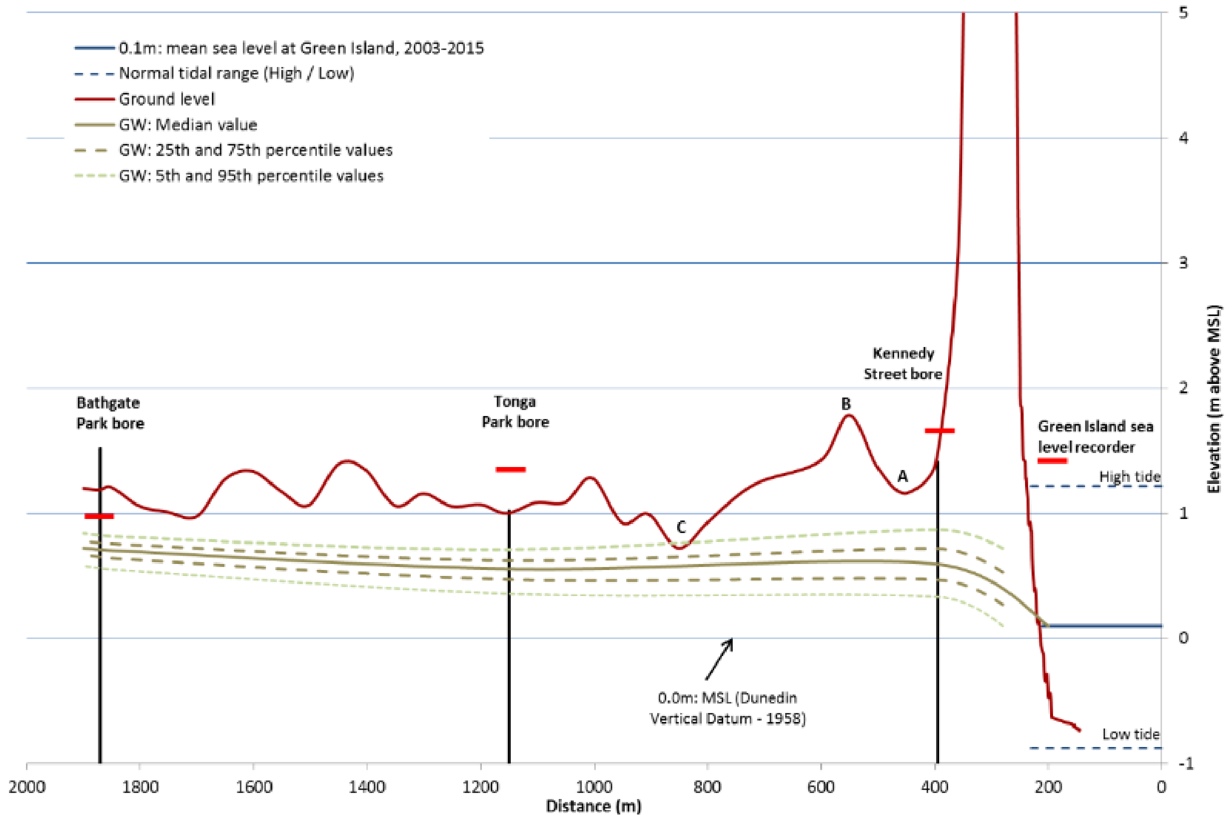

Figure E5. Cross-section from Bathgate Park to the Pacific Ocean (high terrain represents the sea wall)
Source: Otago Regional Council (2020)

Given the old age of sewer and stormwater infrastructure, groundwater seeps into the pipes, and drains or is pumped to the sea. Previous investigations have shown 'that infiltration of groundwater into the storm and wastewater networks fortuitously helps to suppress the water table, preventing surface ponding under normal conditions' (Goldsmith & Hornblow 2016 p. 28). As sea and groundwater levels rise, current stormwater levels of service may not be met in low-lying areas (Dunedin City Council 2018). A program of asset renewals aims at reducing seepage into pipes, yet it may result in the subsequent groundwater level rise (Goldsmith & Hornblow 2016). Consequently, there could be an increased risk of flooding, surface ponding and damage to infrastructure (Dunedin City Council 2018). A possible strategy to mitigate the rise in groundwater levels consists of installation of additional drainage and pumping equipment. To keep the water table at 2010 levels, the proposed infrastructure upgrade would cost an estimated NZD 75 to 148 million in capital expenditure, and NZD 4 to 18 million in operation and maintenance – for minimum and maximum sea level rise scenarios (Glassey 2018). Other towns in New Zealand, such as Opotiki, in the north island, also experience high groundwater tables and infiltration into sewer systems, as depicted in Figure E6.

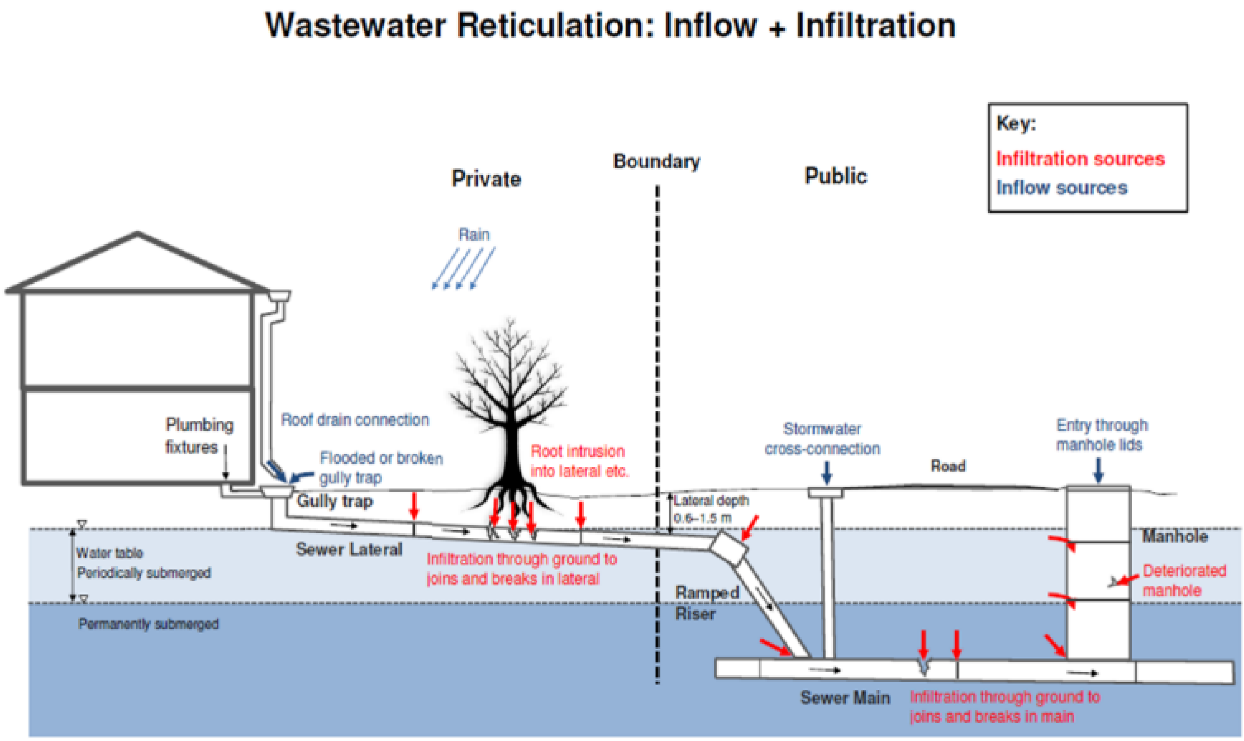

Figure E6. Representation of aged sewer infrastructure in an area of high groundwater
Source: Opotiki District Council (2019)

Chañar Ladeado, Argentina

The town of Chañar Ladeado is located in the Santa Fe province of Argentina, around 400 km west of the capital, Buenos Aires. The town has 5,200 inhabitants and is equipped with a potable water supply system, but no reticulated sewer network (Zimmermann & Riccardi 2000). Following a series of high rainfall years in the 1990s, the water table rose to the surface, flooding cellars and disabling septic tanks. Consequently, a drainage project was designed whereby collector pipes (300 mm and 150 mm) would be installed parallel to sewer pipes, with the aim to keep the water table at least one meter below the surface. As it is common across areas of low topographic slope in Argentina, subsurface drainage systems typically require pumping stations and channels to discharge the drained water (Zimmermann & Riccardi 2000).

Groundwater pumping for secondary use

The Taipei Basin, in northern Taiwan, contains abundant groundwater resources (Jang et al. 2019). Following rapid economic and population growth in the 1950s and 1960s, groundwater levels dropped by circa 50 m, causing subsidence of up to 2.3 m (Jang et al. 2019; Liu et al. 2010). Since 1970, restrictions on groundwater withdrawals have led to a steady recovery of water levels, at 1.3 m/year (see Figure E7). Such high groundwater levels now pose serious risks for underground infrastructure and soil liquefaction. To reduce such risks, previous studies (Liu et al. 2010) have proposed an optimal pumping regime to maintain the water table at least 7.5 m below the surface (Liu et al. 2010). This system requires an extensive network of monitoring wells to reflect the state and trend of groundwater levels across the region.

Pumped groundwater can be used for fire control, public open space irrigation and drinking (Jang et al. 2019). More precisely, given the location of water supply plants and different land uses, groundwater extracted in the southern Taipei Basin is for domestic uses, while withdrawals in the eastern Taipei Basin should be restructured to non-potable uses (Jang et al. 2016).

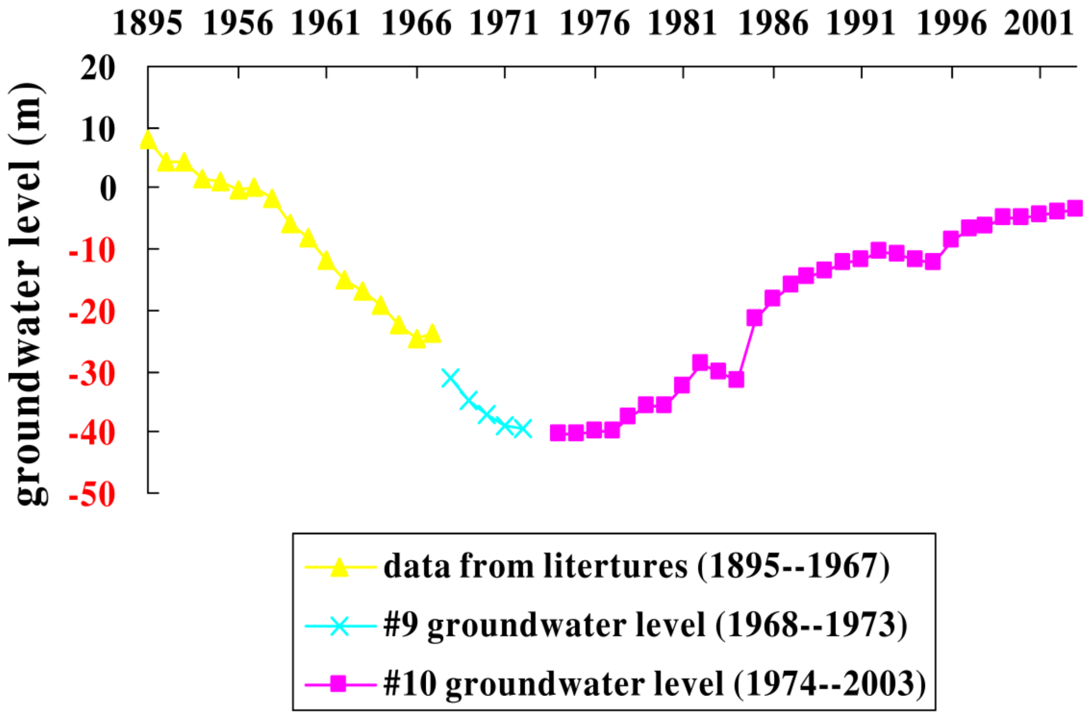

Figure E7. Groundwater levels in the Taipei Basin, 1895–2003
Source: Liu et al. (2010)

Table 1 E: Summary of international cases of urban developments in high groundwater areas

Management strategy	Advantages	Disadvantages	Example locations	References
Constructed wetlands and detention ponds	Excavated sediment can be used as onsite fill. Opportunity for improved habitats.	Limited nutrient treatment capacity (detention ponds)	Southeast Florida, USA Chesapeake Bay Watershed, east coast, USA	Czajkowski et al. (2018); Garcia et al. (2020); Guardo et al. (1995); (Peluso & Marshall 2002; SFWMD n.d.-a); SFWMD (n.d.-b); Sukop et al. (2018)
Surface and groundwater management (*polder* system)	Water level is kept within controlled limits within the catchment	Ongoing pumping costs; subsidence; poor water quality from groundwater seepage	Amsterdam, the Netherlands	de Vries (2007); Yu et al. (2018); Yu et al. (2019)
Subsurface drainage and pumping	Groundwater levels can be managed using existing infrastructure.	High monitoring and pumping costs.	South Dunedin, New Zealand	Dunedin City Council (2018); Glassey (2018); Goldsmith and Hornblow (2016); Otago Regional Council (2019, 2020); Rekker (2012)
		Need to develop drainage system, where not existent. Need to pump and discharge drained water.	Chañar Ladeado, Argentina	Zimmermann and Riccardi (2000)
Withdrawals for secondary use	Groundwater used for potable and non-potable uses.	Requires constant monitoring	Taipei, China	Jang et al. (2019); Liu et al. (2010)

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Appendix F. Summary of inputs from practitioners and researchers

Terminology

Differences in **terminology** hamper international literature review, but people are used to navigating the different terms. For example, average annual maximum groundwater level (AAMGL) is not a clear term, and is dependent on the period of data, climate change, and will be affected by development. It was designed to protect wetlands, not development. Can we come up with a better, risk-based indicator? Further, there is a lack of clear definition of recharge (% of rainfall?). It would be beneficial to develop a glossary, building on the Institute of Public Works Engineering Australasia (IPWEA) Guidelines, Department of Water and Environmental Regulation (DWER) publications, and the like.

Risk-based site assessment

It is understood that certain areas entail higher risks than others, regarding the impact of urban developments on groundwater. Thus, consultants would typically use different approaches for different sites. For example, in high risk areas, higher levels of technical investigations are required. However, there **is no consistent, agreed framework to decide what constitutes a low, medium or high risk site**.

Understanding the science – water balance considerations and issues

There is a mismatch between water availability and its potential for use. Most **rainfall is concentrated in winter**, making onsite storage difficult. However, in summer, there is a shortage of water for irrigation of public open space. For this and other reasons, there is a need for greater innovation in stormwater management.

The occurrence of **clay-rich** soils across Perth affects surface–groundwater interactions, which should be considered. Clay may often be present at depths of 3 m, and is not removed for development. During the first 300–350 mm of rain, as the clay is still relatively dry and cracked, water travels through preferential pathways (i.e., cracks of up to 65 cm deep). It is not until the 300–350 mm of rain threshold has been reached that the clay swells and seals. Therefore, the role of clay cracking beneath developments should be investigated.

There is capacity to predict big floods and yearly events relatively well, **not the in between.**

Drainage rates used in various assessments are typically based on deep water table. But we don't know what they are limited by in areas of high groundwater. There is a lack of understanding on whether the geofabric surrounding the subsoil drains limits the efficiency of that drainage.

There is still no clear tool to estimate **recharge**, and limited understanding of how it changes in post-development conditions. Future research should investigate rates of recharge for various land uses, landforms, vegetation covers, soils and geology. Further, more research is needed for the understanding and representation of mounding under different conditions.

There is a lack of clarity on whether **soil moisture** should be used as a good predictor of runoff coefficient.

Model structure and parameters

There is a lack of **consistency in methods** used. Small to medium size consultants use older methods, while large consultants use pretty consistent methods, following ARR 2016.

In general, the uncertainty in soil parameters, recharge rates, and model 'correctness' are not well understood, meaning that the **margins of error** to be expected around model results are also poorly known.

There is lack of clear, consistent agreement on **clearance to groundwater levels** between local government authorities. Specific levels and clearances within IPWEA guidelines should be subject to ongoing discussion, as there has been indication that the clearances recommended for gardens and playing fields may be insufficient and may result in waterlogging. Other confounding factors may be at play with specific developments also.

Heterogeneities in soil are an important issue. Often, spatial heterogeneities occur locally, to the point that they cannot be captured in the models. For example, care should be taken to delineate areas of clay lensing or limestone. Potentially, models may need to be run separately for different areas of the site where such heterogeneity exists.

There is a need to better know and describe the **'boundary' conditions** that may be applying at smaller scales of investigations and developments.

Technical evaluation of development planning should be undertaken early in the planning process, to account for cumulative impacts. This could potentially be done at the District Water Management Plan stage or earlier. It could also be used to determine what parameters are most appropriate where.

Monitoring

Post-development monitoring often doesn't start until the last phase of development is completed, meaning it can be 15 years between initiation of development and when monitoring is installed. DWER's guidelines for preparing Urban Water Management Plans (UWMPs) indicate that monitoring should extend for at least three years after the last stage of construction of the subdivision. But this applies to the whole development, not each cell. Since many projects are at mid-development stage, they can be 10 years out of monitoring. Although some early monitoring may occur, it is usually for quality, not quantity. This gap in monitoring times represents a lost opportunity for adaptive management when problems do arise. Further, there is currently a lack of well monitored demonstration sites. Post-development monitoring should inform how subsoil drainage systems perform over time, while post-development models could be used to better understand what really happened. Thus, there is a need to assess performance of existing designs. It is advised that longer term monitoring and research of subsoil drainage systems be investigated in several different environments. The Groundwater Steering Group could do demonstration projects to provide more evidence for how well the IPWEA guidance works.

Construction/development practices

More attention on design and management of groundwater drainage presents win-win situations for homeowners, developers and the environment.

Currently, designs tend to be very conservative and therefore unnecessarily increase the use of fill. This results in:

- costs to developers that are passed onto homebuyers, thus increasing costs of housing
- clearing of sand environments from which fill is sourced
- carbon and transportation impacts
- larger changes in the elevation and relief of the built environment, including some 'Frankenstein' landscapes, with unknown impacts on sensitive environments, hydroperiod etc.

Alternatively, insufficiently conservative/poor design is resulting in groundwater flooding and nutrient management impacts. This can result in:

- liability to local governments for infrastructure repairs (~ $1 million for road replacement in one example)
- untested liability of local governments for damages to private property
- exposure to increased regional and local flood hazards
- loss of amenity (soggy backyards, mosquito breeding etc.)
- damage to private property (unclear how insurers and insurance industry are looking at this problem).

One estimate indicated the payoff of additional **testing and modelling** upfront is likely to **be 10:1** or better in terms of reduced fill costs (for developers). Therefore, improved practice in this area represents a great opportunity for WA. But where minimisation of fill is a goal, it remains unknown whether modelling can ever provide a sufficiently precise prediction to avoid residual risk. It is therefore necessary to also achieve further innovation in construction methods/materials.

It is difficult to make consistent **fill blends** at subdivision scale. On one reported occasion, a whole street went ‘soggy’, resulting in direct connection of properties to roadway drainage (although the local government prefers indirect connection).

Lack of **maintenance** is a big issue: biofilters and living stream are good features, but need better expertise to maintain, otherwise there are high costs. Raingardens are difficult because vegetation dies in summer. Other issues include, for example, infiltration going wrong on biofilters, and them not draining as quickly as they should. There is a need to better understand how biofilters perform, differences between rising and falling limbs, and when there is groundwater contribution or no groundwater (groundwater anecdotally reduces performance by about 30 per cent).

Question to be further investigated include:

- What is the loss of porosity in silty soils?
- What is the K value of the compacted fill?

Soakwells

The efficiency of soakwells is not well modelled, because typically ideal drains are assumed. Assumptions about locations are made in models that can influence mounding—handled by assuming they will be in rear of house (conservative approach).

Lots less than 350 square metres can’t get soakwells onsite, especially not anything big enough, so they need direct/indirect connection. The local government can’t control where soakwells go, because it’s up to the owner and builder. But when things go wrong, owners come to the local government and ask for the problem to be fixed (this links to governance and chain of responsibility issues).

There are difficulties of using in-situ sand: if low permeability sand is on top, soggy backyards result, even though high K value sand is below.

There is a lack of clarity on how do silting, and how acid sulphate soils affect soakwell infiltration 10 years down the line.

Consistency between environmental design, civil design, and as-built is a challenge. This challenge may need to be confronted if optimising design requires ensuring soakwells at front of lots, using high quality soakwells etc.

Governance

It is recognised that land development has cumulative environmental impacts (on flooding, water quality and GDEs), although these are currently not adequately captured or managed during early stages of the planning process. Further, Urban Water Management Plans are often only submitted for approvals at later stages of the planning process when, in some cases, it is already too late to incorporate considerations for water balance and implement adequate water management measures. **Late introduction of detailed hydrological assessments** within the planning process is particularly problematic for cumulative impact mitigation. Thus, water balance considerations need to come earlier in the approvals processes.

Different **government agencies have different mandates and responsibilities**, which hinder the water planning processes. The purpose of the Western Australian Planning Commission (WAPC), which operates with the support of the Department of Planning, Lands and Heritage (DPLH), is to undertake and regulate land use planning and development. In contrast, the scope of the Department of Water and Environmental Regulation (DWER) is to manage and regulate the state's environment and water resources. Further, there is a disconnect between local and district level planning. On the one hand, local water management strategies (LWMSs) are approved, on the advice of the DWER and input where required from the Water Corporation, by the WAPC, which operates with the support of the DPLH. On the other hand, UWMPs are approved by the local government authorities (i.e., cities, towns or shires). Therefore, there is a need to consolidate communication and advice between local governments, DWER, the Department of Biodiversity, Conservation and Attractions (DBCA) and other authorities with statutory oversight of cumulative impacts. One suggestion to harmonise advice/approvals is to create working groups between councils or agencies. This could be a centralised technical review/advice hub made up of specialised personnel, which could be situated within regional councils.

There are **breaks in the chain of responsibility** within the planning, design and construction process. These can be exacerbated by separation of responsibilities within state and local government departments, and a shift of responsibility between private and public entities. Once an asset has been handed over to the local government, responsibilities become unclear.

Although council rates do not include fees for managing groundwater in private areas, these can end up being a large expense for local governments, which is why local governments are very conservative and risk averse, and why their engineers may also become so. This potentially leads to unnecessarily high construction costs. In some cases, councils even ask for parameters that aren't appropriate, because of their risk aversion or because they lack adequate expertise to evaluate models. Often, **local governments have limited financial and skill capacity** to review and approve technical hydrological/hydrogeological/engineering works.

The legal framework for **drainage** is fragmented and incomplete, because drainage is not subject to a separate Act. The Local Government Act and by Common Law touch on this issue. Issues such as infrastructure on private land, which needs to be maintained to achieve public good (e.g. subsoil drainage systems), fall into a legal ambiguity.

Appendix G. Glossary

Average annual maximum groundwater level (AAMGL) – the long-term peak groundwater behaviour at a site under pre-development land conditions

Annual exceedance probability (% AEP) – the probability that a given event will occur or be exceeded in any year

Aquifer – a geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water

Baseflow – the portion of streamflow delayed high subsurface flow

Biofilter – a stormwater management device that consists of an excavated basin or trench that is filled with porous media and planted with vegetation

Bore – a narrow, lined hole drilled to withdraw or monitor groundwater

Capacity building program – a holistic approach to knowledge building and transfer, which fosters skill development, competency, innovation and confidence. Also, to facilitate network building, linkages and training for continuous improvement

Capillary fringe – part of the unsaturated zone, where soil voids are filled (or almost filled) with water due to capillary rise

Catchment – a topographically defined area draining surface water to a single outlet point

Channel – the bed and banks of a stream or constructed surface water drain that carries all flows except floods

Clay (soils) – a fine-grained mineral soil consisting of particles less than 0.002 mm in equivalent diameter

Compaction – any process whereby the density of soils is increased. This process results in lower permeability and poorer soil aeration

Controlled groundwater system – a groundwater system that is subject to control or management through the provision of drainage infrastructure

Controlled groundwater level (CGL) – the invert level of groundwater controlling infrastructure

Drainage water – consists of stormwater runoff and/or high groundwater that has been intercepted by drains

Ecological values – particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health and economic activities, and which require protection from the effects of pollution, waste discharges and deposits and from the effects of altered water regimes

Evaporation – the primary pathway that water moves from the liquid state into the water cycle as atmospheric water vapour

Groundwater – water in the soil voids of the saturated zone

Groundwaterdependent ecosystems (GDEs) – ecosystems that require access to groundwater to meet all or some of their water requirements so as to maintain the communities of plants and animals, ecological processes they support, and ecosystem services they provide

Groundwater level – the non-static top of the saturated zone (can include locally perched groundwater)

Hydraulic conductivity – a measure of the ease of flow through a pore space or fractures. Hydraulic conductivity has units with dimensions of length per time (e.g. m/s, m/min, or m/d)

Hydrologic regime – a description of the variation of flow rate or water level over time

Hydrological cycle – the continual cycle of water between the land, the ocean and the atmosphere

Hydrology – the science of the behaviour of water in the atmosphere, on the surface of the earth and within the soil and underlying rocks. This includes the relationship between rainfall, runoff, infiltration and evaporation

Impermeable or impervious surface – the part of the catchment surfaced with materials, either natural or constructed, which prevent or limit the rate of infiltration of stormwater into the underlying soil and groundwater and subsequently increases stormwater runoff flows

Infiltration – the movement of water from the surface to the subsoil and at times, ultimately to the underlying aquifer

Infiltration system – a drainage facility designed to use the hydrologic process of stormwater runoff soaking into the ground, commonly referred to as percolation. Examples include infiltration basins and trenches, soakwells and pervious paving

Interflow – the lateral movement of water in the unsaturated zone. As water accumulates in the subsurface, saturation may occur and interflow may exfiltrate, becoming overland flow

Managed aquifer recharge (MAR) – The controlled infiltration or injection of water into an aquifer. The water can be withdrawn later, left in the aquifer for environmental benefits, or used as a barrier to prevent saltwater or other contaminants from entering the aquifer

Monitoring – the collection of data by various methods for the purpose of understanding natural systems and features, evaluating the impacts of development proposals on such systems, and assessing the performance of mitigation measures

Overland flow – the component of rainfall (excess) that is not removed by infiltration or use and discharges down-gradient as surface flow

Perched groundwater – groundwater that occurs above the regional water table, as a distinct saturated zone embedded within the unsaturated zone due to the presence of an aquiclude or aquitard

Phreatic surface – the non-static top of the saturated zone in a controlled groundwater system

50 per cent AEP phreatic surface – the phreatic surface that will be exceeded in 50 per cent of years (50 per cent chance each year)

20 per cent AEP phreatic surface – the phreatic surface that will be exceeded in 20 per cent of years (20 per cent chance each year)

Receiving water bodies – include waterways, wetlands, coastal marine areas and high groundwater aquifers

Recharge – water infiltrating to replenish an aquifer (note there are terms of NET recharge (i.e. recharge – evaporation or transpiration from the water table) and GROSS recharge (i.e. event scale recharge))

Retention/retain – the process of preventing rainfall runoff from being discharged into receiving water bodies by holding it in a storage area. The water may then infiltrate into the soil or other media, evaporate or be removed by evapotranspiration of vegetation

Risk – the chances of something happening that will have an impact on objectives. It is measured in terms of consequences and likelihood

Risk assessment – the process of risk analysis and risk evaluation

Runoff – water that flows over the surface of a catchment area, including streams

Sand – a soil consisting of particles between 0.02 mm and 2.0 mm in equivalent diameter. Fine sand is defined as particles between 0.02 mm and 0.2 mm, and coarse sand as those between 0.2 mm and 2.0 mm

Saturated zone – the part of the soil profile where voids are completely filled with water

Seasonally perched groundwater – perched groundwater that is seasonally connected to the underlying water table

Silt: – a soil consisting of particles between 0.002 mm and 0.02 mm in equivalent diameter

Soil amendment – involves adding an agent to the soil to improve its structure, porosity, water holding capacity and/or nutrient recycling capacity

Soil permeability – the ease with which gases, liquids or plant roots penetrate or pass through a layer of soil

Soil stabilisation – the use of measures or materials to prevent the movement of soil when loads are applied to the soil

Source controls – non-structural or structural best management practices designed to minimise the generation of excessive stormwater runoff and/or pollution of stormwater at or near the source and protect receiving environments

Stormwater – water flowing over ground surfaces and in natural streams and drains, as a direct result of rainfall over a catchment. Stormwater consists of rainfall runoff and any material (soluble or insoluble) mobilised in its path of flow

Stormwater quality – the chemical, physical and biological characteristics of stormwater

Stormwater quantity – the volume characteristics of stormwater

Subsurface drain – a drain designed to intercept subsoil water and thereby limit the groundwater level

Superficial (unconfined) aquifer – an aquifer containing water with no upper non-porous layer to limit its volume or to exert pressure. The upper surface of the groundwater within the aquifer is called the water table

Surface water – water flowing or held in waterways or wetlands on the surface of the landscape

Swale – a drainage interception and conveyance system with relatively gentle side slopes and high flow depths

Transpiration – the process of water movement through a plant from absorption primarily through the roots to evaporation from aerial parts

Unsaturated zone – the part of the soil profile where voids are only partially filled with water

Urban – land used for residential, rural-residential, commercial or industrial development

Vegetated swale – a swale with vegetation covering the side slopes and base. Vegetation can range from grass to native sedges and shrubs, depending on hydraulic and landscape requirements

Water bodies – waterways, wetlands, coastal marine areas and high groundwater aquifers

Watercourses – a river, stream or creek in which water flows in a natural channel, whether permanently or intermittently

Water dependent ecosystems – those parts of the environment, the species composition and natural ecological processes of which are determined by the permanent or temporary presence of water resources, including flowing or standing water and water within groundwater aquifers

Water sensitive urban design (WSUD) – a design philosophy that provides a framework for managing water related issues in urban areas. WSUD principles include incorporating water resource management issues early in the land use planning process. WSUD can be applied at the lot, street, neighbourhood, catchment and regional scale

Water table – the non-static top of the saturated zone (generally does not include locally perched groundwater)

Waterways – all seasonal, intermittent or permanent streams, creeks, rivers, estuaries, coastal lagoons, inlets and harbours

Wetlands – areas of seasonally, intermittently or permanently waterlogged or inundated land, whether natural or otherwise, including lakes, sumplands, playas, damplands, floodplains, barlkarras, palusplains, paluslopes, palusmonts or tidal flats

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