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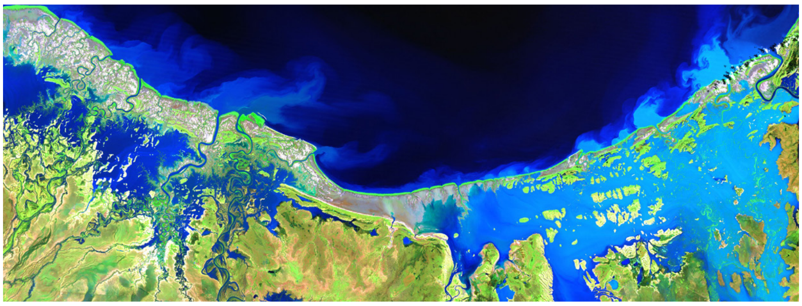

Record 2013/04 | **GeoCat** 74648

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Coastal aquifer typology

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GEOSCIENCE AUSTRALIA
RECORD 2013/04
NOVEMBER 2012

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Australian Government

Geoscience Australia

National Water Commission

National Centre for Groundwater Research and Training
sustaining a vital water resource

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Department of Resources, Energy and Tourism

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Secretary: Mr Drew Clarke

Geoscience Australia

Chief Executive Officer: Dr Chris Pigram
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ISSN 1448-2177

ISBN 978-1-922201-21-8 (Print)
ISBN 978-1-922201-22-5 (PDF)

GeoCat 74648

Bibliographic reference: Ivkovic, K.M., Marshall, S.K., Carey, H., Morgan, L.K., Sundaram, B., Dixon-Jain, P, Caruana, L., Garlapati, N., and Werner, A.D. 2013. *A national-scale vulnerability assessment of seawater intrusion: Coastal aquifer typology*. Record 2013/04. Geoscience Australia, Canberra, and National Centre for Groundwater Research and Training, Adelaide.

Executive Summary

Fresh groundwater stored in Australian coastal aquifers constitutes an important resource for humans and the natural environment. However, many Australian coastal aquifers are vulnerable to seawater intrusion (SWI) – the landward encroachment of seawater into coastal aquifers. SWI can significantly degrade water quality and reduce freshwater availability. The increasing demands for freshwater in coastal areas and the anticipated impacts of climate change (such as sea-level rise and variations in rainfall recharge) may result in increases in the incidence and severity of SWI. Despite these threats, comprehensive investigations of SWI are relatively uncommon and the extent of monitoring and investigations specific to SWI are highly variable across the nation.

To better understand the threat posed by SWI, Geoscience Australia (GA) and the National Centre for Groundwater Research and Training (NCGRT), in collaboration with state and territory water agencies, have undertaken a national-scale assessment of the vulnerability of coastal aquifers to SWI. This assessment aims to identify the coastal groundwater resources that are most vulnerable to SWI, including future consequences of over-extraction, sea-level rise, and recharge–discharge variations associated with climate change. The current study focuses on assessing the vulnerability of coastal aquifers, rather than that of surface waterbodies, to the landward migration of the freshwater–saltwater interface. Project funding was provided through the Raising National Water Standards program, which is administered by the National Water Commission.

In order to achieve the project aims, the study comprised five technical assessments to analyse factors contributing to the vulnerability of coastal aquifers: (i) vulnerability factor analysis (VFA); (ii) coastal aquifer typology; (iii) mathematical analysis; (iv) SWI quantitative and qualitative vulnerability indexing; and, (v) future land surface inundation and population growth analysis.

This report covers the coastal aquifer typology component of the project which includes a characterisation of the different hydrogeological and climatic settings of Australia's coastal aquifers. Using public and confidential information, simplified cross-sectional conceptual models of case study areas were developed and aquifer parameters were tabulated for 28 case study areas (CSAs). The CSAs selected were identified as being at risk of SWI through literature review and in consultation with stakeholders, and had sufficient aquifer parameter data to use as input into the mathematical analysis component of the project, used to provide first-order estimates of SWI extent.

The combination of principal aquifer type and climate group formed the basis of the coastal aquifer typology. The principal aquifer types for the case study areas were classified into: coastal alluvium; coastal sands; unconfined sandstone; multi-layered, deep, consolidated; multi-layered, shallow, unconsolidated; carbonate; basalt and fractured/undivided classes. The climate types included the Köppen-Geiger climate groups: Tropical; Mediterranean; Arid and Temperate. The Köppen-Geiger climate groups were selected to form part of the national-scale coastal aquifer typology because rainfall, temperature and associated seasonal patterns (e.g. hot, dry summers) will have, to varying degrees, an influence on groundwater recharge and extraction patterns, and indirectly reflect land use characteristics. The characteristics of the principal aquifer types based on the 28 case study areas are outlined below.

The **coastal alluvium** types include Cenozoic, unconfined to semi-confined aquifers associated with current river systems. These aquifers tend to have high hydraulic conductivities, with typical values ranging from 50 to 160 m/day. They are located in flat, low-lying areas where groundwater elevations are close to, or just below, sea level, with aquifers exposed to tidal influences at the river outlet and adjacent to tidal estuaries and creeks.

Coastal alluvium aquifers are characterised by relatively shallow aquifer depths and exhibit a relatively thin saturated aquifer thickness. They are particularly vulnerable to drought and often contain preferential flow pathways that are susceptible to localised SWI.

The **coastal sands** types include Cenozoic (mostly Quaternary) unconfined aquifers associated with sand dunes. Typical values of hydraulic conductivity ranged from 3 to 150 m/day. These aquifers are primarily recharged by diffuse rainfall, and because they are relatively thin, they can only store limited amounts of freshwater relative to the amount of rainfall recharge they receive. These aquifers are often located adjacent lagoons that provide a source of saltwater. They also may also contain a freshwater lens sitting over saline water, and the primary mechanism for SWI is a thinning of the lens and up-coning from over-pumping.

The **unconfined, sandstone** aquifer types include Triassic to Cretaceous, sandstone units that are deep and thick. Typical values of hydraulic conductivity ranged from 1 to 15 m/day. These aquifer types are all located within an arid climate group setting, and receive relatively low amounts of groundwater recharge. Head values are close to sea level. These aquifer types generally have a considerable aquifer thickness that allows for substantial storage of fresh groundwater resources. The extension of the unconfined aquifer out to sea, considerable depth and naturally-large inland extent of the saltwater wedge position may facilitate SWI intrusion.

The **multi-layered, deep** aquifer types include Cenozoic to Jurassic, sedimentary sequences, comprising mainly sandstone, coarse silt and sands, and minor limestone, with clay aquitards separating the aquifer systems. The upper-most, unconfined, sand aquifers in these systems share characteristics with the coastal sands type of aquifer. The confined aquifers are deep and thick, making them excellent aquifers for large scale development. Typical values of hydraulic conductivity values ranged from 1 to 10 m/day. In many of these systems the heads have been lowered as a consequence of groundwater extractions. An important mitigating factor is that some of these confined freshwater aquifer systems extend some distance out to sea. However, over-exploitation leading to excessive declines in groundwater pressures may eventually lead to SWI from offshore.

The **multi-layered, shallow** aquifer types include Cenozoic, unconsolidated sediments with multiple aquifers separated by discontinuous clay aquitards that have been deposted within a coastal plain setting. These aquifers are relatively thin and shallow. Typical values of hydraulic conductivity rangd from 5 to 20 m/day. The unconfined aquifers share common features with the coastal sands aquifer types, and are replenished by infiltration of rainfall. The deeper, underlying semi-confined aquifers may also receive considerable net recharge through aquifer leakage, while the confined aquifers may receive little recharge. Because of the reliance on rainfall recharge, these aquifers are vulnerable to droughts and drying climates. The deeper sediments are characterised by variable groundwater salinity, including brackish to saline water, and extensive pumping from the upper aquifer can result in up-coning of seawater.

The **carbonate** aquifer types are primarily Cenozoic-aged and unconfined. Due to karstification, these aquifer types often have very high hydraulic conductivities in some parts, with typical values ranging from 45 to >150 m/day. The karstic nature of carbonate aquifers dramatically increases recharge from rainfall- particularly during intense rainfall events. As a result, groundwater levels rapidly respond to seasonal, climatic and anthropogenic influences on short time scales. Groundwater within the carbonate aquifer often occurs in freshwater lenses and isolated basins, overlying and/or adjacent to saline groundwaters. The isolated freshwater is at risk of drawing in saline waters, especially where the freshwater lenses are relatively thin.

The **basalt** aquifer type was represented by a single CSA, Werribee (Vic). The coastal basalt aquifers in Australia are Cenozoic in age and generally unconfined. These aquifers are formed by layered basalt plains that primarily store groundwater in fractures and vesicles. This aquifer had a typical hydraulic conductivity value of 5 m/day and an aquifer thickness of 50 m. Aquifer recharge occurs primarily through rainfall via fractures and river water losses. Groundwater quality can be variable within the basalt aquifers, with the fresher groundwaters found in areas where there is a greater fracture density and/or permeability. These fracture openings and higher permeability areas may also provide a preferential flow path for seawater migration. Tidal effects along the river may also contribute to ingress of saltwater within adjacent aquifers, especially if fracture orientation is perpendicular to estuarine waters.

The **fractured/undivided** aquifer type of aquifer was represented by a single CSA, Howard Springs and was Proterozoic to Cretaceous in age. This coastal aquifer is characterised by fractured sequences of mixed lithology that have undergone metamorphosis and weathering. The aquifers are unconfined to semi-confined, and hydraulic conductivity varies with the degree of fracture density and weathering. A typical hydraulic conductivity value for the aquifer in this case study area was 40 m/day. The aquifers were relatively deep with heads well above sea level. Recharge to the aquifer occurs at aquifer outcrops as well as through surficial porous sediments and fractures. Recharge through fractures can be relatively quick and groundwater levels can rapidly respond to seasonal, climatic and anthropogenic influences. Aquifer fractures, especially where fracture orientation is perpendicular to the sea, can provide preferential paths for SWI migration.

The range of long term average recharge values to unconfined aquifers, as noted within the aquifer parameter tables for each case study area, were evaluated by climate group. Recharge ranges were found to be the lowest within the **Arid** climate group followed by the **Mediterranean** group, and highest in the **Temperate** (other than Mediterranean) and **Tropical** groups. Admittedly, the data were too few to make any conclusive statements.

Acknowledgements

The authors wish to thank individuals from the various federal, state and territory stakeholder agencies for their support and input into the project through participation in the workshop, steering committee meetings and other means such as through providing data, reports and other information. Their input has contributed immeasurably to the philosophy, content, and structure of the report. Particular acknowledgements are attributed to the following people:

- Peter Hyde, Shane Hogan, Adam Sincock, Cynthia Maher and Melissa Woltmann (National Water Commission);
- Lalage Cherry, Brendan Kelly and Neil Lazarow (Australian Government Department of Climate Change and Energy Efficiency);
- Alex Kern and Chris O'Boy (Department of Water, Western Australia);
- Leon Leach (Department of Environment and Resource Management, Queensland):
- Michael Williams and John Williams (Office of Water, New South Wales);
- Steve Barnett (Department for Water, South Australia);
- Des Yin Foo and Steve Tickell (Department of Natural Resources, Environment, the Arts and Sport, Northern Territory);
- Chris McAuley and Stuart Horner (Department of Sustainability and Environment, Victoria);
- Don Rockliff (Department of Primary Industries, Parks, Water and Environment, Tasmania);
- Richard Cresswell (Sinclair Knight Merz; formerly CSIRO);
- Steven Hosteler (FrOG Tech);
- Ken Lawrie (Geoscience Australia) for initiating the SWI project;
- Luke Wallace, Penny Kilgour, Jon Clarke, David Simon, Gerard Stewart and Veronika Galinec (Geoscience Australia); and
- for providing a peer review of the draft and providing their editorial comments: Peter Somerville and Jane Coram (Geoscience Australia), John Hillier and Eloise Nation (Bureau of Meteorology).

Geoscience Australia would also like to thank its collaborating partners on the project, NCGRT and Naiades Geohydrology. The study was funded by the National Water Commission.

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Abbreviations and Acronyms

ABS	Australian Bureau of Statistics
AEM	Airborne Electromagnetic
AGSO	Australian Geological Survey Organisation
ANRA	Australian Natural Resource Atlas
AHD	Australian Height Datum
AOI	Area of Interest
APT	Aquifer Parameter Table
BRS	Bureau of Rural Sciences
CD	Collector District
CSA	Case Study Area
CVI	Coastal Vulnerability Index
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEE	Australian Department of Climate Change and Energy Efficiency
DEM	Digital Elevation Model
EC	Electrical Conductivity
FAO	United Nations Food and Agriculture Organisation
GA	Geoscience Australia
GIS	Geographic Information System
GH	Ghyben-Herzberg
GMU	Groundwater Management Unit
IPCC	Intergovernmental Panel on Climate Change
ISDR	International Strategy for Disaster Reduction
KMM	Knowledge Monitoring and Management
MSL	Mean Sea Level
NAMS	National Agricultural Monitoring System
NCGRT	National Centre for Groundwater Research and Training
NRM	Natural Resource Management
NT	Northern Territory
NTC	National Tidal Centre
NSW	New South Wales
NWC	National Water Commission
NWI	National Water Initiative 2004
PSC	Project Steering Committee
PWA	Prescribed Wells Area
QDNRM	Queensland Department of Natural Resources and Mines
Qld	Queensland
RNWS	Raising National Water Standards
SA	South Australia
SRTM	Shuttle Radar Topographic Mission
SWI	Seawater Intrusion
TDS	Total Dissolved Solids
TWOH	Tidal watertable over-height
VFA	Vulnerability Factor Analysis
Vic	Victoria
WA	Western Australia

Units

cm	centimetres
km	kilometres
L/s	litres per second
m	metres
mg/L	milligrams per litre
µS/cm	micro-Siemens per centimetre
kL	kilolitre: 1000 litres (equivalent to one cubic metre: m^3)
ML	Megalitre: one million (1 000 000) litres
GL	Gigalitre: one billion litres (equivalent to 1000 megalitres, ML)

1. Introduction

The current project entitled "A national scale vulnerability assessment of seawater intrusion" has been completed by Geoscience Australia (GA) and the National Centre for Groundwater Research and Training (NCGRT) in collaboration with State and Territory agencies. The aim of this project is to identify Australian coastal groundwater resources currently vulnerable to seawater intrusion (SWI), and potentially at risk in the future as a consequence of over-extraction, sea-level rise and/or recharge-discharge variations associated with climate change.

The project has included five technical assessments in order to analyse factors contributing to the vulnerability of coastal aquifers: (i) vulnerability factor analysis (VFA); (ii) coastal aquifer typology; (iii) mathematical analysis; (iv) SWI quantitative and qualitative vulnerability indexing; and, (v) future land surface inundation and population growth analysis. This technical report addresses the coastal aquifer typology component of the project, which includes: a characterisation of the hydrogeological settings of Australia's coastal aquifers based on selected national-scale datasets of relevance to a SWI investigation and provides a catalogue of simplified hydrogeological cross-sections with associated typical aquifer parameters based on case study area information. A summary of this report can be found in Chapter 4.3 of the project summary report (Ivkovic et al., 2012b), whilst the current report provides a complete account of the development of a coastal aquifer typology for the project, including accompanying appendices.

The following material within this introductory chapter provides background information on SWI and the motivating context for the development of this project. Also, within this chapter the concept of vulnerability is introduced; the aims and objectives of the project are listed; and, the project methodology is briefly outlined, placing this technical report into project context. The chapter ends with an overview of the structure of this current report.

1.1. Background to a national-scale vulnerability assessment of seawater intrusion project

Fresh groundwater stored in Australian coastal aquifers is an important resource for the natural environment, as well as for urban, agricultural, rural residential and industrial activities. These aquifers may be vulnerable to seawater intrusion (SWI), which is the landward encroachment of seawater into fresh coastal aquifers. SWI can be caused by hydrologic changes, such as groundwater extraction, groundwater recharge variations, sea-level rise, or modifications to coastal surface water features. SWI poses a threat to the groundwater resources in all of Australia's states and the Northern Territory. Yet despite this existing threat, comprehensive investigations of SWI are relatively uncommon and the extent of monitoring and investigations specific to SWI is highly variable across the nation (Werner 2010). As Werner (2010) stated, "*SWI investigation is a problematic and resource intensive business*" and "*the current scientific challenges of coastal aquifer management in Australia are as complex and diverse as the systems themselves*". Such a statement gives insight into the difficulties associated with investigating SWI.

The vulnerability of Australia's coastal aquifers to SWI is not only an area of current concern but also an area of increasing future concern. The increasing demands for freshwater in coastal areas and the anticipated impacts of climate change, such as sea-level rise and variations in rainfall recharge, may result in increases in the incidence and severity of SWI. An assessment is needed to address the paucity of knowledge of SWI vulnerability at the national scale that considers the extensive and diverse aquifer systems of Australia’s coastal fringe (Werner 2010). An improved awareness and understanding of the key drivers for SWI, the current and emerging SWI vulnerable areas and possible future trends in SWI, will benefit decision makers and groundwater stakeholders across local, state and national levels. Development of a consistent approach for the assessment of SWI vulnerability will assist national, state and regional planning and management strategies.

The national vulnerability assessment of SWI was developed to address the issues highlighted above. The broader project includes a number of technical reports focussing on various factors contributing to SWI vulnerability. The increased stresses being placed upon Australia’s freshwater coastal aquifer systems and the reported threats of SWI within the states and the Northern Territory were strong motivating factors for development of the current project. It was funded by the National Water Commission under the Groundwater Action Plan, and implemented by Geoscience Australia and the National Centre for Groundwater Research and Training (NCGRT) in partnership with state and territory agencies. The project commenced in November 2009 and finished in May 2012.

1.2. Vulnerability concept clarification

The principal focus of this project is assessing the vulnerability of Australian coastal aquifers to SWI, and accordingly a discussion of the concept of vulnerability and its meaning are provided. Vulnerability has numerous definitions, conceptualisations and assessment methods in the literature found both across and within disciplines (Füssel, 2007). This project has utilised several vulnerability definitions that are appropriate for the multiple components of this national vulnerability assessment of SWI.

Füssel (2007) reviewed vulnerability definitions and found that four dimensions were fundamental to describe any vulnerable situation. These four dimensions included:

1. The **System** undergoing analysis;
2. The **Valued Attribute**(s) of the vulnerable (susceptible) system that is threatened by its exposure to a hazard;
3. **Hazard**: A potentially damaging influence on the system of analysis; and
4. **Temporal Reference**: The point in time or period of interest (current, future, number of years into future etc.).

Using these terms, this project can be described as an assessment of the vulnerability of Australian freshwater coastal aquifers (*system and attribute of concern*) to SWI as a consequence of over-extraction and sea-level rise and/or recharge-discharge variations associated with climate change (*hazards*) in the present, and future (*temporal reference*). This is consistent with the fact that SWI vulnerability is a function of the intrinsic characteristics of the aquifer and the management of the water balance in that aquifer.

The Intergovernmental Panel on Climate Change (IPCC) has defined vulnerability in the specific context of climate change as “*the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change*” (IPCC, 2007). Barnett (2007) noted that “*While there is no consensus on the best approach to vulnerability assessment, in general they entail considering one or more of: exposure to climate risks, susceptibility to damage, and capacity to recover”.* The essence of these definitions is captured by (Voice et al., 2006) who states “*vulnerability is a function of exposure, sensitivity and adaptive capacity”.*

By combining the above vulnerability definitions for the purposes of the current study, this report assesses the system of aquifer SWI vulnerability as a function of:

- Exposure to hazards (SWI as a result of groundwater extraction and climate change);
- Sensitivity of the system (coastal aquifers) for attribute of concern (position of the freshwater-seawater interface);
- Time (current and future vulnerability); and,
- Adaptive capacity (monitoring and management specific to SWI).

1.3. Project Aim and Objectives

The aim of ‘A national-scale vulnerability assessment of seawater intrusion’ is to undertake a national assessment of coastal groundwater resources currently vulnerable to SWI, and potentially vulnerable in the future, as a consequence of over-extraction, sea-level rise and recharge-discharge variations associated with climate change.

The project has three principal objectives:

Objective 1: Provide a baseline assessment of the current status and knowledge of SWI around Australia

Objective 2: Provide conceptualisations and assessments of a range of factors contributing to the SWI vulnerability of Australian coastal aquifers, including the influences of over-extraction, sea-level rise and recharge-discharge variations associated with climate change

Objective 3: Provide an integrated assessment of the vulnerability of coastal aquifers in Australia to SWI.

The methodologies employed to meet the above objectives are outlined below.

1.4. Project Methodology

In order meet the project objectives and to achieve a national-scale assessment of aquifer vulnerability to SWI for current and future scenarios, the project adopted a methodology comprising four work phases (Figure 1). These include:

Phase 1: Literature and data reviews to provide a baseline assessment of the state of SWI investigations in Australia and inform the development of the project methodology (Dixon-Jain et al., 2010; Ivkovic et al., 2012a).

Phase 2: Five technical assessment components to analyse key factors contributing to the overall vulnerability of coastal aquifers to SWI. The five technical assessments included:

- Vulnerability Factor Analysis (Cook et al., 2012)
- Coastal Aquifer Typology (this report)
- Mathematical Analysis (Morgan et al., 2012b)
- Quantitative and Qualitative Indexing (Morgan and Werner (2012) and Norman et al. (2012) respectively)
- Future land surface inundation and population growth analysis (contained within the Ivkovic et al. (2012b) project summary report)

Phase 3: The five technical components in phase 2 are integrated to provide an overall SWI vulnerability assessment (Marshall et al., 2012).

Phase 4: A national summary of SWI vulnerability (Ivkovic et al., 2012b) provides an overview of the project findings.

The following general approaches to analysis were adopted throughout this project:

1. SWI vulnerability analysis was restricted to areas within 15 kilometres of the coast, including a limited selection of off-shore islands; areas further than 15 kilometres inland were not considered likely to be vulnerable to SWI.
2. The areas of interest for detailed analysis within the CSAs are those where the groundwater management units or equivalent groundwater management areas intersect the 15 kilometre buffer zone and are connected to the coast.
3. The project focus is on SWI of coastal aquifer systems and there is limited emphasis on investigating the impacts of inundation to coastal environments and communities (human, ecological, infrastructure etc.).
4. Surface water processes are not specifically considered in any detail.
5. The project has been restricted to the synthesis, analysis and interpretation of existing data and there has not been any new field data collection, local mapping or drilling.

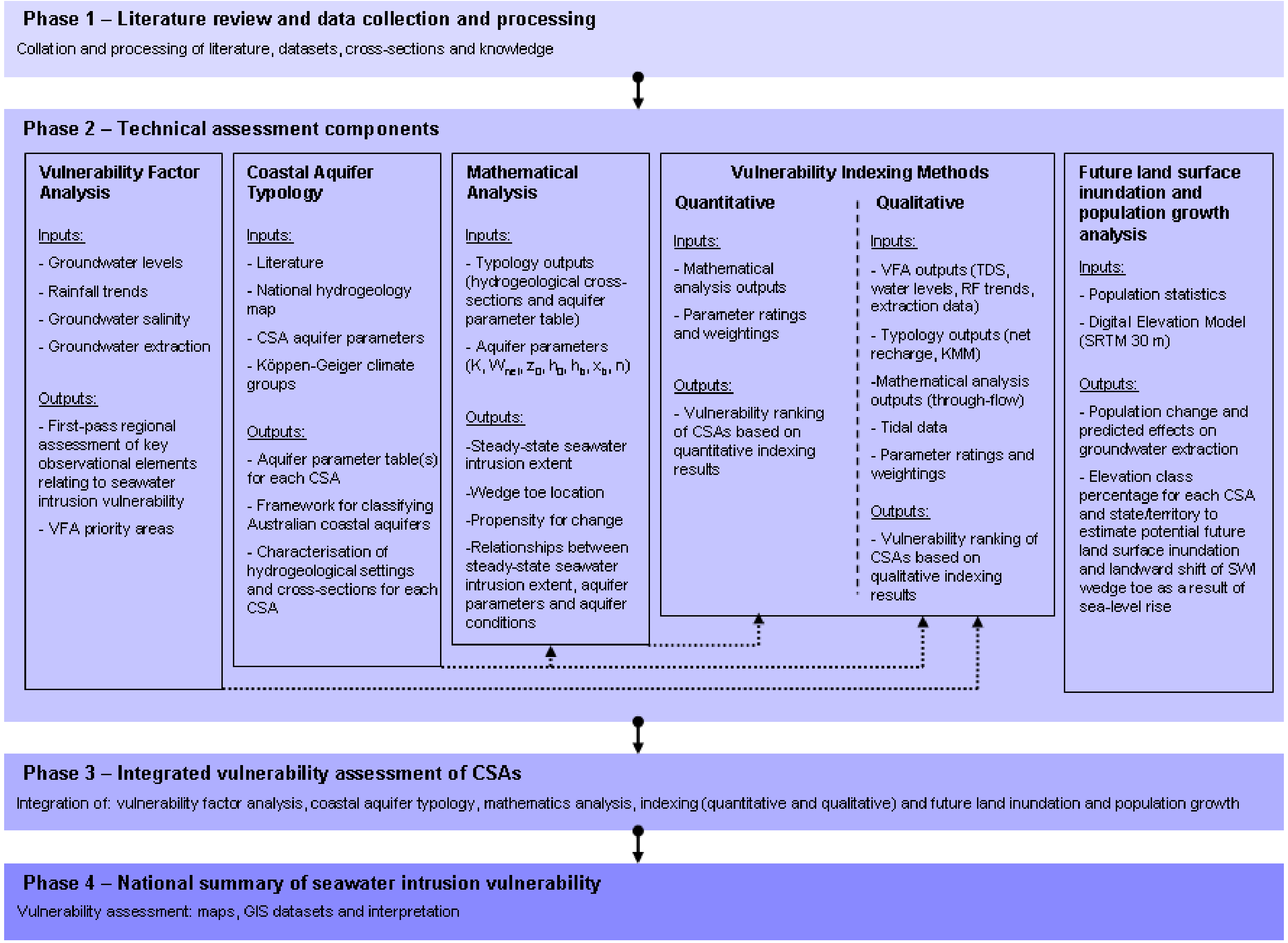

***Figure 1** Methodology of overarching project, 'A national-scale vulnerability assessment of seawater intrusion'.*

1.5. Coastal Aquifer Typology Aims and Objectives

The purpose for developing a coastal aquifer typology within the project was to create a framework for classifying the hydrogeological conditions of Australia's coastal aquifers with the specific objective of assessing their vulnerability to SWI. The coastal aquifer typology was also used to provide the required aquifer parameters for the mathematical analysis component of the project (Morgan et al., 2012b) for the 27 case study areas (CSAs) selected. The definition and the use of typology are further discussed below.

1.5.1. Typology – its definition and use

The word 'typology' is defined as the study, analysis or classification based on type. A typological assessment is typically undertaken in an attempt to classify environments into groups based on physical, structural or other functional similarities for a specific purpose. In the case of this investigation, the purpose is to assess the vulnerability of Australia's coastal aquifers to SWI.

Typologies can be used to reduce complexity in the area of research interest in order to more easily detect patterns, improve understanding, aid with decision making, prioritise and allocate resources, and tailor a variety of activities, strategies and processes (Maru et al., 2011). The advantage of using typology is that, after developing a systematic categorisation, it should allow for a framework that can be used for scaling local investigations to the larger scale, where direct observations may be lacking, by the use of surrogate information to infer processes (Bokuniewicz, 2001). This approach may be of particular utility in the case of assessing SWI on a nationwide scale because of the paucity of comprehensive investigations and data for coastal aquifer systems (Werner, 2010). Through the classification of coastal aquifer types and by evaluating state variables of relevance to a SWI investigation, the possibility is created to extrapolate existing-data to assess and further build upon our understanding of SWI vulnerability. The other key project components, such as the vulnerability factor analysis, mathematical analysis and vulnerability indexing are also critical components of the SWI vulnerability assessment, and will be analysed in conjunction with the coastal aquifer typology discussed in this report.

Typological development in groundwater investigations has commonly included three over-arching components based on: (1) climatological parameters; (2) geomorphic-geologic classes; and (3) aquifer state parameters for example, aquifer thickness, hydraulic conductivity, hydraulic gradient etc. (Bokuniewicz, 2001; Coram et al., 2001). Accordingly, these three components of typology have been investigated and further developed for use within the project using national-scale datasets and local-scale data obtained from CSAs. The typological development outlined within this report has an emphasis on the intrinsic characteristics of coastal aquifer systems in Australia. Another project component, the Qualitative Indexing (Norman et al. 2012), further assesses water balance, water levels and other critical factors important to an SWI investigation. An overview of the steps taken to develop the coastal aquifer typology for the project follows.

1.5.2. Overview of Steps Used to Develop the Coastal Aquifer Typology

The development of the coastal aquifer typology for the project included the following steps:

1. Conceptualise classification for coastal aquifer typology using national-scale climatic and hydrogeological data sets following a top-down approach;
2. Apply coastal aquifer typology at the national-scale ;
3. Select CSAs from areas identified in the literature review to be at threat of SWI. Areas selected based on having the requisite hydrogeological data by which to characterise the aquifer systems and parameterise mathematical equations used to determine the first-order position of the SWI toe;

4. Refine coastal aquifer typology classification based on CSA information using a bottom-up approach based on local-scale data;
5. Produce overviews of the characteristics of the 27 selected CSAs including: location; climate; geology and geomorphology; hydrogeology; land use; and documentation of previous SWI incidences;
6. Develop a simplified hydrogeological cross-section for each CSA ;
7. Tabulate key hydrological parameters into aquifer parameter tables (APTs) for each CSA for subsequent mathematical analysis; and,
8. Discuss key hydrological characteristics for each coastal aquifer type based on the findings from the CSAs

An overview of SWI sites and the selection process for identifying the CSAs used to develop the coastal aquifer typology is discussed in the following sub-sections.

1.6. SWI Sites and Case Study Areas

Ivkovic et al. (2012a) summarised the publically available reports and journal papers where SWI incidences, or the threat of SWI, has been documented in Australia. In addition to the investigations highlighted in the literature review, project stakeholders also identified a number of sites that were possibly vulnerable to SWI. These locations collectively became known as ‘SWI Sites’ for this project; their locations are shown in Figure 2 and listed within the companion summary table (Table 1).

1.6.1. Case Study Areas Selected

Of the SWI sites listed in Table 1, only those sites which had sufficient hydrogeological data available by which to characterise the aquifers sufficiently for future mathematical analysis were selected as CSAs. The aquifer data were derived from literature and from groundwater databases specific to individual CSAs. These were used as input to the steady-state, sharp-interface analytical solutions to provide first-order estimates of the position of the freshwater-saltwater interface in these areas (Morgan et al., 2012a).

Twenty-eight CSAs were selected for the project (Figure 3; Table 2). Subsequent to the Coastal Aquifer Typology, the number of CSAs was decreased to 27, as there was insufficient data available for Rottnest Island to be included in the Qualitative Indexing technical assessment. This report has, nevertheless, included Rottnest Island as a CSA as its information may become useful for future analyses. Western Australia had the most CSAs (11), followed by Queensland and South Australia (5), New South Wales (4), Victoria (2) and the Northern Territory (1). No CSAs were selected for Tasmania. The fact that Western Australia, Queensland and South Australia had the greatest number of CSAs is consistent with the fact that these States/Territory had the greatest number of SWI incidences or threats reported within the literature review (Ivkovic et al., 2012a). Conversely, Tasmania did not have any CSAs due to minimal data. Tasmanian stakeholders, who were consulted about the selection of a potential area for inclusion within the project, stated that SWI investigation was not a priority for them, as the perceived threat of SWI was low. In the case of New South Wales, there was limited published information at the time of the Milestone 2 project literature review (Dixon-Jain et al 2010). However, more recently, additional data for New South Wales became available as a consequence of the investigations targeted to assess the management of the coastal dune aquifers in the Mid North Coast Region (SKM, 2011). Since the literature review conducted at the start of the project (Dixon-Jain et al., 2010), the literature and project methodology has updated to provide a more complete review and more accurately reflects the project directions (Ivkovic et al., 2012a).

In accordance with the project scope, the CSAs represent exploitable aquifers (e.g. of salinity less than 3000 mg/L and at depths less than 400 m) located within 15 km from the coast (with the exception of Howard Springs, NT which was located 18 km inland). Aquifer properties were derived from existing sources of information, generally pertaining to specific locations that had been investigated previously for groundwater development and modelling purposes, or in a few cases, specifically for SWI. The CSAs are located within Groundwater Management Units (GMU's) or equivalent groundwater management areas (Table 2).

Aquifer parameter tables (APTs) and simplified hydrogeological cross-sections have been prepared for the CSAs. The information gained has been used to conceptualise coastal aquifer systems types and also provides a catalogue for the range of coastal aquifer systems found in Australia perceived to be vulnerable to SWI. The following chapter, Chapter 2, discusses the development of a coastal aquifer typology using national-scale and local scale (specific to each CSA) datasets.

1.7. Report Structure

Chapter 1, the Introduction, provided a background to the project: 'A national-scale vulnerability assessment of seawater intrusion'. It provided the key aims and objectives, as well as the structural framework of this project. It included key aims and objectives of the current study: 'Coastal Aquifer Typology'. It also included a definition of typology and an introduction to the selection of CSAs. Chapter 2 provides details about the development of the coastal aquifer typology classification system, including the datasets used to create the typology classification. Chapter 3 contains the typological analysis of each CSA including their key hydrogeological settings. Chapter 4 includes some key findings of the Coastal Aquifer Typology, and includes a discussion about the propensity of aquifer types to SWI. Chapter 5 contains conclusions and future directions of the project. The appendices contain a large proportion of this study's key outputs including the APT tables for each CSA.

Figure 2 *Locations where the threat of SWI has been identified (Ivkovic et al., 2012a).*

Table 1 *Distribution of previous Australian studies that identify the threat of SWI (Ivkovic et al., 2012a).*

Location	SWI Incidence Reported	SWI Monitoring	Degree of SWI assessment[1]
South Australia			
Eyre Peninsula	Yes	Yes, but not SWI interface specific	Moderate
LeFevre Peninsula (Adelaide)	Yes	Yes, but not SWI interface specific	Low
Adelaide Metropolitan	Yes	Yes, but not SWI interface specific	Moderate
Port MacDonnell	No	No	Moderate
Willunga, SA	Yes	Yes, but not SWI interface specific	Low
Victoria			
Werribee	Yes	Yes, but not SWI interface specific	Moderate
Gippsland (Sale and Orbost regions)	No	No	None to Very Low
Point Nepean*	No	No	Low
Koowerup*	No	No	None to Very Low
Moorabbin*	No	No	None to Very Low
Nullawarre*	No	No	None to Very Low
Yangery*	No	No	Low None to Very Low
Western Australia			
West Kimberley Coast (Broome and Derby)	Yes	No	Low
Cape Range	Yes	No	Low
Carnarvon	Yes	Yes, but not SWI interface specific	Moderate
Northern Swan Coastal Plain (Dongara, Leeman, Jurien)	No	No	Low
Perth (other than Cottesloe)	No	Yes, but not SWI interface specific	Moderate
Cottesloe Peninsula (Perth)	Yes	Yes, but not SWI interface specific	Moderate
Rottnest Island	No	Yes	Moderate
Bunbury	Yes	Yes	Low
Busselton	No	Yes, but not SWI interface specific	Moderate
Albany	No	Yes	Moderate
Esperance	Yes	Yes	Moderate
Northern Territory			
McMinns/Howard East (Darwin Rural Area)	No	No	None to Very Low
Lambells Lagoon (Darwin Rural Area)	No	No	None to Very Low
Milikapiti	No	No	None to Very Low
Warruwi (Goulburn island)	No	No	Low
Milingimbi	No	No	None to Very Low
Ngukurr	No	No	None to Very Low

Location	SWI Incidence Reported	SWI Monitoring	Degree of SWI assessment[1]
New South Wales			
Clarence River Floodplain	No	No	None to Very Low
Stuarts Point	No	No	Low
Botany Sands, Sydney	Yes	No	None to Very Low
Stockton	No	No	Low
Hat Head	No	No	Moderate
Queensland			
Mitchell region, Cape York	No	No	None to Very Low
Burdekin River Delta	Yes	Yes	High
Bowen	Yes	Yes	Moderate
Pioneer Valley	Yes	Yes	High
Burnett Heads/Bundaberg	Yes	Yes	High
Bribie Island	Yes	Yes, but not SWI interface specific	Low
Stradbroke Island	No	Yes, but not SWI interface specific	Moderate
Pimpama Coastal Plain	No	No	None to Very Low
Tasmania			
King Island	No	No	None to Very Low
King Island, Grassy scheelite mine site	No	No	None to Very Low
Woolnorth	No	No	None to Very Low
Smithton* (Duck River, Montagu River, Welcome River Catchments)	No	No	None to Very Low

** These areas were highlighted by stakeholders as being potentially vulnerable to SWI, although there may be little to no SWI references/information available*

1Degree of assessment

None to Very Low: No threat of SWI has been identified. Few to no hydrological investigations have been undertaken. No monitoring, management or modelling assessments undertaken.

Low: The threat of SWI has been identified, either in reports or anecdotally by state agencies. The amount of publicly-available bore observation data and research on SWI by which to assess vulnerability factors is low. Infrequent or no monitoring is undertaken to assess the manifestation of SWI.

Moderate: The risk of SWI has been reported and there is a moderate level of publically-available bore observation data and research on SWI by which to assess the vulnerability factors. Monitoring is undertaken to assess the manifestation of SWI, although the monitoring networks have not been specifically designed to interpret the behaviour of the SWI-interface due to the lack of appropriately located and constructed observation bores. In areas, such as Esperance and Bowen for example, the behaviour of the SWI-interface is monitored; however, the degree of the research into SWI processes is not as high as it is within an area in which SWI is actively being managed. Research often includes numerical models developed to manage the risks of SWI.

High: The risk of SWI has been reported and SWI is actively being managed to various extents. There is a high-level of publicly-available bore observation data and research by which to assess the vulnerability factors. Monitoring is routinely undertaken to assess the manifestation of SWI and the monitoring networks have been specifically designed and constructed to interpret the behaviour of the SWI-interface. Groundwater modelling has been undertaken to assist with the management and remediation of SWI (setting trigger levels and/or flux-based pumping regimes.

***Figure 3** Case study area locations.*

***Table 2** Case study areas grouped by State/Territory.*

State/Territory	Number of Areas	Case Study Area Locations	Groundwater management unit
South Australia	5	Adelaide Metropolitan LeFevre Port MacDonnell Uley South Willunga	Central Adelaide PWA Central Adelaide PWA Lower Limestone Coast PWA Southern Basins PWA McLaren Vale PWA
Western Australia	10	Albany (Harbour and Ocean sides) Broome (Cable Beach and Coconut Wells) Busselton Bunbury Carnarvon Cottesloe Derby Esperance Exmouth Perth (Whitfords) Rottnest Island	Albany Broome Busselton-Capel Bunbury Carnarvon Perth Derby Esperance Gascoyne Whitfords Rottnest
Northern Territory	1	Howard Springs	Darwin Rural
Queensland	5	Bowen The Burdekin Burnett Heads (Moore Park and Bargara) North Stradbroke Island Pioneer Valley	Bowen Burdekin Bundaberg North Stradbroke Island Pioneer
New South Wales	4	Botany Hat Head Stockton Stuarts Point	Botany Sandbeds Macleay Coastal Sands Tomago-Tomaree-Stockton Sandbeds Stuarts Point Sandbeds
Victoria	2	Point Nepean Werribee	Nepean Deutgam
Tasmania	0	__	__
Total Case Study Areas	27		

2. Development of a Coastal Aquifer Typology

The purpose of developing a coastal aquifer typology for use within this project was to create a framework for classifying the hydrogeological conditions of Australia's coastal aquifers with the specific objective of assessing their vulnerability to SWI.

As previously mentioned in Section 1.5.1 of this report, typological development in groundwater investigations commonly includes three components based on: (1) climatological parameters; (2) geomorphic-geologic classes; and (3) aquifer state parameters. Selected typological attributes of coastal (climate, geology and principal aquifer lithology) can be extrapolated from existing, national-scale, datasets and are mappable at the national-scale. However, many of the key factors to be assessed within an SWI investigation are location specific (e.g. state of aquifer parameters) and, accordingly, rely on local scale data. Therefore, the typological development for this project has taken both a top-down and a bottom-up approach, utilising two broad sources of information:

1. National-scale data (top-down)
2. CSA data (bottom-up).

This chapter has the primary purpose of describing the use of national-scale data in the development of a coastal aquifer typology. The analysis of local-scale, CSA-specific data is discussed in Chapters 3 and 4.

2.1. National-Scale Datasets Used to Build Coastal Aquifer Typology

An inventory of the national-scale datasets available for use within this project was provided within Phase 1 of the project from a literature Review (Dixon-Jain et al., 2010; Ivkovic et al., 2012a). Of the national-scale datasets available, the Köppen-Geiger climate groups and 1:5 000 000 hydrogeological map of Australia were selected to develop a national-scale coastal aquifer typology. Additional datasets, such as the SRTM 1 second (30 m) DEM, land use and geomorphology are also being used to build upon our understanding of factors that may make an area more vulnerable to, and inform, our understanding of SWI, but they do not strictly form part of the coastal aquifer typology. Land use is briefly discussed in this chapter, whilst a DEM analysis is found in the project summary report (Ivkovic et al., 2012b).

The national-scale coastal aquifer typology developed for this project is based on climate and principal aquifer type data. The process used to develop the coastal aquifer typology follows.

2.1.1. Climate Type Classification

The Köppen-Geiger system of climate classification (Peel et al., 2007) that was selected for use in this project is based on mean annual precipitation, mean annual temperature and seasonality using historical data collected over the 1930 to 2010 period. The Köppen-Geiger classification is commonly used in climate studies, and it was selected to form part of the national-scale coastal aquifer typology because rainfall, temperature and associated seasonal patterns (e.g. hot, dry summers) will have, to varying degrees, an influence on groundwater recharge and extraction patterns. Moreover, because the climate classes represent major patterns in plant growth temperature, moisture indices and seasonality, they will also reflect broad differences in cropping and other land use characteristics (Hutchinson et al., 2005).

There are five main climate types (and thirty climate sub-types) within the Köppen-Geiger classification; however, only three main climate types (and tweleve climate sub-types) are found in Australia including tropical A (8.3 %), arid B (77.8 %) and temperate C (13.9 %) classes (Table 3; Figure 4).

***Table 3** Köppen-Geiger climate classes found in Australia's coastal zone and description.*

Köppen-Geiger Code	Description
Af	Tropical, rainforest
Am	Tropical, monsoon
Aw	Tropical, savannah
BWh	Arid, desert, hot
BWk	Arid, desert, cold
BSh	Arid, steppe, hot
BSk	Arid, steppe, cold
Csa	Temperate, dry summer, hot summer
Csb	Temperate, dry summer, warm summer
Cwa	Temperate, dry winter, hot summer
Cfa	Temperate, without dry season, hot summer
Cfb	Temperate, without dry season, warm summer

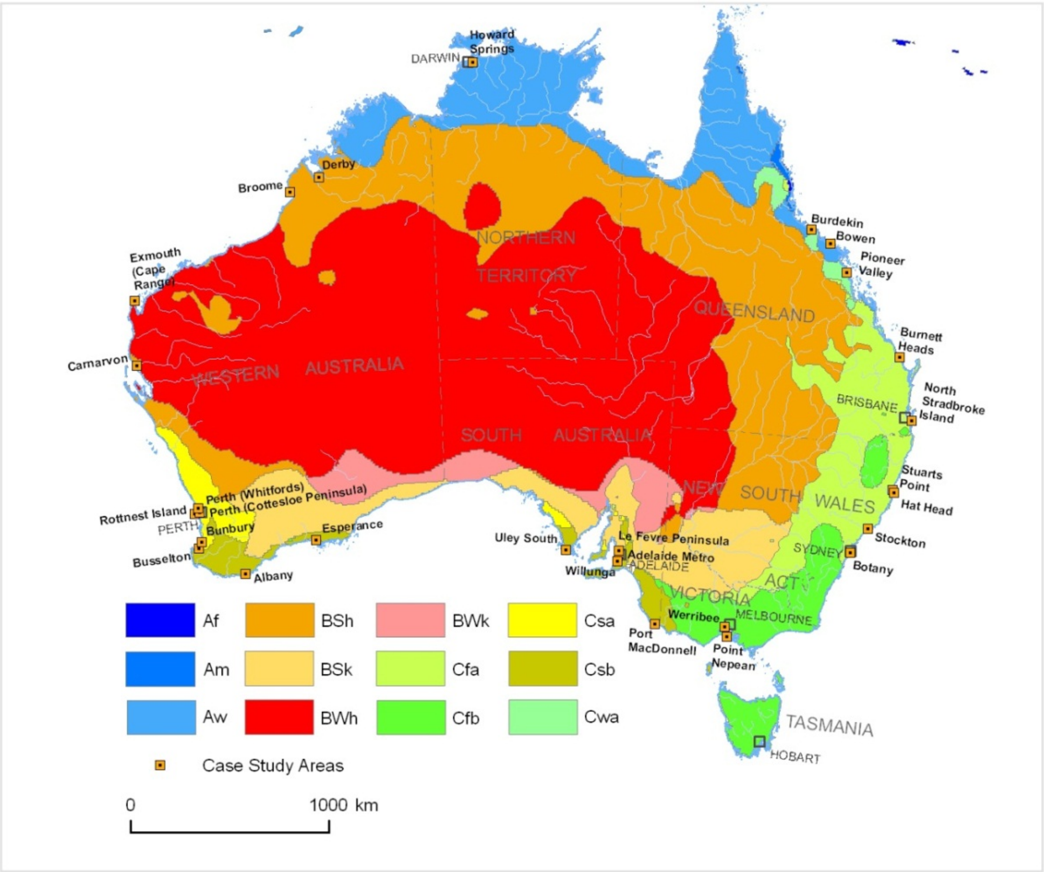

Figure 4 *Köppen-Geiger climate classification of Australia.*

Some of the key characteristics in defining the climate groups include that:

- The arid climate type is characterised by an annual evaporation that exceeds annual precipitation;
- The temperate climate has an average annual temperature between 18 °C and 0 °C; and
- The tropical climate has, across all month, a temperature > 18 °C in the coldest month and a minimum monthly rainfall of > 60 mm.

For further details of the classification criteria, interested readers are referred to Peel et al. (2007).

In order to simplify the number of climate classes used in the development of a coastal aquifer typology, the twelve subclasses were placed into five broad climate groups (Figure 5; Table 4). These groups are consistent with those used by Currie et al. (2010) in the characterisation of aquifer climatic settings across Australia. However, these classes are fewer, because not all of the Köppen-Geiger classes are present within the coastal zone. One can see from the data provided in Table 4 that the climate groups that make up the largest relative percentage area within the 15 km coastal buffer are the Tropical, followed by the Arid and Temperate without dry season classes.

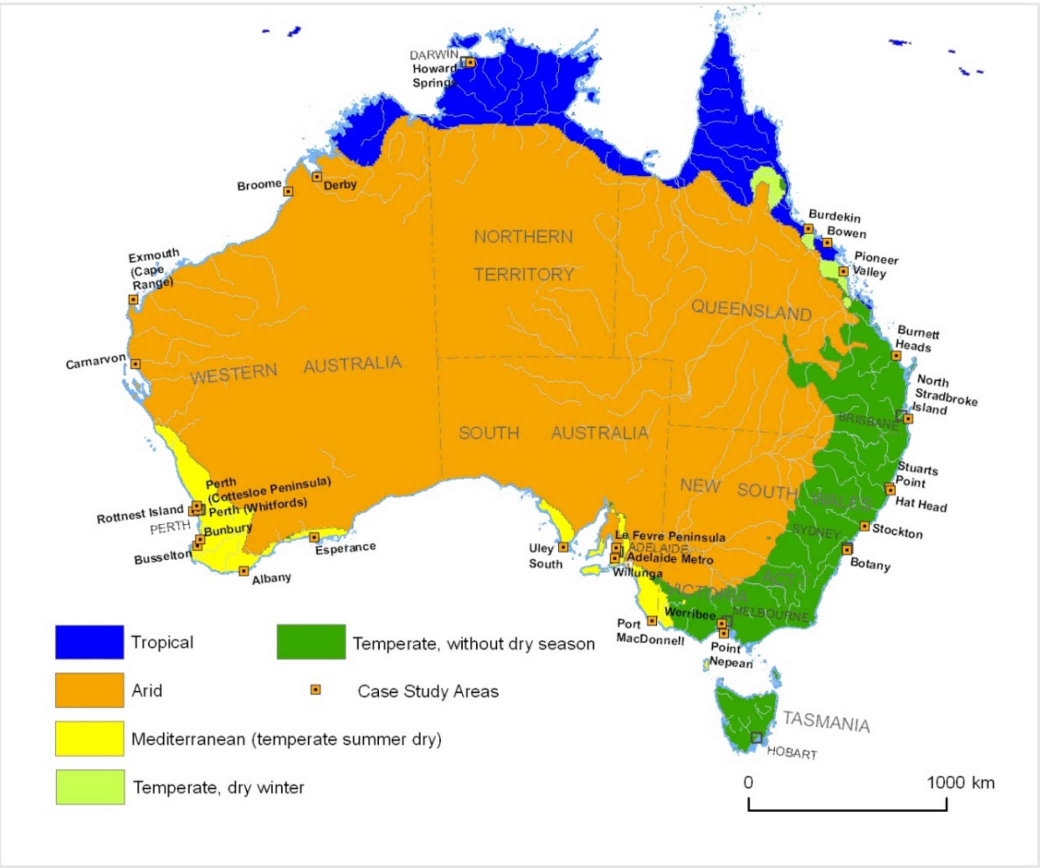

Figure 5 Grouped Köppen-Geiger climate classification of Australia.

***Table 4** Grouped Köppen-Geiger climate classes, description and relative percentages within the 15 km coastal buffer.*

Climate Group	Köppen-Geiger Codes	Description	Percentage
1	Af, Am, Aw	Tropical	36.6
2	BWh, BWk, BSh, BSk	Arid	24.0
3	Csa, Csb	Mediterranean (Temperate, summer dry)	14.0
4	Cwa	Temperate, winter dry	1.6
5	Cfa, Cfb	Temperate, without dry season	23.9

As previously stated, the use of Köppen-Geiger classes within this project is to allow areas with similar climate characteristics to be grouped; this is because the climate will have, to varying degrees, an influence on groundwater recharge as well as extraction patterns. The association between climate classes and groundwater recharge has been supported, to some extent, by Crosbie et al. (2010a) who investigated average recharge data obtained from field studies of varying Köppen-Geiger classes. They found that the tropical classes had the highest volume of groundwater recharge followed by the temperate classes, and that the arid classes had the lowest amount of recharge. A more detailed analysis of the relationship between rainfall and recharge when applying Köppen-Geiger classes/subclasses was hampered by non-linearity in rainfall-recharge relationships and the lack of recharge data that had corresponding vegetation information by which to compare values across vegetation types (Crosbie et al., 2010b).

The processes that drive groundwater recharge are complex and involve interplays between climate, soils, near surface geology, vegetation type/land use, slope, watertable depth and other factors that are too complex to analyse within the current scope of this project. The climate sensitivity of groundwater recharge and potential climate change impacts on groundwater have recently been investigated by Barron et al. (2011). Some of their key findings include that:

- Annual rainfall is a major factor influencing recharge. However, for the majority of the climate types considered, the total annual rainfall had a weaker correlation with recharge than the rainfall parameters reflecting rainfall intensity. This was especially the case for the climate types with winter-dominated rainfall (e.g. Mediterranean climate types).
- Annual recharge under a summer-dominated rainfall pattern tends to be greater than for a winter-dominated pattern; this was presumed to be due to monsoons and cyclones in the north and the frontal weather systems in the south.
- The relationship between a change in rainfall and a change in recharge is not linear, and that for the majority of soil/vegetation/climate type combinations, changes in recharge are two to four times greater than the change in rainfall. This is especially the case in regions with low rainfall, heavy soils and treed land cover under conditions where a low proportion of rainfall becomes recharge.

As one can see, the relationships between climate and groundwater recharge are complex. Furthermore, when considering potential climate change induced variations to groundwater recharge relationships one would need to consider not only rainfall variations, but also increases in temperature, changes in rainfall intensity, changes in solar radiation and carbon dioxide concentration (McCallum et al., 2010).

For the purposes of this investigation, the climate groups listed in Table 4 were used to broadly distinguish CSA climate settings. This information is complemented by long-term average annual groundwater recharge data obtained for CSAs, and tabulated within APTs (see Chapter 3) for use as input to the mathematical analysis component of the project. Scenarios analysed within the mathematical analysis, to assess the potential impacts of climate change on SWI vulnerability, used a 25 % reduction in recharge, for simplicity, in order to assess a drying climate and/or increased abstraction pressures as a worst case scenario for assessing SWI vulnerability (Morgan et al., 2012a).

2.1.2. Principal Aquifer Types

The term ‘principal aquifer’ was defined by Lau et al. (1987) as *“the aquifer which produces the best-quality water at highest yield from the shallowest depth”*. To identify principal aquifer types in this project, a range of national-scale datasets were evaluated. These included the 1:5 000 000 hydrogeomorphic map (GA and BRS, 2007) and the Geoscience Australia 1:1 000 000 geology map (Raymond and Retter, 2010). These datasets were found to have short comings, when used to identify the principal aquifers, due to the fact that they delineated the shallow, surface and water table aquifer systems rather than the principal aquifer systems which might lie below them. Also, in the case of the hydrogeomorphic map, it was difficult to distinguish between porous and fractured sedimentary aquifers. As a result, the 1:5 000 000 hydrogeology map (Jacobson and Lau, 1987) was used to classify the coastal aquifer systems since it was the only national-scale data that provided information on the principal aquifers.

Principal aquifers have been classified, from the national-scale hydrogeology map, as either porous or fractured types, depending on whether the porosity is primarily inter-granular or fractured (Figure 6). The aquifers have also been subdivided into their extent and productivity (Figure 7).

The porous classes are described by Lau et al. (1987) as being associated with sedimentary basins, where the sediments have not been deformed or metamorphosed to any great extent and where extensive permeable sediments are contained. The porous class also included unconsolidated sediments. In contrast, the fractured rock provinces were described as structurally complex and characterized by igneous, metamorphic and older sedimentary rocks lacking in primary porosity. Lau et al. (1987) acknowledged that it can be difficult to classify aquifers into either a porous or fractured class because aquifers can include characteristics of both porous and fractured types of rock. Despite this difficulty in classifying aquifers, the national-scale hydrogeology mapping has been well accepted by the hydrogeological community for use at appropriate scales.

The relative contributions of porous and fractured rock, within the 15 km coastal buffer, are provided below in Table 5, where one can see that the porous rock aquifers dominate the coastal zone.

The principal aquifer types were further mapped by Jacobson and Lau (1987) according to their lithology, and were classed as being either sedimentary and low-grade metamorphic rocks, or, igneous and medium- to high-grade metamorphic rocks. Lithological subclasses were further identified. These comprised the undivided (e.g. no specific lithology was assigned) and limestone classes within the sedimentary and low-grade metamorphic rocks and the undivided, basalt and granite classes within the igneous and medium- to high-grade metamorphic rocks (Figure 8). The relative percentages of principal aquifer types and lithological groups within the 15 km coastal buffer are listed in Table 6, which highlights that the porous, sedimentary and low-grade metamorphic, undivided aquifer types make up more than 50 % of the aquifer types along the coast. The fractured, sedimentary and low-grade metamorphic, undivided aquifers follow at 21.3 %. The remaining classes individually make up less than 10 % of the aquifer types around the coast of Australia.

Table 5 *Principal aquifer types and their relative percentage within the 15 km coastal buffer, based on 1:5 000 000 hydrogeology map.*

Principal Aquifer Type	Percentage
Porous	60.6
Fractured	39.4

Figure 6 *Fractured and porous hydrogeological divisions (after Jacobson and Lau, 1987).*

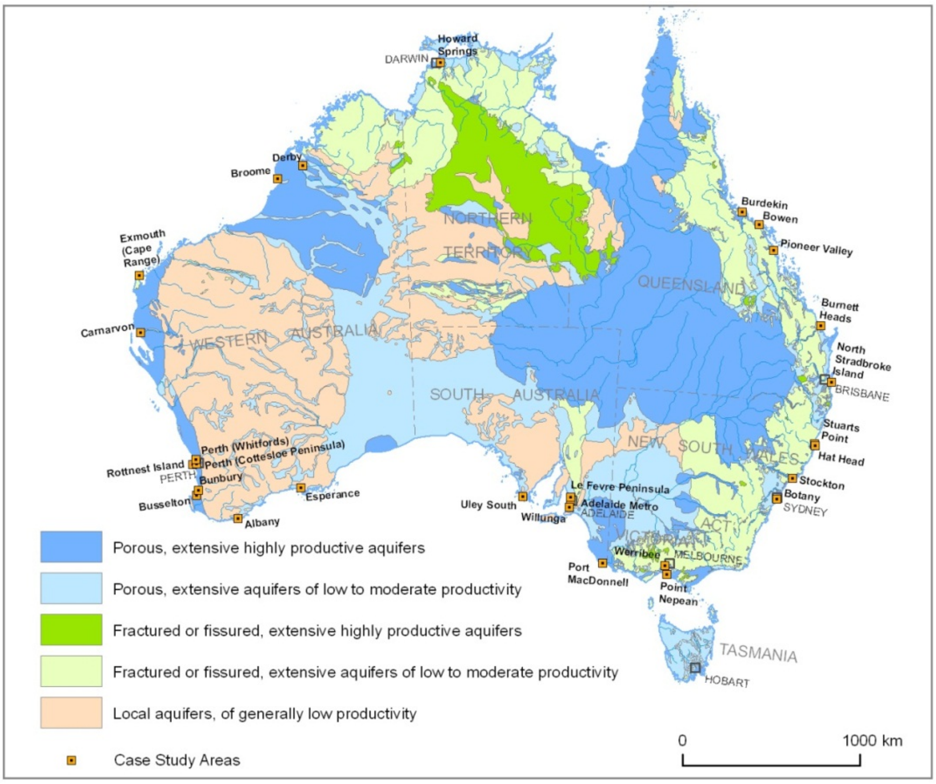

Figure 7 *Aquifer types of Australia (after Jacobson and Lau, 1987).*

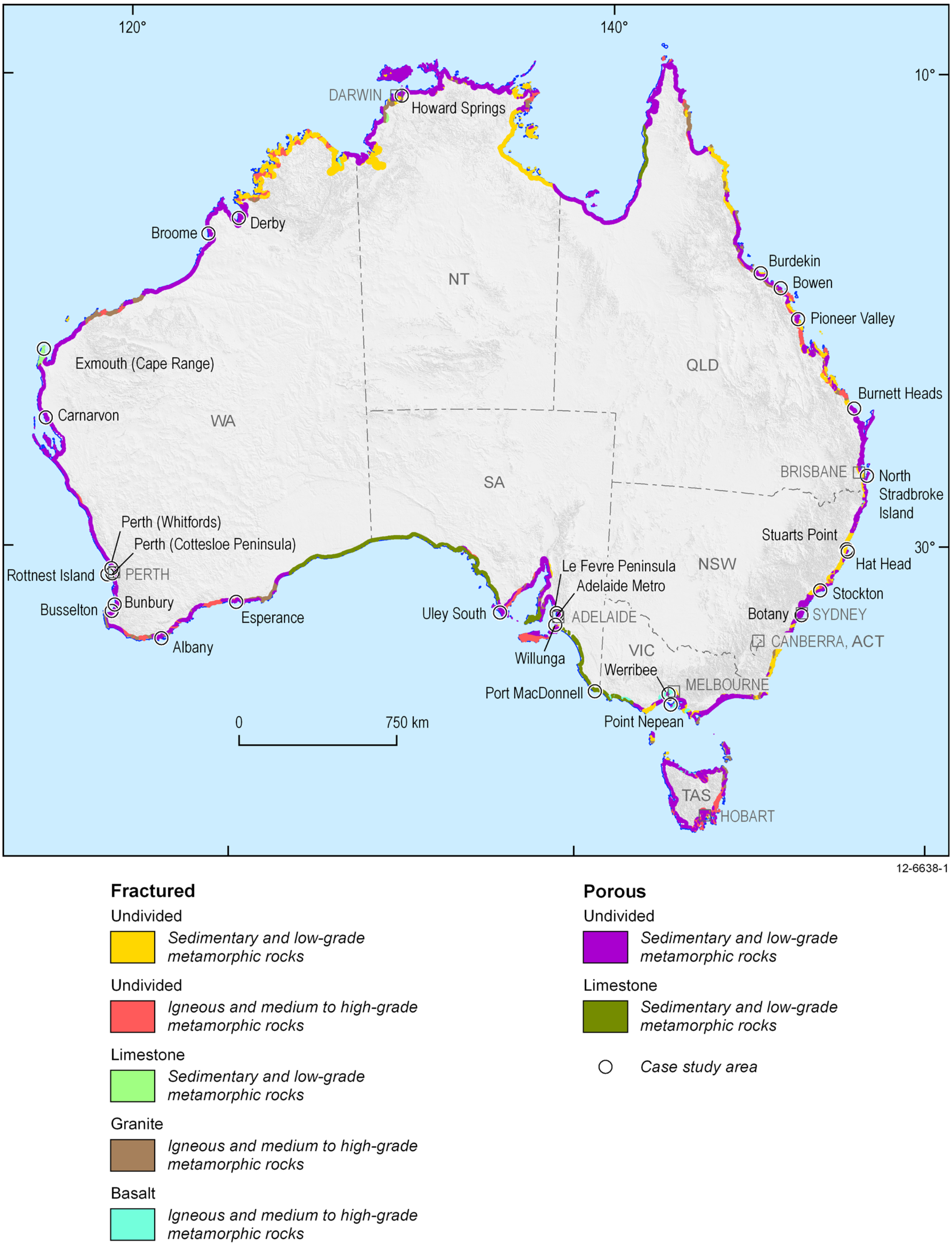

***Figure 8** Principal aquifer lithology (derived from Jacobson and Lau, 1987).*

***Table 6** Relative percentage of principal aquifer lithology types within the 15 km coastal buffer, based on 1:5 000 000 hydrogeology map.*

Principal Aquifer Type	Principal Aquifer Lithology	Lithology Subclass	Percentage*
Porous	Sedimentary and low-grade metamorphic	Undivided	50.7
		Limestone	9.9
Fractured	Sedimentary and low-grade metamorphic	Undivided	21.3
		Limestone	0.6
	Igneous and medium- to high-grade metamorphic	Undivided	9.0
		Granite	7.3
		Basalt	1.2

** The relative percentages should be seen as indicative until the conversion from AutoCAD to GIS format is validated for topological relationships.*

2.1.3. Coastal Aquifer Typology

The seven Principal Aquifer Type classes (Figure 8; Table 6) were combined with the five grouped Köppen-Geiger climate classes (Figure 5 and Table 4) to produce 35 coastal aquifer classes as shown in Figure 9 (WA), Figure 10 (SA), Figure 11(NT), Figure 12 (QLD), Figure 13(NSW), Figure 14 (VIC and TAS), and listed in Table 7. These combined classes form the mappable, national-scale coastal aquifer typology, and is an interim step in developing the final coastal aquifer typology discussed in Section 2.1.3.1. Note that in Figures 9 to 14 one can see a discrepancy between the GIS data for the coastline, and the, at times patchy, data that represents the combined Köppen-Geiger climate classes with the principal aquifer type. This is because the principal aquifer type polygons were derived from AutoCAD format and require further validation and development. And moreover, the Köppen-Geiger climate raster data did not uniformly cover the coastline. However, for the purposes of generally characterising the coastline at the national-scale for this first-pass assessment, the data can be considered to be suitably indicative.

As one can see from Table 7, the coastal aquifer types that make up more than 10 % of the coastal zone are the porous, sedimentary and low-grade metamorphic, undivided aquifers within the tropical, arid and temperate without dry season climate groups; and the fractured, sedimentary and low-grade metamorphic, undivided aquifers within the tropical climate group. The dominant principal aquifer types (comprising greater than 10 % of the coastal zone) are, as one would expect, consistent with those listed in Table 6, but now there is the addition of climate groups by which to further classify the aquifer systems.

Three coastal aquifer type classes listed within Table 7 are unrepresented and include the temperate, dry winter climate group of limestone (porous and fractured) and basalt aquifers. A further three classes comprised less than 0.01 % of the coastal zone; these included limestone aquifers with Mediterranean and temperate without dry season climate groups and basalt aquifers in the tropical climate group (Table 7).

2.1.3.1. Refinement of Coastal Aquifer Typology based on Case Study Areas

The project CSAs (listed in Table 2) were grouped according to the mappable, national-scale, coastal aquifer typology in Table 8. One can see from this table that the greatest proportion of CSAs are found within the porous, sedimentary and low-grade metamorphic, undivided classes. In contrast, none of the CSAs are found within the fractured, igneous and medium- to high-grade metamorphic rock, undivided and granite classes; this is consistent with the fact that these aquifer types tend to be characterised by low productivity. All of the climate groups are represented by at least one CSA.

Given that the largest proportion of CSAs are found within the porous, sedimentary and low-grade metamorphic, undivided class, and that the undivided class is anything porous and sedimentary aside from limestone, it was decided to further subdivide the porous, undivided class into additional aquifer type sub-groups. These additional sub-groups included coastal alluvium, coastal sands and sedimentary basin types of aquifers that had been noted during the preparation of APTs for CSAs. They were selected because each of the sub-groups had unique aquifer characteristics that were thought to be worth considering for this SWI investigation.

Other refinements were also made to the coastal aquifer typology. The unrepresented classes, such as the fractured, igneous and medium- to high-grade metamorphic, undivided and granite classes were removed from the typology. The limestone class was also renamed to carbonate to be more broadly encompassing of all carbonate rocks, including dolomite. The resultant coastal aquifer typology for the porous aquifers is shown in Table 9, and the resultant typology for the fractured and fissured aquifer types in Table 10.

As previously mentioned, the principal aquifer types were further classified into: coastal alluvium, coastal sands, sedimentary basin, carbonate, basalt and fractured/undivided classes. These classes can be briefly described as follows:

- **Coastal alluvium** comprises an unconsolidated mix of gravel, sand, silt and clay deposited within the floodplains of current drainage systems.
- **Coastal sands** comprise recent dune sands of aeolian and marine origin.
- **Carbonates** include deposits such as limestone and dolomite, and commonly exhibit karstic weathering profiles.
- **Sedimentary basins** include three sub-types: 1) thick, unconfined, sandstone aquifers; 2) deep, multiple-layered, stacked aquifers comprised of mostly consolidated sediments; and 3) shallow, multiple-layered, stacked aquifers with unconsolidated coastal plain sediments.
- **Basalt** aquifers comprise layered basalt plains where groundwater is stored primarily in fractures and vesicles.
- **Fractured/undivided** classes comprise other old fractured sequences of mixed lithology that have undergone metamorphosis and weathering.

It is important to make clear that the final project coastal aquifer typology, which includes the additional aquifer type sub-classes (as listed in Table 9 and Table 10), are no longer mappable at the national-scale since they are not based on the 1:5 000 000 hydrogeological map lithology (as they were in Table 8). An attempt was made to use the 1:1 000 000 geology map (Raymond and Retter, 2010) to update the 1:5 000 000 hydrogeological map using the additional sub-classes identified within the porous undivided group (e.g. coastal sands, coastal alluvium) but doing so proved to be a major undertaking and it was considered beyond the scope of this project.

The classification of CSAs by coastal aquifer typology, as shown in Table 9 and Table 10, highlights that the groundwater investigations of relevance to SWI and with sufficient data for APT population, have been, to date, primarily focused within coastal sands and sedimentary basins; and, to a lesser extent, on the basalt, carbonate and fractured/undivided aquifer systems. Most of the CSAs were located in the temperate climate zones, reflecting Australia's population distribution and the associated abstraction pressures on those groundwater systems.

A more detailed hydrogeological characterisation of CSAs, organised by coastal aquifer typology, is provided in Chapter 3.

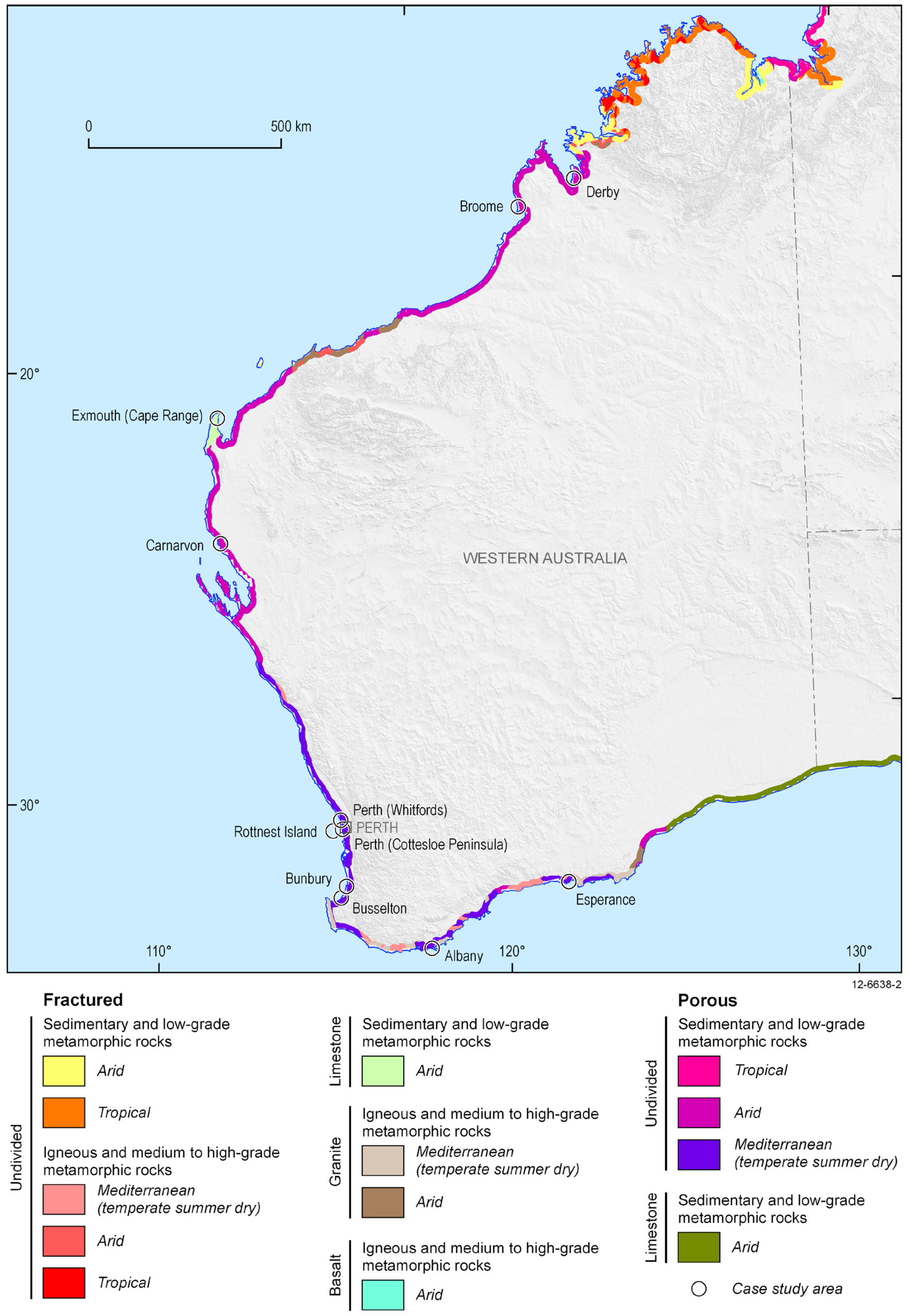

Figure 9 *Coastal aquifer typology for Western Australia derived from combination of grouped Köppen-Geiger climate classes and principal aquifer types derived from the 1:5 000 000 hydrogeology map of Australia.*

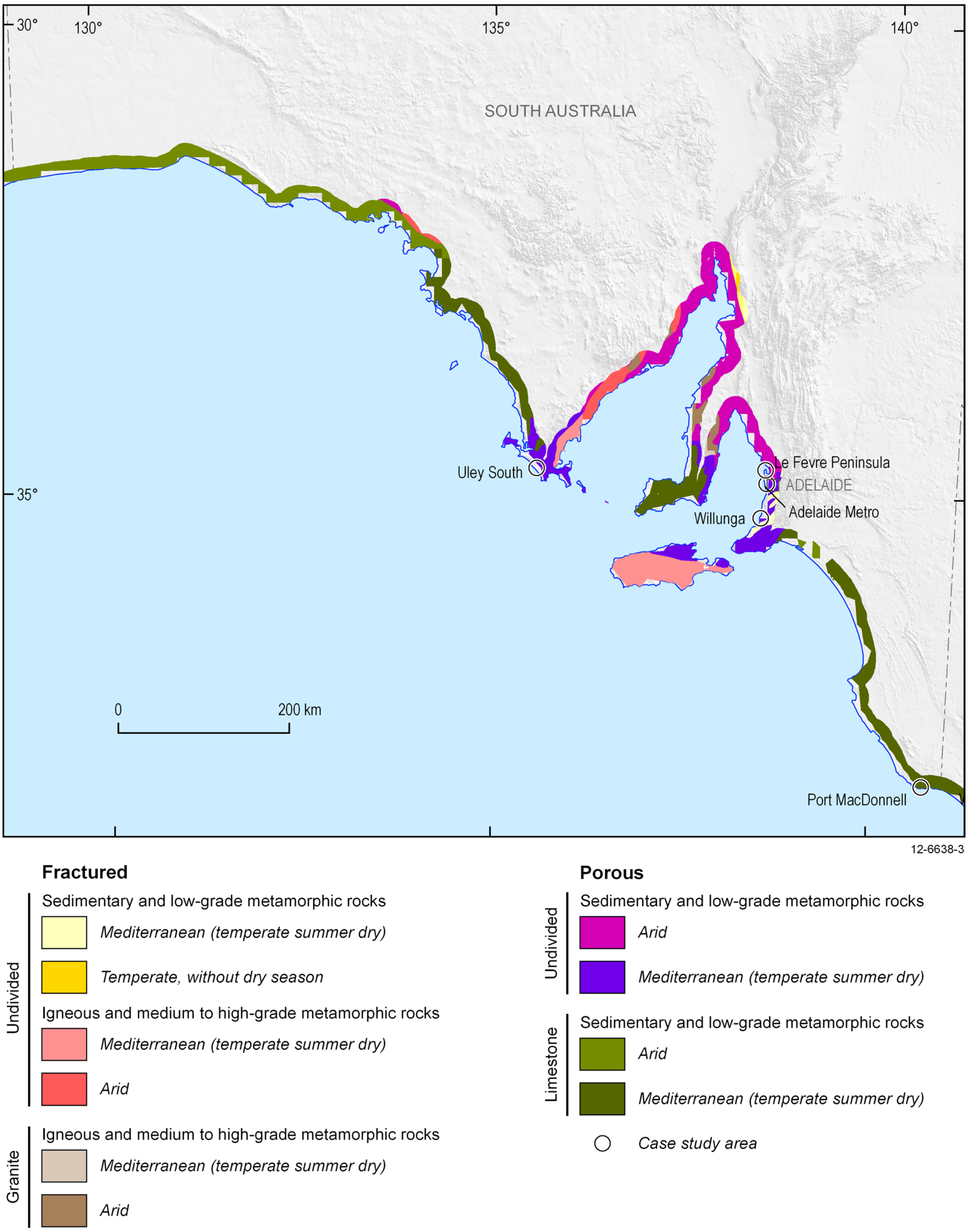

Figure 10 *Coastal aquifer typology for South Australia derived from combination of grouped Köppen-Geiger climate classes and principal aquifer types derived from the 1:5 000 000 hydrogeology map of Australia.*

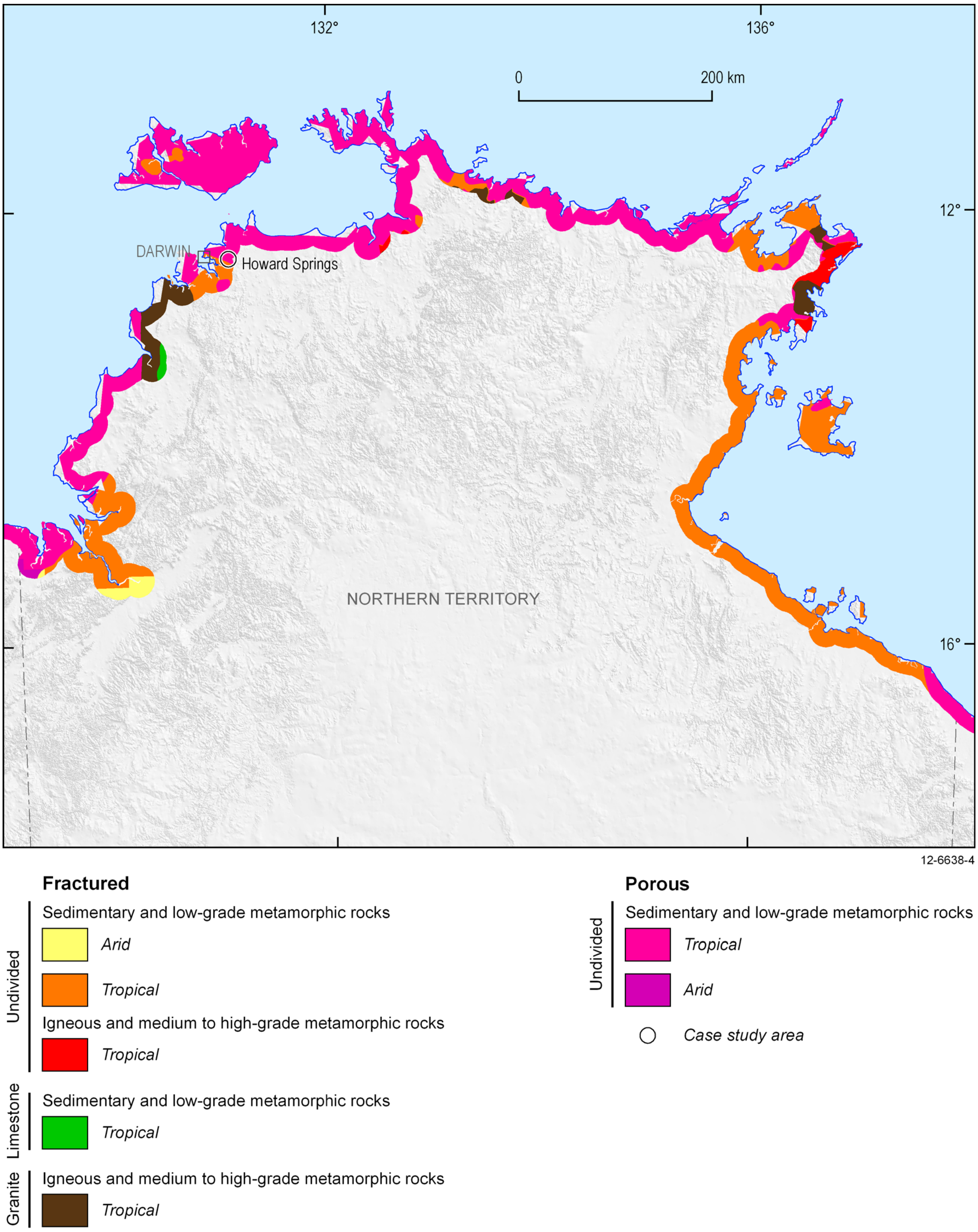

Figure 11 *Coastal aquifer typology for the Northern Territory derived from combination of grouped Köppen-Geiger climate classes and principal aquifer types derived from the 1:5 000 000 hydrogeology map of Australia.*

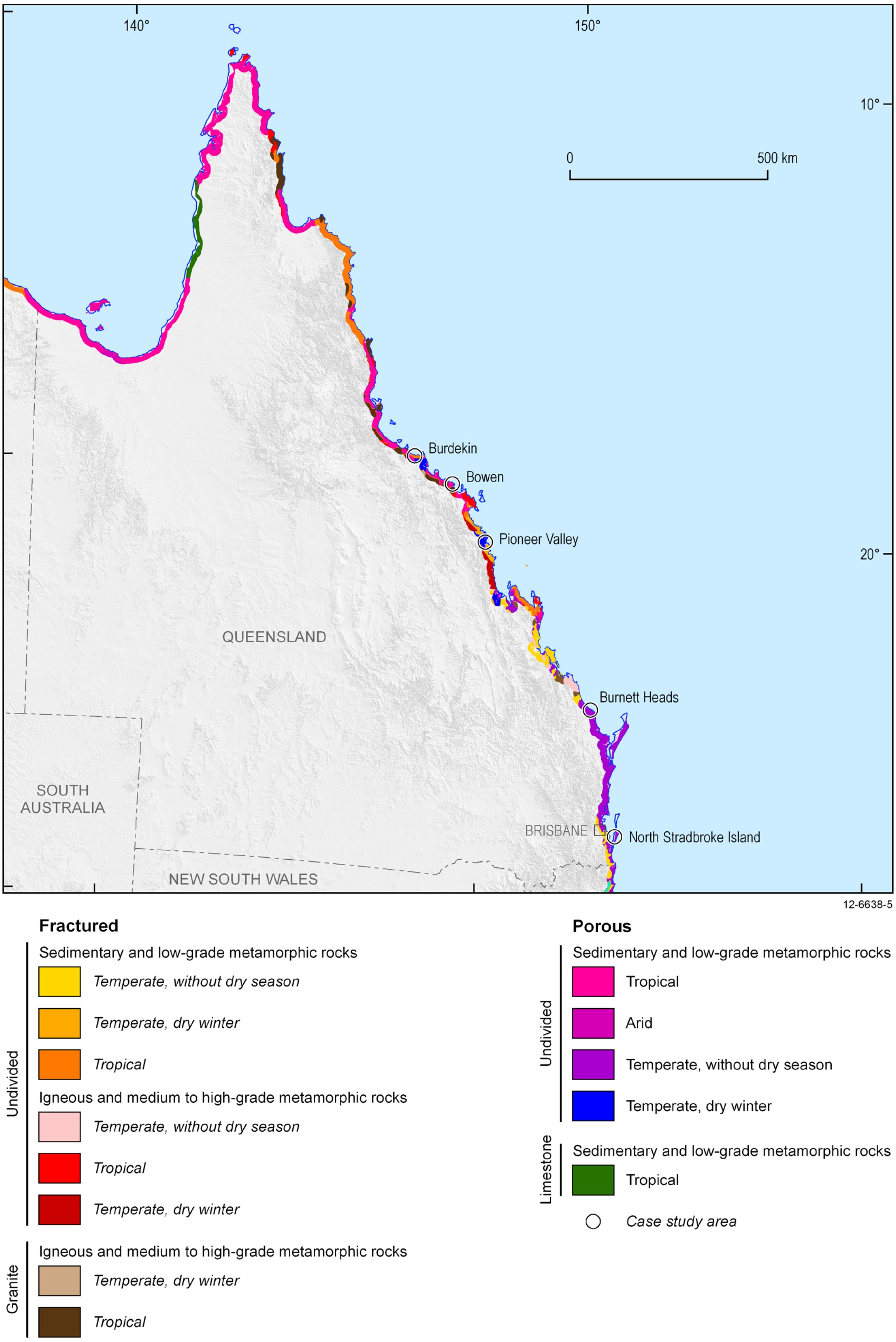

Figure 12 *Coastal aquifer typology for Queensland derived from combination of grouped Köppen-Geiger climate classes and principal aquifer types derived from the 1:5 000 000 hydrogeology map of Australia.*

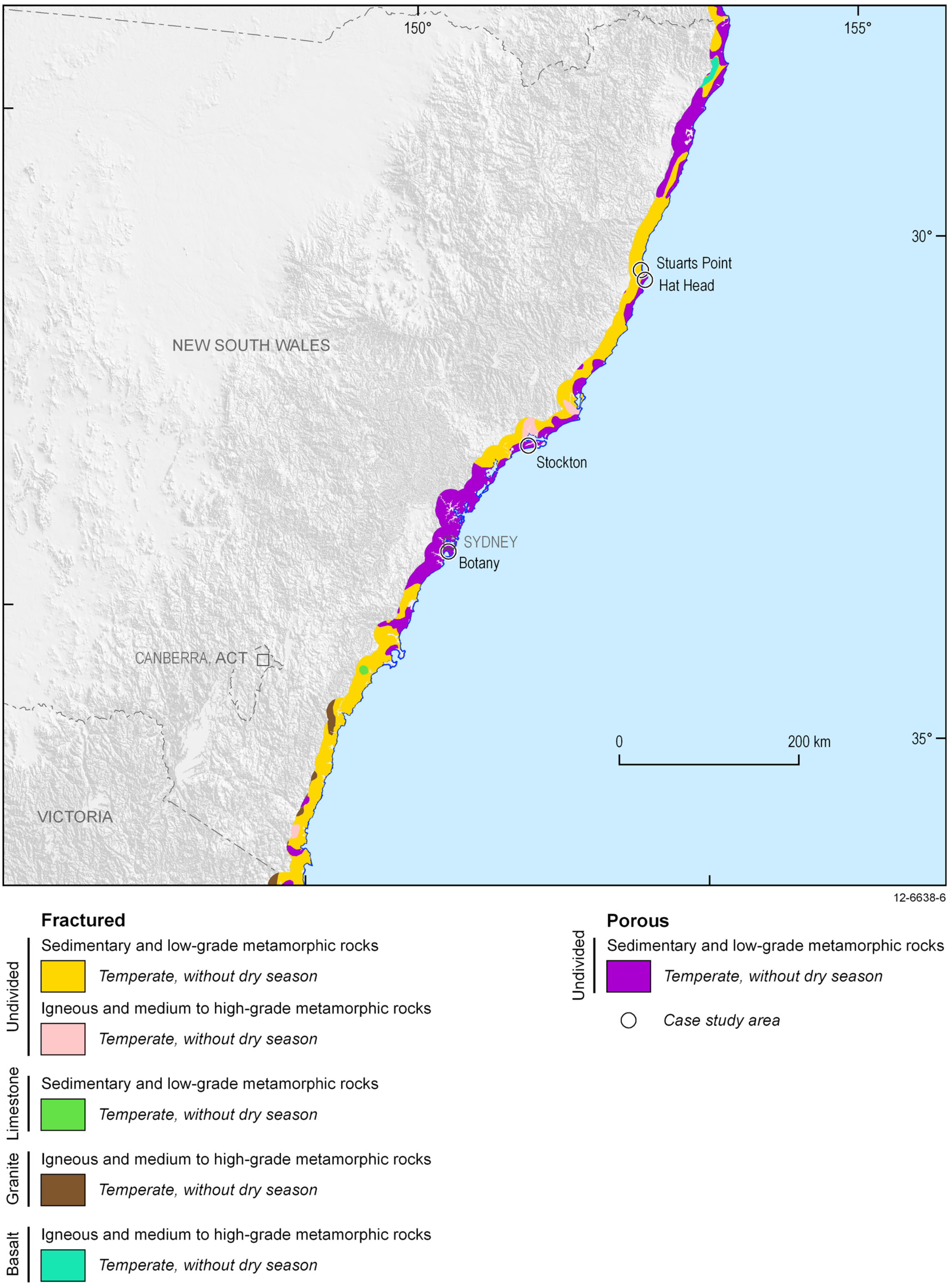

***Figure 13** Coastal aquifer typology for New South Wales derived from combination of grouped Köppen-Geiger climate classes and principal aquifer types derived from the 1:5 000 000 hydrogeology map of Australia.*

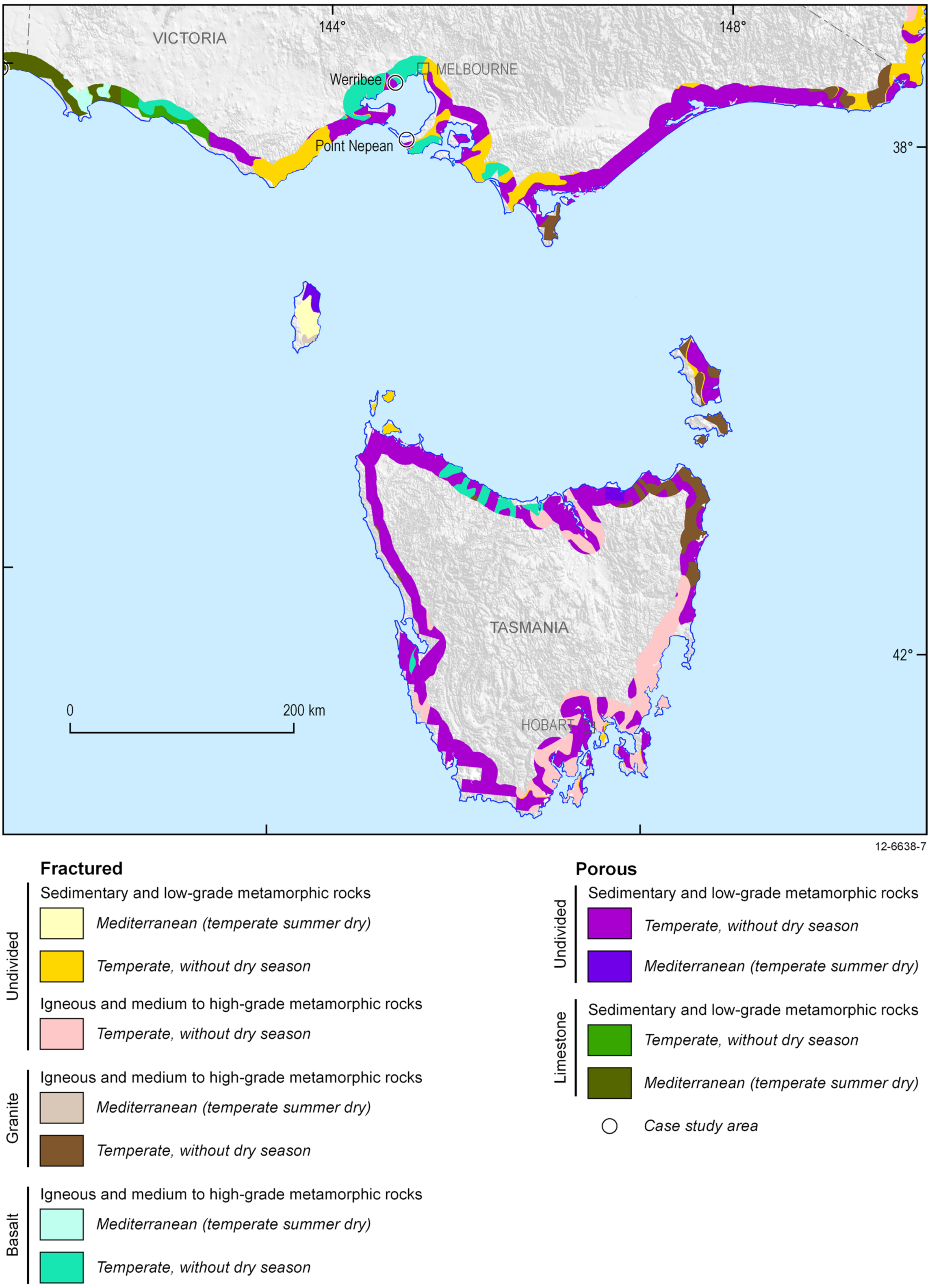

Figure 14 *Coastal aquifer typology for Victoria and Tasmania derived from combination of grouped Köppen-Geiger climate classes and principal aquifer types derived from the 1:5 000 000 hydrogeology map of Australia.*

Table 7 *Mappable coastal aquifer typology and relative percentages within the 15 km coastal buffer.*

Principal Aquifer Type	Principal Aquifer Lithology	Lithology Subclass	Climate Group	Percentage*
Porous	Sedimentary and low-grade metamorphic	Undivided	Arid	13.2
			Mediterranean (temperate summer dry)	6.4
			Temperate, dry winter	0.5
			Temperate, without dry season	12.3
			Tropical	18.0
		Limestone	Arid	4.3
			Mediterranean (temperate summer dry)	3.5
			Temperate, dry winter	__
			Temperate, without dry season	0.2
			Tropical	0.9
Fractured	Sedimentary and low-grade metamorphic	Undivided	Arid	2.9
			Mediterranean (temperate summer dry)	0.3
			Temperate, dry winter	0.4
			Temperate, without dry season	6.3
			Tropical	12.3
		Limestone	Arid	0.5
			Mediterranean (temperate summer dry)	<0.0
			Temperate, dry winter	__
			Temperate, without dry season	<0.0
			Tropical	0.1
	Igneous and medium- to high-grade metamorphic	Undivided	Arid	1.4
			Mediterranean (temperate summer dry)	2.4
			Temperate, dry winter	0.5
			Temperate, without dry season	2.4
			Tropical	2.6
		Granite	Arid	1.7
			Mediterranean (temperate summer dry)	1.4
			Temperate, dry winter	0.1
			Temperate, without dry season	1.4
			Tropical	2.6
		Basalt	Arid	0.1
			Mediterranean (temperate summer dry)	0.1
			Temperate, dry winter	__
			Temperate, without dry season	1.1
			Tropical	<0.0

** The relative percentages should be seen as indicative until the conversion from AutoCAD to GIS format is validated for topological relationships.*

Table 8 *Case study areas grouped by mappable, national-scale coastal aquifer typology.*

Porous sedimentary & low-grade metamorphic rocks	**(1) Tropical**	**(2) Arid**	**(3) Mediterranean Temperate, Summer Dry**	**(4) Temperate, Dry Winter**	**(5) Temperate, Without Dry Season**
Undivided	Bowen (QLD) Burdekin (QLD)	Broome (WA) Carnarvon (WA) Derby (WA)	Albany (WA) Adelaide Metro (SA) LeFevre Peninsula (SA) Bunbury (WA) Busselton (WA) Esperance (WA) Perth, Cottesloe Peninsula (WA) Perth, Whitfords (WA) Rottnest Island (WA) Willunga (SA)	Pioneer (QLD)	Botany (NSW) Burnett Heads (QLD) Hat Head (NSW) North Stradbroke Island (QLD) Point Nepean (VIC) Stockton (NSW) Stuarts Point (NSW)
Limestone	—	—	Port MacDonnell (SA) Uley South (SA)	—	—
Fractured or fissured sedimentary & low-grade metamorphic rocks	(1) Tropical	(2) Arid	(3) Mediterranean Temperate, Summer Dry	(4) Temperate, Dry Winter	(5) Temperate, Without Dry Season
Undivided	Howard Springs (NT)	—	—	—	—
Limestone	—	Exmouth (WA)	—	—	—
Fractured or fissured igneous & medium- to high-grade metamorphic rocks	(1) Tropical	(2) Arid	(3) Mediterranean Temperate, Summer Dry	(4) Temperate, Dry Winter	(5) Temperate, Without Dry Season
Undivided	—	—	—	—	—
Granite	—	—	—	—	—
Basalt	—	—	—	—	Werribee (VIC)

Table 9 *Case study areas organised by coastal aquifer typology using porous aquifer type sub-groups.*

Porous sedimentary & low-grade metamorphic rocks		**(1) Tropical**	**(2) Arid**	**(3) Mediterranean Temperate, Summer Dry**	**(4) Temperate, Dry Winter**	**(5) Temperate, Without Dry Season**
Undivided	Coastal Alluvium	Bowen (QLD) Burdekin (QLD)	Carnarvon (WA)	—	Pioneer (QLD)	Burnett Heads (QLD)
	Coastal Sands	—	—	Perth, Cottesloe Peninsula (WA) Rottnest Island (WA)	—	Botany (NSW) Hat Head (NSW) North Stradbroke Island (QLD) Point Nepean (VIC) Stockton (NSW) Stuarts Point (NSW)
	Sedimentary Basin-unconfined sandstone	—	Broome (WA) Derby (WA)	—	—	—
	Sedimentary Basin-multi-layered, consolidated, deep	—	—	Adelaide Metro (SA) LeFevre Peninsula (SA) Bunbury (WA) Busselton (WA) Perth, Whitfords (WA) Willunga (SA)	—	—
	Sedimentary Basin-multi-layered, unconsolidated, shallow	—	—	Albany (WA) Esperance (WA)	—	—
Carbonate		—	Exmouth (WA)	Port MacDonnell (SA) Uley South (SA)	—	—

Table 10 *Case study areas organised by coastal aquifer typology using fractured aquifer type sub-groups.*

Fractured or fissured rocks	**(1) Tropical**	**(2) Arid**	**(3) Mediterranean Temperate, Summer Dry**	**(4) Temperate, Dry Winter**	**(5) Temperate, Without Dry Season**
Undivided	Howard Springs (NT)	—	—	—	—
Basalt	—	—	—	—	Werribee (VIC)

2.2. Other National-scale Datasets

There are a number of additional national-scale datasets that, although they do not directly form part of the project's coastal aquifer typology, they do support the typological analysis used to assess SWI vulnerability. These datasets include digital elevation model, discussed in Ivkovic et al. (2012b), land use, coastal geomorphic environments, and information derived from other recent national-scale projects. These datasets (excepting the DEM) are briefly outlined in the sub-sections below.

2.2.1. Land Use

Land use activities will have an influence on the water balance of a coastal aquifer, and particular land uses may be associated with increased aquifer vulnerability to SWI. Land use mapping (2001-2002) is available at the national-scale (BRS, 2006). The dominant land uses found within each of the CSAs have been tabulated in the CSA summary table (refer to Appendix 1) and discussed in the descriptions of the CSAs in Chapter 3.

2.2.2. Coastal Geomorphic Environments

Twelve typical Australian coastal geomorphic environments were described by Ivkovic et al. (2012a). The environments described included: classic delta, fan delta, wave-dominated estuary, tide-dominated estuary, coastal lagoon, strandplain, tidal flat/creek, older sedimentary, karstic, fractured bedrock and hydrogeologically complex. The clastic depositional environments, represented by the first seven classes, were mapped along the Australian coast for the areas influenced by Holocene terrigenous sediment by Harris et al. (2002); note that these environments are absent across most of southern and parts of Western Australia (Figure 15, after Harris et al., 2002). The remaining classes such as karstic, fractured and hydrogeologically complex are contained, or are also implicit, within the principal aquifer type (refer to Section 2.1.2). The coastal geomorphic environments for each of the CSAs have been tabulated in the CSAs summary table (refer to Appendix 1).

2.2.3. Information Derived from Concurrent Projects

There are a number of other concurrent projects funded by the National Water Commission such as “A consistent approach to groundwater recharge determination in data poor areas” (Pain et al., 2011); “Investigating the impact of climate change on groundwater resources” (Barron et al., 2010; Barron et al., 2011); and the evolving data analysis and processing contributing to the Australian Soil Resources Information Systems (ASRIS) that could be used to further inform the coastal aquifer typology in the context of SWI vulnerability. However, it is only now, towards the culmination of this project, that the products from these projects are becoming publically available. As a result, it was not feasible to integrate these other products in our analysis at this late stage.

A number of coastal aquifer systems were identified by Currie et al. (2010) as priority aquifers in terms of their importance and sensitivity to the impacts of climate change. It is noteworthy that a large proportion of the priority aquifers listed by Currie et al. (2010) are included amongst CSAs and SWI sites within this project. These priority aquifers include the coastal river alluvium found in QLD and NSW, coastal sands in QLD and NSW, Newer Volcanics in VIC, the Otway Basin in SA and VIC, Port Campbell Limestone in VIC, and the Perth Basin (central and south) in WA.

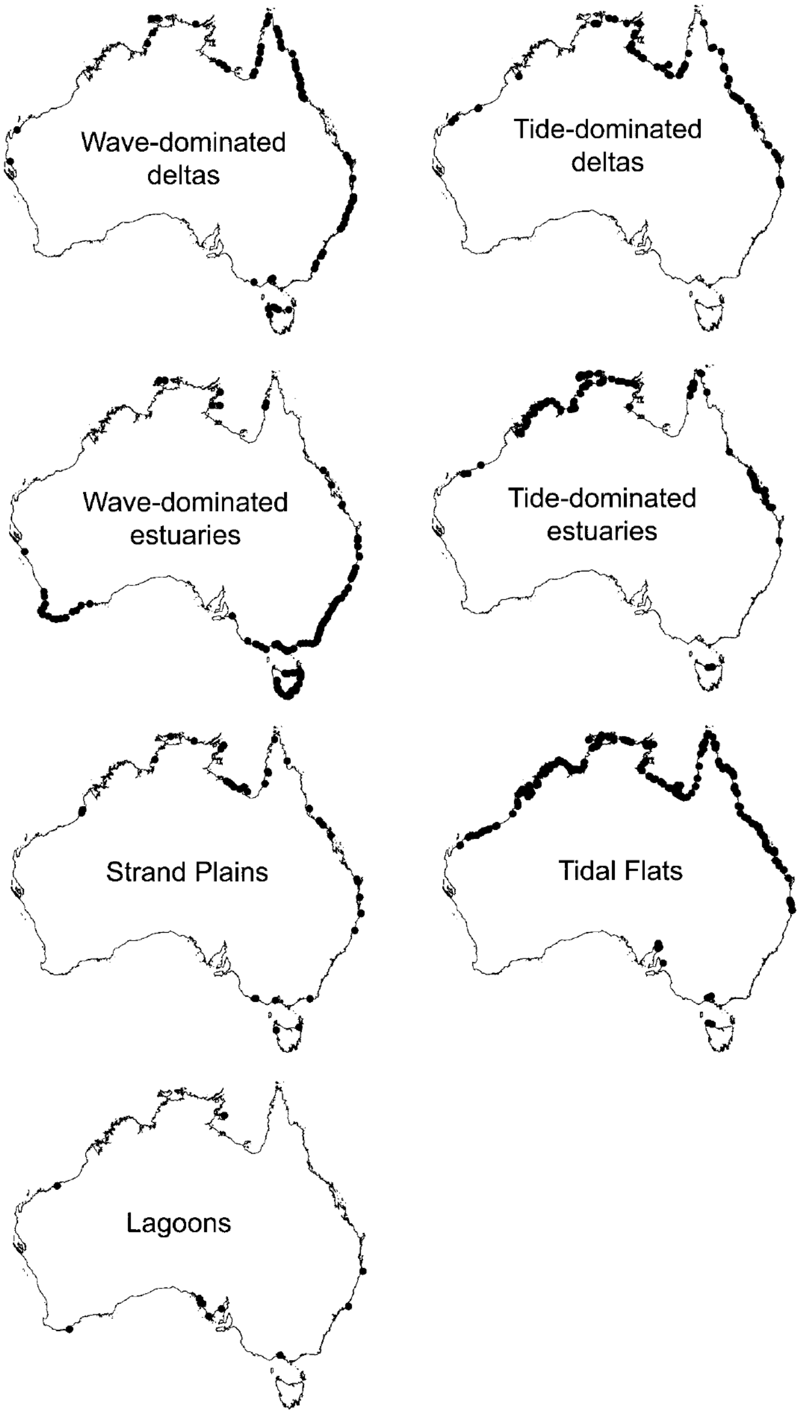

Figure 15 *Distribution of different depositional coast types round the Australian coastline (after Harris et al., 2002).*

3. Typological Analysis of Case Study Areas

3.1. Introduction

The coastal aquifer typology developed for use in this project has the purpose of providing a framework by which to classify the hydrogeological conditions of Australia's coastal aquifers in order to better understand their vulnerability to SWI. In Chapter 2, the development of the coastal aquifer typology was discussed, and it included identifying the principal aquifer types and climate groups found in Australia. The combination of principal aquifer types and climate groups formed the coastal aquifer typology. This chapter provides an overview of the 28 CSAs analysed in this project. The information provided within this chapter is organised according to coastal aquifer type, and forms a catalogue of the types of coastal aquifer systems found in Australia at threat of SWI. Because each of the CSAs has been considered at threat of SWI, or in some cases has had a documented SWI incident, the typological analysis may be used to provide insights into the characteristics that could predispose these aquifers to SWI. This information has then been used in combination with the results of the other project components including mathematical analysis (Morgan et al., 2012b), vulnerability factor analysis (Cook et al., 2012) and vulnerability indexing (Morgan and Werner, 2012; Norman et al., 2012) to provide an overall assessment of aquifer vulnerability in the final summary report (Ivkovic et al., 2012b).

As mentioned in the project overview in Chapter 1, a key component of the typological analysis has included the preparation of simplified, hydrogeological cross-sections with tabulated data containing typical aquifer parameter values based on information obtained from CSAs.

The methods used to prepare the aquifer parameter tables (APTs) and simplified, hydrogeological cross-sections are discussed immediately below in Section 3.1.1 to provide background context. This is followed by the analysis of the individual CSAs in Section 3.2.

3.1.1. Aquifer Parameter Tables

A simplified conceptualisation was made for each of the CSAs that considered a slice perpendicular to the coast by which to characterise local hydrogeological conditions. The conceptualisation is represented in table format by an APT, and visually by a simplified hydrogeological cross-section (Section 3.1.2).

The APTs comprise typical aquifer parameter values that characterise the hydrogeology of the coastal fringe within each CSA. The data values contained within the APTs have also been used as input to the mathematical analysis component of the project; the mathematical analysis of SWI in this study considered a rapid assessment approach using a 1-D, steady state, sharp-interface approximation to the freshwater-saltwater transition zone as described in Morgan et al. (2012b).

The APTs include information on the aquifer 'model' layer, lithology, age and layer type (unconfined, confined, semi-confined or aquitard). In addition, the APTs include the other parameters required as input to the mathematical analysis such as: the elevation of the base of the aquifer, aquifer saturated thickness, inland head, hydraulic conductivity and net recharge. The specific yield or porosity value was also provided in order to estimate the volumes of seawater within the aquifer. The application of the mathematical analysis to CSAs using the aquifer parameter data included within this report is found in Morgan et al. (2012b).

The parameter values listed within the APTs were derived from the published literature, including reports, books, journal articles, groundwater databases, and in a few cases, via stakeholder input. Footnotes are provided below each of the tables in order to provide additional information about the sources of the data and any assumptions made in deriving the parameters. This has allowed for cross-checking and validation by table users and project stakeholders.

The locations of the CSAs within the broader coastal 15 km inland buffer were determined by the availability of the literature that contained the requisite data used to populate the APTs, as well as through consultation with stakeholders. All of the areas selected were identified as being at threat of SWI. The literature from which the aquifer parameter values were derived included groundwater development and/or numerical modelling investigation reports that were prepared for specific locations. The parameter values were selected to characterise the local hydrogeological conditions within the coastal fringe area, usually within 5 km of the coastline or less. The observation bores selected to provide hydraulic head data within the coastal fringe were most often located between 1 km and 5 km from the coastline within the CSA, and had the longest, most-complete, water level records and best quality data.

The aquifer parameter tables are found in Appendix 2.

3.1.1.1. *Net recharge estimates*

Net recharge values are reported within the APTs. The term net recharge used in this study represents the difference between gross aquifer recharge, e.g. water that reaches the aquifer and increases storage within the saturated zone, and any groundwater losses such as ET, losses to surface water and groundwater extractions; however, it is important to note that two different methods have been utilised to conceptualise net recharge within the CSAs. The choice of method used depended on the locations of extraction bores relative to the location of observation bores. The two methods are described below.

In the first conceptualisation, the coastal zone represents a relatively narrow coastal strip in which no groundwater extraction occurs - or more specifically, no (or negligible) groundwater extraction occurs between the coast and the location of the observation bores used to provide the head data for mathematical analysis. In this situation, the net recharge estimate does not include the loss of groundwater as a consequence of groundwater extractions since groundwater pumping is inland of the modelled inland boundary. Any losses in groundwater storage, considered to be occurring from extractions up-gradient, are considered to be implicit within the hydraulic heads and associated inflows within the mathematical analysis. This was the first choice when conceptualising a CSA so that the focus of the analysis was the coastal fringe and avoided the situation where groundwater pumping directly influenced aquifer head values.

In the second conceptualisation, the coastal zone represents a wider coastal strip in which groundwater extractions occur between the coast and the location of the observation bores used to provide head data for mathematical analysis. In this case, because groundwater extractions are occurring within the model boundary, they are included within the net recharge estimations. For these areas net recharge was estimated using a lumped approach applied to the average recharge and extraction volumes over a given area. This was the second choice for conceptualisation, and this approach was used where there were widespread extractions within the coastal fringe and/or if there were no observation bores located within the coastal fringe. In irrigation areas diffuse recharge from irrigation returns was added to gross recharge estimates, and in urban areas leakage from drains was included when available. Inter-aquifer leakage was also considered where this information was available. The confined aquifers were assumed to have a net recharge of zero, a commonly made assumption when carrying out simple, first-order assessments (Morgan et al., 2011), unless there were actual data available.

The data values used to estimate net recharge to the underlying aquifers were obtained from existing literature. The methods reported to estimate groundwater recharge varied from one CSA to the next, ranging from estimates based on the percentage of the average annual rainfall through to chloride mass balance, isotopic/hydrochemical investigations, watertable fluctuations and groundwater modelling. The best available published information on groundwater recharge (i.e. no new estimates of groundwater recharge were made within this study) within each CSA was used to estimate net recharge, and in some cases a range of net recharge values are provided within the APT. In most cases though, a single net recharge value is provided that is representative of the estimated net recharge value based the limited information that was available within the published literature or based on expert opinion through personal communication.

Estimates of aquifer recharge are inherently uncertain and it was considered beyond the scope of this project to assess the uncertainty in the net recharge estimates. For the purposes of this project, the tabulated values were derived from published material and checked for reasonableness with stakeholders; in a minority of cases net recharge and other parameter values were given by personal communication via a stakeholder (this is indicated within the table footnotes).

Water balance components of CSAs, such as the amount of groundwater extraction relative to gross recharge, are considered to be a critical component of a SWI vulnerability analysis, and these aspects are investigated within the SWI qualitative vulnerability indexing component of this project (Norman et al., 2012).

3.1.2. Simplified Hydrogeological Cross-sections

Simplified hydrogeological cross-sections have been drawn to assist with visualising the conceptualisation of the model layers of aquifer systems described in the APTs. It is important to note that, although the aquifer parameters provided within the tables emphasise data for the coastal fringe within 5 km of the coast, the cross-sections show a broader width of coastal strip in order to present a wider perspective of the hydrogeology beyond the fringe. The cross-sections include information on the lithology, position of the saltwater wedge toe, mixing zone, and watertable relative to 0 m AHD where this information was readily available. The cross-sections are based on pre-existing, generalised conceptualisations of the hydrogeology found within the literature. These figures have been placed within the CSA overviews that follow.

3.1.3. Case Study Area Overviews

An overview of the 28 CSAs is provided in the sections below, and has been structured according to coastal aquifer type. Background information including location, geology, geomorphology, hydrogeology, land and water use, as well as any information on any occurrences and modes of seawater intrusion is provided within the overviews. The descriptions included are succinct and focus on key characteristics only; however, interested readers may go to the original sources cited for further information.

A summary is included at the end of each typology section which summarises the characterisation of CSAs and the influence of the Köppen-Geiger climate classes in the context of coastal aquifer type and SWI vulnerability. Chapter 4 summarises the key findings of SWI vulnerability based on the literature review and characterisation of CSAs provided in this chapter. For more information regarding the management and monitoring of groundwater systems in each state, refer to Ivkovic et al. (2012a).

3.2. Coastal Alluvium

The CSAs with aquifers classified as coastal alluvium included the Queensland sites of Bowen, Burdekin, Pioneer and Burnett Heads, and Carnarvon in Western Australia.

3.2.1. Coastal Alluvium, tropical

Two CSAs have been classified as having a coastal alluvium aquifer type with a tropical Köppen-Geiger climate. These are Bowen (Qld), with a large water demand used for irrigation, primarily due to its thriving horticultural industry, and Burdekin (Qld), one of Australia's most groundwater-dependent regions.

3.2.1.1. Bowen, QLD

3.2.1.1.1. Location

Bowen is located between Townsville and Mackay on Queensland's central coast, as shown in Figure 16. Groundwater use is concentrated in the Bowen Irrigation Area, immediately west and inland of the town of Bowen.

3.2.1.1.2. Climate

Bowen is situated in the dry tropics with mean daily maximum temperatures for January and July of 32 °C and 24 °C, respectively. Rainfall is extremely variable, with the annual rainfall ranging from 215 to 2015 mm and averaging 1020 mm (WRC, 1988). Rainfall is strongly seasonal, and 75 % falls from December to March. The area receives frequent flooding in the Don River delta as a result of tropical cyclones, and the area is also prone to periods of drought. Evaporation rates are high, with an annual class A pan evaporation rate estimated at 1900 mm/yr (WRC, 1988).

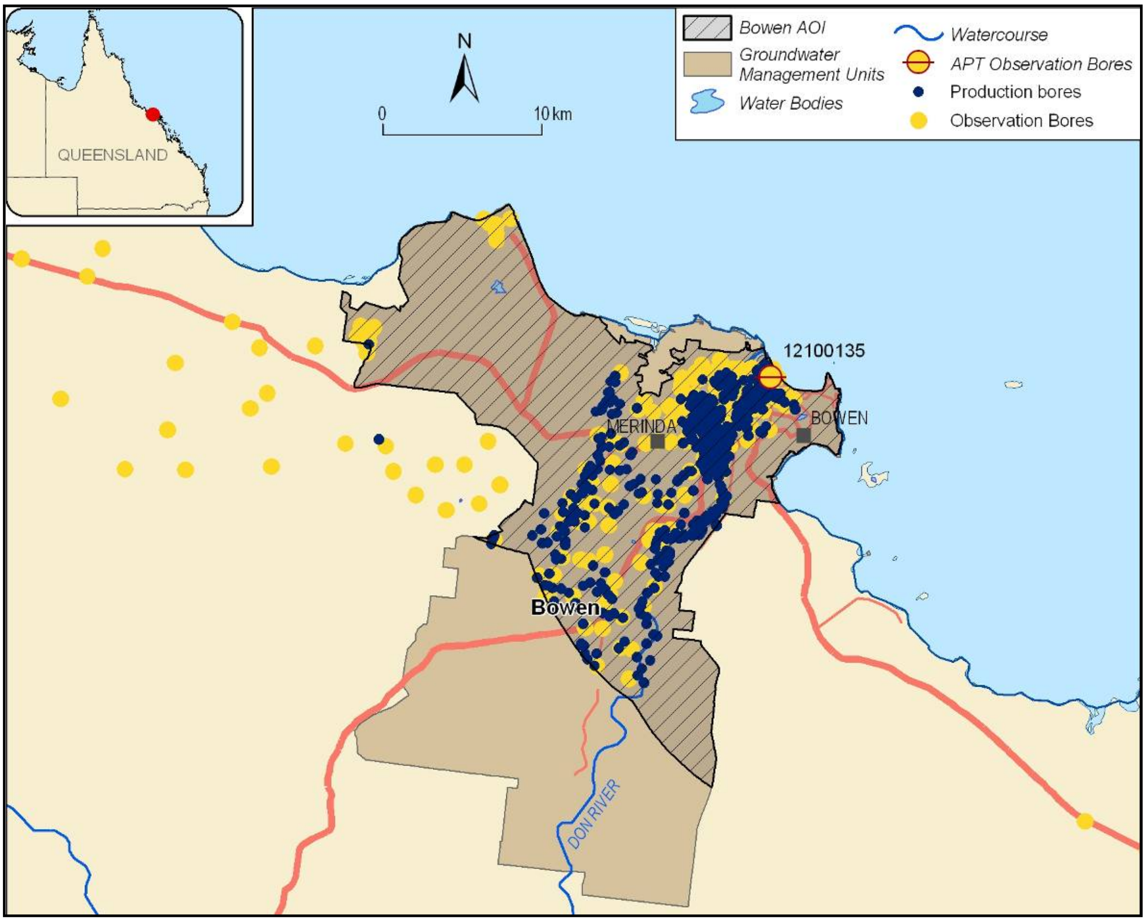

Figure 16 *Location map for Bowen (QLD) displaying observation bores, production bores and GMU extent.*

3.2.1.1.3. Geology and Geomorphology

The basement rock in the Bowen area comprises Carboniferous to Cretaceous intrusive granites, granodiorites, diorites and quartz monzonites. These rocks are exposed as prominent ridges and hills in the area and are commonly topped with a zone of weathering. A series of north-westerly flowing channels have been incised into the basement rocks and are often connected by northerly flowing channels parallel to the present day major Don River.

Overlying the basement unit are Cenozoic, fluvio-deltaic sediments of the Don River/Euri Creek drainage system. These sediments are particularly thick in areas where they drape over the palaeochannels incised into the basement rocks, and otherwise form continuous cover over the region. The sediments have been subdivided into three major stratigraphic components described by Water Resources Commission (1988), ranging from Pliocene to Holocene in age. The fluvio-deltaic sediments comprise weathered and laterised clays, clays, silt, sands and gravels. In the estuarine coastal zone, mangrove muds and silts form the dominant sediment type, as well as localised Holocene beach deposits.

3.2.1.1.4. Hydrogeology

The unconsolidated Quaternary fluvio-deltaic sediments form the most significant aquifer in the Bowen area. A cross-section through these sediments and their relationship with underlying Permian-Cretaceous intrusive basement rocks is shown in Figure 17. Pliocene fluvio-deltaic sediments have no groundwater potential because they occur high in the catchment and are thus unsaturated. Some isolated groundwater supplies may be obtained from fracture zones in basement intrusives, although their groundwater potential is generally low.

Within the Quaternary fluvio-deltaic sediments, groundwater flow direction is seaward, with the in-filled palaeochannels forming areas of preferential flow due to their high transmissivities. These Quaternary aquifers are unconfined to locally semi-confined, and are found at depths of 4 to 12 m below ground level with a thickness up to 18 m. The watertable is at 2 to 5 m depth close to the Don River delta, and drops to 10 m further inland and away from the stream.

The streams influence recharge into the aquifer, primarily where current watercourses are in hydraulic connection from the permeable sediments filling the palaeochannels. Regular overbank flooding during the wet season provides the opportunity for extensive recharge into shallow aquifers. Direct recharge also occurs from rainfall or irrigation water directly into light loam soils of the delta. In the lower delta area, the Don River can be a gaining stream as high watertables allow a hydraulic gradient towards the river. For more detailed information about the hydrogeology of Bowen, refer to the corresponding APT (Table 21, Appendix 2).

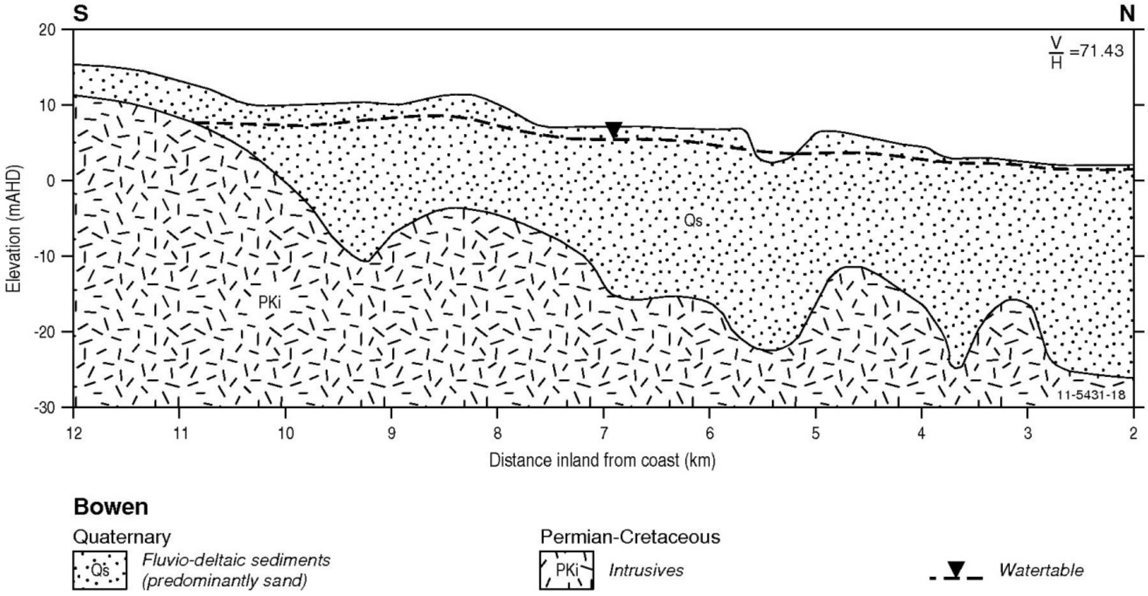

Figure 17 *Cross-section of the Bowen area, adapted from Fig 3.9 in Welsh (2002) (Note that the saltwater interface is not evident in this figure).*

3.2.1.1.5. Land and Water Use

In the Bowen area, the use of groundwater exceeds that of surface water due to unreliable stream flow (Sundaram et al., 2001b). Regional land use is primarily horticultural, with a wide range of crops grown. Apart from irrigation, relatively minor use of the groundwater includes residential, stock and industry use. In recent years, groundwater demand has increased as horticultural land use expands. Potential water demand for irrigation exceeds the available resource.

3.2.1.1.6. Incidence of SWI

Over-pumping of groundwater was identified to have led to seawater entering the aquifer in the Bowen region in 1988 (Water Resources Commission, 1988). Sundaram et al. (2001b) concluded again that seawater intrusion had occurred near the coast following a comprehensive water quality investigation. The potential for over-pumping contributing to seawater intrusion was also identified as a major groundwater management issue by Welsh (2002).

3.2.1.2. Burdekin, QLD

3.2.1.2.1. Location

The Burdekin River Delta is located along the central Queensland coastal plain, approximately 80 km southeast of Townsville, as shown in Figure 18. It has an area of approximately 850 km^2.

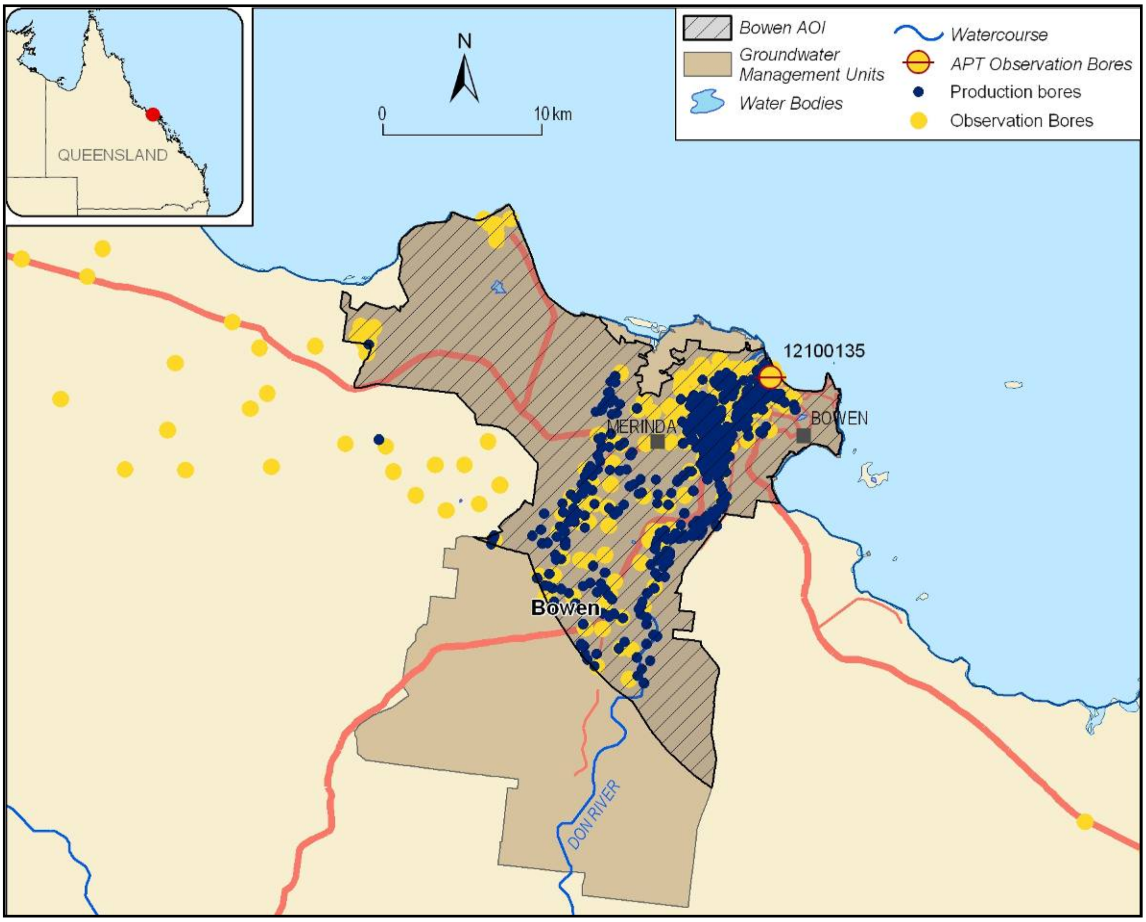

Figure 18 *Location map for the Burdekin (QLD) displaying observation bores, production bores and GMU extent.*

3.2.1.2.2. Climate

The area experiences a tropical climate, with highly seasonal rainfall. Over two-thirds of the annual rainfall occurs during the summer months. Total annual rainfall is variable and ranges from 250 to 2500 mm. The mean annual rainfall recorded in Millaroo is 781 mm (BOM 2000-2011, Milaroo Alert). The rainfall is associated with monsoonal troughs and the area is also affected by cyclones (NRMW, 2006). The region experiences hot summers and mild winters. Daily Class A pan evaporation varies from a high of up to 10 mm/day in November to as low as 2.8 mm/day in June (NRMW, 2006).

3.2.1.2.3. Geology and Geomorphology

The Burdekin River Delta and Haughton-Barratta system together form one of the largest deltaic/alluvial aquifer systems in Australia (NRMW, 2006). To the east of the delta is the Coral Sea, to the north are tidal flats, to the south are outcrops of basement rock known as the Stokes Ranges and to the west, the Stokes Ranges continue and Mt Kelly outcrops (NRMW, 2006).

The land surface slopes gently towards the ocean and both surface water (dominated by the lower Burdekin River) and groundwater discharge into the ocean to the east and north. The plain is dominated by coastal floodplains, mud flats, levee banks and sand dunes. Near the coast, estuarine deposits with mangrove and tidal mud dominate.

The basement rocks present dominantly igneous rocks with some minor metamorphic rocks. The igneous rocks range from granite to diorite with some finer-grained volcanics. Between the basement and alluvial/fluvial sediments exists a weathered sandy to clayey profile up to a few metres in thickness (NRMW, 2006). The Stokes Ranges contain a number of intrusive dykes that possess a northwest-southeast trend (NRMW, 2006).

Deposited on top of the basement rocks are the alluvial/fluvial sediments that form the primary aquifer in the region. These sediments have been deposited from terrestrial deposition (alluvial sands and floodplain silts) and surface channels, as well as from marine deposition (mangrove/tidal muds and estuarine clays) from sea incursions. Each layer is discontinuous over short distances, thus the interpretation of the aquifer from borehole data is difficult to define accurately (NRMW, 2006).

3.2.1.2.4. Hydrogeology

The main aquifer in the area is shallow and unconfined, comprised of heterogeneous, unconsolidated alluvial and deltaic sediments in excess of 100 m (Figure 19). The Quaternary sediments include a mixture of discontinuous lenses of inter-bedded gravel, channel sands, silt, mud and clay. The lenses are vertically connected and interfinger, with the clean permeable channel sands forming areas of high transmissivity compared to the low permeability clay layers. The high complexity of sedimentation and the inconsistent distribution of extensive layers justifies the inclusion of all layers into one hydrostratigraphic unit rather than multiple units (NRMW, 2006).

The hydraulic gradient of the watertable is flat (Narayan et al., 2007). Underlying the alluvial and floodplain deposits is a predominantly granitic basement rock. Groundwater movement through the basement rock is considered to be negligible, although some salts may be leached into adjacent basement outcrops, which suggests some possible connectivity between the two layers as a result of localised fracturing in the basement rock (NRMW, 2006).

Recharge to the alluvial aquifer occurs through a range of mechanisms: including infiltration of rainfall, channel seepage, and percolation through sites of artificial recharge; flood flows and infiltration into overbank deposits; and irrigation returns (McMahon, 2000). For more detailed hydrogeological information about the Burdekin, refer to the corresponding APT (Table 22, Appendix 2).

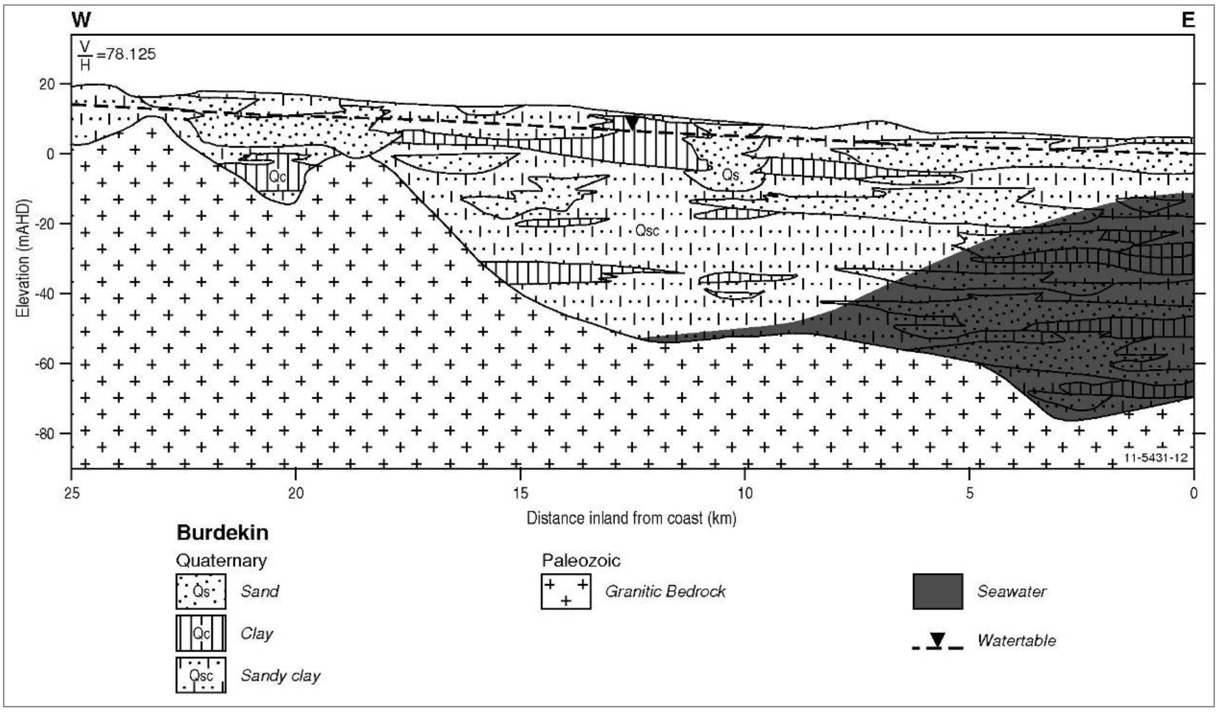

***Figure 19** Cross-section of The Burdekin, adapted from Fig. 73 in McMahon (2004).*

3.2.1.2.5. Land and Water Use

The Burdekin Irrigation area is one of Australia's foremost users of groundwater for irrigation, and northern Australia's largest irrigation area. The region supports approximately 80 000 ha of irrigated sugarcane and other crops, and generates more than $450 million in gross agricultural value (SKM, 2009). An extensive amount of groundwater is extracted and more than 1800 production bores are operational, with an estimated 210-530 GL/yr extracted (Narayan et al 2007). The region also has a high concentration of wetlands.

Natural flows along the Burdekin River have been extensively modified for irrigation with floodplain watercourses and artificial channels used to reticulate surface water to irrigators and artificially recharge aquifers with river water.

3.2.1.2.6. Incidence of SWI

Seawater intrusion within in the Burdekin River Delta groundwater management unit was highlighted as a problem in 1935, following an extended drought that lasted from 1930 to 1935. The drought was associated with extreme reductions in groundwater levels below mean sea level due to extractions which resulted in groundwater salinity increases (ANRA, 2002). During another severe drought in 1965, issues associated with groundwater overdrafts were addressed with the implementation of an artificial groundwater scheme. This involved the use of electric pumping plants to divert river water to areas suitable for groundwater recharge through a system of natural and artificial channels (NRMW, 2006).

Seawater intrusion has also been documented by McMahon (2004) to occur in this area as a result of low rainfall and intense groundwater pumping, which has led to watertables dropping below sea level during intensive drought periods. The areas most under threat are those closest to the shoreline or tidal estuaries, as well as areas adjacent to tidal barrages constructed on the lower delta to restrict the effects of seawater intrusion (NRMW, 2006).

3.2.2. Coastal Alluvium, Arid

Only one CSA experiences an arid climate and has a coastal alluvium aquifer, Carnarvon in WA. The groundwater in this area supports the town of Carnarvon as well as mining, pastures and a horticulture industry. The groundwater resource is essential for the survival of these industries, as well as for the town of Carnarvon, because surface water is limited and not available year around.

3.2.2.1. Carnarvon, WA

3.2.2.1.1. Location

Carnarvon is located approximately 900 km north of Perth at the mouth of the Gascoyne River on the Indian Ocean, as shown in Figure 20.

3.2.2.1.2. Climate

Carnarvon has an arid climate, and annual evaporation exceeds annual precipitation. Rainfall is unreliable; summers are hot and winters are mild. Average annual rainfall is 229 mm/yr, with approximately 38 mm/month falling during winter and approximately 11 mm/month during summer (CyMod Systems Pty Ltd, 2009). The mean annual evapotranspiration is approximately 2620 mm for the region, with an average of 298 mm/month in summer and 126 mm/month in winter (CyMod Systems Pty Ltd, 2009).

3.2.2.1.3. Geology and Geomorphology

The Lower Gascoyne River is the primary geomorphologic influence within this CSA. It flows along a well-confined braided channel through Quaternary alluvial terraces that lie atop Tertiary and Mesozoic sedimentary rocks. The Quaternary alluvial system has been deposited by the current Gascoyne River and earlier channel flows. The sediments are poorly-sorted, ranging from clay to gravel size. Sandy sediments are often laterally discontinuous as different lithologies alternate or grade into one another. Pre-Quaternary rocks, which rarely outcrop in the area, consist of Cretaceous shallow marine limestones and shales. These are unconformably overlain by early Tertiary shallow marine sandstones and limestones.

The Gascoyne River catchment can be divided into two distinct areas: (1) an inland, etched granitic plain; and (2) the Carnarvon Basin, which comprises the Kennedy Range plateau and a flat coastal plain (CyMod Systems Pty Ltd, 2009). The topography of the region is generally flat, dipping gently to the west. The eastern Carnarvon Basin has a greater relief than the coastal plain, yet drainage is better defined at the coast than in the arid interior.

The soils in the region are largely unconsolidated sandy soils. The Gascoyne river channel comprises a wide, sandy bed with abundant sand bars and terrace formations. The coastal plain is composed mostly of bare clay pans, gravel and shingle patches or sand dunes (CyMod Systems Pty Ltd, 2009).

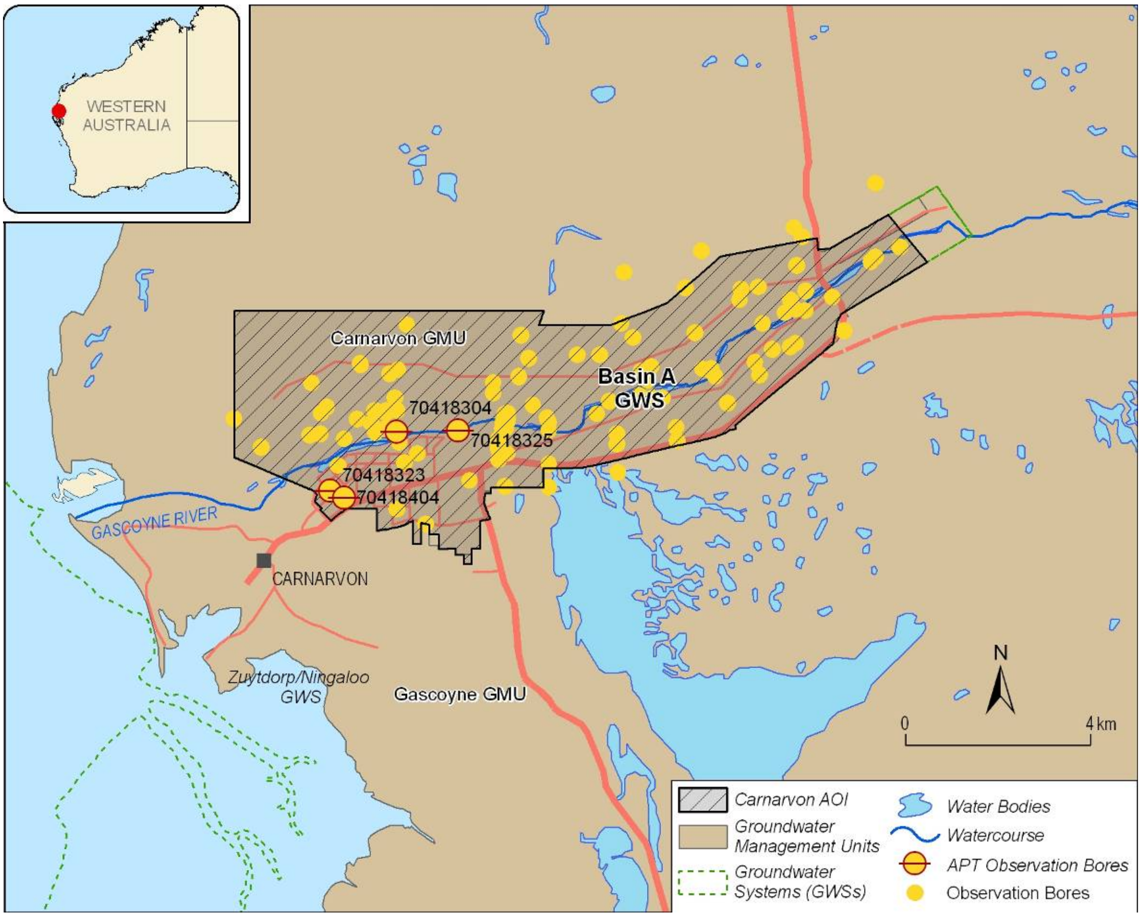

Figure 20 *Location map for Carnarvon (WA) displaying observation bores and GMU extent.*

3.2.2.1.4. Hydrogeology

The Carnarvon hydrogeology consists of two hydraulically connected, unconfined to semi-confined aquifer systems that are bounded to the west by a saltwater interface (Figure 21). The principal aquifer for the region comprises the aggraded sand deposits within and below the Gascoyne River channel, known informally as the River Bed Sand (RBS). The thickness of these deposits varies from a few metres to 18 m (CyMod Systems Pty Ltd, 2009). Older, deeper alluvial terraces provide a secondary aquifer with substantially greater storage, but less efficient recharge, known as the Older Alluvium Aquifer (OAA). A conceptualisation of the RBS aquifer overlying the OAA can be seen in Figure 21. Salinity levels and water quality are highly variable in the older alluvium aquifers. The flows in the Gascoyne River are intermittent; during periods of river flow the aquifer systems are usually fully replenished. The corresponding APT (Table 23, Appendix 2) provides more detailed information about the hydrogeology of Carnarvon.

3.2.2.1.5. Land and Water Use

There is significant groundwater use, both by public and private water supplies and the local horticulture industry, in these areas (CyMod Systems Pty Ltd, 2009), although production bore data could not be obtained for this investigation. Within the Lower Gascoyne River the main agricultural activity is commercial horticulture. Within the wider Carnarvon catchment, the main land and water use is pastoral and mining. Groundwater is also used for the town water supply, and is supplemented by surface water when the river is flowing.

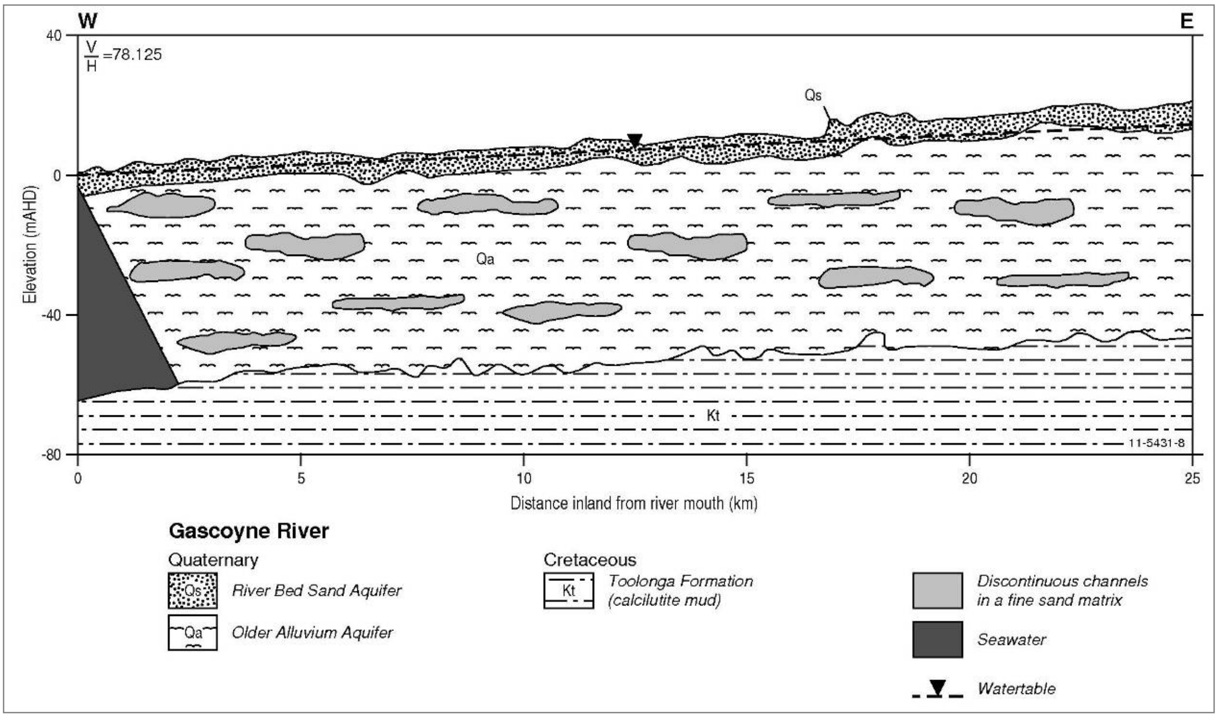

Figure 21 *Cross-section of the Carnarvon area, adapted from Fig. 7 in CyMod Systems Pty Ltd (2010b).*

3.2.2.1.6. Incidence of SWI

During no-flow periods of the Gascoyne River, observation bore data has shown increasing trends of saline to brackish water, presumed to be a consequence of SWI (WRC, 2004). When salinity reaches a TDS value exceeding 1000 mg/L, pumping is ceased until the salinity measurements are reduced. During dry periods, farmers must purchase water from the Older Alluvium Aquifers. According to WRC (2004), no well has experienced any long-term elevated salinity trend when using the cease to pump trigger of 1000 mg/L, although further studies are required to better understand the salinity distribution.

3.2.3. Coastal Alluvium, Temperate, Dry Winter

The Pioneer Valley located in Queensland is the only CSA that experiences a temperate climate with a dry winter and has a coastal alluvium aquifer. The Pioneer Valley is heavily reliant on groundwater to supplement surface water resources in support of its sugarcane industry.

3.2.3.1. Pioneer Valley, QLD

3.2.3.1.1. Location

The Pioneer Valley is located on the northern central coast of Queensland within 50 km of the city of Mackay, as shown in Figure 22.

3.2.3.1.2. Climate

The Pioneer Valley is commonly reported as having a wet tropical climate with a distinct summer wet season. Within the Köppen-Geiger system of climate classification, however, this area is classified as having a temperate climate with a dry winter.

The area is influenced by tropical low pressure systems in the Coral Sea and rainfall, associated with cyclones. Rainfall varies depending on location, with an average annual rainfall ranging from less than 1100 mm in the south to over 2000 mm in the west. Mean daily temperatures in the city of Mackay vary between approximately 13 °C (in winter) to 30 °C (in summer). Mean monthly humidity ranges from approximately 65 % in October to 80 % in April. The mean annual evaporation for Mackay is approximately 2000 mm per annum (Murphey et al., 2005).

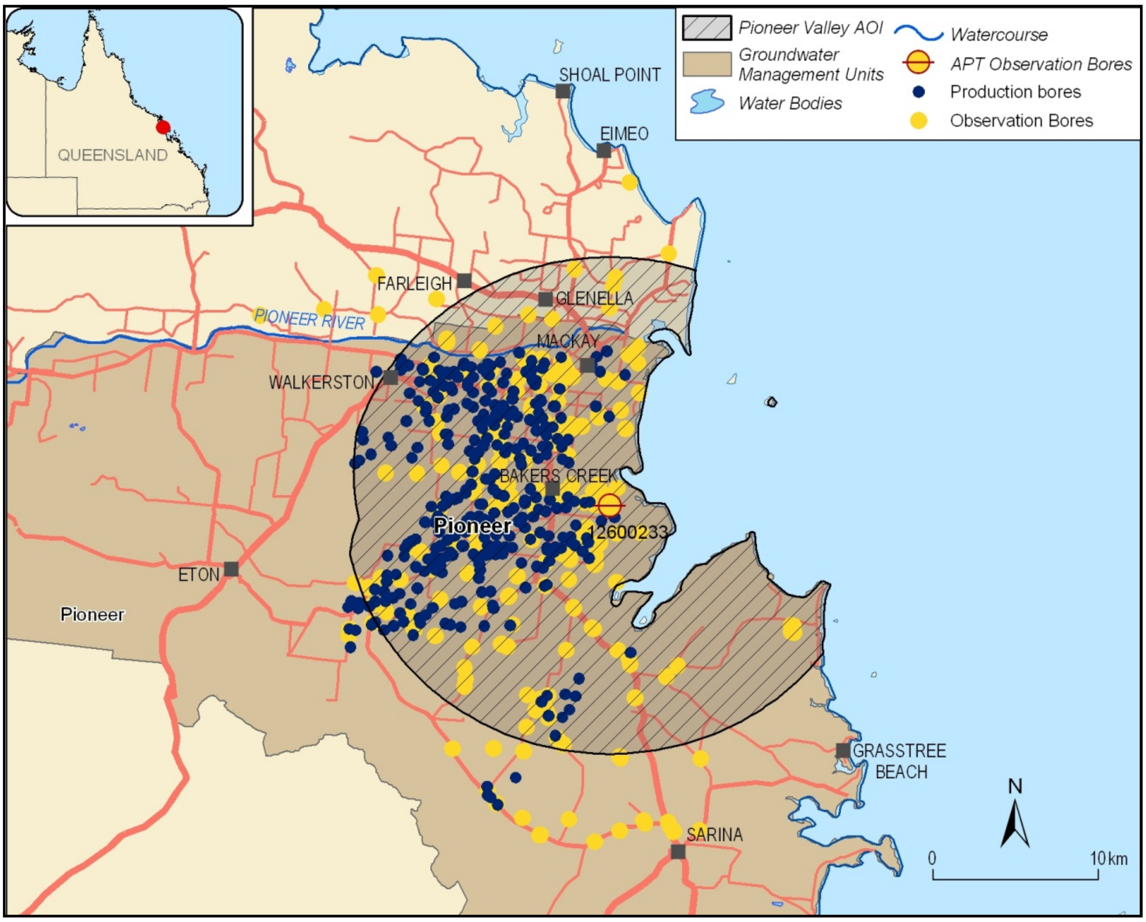

Figure 22 *Location map for Pioneer Valley (QLD) displaying observation bores, production bores and GMU extent.*

3.2.3.1.3. Geology and Geomorphology

The regional geology consists of Quaternary alluvial and fluvial deposits overlying a mostly Palaeozoic basement. The basement rocks include sedimentary, intrusive and volcanic rocks and range in age from Palaeozoic to Cenozoic. Quaternary sediments have been deposited by the Pioneer River, Sandy Creek, Bakers Creek and their tributaries, on the coastal plain. These sediments range in thickness from 5 to 40 m and average approximately 18 m. They comprise interbedded clays, sandy clays, sands, clayey sands and gravel (Murphy and

Sorensen, 2000). These alluvial deposits have been intersected by post-depositional streams and have been subsequently in-filled by channel-fill deposits of coarse to fine sands and gravels. Sand dunes and marine mud deposits occur near the coastline and estuarine fringes.

3.2.3.1.4. Hydrogeology

The Pioneer Valley groundwater resources are contained within alluvial deposits and fractured rock units which behave as a singular aquifer system (Bedford, 1978). A schematic cross-section through this aquifer is shown below in Figure 23. The unconsolidated alluvial aquifers are unconfined and are less than 40 m in thickness (Bedford, 1978). In the lower alluvial domain, above the weathered basement rocks, higher-yielding deposits of coarse sands and gravels are often found. Rainfall is the primary source of recharge to the aquifers, with watertables rapidly responding to rainfall events.

Palaeochannels that have been incised into the basement rock may form preferential flow pathways (Bedford, 1978; Murphy and Sorensen, 2000). These channels reflect the current and previous alignments of the Pioneer River, Bakers Creek and Sandy Creek. Fractures within the basement rocks may also transmit groundwater, forming a continuous aquifer with the weathered zone and the upper alluvium. The APT for the Pioneer Valley (Appendix 2, Table 24) provides more detailed hydrogeological information.

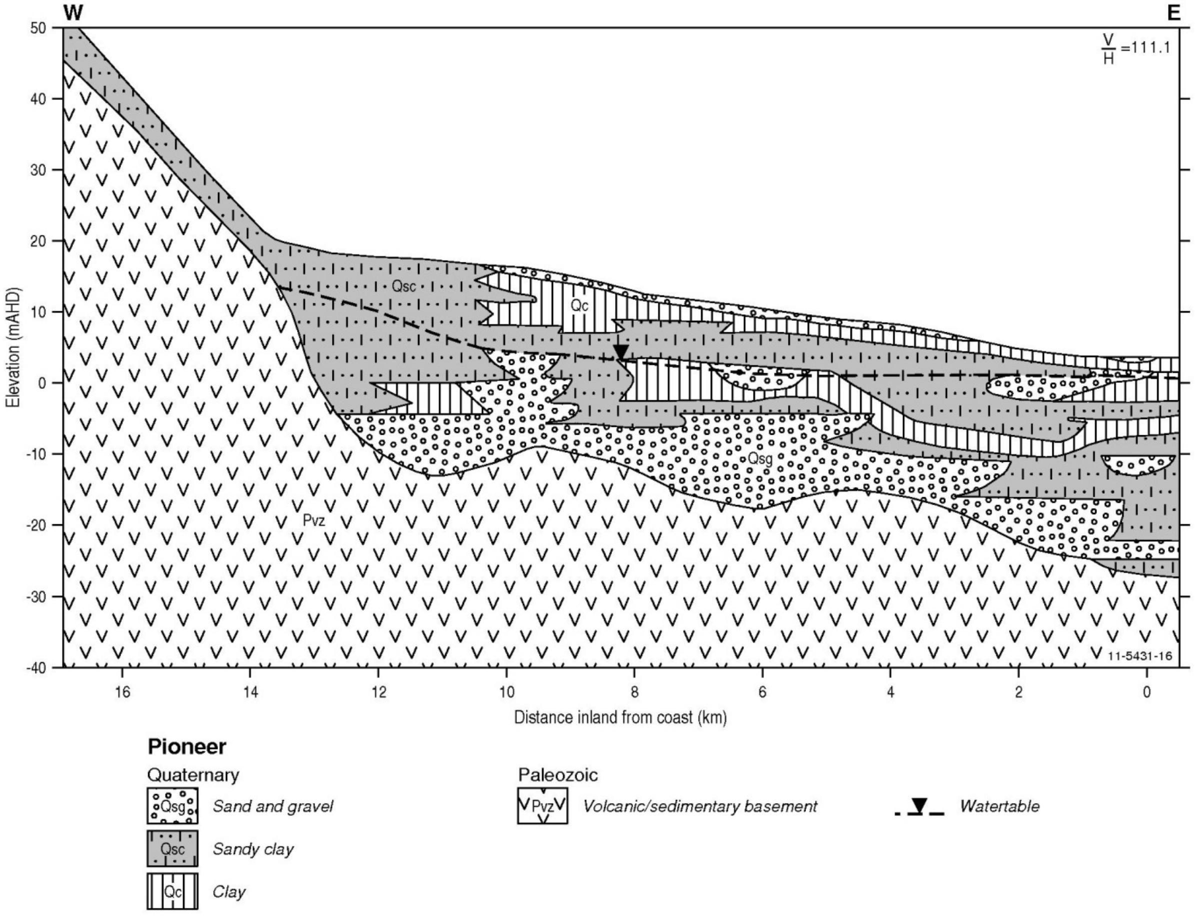

Figure 23 *Cross-section of the Pioneer Valley area, adapted from Cross-section 4 in Murphey (2005) (Note the saltwater interface is not evident in this figure).*

3.2.3.1.5. Land and Water Use

Land use since the 1980's has been primarily for sugarcane growing, with the majority of groundwater irrigation used to supplement rainfall. The groundwater resources are also used by the domestic sugar milling industry; for urban water supply; as stock water; and for farm and rural domestic water supplies.

3.2.3.1.6. Incidence of SWI

SWI was first recognised in 1975 and became a more serious concern in the mid 1990s as a result of below-average rainfall between 1991 and 1997 coupled with an increase in irrigation demand. Subsequently, excessive groundwater abstractions between Sandy Creek and the Pioneer River have been shown to alter the aquifer's hydrogeology. A large number of observation bores have recorded their lowest minimum water level below mean sea level, which increases the susceptibility of the aquifers to SWI (Murphy and Sorensen, 2000; Werner and Gallagher, 2006). The large tides, flat topography, location of the pumping bores close to areas of tidal influence and over-extraction of groundwater, have led to the deterioration of water quality in a number of observation bores and have increased their susceptibility to SWI.

3.2.4. Coastal Alluvium, Temperate, Without Dry Season

One CSA, Burnett Heads (Qld), has a coastal alluvium aquifer and experiences a temperate climate without a dry season. This climate is similar to Pioneer Valley in that the temperature of the hottest month is greater than 10 °C and the temperature of the coldest month is between 0 and 18 °C. It does not, however, have a pronounced dry season. Burnett Heads is also an area with a large sugarcane industry that depends on groundwater. The threat of SWI was first reported here in 1960.

3.2.4.1. Burnett Heads, QLD

3.2.4.1.1. Location

Burnett Heads is located within the Queensland subtropics approximately 10 km from the town of Bundaberg, as shown in Figure 24.

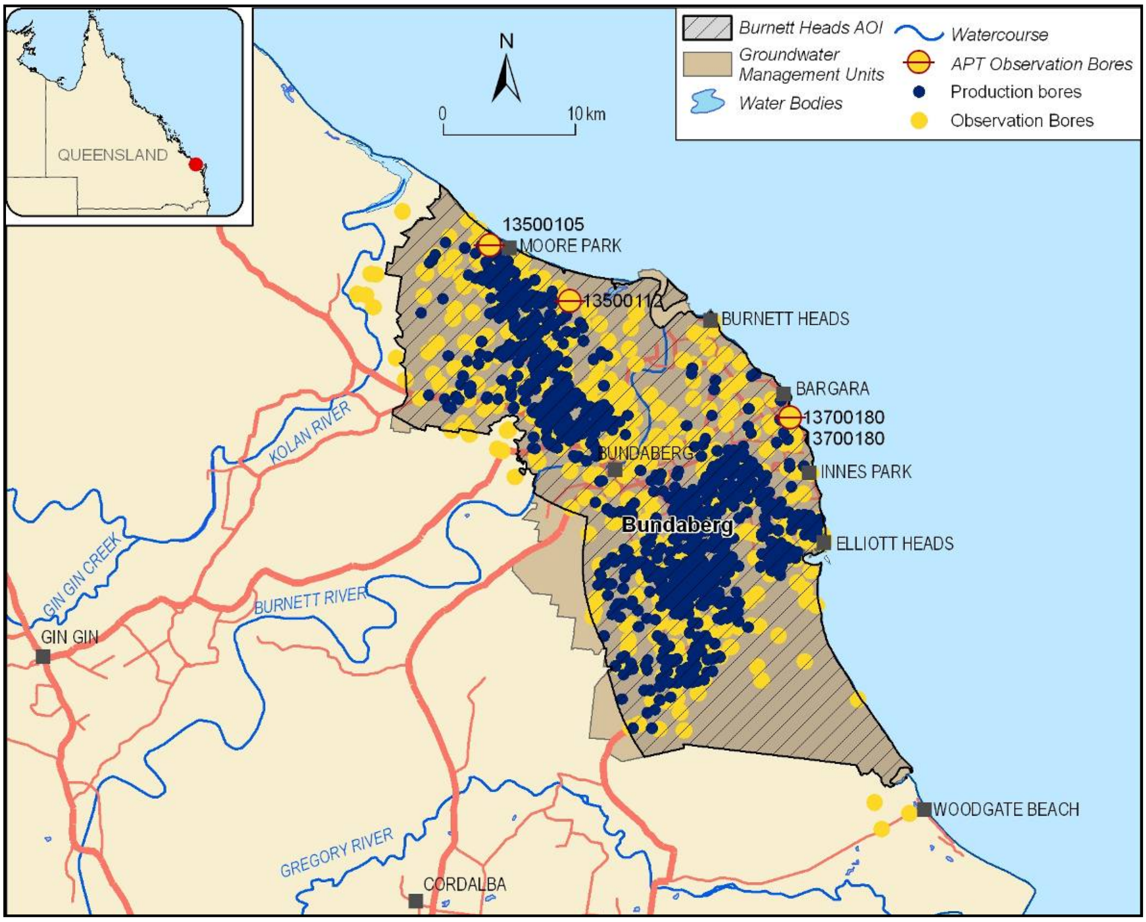

Figure 24 *Location map for Burnett Heads (QLD) displaying observation bores, production bores and GMU extent.*

3.2.4.1.2. Climate

The area experiences hot summers and mild winters. The average maximum temperature is 29.8 °C in summer, 22.6 °C in winter, and 26.6 °C for the year. More rain falls in the summer months. The average annual rainfall is approximately 1023 mm with approximately 45% occurring in summer and 12% in winter (BOM 1959-2011, Bundaberg Aero).

3.2.4.1.3. Geology and Geomorphology

The Burnett area consists of Quaternary aged coastal dune sands and recent alluvium. These sediments comprise unconsolidated gravels, sands, muds and clays of dunal and estuarine origin. Alluvial unconsolidated sediments have been primarily deposited by the Kolan, Burnett and Elliot Rivers (Moser, 2004). These Quaternary sediments are not regionally extensive, and they overlie the Tertiary-aged Elliot Formation, which is one of the primary aquifers in the area. The Elliot Formation comprises semi-consolidated to unconsolidated alluvial sediments of quartzose sandstone, conglomerate, siltstone, mudstone and shale. The Gooburrum Clay unit is also of Tertiary age, and although it is composed predominantly of clay, it also includes sandy sediments in the upper sections. The Tertiary Fairymead Beds comprise unconsolidated sands, gravels and clays that are locally confined to an area known as the Bundaberg Trough.

The Burrum Coal Measures form the basement material for this area. These are Cretaceous in age and comprise greywacke, sandstone, mudstone, shale, coal and minor conglomerate. The area also contains two basalt units of Quaternary and Tertiary age. These have little groundwater potential.

3.2.4.1.4. Hydrogeology

Groundwater occurs in two main aquifers, the upper Elliot Formation and the underlying Fairymead Beds. These can be seen in Figure 25. In addition, Quaternary coastal dune sands and alluvium have a minor to moderate groundwater potential in locally perched aquifer systems. The major Elliot and Fairymead aquifers are composed of Tertiary unconsolidated to semi-consolidated alluvial sediments, which unconformably overlie the Lower Cretaceous Burrum Coal Measures basement (Bajracharya et al., 2006). Both aquifers have been described as having *"moderate to high groundwater potential"* (Moser, 2004), although this may be regionally variable. A leaky aquitard clay layer, referred to as the Gooburrum clay, separates the two aquifers. The clay is of variable thickness and distribution, and contributes to a spatially variable hydraulic connection.

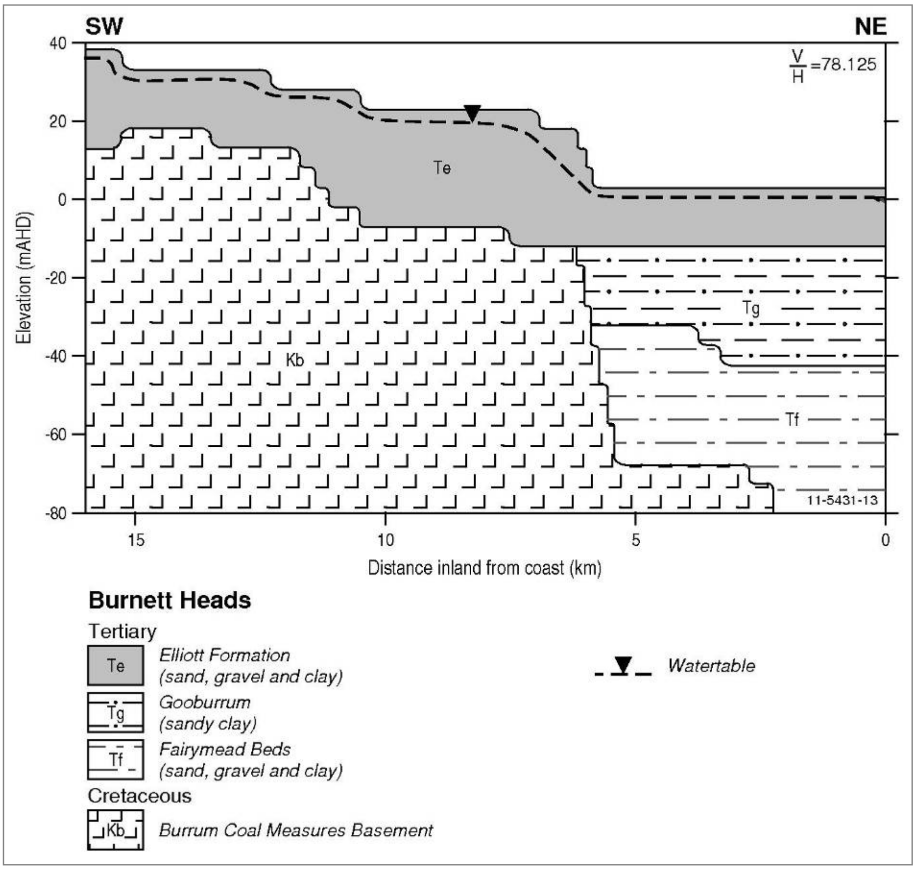

Figure 25 *Cross-section of the Burnett Heads area, adapted from Fig 2 in Zhang et al. (2004) (Note that the saltwater interface is not evident in this figure).*

Rainfall is the primary source of recharge to the unconfined to semi-confined aquifer systems, and the groundwater is generally of very high quality; commonly less than 500 µS/cm in the inland areas. About 50 % of the Elliot Formation aquifer is located below mean sea level, while the Fairymead Beds are entirely below mean sea level. The deepest section is approximately 80 m below mean sea level near the coast (Zhang et al., 2004). The corresponding APT for Burnett Heads Table 25 (Appendix 2) contains more detailed hydrogeological information.

3.2.4.1.5. Land and Water Use

The dominant land and water use in the Burnett area is to grow sugarcane, and to support associated industries. Other horticultural activities are also prominent. Groundwater is the main source of reliable water and is used for irrigation, industry and for urban water supply.

3.2.4.1.6. Incidence of SWI

SWI was first reported in the 1960s when the high price of sugarcane led to the intense use of groundwater for irrigation. The 1960s also coincided with drought conditions, which led to declining groundwater levels in excess of 5 m below mean sea level in the Burnett Heads area (Bajracharya et al., 2006). During the period of 1977-79, rainfall was well below average, and groundwater levels were drawn down in excess of 3 m below mean sea level for a period lasting over 15 months (Dempster, 1994; Zhang et al., 2004). At this time, considerable SWI occurred, and salinity increased to 50 000 µS/cm in some areas.

There has been a succession of drought years since the 1960s, and SWI has been detected over a large area. It is estimated that 12 500 hectares of land in the Gooburrum area have been lost to seawater intrusion, and according to Bajracharya et al. (1998), the SWI interface has been estimated to be moving at approximately 100 m per year, primarily within the highly permeable aquifer channels in hydraulic connection to the sea.

3.2.5. Summary, Coastal Alluvium

Five CSAs were classified as having coastal alluvium aquifers, and these were situated within four different climate types: tropical, arid, temperate dry winter and temperate without dry season. There are many similarities between these CSAs.

Each CSA has an aquifer comprising semi-consolidated to unconsolidated alluvial sediments, which range from very fine to very coarse grained. The aquifers are heterogeneous in composition and contain discontinuous, interfingering lenses of gravel, sand and clay. Coarser sediment layers provide areas of very high transmissivity, whereas clay packages inhibit localised flow. These aquifers are unconfined or semi-confined and are usually considered as a lumped aquifer layer. Burnett Heads and Carnarvon are exceptions to this, as they have been divided into two major alluvial aquifers that are separated by leaky aquitards. Burnett Heads primary aquifers are Tertiary in age, while the other CSAs have Quaternary aquifer.

The aquifers encompass a range of hydraulic properties. In general, the coastal alluvium aquifers comprise recent sediments that have not been lithified. Without detailed borehole data - due to their heterogeneities - their stratigraphy can be difficult to conceptualise, which can make groundwater management for SWI challenging. The characteristics of coastal alluvium aquifers will depend upon the nature of the river depositing the sediment, and from where the sediment has been derived. The aquifer geometry will also be influenced by the basement configuration; in this report, each CSA has a Palaeozoic or Mesozoic basement. The nature of the basement rock - and whether it is fractured or contains a weathering profile - influences its capacity to store and transmit groundwater. In the Burdekin, for example, there is negligible movement of groundwater through the basement rock; while in the Pioneer Valley, the underlying fractured rock forms an extension to the overlying alluvial aquifer system. The basement rocks have been incised and eroded by overlying alluvial systems, creating palaeochannels. Palaeochannels then become in-filled by alluvial sediments, forming the thickest (and often coarsest) parts of the aquifer. Because the river courses may often run perpendicular to the coast, packets of alluvial sands and palaeochannels can act as rapid conduits of groundwater flow inland. SWI can preferentially occur through aquifer palaeochannels, leading to a heterogeneous distribution of the saltwater wedge, which occurs in the Pioneer Valley.

The Coastal alluvium aquifers are also associated with estuaries and areas of tidal influence. The large tidal extent and flat topographies that characterise this typology can increase the risk of SWI. Conversely, estuarine mud can act as a barrier for seawater intrusion.

The climate will influence a coastal alluvium aquifer’s susceptibility to SWI. In these areas, the primary mechanism for recharge is via rainfall directly infiltrating into the ground and river losses. In tropical and temperate areas where there is high rainfall and a possibility of cyclone-related flooding, overbank flows and floods contribute considerably to groundwater recharge. Carnarvon, however, experiences a lower rainfall, with little to no rainfall in dry months, during which time surface water ceases to flow. In the dry months, the threat of SWI is increased considerably through groundwater extraction.

High rainfall areas within the coastal alluvium aquifer types are often associated with high irrigation demands, especially during dry periods and droughts, to meet the required water supply for growing sugar cane and other horticultural products. SWI can be seen to correlate strongly with times of decreased rainfall and with high extractions in all cases, which is exacerbated by high transmissivities of the sediments, a lack of aquifer confinement and the dependence on rainfall for groundwater recharge.

3.3. Coastal Sands

The CSAs classified to have a coastal sands principle aquifer type include Cottesloe Peninsula (WA), Rottnest Island (WA); North Stradbroke Island (Qld); Botany (NSW), Hat Head (NSW), Stockton (NSW), Stuarts Point (NSW), and Point Nepean (Vic).

3.3.1. Coastal Sands, Temperate, Without Dry Season

Six CSAs have coastal sands principle aquifer type and a temperate, without dry season Köppen-Geiger climate type. Characteristics of them are outlined below, which are followed by a summary of the key findings for this Coastal Aquifer Typology.

3.3.1.1. North Stradbroke Island, QLD

3.3.1.1.1. Location

North Stradbroke Island is located in Moreton Bay, 40 km east of Brisbane city (Figure 26). It belongs to a group of massive sand islands in the south-east of Queensland. These include South Stradbroke Island, North Stradbroke Island, Moreton Island, Bribie Island and Fraser Island. North Stradbroke Island has a land area of approximately 267 km^2 (Chen, 2001).

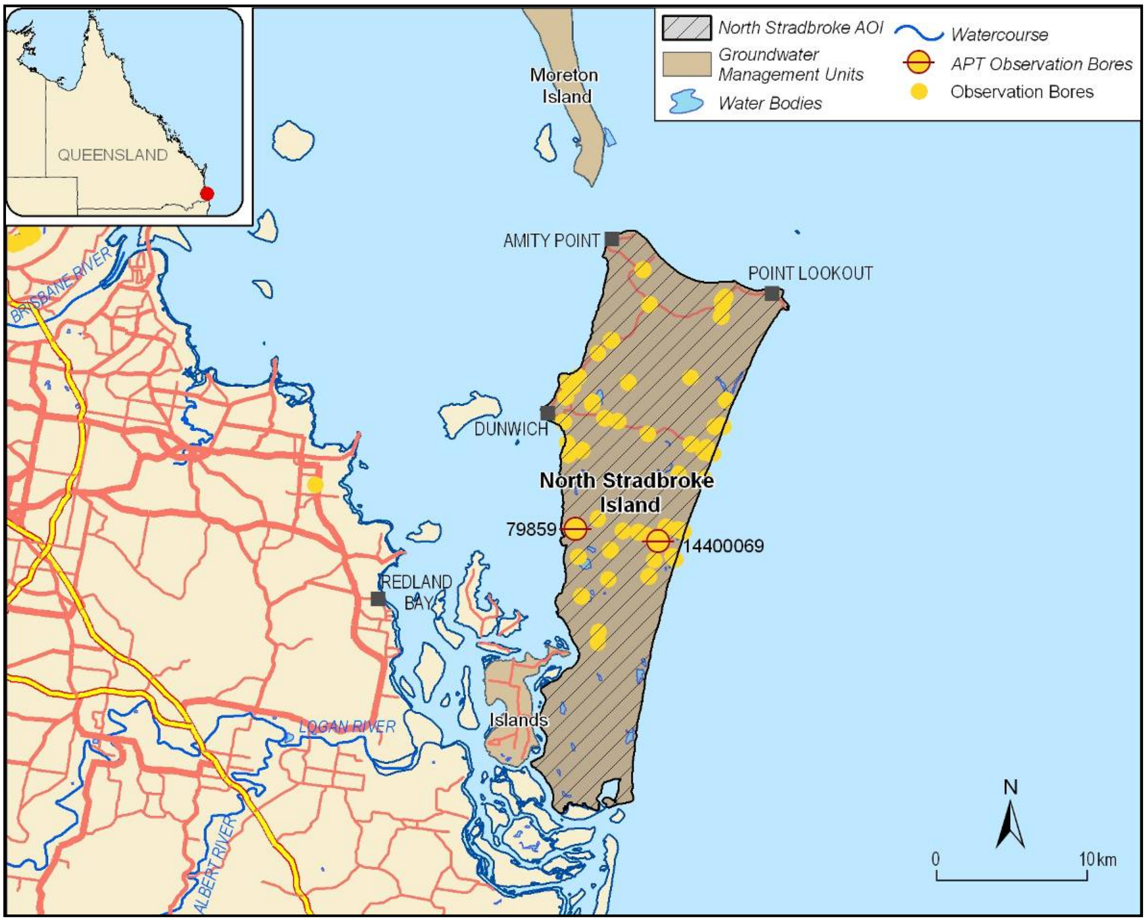

Figure 26 *Location map for North Stradbroke Island (QLD) displaying observation bores and GMU extent.*

3.3.1.1.2. Climate

The climate of North Stradbroke Island is sub-tropical with moderate rainfall. The average rainfall is approximately 1529 mm, with approximately 28 % falling in summer and approximately 21 % in winter. The average maximum temperatures are 25.3 °C (annual), 26 °C (in summer) and 21.4 °C (in winter). Class A pan data shows that evaporation in the regions are seasonally varying with a maximum of approximately 200 mm/month from February to July and a minimum of approximately 50 mm/month between August and October (Chen, 2001).

3.3.1.1.3. Geology and Geomorphology

North Stradbroke Island is approximately 37 km long, and is approximately 11 km wide in the north and 4 km wide in the south. The island has a land area of about 267 km^2 (Chen, 2001; EHA, 2005). Vegetated sand dunes are one of the main topographic features of the island, and they form northwest-trending ridges. North Stradbroke Island is dominated by Quaternary unconsolidated sediments, including extensive elevated sand dunes. The sand dunes consist of fine to medium grained quartz sand with minor interbedded peat layers; carbonaceous sands; and some ironstone bands, with heavy minerals distributed throughout. The dune sands extend from approximately -80 to 200 m MSL and have be divided into three different dune series, those that formed 300 000 (‘ancient’), 150 000 (‘old’) and 70 000-20 000 (‘recent’) years ago. During a period of elevated sea level 6500 years ago, a coastal platform was also established around the island (Chen, 2001). Quaternary sediments form a blanket over Mesozoic sedimentary and volcanic rocks and Palaeozoic metasediments.

The island contains a unique freshwater peat swamp known as Eighteen Mile Swamp, which acts as a trap for lateral groundwater seepage and diverts the water south via Freshwater Creek into Swan Bay.

3.3.1.1.4. Hydrogeology

The hydrogeology of North Stradbroke Island is described by Laycock (1975), Chen (2001) and EHA (2005). These studies indicate that good quality groundwater is stored within the Quaternary dune sands comprising porous quartz sand, which can be quite thick and elevated in places, reaching a height of 76 m above sea level. The average depth to groundwater on the island is 16 m, and the maximum elevation of the groundwater is 50 to 60 m AHD in the central-north of the island, forming a groundwater mound, as is shown in Figure 27. Seawater has formed a wedge around the perimeter of the island and its position changes with the amount of fresh groundwater discharged to the coast, which is mostly influenced by the balance between recharge to the groundwater system and extraction. For more detailed information about the hydrogeology of North Stradbroke Island, refer to its corresponding APT (Table 26, Appendix 2).

3.3.1.1.5. Land and Water Use

North Stradbroke Island land uses include settlements, sand mining, reserves, and significant wetlands, lakes and lagoons. Groundwater on the island is used to provide town water supplies, including supply to the mainland, and it is also used in sand mining activities. Note that production bore data could not be obtained for use in this study.

3.3.1.1.6. Incidence of SWI

North Stradbroke Island has been recognised as being at threat of SWI. Modelling has determined the following: groundwater extractions from the central groundwater mound will have the least impact on SWI; some production bores have shown a downward trend in water-levels due to below-average rainfall (Chen, 2001); swamps on the island may act as a hydraulic barrier to SWI (Kaegi, 2006); and, the island has an insufficient number of suitably constructed monitoring bores to determine the position of the saltwater interface (EHA, 2005).

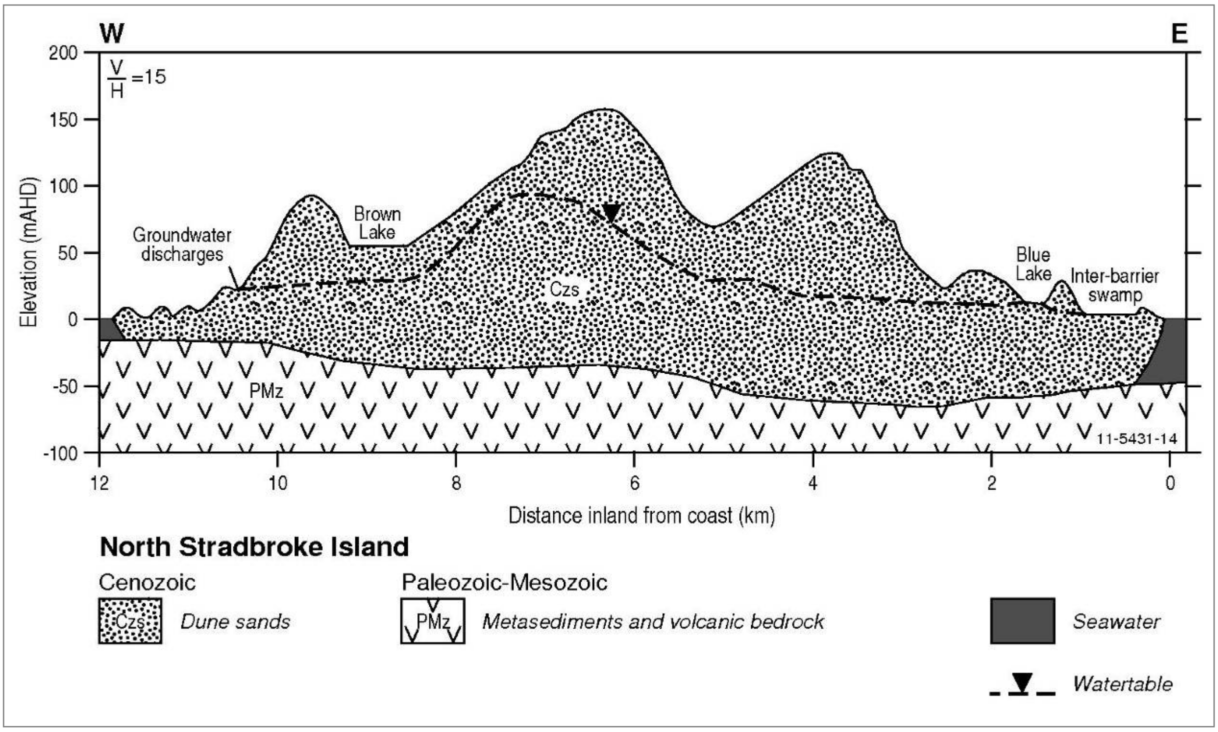

Figure 27 *Cross-section through North Stradbroke Island, adapted from Fig 2 in Laycock (1978).*

3.3.1.2. Botany, NSW

3.3.1.2.1. Location

Botany is located in Sydney NSW, on the eastern Australian coast, between Port Jackson and Port Hacking (Figure 28). The following section is a summary of the Botany aquifer systems, which have been described in detail by Bish et al. (2000).

3.3.1.2.2. Climate

The climate in the Botany Bay area ranges from humid in the summer to temperate for most of the year. The Average annual maximum temperature is 22.2 °C, varying from 17.6 °C in winter to 26.1 °C in summer. Mean annual rainfall is 1084 mm and is seasonal, with most (approximately 55 %) falling during the summer and autumn months (BOM 1939-2010, Sydney Airport AMO). The area has a history of droughts, alleviated by periods of heavy rainfall, which cause the aquifer to recharge significantly. During the majority of the year, evaporation rates exceed rainfall, except in the autumn months and in February when the rainfall is the greatest.

3.3.1.2.3. Geology and Geomorphology

The Botany area is located within the Botany Basin, and is almost at sea level with little topographic relief (Bish et al., 2000). The Botany Basin is a sediment-filled topographic depression surrounded by sandstone hills, which are capped with shales or sand. The surface of the Botany Basin gently slopes towards Botany Bay and is dissected by three stream valleys.

The basin was formed during the Tertiary period by the erosion of Triassic sediment, which has defined the incised shape of the basin. The Triassic sedimentary rocks now form the basement and the erosional depression is filled with unconsolidated Quaternary sands, silts, clays and peat, known as the Botany Sand Beds.

The Botany Sand Beds comprise tidal swamp sediments, aeolian dune sands and alluvial material that form four identifiable stratigraphic units. The basal unit comprises fluvial sand associated with minor gravel, and it grades upwards into marine sand with estuarine shells and peaty marine muds. The second unit is composed of clay and clayey quartz sands, containing minor peat beds. The third unit consists of clean, well-sorted, medium-grained sands with low carbonate content, interbedded with some discontinuous lenses of peat and silty clay. The uppermost unit is composed of Holocene deposits of clean, fine to medium grained sands with silt and clay.

The Triassic sediments underlying the basin include both the Wianamatta Group, which contains interbedded shales and sandstones and the Hawkesbury Group, which includes primarily a massive bedded rock comprising coarse to medium well-rounded and well-sorted quartz grains in a clay matrix with secondary quartz cement.

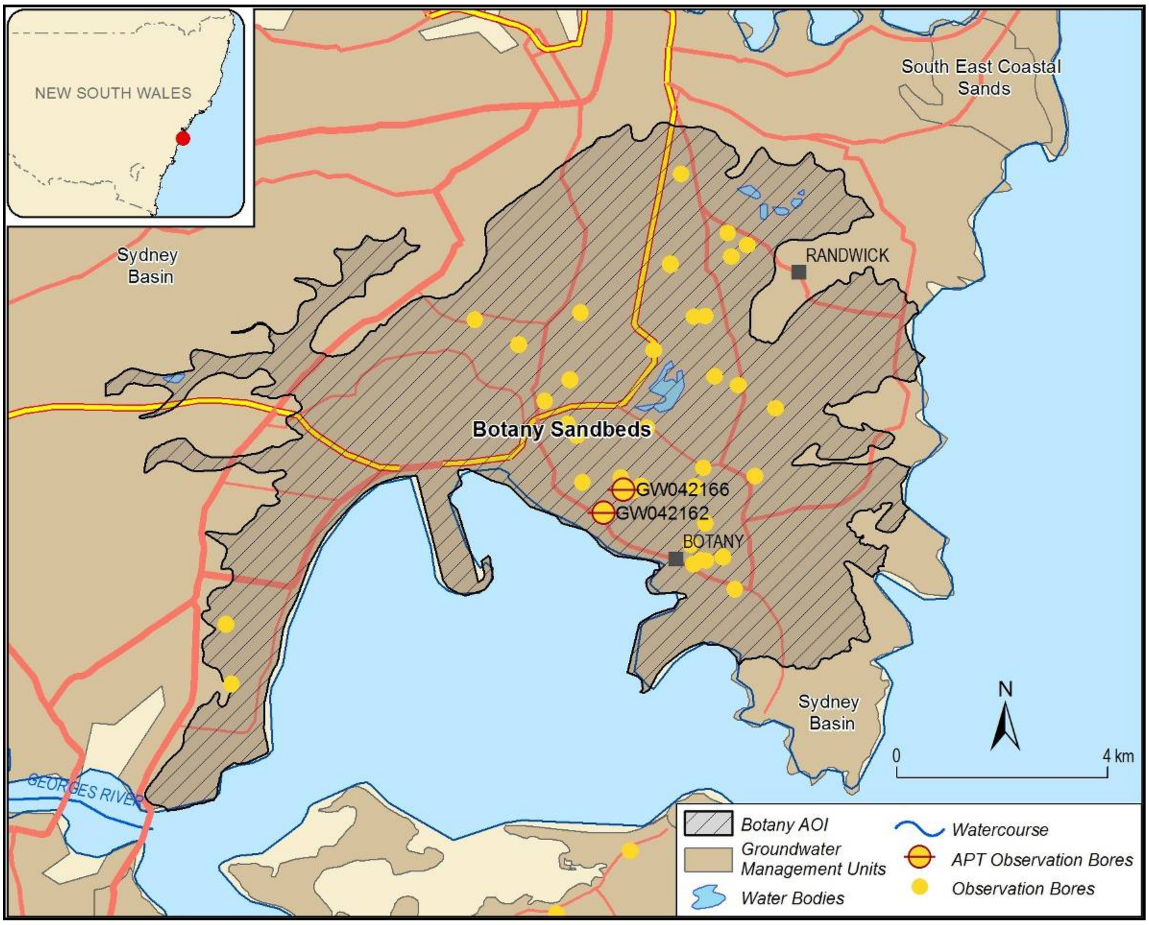

Figure 28 *Location map of Botany (NSW) including location of observation bores and GMU extent.*

3.3.1.2.4. Hydrogeology

There are two main groundwater systems operating within the Botany Sand Beds; the deeper, confined fractured/porous Triassic Hawkesbury Sandstone and the upper Quaternary Botany Sand Beds, as shown in Figure 29. The Botany Sand Beds aquifer is shallow and unconfined to semi-confined. Its sediments are mostly highly permeable; therefore, it is a very productive aquifer (Bish et al., 2000). They are also, however, highly heterogeneous, leading to a variable hydraulic conductivity across the aquifer.

The aquifer is influenced by the structure of Botany Basin, which has large palaeochannels incised into the basement that act as conduits for groundwater flow. The thickness of the aquifer is greatest (up to 80 m) in the north, due to the presence of a large palaeochannel. Layers of peat, clays and indurated sands all affect the movement of groundwater through the aquifer. It is understood that some leakage occurs from the basement aquifer into the Botany Sand Beds, although the nature of the relationship is not well understood (Bish et al., 2000).

Due to the high permeability of the aquifer, rainfall infiltration is the predominant recharge mechanism (Bish et al., 2000). The urban environment has, however, substantially modified surface drainage. Runoff is drained from the stormwater channels that have been constructed within residential, commercial, industrial and open space land areas. Botany's corresponding APT (Table 27, Appendix 2) contains additional hydrogeological information about the Botany Sand Beds aquifer system.

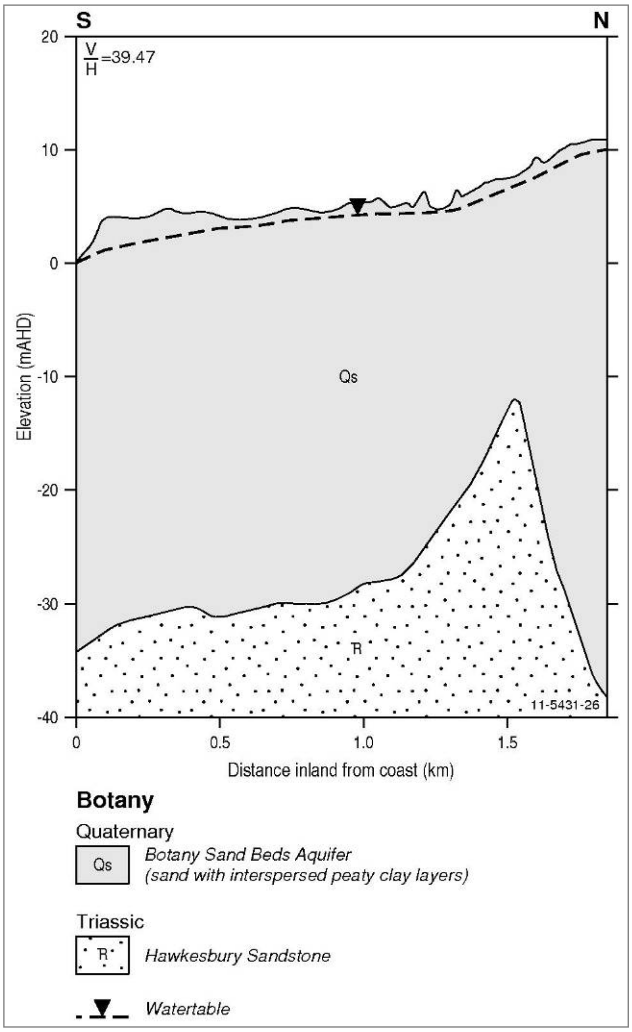

Figure 29 *Cross-section through the Botany area, adapted from Fig 3 in Benker et al. (2007) (Note that the saltwater interface is not evident in this figure).*

3.3.1.2.5. Land and Water Use

The Botany Sand Beds Aquifer is the oldest producing groundwater system in Australia still in active use. The major use for the groundwater today includes domestic garden, industrial and recreational (such as golf courses) use. These areas flank environmentally significant wetlands (Bish et al., 2000). Note that production bore data could not be obtained for use in this project.

3.3.1.2.6. Incidence of SWI

The Botany Sand Beds Aquifer was documented to have experienced SWI in the 1960's as a consequence of extracting groundwater resources for industrial processes (Timms et al., 2008). The production bores were shut down as a consequence of SWI and usage from the aquifer was subsequently moved further inland.

3.3.1.3. Hat Head, NSW

3.3.1.3.1. Location

Hat Head is located on the north coast of NSW between the village of Crescent Head and the town of South West Rocks, approximately 36 km from the regional centre of Kempsey (Figure 30).

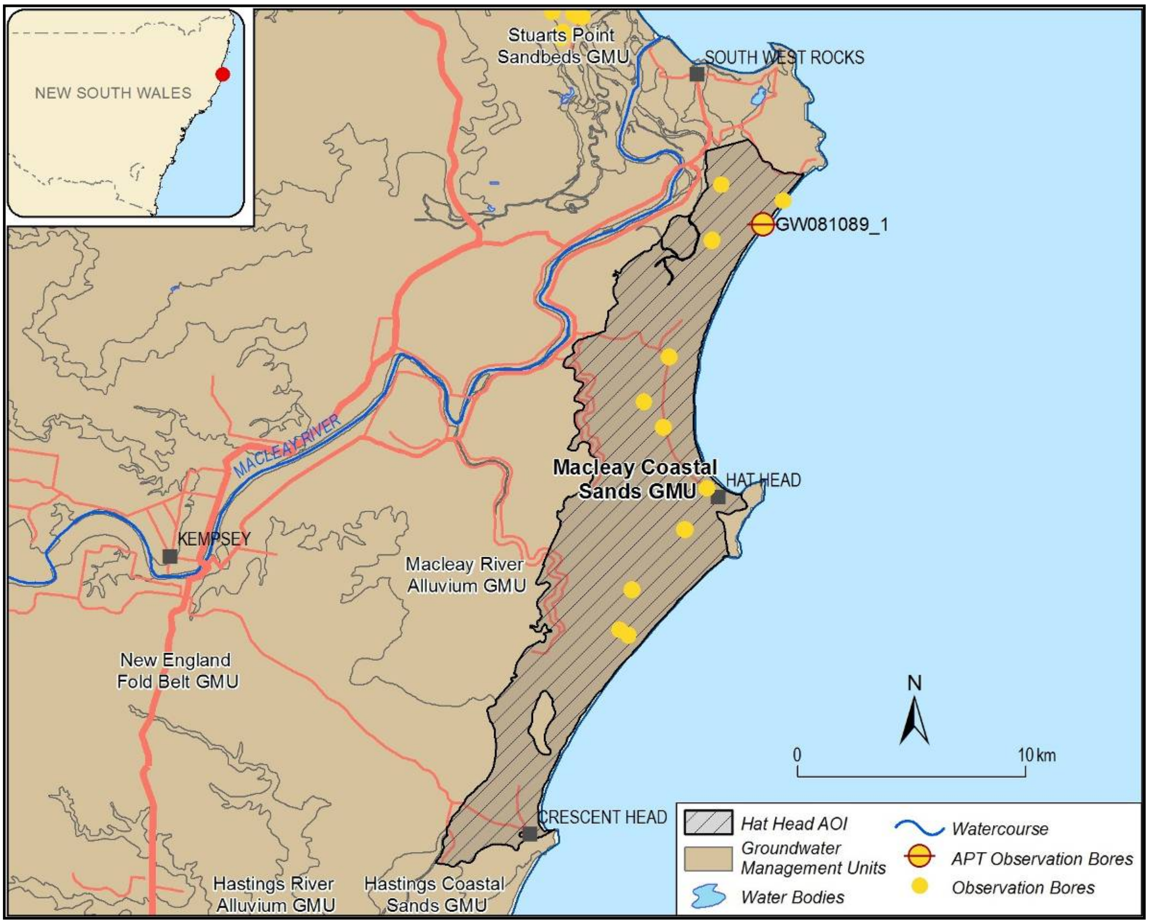

Figure 30 *Location map for Hat Head (NSW) displaying observation bores.*

3.3.1.3.2. Climate

Hat Heads experiences a temperate climate, with no dry season. The mean annual rainfall for South West Rocks is 1493 mm (BOM 1939-2011, South West Rocks). Rainfall throughout the year is relatively consistent, with approximately 29 % occurring in summer and 20 % occurring in winter. The monthly mean maximum temperatures are 26.5 °C (summer), 19.2 °C (winter) and 23.2 °C (annual) (BOM 1939-2011, South West Rocks).

3.3.1.3.3. Geology and Geomorphology

Hat Head is situated at the headland of a coastal plain. The surface has minor undulations but generally the topography is flat. Along the coast, surface elevation can range from sea level to 50 m AHD, due to dune systems. The plain has been dissected by the Macleay River and its minor tributaries. The Macleay River runs from the southwest to the northeast and discharges approximately 20 km to the north of Hat Head at South West Rocks. The plain is underlain by marine and estuarine deposits of clay and silt, with minor layers of marine sand. There is a thin layer of alluvial (thicker in the vicinity of the Macleay River) and aeolian deposits. The area is also underlain by Permian and Palaeozoic sedimentary rocks that have been subjected to folding, fracturing and low-grade metamorphism. These rocks constitute hills and other topography to the west of the area.

The coastline is characterised by a series of headlands between stretches of long, sandy beaches. The beaches are coupled with sand dunes, forming a narrow strip along the coast. The sand dunes have formed as a result of sea level fluctuations, a transgression and a regression during the late Quaternary. Continuity between the dunes has been interrupted in parts by estuarine and alluvial material that was deposited during the late Pleistocene sea level decline (Woolley, 2011). The dunes are 30 to 45 m deep and overly mostly estuarine clay and silts, and in some areas may overlie weathered Palaeozoic rocks (Woolley, 2011).

3.3.1.3.4. Hydrogeology

In the area, the marine clay basement material contains saline water. It is of low permeability and does not have a high-yielding capacity. It is possible that in some localised areas, this unit could have pockets of higher permeability sediments containing low salinity groundwater, but overall it does not form a suitable aquifer (Woolley, 2011). Coastal sand dune sediments, on the other hand, form excellent aquifers due to their thickness, areal extent and high permeability. A schematic representation of this aquifer can be seen in Figure 31. The hydraulic conductivity of the sediments is affected by the presence of “coffee rock”, which is a sand layer containing humic and ferruginous material, causing it to become slightly to severely cemented. Higher conductivity layers within the aquifer are separated by lower conductivity areas, and there is some degree of disconnection between the layers. Recharge into these sands is via infiltration of rainfall, and discharge occurs into local wetland areas and estuaries. Water is also lost by evapotranspiration. For more detailed information about the hydrogeology of Hat Head, refer to the corresponding APT (Table 28, Appendix 2).

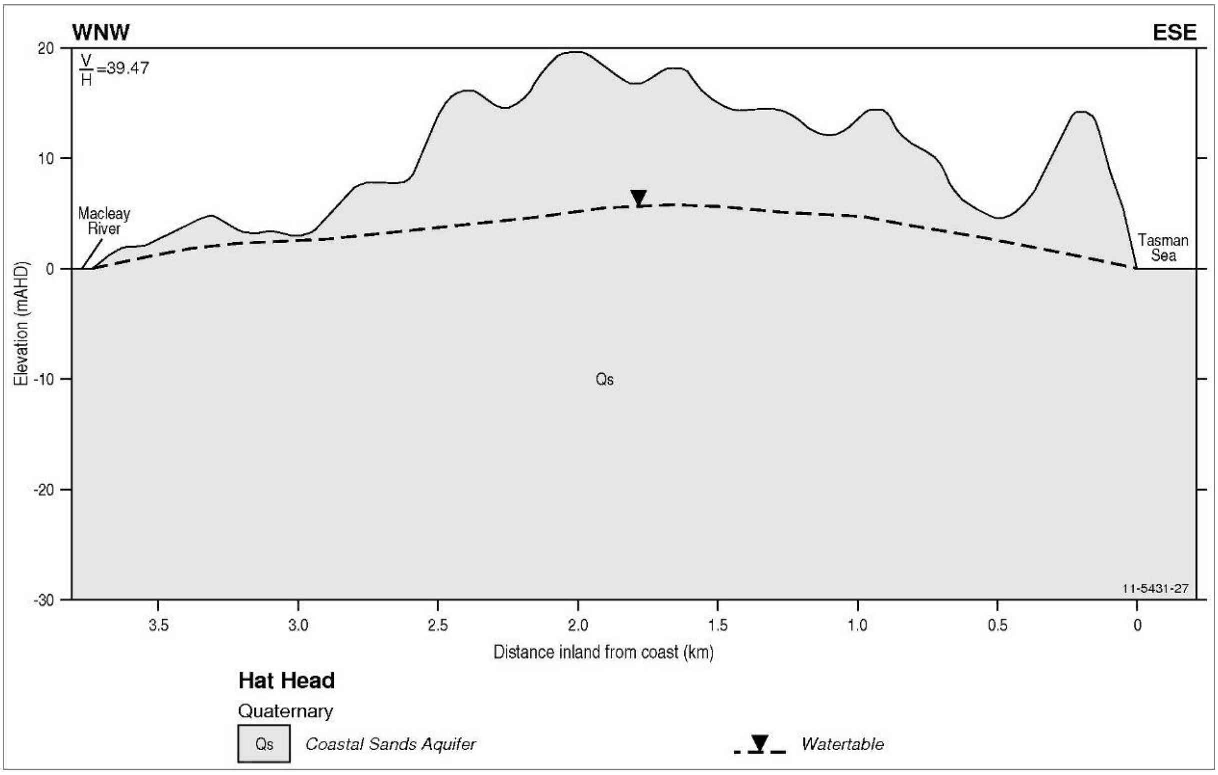

Figure 31 *Cross-section through the Hat Head area, adapted from Fig 4.4 in SKM (2011) (Note that the saltwater interface is not evident in this figure).*

3.3.1.3.5. Land and Water Use

Hat Head is a town of approximately 300 people (Australian Bureau of Statistics, 2007) next to Hat Head National Park, which contains 7220 ha of protected land. The Kempsey Municipal Council uses groundwater from a number of borefields within the national park, and groundwater is also used for urban use. Note that production bore data could not be obtained for use in this project.

3.3.1.3.6. Incidence of SWI

A detailed study into the Hat Head area was provided by (Woolley, 2011), which aimed to improve the management of groundwater in the coastal aquifers that are used to supply water for the mid coast area. The investigation found that, over its period of study, pumping had *"not created a long term decline of water level in any part of the aquifer*". It also found that, while the groundwater is mostly fresh, some of the deep bores have higher salinities and ionic ratios similar to seawater, potentially suggesting a risk of seawater intrusion resulting from high extractions.

3.3.1.4. Stockton, NSW

3.3.1.4.1. Location

Stockton is located immediately northeast of the city of Newcastle on the Newcastle Bight on the NSW coast (Figure 32).

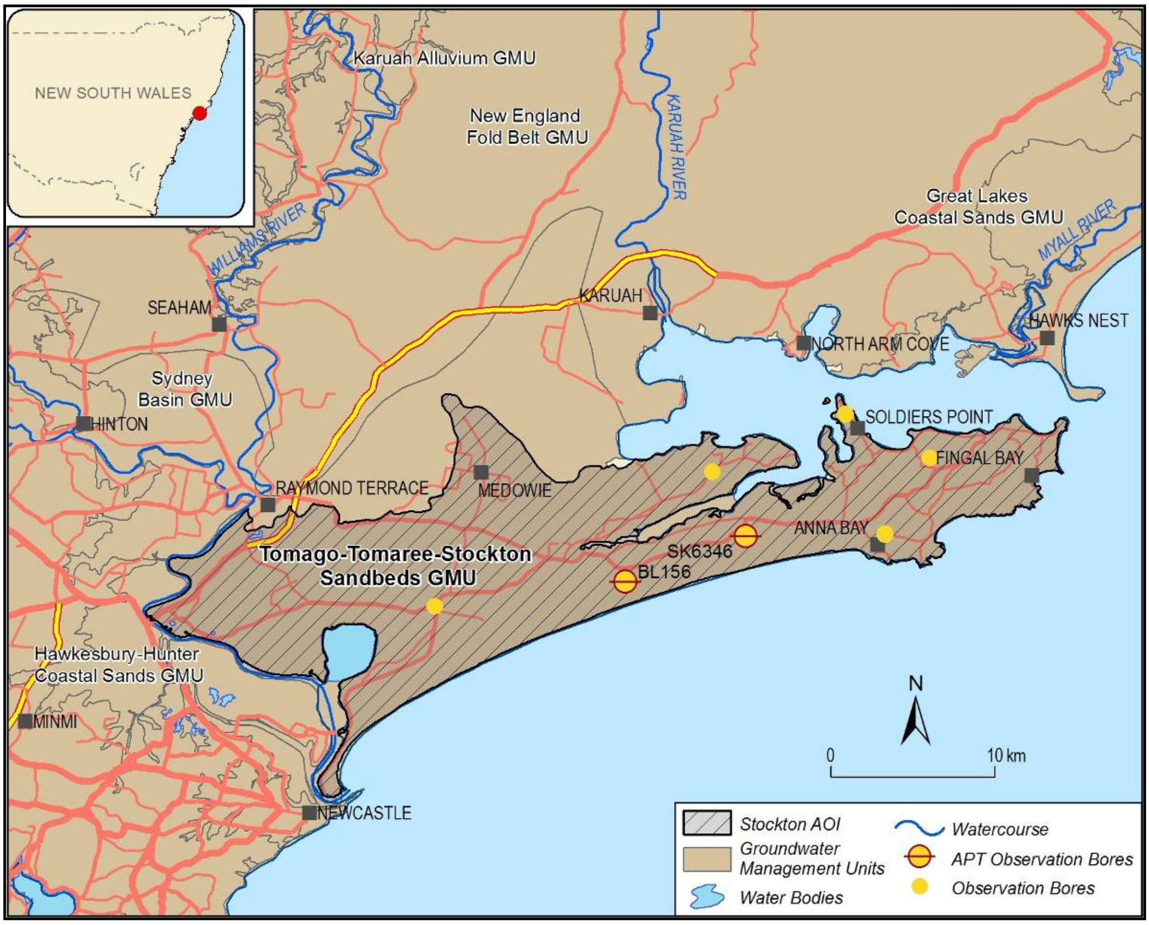

Figure 32 *Location map for Stockton (NSW) displaying the location of observation bores and the GMU extent.*

3.3.1.4.2. Climate

Stockton experiences a temperate climate. The mean annual rainfall for Newcastle is 1134 mm. Rainfall throughout the year is relatively consistent, with approximately 24 % occurring in summer and 25 % occurring in winter. The monthly mean maximum temperature is 25.3 °C for summer, 17.4 °C in winter, and 21.8 °C for the year (BOM 1862-2011, Newcastle). The average annual pan evaporation is approximately 1750 mm (1974-2010; BOM from SKM 2011).

3.3.1.4.3. Geology and Geomorphology

The ground surface in the Stockton area is relatively flat lying except for relatively high dunes along the shoreline, which can reach 40 m AHD. The area is bound by the mouth of the Hunter River in the southwest, Anna Bay in the northeast, the Tasman Sea in the south and Tilligerry Creek in the north (SKM 2011). The area contains three geomorphologically distinct areas. These include a mobile, non-vegetated dune system between 0.5 km and 1.5 km inland; vegetated, stabilised transgressive dunes immediately inland of the mobile dunes with a lower elevation; and also an inter-barrier depression and flood plain, which is low lying and less than 1 m AHD.

The embayment that is the Newcastle Bight forms part of the Sydney Basin with basement rocks of Carboniferous and Permian age. Subsequent to the deposition of the Sydney Basin, there have been two major episodes of deposition. The deposition included the underlying inner barrier sands (known as the Tomago Sandbeds) and the outer barrier sands (known as the North Stockton Sandbeds) during the Pleistocene and the Holocene, respectively. In between these two depositional periods there was an episode of transgression resulting in the deposition of estuarine clays and silts.

3.3.1.4.4. Hydrogeology

The area contains aquifers derived from the North Stockton Sandbeds and the Tomago Sandbeds. These two aquifers are separated by estuarine mud which forms a confining layer in some parts; this is shown as the Tilligerry Mud Member in Figure 33. At the base of these aquifers the Medowie Clay member forms a continuous aquitard and the base slopes away from the coast where it has a height of -20 m AHD, and towards Tilligerry Creek, where the base is at -40 m AHD.

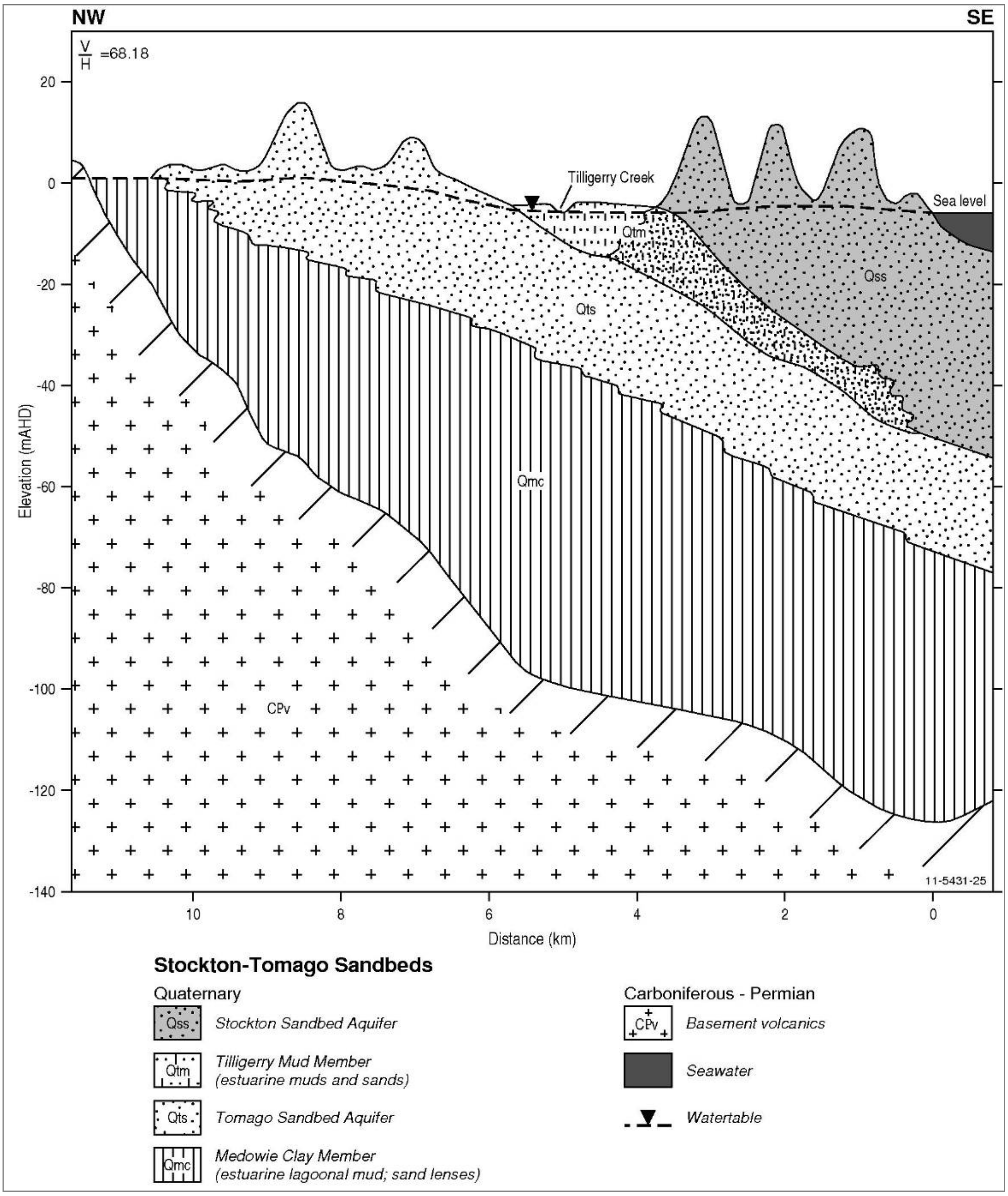

Figure 33 *Cross-section through Stockton-Tomago Sandbeds, adapted from Fig 2.2 in Woolley et al. (1995).*

Groundwater flow is both northwest, towards the estuary and southeast, towards the ocean, as a groundwater divide runs parallel to the coast along the centre of the aquifer. Recharge occurs primarily as infiltration into the dunes directly from rainfall and discharges occur to the ocean and Tilligerry Creek, as well as through evapotranspiration and via groundwater abstractions or engineered drains.

The basement Carboniferous and Permian rocks are relatively impermeable, and thus they do no have the capacity to be good aquifers. The APT for Stockton Sandbeds (Table 29, Appendix 2) contains detailed hydrogeological information for the sandbeds, including a comparison of the aquifer parameters on the ocean and estuarine sides of the aquifer system.

3.3.1.4.5. Land and Water Use

Groundwater is used for stock and domestic activities, sand mine and mineral processing, small scale irrigation and industry. Note that production bore data could not be obtained for use in this project.

3.3.1.4.6. Incidence of SWI

Saline water has migrated southward in the aquifer from the Tilligerry Creek, probably as a result of an extensive drainage network on the southern banks of the estuary; however, there has been no increase in salinity observed at the seaward coastline (SKM, 2011).

3.3.1.5. Stuarts Point, NSW

3.3.1.5.1. Location

Stuarts Point is located on the Mid North Coast in NSW, approximately 45 km northeast of Kempsey near the villages of Fishermans Reach and Grassy Head (Figure 34).

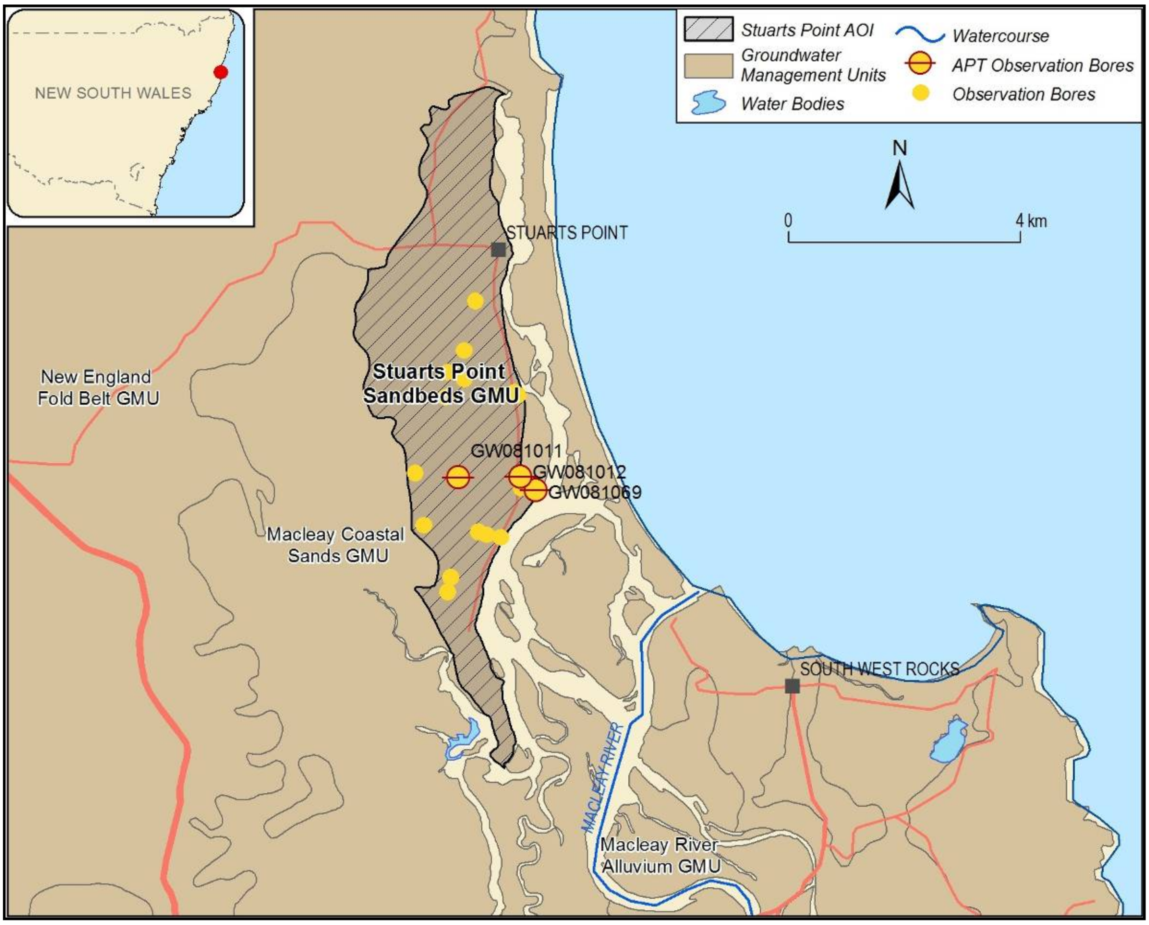

Figure 34 *Location map for Stuarts Point (NSW) displaying observation bores and GMU extent.*

3.3.1.5.2. Climate

Stuarts Point experiences a temperate climate. The mean annual rainfall is 1134 mm. Rainfall throughout the year is relatively consistent, with approximately 24 % occurring in summer and 25 % occurring in winter. The monthly mean maximum temperature is 25.3 °C for summer, 17.4 °C in winter, and 21.8 °C for the year (BOM 1862-2011, Newcastle).

3.3.1.5.3. Geology and Geomorphology

The area surrounding Stuarts Point is a sand plain with a generally flat to gently undulating topography. Its elevation is just 4-5 m above sea level. The geomorphology of Stuarts Point is dominated by the Macleay River, which forks south of Stuarts Point, at South West Rock, where one of its tributaries discharges into the ocean, and another continues to run parallel to the shoreline north of Stuarts Point to Grassy Head. Stuarts Point is underlain by Palaeozoic fractured, folded and/or metamorphosed basement sedimentary rocks. These are overlain by marine estuarine mud and clays, as well as alluvial sediments associated with the Macleay River. The coast contains dual barrier dunes formed during the Quaternary. The inner sand barriers were formed earlier than the outer sand barriers. These sand bodies are essentially uniform, but their thickness varies. The sand sediments often contain a layer within them known as ‘coffee rock’, which comprises humate-cemented, indurated sands, and that may act as a semi-confining, discontinuous, layer.

3.3.1.5.4. Hydrogeology

The aquifers at Stuarts Point comprise mostly sands (Figure 35). They can also contain muds and clays when associated with the Mcleay River or estuarine deposits.

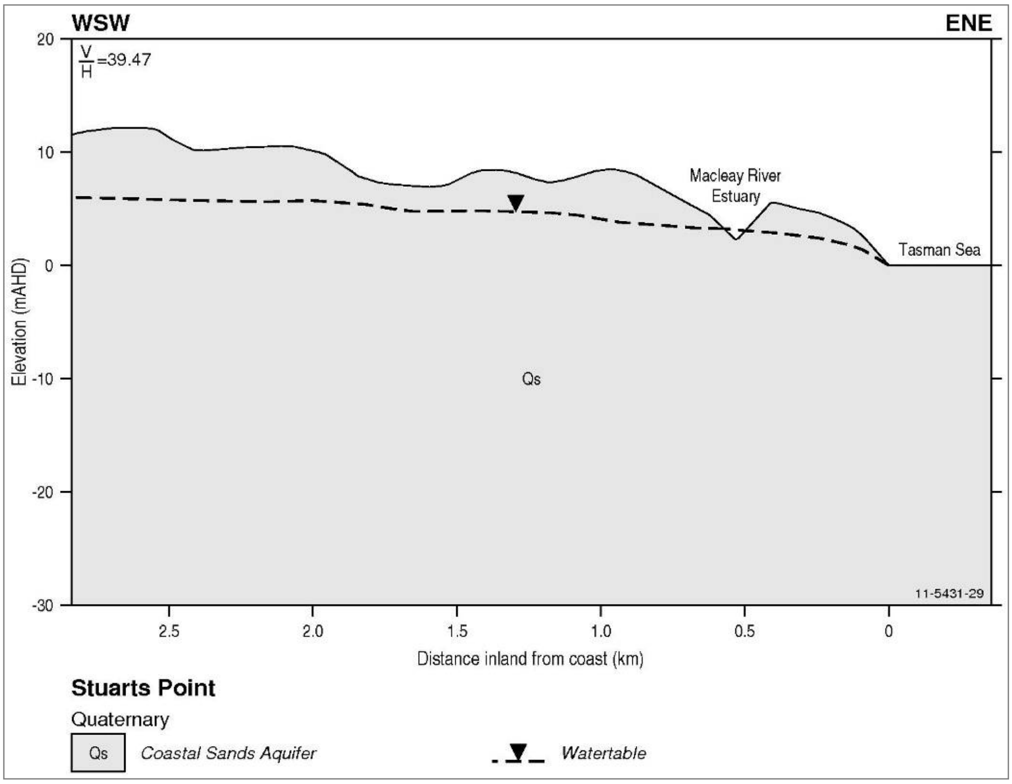

***Figure 35** Cross-section through the Stuarts Point area, adapted from Fig 4.10 in SKM (2011) (Note that the saltwater interface is not evident in this figure).*

Groundwater within the aquifer exists either as a perched aquifer system or within a shallow, unconfined aquifer. The perched aquifers are common, but they are not laterally extensive. In parts they are supported by an almost impermeable coffee rock layer, which is only locally extensive (and has not been represented in Figure 35). This rock layer suppresses, though doesn't entirely inhibit, infiltration of groundwater as it creates a perched aquifer. The coffee rock is located approximately 2-5 m below ground. Below this, a shallow, sandy aquifer exists, which overlies a laterally extensive clay package. The two layers are hydraulically connected and have been included as one unit in this investigation. Beneath the clay layer, there is a deeper aquifer that contains groundwater with elevated arsenic concentrations (Government NSW., 2004). There was insufficient data to characterise the deeper aquifer.

The aquifers receive the majority of their recharge from direct infiltration of rainfall into the sediments. Discharge occurs via subsurface flow to surface water bodies, groundwater abstraction and evapotranspiration. The APT for Stuarts Point (Table 30, Appendix 2) contains detailed information about the hydrogeology.

3.3.1.5.5. Land and Water Use

In the Stuarts Point area, groundwater is used for individual domestic use, town supply as well as for horticulture. The dominant type of horticulture includes avocadoes, potatoes, flowers and stone fruit. There is a Nature

Reserve immediately south of Stuarts Point. Note that production bore data could not be obtained for use in this project.

3.3.1.5.6. Incidence of SWI

A status report by DNR (2006) found there was clear evidence of seawater intrusion at Stuarts Point based on observed salinity increases. However, it was unclear as to whether the salinity increases were due to lower than average rainfall, extraction, or both. Overall, the impact of seawater intrusion to the entire aquifer was considered to be minor. SKM (2011) conducted FEFLOW modelling of the Stuarts Point aquifer along with six other pilot sites in NSW. Using model predictions based on an abstraction rate of 60 ML/day for 100 years, the saline TDS concentrations were reported to potentially reach 1,000 mg/L in less than 20 years across the entire aquifer, a level considered unfit for human and animal consumption, and detrimental to groundwater dependent ecosystems. Sea level rise and changes in the seasonal rainfall pattern were found to have little impact on the salt water intrusion compared to changes induced by groundwater abstraction.

3.3.1.6. Point Nepean, VIC

3.3.1.6.1. Location

Point Nepean is approximately 60 km south-southwest of Melbourne at the end of the Nepean Peninsula, which separates Port Phillip Bay from the Bass Straight, as shown in Figure 36.

3.3.1.6.2. Climate

Point Nepean experiences a temperate climate without a dry season. The mean annual rainfall is 603 mm. Rainfall throughout the year is relatively consistent, with approximately 19 % occurring in summer and 29 % occurring in winter. The monthly mean maximum temperatures are 22.0 °C (summer), 13.4 °C (winter) and 17.8 °C (annually) (BOM 1898-2011, Queenscliff).

3.3.1.6.3. Geology and Geomorphology

The topography in the area is flat and low-lying, with a height approximately at sea level along the coast (Parsons Brinckerhoff, 2010). Point Nepean is highly affected by urban development, due to its location at the southmost extent of Victoria’s capital city, Melbourne. Parsons Brinkerhoff (2010) conducted an extensive reappraisal of groundwater resources in Southeast Melbourne, and the following information was largely derived from this study.

Point Nepean is located on the down-thrown side of the fault block associated with the Selwyn Fault, and is overlain with up to 1000 m of Quaternary and Tertiary sediments. This is in contrast to the Melbourne area, which is located on the up-thrown fault block where the Quaternary and Tertiary sediments are just 90 m thick. The Nepean Peninsula contains dune sands overlying the Quaternary sandy sediments of the Bridgewater and Wannaeue Formations. Underlying these are Upper Tertiary sediments, including the Brighton Group and Fyansford Formation. The Brighton Group comprises marine and non-marine fine to coarse grained sands, clay, silt and sandstone and the Fyansford Formation comprises interbedded clay, silt and sand.

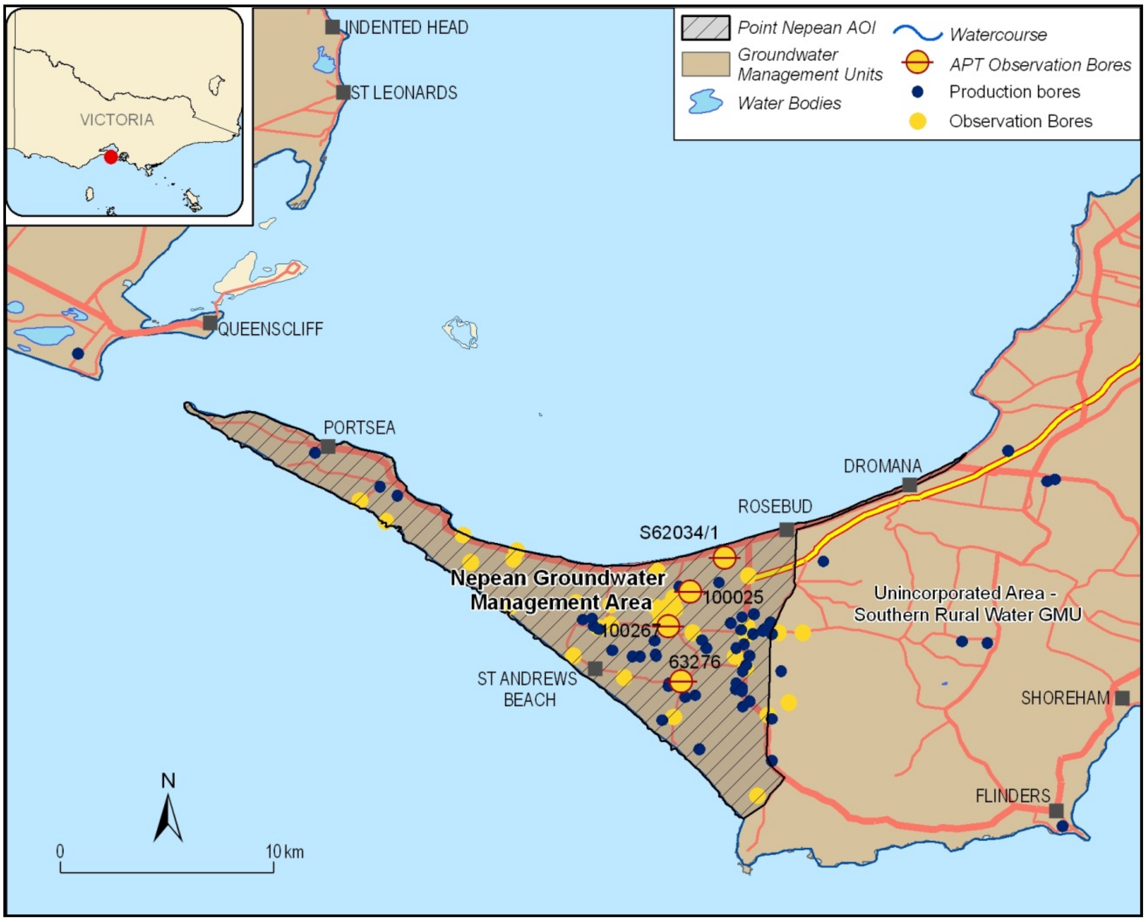

Figure 36 *Location map for Point Nepean (Vic) displaying observation bores, production bores and GMU extent.*

3.3.1.6.4. Hydrogeology

Point Nepean is the site of unconfined Quaternary and Tertiary aquifers. The heterogeneity of the sediments comprising the aquifers means that localised confined or perched aquifers can exist due to the presence of clay, sandy clay or palaeosol. Quaternary sedimentary aquifers dominate along the Nepean Peninsula. These sediments are generally highly permeable. Groundwater flow is toward the west from the Mornington highland area, to Nepean Peninsula. Along Nepean Peninsula, parallel to the shoreline, there is a groundwater divide and groundwater either flows north into the Port Phillip Bay or southward toward the Bass Straight. This has resulted in a freshwater lens within the Quaternary aquifer and a saltwater interface within the Tertiary aquifer (see Figure 37). More detailed information about the hydrogeology of the Quaternary aquifers in Point Nepean is contained within its corresponding APT (Table 31, Appendix 2).

3.3.1.6.5. Land and Water Use

Point Nepean is highly urbanised, especially along the northern coastline. It contains some land dedicated to recreation and a national park. Groundwater is allocated for both stock and domestic use. In the south-western Melbourne area, groundwater is relied upon more heavily during, and following, years of lower than average rainfall. 36 % of all of Southwest Melbourne groundwater licenses are in the Nepean zone, yet this area accounts for 72 % of all of the licensed volume in the area.

3.3.1.6.6. Incidence of SWI

Declining rainfall and increased groundwater bore installations in recent years have coincided with a significant decrease in groundwater levels across the study area. Steady declines in water levels have been documented along the Nepean Peninsula since 1997 and these conditions are expected to continue, leaving Point Nepean at considerable risk to SWI. To date there have been few investigations by which to document the evidence of SWI and monitoring bore data is limited.

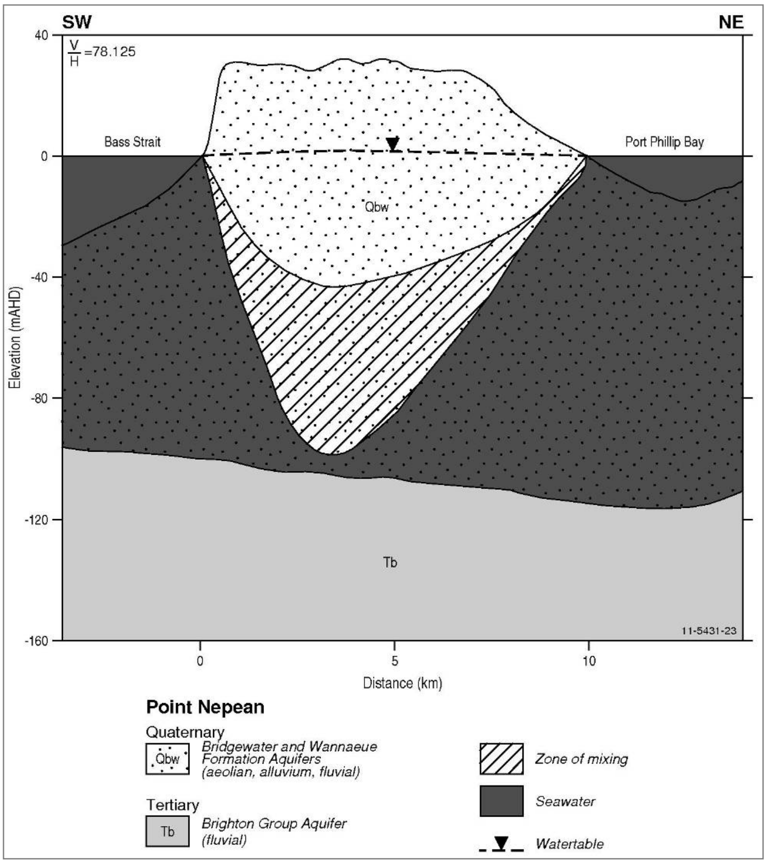

Figure 37 *Cross-section through the Port Nepean area, adapted from Fig. 6 in Parsons Brinckerhoff (2010).*

3.3.2. Coastal Sands, Mediterranean, Temperate Summer Dry

Two case study areas have coastal sands aquifer types with a Köppen-Geiger climate classification of Mediterranean, Temperate Summer Dry. These areas include the Cottesloe Peninsula and Rottnest Island. Both are located within the Perth region, with Cottesloe being a suburb of Perth and Rottnest Island occurring as an island immediately off the coast of Perth. Perth and Cottesloe each are highly urbanised areas and their groundwater is a highly useful resource to the capital city of Perth. Rottnest Island is a popular tourist destination with some residential properties that are reliant on groundwater especially during the summer months.

3.3.2.1. Perth (Cottesloe)

3.3.2.1.1. Location

Cottesloe Peninsula is located north of the Port of Fremantle in Perth, Western Australia where the Swan River reaches the Indian Ocean (Figure 38).

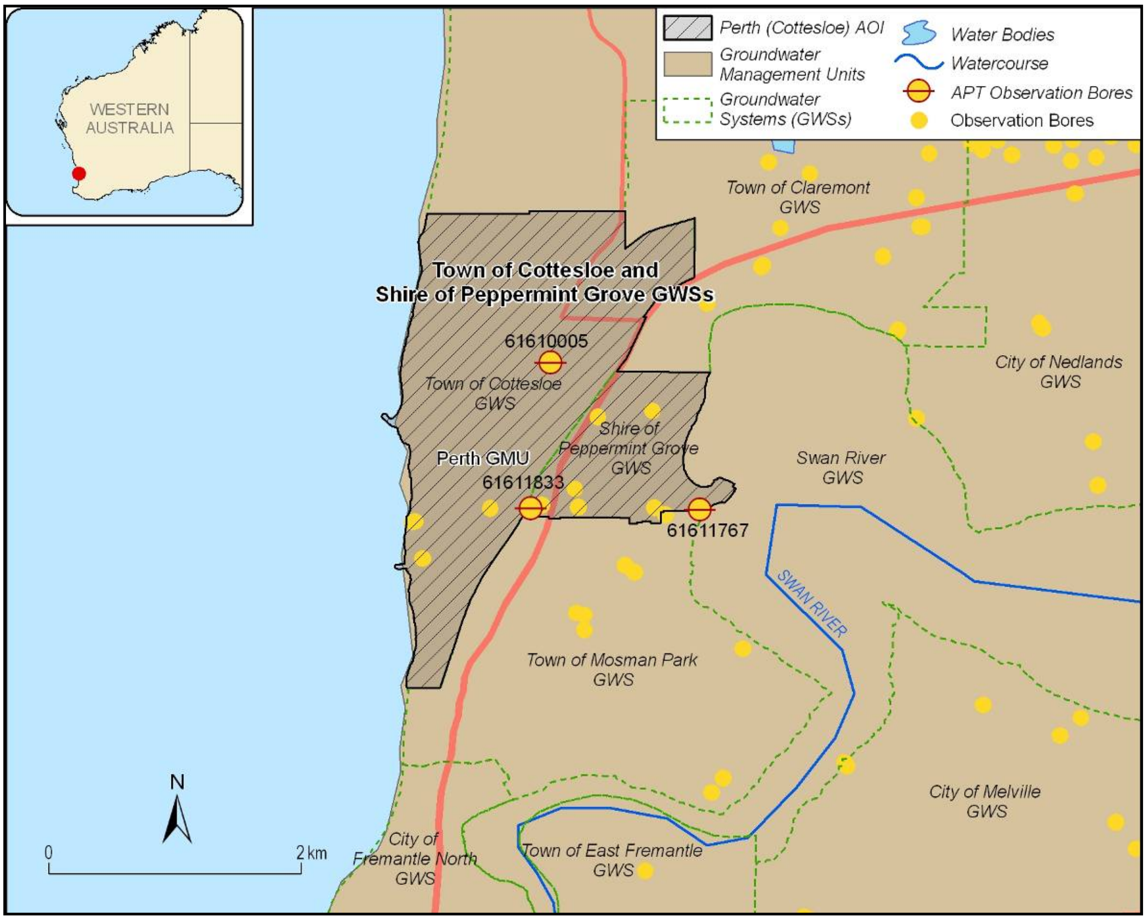

Figure 38 *Location map for Cottesloe Peninsula (WA) displaying observation bores, production bores and GMU extent.*

3.3.2.1.2. Climate

Cottesloe Peninsula experiences a Mediterranean climate with cool, wet winters and hot, dry summers. The average annual rainfall on the Cottesloe Peninsula is approximately 725 mm (BOM 1967-2012, Subiaco Treatment Plant). The mean summer maximum temperature is 29.2 °C in summer and 18.6 °C in winter. Approximately 5 % of the annual rainfall occurs in summer and 55 % falls in winter BOM 1993-2012, Swanbourne).

3.3.2.1.3. Geology and Geomorphology

The Cottesloe Peninsula is underlain by recent aeolian sediments of the Tamala Limestone. The Tamala limestone is sandy and variably lithified, consisting of medium- to coarse-grained sands with shell fragments

(Appleyard, 2004). Appleyard (2004) conducted a preliminary assessment of water resources on Cottesloe Peninsula, and information derived from this assessment forms most of the following summary.

3.3.2.1.4. Hydrogeology

The Tamala limestone is highly permeable, but also heterogeneous, resulting in a variable suite of hydraulic properties. Within the limestone, the dissolution of lime along former root paths and on joint surfaces or bedding planes has created a network of preferential flow paths for the groundwater.

Groundwater on the peninsula pertains to a local, rather than regional flow regime, due to its isolation by the Swan Estuary. A lens of groundwater exists, floating above the saline water that underlies the entire peninsula, as can be seen in Figure 39. The lens has been described as having a maximum thickness of approximately 20 m, thinning towards the coast, with a thickness of less than 5 m in many coastal areas (Appleyard, 2004).

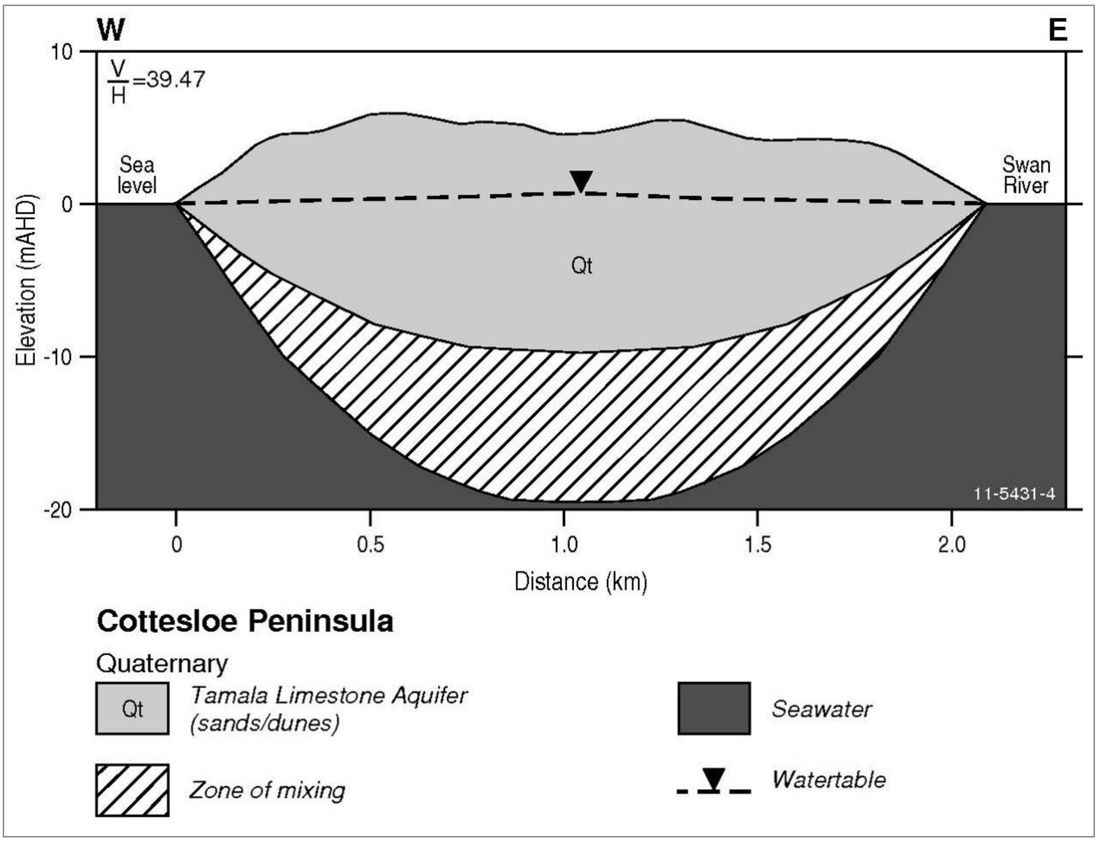

Figure 39 *Cross-section through the Cottesloe area, adapted from Fig 2.1 (Appleyard, 1989).*

Groundwater flows both towards the Swan estuary and towards the coast, and the northern parts of the peninsula receive groundwater from the north and east. The primary recharge mechanism is from local rainfall. Stormwater drainage systems on the surface are maintained to divert runoff into infiltration basins. The aquifer also receives water for recharge from reticulated water via excessive watering of gardens (Appleyard, 2004). Further information pertaining to the hydrogeology of the Cottesloe Peninsula is found within the corresponding APT provided (Table 32, Appendix 2).

3.3.2.1.5. Land and Water Use

The land between the Swan Estuary and the Cottesloe Peninsula coast is urban and includes some of Perth's most valuable real estate. There is a high demand for groundwater resources in this area to maintain gardens, public open spaces, school grounds and sporting grounds (Appleyard, 2004).

3.3.2.1.6. Incidence of SWI

The lens of water is thin near the coast, and the saltwater interface moves inland on a seasonal basis in some areas. Some garden irrigation bores near the coast have been described as becoming saline in the late summer (Appleyard, 2004).

Appleyard (2004) estimated that the amount of water beneath the Cottesloe Peninsula had been reduced by about 40 % due to groundwater abstractions. An increase in salinity was noted by EPA (2005), showing that groundwater salinity had an average value of 1460 mg/L TDS in 2003, which is the highest salinity value recorded since monitoring began in the Peninsula in 1996. The Cottesloe Peninsula has recently become a test case area for managed aquifer recharge using treated wastewater.

3.3.2.2. Rottnest Island, WA

3.3.2.2.1. Location

Rottnest Island is the largest of a chain of limestone islands and reefs on the continental slope, approximately 18 km offshore from Perth. It is approximately 10.5 km long and 4.5 km wide, oriented east to west (Figure 40).

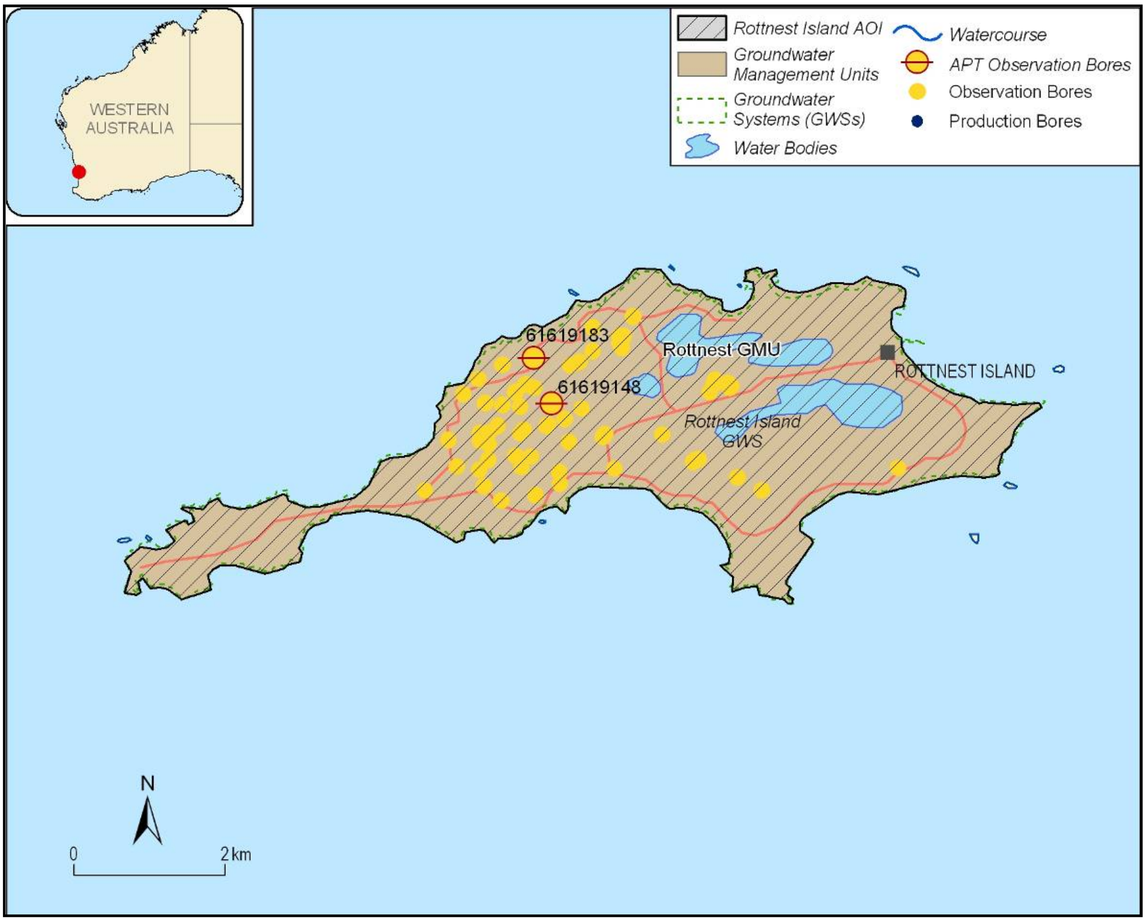

Figure 40 *Location map for Rottnest Island (WA) displaying observation bores and GMU extent.*

3.3.2.2.2. Climate

Rottnest Island has an extreme Mediterranean climate, characterised by wet winters and extremely dry summers. The mean maximum temperature is approximately 26 °C in summer and 18 °C in winter. The average annual rainfall is approximately 580 mm with approximately 5 % of that falling in summer and 55 % in winter (BOM 1983-2011, Rottnest Island).

3.3.2.2.3. Geology and Geomorphology

Information about the geology and geomorphology of Rottnest Island was obtained from Playford and Leech (1977). Rottnest Island is composed of Pleistocene to early Holocene dune limestone with thin intercalations of marine limestone, overlain by middle to late Holocene dune sand, shell beds, beach sand, swamp deposits, and lake deposits. The Tamala Limestone is a Pleistocene unit forming a significant portion of the island's stratigraphy. Tamala Limestone is up to approximately 115 m thick and varies from strong to weakly lithified, with lithification often occurring as a cap rock. It is composed of fragmental shell grains which are coarse to fine, subangular to rounded and poorly to moderately sorted. Another limestone present is known as the Herschell Limestone. This is composed of shell beds and lime sand, and contains clay. These units are overlain by modern dune sands, which are calcareous and in the process of lithification.

The total sedimentary section below Rottnest Island is thought to be approximately 10 000 – 12 000 m thick, composed of Quaternary, Tertiary, Cretaceous, Jurassic, Permian and possibly older units of Palaeozoic age (Playford and Leech, 1977).

The island's topography is undulating, and is characterised by a series of hills and sand dunes. It reaches a maximum elevation of 45.2 m in the centre, with approximately 43 % of the island at 10 m above sea level and 12 % above 20 m. The coastline is characterised by bays with wide, sandy beaches and sand dunes alternated with rocky headlands. Off the coast, there are reefs as well as small islands. In the northeast, the island encloses a belt of salt lakes. There are no significant watercourses on the island.

3.3.2.2.4. Hydrogeology

Groundwater exists within a sedimentary unconfined aquifer in the form of a freshwater lens that overlies brackish and salty water, as shown in Figure 41. The lens reaches 0.5 m above sea level and extends to 8.5 m below sea level (Leech, 1976). Below the freshwater lens, there is a gradation with depth to saltwater known as the zone of mixing.

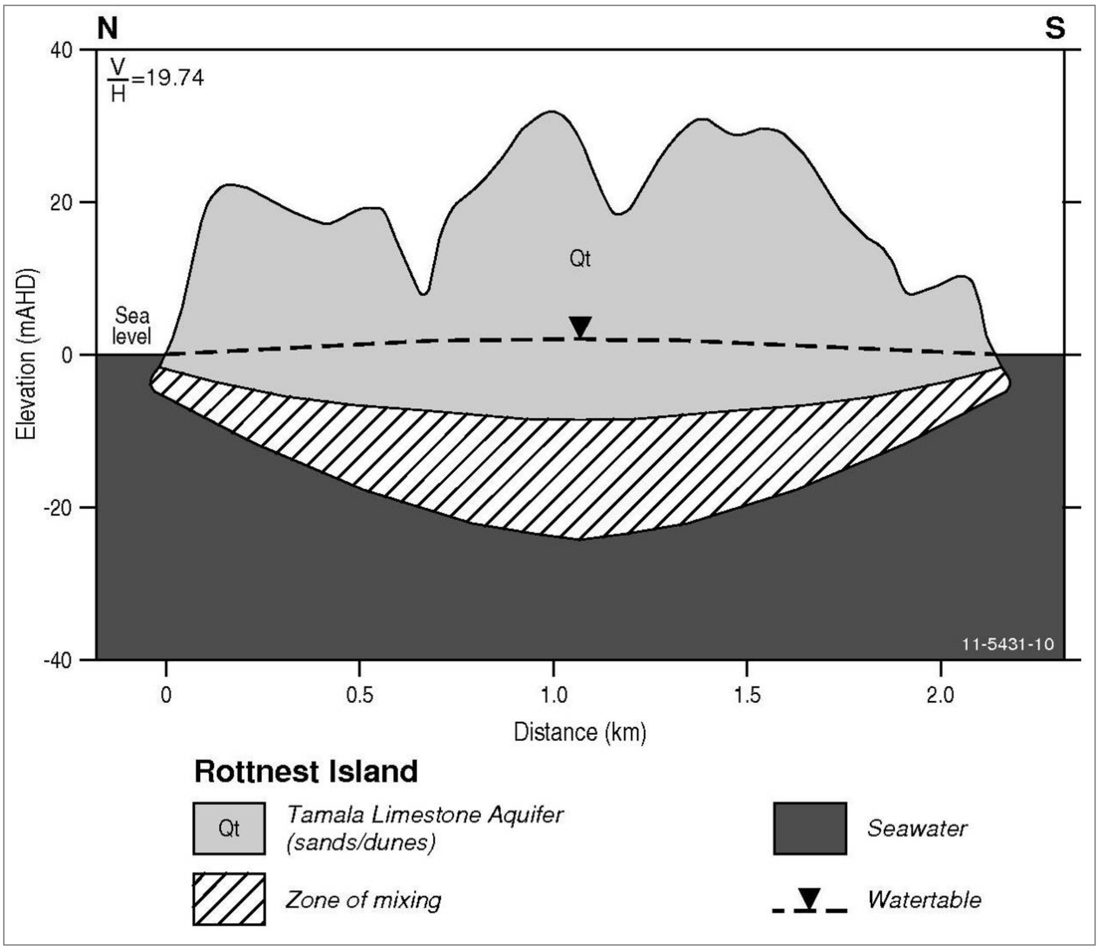

Figure 41 *Cross-section through Rottnest Island, adapted from Fig 30, Playford. and Leech (1977).*

Rottnest Island is an offshore extension of similar sediments to those found in the Swan Coastal Plain that were deposited during periods of low sea level. The island is composed largely of indurated calcareous sands (aeolinite), and like other sand islands has the potential for shallow freshwater lenses and SWI. The predominant rock unit forming an aquifer is the Tamala Limestone, which is also the most widespread unit. The Herschell Limestone is a poor aquifer, because of its proximity to salt lakes and its low elevation. Dune sands are porous but do not form aquifers because they are situated above the watertable.

Recharge to Rottnest Island aquifers occurs through rainfall infiltration into sediments. During summer, the watertable falls due to lack of rainfall recharge. Confined Mesozoic aquifers have been assessed for suitability as a freshwater source for the island (Playford and Leech, 1977), but these aquifers were too saline for domestic use. The APT for Rottnest Island (Table 33, Appendix 2) contains further hydrogeological information.

3.3.2.2.5. Land and Water Use

Surface runoff water is used for domestic consumption and groundwater is used for washing, showering and sanitary purposes within the Thompson Bay settlement. An increase in numbers of summer visitors to Rottnest Island has led to an increased groundwater demand. Note that production bore data could not be obtained for this investigation.

3.3.2.2.6. Incidence of SWI

Groundwater salinity is variable depending on location. Leech (1976) commented that without properly managed withdrawal, seawater intrusion will be induced. In 1995 a desalination plant was established on the island to provide freshwater.

3.3.3. Summary, coastal sands

Eight CSAs were classified as having coastal sands as their principal aquifer type. Six of these had a Köppen-Geiger climate class of Temperate, without a dry season, and two had a Köppen-Geiger climate class of Mediterranean, temperate summer dry.

Coastal sands aquifers comprise dune sands of aeolian and marine origin. These areas are characterised by flat to slightly undulating topographies, due to the accretion of sand dunes. Often, a large portion of the aquifer is below sea level, making it vulnerable to the encroachment of seawater. In coastal sands aquifers, the aquifer often occurs as a saltwater lens, sitting over seawater. This makes the aquifer susceptible to SWI from each side of the lens, as well as via seawater up-coning into the aquifer as a consequence of groundwater extractions.

These aquifers may include a series of dunes, such as seen on North Stradbroke Island, where there have been three distinct dune ages identified; or in Stockton, where two different ages of dunes have formed layered aquifers. ‘Coastal sands’ can be a misleading title for this aquifer type, because each CSA has aquifers that are, in fact, heterogeneous in composition. Sands have combined with silt, peat, organic matter or limestone to form aquifers with varying hydraulic conductivities depending on the composition of the sediment. The Botany Sands aquifer, for example, is stratified with four distinct and varying layers. In Stuarts Point, Hat Head and Stradbroke Island, a layer of the sand has cemented to form what is known as ‘coffee rock’, impeding groundwater flow and supporting perched aquifers. In Stockton a layer of clay provides a leaky hydraulic barrier between two different coastal sands aquifers and in Perth, Cottesloe and Rottnest Island, the dune sands comprise a large portion of carbonate. This means that in parts, dissolution of lime can occur, which creates preferential flow paths for the groundwater/seawater.

The coastal sands aquifers are often associated with other geomorphological coastal features such as rivers, estuaries or swamps. These can provide sources of silt and mud to the aquifer, resulting in lenses of lower transmissivities within the sands and, where present, these finer grained sediments can provide a barrier to inhibit seawater migration.

Overall, there have been relatively few serious incidences of SWI to coastal sands aquifers recorded, particularly in those with a temperate climate (although it must also be noted that there were few observation bore networks in the project data collected by which to monitor the risk and occurrence of SWI). Lack of SWI reporting could be due to the relatively small size of the aquifer storage volume compared to the amount of recharge, which often renders these aquifers unsuitable for large-scale developments. These aquifers are usually confined to narrow strips in coastal areas. They are highly permeable so that, when rainfall is high, recharge is rapid. Constant replenishment of freshwater in temperate climates may be able to flush out salt water. Coastal sands aquifers are, however, under increased pressure as a consequence of increasing groundwater extractions, largely due to population growth within coastal areas.

Due to their high transmissivities, encroaching seawater is able to move quickly into coastal sands aquifers. Point Nepean was identified to be at risk of SWI because groundwater extraction pressures have increased along with urban development in this area. In Botany, an occurrence of seawater intrusion was identified, and then managed by moving extractions further inland. In North Stradbroke Island, as well, it was identified that if extractions were to be maintained in the centre of the island away from the coast, that this would place the least SWI threat on the aquifer. The Mediterranean climate CSAs demonstrate a greater threat of SWI when groundwater recharge volumes diminish. For example in summer, when rainfall is low, SWI may occur (as has been found in Cottesloe Peninsula) on a seasonal basis.

3.4. Sedimentary Basins

The CSAs with aquifers classified as sedimentary basins include Broome, Derby, Perth, Bunbury, Busselton, Albany and Esperance in Western Australia; and Adelaide/LeFevre Peninsula, and Willunga in South Australia.

3.4.1. Sedimentary Basins, Arid

Two arid-climate CSAs characterised as sedimentary basin aquifers were analysed in this report; these are Broome and Derby in Western Australia in the northwest of Australia. These areas belong to the thick, unconfined, sandstone aquifer sub-types. These two areas both withdraw groundwater from aquifers within the Canning Basin. Broome is a popular tourist town and also a region of horticulture that is reliant on groundwater for many of its industries. Derby is 220 km northeast of Broome and the area is largely a hub for beef cattle production. Descriptions of the two areas follow.

3.4.1.1. Broome, WA

3.4.1.1.1. Location

Broome is located in the southwest Kimberly region of Western Australia, approximately 1700 km north-northeast of Perth. The town of Broom sits on the 4 km-wide Broome Peninsula, which lies at the southwest extremity of the Dampier Peninsula (Figure 42). Cable Beach and the Indian Ocean; and Roebuck Bay lie to the immediate west and east of Broome.

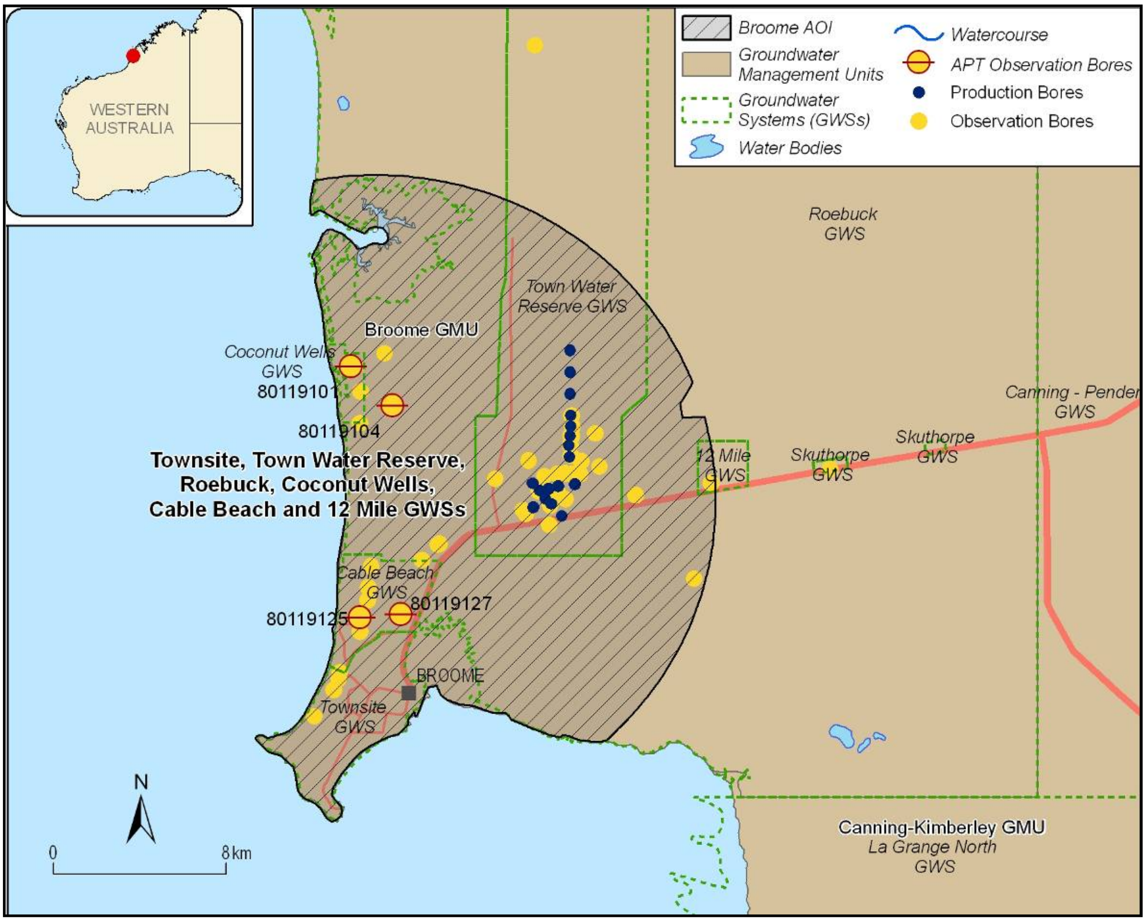

Figure 42 *Location map for Broome (WA) displaying observation bores, production bores and GMU extent.*

3.4.1.1.2. Climate

Broome has a hot tropical climate with a distinct wet and dry season, although it lies within an Arid Köppen-Geiger class because its climate is characterised by an annual evaporation rate that exceeds annual precipitation. The mean annual rainfall is 605 mm, and approximately 75 % of the rainfall occurs from January to March; during August to October rainfall can be as little as 0.7 %. The wet season is not always present, and Broome can receive exceptionally low rainfall; for example, only 131 mm was recorded in 1992 (Groundwater Consulting Services Pty Ltd., 2008). The monthly mean maximum temperatures recorded were approximately 33.3 °C for summer, 29.4 °C for winter and 32.2 °C for the year (BOM 1939-2011, Broome Airport).

3.4.1.1.3. Geology and Geomorphology

In the middle of the Broome Peninsula, the elevation rises to approximately 22 m AHD. The western and south-eastern coastlines comprise aeolian sand dunes, which are approximately 30 m high and 300 m wide. These can reach 1000 m wide at the north of Cable Beach. The land slopes gently towards the southwest with a maximum elevation of approximately 220 m AHD in the northeast. Broome is situated on a sandplain with extensive undulating plains that express little or no surface drainage. Outcrops of Broome Sandstone form extensive platforms and low cliffs.

Broome lies within the Fitzroy Trough, a northwest trending graben occurring on the northern side of the Canning Basin. The Canning Basin is a large intercratonic basin located between the Halls Creek Province and the Pilbara

Block, and contains faulted and folded sedimentary rocks of Phanerozoic age. In the Broome area, the Fitzroy Trough contains Devonian to Carboniferous, Permian, Jurassic and Cretaceous sediments with Precambrian igneous, metamorphic and sedimentary rocks forming the basement unit. The sequence is very thick and includes mostly, sandstone, shales and siltstones with some conglomerate and coal beds. The sediments were deposited during basin subsidence and during a series of marine transgressions and regressions within the basin (Laws, 1984).

3.4.1.1.4. Hydrogeology

The Broome Sandstone forms a major unconfined aquifer in the area. A schematic cross-section through the Broome area can be seen in Figure 43. The Broome Sandstone is mostly composed of sandstone, with minor beds of grey siltstone and claystone. The grain sizes range from very fine to very coarse and there are minor, thin pebble conglomerate bands. It thins eastwards from potentially 280 m thick near the coast to a zero thickness east of Mt Jowlaenga (Laws, 1984). There has been little hydraulic testing carried out on the Broome Sandstone to determine its hydraulic parameters. General groundwater flow is from the northeast, where the watertable is highest, to the south, southwest and west.

The Jarlemai Siltstone acts as an aquiclude beneath the Broome Sandstone, separating it from underlying units. It comprises mostly siltstone and claystone sediments with minor sandstone and sandy siltstone. The Jarlemai siltstone is underlain by two deeper sandstone aquifers, although there has been little groundwater development of either (Laws, 1984). This unit is extensively and unconformably overlain by the Broome Sandstone.

Quaternary and Tertiary superficial deposits form an unconfined aquifer in the area. These sediments include sands, silts, clays and minor gravel. In the north of Broome, Quaternary aeolian sands contain significant perched groundwater resources and to the southwest, the coastal dunes contain groundwater in hydraulic continuity with the Broome Sandstone. More detailed information about its hydrogeology is contained in the APT (Table 34 in Appendix 2).

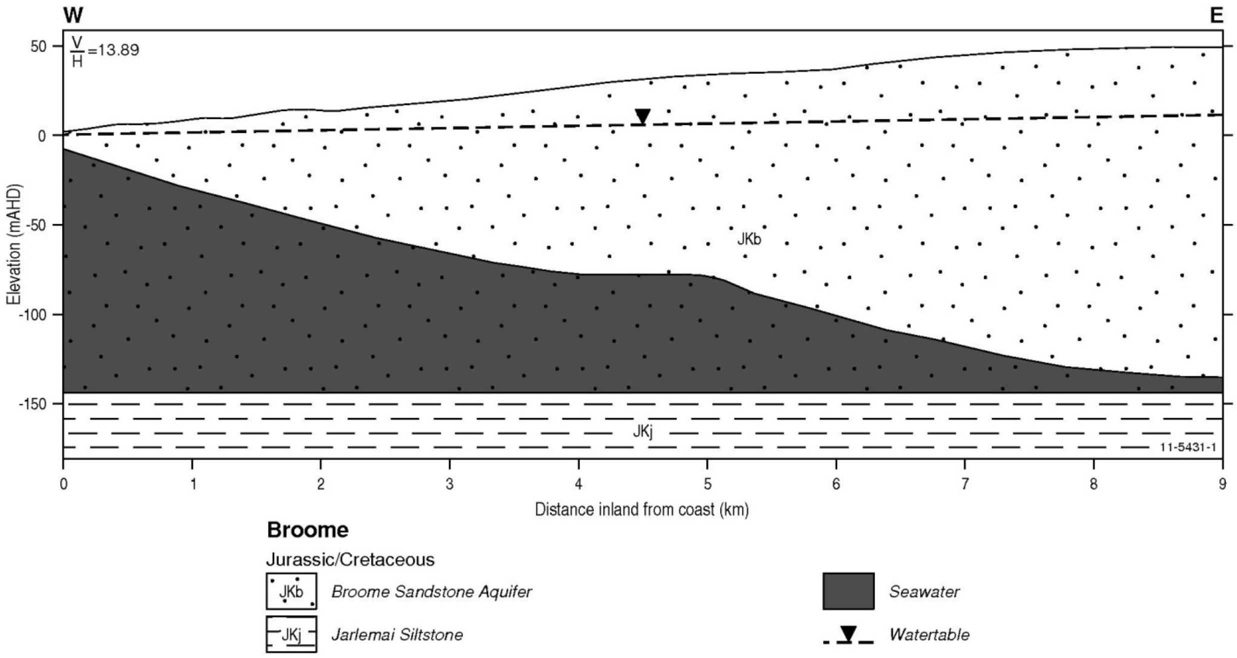

Figure 43 *Cross-section through the Broome area, adapted from Fig 9 of Laws (1991).*

3.4.1.1.5. Land and Water Use

Broome is reliant on groundwater for its potable water supply. Groundwater is also used for horticulture, watering of parks and gardens, domestic and industrial purposes. Most of the groundwater development is near the coast.Incidence of SWI

3.4.1.1.6. Incidence of SWI

SWI has been documented in the unconfined Jurassic-Cretaceous Broome sandstone aquifer, as well as in the confined Jurassic Alexander Formation and Wallal Sandstone aquifer that lie below the Jarlemai Siltstone (Water Authority of Western Australia, 1994). Limited groundwater elevation and salinity data are available and no published reports have specifically addressed SWI.

3.4.1.2. Derby, WA

3.4.1.2.1. Location

Derby is situated on eastern side of King Sound within a peninsula in the southwest Kimberly region of Western Australia (Figure 44), approximately 220 km northeast of Broome.

3.4.1.2.2. Climate

Derby has an arid climate with a distinct wet and dry season. The mean annual rainfall is 683 mm, and approximately 78 % of the rainfall occurs from January to March; August to October can receive as little as 0.7 %. The monthly mean maximum temperature is 35.5 °C for summer, 31.2 °C in winter and 34.5 °C for the year (BOM 1972-2011, Derby Aero). The humidity in Derby is high, with frequent thunderstorms. Evaporation rates are high, and an annual evaporation rate of 3352 mm was recorded from 1972-1981 (Groundwater Consulting Services Pty Ltd, 2008).

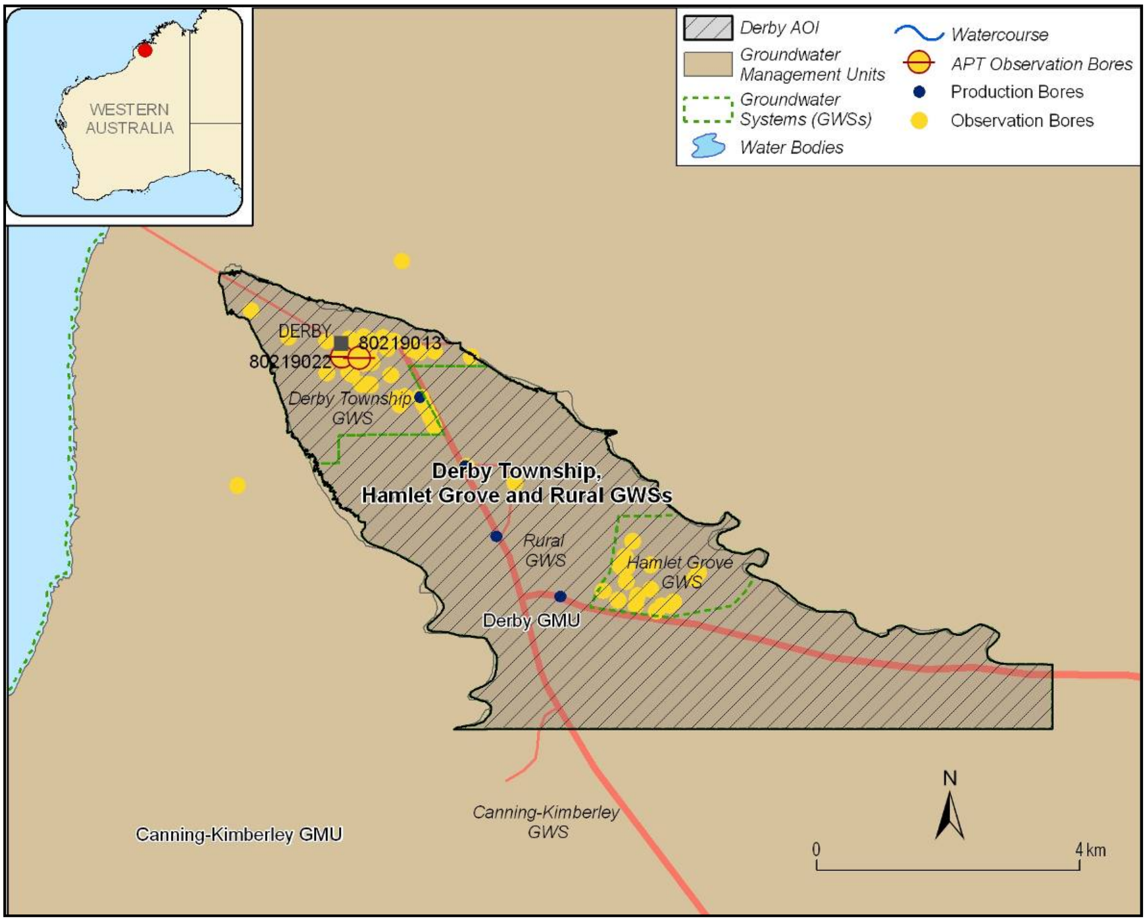

Figure 44 *Location map for Derby (WA) displaying observation bores, production bores and GMU extent.*

3.4.1.2.3. Geology and Geomorphology

The peninsula, on which Derby is located, is approximately 2 km wide and flanked by mudflats. The centre of the peninsula has a maximum elevation of 22 m. The area is strongly tidal and high tides can reach up to 12 m.

Derby is located in the northern part of the Canning Basin, which is a large intracratonic basin between the halls Creek Province and the Pilbara Block. The basin contains sedimentary rocks that are approximately 3000 m thick to the northeast of Derby, and which thicken to a depth of approximately 8000 m below Derby. The basin continues to thicken towards the south. The sedimentary package beneath Derby ranges from Ordovician to Quaternary in age. It varies in lithology and includes units of very fine grained siltstones; mudstones and shales to coarse sands; conglomerates; as well as limestone (Laws and Smith, 1988).

3.4.1.2.4. Hydrogeology

In Derby, there are two major aquifer systems that are utilised for groundwater, the Wallal aquifer and the underlying Lower Erskine aquifer (Figure 45). The Wallal aquifer is unconfined and is hydraulically connected to the Upper Erskine aquifer, which contains relatively poor quality groundwater. The Wallal aquifer comprises two units, the Meda Formation as well as the Wallal Sandstone. It contains extreme lithological variation and therefore variable aquifer transmissivity values (ranging from 90-630 m^2/day). It contains water that is low in salinity (< 200 mg/L) although it can be high in magnesium or iron. Recharge into the aquifer is through direct rainfall infiltration, and water from the aquifer is thought to discharge beneath mudflats near Derby (Groundwater Consulting Services Pty Ltd, 2008).

Between the Wallal aquifer and the Erskine Sandstone, the Munkayarra Shale acts as an aquitard, except for where it has been eroded from an anticline beneath the Derby peninsula. The two aquifers are therefore in hydraulic connection beneath Derby and the contact between the Wallal aquifer and Upper Erskine can be difficult to determine. Recharge occurs mostly from downward leakage from overlying aquifers and discharge occurs into the May River or directly into King Sound (Groundwater Consulting Services Pty Ltd, 2008). More information about the hydrogeology of Derby is contained in its corresponding APT (Table 35, Appendix 2).

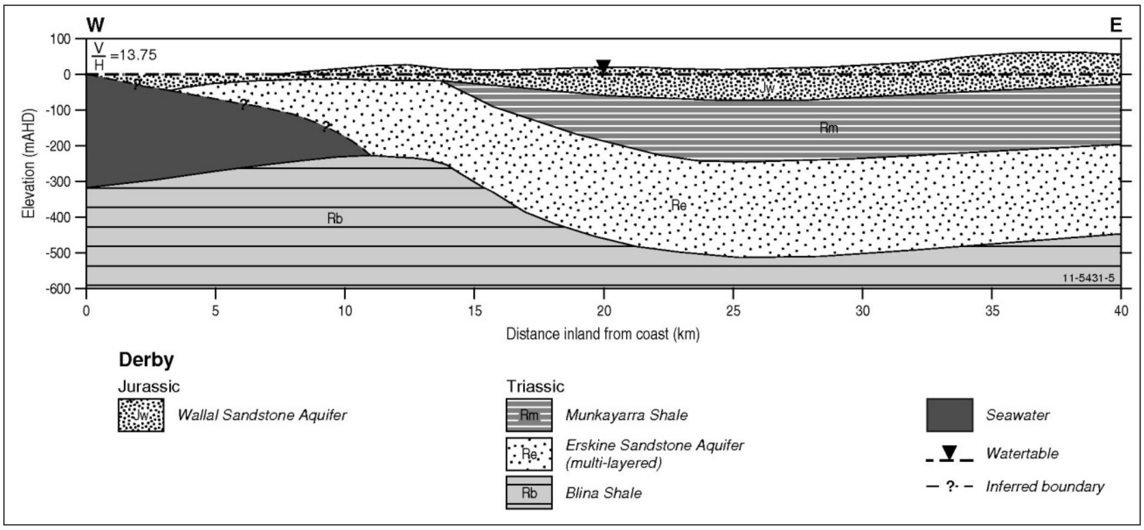

Figure 45 *Cross-section through the Derby area, adapted from Fig 6 of Laws and Smith (1988).*

3.4.1.2.5. Land and Water Use

The dominant land use is beef cattle production on large pastoral leases. There is horticultural and other varied agriculture near Derby, which is an urban centre of approximately 3000 people (Statistics, 2007). Derby is reliant on groundwater as a water supply (Groundwater Consulting Services Pty Ltd, 2008). Seventy-five percent of groundwater extracted from within the Wallal aquifer is used for domestic private use and the remainder is used for gardens and stock. Water extracted from the Lower Erskine aquifer is used for town water supply only.

3.4.1.2.6. Incidence of SWI

SWI exists within the Wallal and Erskine System aquifers, along the edges of the peninsula. The shape of the interface, however, is complicated and salinity varies with depth and with the presence of shale layers. The interface is in direct contact with seawater in the upper, unconfined aquifers when inundation occurs onto mudflats flanking the peninsula and during this time seawater intrusion can occur also temporarily (Groundwater Consulting Services Pty Ltd. 2008a).

3.4.2. Sedimentary Basin, Mediterranean, Temperate Summer Dry

Eight CSAs were contained multi-layered aquifers within a sedimentary basin, and all of these areas have been classified as having a Mediterranean, temperate summer dry type of climate. The CSAs within the deep, mostly consolidated sediments sub-type include: Adelaide Metropolitan, the adjacent LeFevre Peninsula and Willunga in

South Australia; and Perth, Busselton and Bunbury in Western Australia. Those CSAs belonging to the shallow, unconsolidated sub-type included Albany and Esperance in Western Australia.

3.4.2.1. Adelaide Metropolitan, SA

3.4.2.1.1. Location

Adelaide, the capital city of South Australia, is located north of the Fleurieu Peninsula between the Gulf St. Vincent and the Mount Lofty Ranges on Australia's southern coast (Figure 46).

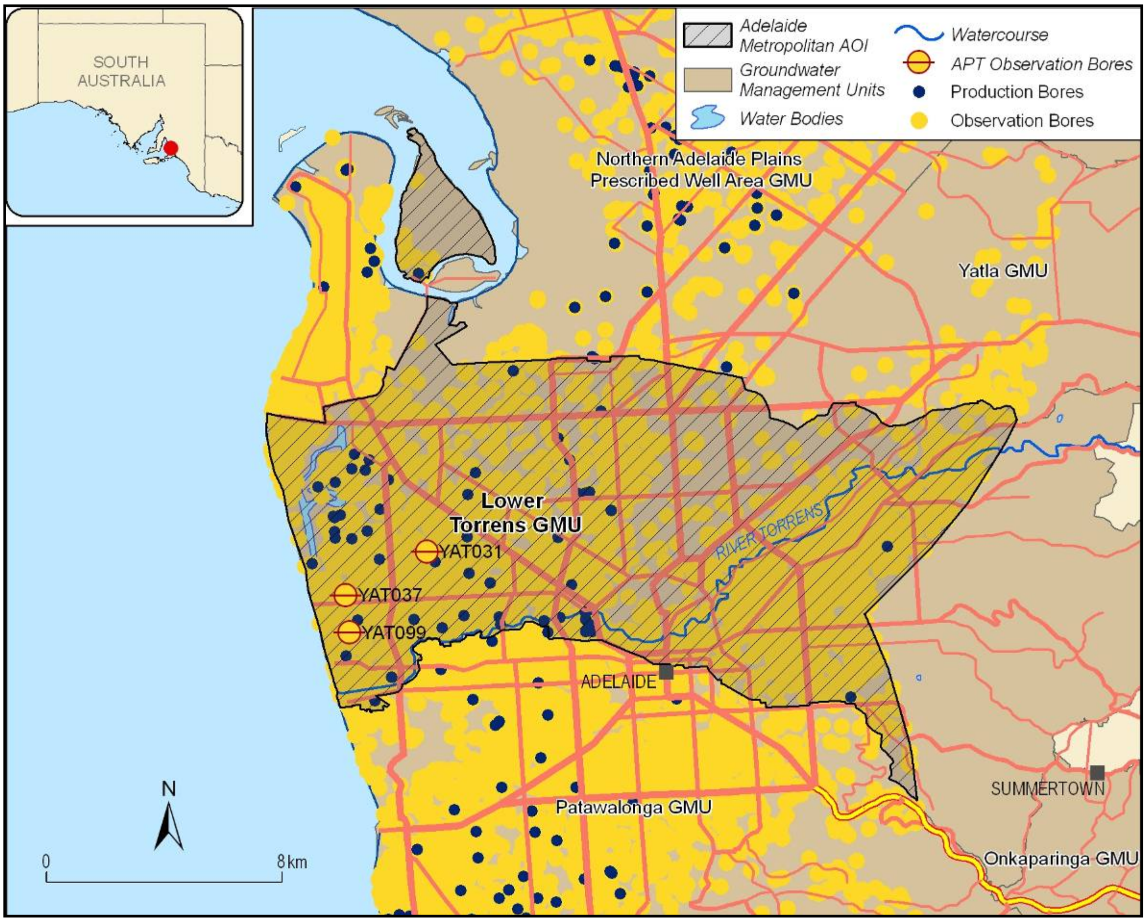

Figure 46 *Location map for Adelaide metropolitan (SA) showing the locations of production bores, observation bores and the PWA extent.*

3.4.2.1.2. Climate

The Adelaide region experiences a Mediterranean-type climate with hot dry summers and cool, wet winters. The mean annual rainfall for Adelaide is 542 mm with approximately 13 % occurring in summer and 38 % occurring in winter. The mean maximum temperature is 28.5 °C for summer, 16 °C in winter and 22.3 °C for the year (BOM 1977-2011, Kent Town).

3.4.2.1.3. Geology and Geomorphology

The Adelaide coastal plain is bounded to the east and to the southeast by the Adelaide Hills, which consist of Proterozoic metasediments; and to the west by the Gulf St. Vincent. The oldest rocks in the area are the Precambrian crystalline 'Barossa Complex', composed of schist and micaceous gneiss. These are unconformably overlain by a Precambrian cover forming what is known as the 'Adelaide Geosyncline'. These rocks include tillites, quartzites, feldspathic quartzites, dolomites, phyllites, slates and siltstones. During the Tertiary, faulting occurred, which provides the half-graben geology of the region today (Lamontagne et al., 2005).

Sedimentation was initiated by further subsidence, and followed by marine transgression. This has allowed for the deposition of Tertiary and Quaternary sediments up to 600 m in thickness. These sediments have not been strongly deformed, but often dip towards the southwest. The Tertiary and Quaternary sediments are described below.

3.4.2.1.4. Hydrogeology

The hydrological setting of the Adelaide Coastal Plains is complex. A cross-section through the Adelaide Metropolitan area is shown in Figure 47. The Quaternary and Tertiary sediments within the Adelaide Geosyncline are up to 600 m thick, containing up to 10 semi-confined to confined aquifer systems. These sediments overlie a Precambrian fractured rock aquifer. Prior to development on the Adelaide coastal plain, the Quaternary and Tertiary aquifers were artesian.

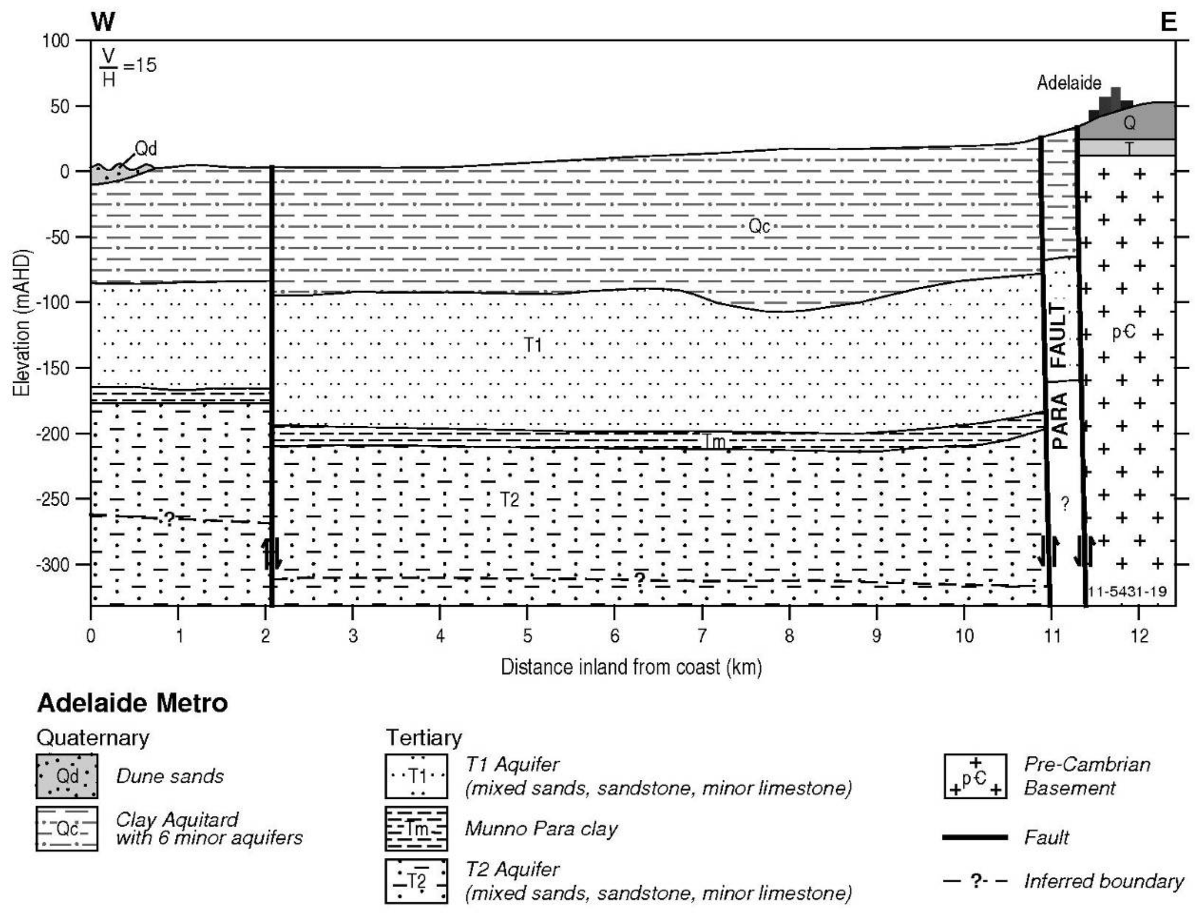

Figure 47 *Cross-section through the Adelaide area, adapted from Fig.1 in Gerges (1996) (Note that the saltwater interface is not evident in this figure).*

The Quaternary sediments are comprised of fluvio-lacustrine clays with inter-bedded minor sands and gravel. The majority of Quaternary aquifers (Q1-Q6) tend to be insignificant due to their low yields and high salinity, although there are localised areas where the more shallow aquifers provide good quality water. These aquifer units vary greatly in thickness (from 1-18 m), lithology and hydraulic conductivity (Lamontagne et al., 2005). The main groundwater resources in the Adelaide Plains are contained in four, confined Tertiary aquifers (T1-T4). The Tertiary sands, sandstones and limestone form the aquifer units, while clay, chert and marl form leaky confining beds. The uppermost two Tertiary aquifers are the most productive and hold good quality groundwater.

Recharge to the Tertiary aquifers primarily occurs through outcrops on the western slopes of the Mount Lofty Ranges and along the Eden Burnside Fault (Gerges, 1996). More detailed information about each of Adelaide's aquifers is contained in its corresponding APT (Table 36, Appendix 2).

3.4.2.1.5. Land and Water Use

Adelaide is the capital city of South Australia and is highly urbanised. Land use is mostly divided between urban and residential, industrial, recreational and parks. The city is flanked on its western coast by sandy beaches and a port, and by hills on its eastern side. The uppermost two Tertiary aquifers are the most productive and hold good quality groundwater which is used by industry and for irrigating recreational areas such as parks and golf courses. Groundwater resources stored within the uppermost Tertiary aquifer have occasionally been used to supplement the Adelaide metropolitan water supply. The T1 and T2 aquifers exhibit cones of depression due to heavy use, with groundwater elevations at the centre of the depression below sea level. These aquifers are also used for managed aquifer recharge using storm water (Gerges, 2000).

3.4.2.1.6. Incidence of SWI

Lamontagne et al. (2005) assessed the volumes of water being discharged to coastal waters between Port Gawler to Sellicks Beach in the Gulf St Vincent. They suggested that intrusions of seawater may be more widespread than previously thought along the length of the Adelaide coastline. Unfortunately, a poor monitoring network makes the potentiometric surface somewhat uncertain.

3.4.2.2. LeFevre Peninsula, SA

3.4.2.2.1. Location

The LeFevre Peninsula (Figure 47) is located within the northwestern quadrant of the Adelaide metropolitan area, and encompasses the suburbs of Semaphore and Port Adelaide. It includes the beaches from North Haven to Semaphore South and is situated adjacent the Port River. Most information that follows is taken from Russell (1996).

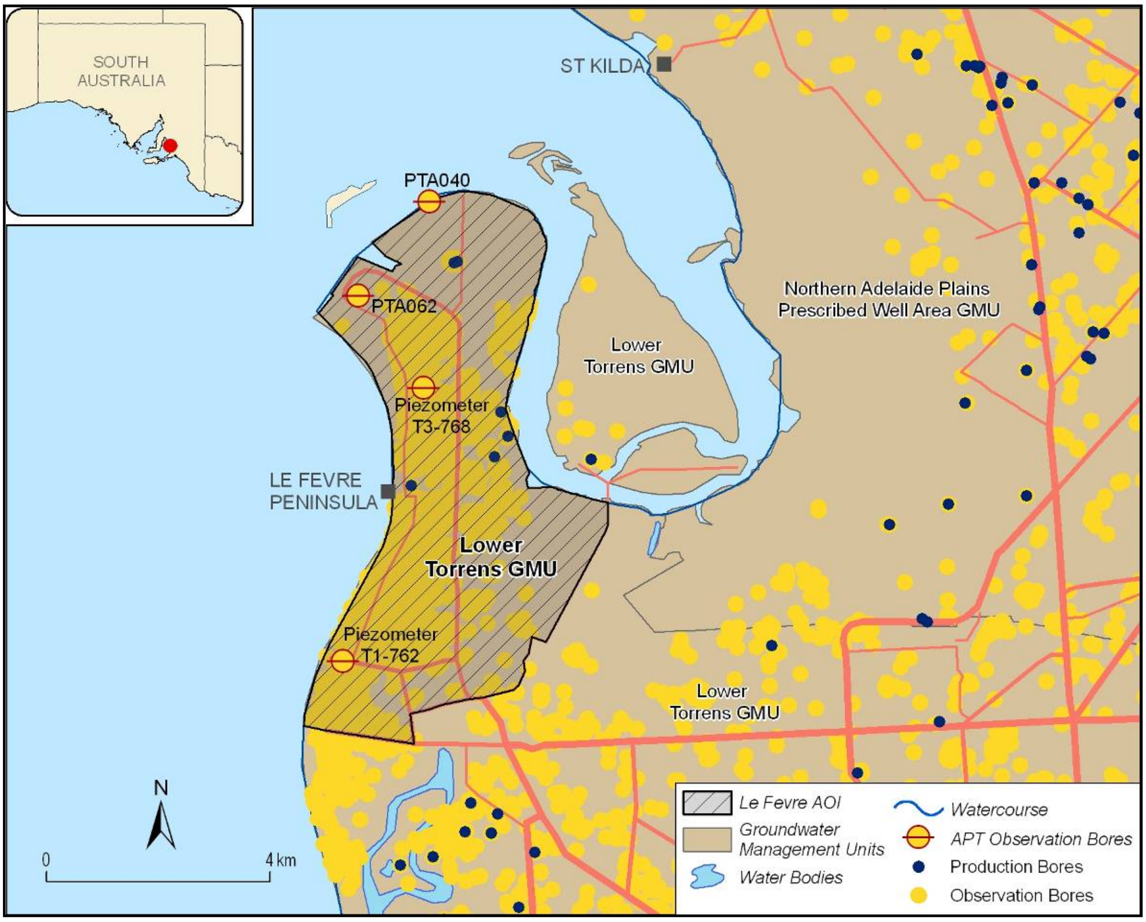

Figure 48 *Location map of LeFevre Peninsula (SA) displaying observation bores, production bores and PWA extent.*

3.4.2.2.2. Climate

The LeFevre Peninsula experiences a Mediterranean-type climate with extended hot dry summers and cool to mild, wet winters. The mean annual rainfall is 446 mm; approximately approximately 13 % of the rainfall falls in summer, and winter receives approximately 37 %. The monthly mean maximum temperature is 27.3 °C for summer, 15.6 °C in winter and 21.5 °C for the year (BOM 1955-2011, Adelaide Airport). Mean annual Class A Pan evaporation is 1720 mm per year.

3.4.2.2.3. Geology and Geomorphology

The peninsula covers an area of 18.7 km^2 and was formed during the Holocene from multiple shore-parallel beach ridges. Quaternary Holocene sediments, consisting principally of the Semaphore Sands, form aeolian dunes up to 12 m high on the western reaches of the peninsula. Estuarine muds and silts of the St. Kilda Formation then are confined along the Port Adelaide estuary margin (Russell, 1996). Underlying the Quaternary sediments are thick sequences of Tertiary sediments which overlie the PreCambrain sediments and basement rock that collectively form the Adelaide Geosyncline (see also the geology and geomorphology descriptions for the Adelaide Metropolitan area in the section above).

3.4.2.2.4. Hydrogeology

In the LeFevre Peninsula the uppermost Q1 aquifer is overlain by dune sands, known as the St. Kilda Formation (including the Semaphore Sands unit), which store good quality water due to local, direct recharge from rainfall (refer to dune sands in Figure 47). Q1 sediments are underlain by the hydraulically connected Q2 aquifer, which has a salinity of up to 21 000 mg/L. The Hindmarsh Clay underlies the unconsolidated Quaternary sediments and is highly impermeable. It forms an aquitard, interbedded with minor aquifers that are highly saline. Thick sequences of Tertiary sediments underlie the Quaternary sediments. The main groundwater resources in the Adelaide Plains are contained in four, confined Tertiary aquifers (T1-T4). The Tertiary sands, sandstones and limestone form the aquifer units, while clay, chert and marl form leaky confining beds. The uppermost two Tertiary aquifers are the most productive and hold good quality groundwater.

For more detailed hydrogeological information about LeFevre Peninsula, refer to its corresponding APT (Table 37, Appendix 2).

3.4.2.2.5. Land and Water Use

LeFevre Peninsula is heavily urbanised with residential and industrial developments. Reclamation of land has occurred along the Port Adelaide River, and mangroves are found along the estuary. Groundwater in the LeFevre Peninsula is increasingly being used by industry, exploiting the Tertiary aquifers as a water source. The groundwater in the Q1 aquifer is used extensively for watering domestic gardens and recreational parks.

3.4.2.2.6. Incidence of SWI

The risk of SWI, based on salinity and groundwater level data, was identified by Gerges (1996). Groundwater resources on the peninsula are at risk of saline water intrusion because of increased abstractions from bores (Russell, 1996); but an actual SWI occurrence has not been reported. Over-pumping of the Q1 aquifer has the potential to cause up-coning from the underlying salty aquifer. Heavy pumping from the underlying Tertiary aquifers in the area has led to an expanding cone of depression that has induced downward leakage and the lowering of the watertable in the Q1 aquifer.

3.4.2.3. Willunga, SA

3.4.2.3.1. Location

The Willunga Basin is located in South Australia, approximately 40 km south of Adelaide as shown in Figure 49.

3.4.2.3.2. Climate

Willunga experiences a Mediterranean-type climate with hot dry summers and cool, wet winters. The mean annual rainfall for Willunga is 647 mm with approximately 10 % occurring in summer and 41 % occurring in winter (BOM 1965-2011, Willunga). The mean maximum temperature is 27.5 °C for summer, 15.4 °C in winter and 21.6 °C for the year (BOM 2000-2011, Norlunga).

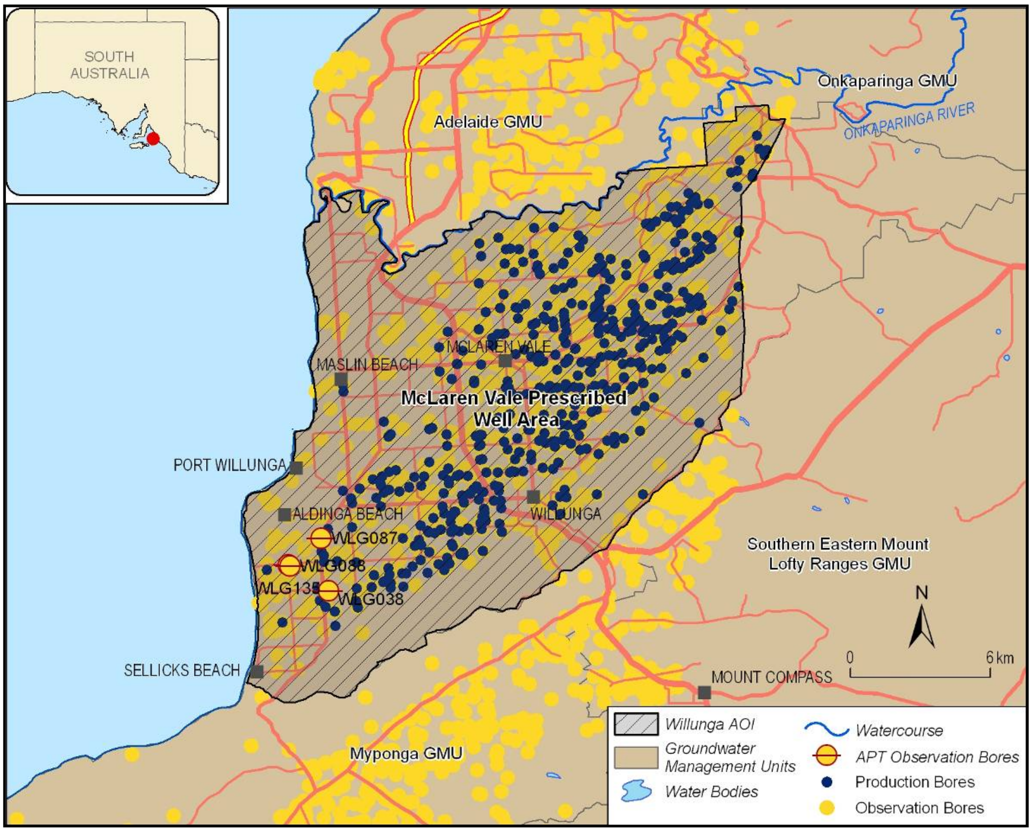

Figure 49 *Location map for Willunga (SA) displaying observation bores, production bores and PWA extent.*

3.4.2.3.3. Geology and Geomorphology

The Willunga Basin is a sub-basin within the larger St. Vincent Basin, which was created by rejuvenated Palaeozoic faults when Australia separated from Antarctica during the Eocene. The Adelaide and Mount Lofty Ranges NRM Board (2007) conducted a review of the Willunga for the purpose of developing a water allocation plan for the McLaren Vale PWA. Information from the review was largely used to write this summary of the Willunga CSA. The Willunga basin is sedimentary, characterised by mostly mid- to late-Tertiary and Quaternary sediments comprising mostly sand and clay, with minor limestone units. These were deposited on the western side of the Willunga Fault within a half-graben structure that formed in the early Tertiary. The sediments are not strongly deformed but do dip towards the southwest. The basin is underlain and bounded to the north, south and east by Late Precambrian and Cambrian aged rocks of the Adelaide Geosyncline. These basement rocks include interbedded slates, quartzites and dolomites that have experienced low to moderate levels of metamorphism (Martin, 1998).

3.4.2.3.4. Hydrogeology

The Willunga Basin is a complex multi-aquifer system (Board, 2007). A cross-section through the Willunga Basin is shown in Figure 50. Groundwater is withdrawn from aquifer layers within the Quaternary and Tertiary sediments, as well as from the basement rocks. The system has been divided into four aquifer systems, Fractured Rock (or Basement aquifer), Maslin Sands, Port Willunga Formation and Quaternary (Lamontagne et al., 2005).

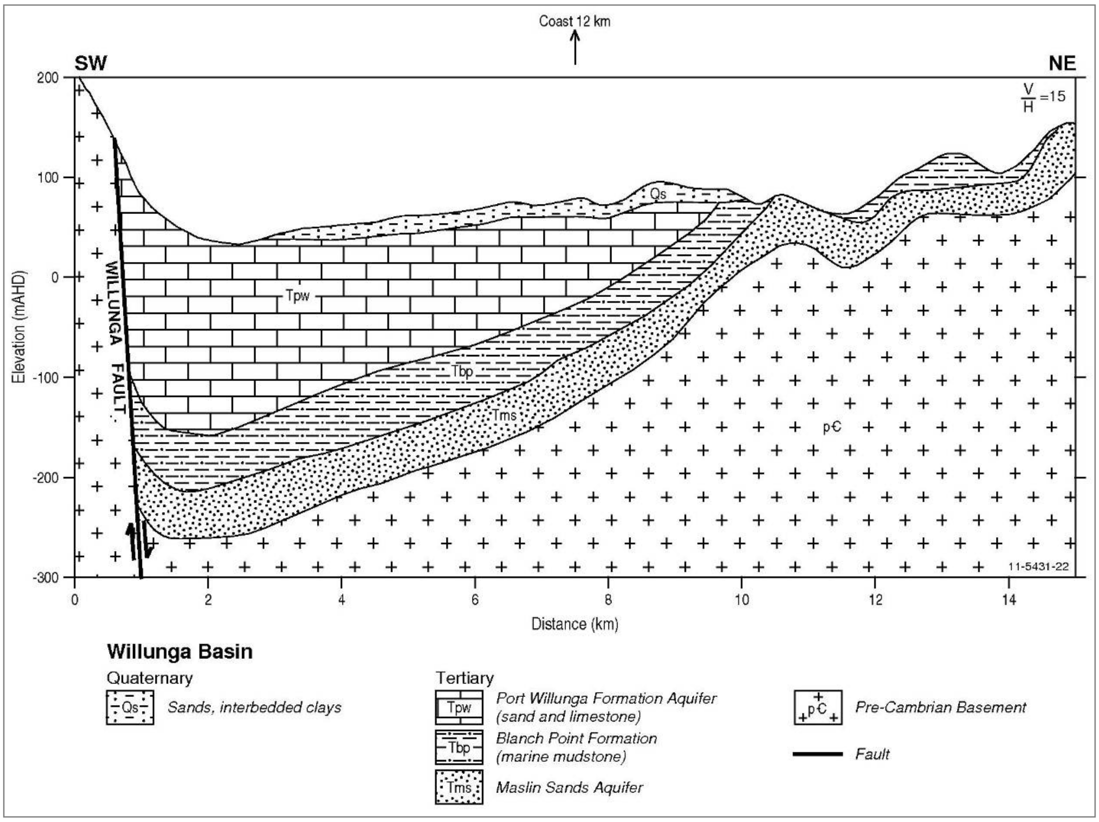

Figure 50 *Cross-section through the Willunga area, adapted from Fig 1.4 in Lamontagne et al. (2005) (Note that the saltwater interface is not evident in this figure).*

The Quaternary aquifer is largely unconfined; it comprises silts, clays and floodplain sediments. It is a low yielding aquifer and is not used as a resource to meet large scale irrigation demand. The Port Willunga Formation is generally unconfined but is confined in some areas. It is the most productive aquifer and is separated from the overlying Quaternary aquifer by the Ngaltinga Formation, which is a silty clay. The Maslin Sands aquifer, underlying the Port Willunga Formation, is confined and comprises fine to coarse sands and clays. It is generally lower yielding than the Port Willunga Formation aquifer. The Fractured Rock aquifer underlies the sedimentary aquifers. Groundwater flow through this aquifer occurs through fractures and fissures. Due to the heterogeneity of the aquifer properties, both the hydraulic conductivity and salinity of the groundwater is highly variable. The direction of groundwater flow is from the northeast corner of the basin towards the coast.

Recharge into the Quaternary aquifer results from infiltration of rainfall directly into sediments or through streambeds and banks during the winter months. Recharge to the sedimentary aquifers of the Maslin Sands and Port Willunga Formation occurs via direct infiltration where the aquifers outcrop on the western Mount Lofty Ranges, as well as from streams and outflows from basement rocks. For more detailed information about the Willunga aquifers see the corresponding APT (Table 38, Appendix 2).

3.4.2.3.5. Land and Water Use

Groundwater is used in Willunga to support high agricultural production, mostly for viticulture and almonds. It also supplies most of the stock water needs and some industrial requirements in the area. The resource is being subjected to increasing pressure as the viticulture industry in the area grows (Martin, 1998).

3.4.2.3.6. Incidence of SWI

In the Willunga Basin, hydrographs showed that more than half of all monitored wells had a declining water level trend (Lamontagne et al., 2005). Salinity was also shown to be increasing in the centre of the basin and along the northern and coastal margins (Lamontagne et al., 2005). However increased salinity and declining water levels were thought to be linked to a period of decreased rainfall causing reduced recharge and/or downward leakage from the aquitard (S. Barnett pers. comm., 2012) and salinities and water levels are said to have since recovered.

3.4.2.4. Perth (Whitfords), WA

3.4.2.4.1. Location

Perth is the capital city of Western Australia and is located in the southwest of Australia. It is situated on the western coast at the mouth of the Swan River, adjacent the Indian Ocean (Figure 51). Whitfords is a groundwater management area (GMA) in the heart of Perth, adjacent to the coast.

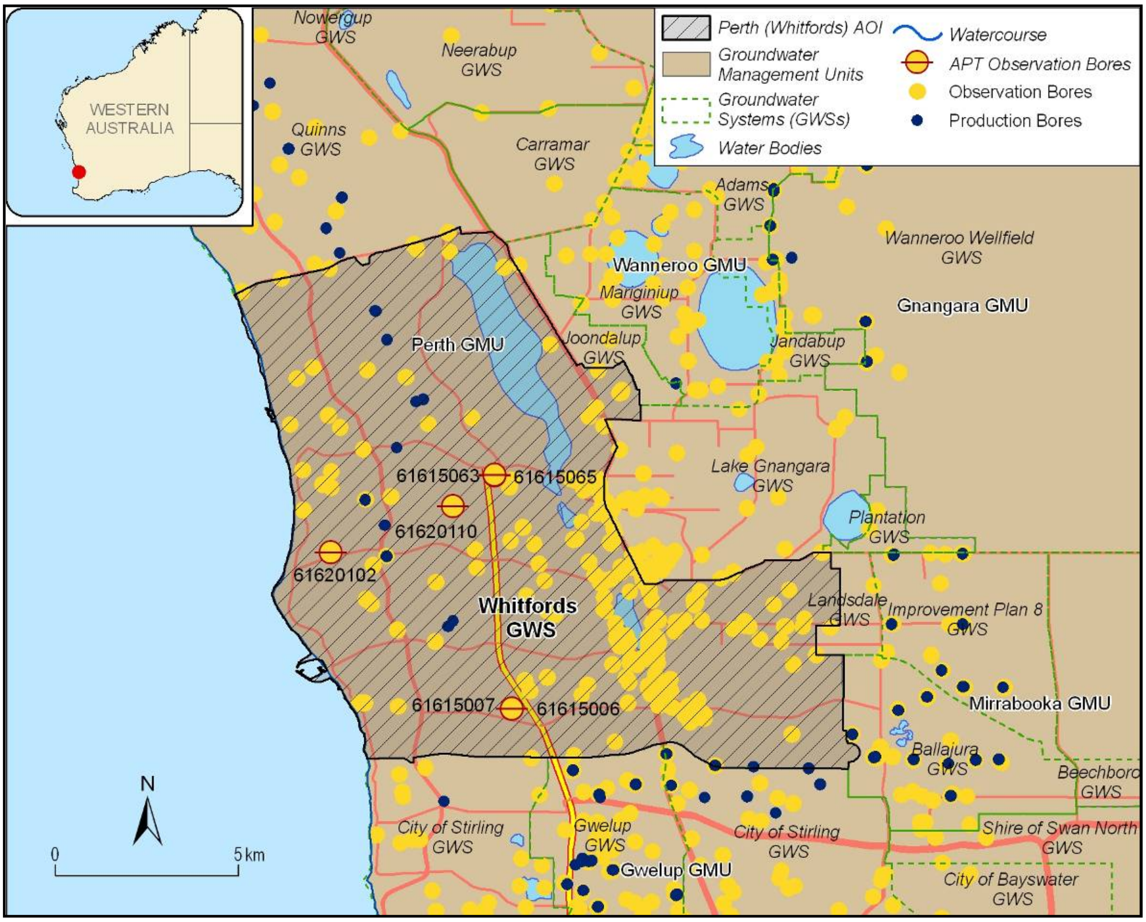

***Figure 51** Location map for the Perth Whitfords (WA) displaying observation bores, production bores and GMU extent.*

3.4.2.4.2. Climate

The Perth metropolitan region has a Mediterranean climate with hot, dry summers and mild, wet winters. The mean annual rainfall for the metro area is 812 mm, with approximately 5 % occurring in summer and 55 % in winter. Mean maximum temperature is 30.4 °C in summer and 18.7 °C in winter (BOM 1905-2012, Wanneroo).

3.4.2.4.3. Geology and Geomorphology

Information used to summarise the Perth aquifer system was largely derived from Davidson (1995). The Perth region is located on the Swan Coastal Plain adjacent the Swan River. The Swan Coastal Plain is about 36 km wide in the north and 23 km wide in the south. It is bounded by the Gingin Scarp and the Darling Fault in the east. In the east, the Ridge Hill Shelf forms a narrow strip of colluvial material at the foothills of the Darling Scarp. Westward of this is the relatively flat Pinjarra Plain composed of unconsolidated alluvial sediments. This is 12 km wide and is terminated sharply by coastal dunes on its western edge. There are numerous wetlands located in the Perth region.

South of Perth, the coastal plain has an average elevation of approximately 25 m AHD, with a maximum of about 75 m. To the north, the plain rises gradually from the coast to approximately 100 m AHD. The surface is more undulating along the coastal strip, where dune systems are present, than in the central and eastern areas.

The Perth region is covered by late Tertiary to Quaternary superficial sediments that unconformably overlie Mesozoic to Early Tertiary formations. The superficial sediments include the Safety Bay Sand, Becher Sand, Tamala Limestone, Bassendean Sand, Gnangara Sand, Guildford Clay, Yoganup Formation and Ascot Formation. They are up to 90 m thick and comprise laterally and vertically variable sequences of sand, limestone, silt and clay. Towards the coast, calcareous marine sands and coastal limestones are more abundant, whereas inland sediments are characterised by variable sequences of fine and medium sands with minor silt and limestone that inter-finger with a sequence of clay and clayey sands towards the foothills of the Gingin and Darling scarps. Mesozoic to early Tertiary sedimentary rocks unconformably underlie the superficial sediments. These were deposited as the Perth Basin experienced periods of rifting and sagging, which culminated in the break-up of Gondwana in the Early Cretaceous. The sediments are marginal marine, transitioning from sandstones, siltstones and shales of Jurassic and lower Cretaceous age to glauconitic mudstones, siltstones, shales and sandstones deposited in the upper Cretaceous. The Jurassic Cattamarra Coal Measures and older sediments underlie these sediments.

3.4.2.4.4. Hydrogeology

In Perth, groundwater is present within Quaternary superficial sediments as an unconfined aquifer, and in the deeper stratigraphic successions as confined to semi-confined aquifers (Figure 52).

Within the superficial sediments (known as the Superficial Aquifer), there are two major bodies of groundwater; the Gnangara Groundwater Mound to the north of Perth and the Jandakot Groundwater Mound to the south (Davidson, 1995). Groundwater flow occurs from the crests of mounds and mostly westwards, discharging into the estuary and the Indian Ocean. The groundwater age within this aquifer ranges from the present at the watertable to about 2000 years at the base of the aquifer (Davidson, 1995). The Superficial Aquifer is unconfined and is in hydraulic connection with the underlying Mesozoic sediments in some areas. The hydraulic properties of the Superficial Aquifer vary significantly depending on the lithology, due to the heterogeneous nature of the sediments.

The deeper, confined aquifer systems are bound to the east by the Darling Fault and by offshore faults in the west. These aquifers comprise sandstones, greensands and chalk limestones and are interbedded with mudstones, shales and siltstones forming aquitards. The water within these aquifers ranges from approximately 600-37 700 years (Davidson, 1995).

Groundwater recharge is mostly from direct winter rainfall recharge on the coastal plain and a small component is derived from local runoff from the Darling and Dandaragan Plateaus. In the deeper, confined aquifers, groundwater flows into the area from the east.

The corresponding APT (Table 39, Appendix 2) for the Perth, Whitfords area contains more detailed hydrogeological information about this aquifer system.

3.4.2.4.5. Land and Water Use

Groundwater in the Perth region is used mostly for the city's residential or industrial use as well as agriculture in the rural fringes of the city. More than half of Perth's water supply is obtained from the groundwater resources found within the Swan Coastal Plain aquifers. As the population continues to grow in Perth, groundwater use has also been increasing.

3.4.2.4.6. Incidence of SWI

The contact between fresh and saline water near the Swan-Canning estuary, and at the coast, forms a saltwater interface with a transitional salinity zone wedge. It has been suggested there could be several saltwater wedges that are separated vertically by clay layers (Cargeeg, 1978). Declining groundwater trends and the risk of SWI was identified by Smith et al. (2005) for the Safety Bay and Stakehill Mounds; Rockingham-Warbro areas; and the northern coastal strip between Whitfords and Yanchep.

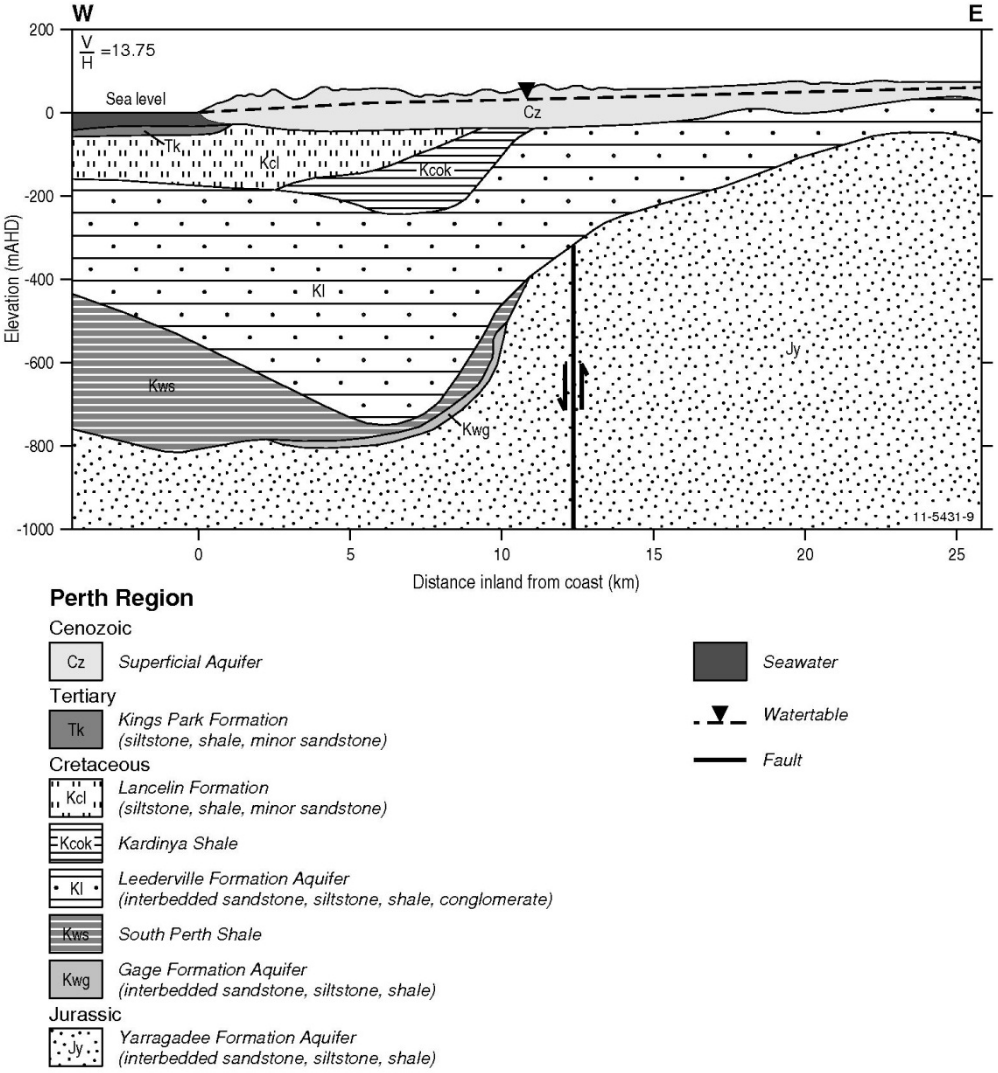

***Figure 52** Cross-section through the Perth area, adapted from Fig. 10, Section B, Davidson and Yu (2008).*

3.4.2.5. Busselton WA

3.4.2.5.1. Location

Busselton is located approximately 200 km south of Perth, and is situated on the south-western coast of Australia on what is known as the Swan Coastal Plain (Figure 53).

3.4.2.5.2. Climate

The area experiences a Mediterranean climate with cool wet winters and hot dry summers. The mean annual rainfall is 809 mm; approximately 4 % of the rainfall falls in summer, and winter receives approximately 56 %. The monthly mean maximum temperature is 27.8 °C for summer, 16.8 °C in winter and 22.0 °C for the year (BOM 1990-2011, Busselton Shire). Annual potential evaporation is close to 1100 mm (Schafer et al., 2008).

3.4.2.5.3. Geology and Geomorphology

The Swan Coastal Plain has an average width of 15 km, and is bounded in the west by the Leeuwin-Naturaliste Ridge and in the south and southeast by the Whicher Scarp. The Whicher Scarp was formed by marine erosion along an old coastline, and separates the coastal plain from the Blackwood Plateau in the south. The plateau rises from about 40 m at the foot of the scarp to an average elevation of 160 m AHD (Hirschberg, 1989). The area also includes a number of drainage systems arising from the Blackwood Plateau that flow northwards towards the coast, as well as wetlands that receive seasonal inundation from these flows.

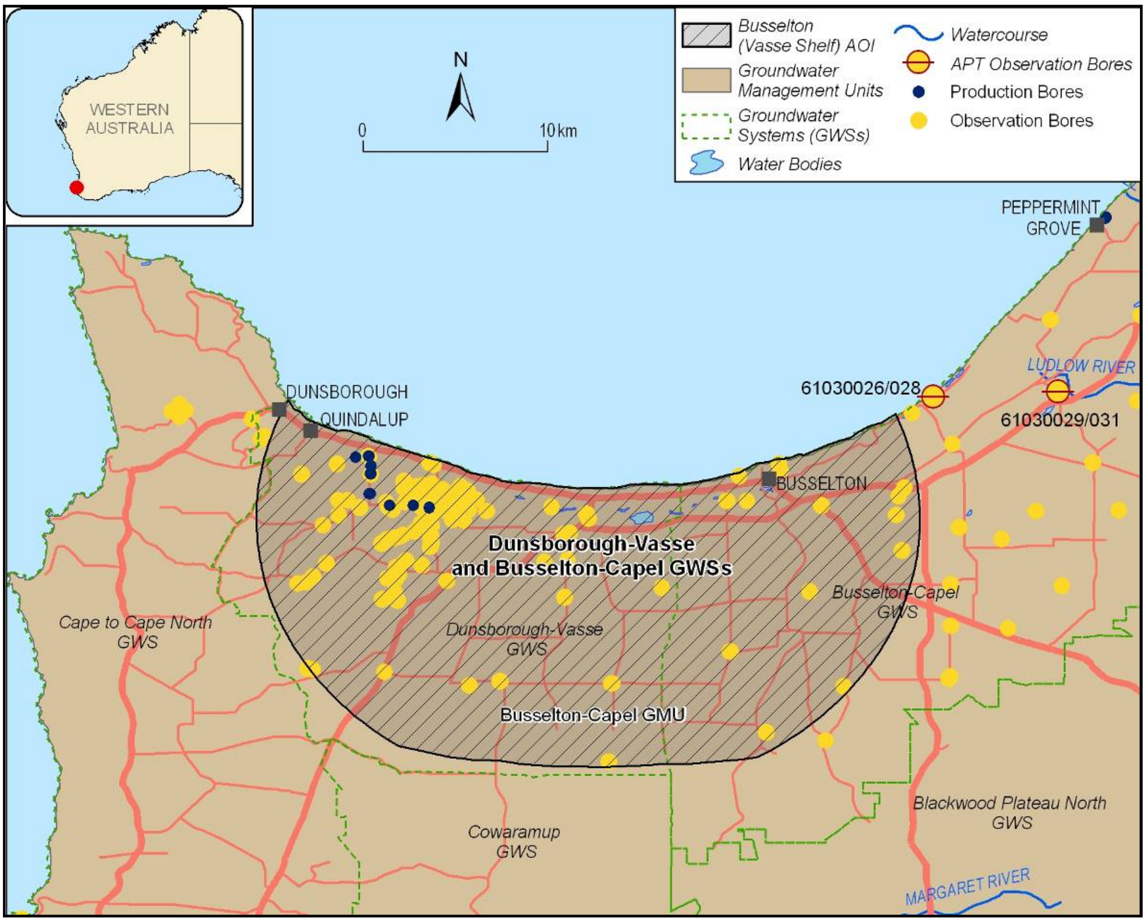

Figure 53 *Location map for Busselton (WA) displaying observation bores, production bores and GMU extent.*

The town of Busselton lies within the Bunbury Trough, a deep half-graben associated with the major north-south trending Busselton Fault. West of the fault lies the area known as the Vasse Shelf, a relatively shallow fault block. The Vasse Shelf is bounded by the Busselton Fault in the east and the Dunsborough Fault in the west. The Bunbury Trough and Vasse Shelf structures are both contained within the southern Perth Basin, which is situated between the Yilgarn Craton to the east and the Leeuwin Complex to the west (Schafer and Johnson, 2009).

Local sedimentary rocks within the Vasse Shelf range in age from Early Permian to Quaternary (Panasiewicz, 1996). The lowermost unit is the Permian Sue Coal Measures, comprising well-consolidated sandstone and shale with seams of coal and carbonaceous material (Panasiewicz, 1996). Cretaceous sedimentary rocks form the dominant stratigraphy of the area, and they have not been deformed by the Busselton Fault. The lowermost Cretaceous unit, the Leederville Formation, underlies a broad area, and consists of interbedded sandstone, siltstone and shale with minor conglomerate and coal seams that were deposited as onshore fluvial and swamp deposits. Overlying Cretaceous sediments are Quaternary to Late Tertiary sand, silt clay or limestone units.

3.4.2.5.4. Hydrogeology

On the Vasse Shelf area there are two regional aquifers known as the Superficial and Leederville aquifers (Figure 54). The Superficial aquifer is thin and unconfined. It comprises the Tamala Limestone, Bassendean Sand, Guildford Formation and Yoganup Formation. Due to the variability in the aquifer substrate, there is a large variation in its permeability. Recharge into the Superficial Aquifer occurs mostly by direct infiltration of rainfall and is greater over areas of cleared land. Groundwater flow is generally northward (Schafer et al., 2008).

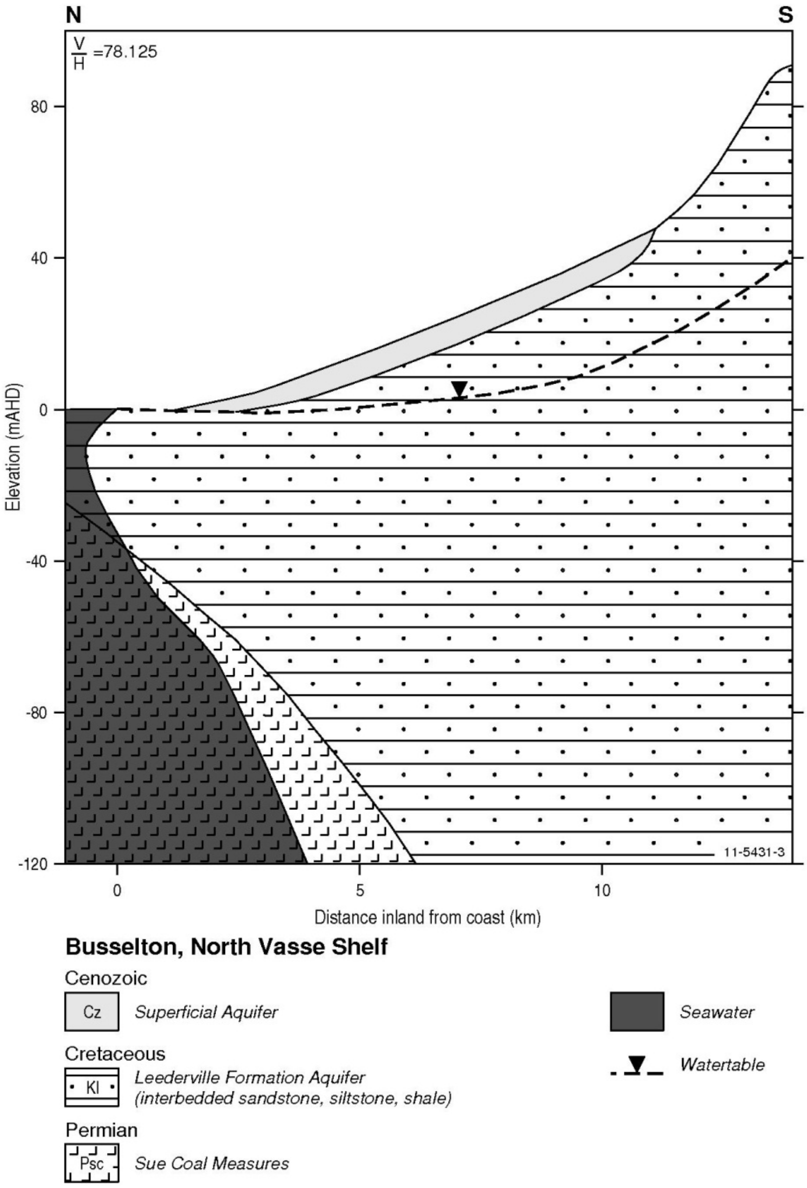

Figure 54 *Cross-section through the Busselton adapted from Fig. 13 of Hirschberg (1989).*

The Leederville aquifer is a multi-layered aquifer system. It comprises discontinuous interbedded sequences of sand and clay, incorporating six distinct members of the Leederville Formation. The hydraulic properties of the aquifer are variable depending on the sediment type, and as the sediments become more consolidated with depth (Schafer et al., 2008). The Leederville Formation Aquifer receives recharge from direct infiltration of rainfall where the formation outcrops as well as from downward leakage from overlying superficial formations (Hirschberg, 1989).

The Permian Sue Coal Measures (Sue aquifer) do not have well documented groundwater occurrence, though it has been estimated to contain fresh groundwater via leakage from the overlying Leederville Formation (Panasiewicz, 1996).

The rate of flow and interconnection between the Leederville and Superficial aquifers is not considered significant (Schafer and Johnson, 2009). Groundwater flow between the Leederville aquifer and the underlying Sue aquifer is also considered to be very small and there is little interconnection with basement Leeuwin Complex rocks (Schafer and Johnson, 2009). The corresponding APT for the Northern Vasse Shelf (Table 38) provides more detailed hydrogeological information about this area.

3.4.2.5.5. Land and Water Use

The land is mostly used for mixed farming of horticulture, pasture production, viticulture, olives, plantation forestry, dairying and grazing. Along the coast there is urban and light industrial development.

3.4.2.5.6. Incidence of SWI

On the Vasse Shelf, the seawater interface extends 4-5 km inland, cutting across the older succession of Cretaceous (Leederville Formation) and Permian (Sue Coal Measures) aged sediments at depth. The area is being actively monitored (Panasiewicz, 1996).

3.4.2.6. Bunbury, WA

3.4.2.6.1. Location

Bunbury is located on the western coast of Australia approximately 120 km south of Perth within the Swan Coastal Plain as shown in Figure 55.

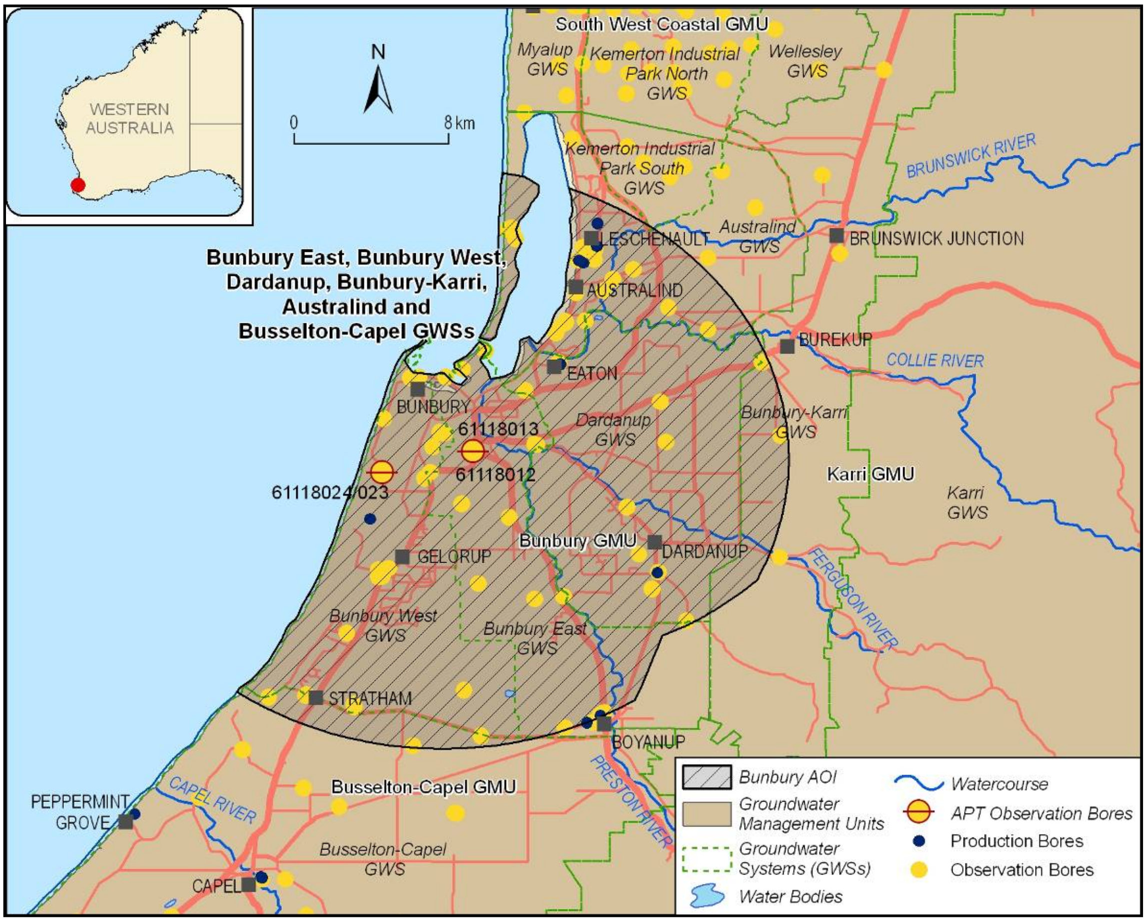

Figure 55 *Location map for Bunbury (WA) displaying observation bores, production bores and GMU extent.*

3.4.2.6.2. Climate

Bunbury experiences a Mediterranean climate, with hot dry summers and cool wet winters. The mean annual rainfall is 721 mm. Approximately 5 % of the rainfall falls in summer, and winter receives approximately 57 %. The monthly mean maximum temperature is 28.9 °C for summer, 17.7 °C in winter, and 23.0 °C for the year (BOM 1995-2011, Bunbury). Average annual evaporation has been reported to be about 1400 mm (Deeney, 1988).

3.4.2.6.3. Geology and Geomorphology

Bunbury lies adjacent to the coast on the Swan Coastal Plain. The Swan Coastal Plain slopes gently to the coast from about 40 m above sea level at the base of the Darling Scarp. The plain is developed upon a marine erosional surface over the underlying Mesozoic rocks that are covered by late Pliocene-Holocene sediments. The inner part of the plain is an extension of the flat Pinjarra Plain, while the coastal belt contains low dune systems comprising the Bassendean, Spearwood and Quindalup Dunes that parallel the coast. The dune systems increase in height and width eastwards and northwards. The Swan Coastal Plain is drained by rivers and streams rising in the Whicher and Darling Ranges. The Pinjarra Plain becomes waterlogged during winter and has been artificially drained. (Deeney, 1988).

Bunbury is located within the Bunbury Trough part of the Southern Perth Basin, which is bounded to the east by both the Darling Fault and Precambrian rocks of the Yilgarn Craton. The uppermost sediments in the area have been labelled the Superficial Formation. These gently dip towards the west and unconformably overly Mesozoic sediments. The sediments are thickest where they have been deposited in palaeochannels within the Mesozoic sediment (Deeney, 1988).

Beneath the Superficial Formation are the Jurassic Cockleshell Gully and Yarragadee Formations. These form a conformable sequence of sands and shales. They are unconformably overlain by the Cretaceous Leederville Formation, and in some areas the Bunbury Basalt is also found. The Bunbury Basalt exists as a north-south trending strip in the Bunbury area. The Leederville Formation comprises interbedded sands, siltstone, clays and shale (Commander, 1981).

Bunbury is located on the eastern limit of an anticline so the Leederville and Yarragadee Formations dip and thicken towards the east (Commander, 1981).

3.4.2.6.4. Hydrogeology

Bunbury aquifers include the Superficial Formation, Leederville Formation, Bunbury Basalt, Yarragadee Formation and Cockleshell Formation (Figure 56). The Superficial sediments, consisting predominantly of clay and sand in the east and of sand and limestone in the west, form an unconfined aquifer. The watertable ranges from 1-30 m deep. The aquifer is anisotropic and heterogeneous due to lithological variability and stratification of the sediment. The aquifer is recharged directly by rainfall but the amount varies with lithology, depth to the watertable and topographic gradient. Groundwater discharge is through major and minor watercourses, inlets, coastal swamps, evapotranspiration as well as downward leakage to Mesozoic sediments (Deeney, 1988).

The Yarragadee and Cockleshell Formations are hydraulically connected. They consist of coarse to very coarse quartz sands with minor interbeds of weathered shale. The proportion of shale increases with depth. Recharge occurs predominantly where these formations outcrop on the Blackwood Plateau; some recharge occurs, from downward leakage from overlying formations. Groundwater flow in the upper aquifer is toward the northwest. Some discharge occurs along the coast to the Superficial Formations but most groundwater discharge is out to sea. Groundwater levels fluctuate and are lowest during the summer due to increased abstraction (Commander, 1981).There is some connectivity between the Superficial Formation aquifer and lower Mesozoic aquifers as both upward and downward leakage occur (Deeney, 1988). For more information about the hydrogeology of Bunbury refer to its corresponding APT (Table 41, Appendix 2).

3.4.2.6.5. Land and Water Use

Most of the land has been cleared for agriculture, which uses predominantly groundwater for irrigation. Other than agriculture the area contains native vegetation, State Forest pine plantations and urban districts (Deeney, 1988).

3.4.2.6.6. Incidence of SWI

In the Bunbury area a saltwater interface intrudes up to 3 km inland within the Yarragadee Formation (Wharton, 1989). Recent observations of increased salinity in the Yarragadee aquifer have been documented in the Bunbury area.

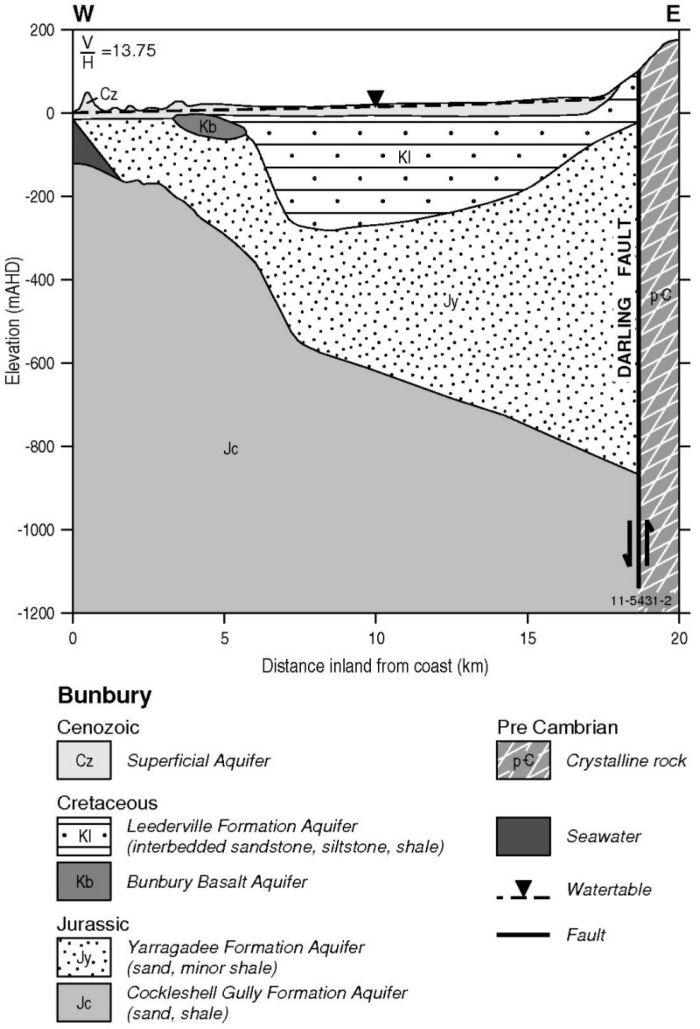

Figure 56 *Cross-section through the Bunbury area, adapted from Plate 1, Section D, Commander (1982).*

3.4.2.7. Albany, WA

3.4.2.7.1. Location

Albany is located approximately 390 km southeast of Perth on the south coast adjacent Princess Royal harbour and King George Sound (Figure 57). Adjacent the harbour is the South Coast Peninsula.

3.4.2.7.2. Climate

Albany experiences a Mediterranean-type climate with hot dry summers and cool, wet winters. The mean annual rainfall is 929 mm. Approximately 8 % of the rainfall falls in summer, and winter receives approximately 43 %. The monthly mean maximum temperature is 22.5 °C for summer, 16.2 °C in winter and 19.5 °C for the year (BOM 1880-2011, Albany). Between 1980 and 2009 the average annual pan evaporation was 1 439 mm (Water Corporation, 2010).

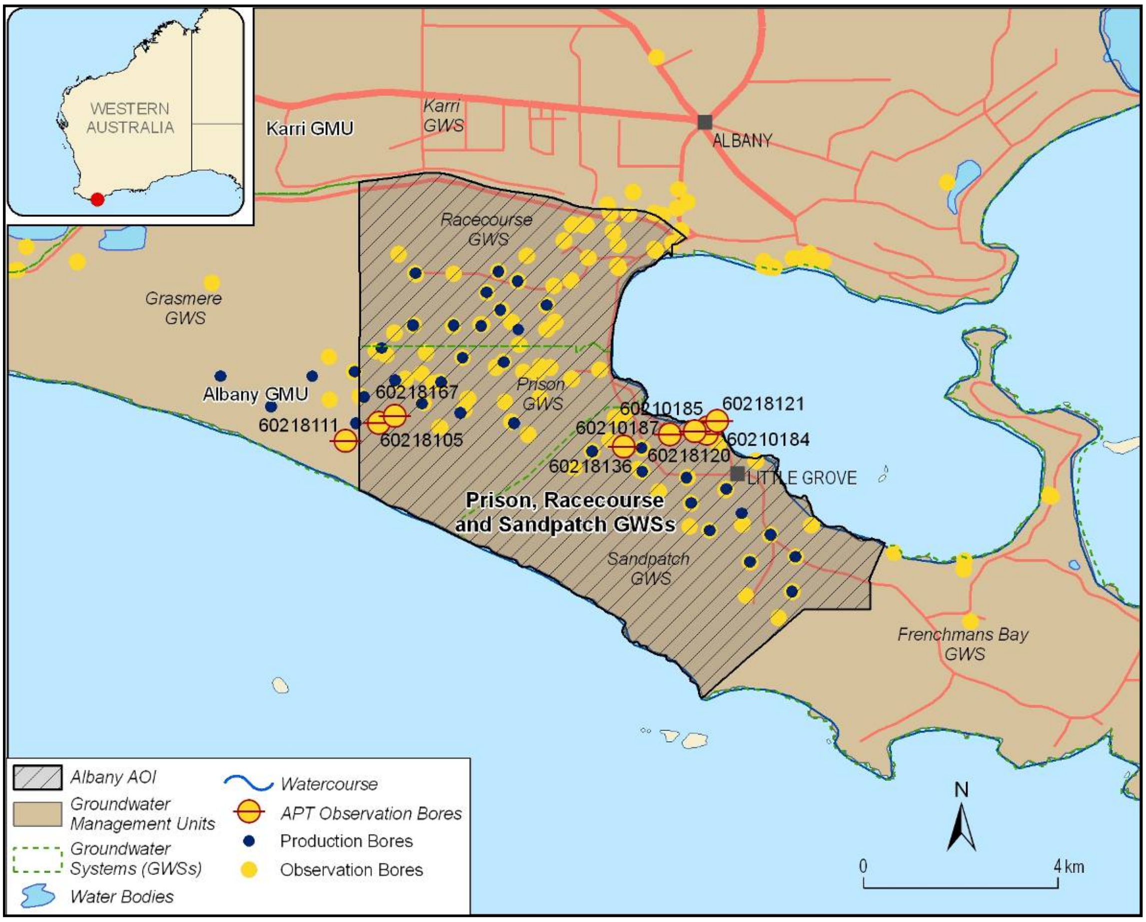

Figure 57 *Location map for Albany (WA) displaying observation bores, production bores and GMU extent.*

3.4.2.7.3. Geology and Geomorphology

Information about the geology and geomorphology of Albany has been mostly derived from Water Corporation (2010). The Albany area has been classified into two distinct geomorphologic categories, a dissected plain centred on the Napier Creek, and the ‘Coastal Strip’. The Napier plain is flat to gently undulating, sloping towards the coast from approximately 180 m AHD adjacent the Porongurup Range. The plain contains broad and flat valleys, numerous lakes and swamps as well as protruding, rounded hills of granite and gneiss. The Coastal Strip is situated between the Napier Plain and the coastline and is characterised by a series of headlands and bays as well as the South Coast Peninsula. Major geomorphological features of the plain include coastal dunes, alluvial areas and a 40 m high limestone ridge that forms cliffs where it lies adjacent the coast.

There are three main stratigraphic subdivisions in the Albany area, Quaternary (superficial) sediments, Tertiary sediments and pre-Cambrian basement rocks. These have been described by Forth (1973). Albany lies within the Proterozoic Albany-Fraser Orogen, and gneisses and granites form the basement rocks of the area. Subsequent to the Proterozoic orogeny, sedimentation and erosion has occurred. A series of marine transgressions, resulting in the deposition of the Werillup Formation, occurred during the Eocene. During the Quaternary, windblown sands have formed coastal dunes.

3.4.2.7.4. Hydrogeology

Three main aquifer units and two aquitards form the Albany aquifer system. These are the Quaternary Superficial Sediments, the Middle Sequence (capped by the Superficial Clay aquitard) and the Werillup Formation (which also contains an upper clay aquitard unit). A schematic cross-section through this aquifer system is shown in Figure 58. Information about the hydrogeology of Albany was mostly taken from Water Corporation (2010).

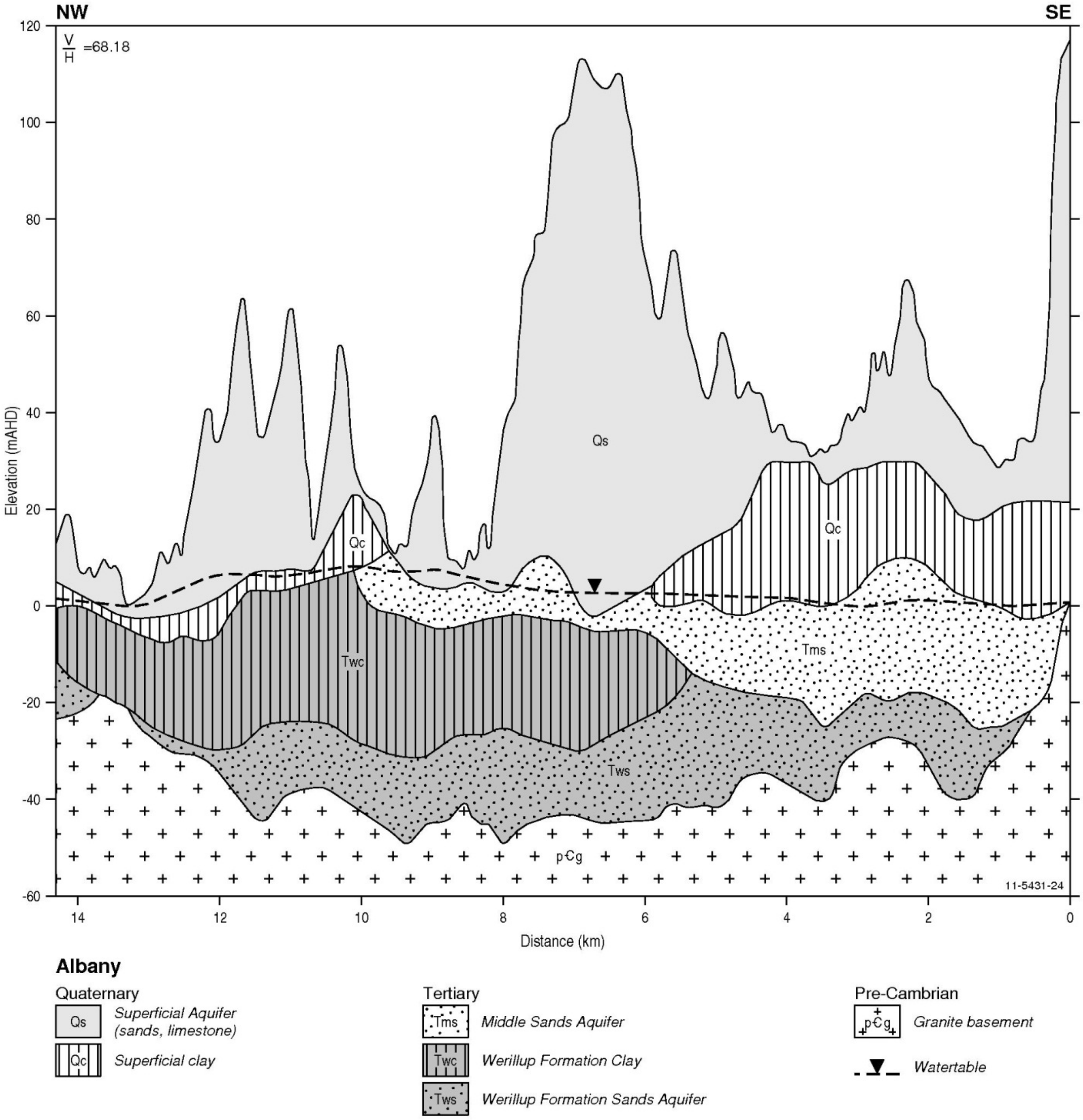

Figure 58 *Cross-section through the Albany area, adapted from Fig 5.1 of Water Corporation (2010) (Note that the saltwater interface is not evident in this figure).*

The Quaternary sediments form regionally significant superficial and sedimentary aquifers. These are approximately 5-100 m thick and comprise dune sands and shelly limestone. These sediments are highly permeable and store good quality water from rainwater recharge.

The Middle Sequence is present beneath most of the coastal strip, comprising fine- to medium-grained quartz sand that is clayey in part. The Superficial Clay forms an aquitard of soft plastic clay beneath the central and eastern portion of the peninsula.

Tertiary fluvial and lacustrine sediments of the Lower Werillup Formation form an important aquifer. These sediments include permeable fine to coarse grained sands. Overlying these, the Upper Werillup Facies acts as an aquitard as it comprises low permeability clays and sands. The Tertiary aquifers have good hydraulic connectivity with the Quaternary aquifer in general except where non-extensive superficial clay forms an aquitard between the two layers. Where they are hydraulically linked, they contain good quality water (URS/Dames & Moore, 2010).

Recharge into the groundwater systems is primarily from rainfall infiltration; however the superficial clay unit can retard downward migration of water in parts. There are two APTs for Albany reflecting different sides of the South Coast Peninsula. These are found within Appendix 2 in Table 42 (Princess Royal Harbour side) and Table 43 (ocean side).

3.4.2.7.5. Land and Water Use

Albany is a growing tourist and retirement port city that has been built around fishing, whaling and agricultural industries. Groundwater is used for town water, domestic, agricultural and industrial supplies, as well as for irrigated recreational areas, parks and gardens. Albany also has an extensive urban use of rainwater. The region is rapidly growing, which puts additional pressure on the available water resources.

3.4.2.7.6. Incidence of SWI

Estimations made by the Water Corporation (2010) suggest that the saltwater interface would be expected to occur at approximately -40 m AHD, 800 m inland from the coast using the Ghyben-Herzberg principle. A saltwater interface has not, however been observed through well data. EM geophysics has suggested the presence of the SWI interface along the Princess Royal Harbour shoreline at Pelican Point, extending approximately 80 m inland, but this was thought to be due to brackish to saline water within the clay aquitard.

3.4.2.8. Esperance, WA

3.4.2.8.1. Location

Esperance is located on the southern coast of Australia in the south eastern corner of Western Australia, approximately 600 km east-southeast of Perth (Figure 59).

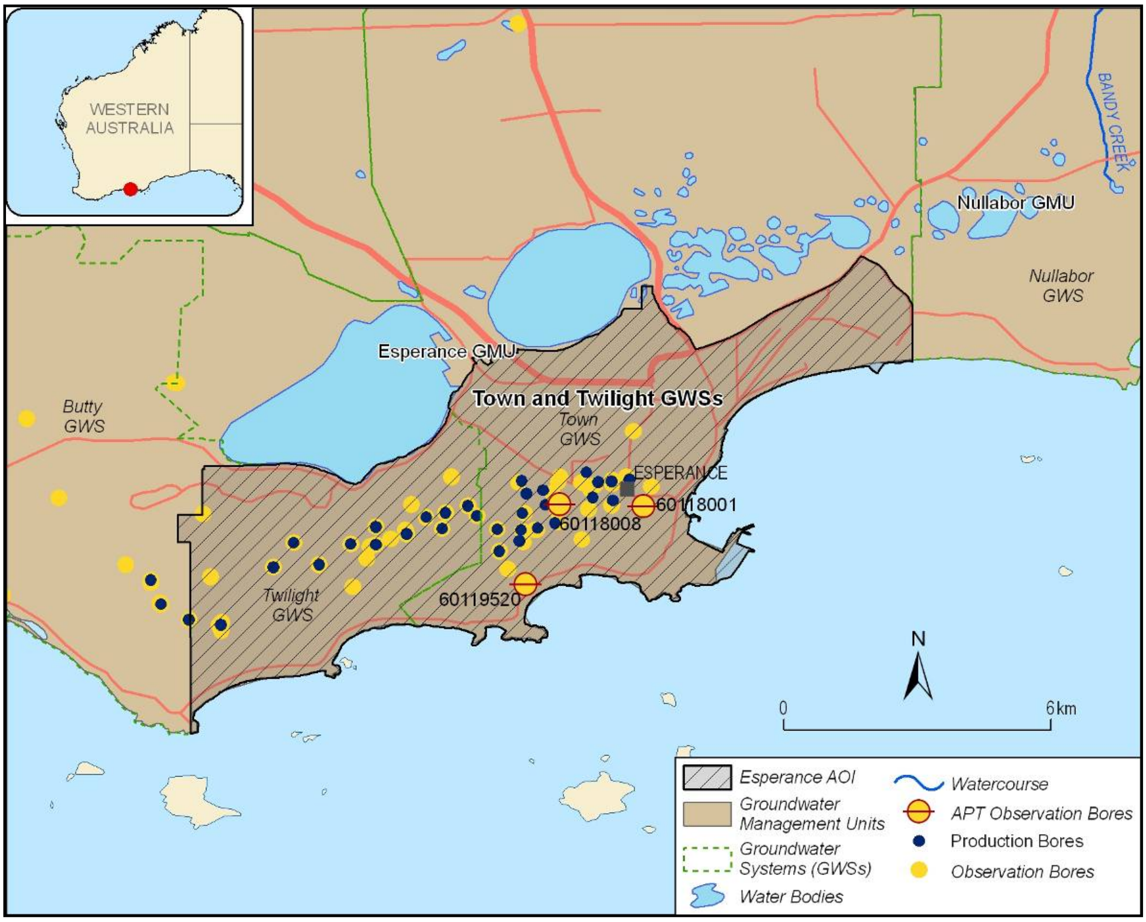

Figure 59 *Location map for Esperance (WA) displaying observation bores, production bores and GMU extent.*

3.4.2.8.2. Climate

Esperance has a Mediterranean climate with hot dry summers and cool, wet winters. The mean annual rainfall is 618 mm. Approximately 11 % of the rainfall falls in summer, and winter receives approximately 42 %. The monthly mean maximum temperature is 25.6 °C for summer, 17.7 °C in winter, and 21.8 °C for the year (BOM 1969-2011, Esperance).

3.4.2.8.3. Geology and Geomorphology

Esperance is situated on coastal plain comprising large ridges of dune sands that are interbedded with limestones and siltstones. An extensive area of saline alluvium occurs on the coastal plain behind the coastal sand dunes where saline lakes and wetlands are found. Ephemeral creek systems, draining from the north, flow into the wetland systems. An escarpment, which was probably an erosional shoreline, marks the inland extent of the coastal plain (Crisalis International Pty Ltd., 2010).

The Esperance region is mainly underlain by highly deformed granite, gneiss, quartzite and mafic rocks of the Albany-Fraser Orogen. The basement rocks have formed discontinuous ridges trending northeast, which influence the topography of the area. The upper portion of basement rocks has been weathered to dense kaolonitic clay (Crisalis International Pty Ltd., 2010).

Unconformably overlying the basement rock are Tertiary sedimentary rocks from the Plantagenet group, which contain the Werillup Formation and the Pallinup Sandstone. The Werillup Formation consists of fine to coarse grained sand, lignite and carbonaceous clay that has been deposited into topographic depressions in the weathered bedrock. The Pallinup Sandstone consists of siltstone to fine grained clayey sandstone with minor glauconite, spongolite and various marine fossils.

Overlying the Tertiary rocks are Quaternary coastal sediments. These are thickest on the coastal plain in the form of prominent sand dunes to the south of a lake system. These are underlain by Pallinup Siltstones, which are 16-20 m thick, fine to coarse-grained, moderately to poorly sorted, calcareous sands overlying a sequence of interbedded clay, silt and quartz sands.

3.4.2.8.4. Hydrogeology

Quaternary and minor Tertiary sediments along the coastline form the regionally significant superficial aquifers (Department of Water, 2007) (Figure 60). The Quaternary coastal sediments, composed of dune sands and limestone, are approximately 10-30 m thick; they are highly permeable, and store good quality water from rainwater recharge. The underlying sediments contain brackish to saline groundwater, and are hypersaline in the vicinity of the Pink Lake. The groundwater system has been represented by a schematic cross-section in Figure 60. The corresponding APT (Table 44, Appendix 2) contains more detailed information about the various aquifers in the area.

3.4.2.8.5. Land and Water Use

Esperance is a growing tourist and retirement town that traditionally has been used for fishing and agriculture. Groundwater is used for the town water supply, domestic, agricultural and industrial supplies, and irrigating recreational areas, parks and gardens. The town is thus heavily reliant on groundwater including for drinking. Continued growth is expected for the area.

3.4.2.8.6. Incidence of SWI

According to a report by the Department of Water (2007), localised saltwater intrusion and up-coning have been reported in the Town and Twilight groundwater management sub-areas, particularly to the south of the Pink Lake. The risks to groundwater dependent ecosystems have also been identified as a consequence of reduced groundwater levels and salinisation around wetlands.

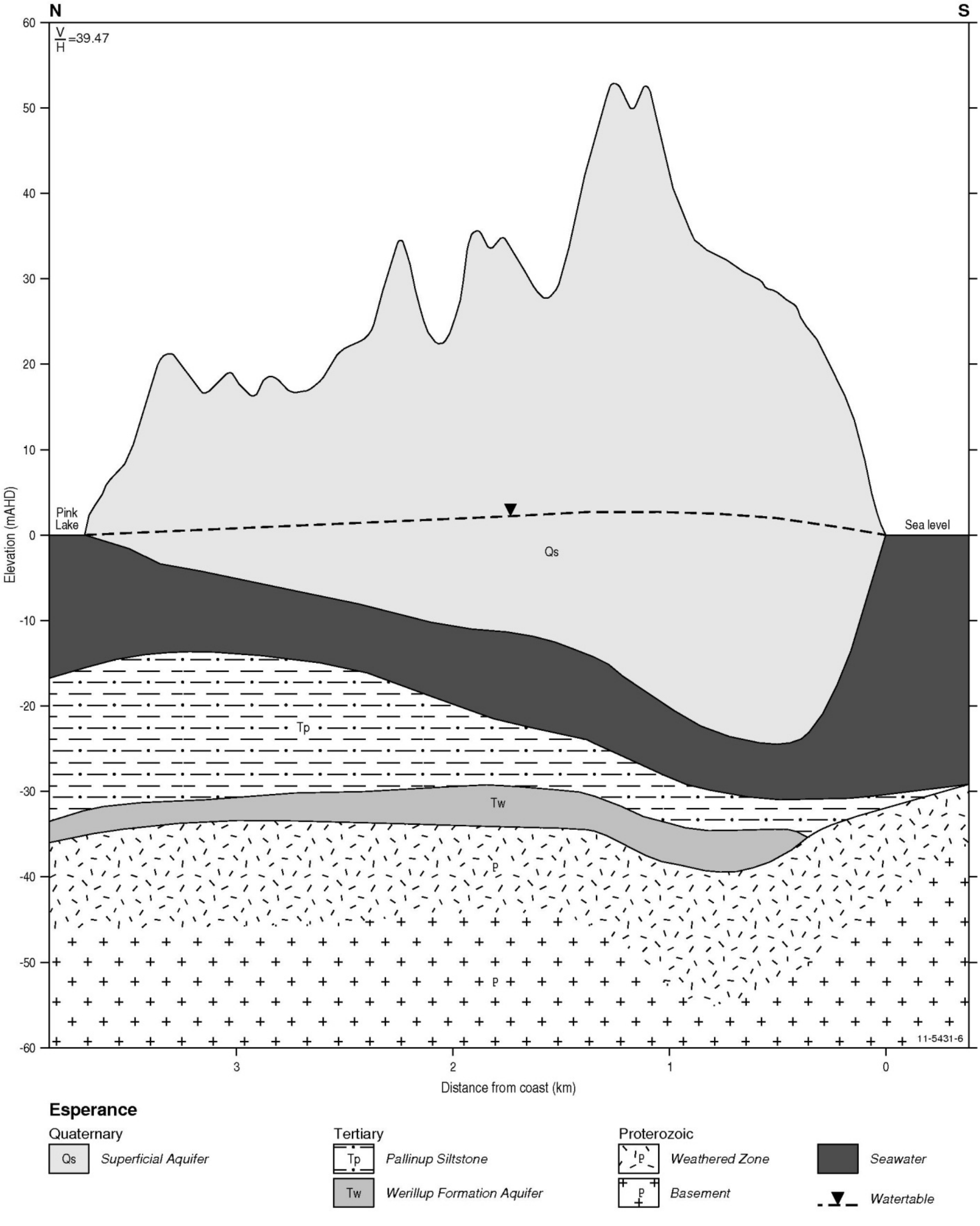

Figure 60 *Cross-section through the Esperance area, adapted from Fig. 3, Section B-B1 in Department of Water (2007). NB the saline water from Pink Lake and SWI interfaces merge within the Superficial sediments.*

3.4.3. Summary, Sedimentary Basins

Nine case study areas were situated within the sedimentary basin principal aquifer type; two of which have an arid climate, and seven a Mediterranean, temperate summer dry climate. Such climates vary considerably. While the Australian arid climates are reliant on monsoonal rains during summer and receive virtually no rainfall during summer, the Mediterranean, temperate summer dry climate type receives majority of its rainfall during winter. In the arid climate types, some years may not receive monsoonal rains at all, resulting in large climatic variations from year to year. Both climate types can have hot winters, but Mediterranean, temperate summer dry climates have milder winters than the arid climate. Both climate types have dry seasons or years, and it is during these times that the dependence on groundwater is greatest. The CSAs are scattered along the western and southern coast of Australia in Western Australia and South Australia where the land and groundwater use is versatile, ranging from water for beef cattle production to the watering of inner-city golf courses.

Sedimentary basins include multiple-layered, stacked aquifers of consolidated sediments that extend to considerable depths. Due to their thicknesses, they have the capacity to store large volumes of freshwater and are often suitable for large-scale extractions required for urban development. Many of the CSAs extract groundwater from basins that were formed during the Palaeozoic and Mesozoic Eras within large intercontinental rift basins. For this reason, the geometry of the basins is usually defined by large faults, such as the Eden-Burnside and Parra Faults in the Adelaide area or the Darling Fault for the south-western CSAs. The sedimentary rocks within the basins are consolidated and include a wide variety of lithologies, meaning that their hydraulic properties are also variable.

Groundwater within these basins is often confined, with confined aquifer systems receiving their recharge where they outcrop inland. Recharge locations are often at higher elevations and this provides considerable head to drive groundwater flow towards the coast. Beyond the coast, the aquifers may extend considerable distances seawards. Confining units can be leaky and create hydraulic connectivity between aquifers. This is the case in Derby, where a confining layer has eroded across an anticline structure, allowing groundwater flow between stacked aquifers.

Often unconsolidated or superficial sediments also form important aquifers on top of the sedimentary basin aquifers and these aquifers share characteristics with coastal sands aquifers. These can be hydraulically connected to the underlying units, such as seen in Albany where confining layers are absent; or in Busselton where there is some, albeit low, connectivity between superficial and lower aquifers. It is very important to establish the degree of connectivity between stacked aquifers because this will influence the SWI potential of the aquifer system. On the other hand, confined aquifers may prevent seawater movement: a series of seawater wedges could develop in lower stacked aquifers, while the overlying aquifer could still contain valuable fresh water suitable for extraction.

Fractured rock basement units may also store and transmit water and be hydraulically connected to overlying aquifers, such as in Willunga. If basement rock aquifers contain saline water there is a possibility of saline up-coning in these cases.

In sedimentary basin aquifers, SWI vulnerability may be induced where there have been large losses to piezometric heads. This is mostly due to high abstractions from bores where recharge has not been sufficiently high to maintain aquifer storages. The arid climate aquifers of Broome and Derby may be more vulnerable to SWI because they may not be receiving as much recharge due to a relatively low rainfall and high rate of evaporation. However, Mediterranean, temperate summer dry climate types may also be vulnerable, particularly due to the susceptibility of this climate type to long periods of drought. Many of the sedimentary basin aquifers had a documented incidence of SWI, including the areas of LeFevre Peninsula, Broome, Derby, Bunbury and

Esperance. The management and installation of monitoring bores can be more costly in the deep, multi-layered consolidated aquifers than the shallower, multi-layered, unconsolidated aquifer types.

3.5. Carbonate

The CSAs with aquifers classified as carbonate include Exmouth in Western Australia and Port MacDonnell and Uley South in South Australia.

3.5.1. Carbonate, Arid

One carbonate aquifer type with an arid climate class has been identified - Exmouth on the Western Australian coast. This area is also known as Cape Range. It is a developing town, building on its tourism and recreational, fishing, mining and pastoral industries.

3.5.1.1. Exmouth (Cape Range) WA

3.5.1.1.1. Location

Exmouth is located approximately 1260 km to the north of Perth on the Cape Range Peninsula, bounded by the west by the Indian Ocean and to the east by the Exmouth Gulf (Figure 61).

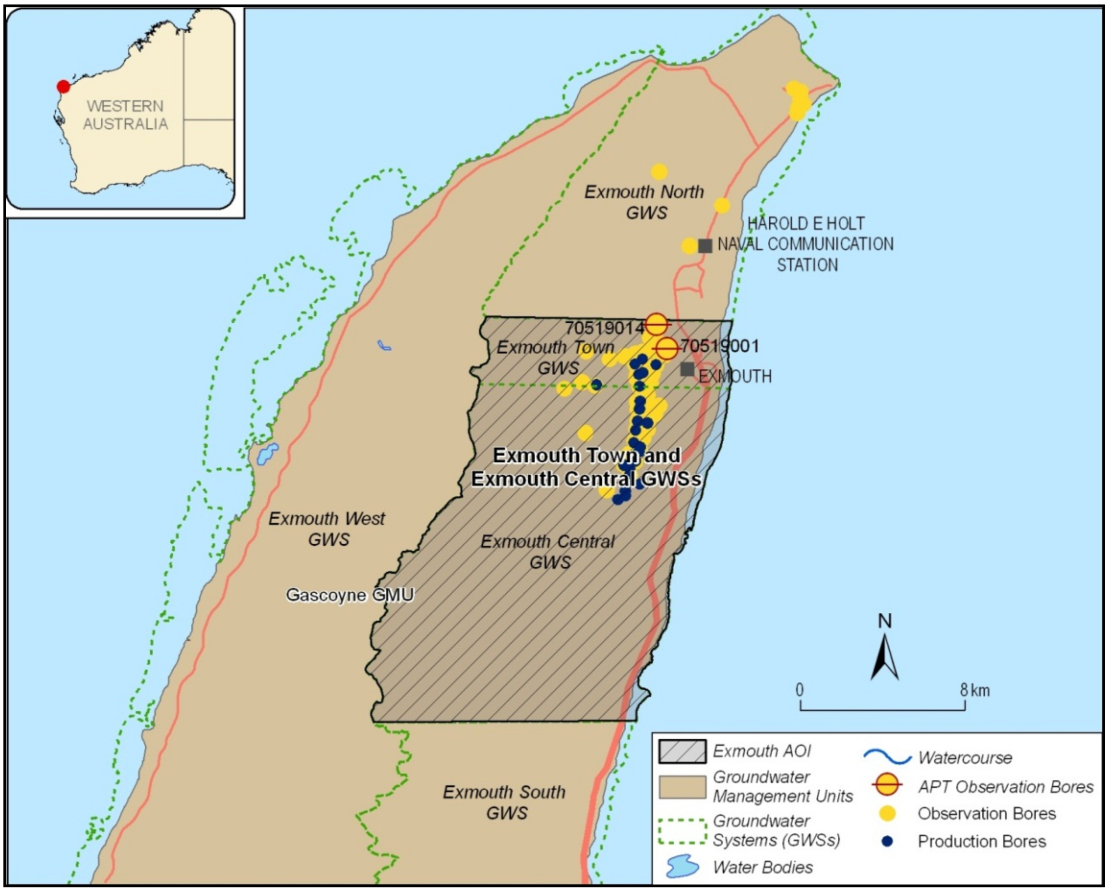

***Figure 61** Location map for Exmouth (WA) displaying observation bores, production bores and GMU extent.*

3.5.1.1.2. Climate

Exmouth has a semi-arid climate with hot dry summers and mild winters (Water and Rivers Commission, 1999). The mean annual rainfall is 262 mm. Approximately 31 % of the rainfall falls in summer, and winter receives approximately 30 %. The monthly mean maximum temperature is 37.4 °C for summer, 25.1 °C in winter and 31.8 °C for the year (BOM 1975-2011, Learmonth Airport). The region receives tropical cyclones approximately every three to six years and has experienced lower than average rainfall over recent years.

3.5.1.1.3. Geology and Geomorphology

The Cape Range Peninsula is approximately 96 km from north to south and 21 km from east to west. The coastal plain along the centre of the peninsula is approximately 20 m above sea level. From the coastal plain to Cape Range, along the axis of the peninsula, the topography rises to approximately 300 m above sea level. The area consists of uplifted and highly dissected karst terrain flanked by coastal plain sediments and a series of wave-cut uplifted reef terraces. The peninsula includes caves, rock shelters, sink-holes, streams that disappear underground, biokarstic phenomena (such as Ningaloo Reef), protocaves and mesocaverns, largely due to the karst landscape (Water and Rivers Commission, 1999). The limestone and karst formations support diverse subterranean fauna.

Exmouth is located within the Carnarvon Basin, and is underlain by Palaeozoic to Cenozoic rocks. Above these, Tertiary calcareous sediments and minor Quaternary deposits have formed the peninsula. The Tertiary sediments in the area comprise mostly the Cape Range Group. This group contains *"friable to dense fossiliferous limestone and marl with local interbeds of sand"* including the Trealla, Tulki and Mandu units (Water and Rivers Commission, 1999). The Cape Range Group limestone units are underlain by the Birdrong Sandstone formation at 1000-1500 m below sea level in the northwest of the peninsula.

3.5.1.1.4. Hydrogeology

The Exmouth Peninsula has limited groundwater resources due to its relatively small size and low rainfall. Coastal plain aquifers, known as Quaternary deposits are comprised of alluvial fan units that hold little to no freshwater other than for intermittent periods at times after cyclonic rains.

The main freshwater groundwater resources are located in the hinterland within the Tertiary Cape Range Group. A cross-section through the aquifer system is shown in Figure 62. The Cape Range Group Tertiary limestone has been calcified to a depth of 50 m. This aquifer is unconfined to semi-confined. The Mandu Formation forms the base and each unit slopes towards the east. Deeper aquifer and Mesozoic to Palaeozoic basement rocks both contain saline water (Martin, 1990).

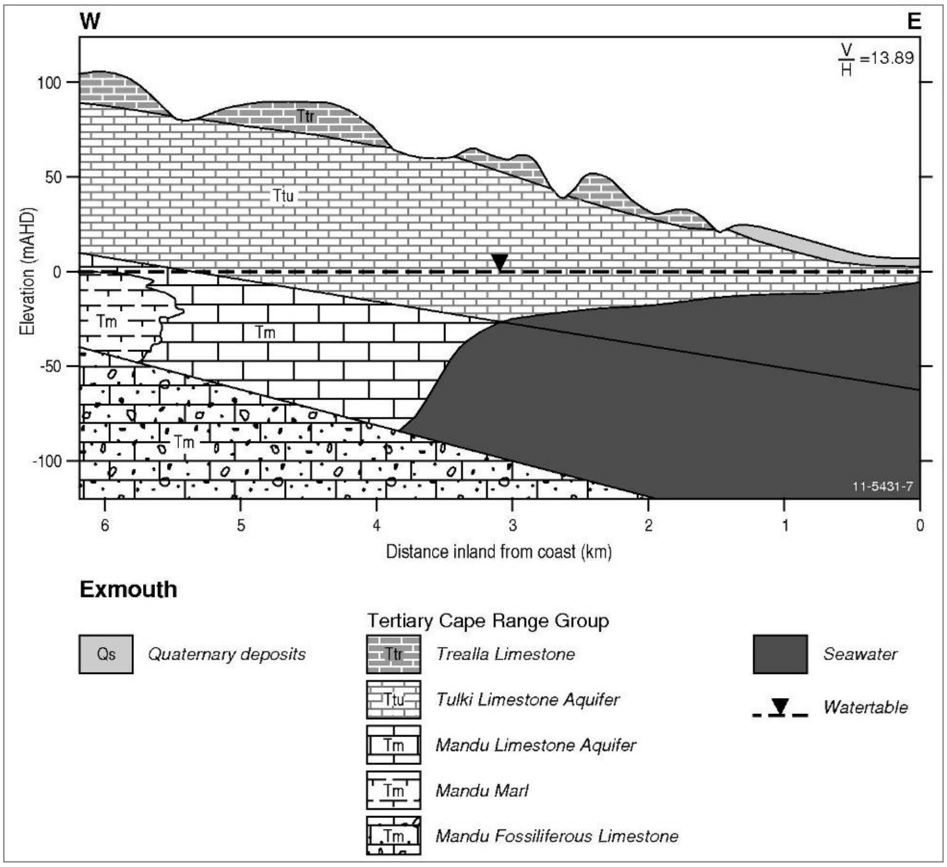

Figure 62 *Cross-section through the Exmouth area modified from Fig 6 of Water and Rivers Commission (1999).*

Recharge into the unconfined aquifers occurs predominately by direct rainfall infiltration or through the ephemeral streams while discharge occurs through abstraction, evapotranspiration, flow into the ocean or via springs (Water and Rivers Commission, 1999). The watertable lies a couple of metres above sea level near the coast and rises to 15 m in elevation inland (EPA, 1999). The corresponding APT for Exmouth (Table 45, Appendix 2) provides more detailed hydrogeological information about the Cape Range Group aquifers.

3.5.1.1.5. Land and Water Use

Exmouth attracts tourism and recreational activities and supports fishing, mining and pastoral industries. Potable water is limited to groundwater, which is carefully harvested from within the sensitive karst system (EPA, 1999).

3.5.1.1.6. Incidence of SWI

SWI has been reported in some bores in the coastal and karst hinterland aquifers based on groundwater samples collected annually after periods of intense pumping (Lee, 2004).

3.5.2. Carbonate, Mediterranean, Temperate Summer Dry

Two carbonate aquifers within a Mediterranean, temperate summer dry climate class have been investigated and these at Port MacDonnell and Uley South, both in South Australia.

3.5.2.1. Port MacDonnell, SA

3.5.2.1.1. Location

Port MacDonnell is located in the southwest corner of South Australia, approximately 30 km south of Mount Gambier on what is known as the Limestone Coast (Figure 63). The region surrounding Port MacDonnell hosts a wide variety of industries and groundwater is the main source of water used.

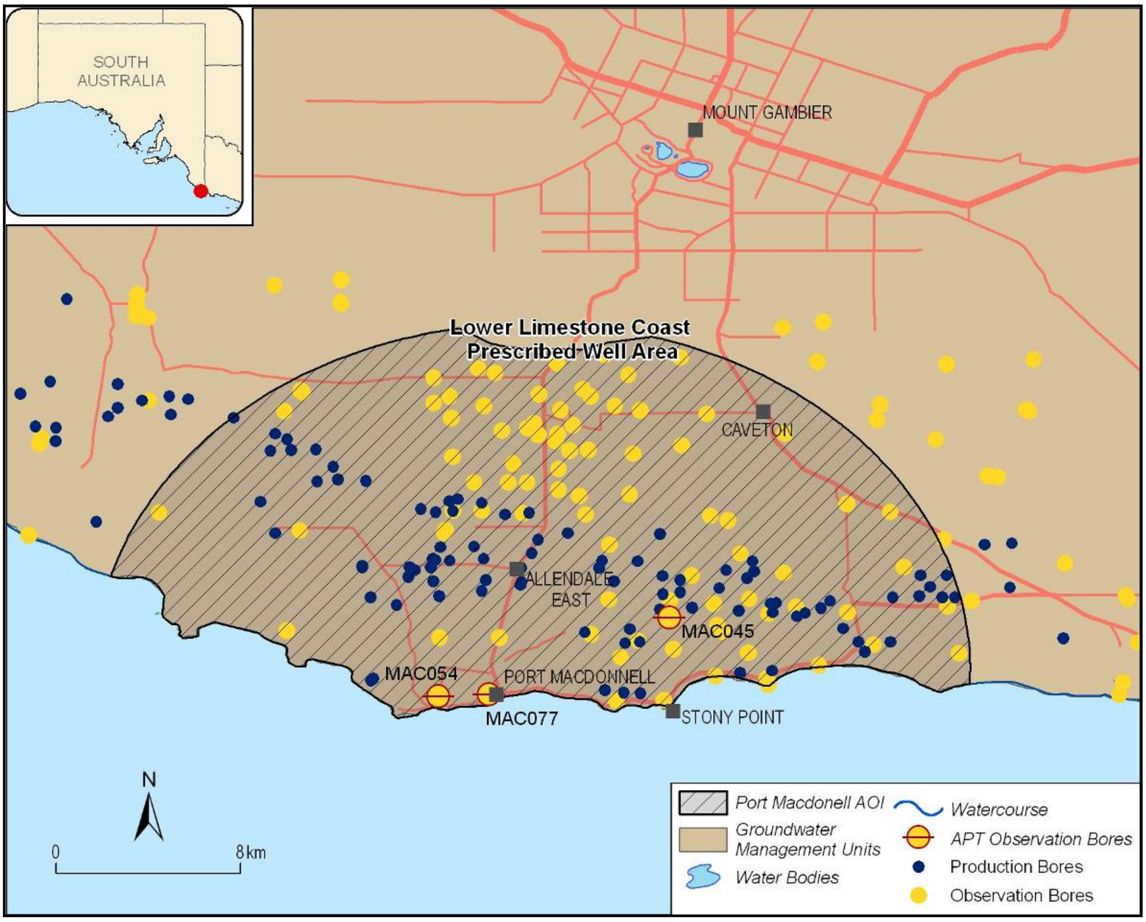

Figure 63 *Location map of Port MacDonnell (SA) showing production bores, observation bores and PWA extent.*

3.5.2.1.2. Climate

Port MacDonnell has a Mediterranean climate, with cool wet winters and milt to hot, dry summers (Paydar et al., 2009). The mean annual rainfall is 711 mm. Approximately 13 % of the rainfall falls in summer, and winter receives approximately 39 %. The monthly mean maximum temperature is 24.4 °C for summer, 13.7 °C in winter and 18.9 °C for the year (BOM 1942-2011, Mount Gambier Aero).

3.5.2.1.3. Geology and Geomorphology

In the Port MacDonnell area, the landscape is an extensive plain with belts of sand dunes and swamps. There is little topographic relief, except from a series of sand dunes parallel to the coast that are between 25 and 50 m high. There are a variety of wetland systems in the area. The geology of the area is predominantly limestone, but also includes volcanic sediments and surface features such as the Blue Lake and Crater Lakes of the nearby

Mount Gambier. The area is host to karst features such as cave systems, sinkholes and spring lakes as well as coastal lakes.

Groundwater in Port MacDonnell is a part of the Gambier Basin, which is a sub-basin of the larger Otway Basin. The Gambier Basin is composed of a sedimentary sequence that was deposited intermittently from the Jurassic through to recent times.

3.5.2.1.4. Hydrogeology

Information about the hydrogeology of Port MacDonnell was derived from King and Dodds (2002).

Within the area there are two main regional aquifer systems that are separated by aquitards (refer to Figure 64). The main hydrogeological units are the Tertiary Gambier Limestone unconfined aquifer and the Tertiary Dilwyn Formation confined aquifer. These are separated by the Dilwyn Formation aquitard, which comprises poorly consolidated marls and clays. The Tertiary Gambier Limestone ranges in thickness from 100 to 300 m. In some areas numerous karstic features have formed a well-developed secondary permeability. The Dilwyn Formation is up to 800 m in thickness and is composed of interbedded quartz sand, finer grained sediment and clay horizons.

The unconfined Gambier Limestone Aquifer receives recharge from lateral flow, infiltration of rainfall and upward leakage of groundwater from the confined aquifer. Recharge to the confined Dilwyn Formation aquifer occurs in the area north of Mount Gambier as leakage where the potentiometric head of the confined aquifer is lower than that of the unconfined aquifer.

Numerous karst features are present. Groundwater flow is generally from the north towards the south or southwest, with discharge at the coast. There are a number of significant coastal spring discharges occurring, with the total discharge from these springs estimated to be about 160 000 ML/year.

The upper unconfined aquifer is the major source of groundwater used near Port MacDonnell. For detailed information and hydrogeological information about the two aquifers and the confining layer at Port MacDonnell, refer to Table 46, Appendix 2.

3.5.2.1.5. Land and Water Use

The area around Port MacDonnell is used for a diverse range of industries including sheep, beef and dairy production, cereal cropping, wine grapes, annual horticulture crops, crop and pasture seed production and forestry. Groundwater is the main source of water in the area, with irrigation and forestry being the two biggest users of the groundwater. Water is also used for recreation and drinking supplies.

3.5.2.1.6. Incidence of SWI

Early scoping for potable water was conducted by Barnett (1976), who found highly saline groundwater approximately 500 m inland of the coast. In the year 2000, it was reported that there was a risk of salinisation of groundwater if over-pumping occurred in the area (Stadter and Yan, 2000). This was followed by an investigation by King and Dodds (2002) who subsequently conducted a transient electromagnetic survey to determine the potential presence of the saltwater interface at a depth of approximately 200 m.

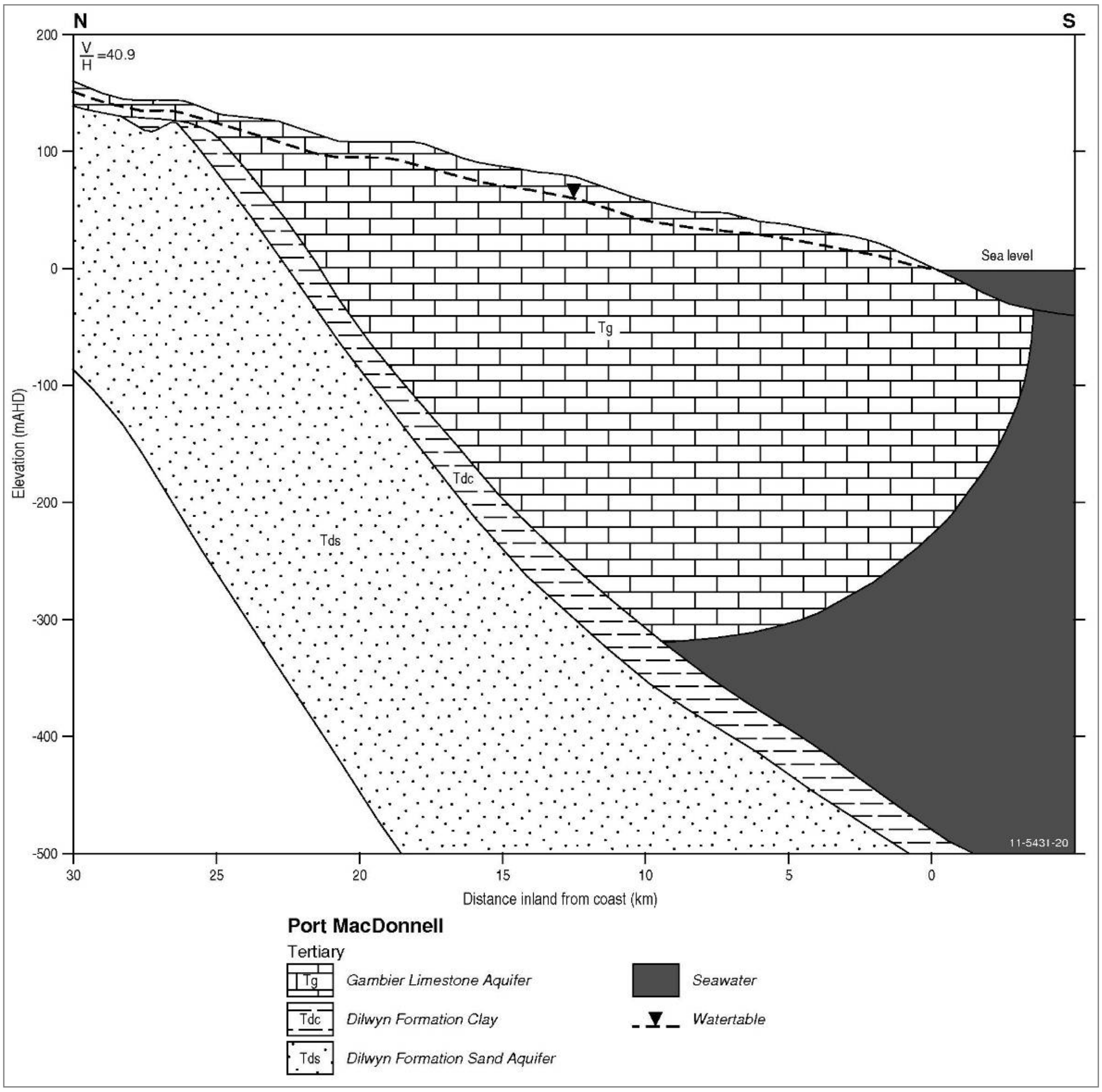

Figure 64 *Cross-section through the Port MacDonnell area, adapted from Fig. 2 in King and Dodds (2002).*

3.5.2.2. Uley South, SA

3.5.2.2.1. Location

Uley South is located at the southern extent of the Eyre Peninsula, in South Australia. It is approximately 30 km west of Port Lincoln and is situated on coastline adjacent the Great Australian Bight (Figure 65).

3.5.2.2.2. Climate

Uley South on the Eyre Peninsula experiences a semi-arid climate. The mean annual rainfall is 388 mm, with approximately 13 % of the rainfall falling in summer, and approximately 43 % in winter. The monthly mean maximum temperature is 25.4 °C for summer, 16.6 °C in winter, and 21.1 °C for the year (BOM 1992-2011, North Shields, Port Lincoln AWS).

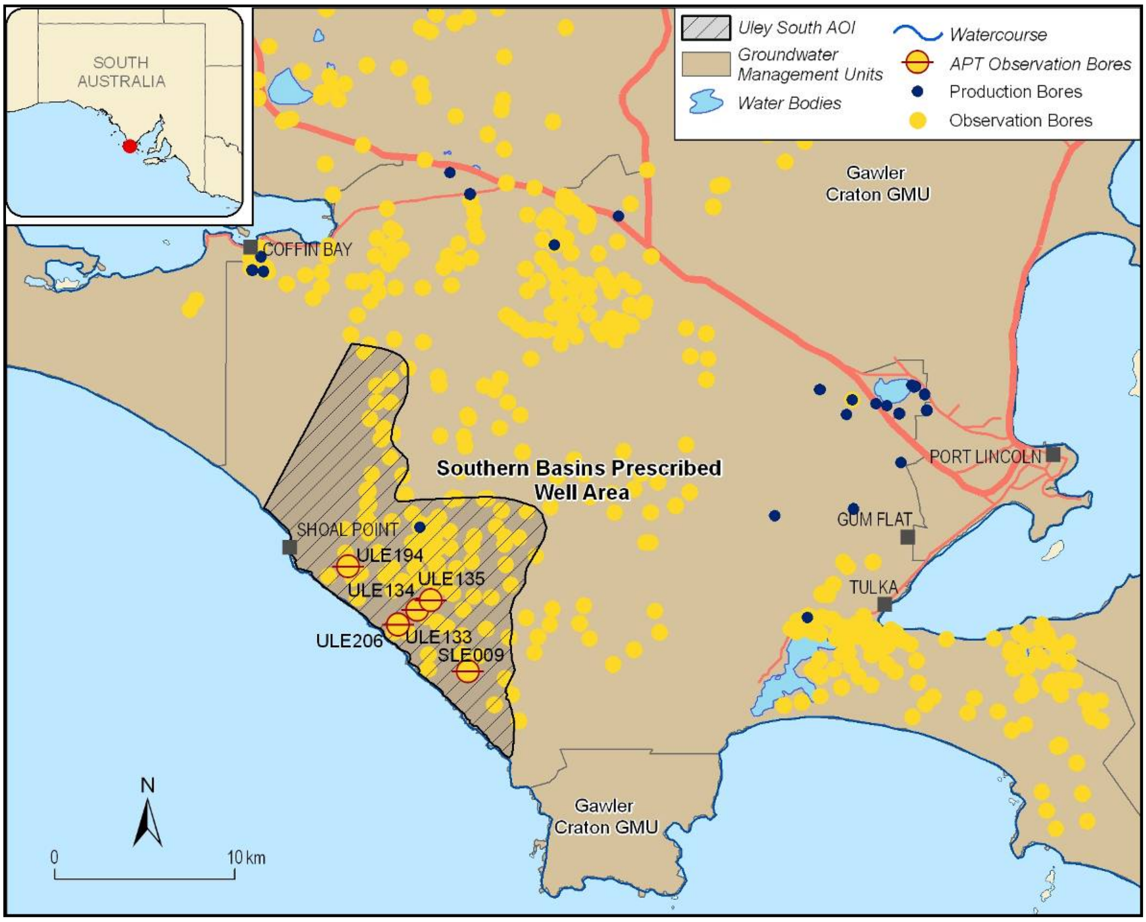

Figure 65 *Location map of Uley South (SA) displaying the location of observation bores, production bores and the PWA extent.*

3.5.2.2.3. Geology and Geomorphology

Uley South is topographically flat to slightly undulating with an elevation of less than 20 m AHD. It is bounded in the south by coastline to the Southern Ocean, where cliffs rise to a height greater than 140 m AHD (Seidel, 2008). To the west, north and east the topography rises between 70 to 140 m AHD. The Precambrian basement unit strongly controls the thickness and geometry of the stratigraphy overlying it. The wider region has been described by Evans (2002) as exhibiting an undulating topographic relief that is typical of an ancient dunal system, with dramatic coastal cliffs and large internal drainage catchments. The land elevation ranges widely from 140 m high coastal cliffs and bedrock highs of up to 200 m, through to inland depressions at sea level containing saline lakes.

Zulfic et al. (2006) provide a description of the geology and hydrogeology in the area. The basement units of Uley South are believed to consist of both weathered and unweathered Archaean quartz-feldspar gneiss and feldspathic quartzite. Directly overlying the basement rocks are Tertiary sediments comprising fluvial sands, clays and grit with some lignitic lenses. These units are over 60 m thick in the basement palaeovalley troughs. At the top of the Tertiary sands there exists a 5-25 m thick clayey laterite palaeosol horizon underneath Quaternary limestone, known as the Bridgewater Formation. The limestone’s thickness depends on its location, as it drapes over the undulations and channels provided by the underlying units. It is over 130 m thick in the Uley South region. The sediments are mostly aeolian fine sand-sized shell fragments that are generally unconsolidated or loosely aggregated. It can be consolidated in parts and is laterally variable in composition.

3.5.2.2.4. Hydrogeology

Groundwater in the Uley Basin predominantly occurs within three aquifer units: the Quaternary Bridgewater Formation, Tertiary Wanilla Formation and a volcano-metasedimentary basement sequence. A cross-section through this system is shown in Figure 66. Tertiary and Quaternary age sediments form the major low salinity aquifers within the Eyre Peninsula and these overlie the crystalline basement rocks and volcanics of the Gawler Craton. A number of groundwater basins, such as Uley South, are found within north-south trending palaeovalley depressions situated within the fractured basement rock. These depressions have been filled by Tertiary sands, clays and carbonaceous sediments. Tertiary clay overlies the Tertiary sands aquifer, and it forms a relatively effective aquitard but is not continuous; therefore, there may be a number of areas where there is connection between Quaternary and Tertiary sediments (Zulfic et al., 2006).

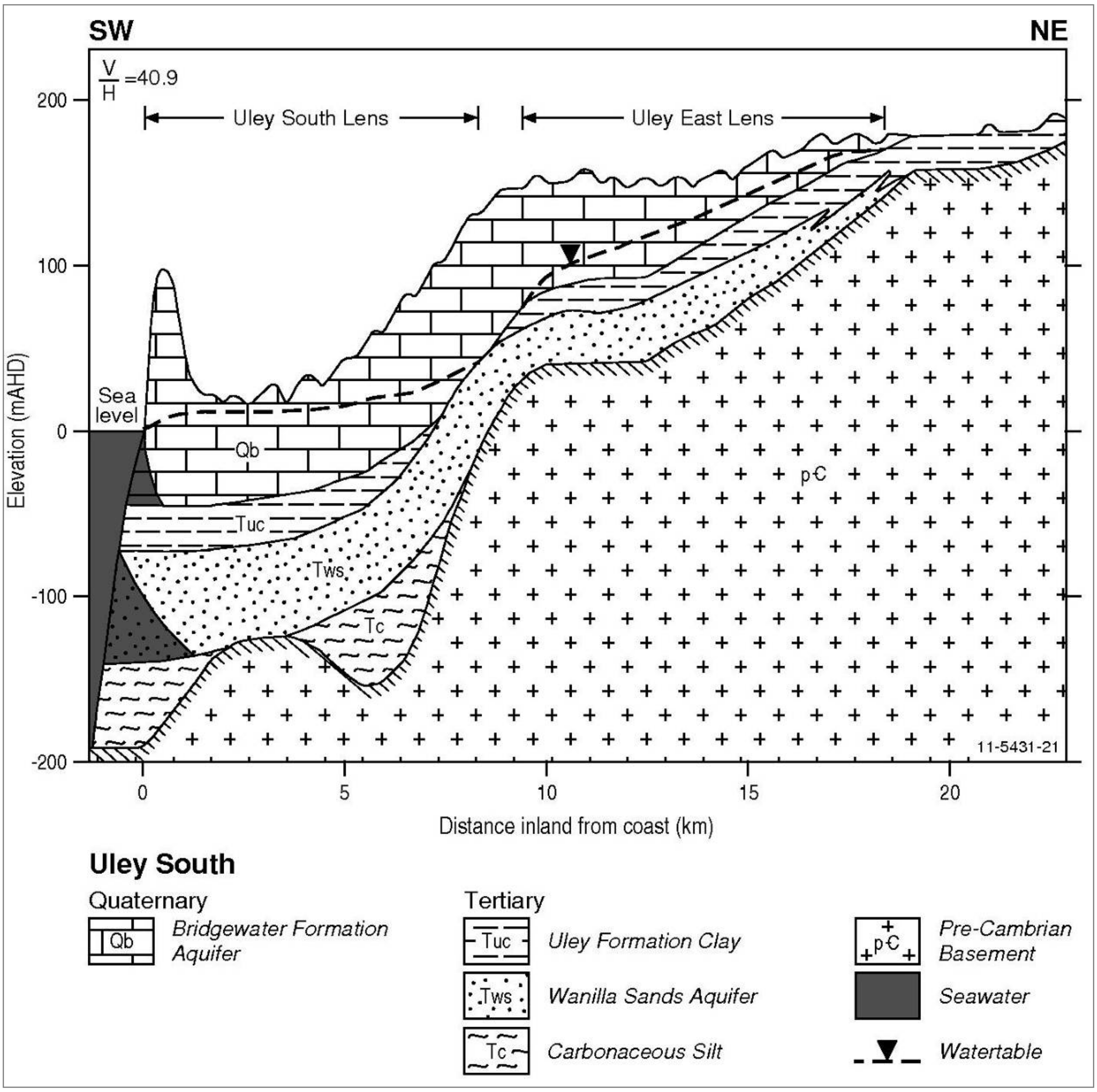

Figure 66 *Cross-section through the Uley South area, adapted from Fig. 2 of Evans (2002).*

The Tertiary sediments have been subsequently overlain by the Quaternary Bridgewater Formation. The karstic nature of this aquifer dramatically increases the amount of recharge available to the underlying aquifers during intense rainfall events, and the volumes of recharge are much higher than would normally be expected.

Rainfall is the primary source of recharge to the Bridgewater Formation Limestone aquifer. The soils over the limestone are thin, which promote rapid infiltration of rainfall, favouring relatively high recharge rates in selective areas.

The underlying Tertiary Wanilla Sands Aquifer is mostly adjacent to the Southern Ocean coastline. This aquifer is mostly confined, but in some parts is unconfined and has poor to moderate yields. More detailed hydrogeological information about Uley South aquifers can be found within the corresponding APT (Table 47, Appendix 2).

3.5.2.2.5. Land and Water Use

Groundwater is the main source of potable water on the Eyre Peninsula and the South Australian Water Corporation (SA Water) is the largest user. Groundwater is used to provide domestic supplies to the town of Port Lincoln and other townships, as well as for irrigation and industry. The main land uses include recreational grounds, pastures, horticulture, townships, and cropping.

3.5.2.2.6. Incidence of SWI

Below-average rainfall and increased demands for water have led to concerns regarding the sustainability of groundwater resources and the risks of SWI on the Eyre Peninsula. There have been noticeable declines in groundwater levels from the Uley Basin due to over-extractions. Since salinity measurements began, there have been no significant increases in TDS reported. The monitoring, however, has not been seawater interface specific and SWI investigations are in progress.

3.5.3. Summary, Carbonate

The carbonate-aquifer CSAs may be multilayered and can be associated with other aquifer types. For example, in Exmouth, very small amounts of groundwater are stored in alluvial fans overlying the carbonate aquifer. In Port MacDonnell, there are two aquifers that are separated by an aquitard with the lower aquifer comprising interbedded sands and silts. In Uley South, two primary aquifer systems are identified, with the carbonate aquifer having the main groundwater resource.

The carbonate aquifers often contain karstic morphologies, such as caves, sink holes and spring lakes. The karstic nature of the aquifer means that the aquifer often will rapidly transmit and receive recharge through rainfall infiltration. It also means, however, that there is extreme anisotropy in the hydraulic conductivities of the aquifers. Transmissivities can be very high, and for this reason the water level in the aquifer will rapidly respond to seasonal, climatic and anthropogenic influences. Exmouth - and arid climates in general - are vulnerable to periods of very low rainfall and recharge. The mean annual rainfall of Uley South is also very low, and periods of low rainfall can also be characteristic of Mediterranean, temperate, summer dry climates.

Groundwater can occur in freshwater lenses that overlie saline groundwater; also, the distribution of the groundwater depends on the morphology of the basement rock underlying the carbonate deposits. At Uley South, for example, carbonate rock units are particularly thick, with aquifers having formed within basement rock palaeochannels.

3.6. Basalt

Werribee, Victoria is the only CSA in this study that has a basalt aquifer type.

3.6.1. Basalt, Temperate, Without Dry Season

Werribee is a rural and residential area that uses groundwater to support its diverse land uses, in particular horticulture. Groundwater is particularly essential in times of low rainfall. This CSA sits within a temperate climate, without a pronounced dry season.

3.6.1.1. Werribee, VIC

3.6.1.1.1. Location

Werribee is located in Victoria on Port Phillip Bay, approximately 25 km southwest of Melbourne (Figure 67).

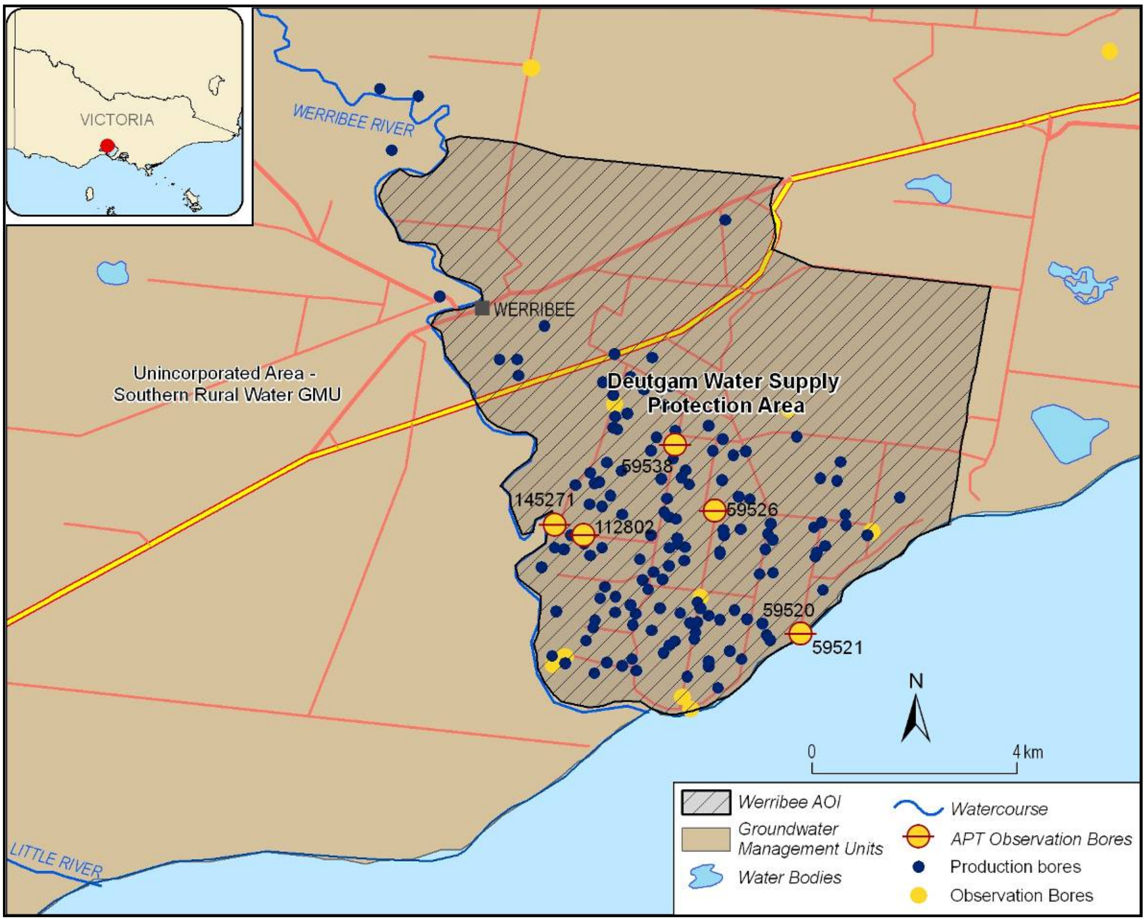

Figure 67 *Location map for Werribee (VIC) displaying observation bores, production bores and GMU extent.*

3.6.1.1.2. Climate

Werribee experiences a Mediterranean-type of climate, with hot, dry summers and cool, wet winters. The mean annual rainfall is 543 mm. Approximately 25 % of the rainfall falls in summer, and winter receives approximately

22 %. The area can be subjected to periods of drought, for example the years from 2002-2009 were particularly dry. The monthly mean maximum temperature is 25 °C for summer, 14.2 °C in winter, and 19.6 °C for the year (BOM 1943-2011, Laverton RAAF).

3.6.1.1.3. Geology and Geomorphology

Werribee is the site of the Werribee Delta plain, associated with the Werribee River, which discharges to Port Phillip Bay. The topography of the area is generally flat, with minor undulations. The surface geology includes Quaternary plain deposits, alluvium, colluvium and gully alluvium, as well as lagoon and swamp deposits (Dahlhaus et al., 2004). The Werribee River is tidal, with tidal influences evident up to 4 km upstream from the river mouth (SKM, 2005).

The Werribee Delta was formed by the accumulation of sediments carried by the Werribee River and its tributaries. The sediments that overlie the Newer Volcanics are of mixed provenance, though mostly derived from the erosion of the Roweley (Parwan) Valley since the Pliocene. The Newer Volcanics are terrestrially deposited basalts that have been subjected to fracturing since their deposition in the Quaternary and Tertiary. These overlie Tertiary Brighton Group sediments, which comprise marine to non-marine clay, silt and fine sand. Also of Tertiary age are the marine marls, clays and silts of the Fyansford Formation and the Werribee Formation. The Werribee Formation comprises alluvial and marginal marine clay, silt and fine sands (SKM, 2005).

3.6.1.1.4. Hydrogeology

The aquifer in the Werribee District is a shallow unconfined system comprised of the alluvial sediments and basalts that form the Werribee River Delta (Figure 68). The alluvial sediments are hydraulically connected to the underlying basalts. The aquifer is generally 50 m thick, and the most permeable horizons are believed to be the fractured basalts and the coarser sediments immediately overlying the basalts (SKM, 2005).

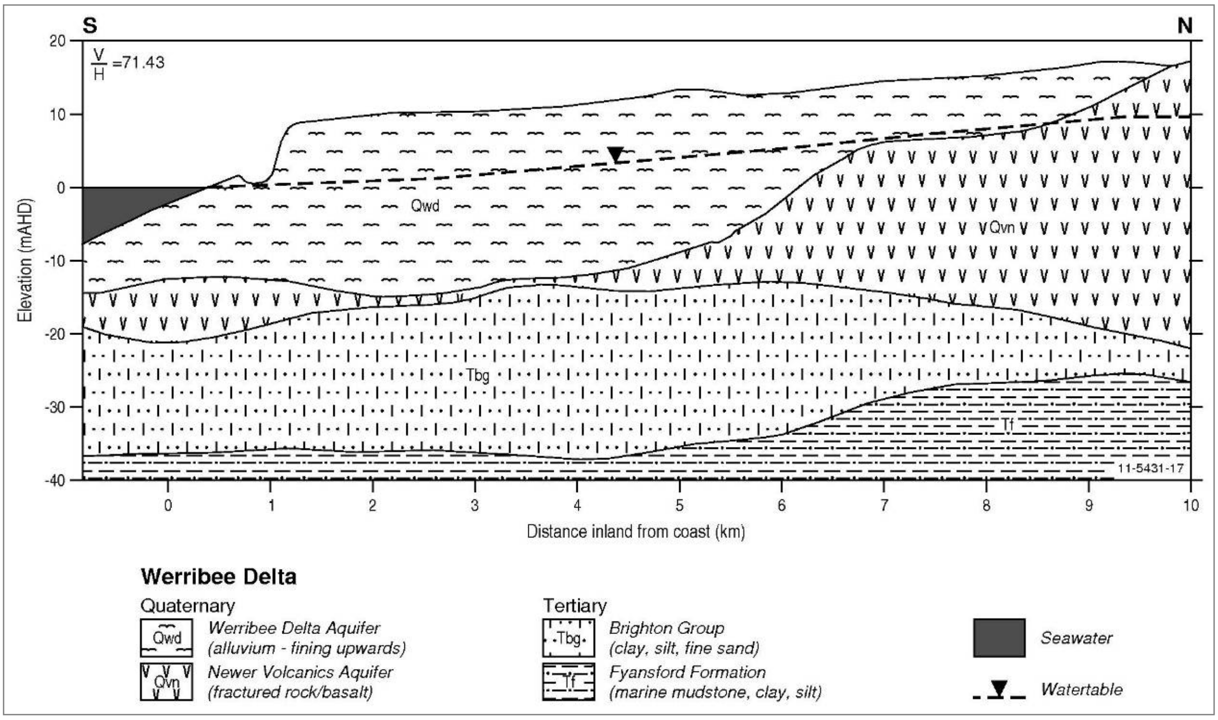

***Figure 68** Cross-section through the Werribee area, adapted from Fig 5 of SKM (2005).*

Recharge to the aquifer is through rainfall, as well as through a network of constructed channels used to distribute surface water for irrigation. Without irrigation, groundwater generally flows in a north to south direction, discharging into the bay and the Werribee River. Groundwater gradients and movement have, however, have been altered with extraction. To the west of the river, treatment lagoons and effluent irrigation on Melbourne Water land represent an important recharge mechanism for that part of the aquifer. In Appendix 2, there are two APTs for Werribee. These are Table 48 and Table 49, which represent conceptualisations parallel to, and perpendicular to, the Werribee River, respectively.

3.6.1.1.5. Land and Water Use

Groundwater and surface water are both used for irrigation to support the major horticultural industry on the eastern portion of the Werribee Delta. Shallow bores provide water for stock and domestic supplies. In addition to horticulture, the dominant land uses in the area are urban and industrial development, sewerage treatment lagoons, conservation areas, recreational developments and a government aviation base. Drought conditions from 2002 to 2011 have resulted in decreased rainfall recharge and reduced surface water availability. As a consequence groundwater demand has increased.

3.6.1.1.6. Incidence of SWI

The Werribee Irrigation District is the only location in Victoria where SWI is reported to have occurred. According to SKM (2005), between 2002 and 2004, the aquifer experienced high demand as a result of on-going drought conditions. Increased groundwater extractions and reduced recharge led to excessive drawdowns. In 2004, concerns were raised regarding the potential for saltwater intrusion into the aquifers from seawater, as well as saline water within the Werribee River’s tidal reach. In the study by SKM (2005), only one bore showed an impact of seawater influx based on hydrochemistry. This bore was one of the deeper bores in the area (screened 26-28 m), located immediately adjacent Port Phillip Bay.

3.6.2. Summary, Basalt

Werribee’s major aquifer includes fractured basalts that are in hydraulic connection with overlying alluvial sediments deposited by the Werribee River. The layered aquifers in Werribee are semi-confined to unconfined, and are primarily replenished through rainfall recharge, as well as river losses and irrigation returns. Werribee has been affected by SWI as a consequence of drought and excessive groundwater extractions.

Basaltic aquifers do not necessarily have a high primary porosity, unless they contain abundant vesicles. The ability for the aquifer to store groundwater therefore depends on the nature of the secondary porosity through fracturing. Areas that contain more fractures and hydraulically connected vesicles will be able to store better quality groundwater for resource exploitation. The degree of SWI vulnerability therefore depends on the orientation of the fractures with respect to the coast and the possibility for seawater to transmit through these fractures.

3.7. Fractured, Undivided

Howard Springs, NT is the only CSA with a fractured/undivided classification. Recall that the term undivided refers to the fact that the lithology is mixed, and that the lithology has not been mapped at the national-scale, as was previously discussed in Section 2.1.2. This class is distinct from the basalt principal aquifer type, which is another class of fractured rock, and karstified rocks, which are included in the carbonate class.

3.7.1. Fractured, Undivided, Tropical

Howard Springs, NT is the only CSA in the Northern Territory. It is also the only CSA in this study that contains a fractured/undivided principle aquifer type. The CSA experiences a tropical climate. Often fractured rocks form the basement unit of coastal aquifers, which have subsequently been overlain by younger sediments that form the primary aquifer. In this case, however, the fractured rocks of Howard Springs provide an important aquifer to support domestic and agricultural use in the area.

3.7.1.1. Howard Springs, NT

3.7.1.1.1. Location

Howard Springs is located in Northern Territory, on the northern coast of Australia, approximately 25 km northeast of Darwin (Figure 69).

3.7.1.1.2. Climate

Howard Springs experiences a monsoonal climate marked with wet summers and dry winters. The mean annual rainfall is 1734 mm, with about 79 % of the rainfall falling between December-March, and 0.5 % during winter. There is little change in mean temperature throughout the year, as the monthly mean maximum temperature is 31.9 °C for summer, 30.8 °C in winter, and 32 °C for the year (BOM 1941-2011, Darwin Airport).

3.7.1.1.3. Geology and Geomorphology

Elevations in the area range from about 140 m in the southern foothills to sea level on the northern coast. The area is characterised by extensive intertidal flats, mangroves, swamps, estuarine plains, ephemeral and perennial lagoons and broad drainage channels. At the coast, the geomorphological characteristics depend on the type and frequency of sediment being supplied via channels, as well as topographic and tidal influences. Saline and calcic mud, clay and silt are deposited in tidal flats, for example, while mangroves dominate where freshwater drainage channels deposit silt and clay. The inland regions can mostly be described as flat to undulating plains with some areas of dissected plateaus or undulating granitic woodlands. Laterite and Cretaceous sediments form much of the superficial cover in this area

To the east of Howard Springs, the bedrock geology in the area consists of dolomite, sandstone, shale, siltstone, schist. These units have been highly deformed and folded almost vertically. To the south and southwest of Howard Springs the area is distinguished by more igneous intrusives, resistant and highly deformed sandstone as well as metamorphic rocks. The bedrock is Lower Proterozoic in age and is covered by 20-50 m of Cretaceous sandstone, siltstone and claystone, overlain by approximately 10 m of laterite (Haig and Townsend, 2003).

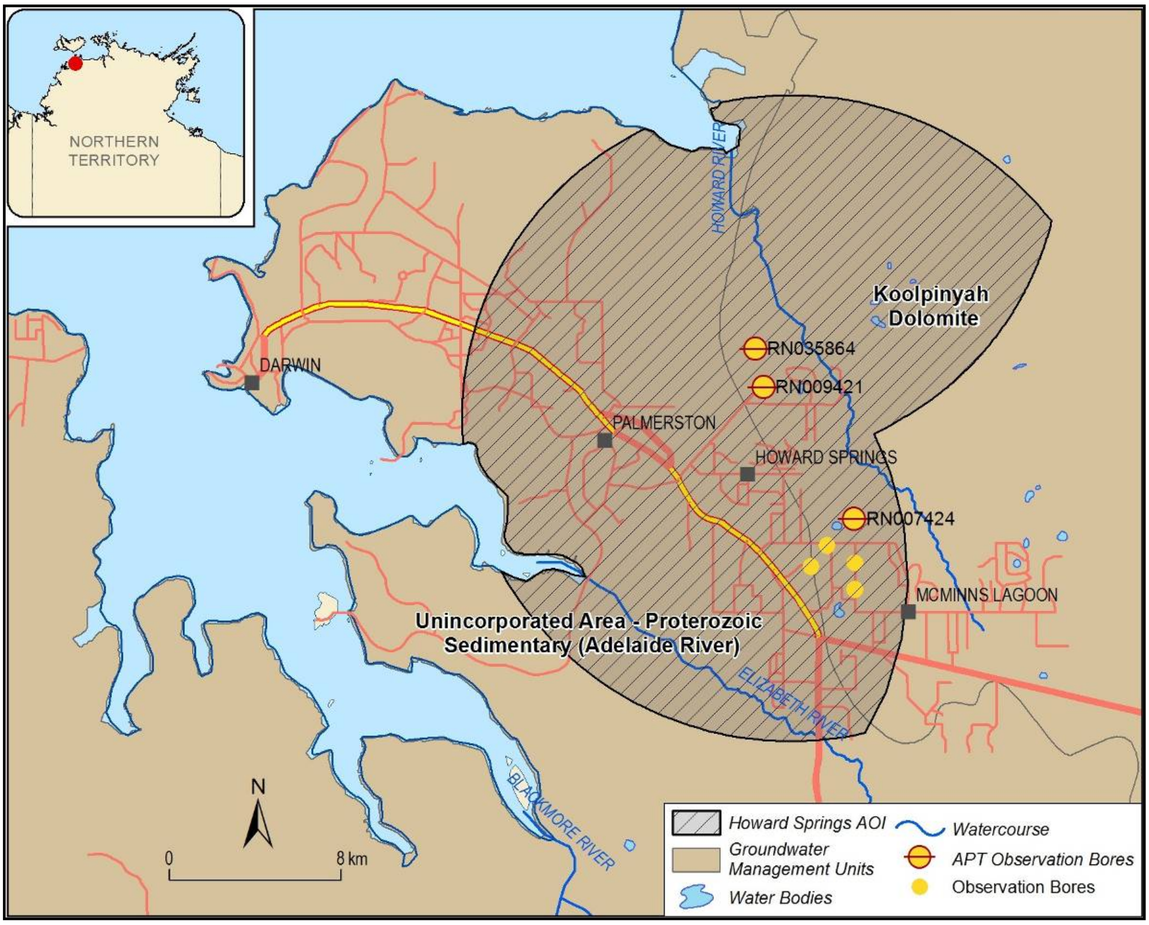

Figure 69 *Location map for Howard Springs (NT) displaying observation bores, production bores and GMU extent.*

3.7.1.1.4. Hydrogeology

The hydrogeology of the Howard Springs area is shown in Figure 70. The shallow laterite sediments comprise a regional unconfined aquifer system that is approximately 10 m thick and exerts preferential flow. Beneath these lie 30-60 m of Cretaceous aged sediments making up the Darwin Member of the Bathurst Island Formation. The lithology of the Darwin member is a quartz conglomerate. The Darwin member overlies the weathered zone of the Coomalie/Koolpinyah Dolomite, and together these sediments form a low yielding aquifer. The Coomalie/Koolpinyah dolomite acts as the major aquifer in the area and is considered to be a high yielding aquifer (Haig and Townsend, 2003).

Recharge occurs by direct infiltration of water into the regional aquifers during the wet season. It occurs with prolonged rainfall, and recharge also includes infiltration via river channels and floodplains. Although the aquifers are recharged during the wet season, they become depleted during the dry season (CSIRO, 2009a). Groundwater in the area flows from high elevation to low elevation, with discharge occuring via springs, swamps, wetlands and river channels, and out to the sea. At the end of dry season, there are areas of wetland that persist due to perched aquifers, although most shallow groundwater has discharged (Haig and Townsend 2003). For more detailed information about the hydrogeology of Howard Springs, refer to the corresponding APT (Table 50, Appendix 2).

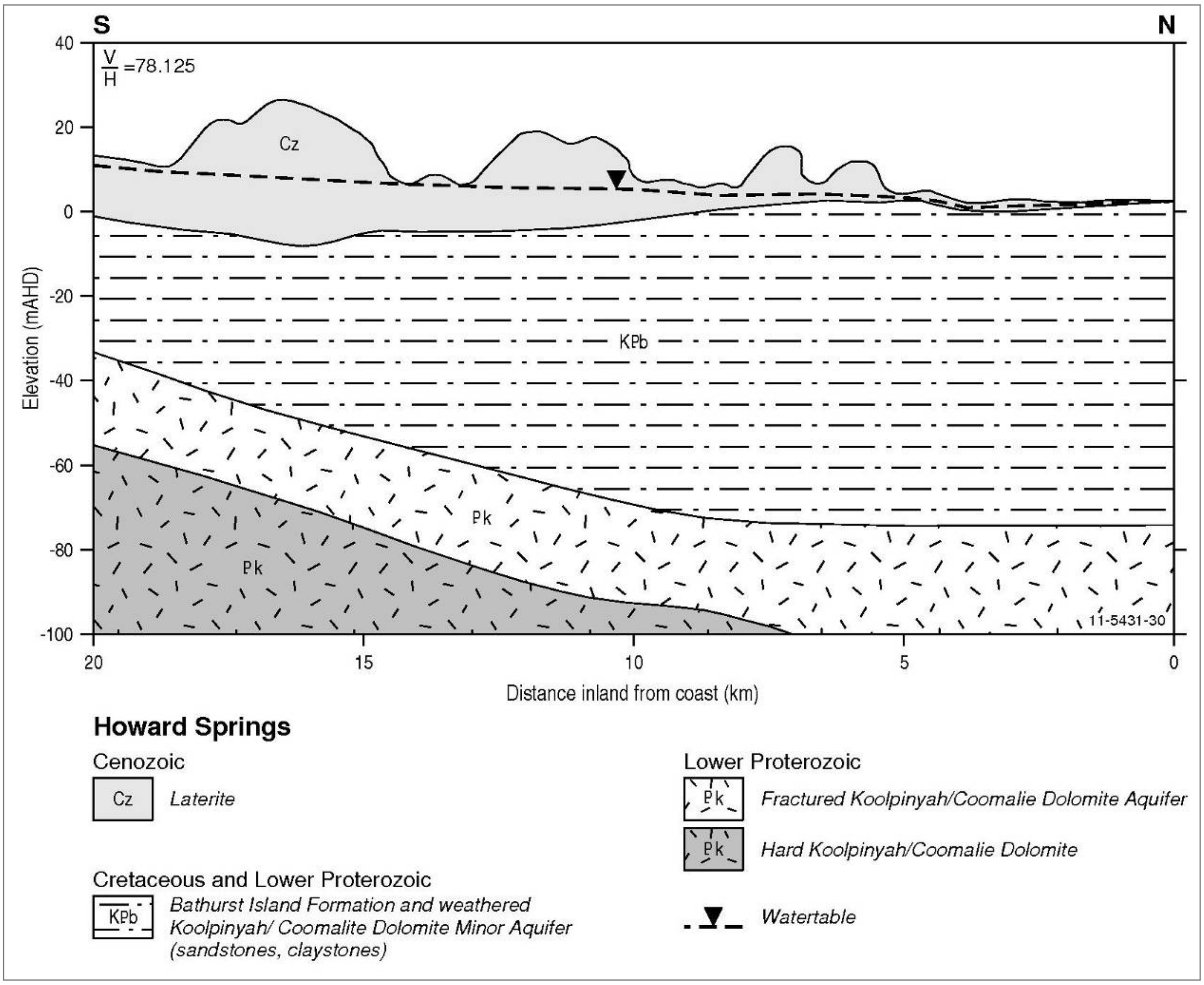

Figure 70 *Cross-section through the Howard Springs area modified from Fig 37 of EHA (2009) (Note that the saltwater interface is not evident in this figure).*

3.7.1.1.5. Land and Water Use

The Howard Springs area uses groundwater for the public water supply, as well as for rural, domestic use and agriculture. Aquiculture is a major industry in the area, and currently relies on both saline and fresh surface water for use (Haig and Townsend, 2003).

3.7.1.1.6. Incidence of SWI

Lambells Lagoon, which is approximately 33 km southeast of Howard Springs, is the only region in the Northern Territory where the risk of SWI has been reported, with the main driving factor identified as groundwater extractions for horticultural and domestic use during the dry season (CSIRO, 2009b).

3.7.2. Summary, Fractured/Undivided

Fractured/undivided classes include fractured sequences of mixed lithology that have undergone metamorphism and weathering. Howard Springs has a layered aquifer system includeing fractured metasediments, dolomite and a laterite horizon. There is a high degree of connectivity between the layers. The surface of the aquifer at the coast is covered by estuarine and swamp mud, which can form a barrier, impeding seawater migration. The area is tidal, and is situated along a low-lying undulating plain, which allows seawater to be carried into the aquifer from the surface during high tides.

The fractured rock systems are characterised by highly variable hydraulic conductivities that vary with fracture size and density, as well as the degree of weathering. Similar to the basalt typology, groundwater is stored and transmitted within fractures, and the orientation of the fractures along the coast will affect the seawaters ability to encroach to the aquifer (e.g., fractures perpendicular to the coast will allow for seawater to migrate landward).

Howard Springs, NT is the only CSA in the Northern Territory. It is also the only CSA in this study that contains a fractured rock principle aquifer type. The CSA experiences a tropical climate. Often fractured rocks form the basement unit of coastal aquifers, and have been overlain by younger sedimentsthat become the primary aquifer. In this case, however, the fractured rocks of Howard Springs provide an important aquifer to support domestic and agricultural use in the area.

4. Propensity of Coastal Aquifer Types to SWI

4.1. Introduction

This chapter brings together some of the key findings of SWI vulnerability based on the literature review and characterisation of CSAs provided in Chapter 3. The characteristics of different coastal aquifer types and their propensity for SWI vulnerability based on the typological characterisation are assessed. It is important to state at the outset of this chapter that the discussion that follows is based solely on the hydrogeological conceptualisation of CSAs, and a more complete understanding of SWI vulnerability is provided within the final project summary report in which the five technical assessments are brought together for the final SWI vulnerability assessment (Ivkovic et al., 2012b; Marshall et al., 2012).

It was noted during the characterisation of the CSAs that there were common elements across all coastal aquifer types. As previously mentioned, the threat of SWI was reported across the range of coastal aquifer typologies analysed within this project. In addition, all of the coastal aquifers in this investigation have their aquifer base below sea level (perhaps an obvious statement, yet still worth noting). Anthropogenic stresses arising from groundwater pumping whereby groundwater extraction reduced the coastal freshwater discharge was a key factor reported within the review of the literature on SWI in Australia, and this appears to to be driving the threat of SWI across all coastal aquifer types. This finding is consistent with other international investigations that found groundwater pumping to be the primary cause of SWI across a range of hydrogeological settings (Barlow and Reichard, 2010; Bocanegra et al., 2010; Custodio, 2010; Steyl and Dennis, 2010). Furthermore, a recent investigation by Ferguson and Gleeson (2012) found that coastal aquifers are more vulnerable to groundwater extraction than to predicted sea-level rise under a wide range of hydrogeologic conditions and population densities, and that human water use is a key driver in the hydrology of coastal aquifers.

In order for human water use and groundwater extraction to be a driver of SWI, there, clearly, also has to be a nearby source of seawater (ocean, estuary) relative to the position of the extraction bores, as well as permeable aquifer material and/or fractures that allow for saltwater to move within an aquifer or between multi-layered aquifer systems. High permeability layers will form conduits for seawater inflow, especially in areas where freshwater heads are reduced. Confining layers, and the juxtaposition of impermeable material, such as through faults, folds and intrusions will have an impeding effect on the movement of seawater within an aquifer. These are important factors when considering the extent of SWI. Some of these considerations have been discussed on an individual CSA basis in Chapter 3. However, investigating such complex geological structures and heterogeneities in hydraulic properties within this national-scale investigation of SWI vulnerability is not feasible, as this requires detailed, local-scale, hydrogeological investigations to more clearly identify the pathways by which seawater moves, or is impeded, within individual aquifer systems. Nevertheless, some generalisations can be made based on our CSA assessment of climate groups and coastal aquifer types, and these are discussed in the sub-sections that follow.

It is important to keep in mind, that although generalisations are made, small differences in aquifer characteristics, such as anisotropic conditions, the existence of clay lenses and other geological discontinuities can produce significant changes in the saltwater-freshwater relationships, as discussed by Custodio and Bruggeman (1987). Moreover, the groundwater extraction and recharge variations across a given CSA, a component assessed within the SWI vulnerability indexing technical assessment (Norman et al., 2012), add to the complexity of inferring SWI vulnerability based solely on the aquifer characterisation at the national-scale.

4.1.1. Climate Groups

The Köppen-Geiger system of climate classification forms part of the coastal aquifer typology, as discussed in Chapter 2.1.1. The range of estimated, long-term average net recharge values to the unconfined aquifers, as noted within the APTs for each CSA, were organised by climate group and tabulated within Table 11. As one can see from this table, recharge rates are the lowest within the Arid climate group followed by the Mediterranean group, and are highest in the Temperate (other than Mediterranean) and Tropical groups. Admittedly, the data are too few to make any conclusive statements. As previously discussed within Chapter 2, the factors that influence groundwater recharge are complex and include considerations such as soil type, near surface geology, vegetation type/land use, slope and watertable depth. A potentially useful aspect of the climate group type is the inference of seasonality on groundwater recharge as discussed in Chapter 3. The recharge to extraction ratios have been assessed within the vulnerability indexing component of the project, and provide further information on water balance aspects of SWI vulnerability (Norman et al., 2012).

***Table 11** Range of estimated long-term average recharge values to unconfined aquifers within each climate group.*

Climate Group	Description	Number of Case Study areas	Recharge (mm/yr) to unconfined aquifer
1	Tropical	3	40-200
2	Arid	4	20-25
3	Mediterranean, summer dry	10	15-160
4	Temperate, dry winter	1	110
5	Temperate, without dry season	8	20-340

4.1.2. Principal Aquifer Types

In order to more easily obtain an overview of the coastal aquifer type characteristics, the aquifer parameter values for each of the CSA aquifers were grouped by principal aquifer type (Tables 12-19). The aquifer parameters were analysed in the context of the key findings from Chapter 3, and informed by the aquifer parameter sensitivity analysis, as reported in Appendix A of Morgan et al. (2012a). The sensitivity analysis had the objective of providing information on the relative influences of aquifer parameter values on the theoretical SWI steady-state toe length (e.g. the distance inland from the coast to inland extent of saltwater wedge). Some of the key findings of the sensitivity analysis were:

For the unconfined aquifer systems, the theoretical steady-state toe length is further inland in deep aquifers with low recharge, high hydraulic conductivity and low inland heads. The most sensitive parameters are the depth of the aquifer base below sea level followed by inland head, and then, equally sensitive to hydraulic conductivity and net recharge.

For the confined aquifer systems, the theoretical steady-state toe length is further inland from the coast in deep aquifers with large aquifer thickness and low inland heads. Confined aquifers are insensitive to hydraulic conductivity (when heads are fixed). While sensitivity for recharge was not assessed (it was assumed to be zero), toe length is greater in confined aquifers with low recharge.

The parameter notation used in the APT summaries listed in Tables 11-18 is as follows: hydraulic conductivity (K), net recharge (W_{net}), the depth of the aquifer base below sea level (z_0), saturated aquifer thickness (h_0), inland head (h_b), inland distance to inland head (x_b). Unconfined aquifers are shaded in green and confined aquifers in blue. The characteristics of each coastal aquifer typology are discussed below.

4.1.2.1. Coastal Alluvium

The **coastal alluvium** types include Cenozoic, unconfined to semi-confined aquifers associated with current-day river systems. They have highest hydraulic conductivities of all coastal aquifer types (Table 12) with the exception of karstic carbonate sediments. Coastal alluvium aquifers tend to be located in flat, low-lying areas and have shallow aquifer depths, typically < 70 m AHD below sea level, and relatively shallow saturated aquifer thicknesses < 60 m. Because of their shallow groundwater hydraulic gradients, freshwater outflows can be low, and so seawater may be more able to move landwards.

The coarse channels deposits within the alluvium will act as preferential flow paths for seawater to enter the aquifers. For example in the Burnett Heads CSA, the seawater intrusion interface was estimated to be moving at 100 m per year, primarily within the highly permeable aquifer channels that are in hydraulic connection to the sea (Bajracharya et al., 1998). In the cases of deeper semi-confined to confined aquifers with a similar hydraulic conductivity value, they can be relatively more vulnerable to SWI than the shallower, unconfined aquifers because of the greater depth of aquifer below sea level, lower amounts of net recharge they receive, as well as the lowered heads they exhibit when exploited.

Head values within this type of aquifer are close to, and at times slightly below, sea level, which will facilitate inland migration of seawater, especially over prolonged periods of time when net recharge is low. Coastal alluvial systems are, therefore, potentially vulnerable to SWI as a consequence of droughts and a drying climate since most groundwater recharge occurs though rainfall-runoff and associated river losses.

The outlet of the rivers associated with these coastal aquifer types will be subject to tidal influences to varying degrees, which will increase the thickness of the mixing zone (Custodio and Bruggeman, 1987). For example, in the case of the Pioneer CSA, there is an approximate 16.5 km inland tidal limit along the Pioneer River; the extraction of groundwater from bores adjacent areas of tidal influence is thought to have contributed to estuarine SWI (Werner and Gallagher, 2006).

***Table 12** Typical aquifer parameters for coastal alluvium in coastal fringe.*

Climate Group	Case study area	Aquifer	Age[3]	K (m/d)	W_{net} (mm/a)	z_0 (mAHD below surface)	h_0 (m)	h_b (mAHD)	x_b (m)
Tropical	Bowen (QLD)	Unconfined	Q	100 (0.1-100)	40 (13-70)	20 (15-25)	21[2]	0.8 (0.2-2.5)	1000
	Burdekin (QLD)	Unconfined	Q	50 (10-200)	103	38 (30-45)	39[2]	0.4 (0.2-1)	1000
Arid	Carnarvon (WA)	Riverbed Sand	Q	150 (20-800)	25	5 (0-7)	5[2]	2.1 (0.2-5)	5000
		Older Alluvium	Q	11 (1-120)	11[1]	55 (45-65)	45 (30-60)	1.0 (-1.2-3.4)	4200
Temperate dry winter	Pioneer (QLD)	Unconfined	Q	160 (60-200)	110	30 (25-40)	35[2]	3.2 (1.6-4.8)	1600
Temperate without dry season	Burnett Heads, Moore Park (QLD)	Elliot Formation	T	100 (10-1000)	90 (60-90)	15 (12-18)	15[2]	0.8 (0.2-2.2)	750
	Burnett Heads, Bargara (QLD)	Elliot Formation	T	100 (10-1000)	90 (60-90)	15 (12-18)	15[2]	0.9 (0.2-1.1)	200
		Fairymead Beds	T	50 (10-100)	0[1]	70 (65-80)	29 (28-30)	0.4 (0.2-1.1)	200
		Unconfined aquifers				Semi/Confined aquifers			

[1] Value reported within aquifer parameter table (APT); however, zero value assigned to net recharge in confined systems for mathematical analysis; [2] Mid range value reported in APT for unconfined system; this will change with variations in hydraulic head; [3] Q- Quaternary from 2.5 Million years ago to present; T – Tertiary - from 65 Million years ago to 2.5 Million years ago

4.1.2.2. Coastal Sands

The **coastal sands** types include Cenozoic (mostly Quaternary) unconfined aquifers associated with sand dunes. Typical values of hydraulic conductivity ranged from 3 to 150 m/day (Table 13). These aquifers are primarily recharged by diffuse rainfall, and because the aquifers are relatively thin, they can only store limited amounts of freshwater relative to the amount of rainfall recharge they receive. These aquifers are often located adjacent to lagoons that provide a source of saltwater. They also may also contain a freshwater lens sitting over saline water, and the primary mechanism for SWI is a thinning of the lens and up-coning from over-pumping.

Table 13 *Typical aquifer parameters for coastal sands in coastal fringe.*

Climate Group	Case study area	Aquifer	Age[4]	K (m/d)	W_{net} (mm/a)	z_0 (mAHD below surface)	h_0 (m)	h_b (mAHD)	x_b (m)
Mediterranean	Cottesloe Peninsula (WA)	Tamala Limestone sands	Q	150	55	—[1]	8[2]	0.2	1000
	Rottnest Island (WA)	Tamala Limestone sands	Q	10	120	—[1]	4[2]	0.4	500
Temperate, without dry season	Botany (NSW)	Botany Sand Beds	Q	30 (20-85)	430	25 (23-30)	35[3]	1.2 (-0.5-4)	1000
	Hat Head (NSW)	coastal sands	Q	20	270	35 (30-40)	38[3]	5	1750
	Stockton (NSW)	Stockton Sandbeds	Q	20	280	15 (10-20)	15[3]	2.5 (0.5-3.8)	1400
	Stuarts Point (NSW)	coastal sands	Q	20	270	35 (30-40)	36[3]	5.5 (2.5-6.5)	1750
	North Stradbroke Island, East (QLD)	coastal sands	Q/T	3 (0.5-5)	339	40 (10-60)	25[3]	6.0 (5.5-7.0)	500
	North Stradbroke Island, West (QLD)	coastal sands	Q/T	70 (1-155)	339	40 (10-60)	25[3]	22 (21-24)	500
	Point Nepean (VIC)	Quaternary mixed	Q	20	40	—[1]	50[3]	1.5	1700
		Unconfined aquifer				Semi/Confined aquifer			

[1] Not relevant in the case of a freshwater lens; [2] Mid range value reported in APT for freshwater lens thickness; [3] Mid range value reported in APT for unconfined system; this will change with variations in hydraulic head and freshwater lens thickness; [4] Q- Quaternary from 2.5 Million years ago to present; T – Tertiary - from 65 Million years ago to 2.5 Million years ago

4.1.2.3. Sedimentary Basin

Three sub-types of sedimentary basins were noted during the classification of coastal aquifer types: (1) unconfined, sandstone; (2) multi-layered, deep, consolidated; and (3) multi-layered, shallow, unconsolidated (carbonate aquifers were placed into a separate class). Their characteristics are described as follows.

4.1.2.3.1. Unconfined sandstone

The **unconfined, sandstone** aquifer types include Triassic to Cretaceous, sandstone units that are deep (> 200 m AHD below sea level) and thick thick (> 190 m). Typical values of hydraulic conductivity range from 1 to 15 m/day (Table 14). The representative CSAs are all located within the arid climate group and receive relatively low amounts of net recharge. Head values are close to sea level. This combination of factors means these coastal aquifer types naturally have the greatest inland SWI toe extent of all coastal aquifer types. These aquifer types generally have a considerable aquifer thickness that allows for substantial storage of fresh groundwater resources.

Table 14 *Typical aquifer parameters for unconfined sandstone, sedimentary basin in coastal fringe.*

Climate Group	Case study area	Aquifer	Age[2]	K (m/d)	W_{net} (mm/a)	z_0 (mAHD below surface)	h_0 (m)	h_b (mAHD)	x_b (m)
Arid	Broome, Coconut Wells (WA)	Broome Sandstone	J/K	15 (8-25)	25 (20-30)	200 (120-280)	225[1]	3.5 (3.2-6.0)	2500
	Broome, Cable Beach (WA)	Broome Sandstone	J/K	15 (8-25)	25 (20-30)	200 (120-280)	225[1]	2.0 (0.2-4.5)	1000
	Derby	Wallal/Erskine Sandstone	T_R/J	1 (0.2-3)	20	350 (225-500)	190[1]	2.0	4000
		Unconfined aquifers			Semi/Confined aquifers				

[1] Mid-range value reported in APT for unconfined system; this will change with variations in hydraulic head; [2] T_R- Triassic – from 250 Million years ago to 200 Million years ago; J- Jurassic - from approximately200 Million years ago to 145 Million years ago; K – Cretaceous - from 145 Million years ago to 65 Million years ago

4.1.2.3.2. Multi-layered, deep

The **multi-layered, deep** aquifer types include Cenozoic to Jurassic, sedimentary sequences, comprising mainly sandstone, coarse silt and sands, and minor limestone, with clay aquitards separating the aquifer systems (Table 15).

The upper-most unconfined aquifer is unconsolidated, in contrast to the aquifers that lie below, and thus the upper aquifer shares characteristics of the coastal sands aquifer type. In some areas the upper unconfined aquifer may overlie more saline water, such as is the case in the LeFevre Peninsula. In these areas over-extraction from the unconfined aquifer may lead to up-coning and lateral intrusion.

The confined aquifers of these types of multi-layered systems are deep (100 to > 1750 m AHD below sea level) and thick (65 to > 300 m), making these excellent aquifers for large scale development. The heads in the confined aquifers pre-development were naturally elevated because recharge occurs through aquifer outcrops at higher elevations; however, in many of these systems the heads have been lowered as a consequence of intense groundwater extractions: in some cases heads have been lowered to as much as 21 to 24 m AHD below sea level, as is seen in the Adelaide and Perth areas. These lowered heads have resulted in downward leakage from the upper aquifer systems. Moreover, the effects of urbanisation, e.g. paving and concrete drainage systems, further reduce aquifer recharge.

The combination of large aquifer depths and thickness, with low net recharge makes the theoretical SWI toe extent within the confined aquifers relatively large, particularly in those areas where heads have been drawn down below sea level. An important mitigating factor is that some of these confined freshwater aquifer systems extend some distance out to sea: the extent to which has not been investigated in Australia– which may result in the SWI interface occurring offshore. However, over-exploitation leading to excessive declines in the piezometric surface may eventually lead to SWI from offshore. The generally long delayed response of the SWI interface or mixing zone tends to give a false sense of security leading to sustained exploitations that exceed the safe yield of the system (Custodio and Bruggeman, 1987).

Some of the deeper, semi-confined and confined aquifers, such as found in the Perth Basin, become unconfined towards the coastal margin making them relatively more vulnerable to SWI when they come into direct hydraulic contact with seawater. Due to variations in hydraulic conductivity and the locations of clay layers, the saltwater interface may occur as a series of tongues of saline water separated by intervening clay beds.

Table 15 *Typical aquifer parameters for multi-layered, deep sedimentary basin in coastal fringe.*

Climate Group	Case study area	Aquifer	Age[3]	K (m/d)	W_{net} (mm/a)	z_0 (mAHD below surface)	h_0 (m)	h_b (mAHD)	x_b (m)
Mediterranean	Adelaide Metro (SA)	T1	T	3 (0.1-10)	-4[1]	175 (130-220)	80 (25-120)	-10.0 (-24.0-6.5)	5000
		T2	T	3 (1-10)	-4[1]	290 (260-320)	105 (80-110)	3.8 (2.0-6.0)	5000
	LeFevre (SA)	Semaphore Sands	Q	8 (4-13)	90	10	112	1.6 (1.3-1.8)	1000
		T1	T	10 (0.5-10)	-4[1]	175 (130-220)	80 (25-120)	-11.0 (-13.0-0)	500
		T2	T	3 (1-10)	-4[1]	290 (260-320)	105 (80-110)	-6.6 (-10.0-1.0)	500
	Willunga (SA)	Quaternary	Q	10 (0.1-10)	20 (15-30)	20	202	3.0 (1.0-6.0)	3500
		Port Willunga Formation	T	10 (0.1-20)	0	120 (80-175)	90 (60-155)	1.5 (0.7-2.0)	3500
		Maslin Sands	T	1 (0.1-1)	0	225 (160-285)	65 (10-70)	2.0 (0-2.5)	3500
	Bunbury (WA)	Superficial	Q	10 (3-16)	30 (10-60)	15 (10-20)	352	6.2 (5.6-6.6)	3000
		Yarragadee	J	20	0	400 (175-700)	300 (175-500)	3.0 (0.5-4.5)	3000
	Busselton, Vasse Shelf (WA)	Superficial	Q	2 (0.5-5)	30 (10-60)	10	52	0.7 (-0.9-2.5)	1500
		Leederville	K	1 (0.2-2)	0	80 (20-100)	65 (25-105)	1.2 (-0.1-2.3)	4300
	Perth, Whitfords (WA)	Superficial	Q/T	15 (8-50)	30	75 (50-100)	752	3.5 (2.2-4.5)	3500
		Leederville	K	1 (0.1-10)	0	275 (250-300)	175 (150-200)	4.2 (-5.0-7.0)	3500
		Yarragadee	J	2 (1-3)	0	1750 (165-1850)	1500 (1450-1550)	17.0 (-21.0-30.0)	4500
		Unconfined aquifers			Semi/Confined aquifers				

[1] *Value reported within APT; however, zero value assigned to net recharge in confined systems for mathematical analysis;* [2] *Mid range value reported in APT for unconfined system; this will change with variations in hydraulic head;* [3] *J- Jurassic - from approximately200 Million years ago to 145 Million years ago; K – Cretaceous - from 145 Million years ago to 65 Million years ago; T – Tertiary - from 65 Million years ago to 2.5 Million years ago; Q-Quaternary from 2.5 Million years ago to present.*

4.1.2.3.3. Multi-layered, shallow

The **multi-layered, shallow** aquifer types include Cenozoic, unconsolidated sediments that have been deposted within a coastal plain setting. These shallow sedimentary deposits (<50 m AHD in depth) comprise unconsolidated, sediments with multiple aquifers separated by discontinuous clay aquitards (Table 16). The aquifers are relatively thin, between 2 to 40 m thick. The unconfined aquifers share common features with the coastal sands aquifer types. The upper aquifers are replenished by infiltration of rainfall, and the underlying semi-confined aquifers can receive considerable net recharge through aquifer leakage. However, in areas where the deeper aquifers are confined, they receive little recharge. Because of the reliance on rainfall recharge, these aquifers are vulnerable to droughts and drying climates. The deeper, Tertiary sediments are characterised by variable groundwater salinity, including brackish to saline water in some places, and extensive pumping from the over-lying aquifer can result in up-coning.

***Table 16** Typical aquifer parameters for multi-layered, shallow sedimentary basin in coastal fringe.*

Climate Group	Case study area	Aquifer	Age[3]	K (m/d)	W_{net} (mm/a)	z_0 (mAHD below surface)	h_0 (m)	h_b (mAHD)	x_b (m)
Mediterranean	Albany, Ocean side (WA)	Superficial/ Pallinup Sands/ Werrilup Formation	Q/T	5 (1-50)	160	20 (15-25)	40[1]	6.0 (4.0-8.0)	1500
	Albany, Harbour side (WA)	Superficial	Q	5 (2-60)	160	5 (5-10)	2[1]	2.0 (1.7-5.5)	250
		Werrilup Formation	T	5	131[2]	25	20	1.8	800
	Esperance (WA)	Superficial/ Pallinup Sandstone	Q/T	20 (2-40)	15 (2-30)	20 (10-30)	30[1]	0.8 (0.1-3)	1600
		Werrilup Formation	T	10 (8-12)	0	32 (18-46)	10 (0.1-33)	0.5 (0.5-0.7)	300
		Unconfined aquifers			Semi/Confined aquifers				

[1] Mid range value reported in APT for unconfined system; this will change with variations in hydraulic head ; [2] Value reported within APT from leakage; however, zero value assigned to net recharge in confined systems for mathematical analysis; [3] T – Tertiary - from 65 Million years ago to 2.5 Million years ago; Q- Quaternary from 2.5 Million years ago to present

4.1.2.4. Carbonate

The **carbonate** aquifer types are primarily Cenozoic-aged and unconfined. Due to karstification, these aquifer types often have very high hydraulic conductivities in some parts, with typical values ranging from 45 to >150 m/day (Table 17). The karstic nature of carbonate aquifers dramatically increases recharge from rainfall-particularly during intense rainfall events. As a result, groundwater levels rapidly respond to seasonal, climatic and anthropogenic influences on short time scales. Groundwater within the carbonate aquifer often occurs in freshwater lenses and isolated basins that are overlying and/or adjacent to saline groundwaters. The isolated freshwater is at risk of drawing in saline waters, especially where the freshwater lenses are relatively thin.

The depths of the carbonate aquifers varied from about 15 to 300 m AHD below sea level and ranged in thickness from 20 to > 400 m. The theoretical SWI toe extent will be greatest in the deepest and thickest units, such as found in the Port MacDonnell area. Variability in hydraulic conductivity values may result in an irregular shaped SWI interface.

The deeper, confined sand aquifers can be locally important, although they are relatively low yielding aquifers in comparison to the upper carbonate aquifer. For those aquifers that are deep and thick, such as the Dilwyn Formation sands, which have an aquifer base of up to 800 m AHD below sea level and a thickness of 400 m, the theoretical SWI toe extent is naturally considerable. In the case of the Dilwyn Formation, the elevated head value suggests a mitigating effect to counter sea water pressures; however, there were few head data for the Dilwyn Formation aquifers.

Table 17 *Typical aquifer parameters for carbonate in coastal fringe.*

Climate Group	Case study area	Aquifer	Age[3]	K (m/d)	W_{net} (mm/a)	z_0 (mAHD below surface)	h_0 (m)	h_b (mAHD)	x_b (m)
Arid	Exmouth (WA)	Cape Range Group	T	150 (20-200)	25	85 (50-120)	60[1]	0.7 (-1.5-1.4)	2700
Mediterranean	Port MacDonnell (SA)	Gambier Limestone	T	45 (4-90)	30 (5-90)	290 (250-350)	300[2]	4.5 (3.2-7.0)	5000
		Dilwyn Fm Sand	T	10 (0.5-10)	0	780 (700-800)	400 (350-450)	20.5	5000
	Uley South (SA)	Bridgewater Formation Limestone	Q	150 (5-1400)	100 (50-150)	15 (10-20)	20[2]	1.6 (1.1-2.3)	2000
		Wanilla Sands	T	90 (20-150)	0	45 (25-60)	30	2.0 (1.3-3.1)	2000
		Bridgewater & Wanilla Sands	Q/T	150 (5-1400)	100 (50-150)	45 (40-60)	65[2]	1.6 (1.1-2.3)	2000
		Unconfined aquifers			Semi/Confined aquifers				

[1] Not relevant in the case of a freshwater lens, value represents lower end of freshwater thickness; [2] Mid range value reported in APT for unconfined system; this will change with variations in hydraulic head; [3] T – Tertiary - from 65 Million years ago to 2.5 Million years ago; Q- Quaternary from 2.5 Million years ago to present

4.1.2.5. Basalt

The coastal **basalt** aquifers in Australia are Cenozoic in age and generally unconfined. There was only one CSA, Werribee (VIC) with a primary basalt aquifer (Table 18). This is not surprising since basalt aquifers comprise only a relatively small percentage area, about 1.2 %, within the 15 km coastal buffer zone. In these types of aquifers, layered basalt plains store groundwater primarily in fractures and vesicles. As was found in the CSA of Werribee, basalt aquifers may be overlain by flood plain deposits associated with a current river system that is in hydraulic connection with the primary basalt aquifer. The aquifer is considered unconfined, although less permeable basalt layers may form semi/confining layers. Aquifer recharge occurs primarily through rainfall via fractures and river water losses. In the case of Werribee, deep drainage of surface water irrigation is also an important source of recharge to the aquifer. Groundwater quality can be variable within basalt aquifers. The fresher groundwaters are found in areas where there is a greater fracture density and/or permeability. These fracture openings and higher permeability areas may provide a preferential flow path for seawater migration, especially when oriented perpendicular to the source of sea water. There aren't any remarkable characteristics of this type of aquifer type that might make it more vulnerable to SWI than others. In the case of Werribee, an extended drought led to reduced heads in the aquifer, and this appears to have resulted in SWI adjacent Port Phillip Bay (SKM, 2005). Concerns have been raised by stakeholders about the risks of SWI associated with tidal effects within the Werribee River.

Table 18 *Typical aquifer parameters for basalt in coastal fringe.*

Climate Group	Case study area	Aquifer	Age^2	K (m/d)	W$_{net}$ (mm/a)	z$_0$ (mAHD below surface)	h$_0$ (m)	h$_b$ (mAHD)	x$_b$ (m)
Temperate without dry season	Werribee (VIC)	Alluvium & Newer Volcanics	Q/T	5 (0.6-23)	85	20 (15-22)	50^1	7.0 (4.0-9.0)	2500
		Unconfined aquifers			Semi/Confined aquifers				

^{1} Mid range value reported in APT for unconfined system; ^{2} T – Tertiary - from 65 Million years ago to 2.5 Million years ago; Q- Quaternary from 2.5 Million years ago to present

4.1.2.6. Fractured/Undivided

The **fractured/undivided** aquifer type of aquifer was represented by a single CSA, Howard Springs and was Proterozoic to Cretaceous in age (Table 19). This type of coastal aquifer is characterised by fractured sequences of mixed lithology which have undergone metamorphosis and weathering. The aquifers comprise a number of different stratigraphic units with a high degree of interconnectivity through fractures. In the CSA of Howard Springs, the primary carbonate aquifer is included within the mix of lithologies, and so this aquifer shares characteristics in common with other carbonate aquifer systems, such as karst weathering.

Table 19 *Typical aquifer parameters for fractured/undivided in coastal fringe.*

Climate Group	Case study area	Aquifer	Age^2	K (m/d)	W$_{net}$ (mm/a)	z$_0$ (mAHD below surface)	h$_0$ (m)	h$_b$ (mAHD)	x$_b$ (m)
Tropical	Howard Springs	Fractured sediments & Koolpinyah/ Coomalie Dolomite	K/ Proterozoic	40 (10-170)	601	100 (55-100)	25 (20-25)	10.0 (8.5-15)	2000
		Unconfined aquifer			Semi/Confined aquifer				

^{1} Value reported within APT; however, zero value assigned to net recharge in confined systems for mathematical analysis;^{2} K – Cretaceous from 145 Million years ago to 65 Million years ago; Proterozoic from approximately2500 Million years ago to 540 Million years ago

It is the weathered and fractured dolomite that is the productive aquifer in Howard Springs, although, the overlying fractured metasediments also store groundwater. The aquifers are unconfined to semi/confined aquifers and their hydraulic conductivity varies with the degree of fracture density and weathering. Recharge to the aquifer occurs where aquifer outcrops as well as through via porous sediments and fractures at the surface. Recharge through fractures can be relatively quick. Because of the karstic nature of the underlying aquifer, groundwater levels can rapidly respond to seasonal, climatic and anthropogenic influences on short time scales. For example, groundwater levels have been observed to rise and fall by up to 17 m/yr in the Darwin Rural area as aquifers become depleted during the dry season and subsequently are recharged during the wet season.

The aquifers in Howard Spring are relatively deep (100 m AHD below sea level). Where hydraulic conductivity and fracture density are high, and the aquifer in contact with sea water, fractures may provide preferential flow paths for SWI migration: especially when fracture orientation is perpendicular to the source of sea water. Because these aquifers are recharged in the elevated hinterland, the groundwater heads are comparatively high, making these aquifers more able to counter seawater pressures. However, there is a considerable tidal range north of the Howard Springs area, approximately 8 km inland from the coast, and preliminary AEM survey results yet to be confirmed suggest that SWI has occurred via the fractured dolomite at the base of the metasediments.

4.2. Summary

The main characteristics of the principal aquifer types based on the analysis of CSAs is summarised below in Table 20. It is important to note that there can be some degree of over-lap in the characteristics of principal aquifer types since some hydrogeological settings will share common elements. For example, the shallow, unconfined sand aquifers found within sedimentary basins will have similar characteristics to the coastal sands aquifer type. The basalt aquifer types, may be also be associated with a river as is the case in the Werribee (VIC) CSA, and therefore will also include alluvial sediments. The carbonate aquifer types in this study were sometimes also underlain by semi-confined to confined sand aquifers. Moreover, the fractured, undivided class may have a multiple types of aquifers (e.g, carbonate and metasediments) within the broad mix of fractured rock aquifers as found within the Howard Springs (NT) CSA. Despite these over-laps, the distinct principal aquifer types tend to have unique characteristics and implications for SWI.

Table 20 *Characteristics of principal aquifer types.*

Principal Aquifer Type	Aquifer Age	Aquifer Description	Aquifer Types	Aquifer Characteristics	SWI Implications
Coastal Alluvium	Cenozoic, primarily Quaternary	• Unconsolidated mix of gravel, sand, silt and clay deposited within floodplains of current drainage systems • A delta is found at the river outlet in areas where sediment supply exceeds rate of sediment removal • Aquifer thickness generally less than 70m	• Unconfined to semi-confined	• Recharged primarily through river losses and floods • High connectivity between multiple stacked aquifers • Watertable fluctuates with river recharge • Rich floodplain soils and easy access to groundwater make these systems attractive for irrigated agriculture (horticulture, sugar cane)	• May have preferential flow path connectivity with seawater through coarse, channel deposits • Where tides are high and the topography low and flat, the risk of SWI is heightened • During prolonged droughts, when river flows are less and hydraulic heads are lowered, these systems are at increased risk of SWI as a consequence of groundwater extraction
Coastal Sands	Quaternary	• Dune sands of aeolian and marine origin • Aquifer thickness generally less than 60m • Layers of cemented sand form “coffee rock”	• Unconfined	• Recharge primarily occurs as diffuse recharge of rainfall • Discharge occurs into nearby wetlands and estuaries • Commonly characterised by a freshwater lens sitting over saline water • Aquifer storage volumes tend to be relatively small relative to recharge • Local sources of groundwater are commonly exploited for domestic water use, as well as parks and gardens • Under increasing pressure due to increased population growth in coastal areas	• The relatively low amounts of groundwater storage relative to rainfall recharge mean that these aquifers are particularly vulnerable to excessive pumping, which may result in up-coning of seawater and/or lateral SWI intrusion
Sedimentary Basins: Unconfined sandstone	Triassic to Cretaceous	• These aquifer types comprise deep (>200m AHD	• Unconfined	• Indurated sedimentary aquifers may extend large distances out	• The extension of the unconfined aquifer out to sea may facilitate

Principal Aquifer Type	Aquifer Age	Aquifer Description	Aquifer Types	Aquifer Characteristics	SWI Implications
		below sea level), thick (>190m), unconfined, sandstone units		to sea • Thick sedimentary sequences store large volumes of water • Provide a source of water (town water supply and horticulture) in arid areas • Relatively low recharge rates	seawater migration • Naturally large inland SWI toe extent
Sedimentary Basins: Multi-layered, consolidated, deep	Cenozoic through to Quaternary	• Basin thickness thousands of metres • Sedimentary sequences comprising sandstone or multiple-layering of sand, sandstone, coarse silt and minor limestone aquifers, with clay aquitards in-between • Commonly mantled by recent sediments, often sands, that form an upper, unconfined aquifer	• Unconfined upper aquifer • Stacked multiple confined aquifers	• Sand veneer upper aquifers share characteristics with coastal sands • Deep confined aquifers are recharged at aquifer outcrops, usually at higher elevations – generating significant heads • Indurated sedimentary aquifers may extend large distances out to sea • Thick sedimentary sequences store large volumes of water • Large volumes of groundwater stored in confined aquifers make them suited to large scale development (domestic, parks/gardens, industrial, agricultural) • Intensive development in some areas has led to large piezometric head declines	• Upper unconsolidated aquifer has similar SWI vulnerabilities as coastal sands • The deeper confined indurated aquifers are generally characterised by elevated hydraulic heads which make them more robust to SWI, especially in areas where the freshwater aquifer extends some distance out to sea • The suitability of the deep, thick, confined aquifers for large scale development means that they are often highly developed with the lowest heads of all coastal aquifer types, making them potentially more susceptible to SWI from off-shore • Inter-aquifer contamination of seawater may occur through aquifer leakage
Sedimentary Basins: Multi-layered, unconsolidated, shallow	Cenozoic	• Shallow sedimentary deposits (<50 m AHD below sea level) of unconsolidated, sediments with multiple aquifers separated by discontinuous clay aquitards • Aquifers relatively thin,	• Unconfined upper aquifer • Multiple confined aquifers	• Sand veneer upper aquifers share characteristics with coastal sands • Upper unconfined aquifer recharged by diffuse recharge of rainwater	• Upper unconsolidated aquifer has similar SWI vulnerabilities as coastal sands • Inter-aquifer contamination of seawater may occur through aquifer leakage

Principal Aquifer Type	Aquifer Age	Aquifer Description	Aquifer Types	Aquifer Characteristics	SWI Implications
		between 2 to 40m thick • Commonly mantled by sand veneer		• Semi-confined aquifers are recharged by downward leakage from upper aquifer • Confined aquifers receive little recharge and may be brackish in places • Provide local sources of groundwater that are important for town water supply	• Some of the aquifers are brackish, there is the risk of up-coning through groundwater abstraction
Carbonate	Cenozoic	• Carbonate deposits such as limestone and dolomite • Karstic in nature • Primary carbonate aquifer may be shallow or up to several hundreds of meters thick • Often have a secondary deeper sand aquifer • There may be a semi/confining layer separating the two aquifer systems	• Unconfined primary carbonate aquifer overlying deeper semi/confined sand aquifer	• Extreme anisotropy in hydraulic conductivity • Karstic carbonate aquifer dramatically increases amount of recharge available during intense rainfall events • Groundwater levels rapidly respond to seasonal, climatic and anthropogenic influences • Groundwater occurs in freshwater lenses/basins, overlying and/or adjacent to saline groundwaters • Freshwater lenses provide water to local towns and for irrigated agriculture	• Isolated lenses at risk of drawing in saline waters, especially where hydraulically connected to seawater or where overlying freshwater lenses are relatively thin • Solution cavities within karst aquifer provide preferential flow paths • Rapid response of aquifer storage to changes in climate may make these systems susceptible to SWI during drought periods
Basalt	Cenozoic	• Layered basalt plains storing groundwater primarily in fractures and vesicles • May be overlain by flood plain deposits that are in hydraulic connection with the primary basalt aquifer	• Generally unconfined, although less permeable basalt layers may form semi/confining layers	• Aquifers recharged by rainfall via fractures and surface water losses • Freshest groundwaters found in areas where there is a greater fracture density and/or permeability	• Fracture openings and higher permeability areas may provide a preferential flow path for seawater migration, especially when oriented perpendicular to the coast
Fractured Undivided	Cretaceous through to	• Local to broad extent, older –aged, fractured sequences	• Unconfined to semi/confined	• Tend to have variable productivity and salinity	• Fracture openings may provide a preferential flow path for seawater

Principal Aquifer Type	Aquifer Age	Aquifer Description	Aquifer Types	Aquifer Characteristics	SWI Implications
	Proterozoic	of mixed lithology that have undergone metamorphosis and weathering • May be mantled by alluvial, aeolian or colluvial veneer • Aquifers comprise a number of different stratigraphic units with a high degree of interconnection • May include karstic carbonate aquifers within the mix of lithologies, and thus may share characteristics in common with other carbonate aquifer systems	aquifers	• Recharge occurs where aquifer outcrops as well as through via porous sediments and fractures at the surface • Vertical recharge through fractures can be relatively quick • Typically connected with elevated hinterlands and so heads can be comparatively high • Hydraulic conductivity is highly variable, and is dependent on fracture density • Can store large volumes of groundwater in fractures and therefore may provide local supplies of varying yields and quality	migration, especially when oriented perpendicular to the coast

5. Conclusions and Future Directions

The aim of this project is to identify at a national-scale the coastal groundwater resources currently vulnerable to seawater intrusion (SWI), and potentially at risk in the future as a consequence of over-extraction, sea-level rise and/or recharge-discharge variations associated with climate change. The project has included five technical assessments in order to analyse a range of factors contributing to the vulnerability of coastal aquifers, including: (i) vulnerability factor analysis (VFA); (ii) coastal aquifer typology; (iii) mathematical analysis; (iv) SWI quantitative and qualitative vulnerability indexing; and, (v) future land surface inundation and population growth analysis.

This report has addressed the coastal aquifer typology component of the project which has: provided a characterisation of the hydrogeological settings of Australia's coastal aquifers, as well as a catalogue of simplified hydrogeological cross-sections with associated typical aquifer parameters based on information obtained from 28 CSAs where the threat of SWI has been identified. The aquifer parameter data were derived from the literature and from groundwater databases specific to individual CSAs. These data have been used as input to the steady-state, sharp-interface analytical solutions in order to provide first-order estimates of the position of the freshwater-saltwater interface in these areas, reported by Morgan et al. (2012b).

The principal aquifer types identified as part of the typological analysis included: coastal alluvium, coastal sands, carbonate, other sedimentary basins (including unconfined, sandstone; multi-layered, deep consolidated; and multi-layered, shallow, unconsolidated sub-types), basalt and fractured/undivided classes. The climate types represented included tropical, arid and temperate climate groups. The typical characteristics of these coastal aquifer types were described in Chapters 3 and 4 of this report using data and literature obtained for selected CSAs. Table 20 provides an overview of the the eight principal aquifer types including the age of the aquifers, aquifer descriptions, aquifer types (eg confined, unconfined, semi-confined), characterisitics and implications for SWI.

The characterisation provided in this investigation for the eight principal aquifer types are based soley on the assessment of the 28 selected CSAs, with some classes more represented by CSAs than others. For example, there are six CSAs that represent the sedimentary basin, multi-layered, deep aquifer types, whilst only one CSA represents the basalt and the fractured undivided classes. The classification of CSAs by coastal aquifer typology has highlighted that the groundwater investigations of relevance to SWI, and with sufficient data for APT population, have been, to date, primarily focused within coastal alluvium, coastal sands and multi-layered, deep sedimentary basins; and, to a lesser extent, on the unconfined sandstone; multi-layered, shallow sedimentary basin; basalt; carbonate; and fractured/undivided aquifer systems. Most of the CSAs were located in the temperate climate zones, reflecting Australia's population distribution and the associated abstraction pressures on those groundwater systems.

It is hoped the coastal aquifer typology classification and associated characterisation will be further developed as more data becomes available by which to build upon our understanding of coastal aquifer type settings. Moreover, it would be useful to gain greater insights into the SWI timeframes of different coastal aquifer types and the most effective and appropriate SWI monitoring management activities for each type.

One recommendation to assist with characterising aquifer systems at the national-scale is to refine the mapping of the undivided aquifer lithology classes (which make up the largest aquifer class) within the 1:5 000 000 hydrogeology map (Jacobson and Lau, 1987), which is currently the best available national-scale hydrogeological map. This would provide greater utility for national-scale groundwater investigations.

The development of a coastal aquifer typology for use in this project has created the possibility of extrapolating existing-data and knowledge in the evaluation and investigation of SWI vulnerability. An integrated assessment of SWI vulnerability based on the information gathered within each of the project components has been reported in Marshall et al. (2012) and summarised in Ivkovic et al. (2012b).

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Geological Time Scale

Ka = thousand years Ma = million years

Eon	Era	Period	Epoch
Phanerozoic 0-542 Ma	Cenozoic 0-65.5 Ma	Quaternary 0-2.6 Ma	Holocene 0-11.7 ka
			Pleistocene 11.7 ka-2.6 Ma
		Neogene 2.6-23 Ma	Pliocene 2.6-5.3 Ma
			Miocene 5.3–23 ma
		Palaeogene 23-65.5 Ma	Oligocene 23-33.9 Ma
			Eocene 33.9-55.8 Ma
			Paleocene 55.8-65.6 Ma
	Mesozoic 65.5-250 Ma	Cretaceous 65.5-145.5 Ma	
		Jurassic 145.5-199.6 Ma	
		Triassic 199.6-250 Ma	
	Palaeozoic 250-242 Ma	Permian 250-299 Ma	
		Carboniferous 299-359 Ma	
		Devonian 359-416 Ma	
		Silurian 416-444 Ma	
		Ordovician 444-488 Ma	
		Cambrian 488-542 Ma	
Proterozoic 542-2500 Ma			
Archaean >2500 Ma			

Glossary

Note: Words in italics are cross-referenced

Australian Geological Survey Organisation (AGSO): The precursor to GA.

Anthropogenic: Features created by human activity. Anthropogenic coasts are those heavily modified by excavation, fill, etc., so that the original coastal processes and features are no longer readily evident.

APT Observation Bores: The bores used within the case study areas to define hydrogeological information that is contained within the APTs. The bores used are shown on locality figures.

Aquifer: A geological unit that holds, transmits and yields water at useful rates and quantities. The water in an aquifer is contained within its porosity. An unconfined aquifer has a watertable as its upper boundary. A confined aquifer is bounded between two low permeability units, or aquitards.

Aquifer parameter table (APT): This refers to a table displaying all aquifer parameters, such as hydraulic conductivity, thickness and porosity for each CSA. These were derived from the Coastal Aquifer Typology component of the project.

Aquitard: A geological unit of low permeability that results in low groundwater flow rates. Low permeabilities preclude extraction of water at useful rates and quantities from aquitards. However, aquitards may transmit water in quantities that are significant on a larger scale

Area of Interest (AOI): This is the area within the case study areas from which hydrogeological information was obtained.

Artificial recharge: The deliberate recharge of aquifers through pumping water into them via bores or increasing surface water infiltration. Also known as managed aquifer recharge. Artificial recharge in coastal aquifers may slow, contain, or reverse seawater intrusion.

Australian Height Datum (AHD): the reference level used for measuring altitude or elevation in Australia. The datum surface passes through mean sea level measured at thirty points around the Australian coast from 1966 to 1968.

Barrier-lagoon: A wave-dominated coastal deposit characterised by a barrier beach on the seaward side of an embayment sheltering a fresh to saline-water lagoon behind. The lagoons are often the locations of river estuaries.

Basement: The native, consolidated rock, usually considered to be impermeable that underlies the permeable stratum of interest. Bedrock is often composed of crystalline rocks such as granite or metasediments.

Bedrock: Solid rock present at surface or beneath loose surface cover such as unconsolidated sediment, soil or weathered bedrock.

Cemented: Sedimentary deposits that have been cemented by mineral precipitation to form a consolidated rock (sand becomes sandstone, silt becomes siltstone, etc.). The degree of cementation is variable.

Confined: See aquifer

Consolidated: See cemented.

Case study area (CSA): An area along Australia's coast assessed by this study for seawater intrusion vulnerability.

Delta: A deposit of sediment built up where a river flows into the sea. They are commonly more or less triangular in shape (similar to the Greek letter delta). Deltas can be river, tide, or wave dominated, depending on which the most important depositional process acting along the coastline.

Digital Elevation Model (DEM): A derived 'bare earth' map of earth's surface with the heights of anthropogenic and natural features such as vegetation removed from the elevation data.

Discharge: The outflow of groundwater to surface water, bores, from one aquifer to the other or the sea. Also includes evapotranspiration from shallow aquifers.

Distributed net recharge: The net distributed inflows to an aquifer through the land surface, accounting for infiltration, evapotranspiration and distributed pumping.

Estuary: An inlet formed where a river meets the sea along a wave or tide-dominated coast. They are commonly funnel shaped.

Facies: Specifically, a package of sediments that share a common formation environment, for example the deposited sands, silts, and peat associated with a river delta are grouped as a deltaic facies.

Freshwater lens: A lens-shaped body of less dense fresh water floating on top of denser saline water in an unconfined coastal aquifer. See Ghyben-Herzberg lens.

Geomorphology: The study of landforms, the processes that shape them, and their history.

Ghyben-Herzberg lens: A coastal freshwater lens in direct contact with seawater. The depth to which the lens extends below sea level is dependent on the density contrast between the lens fluid and seawater. The approximate maximum depth a lens can extend below sea level is forty times the height of the water table above sea level, in accordance to the Ghyben-Herzberg equation.

Groundwater: Water below the earth's surface.

Hazard: A source of potential harm or a situation with a potential to cause loss.

Hydraulic conductivity: Coefficient of proportionality describing the ease with which water can flow through a permeable medium. More specifically, it refers to the volume of water that will flow through a unit cross sectional area of a medium under a unit hydraulic gradient per unit of time.

Hydraulic gradient: the rate of change in hydraulic head per unit distance of flow in a given direction.

Hydraulic head: Represents the potential energy of water in an aquifer, expressed in terms of a height of water rising above a given datum. The watertable is the hydraulic head at the top of an unconfined aquifer, and this (plus the capillary rise zone) represents the zone of saturated aquifer.

Hydrogeology: The study of the interrelationship between geology and groundwater.

Indurated: Hardened sediments or rocks, also see cemented

Interface depth: Related to the hydraulic head by the Ghyben-Herzberg relationship which accounts for the density ratio of seawater to freshwater.

Karst: Landscapes and subsurface features formed by the large-scale solution of soluble rocks, usually limestones and dolostones.

Mean Sea Level (MSL): The average height of the ocean's surface taking into account tidal and wave oscillations.

Metasediments: Sedimentary rocks that have been recrystallised through heat and pressure.

Model: Used in two senses in this report: hydrological models are based on mathematical equations that allow the behaviour of a hydrologic system to be quantitatively predicted; conceptual models are qualitative descriptions of systems and features such as aquifers or coastal landforms.

National-scale: A synoptic view of a specific problem (e.g. seawater intrusion) across the nation and across jurisdictional boundaries. On a specific map scale, typically refers to maps at scales of between 1:1 000 000 and 1:2 000 000.

Net Recharge: The difference between gross aquifer recharge (being water that reaches the aquifer and increases storage within the saturated zone), and any groundwater losses such as evapotranspiration, losses to surface water and groundwater extraction.

Porosity: Open spaces in rocks and sediments that can hold water. Primary porosity formed when the deposit was laid down. This can be variably filled in by cement, leaving remnant primary porosity. Secondary porosity forms through modification of rocks, such as the solution of soluble grains or the formation of fractures.

Primary porosity: See porosity.

Potentiometric surface: For a confined aquifer, this is an imaginary surface representing the level to which water rises in a core or well that taps a confined aquifer. For an unconfined aquifer, the potentiometric surface can be represented by the watertable

Recharge: The process by which water is added to an aquifer.

Risk: A concept used to describe the likelihood of harmful consequences arising from the interaction of hazards, communities and the environment.

Saltwater wedge: Saltwater has a greater density than freshwater, and as a result it moves in the form of a seawater wedge beneath freshwater.

Seawater interface: The front that exists between seawater and freshwater in a coastal aquifer, whereby less dense freshwater sits above, and adjacent to, a denser seawater wedge.

Seawater toe: The leading landward edge of the seawater wedge is referred to as the toe, and it is located where the freshwater-seawater interface intersects the bottom of the aquifer.

Secondary porosity: See porosity.

Sharp-interface: See transition zone.

Seawater intrusion (SWI): The landward movement of seawater into coastal aquifers.

Shuttle Radar Topographic Mission (SRTM): The 2000 Shuttle Radar Topographic Mission (STS-99) which has resulted in the 1-second and 3 second SRTM DEM.

Toe length (see also seawater toe): The distance from the coast to inland extent of saltwater wedge.

Transition zone: The zone of brackish water between the freshwater and seawater in a coastal aquifer. A sharp-interface is an infinitesimally thin approximation of the transition zone.

Typology: The systematic classification of types that have characteristics or traits in common.

Uncemented: Unconsolidated sedimentary deposits that have not been cemented to form a rock. See cemented.

Unconfined: See aquifer.

Unconsolidated: Loose sedimentary material.

Vulnerability: The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.

Water table: The surface where fluid pressure in the pores of an aquifer is exactly atmospheric pressure. The upper surface of groundwater within an unconfined aquifer. See also potentiometric surface.

Wedge toe location: see Seawater toe.

Wetlands: Low lying areas subject to partial or continuous inundation. Also known as swamps.

Appendix 1 Case Study Areas Summary Table

Coastal Alluvium								
Case Study Area	**Gma**	**Climate Group**	**Hydrogeological Type Setting**	**Aquifer Type**	**Aquifer Lithology**	**Coastal Geomorphic Type**	**Land Use Based on BRS (2006) National Landuse Map**	**Groundwater Use Based on Ivkovic et al. (2012a) Literature Review**
Bowen (QLD)	Bowen	Tropical	Unconsolidated	Unconfined	Unnamed Quaternary alluvium; palaeochannels in bedrock	Wave-dominated delta	Irrigated modified pastures; irrigated cropping; grazing; natural vegetation	Horticulture
Burdekin (QLD)	Burdekin	Tropical	Unconsolidated	Unconfined	Unnamed Quaternary alluvium	Wave-dominated delta	Irrigated cropping; grazing natural vegetation; irrigated modified pastures	Sugarcane; wetlands; adjacent Great Barrier Reef
Burnett Heads (QLD)	Bundaberg	Temperate (no dry season)	Unconsolidated	Unconfined through to confined	Tertiary alluvial Elliot Fm overlying Fairymead Beds	Wave-dominated delta	Irrigated cropping; urban intensive uses; nature conservation; grazing natural vegetation	Sugarcane and associated industries
Carnarvon (WA)	Carnarvon	Arid	Unconsolidated	Unconfined through to confined	Quaternary alluvium Riverbed Sand overlying Older Alluvium	Wave-dominated delta	Grazing natural vegetation; irrigated horticulture	Domestic; horticulture
Pioneer Valley (QLD)	Pioneer	Temperate (dry winter)	Unconsolidated	Unconfined	Unnamed Quaternary alluvium; palaeochannels in bedrock	Wave-dominated delta	Irrigated cropping; urban intensive uses; grazing; natural vegetation	Sugarcane and associated industries; stock, residential; domestic

Coastal Sands								
Case Study Area	**Gma**	**Climate Group**	**Hydrogeological Type Setting**	**Aquifer Type**	**Aquifer Lithology**	**Coastal Geomorphic Type**	**Land Use (National Map)**	**Groundwater Use (Literature Review)**
Perth, Cottesloe Peninsula (WA)	Perth	Mediterranean	Unconsolidated	Unconfined	Quaternary Tamala Limestone dune sands	Strandplain, minor karstic	Urban intensive uses	Parks, gardens, golf courses and other recreation
Rottnest Island (WA)	Rottnest	Mediterranean	Unconsolidated	Unconfined	Quaternary Tamala Limestone dune sands	Small sedimentary Island	Other minimal use	Parks, and recreation
North Stradbroke Island (QLD)	North Stradbroke Island	Temperate (no dry season)	Unconsolidated	Unconfined-Semi confined	Unnamed Quaternary sand dunes	Barrier/ strand plain	Other minimal use; plantation forestry; irrigated plantation	Town water supply, including off-island; wetlands, lakes, and lagoons; sand mining
Botany (NSW)	Botany Sandbeds	Temperate (no dry season)	Unconsolidated	Unconfined	Quaternary Botany Sands	Strandplain	Urban intensive uses	Industry; golf courses
Hat Head (NSW)	Macleay Coastal Sands	Temperate (no dry season)	Unconsolidated	Unconfined	Unnamed Quaternary sand dunes	Strandplain	Conservation area- national park	Council; urban & domestic
Stockton (NSW)	Tomago-Tomaree-Stockton Sandbeds	Temperate (no dry season)	Unconsolidated	Unconfined	Quaternary Stockton Sand Beds	Lagoon	Grazing; rural residential; tree cover, national forest	Stock & domestic; sand mine & mineral processing; small scale irrigation; industry
Stuarts Point (NSW)	Stuarts Point Sandbeds	Temperate (no dry season)	Unconsolidated	Unconfined	Unnamed Quaternary sand dunes	Strandplain	Grazing natural vegetation; other minimal use	Domestic
Point Nepean (Vic)	Nepean	Temperate (no dry season)	Unconsolidated	Unconfined	Unnamed Quaternary dunes	Strandplain	Urban intensive uses; grazing; modified pastures	stock and domestic

Sedimentary Basin: Unconfined Sandstone								
Case Study Area	**Gma**	**Climate Group**	**Hydrogeological Type Setting**	**Aquifer Type**	**Aquifer Lithology**	**Coastal Geomorphic Type**	**Land Use (National Map)**	**Groundwater Use (Literature Review)**
Broome (WA)	Broome	Arid	Consolidated	Unconfined	Jurassic-Cretaceous Broome Sandstone	Older sedimentary	Grazing natural vegetation	Town water supply; irrigation
Derby (WA)	Derby	Arid	Consolidated	Unconfined	Triassic-Jurassic Wallal/Erskine Sandstone	Older sedimentary	Other minimal use	Town water supply

Sedimentary Basin: Multi-Layered & Deep								
Case Study Area	**Gma**	**Climate Group**	**Hydrogeological Type Setting**	**Aquifer Type**	**Aquifer Lithology**	**Coastal Geomorphic Type**	**Land Use (National Map)**	**Groundwater Use (Literature Review)**
Adelaide Metro/ LeFevre Peninsula (SA)	Central Adelaide PWA	Mediterranean	Multi-layer consolidated	Confined	Tertiary T1 and T2	Complex coast - tide-dominated estuary over older sedimentary deposits, minor karstic aquifer	Urban intensive uses; irrigated perennial horticulture; grazing; modified pastures	Urban parks and gardens, horticulture, industrial
LeFevre Peninsula (SA)	Central Adelaide PWA	Mediterranean	Multi-layer unconsolidated/ consolidated	Unconfined/ confined	Quaternary Semaphore Sands overlying Tertiary consolidated T1 and T2 multi-layered sandstones	Complex coast - tide-dominated estuary over older sedimentary deposits, minor karstic aquifer	Urban intensive uses; irrigated perennial horticulture; grazing modified pastures	Urban parks and gardens, horticulture, industrial
Willunga (SA)	McLaren Vale PWA	Mediterranean	Multi-layer unconsolidated/ consolidated	Unconfined/ confined	Unnamed Quaternary sands overlying Tertiary Port Willunga Fm and Maslin Sands	Tertiary consolidated sediments, possibly minor fractured bedrock and coastal sands	Grazing- modified pastures; production from dry land agriculture and plantations; rural residential; conservation; irrigated vine fruits	Viticulture; almonds; livestock; industrial
Bunbury (WA)	Bunbury	Mediterranean	Multi-layer unconsolidated/consolidated	Unconfined/ semi-confined/ confined	Quaternary Superficial coastal sands overlying minor Cretaceous Leederville Fm, Cretaceous	Strandplain, minor karstic	Urban intensive uses; grazing natural vegetation; grazing modified pastures; urban intensive uses; intensive	Urban and rural

Sedimentary Basin: Multi-Layered & Deep								
Case Study Area	**Gma**	**Climate Group**	**Hydrogeological Type Setting**	**Aquifer Type**	**Aquifer Lithology**	**Coastal Geomorphic Type**	**Land Use (National Map)**	**Groundwater Use (Literature Review)**
					Basalt, Jurassic Yarragadee and Cockleshell Gully Fm		animal; plantations	
Busselton (WA)	Busselton-Capel	Mediterranean	Multi-layer unconsolidated/consolidated	Unconfined/ confined	Quaternary Superficial coastal sands overlying Cretaceous Leederville Formation and Permian Sue Coal Measures	Strandplain, minor karstic	Dryland cropping; managed resource protection; grazing modified pastures; intensive animal production; natural conservation ; forestry and urban intensive uses	Urban and rural
Perth, Whitfords (WA)	Whitfords	Mediterranean	Multi-layer unconsolidated/ consolidated	Unconfined/ semi-confined/ confined	Quaternary Superficial coastal sands overlying Cretaceous Leederville Fm and Jurassic Yarragadee Fm	Strandplain, minor karstic	Urban intensive uses; dryland cropping	Domestic; urban, horticulture; parks and gardens; plantations

Sedimentary Basin: Multi-Layered & Shallow								
Case Study Area	**Gma**	**Climate Group**	**Hydrogeological Type Setting**	**Aquifer Type**	**Aquifer Lithology**	**Coastal Geomorphic Type**	**Land Use (National Map)**	**Groundwater Use (Literature Review)**
Albany (WA)	Albany	Mediterranean	Unconsolidated/ consolidated	Unconfined/ semi-confined/ confined	Quaternary Superficial Sediments Aquifer overlying Tertiary Middle Sands and Werillup Fm Sands	Complex coast-barrier lagoon, older sedimentary coast, fractured bedrock	Dryland cropping; nature conservation; other minimal use and plantation forestry	Town water supply; domestic; agricultural irrigation; industrial; parks and gardens
Esperance (WA)	Esperance	Mediterranean	Unconsolidated/ consolidated	Unconfined/ semi-confined/ confined	Quaternary Superficial sediments/Pallinup Fm overlying Werillup Fm	Complex coast-barrier lagoon, older sedimentary coast, fractured bedrock	Dryland cropping; nature conservation	Town water supply; domestic; agricultural; industrial; parks and gardens

Carbonate								
Cape Range (WA)	Gascoyne	Arid	Unconsolidated	Unconfined	Tertiary karst limestone of the Cape Range Group	Karstic	Nature conservation; dryland cropping and other minimal use	Domestic; gw dependant aquatic cave fauna
Port MacDonnell (SA)	Lower Limestone Coast PWA	Mediterranean	Consolidated/ unconsolidated	Unconfined/ semi-confined/ confined	Tertiary Gambier limestone; overlying Dilwyn Formation sands	Sedimentary basin with karst	Grazing modified pasture; grazing natural vegetation; plantation forestry	Irrigated agriculture; improved pasture; stock; domestic; industrial; gw dependant ecosystems
Uley South, Eyre Peninsula (SA)	Southern Basins PWA	Mediterranean	Unconsolidated/ consolidated	Unconfined/ confined	Quaternary karst in Bridgwater Formation overlying Tertiary Wanilla Sands	Complex coast-karstic aquifer in recent sediments over older sediment, fractured bedrock	Nature Conservation, Other minimal use, Grazing natural vegetation	Domestic; Grazing, cereal

Basalt								
Case Study Area	**Gma**	**Climate Group**	**Hydrogeological Type Setting**	**Aquifer Type**	**Aquifer Lithology**	**Coastal Geomorphic Type**	**Land Use (National Map)**	**Groundwater Use (Literature Review)**
Werribee (VIC)	Deutgam Water Supply Protection Area	Temperate (no dry season)	Unconsolidated/ consolidated	Unconfined/ semi-confined	Quaternary unnamed alluvial delta sands overlying Quaternary/Tertiary Newer Volcanic Basalt; small extent clastic aquifer	Tide delta/basalt	Urban intensive uses; irrigated modified pastures; grazing modified pastures	Horticulture

Fractured/Undivided								
Howard Springs (NT)	Darwin Rural	Tropical	Unconsolidated/ consolidated	Unconfined/ semi-confined	Weathered Cretaceous sediments (Darwin Member) & Proterozoic bedrock, fractured Proterozoic Koolpinyah Dolomite	Karstic	Other minimal use; nature conservation; rural residential; irrigated modified pastures	Town water supply; rural domestic use; agriculture

Appendix 2 Aquifer Parameter Tables

Table 21 *Aquifer parameter table for Bowen, Queensland*

Aquifer Layer	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD) [1]	Inland Head Distance (m) [1]	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Single unit (fluvio-deltaic sands)	Quaternary [2]	Unconfined [2]	Near the coast -15 to -25 [3]	20 to 27 [4]	Range: 0.16 to 1.89 Median: 0.51 Mean: 0.58 [5]	From coast: 400 From nearest estuary: 1400 (Don River)	K_h alluvial = 0.1 to 100 from standard texts [6] K_h basement = 20 [9]	Specific yields 0.01 to 0.3, with calibrated SY of 0.06 [8]	13 to 70 [7]

Notes:
1 DERM (2010)
2 Sundaram et al. (2001a)
3 Sundaram et al. (2001a)
4 Approximated from near coastal sections in Sundaram et al.(2001a), (Figure 3.8 Euri Creek, Figure 3.9 Left Bank of the Don River, Figure 3.10 Right Bank of the Don River)
5 Bore RN: 12100135, Pipe A, This bore is selected as it is seaward of extraction bores, the closest extraction bore is 200m away. The natural surface elevation is 4.65 m AHD. The bore is screened within the lower parts of the alluvium above the weathered basement from -11.3 to -11.3 m AHD.
6 Welsh (2007) and Welsh (2008). For alluvial material, horizontal hydraulic conductivity references standard text (Freeze and Cherry 1979) values for identified bore stratigraphy.
7 Assessment of Wnet is from Welsh (2002). It is assumed that there is little to no extraction within 1 km of the coast.
8 No porosity values are available. Welsh (2008) indicates model has specific yields defined but these are from Freeze and Cherry (1979) with a calibrated SY of 0.06
9 Welsh (2007) and (2008). For weather basement material, horizontal hydraulic conductivity references standard Freeze and Cherry (1979) values for identified bore stratigraphy.
Other information:
Sundaram et al.(2001a) – "The combination of the Holocene and Pleistocene alluvial deposits and the weathered remnants of the granitic basement act as an unconfined to locally semi-confined aquifer system. The seaward groundwater flow is influenced by preferential flow in the more transmissive zones developed in the infilled channels."
Welsh (2007), dry tropics, rainfall varies from 255 to 2358 mm/yr with and average of 944 mm/yr
Significant number of extraction bores in the vicinity of the township of Bowen

***Table 22** Aquifer parameter table for Lower Burdekin Delta, Queensland*

Aquifer Layer	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD) [1]	Inland Head Distance (m) [1]	K (m/d)	Specific Yield	Net recharge (mm/a)
1	Alluvio-deltaic sediments	Pleistocene – Holocene [2]	Unconfined on a regional scale [2]	-30 to -45 [3]	32 to 50 [4]	-0.60 to 2.58 (Avg 0.55; Med 0.49) [5]	6500 from coast 850 from river	50 (10 to >200) [6]	0.21 to 0.3 [7]	103 [8]

Notes:
1 DERM (2010)
2 Arunakumaren et al. (2000)
3 Narayan et al. (2007) the model conceptualisation identifies inland basement as being -35 m below the surface and -45 m below the natural surface at the coast. This is over a distance of 5 km.
4 Narayan et al. (2007) The SWI model imposes a 2 m AHD inland head and a zero hydrostatic pressure for the seaward boundary. In the steady state model without tidal fluctuations, this seaward boundary condition is assumed to be 0m AHD.
5 Refer to DERM Observation Bore RN12000147 with 343 records collected between 18/02/1964 and 02/10/2006; Trendline: y = 6E-5 -1.38, R2 = 0.28
6 Fig 29 in Wang et al. (2012) provides PEST calibrated estimates for hydraulic conductivity values and these are used to provide base case estimate of 50 m/d for the southern fan area around RN12000147. The range of K values reported by Narayan et al. (2007) were from 10 to > 200 m/d within the delta.
7 Fig 30 in Wang et al. (2012) provides PEST calibrated estimates for specific yield values.
8 Net recharge estimate includes 18 990 ML/yr of rainfall plus 18 270 ML/yr of river recharge minus 5 150 ML/yr of ET over the 311 km2 Burdekin Delta area during the 1996-2006 period (L. Leach, personal communication, 9 Feb 2012)
Other information: Average groundwater extraction is approximately 9040 ML/yr (L. Leach, personal communication, 9 Feb 2012)

Table 23 *Aquifer parameter table for Carnarvon, Western Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Riverbed Sand	Quaternary	Unconfined	-7 to 0 [2]	4 to 5 [2]	0.5-2.21 (Avg 1.03; Med 1.01) [7]	2370	164 (20-812) [4]	0.3 (0.29-0.32) [4]	26 [6]
						-3.5 to 1.1 (Avg 0.13; Med 1.09) [8]	2490			
						0.23-5.02 (Avg 2.0; Med 2.14) [9]	5120			
2	Older Alluvium	Quaternary	Semi-confined to confined	-65 to-45 [5]	30-60 [3]	-1.18 to 3.38 (Avg 1.05; Med 1.06) [10]	4174	11 (0.8-121) [4]	0.15 [4]	11 [6]
3	Toolonga Fm calcilutite	Cretaceous	Base	—	—	—	—	—	—	—

Notes:

[1] The reference used is CyMod Systems Pty Ltd (2009) and the parameters pertain to Basin A. Parameters derived for approximately5 km coastal fringe and it is assumed that little to no groundwater extraction occurs within this zone. All footnotes cross-reference to this report.

[2] Refer to Fig 7 for distance less than 5 km

[3] Refer to Table 2

[4] Refer to Table 7

[5] Refer to Fig B5

[6] Calculation based on water balance estimates for 'normal' (1990-1999) years within Basin A, which is estimated to have an area of 46.1 km^2. The calculation was based upon river recharge (R) and evaporation (E) for Zones 1, 2 and 5 (which cover Basin A). Data for Zone 1 and Zone 2 were summed to provide an aggregate for the Riverbed Sand aquifer, while Zone 5 represents the Older Alluvium Aquifer. Little aquifer recharge occurs from rainfall and is assumed to be zero.

The data for the normal period came from Table 31 (units in GL/yr) and was determined as follows for the sum of Zones 1&2:

([10.25 (R) - 9.07(E)]*1000) /46.1 = 26 mm/yr

And for Zone 5: ([0.51 (R, as inflows from upper layer) -0 (E)]*1000) /46.1 = 11 mm/yr

[7] Refer to DoW observation bore 70418323 with 202 records collected between 17/12/1974 and 04/09/2002; Trendline: $y= 2E^{-5}x+0.49$, $R^2=0.02$

[8] Refer to DoW observation bore 70418404 with 4 records collected between 10/12/2008 and 14/09/2009

[9] Refer to DoW observation bore 70418325 with 129 records collected between 17/12/1974 and 04/09/2002; Trendline: $y= 1E^{-4}x-1.32$, $R^2=0.02$

[10] Refer to DoW observation bore 70418304 (L8) with 204 records collected between 29/03/1974 and 09/09/2009; Trendline: $y= 2E^{-6}x+0.99$, $R^2=0.002$

Other water balance information: Approximately 4170 ML/yr extracted during 1990-1999 from Basin A

Table 24 *Aquifer parameter table for Pioneer Valley, Queensland*

Aquifer Layer	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD) [1]	Inland Head Distance (m) [1]	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Single unit (Alluvium with weathered fractured rock base) [2]	Quaternary to Permian	Unconfined	-37 to 0 thinning inland, north and south [3] In general -40 to -20	0.5 to 40 [4] due to shallow basement In general 25 to 40	Range: -1.58 to 4.82 Median: 3.15 Mean:3.19 [5]	1600 from coast 2400 from closest estuary (Baker's Creek)	166 [6] 63-200; mean = 159 [9]	Specific Yield = 0.02 to 0.25, mean = 0.12 [8]	Mean = 2.4 [7] 110 [10]

Notes:

[1] DERM (2010)

[2] Composite single aquifer defined in modelling study

[3] Murphy et al. (2005), Identified from aquifer basement map (Fig 3.2, p37) and from cross-section in Appendix 2, Section 4-Coastal Plain Section Sub-area BSY.

[4] Murphy et al. (2005) Estimated from aquifer basement map (Fig 3.2, p37) and Groundwater level contours in July 1996 for average watertable (Fig 3.10, p51)

[5] Bore RN: 12600233. Bore select for position from extraction bores. Bore is close to shore and very likely to have tidal variations (no daily data to confirm). Data appears to be collected quarterly. Bore is representative of coastal fringe scenario, removed from pumping for the southern regions of the PVA.

[6] Murphy et al. (2005) p40 Table 3.2. For the alluvium, averaged K derived from 375 pump tests associated with this aquifer. No range of K values given average thickness is also given as 8 m

[7] Detailed water balance study investigated in Murphy et al.(2005) using SPLASH 1D estimates for deep drainage are spatially scaled and extrapolated with STRESGEN for the area covered by the Alluvium and Mt Vince fractured rock areas. Average recharge 1952 ML/yr, converted to mm/yr using the coverage of the areas described. Area encompassed by Alluvium and Mt Vince Fractured rock areas = 826.11 km^2-NOTE-This area extends a significant distance inland, up to 72 km to the Pioneer River headwaters.

[8] Murphy et al. (2005) Table 3.1, p38, from Bedford (1978)

[9] Bedford (1978), calculated from 161 pump tests in alluvial sub areas, range is derived from 25th percentile and 75th percentile of available K from these tests. Mean thickness for intercepted alluvium in Bedford (1978) was 6.3m.

[10] From Werner et al. (2012) for Pioneer Valley Aquifer Case Study 2a and 2b. It is assumed that there is little to no extraction within 2 km of the coast.

Other information:

From Murphy et al.(2005), p35, “Examination of lithological logs and the construction of cross-sections (Appendix 2) of the alluvial system support the theory that the aquifer is a single-layer aquifer system. Despite the presence of laterally continuous clay layers, water level observations from within various aquifer layers demonstrate vertical hydraulic connectivity.”

Murphy et al.(2005), p36, “The aquifer basement in the Pioneer Water Resources Plan (WRP) area is not representative of a previous land surface or a geological feature but represents the depth to which usable supplies of groundwater can be withdrawn.”

__Table 25__ Aquifer parameter table for Burnett Heads, Queensland

Aquifer Layer	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD) [1]	Inland Head Distance (m) [1]	K (m/d)	Specific yield	Net recharge (mm/yr)
1	Elliott Formation Sand and gravels with minor clay) [2]	Tertiary [3]	Unconfined [2]	-12 to -18m [4]	12 to 20 [5]	Range: 0.24-to 2.24 Median: 0.77 Mean: 0.86 [6]	From Coast 750m From nearest estuary 700m	Permeability values available [7], reference values used 10–1000	0.34 [8]	60 to 90 [9]
						Range: 0.18 to 1.64 Median: 0.87 Mean: 0.89 [10]	From Coast 160m From nearest estuary 10+km			
2	Gooburrum Clay (Silty or sandy clays and clays) [2]	Early Miocene [3]	Leaky aquitard [2]	-32 to -42m [4]	20 to 30 [5]	N/A	N/A	0.01–0.1	—	—
3	Fairymead beds[(Sands, gravels and clay-Fluvial) [2]	Early Miocene to Early Eocene [3]	Semi-confined	-64 to -80m [4]	28 to 30 [5]	Range: -6.28 to 1.94 Median: 0.61 Mean: 0.16 [11]	From Coast 2200m From nearest estuary 6600m	10–100 [12]	0.34 [9]	—
						Range: -0.15 to 1.13 Median 0.41 Mean 0.42 [13]	From Coast 160m From nearest estuary 10+km			

Notes:

[1] DERM (2010)

[2] Zhang et al., (2004)

[3] Geoscience Australia (2011)

[4] Liu et al., (2006) and Zhang et al., (2004) have similar conceptualisations with the base of the upper aquifer set to no flow boundaries or the semi-permeable aquitard. The thickness the aquifers are extracted from these numerical model sections till a detailed conceptualisation reference is available

[5] Approximated from Liu et al., (2006) and Zhang et al., (2004) numerical model section based on Bajracharya et al., (1998). Requires refinement from a detailed conceptualisation reference.

[6] Bore RN: 13500105. This bore is selected as it is seaward of extraction bores and has a detailed data set. The bore is seaward of a drain/wetland that can empty into the Kolan River but is not always connected via surface water way (eyeballed google earth no further information). The extraction bores immediately adjacent are generally low use bores with exceptions in the period of 2000 to 2002. The natural surface elevation is 4.35 m AHD. The bore is screened within the coastal alluvium from 1.35 to - 0.65 m AHD.

[7] Zhang et al., (2004), identifies horizontal permeabilities for each of the model sub-areas in their Table 2

[8] Zhang et al., (2004) From Gooburrum Groundwater flow and solute-transport model, value listed in table 2 of reference. Vertical permeabilities are assumed to be 1000th of horizontal values, thus biasing model to horizontal flow and limited vertical exchange

[9] Zhang et al., (2004), from Bajracharya et al., (1998), values for rainfall recharge estimated from rainfall data.

[10] Bore RN: 13700180, Pipe B, screened between –4.8 to 24.3m AHD in the upper alluvium, natural surface: 5.18 m AHD, date range: 16/09/1992 to 25/02/2011, # of records: 279, Linear trend Eq: $y = 0.00004x-0.5958$, $R^2 = 0.0405$, NOTE: This bore is selected as it has two pipes screened in the upper and lower aquifers. The bore is removed from extraction bores and adjacent to the coast. Pipe B is the shallower of the two pipes

[11] Bore RN: 13500112, Pipe A, screened between -23 to -56.6 m AHD in the lower fluvial Fairymead beds, natural surface: 3.87 m AHD, date range: 31/08/1989 to 08/02/2011, # of records: 650, Linear trend Eq: $y = 0.0002x-7.829$, $R^2 = 0.09$. NOTE: This bore is selected as it has two pipes screened in the upper and lower aquifers. The bore is removed from extraction bores and borders a cropping area. Pipe A is the deeper of the two pipes

[12] Zhang et al., (2004), permeabilities listed for lower aquifer are similar in magnitude as upper aquifer hence applied reference values are of the same magnitude.

[13] Bore RN: 13700180, Pipe A, screened between –27.3 to 40.8 m AHD in the lower fluvial Fairymead Beds, natural surface: 5.18 m AHD, date range: 16/09/1992 to 25/02/2011, # of records: 277, Linear trend Eq: $y = 0.00004x-0.8984$, $R^2 = 0.0582$ NOTE: This bore is selected as it has two pipes screened in the upper and lower aquifers. The bore is removed from extraction bores and adjacent to the coast. Pipe A is the deeper of the two pipes

Other information:

From Liu et al., (2006) after “This is a heterogeneous and anisotropic aquifer system and section A–A0 [to the NW of Burnett Head] comprises two aquifers that are separated by a leaky layer.”

Note: the Liu et al., (2006) model is representative of the coast line to the north west of Burnett Heads. The model is discretised into 8 segments, with 1-5 representing the upper aquifer from the coast to 15km inland, segment 6 represents the aquitard, and segments 7-8 represent the lower aquifer up to 5km from the coast.

Bajracharya et al.(1998), SWI moving landward at 100m/year in some areas.

Zhang et al., (2004), the exact location and extent of the connection between the aquifers and the ocean is unknown, particularly for the lower Fairymead beds. Based on the national Bathymetric map series for Bundaberg, the aquifers for the models are extended 1.8km from the shoreline, following the observed seabed gradient, to a vertical model boundary (see model section). Lower semi-confined aquifer likely to have vertical recharge from overlying aquifer, but this is unquantified

***Table 26** Aquifer parameter table for North Stradbroke Island, Queensland*

Aquifer Layer	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD) [1]	Inland Head Distance (m) [1]	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Fine sand [1]	Cenozoic [2]	Unconfined [2]	-80 to 0 Generalised depth is -10 to -60 [3]	0 to 100 Generalised thickness is 15 to 60 [4]	Range: 5.35 to 7.28 Median:6.25 Mean: 6.18 [5]	1400 from eastern shore	0.74 to 5.01 mean = 2.59 [6]	0.22 [8]	339 [7]
						Range: 21.02 to 24.1 Median: 21.96 Mean: 22.12 [9]	500m from western shore	0.086 to 155 [10]		

Notes:

[1] DERM (2010)

[2] Laycock (1978), drawing from Laycock (1975)

[3] EHA (2005); after Chen (2001); Fig 8, p20, Stradbroke Island basement contours. Also from Laycock (1978), “The sand is continuous down to -90 m below sea level”. Basement defined as 0 m AHD as in some instances there is shallow basement (near Pt Lookout (NE corner of island) or indurated sands (“coffee rock”) with low permeability.

[4] Visually identified using EHA (2005), after Chen (2001), from Fig 9, p23 “a synthetic set of steady-state groundwater elevation contours for the island produced using the NR&M whole-of-island groundwater flow model”-this needs to be refined. Note, from Laycock (1978), “The maximum elevation of the potentiometric surface is about 60m above sea level”. Chen (2001) indicated that the mound probably did not exceed 50 m AHD.

[5] Bore RN: 14400069, Pipe A, screened between -17.3 to -41.3 m AHD, intersecting claystone, sandstone and sand, natural surface is 14.7 m AHD, date range: 26/05/1990 to 10/02/2011, # of records: 215, Linear trend Eq: y = -0.0002x+12.581, R^2 = 0.646. NOTE: bore is selected for data quality and quantity. The bore is representative of the eastern side of the North Stradbroke aquifer, it is located landward of 18 Mile Swamp.

[6] Guard (2000), soil core measurements using a constant head permeameter

[7] Leon Leach, personal coms. Estimated overall groundwater recharge to the island is 90,550 ML/yr. Converted to mm/yr using area of 267 km^2. Assume to not include discharges

[8] No porosity information readily available

[9] Bore RN: 79859, Pipe A, open bottom aperture at 6.74 m AHD, natural surface is 39.74 m AHD, date range: 16/01/1997 to 10/02/2011, # of records: 3917, Linear trend Eq: y = 0.00003x+5.7259, R^2 = 0.0032. NOTE: bore is selected for data quantity and quality as well as being representative of the western side of the North Stradbroke aquifer. It is seaward of Blaksley Lagoon with no apparent extraction in the vicinity.

[10] Kaegi (2006), from Laycock (1975), vertical permeability from pump test, laboratory tests, and grain size analysis using Hazen’s formula.

Other information:

Laycock (1978), Groundwater occurs on North Stradbroke Island as a lenticular body… built up… by the combined effects of rainwater excess, the permeability of the sand mass and the higher density sea water barrier.

EHA 2006 “[Laycock (1975)] indicated that this lens is not “floating” over a seawater base but because of the relatively shallow depth of the aquifer base the seawater has formed only a relatively short landward trending wedge around the perimeter of the island with its position being determined by the rate of lateral seepage.”

Laycock (1978), The groundwater surface conforms generally with the natural surface and where spring lines occur swamps have developed.

Marshall et al (2006), the rate of infiltration of rainfall into the sand is such that relatively little runoff occurs even during periods of high intensity rainfall

***Table 27** Aquifer parameter table for Botany, New South Wales*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific yield	Net recharge (mm/yr)
1	Botany Sand Beds (interspersed peaty,clay beds)	Quaternary	Unconfined to semi-confined	-23 to -30 [2]	35 (20-40)	-2.43 to 1.50 (Avg 0.12; Med 0.50) [6]	435	30 (20-85) [3]	0.37 (0.33-0.40) [4]	433 [5]
						-0.52 to 4.31 (Avg 1.19; Med 1.19) [7]	970			
2	Hawkesbury Sandstone	Triassic	Fractured	—	—	—	—	—	—	—

Notes:

[1] The conceptualisation corresponds to the Banksmeadow area along Foreshore Road between Sydney Airport and Orica chemical manufacturing plant. It is assumed that anthropogenic alteration along this section has little influence on the characterisation. Currently there are a range of construction and land reclamation activities planned along the northern shore of Botany Bay that could alter the validity of this conceptualisation into the future.

[2] Refer to bedrock elevations shown in Fig 3 of Merrick and Knight (1997).

[3] Hydraulic conductivity values are highly variable due to lithological variations; range of values reported on pg 20 of Bish et al. (2000).

[4] Refer to estimated range of porosity values on pg 17 of Bish et al. (2000).

[5] A recharge rate of 37 % has been modelled for the sandy sediments comprising the Northern Zone and according to Bish et al. (2000) on pg 21. Average annual rainfall is reported for the 1929 to 1999 period as 1170 mm/yr on pg. 5 of Bish et al. (2000). It is assumed that no groundwater extraction occurs within the 970 m coastal fringe.

[6] Refer to NSW groundwater database observation bore GW042162 with 103 records collected between 21/09/1978 and 12/08/1991; Trendline: $y= 2E^{-4}x + 6.32$, $R^2 = 0.06$

[7] Refer to NSW groundwater database observation bore GW042166 with 110 records collected between 13/02/1975 and 22/03/1991; Trendline: $y= 4E^{-4}x + 11.88$, $R^2 = 0.6$

Table 28 *Aquifer parameter table for Hat Head, New South Wales*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Effective Porosity	Net Recharge (mm/yr)
1	Coastal Sands	Quaternary	Unconfined	-30 (-30 to -40) [2]	38 (30-47) [2]	1.38-1.95 (Avg 1.62; Med 1.59) [3]	150	20 [5]	0.1 [6]	270 [7]
						5 [4]	1750			
						0.5 [4]	3500 (adjacent to Macleay River)			
3	Marine clay basement	—	—	—	—	—	—	—	—	—

Notes:

[1] The reference used is SKM (2011), Stage 2 and is typical of the aquifer located between Smoky Cape and Hat Head extending between the Macleay River and ocean. The distance between the Macleay River and the coast is approximately 3.5 km

[2] Refer to pgs 73 and 80, Table 3.1 and Figure 3.1; Note that although there is a discontinuous low permeability unit at about -10m AHD (and approximately 1m thick), the aquifer is modelled as a single layer due to few data for a more detailed characterisation.

[3] Refer to NSW groundwater database observation bore GW081089_1 with 82 records collected between 4/4/2010 and 18/11/2010; Trendline: $y= 2.2E^{-3}x -85.67$, $R^{2} = 0.18$

[4] Assumptions made in the absence of data. Reference head set to 5m below the natural surface (see pg 88) which at the midpoint (at 1750 m inland from the coast) is about 10 m AHD resulting in an estimage for the inland head of 5 m AHD. Table 3.2 (pg 87) provides the estimated freshwater head for the Macleay River of 0.5m AHD.

[5] Refer to assumed values in Table 3.3

[6] Refer to assumed values in Table 3.4

[7] Average annual rainfall is approximately 1350 mm/yr and assumes that 20 % becomes groundwater recharge as indicated in Table 3.5 (pg 89). This conceptualisation assumes no extractions within the coastal fringe.

Table 29 *Aquifer parameter table for Stockton, New South Wales*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	North Stockton Sandbeds (outer barrier dune sands)	Quaternary (Holocene)	Unconfined	-10 to -20 [2]	10-20	0 [9]	0	20 [4]	0.1 [5]	281 [7]
						0.46-3.35 (Avg 2.05; Med 2.05) [10]	1900 (from Ocean) 2100 (from Tilligerry Ck)			
						0.44-3.84 (Avg 2.46; Med 2.50) [11]	1450 (from Ocean) 2500 (from Tilligerry Ck)			
2A (On ocean side)	Tomago Sandbeds (inner barrier dune sands)	Quaternary (Pleistocene)	Semi-confined	-40 to -20 [2]	20-40 [2]	—	—	20 [4]	0.1 [5]	
2B (On estuary side)	Estuarine mud in NW through to Tomago Sandbeds in SE	Quaternary	Semi-confined	-40 to -20 [2]	20-40 [2]	—	—	10 [4]	0.1 [6]	
3	Medowie Clay Member	Quaternary	Aquitard	0 to -110 [3]	20-60 [3]	—	—	—	—	—

Notes:

[1] The reference used is SKM (2011) and parameters correspond to the approximately3.75 km distance between Tilligerry Creek to the west and the Ocean to the east.

[2] Refer to Figs 3.1 and 3.2 in SKM (2011)

[3] Refer to Fig 2.3 in SKM (2011)

[4] Refer to Table 3.2 in SKM (2011)

[5] Refer to average specific yield value from pumping test data on aquifers

[6] Not specifically mentioned for this layer –assume about the same as for layer 3A.

[7] Average annual rainfall is approximately 1124 mm/yr as recorded at Williamtown RAAF base (pg 11); Assume that about 25 % of rainfall recharges aquifer (including ET losses) (pg 23).

[9] Salt water head set to mean sea level (0 m AHD) at both the ocean and estuary boundaries. The influence of the tidal gates on heads along Tilligerry Creek are not assessed due to lack of data and is considered beyond the scope of this investigation.

[10] Refer to Hunter Region observation bore SK6346 with 517 records collected between 28/05/1979 and 18/02/2010; Trendline: y= 3E-5x + 0.90, R^2 = 0.00

[11] Refer to Hunter Region observation bore BL156 with 520 records collected between 03/11/1994 and 18/02/2010; Trendline: y= 6E-5x + 0.23, R^2 = 0.02

Other water balance information:

Existing groundwater usage includes stock and domestic, sand mine and mineral processing, small scale irrigation and industrial; however no data on the water extractions is available-refer to pg 17 of SKM (2011).

Salinty information:

It is assumed that highly saline water (equivalent to seawater) exists in the aquifer immediately beneath Tilligerry Creek (pg 17). The combined action of levee banks, tidal flap gates and constructed drains have resulted in the lowering of watertables around the estuary to levels that are below mean sea level. The resultant hydraulic gradients have caused saline water to migrate up to one kilometre inland from the estuary.

Table 30 *Aquifer parameter table for Stuarts Point, New South Wales*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Effective Porosity	Net Recharge (mm/yr)
1	Coastal Sands	Quaternary	Unconfined	-30 (-30 to -40) [2]	36 (20-40) [2]	2.84-3.24 (Avg 3.04; Med 3.04) [3]	500 from ocean adjacent estuary	20 [6]	0.1 [7]	270 [8]
						1.28-3.17 (Avg 2.68; Med 2.75) [4]	1000 from ocean or approximately 500 from estuary/ Macleay River			
						2.43- 6.83 (Avg 5.47; Med 5.67) [5]	1750 from ocean or approximately1250 from estuary/ Macleay River			
3	Marine clay basement	—	—	—	—	—	—	—	—	—

Notes:

[1] The reference used is SKM (2011), Stage 2. Typical of aquifer located between Yarrahapinni Hills in the west through to the coast in the east. The conceptualisation is of the area to the west of the estuarine Macleay River, which is considered as an influence having a salinity equal to seawater. It is assumed that there are no groundwater extractions within the 1.75km coastal fringe. note, that the SKM (2011) report modelling of Stuarts Point doesn't consider the location of the Macleay River which forms an inlet with the sea at approximately 500m inland west/inland of the coast.

[2] Refer to pg 81, Table 3.1 and Figure 3.4; Note that although there is a discontinuous low permeability unit at about -10m AHD (and approximately 1m thick), the aquifer is modelled as a single layer due to insufficient data for more detailed characterisation.

[3] See NSW groundwater database record for GW081069 with 93 records collected between 14/03/2010 and 14/06/2010; Trendline: $y= -3.9E^{-3}x + 159.34$, $R^2 = 0.82$

[4] See NSW groundwater database record for GW081012 with 2743 records collected between 13/12/2001 and 29/9/2010; Trendline: $y= -1E^{-4}x + 7.44$, $R^2 = 0.16$; Head estimated from Figure B8 in SKM (2011), Stage 2 at distance of 1000 m inland from the coast is approximately 2.5m. note, that the SKM (2011) report doesn't consider the location of the Macleay River which forms an inlet with the sea at approximately 500m inland from the coast.

[5] See NSW groundwater database record for GW081011 with 3769 records collected between 16/03/2000 and 29/9/2010; Trendline: $y= -2E^{-6}x + 5.56$, $R^2 = 0.00$;

[6] Refer to assumed values in Table 3.3

[7] Refer to assumed values in Table 3.4

[8] Average annual rainfall is approximately 1350 mm/yr and assumes that 20 % becomes groundwater recharge as indicated in Table 3.5 (pg 89). This conceptualisation assumes no extractions within the coastal fringe.

Other salinity information:

The saltwater interface is thought to be at between 14 to 17 m below natural surface as observed in Observation bore GW001069 at Fishermans Tail (see section 1.2 of DNR (DNR, 2006)

Table 31 *Aquifer parameter table for Point Nepean, Victoria*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Recent Deposits (aeolian, alluvium, fluvial) within Bridgewater and Wannaeue Fms	Quaternary	Unconfined	-92 to -120 [2]	47-55 [2]	1.19-2.01 (Avg 1.60; Med 1.63) [7]	900 (Bass Strait, southern side of peninsula)	20 [3]	0.3 [4]	220 (rainfall recharge prior to 1997 approximatelypredev) [5] 43 [6]
						2.55-2.72 (Avg 2.64; Med 2.65) [8]	3000 (Port Phillip Bay, northern side close to mid point of peninsula transect)			
						0.63-2.35 (Avg 1.46; Med 1.50) [9]	1700 (Port Phillip Bay, northern side close to mid point of peninsula transect)			
						0.75-1.41 (Avg 1.01; Med 0.93) [10]	600 (Port Phillip Bay, northern side close to mid point of peninsula transect)			
2	Upper Tertiary fluvial including Brighton Group	Tertiary	Unconfined	-140+ [2]	—	—	—	—	—	—

Notes:

[1] The reference used to determine aquifer parameters is Parsons Brinckerhoff (2010); Observation bore data obtained from transect where the Nepean Peninsula is approximately 9 km wide from north to south.

[2] Refer to Fig 6

[3] Refer to Pg 9

[4] Specific yield value reported on Pg 28

[5] Refer to Pg 24 for 1970-1996 period over which approximately 17 % of long term average annual rainfall has been estimated to recharge aquifer.

[6] Refer to water balance estimates on Pg 26 for the Nepean Peninsula where rainfall recharge (13.2 GL or 126 mm) and sewers/septic tank/water transmission gains (4.17 GL or 40 mm) minus licensed extractions (12.4 GL or 118 mm) and stock & domestic bores (0.55 GL or 5mm) provides a net recharge value of approximately 4.47 GL. This equates to 43 mm/yr over an area of 105.15 km^2

[7] Refer to GMS observation bore 63276 with 177 records collected between 4/5/1978 and 19/2/2010; Trendline: $y= -1.7E^{-3}x + 1.75$, $R^2 = 0.32$

[8] Refer to GMS observation bore 100267 with 4 records collected on 29/9/1993, 17/12/1993, 23/3/1994 and 29/9/1994

[9] Refer to GMS observation bore 100025 with 148 records collected between 26/2/1981 and 19/12/2010; Trendline: $y= -8E^{-4}x + 1.52$, $R^2 = 0.01$

[10] Refer to GMS observation bore S62034/1 with 10 records collected between 30/5/2008 and 3/1/2010; Trendline: $y= -5E^{-3}x + 1.03$, $R^2 = 0.00$

Other water balance information:
Groundwater use is primarily domestic, parks and gardens, and livestock

Table 32 *Aquifer parameter table for Perth Cottesloe Peninsula, Western Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Tamala Limestone	Quaternary	Unconfined	__ [1]	5-20 [2]	-0.18 to 0.38 (Avg 0.07; Med 0.06) [3]	1100 from ocean and 1250 from estuary	150 [2]	0.3 [7]	35 [6]
						0.23-0.74 (Avg 0.49; Med 0.47) [4]	960 from ocean and 1400 from estuary			
						-0.03-0.22 (Avg 0.13; Med 0.15) [5]	2400 from ocean and 50 from estuary			

Notes:

[1] The fresh groundwater within the Cottesloe Peninsula exists as a lens overlying saline water. The peninsula is approximately 2.4 km wide, nestled between the Indian Ocean and the Swan Estuary.

[2] Refer to Appleyard (2004)

[3] Refer to DoW observation bore 61610005 in Town of Cottesloe with 191 records collected between 01/06/1978 and 30/04/2010; Trendline: $y= 3E10^{-6} x -0.04$, $R^2=0.01$

[4] Refer to DoW observation bore 61611833 in Shire of Peppermint Grove with 26 records collected between 20/06/1996 and 25/05/2010; Trendline: $y= 3E10^{-5}x-0.45$, $R^2=0.00$

[5] Refer to DoW observation bore 61611767 in Shire of Peppermint Grove with 9 records collected between 9/08/1992 and 29/03/1993; Trendline: $y= 1.93E10^{-2}x+0.22$, $R^2=0.42$

[6] Estimate derived from Table 2.1 in Appleyard (2004). Assumes rainfall recharge of 250 mm plus scheme water recharge of 20 mm minus domestic bore use of 140 mm and licensed bore use of 75 mm.

[7] Avg specific yield value reported on pg 39 of Davidson and Yu (2008).

Table 33 *Aquifer parameter table for Rottnest Island, Western Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance - north side (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Dune sands and Tamala Limestone	Quaternary	Unconfined	-14.4 [2]	4 (<0.5 to 8.5) for freshwater lens [3]	0.09-0.36 (Avg 0.19; Med 0.18) [6]	330	39.5-101 [4]	0.15 [8]	128 [5]
						0.00-1.18 (Avg 0.36; Med 0.34) [7]	950			

Notes:

[1] Aquifer parameters derived primarily for the central-west area of Rottnest Island using the work of Leech (1976) as primary reference. Island width from north to south at site of observation bore transect approximately 2km wide heading due south from Charlotte Point. The conceptualisation assumes that some groundwater is extracted in this portion of the island.

[2] Refer to Pg 18 of Appendix 1 in Leech (1976)

[3] Refer to Table 1 in Leech (1976)

[4] Refer to Table 4 in Leech (1976)

[5] Calculated as difference between aquifer recharge and extraction over area of 4.16 km^2. Refer to Pg 18 in Leech (1976) in safe yield sub-section where avg annual recharge to aquifer estimated as 18 % of mean annual rainfall (736 mm/yr) which gives approximately132 mm/yr or 551 ML/yr and on Pg 1 where requirement for 18.2 ML/yr (approximately4 mm/yr) of groundwater to supply surface water deficit.

[6] Refer to non-DoW observation bore 61619183 with 11 records collected between 07/06/1991 and 19/10/1995; Trendline: $y= -2.7E^{-3}x+3.22$, $R^2 = 0.25$

[7] Refer to non-DoW observation bore 61619148 with 94 records collected between 01/04/1981 and 06/06/1991; Trendline: $y= -3.0E^{-5}x+1.32$, $R^2 = 0.06$. Island distance from north to south approximately 2 km and therefore 945 m represents the mid-point distance of the island.

[8] Refer to Pg 19 in Leech (1976) where suggested realistic aquifer storage value is given

Table 34 *Aquifer parameter table for Broome, Western Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Porosity	Net Recharge (mm/yr)
1	Superficial deposits	Quaternary and Tertiary	Unconfined	4.3 to -4.3 [2]	0 to 10 [3]	—	—	—	—	—
2	Broome Sandstone	Jurassic/ Cretaceous	Unconfined	-128 to -280 [2]	175 to 270 [4]	2.46 - 3.33 (Avg 2.71; Med 2.68) [7]	900 (Coconut Wells Area)	15 (7.5-23) [5]	0.05-0.3 [11]	24-30 [6]
						3.14 - 5.91 (Avg 3.16; Med 3.76) [8]	2430 (Coconut Wells Area)			
						0.21 - 4.46 (Avg 2.10; Med 1.94) [9]	1080 (Cable Beach Area)			
						1.64-2.37 (Avg 1.90; Med 1.79) [10]	2830 (Cable Beach Area)			
3	Jarlemai Siltstone	Jurassic/ Cretaceous	Aquitard	—	—	—	—	—		

Notes:

[1] Aquifer parameters derived primarily within a 15 km radius of Broome, with observation bores selected within 3km of the coastal fringe. Conceptualisation assumes minimal extraction within the coastal fringe.

[2] Refer to Table 2 for the Crab Creek and Broome TWS bores in Laws (1984)

[3] Estimate made for dune sands based on Pg 11 of Laws (1991)

[4] Refer to Figure 6c in Laws (1991) within 15 km radius of Broome

[5] Refer to Pg 8 of Laws (1985)

[6] Assume recharge of between 4 to 5 % of 600 mm/yr reported average annual rainfall (Pgs 6 and 15 of Laws (1991))

[7] Refer to DoW observation bore 80119101 in Coconut Wells area with 87 records collected between 25/11/1986 and 21/04/2010; Trendline: $y= 4E^{-5}x+1.34$, $R^2=0.23$

[8] Refer to DoW observation bore 80119104 in Coconut Wells area with 67 records collected between 25/11/1986 and 31/07/2001; Trendline: $y= 7E^{-5}x+1.57$, $R^2=0.06$

[9] Refer to DoW observation bore 80119125 in Cable Beach area with 178 records collected between 25/11/1986 and 19/04/2010; Trendline: $y= 2E^{-4}x-2.93$, $R^2=0.04$

[10] Refer to DoW observation bore 80119127 in Cable Beach area with 51 records collected between 25/11/1986 and 13/04/1989; Trendline: $y= 4E^{-5}x+0.64$, $R^2=0.00$

[11] Refer to reported range of porosity values for sandstone in Freeze and Cherry (1979)

Other information:

Saltwater interface noted up to 15 km inland. Intersected at -76 and -136 m AHD in the Broome Town Water Supply Wellfield (Pg 23 of Laws, 1991).

Table 35 *Aquifer parameter table for Derby, Western Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Porosity	Net Recharge (mm/yr)
1	Wallal Sandstone (with overlying Quaternary surficial sediments)	Jurassic	Unconfined	30 to -30 [2]	0 to 77 (Avg 20) [3]	—	—	0.8 to 16 [4]	0.03-0.5 [10]	18 [7]
2	Erskine Sandstone multilayered	Triassic	Unconfined on Derby Peninsula	-225 to -500 [2]	170 to 270 (Avg 170) [5]	-1.91 to 9.41 (Avg 1.51; Med 1.31) [8]	3930	0.2 to 3 [6]		
						-31.33 to 4.74 (Avg 1.94; Med 3.53) [9]	4180			

Notes:

[1] Parameters determined for the study area described in Laws and Smith (1988); Conceptual model for Derby Peninsula assumes that the Munkayarra shale aquitard is not present. The full extent of the Munkayarra Shale aquitard in the study area is not completely known. The shale is thought to have been eroded from the anticline beneath the town of Derby and therefore likely to occur primarily outside of the peninsula. The conceptualisation assumes that no extractions occur within the approximately4km coastal fringe.

[2] Refer to Fig 6

[3] Refer to Pg 12 and Pg 19

[4] Refer to Pg 13

[5] Refer to Pg 8 and Pg 24

[6] Refer to Pg 14

[7] Rainfall recharge to Wallal Sandstone over an area of 450 km^2 estimated as $8.2x10^3$ ML/yr (pg 20) which is equivalent to 18 mm or 3 % of average annual rainfall of 627 mm/yr. Assume that this full amount of recharge reaches the Erskine Sandstone and that the two aquifer systems are in full hydraulic connection.

[8] Refer to Water Corp observation bore 80219022 (Derby TWS) with 113 records collected between 24/10/1969 and 04/07/1998; Trendline: $y= 2.17E^{-2}x+0.27$, $R^2=0.15$

[9] Refer to Water Corp observation bore 80219013 (Derby TWS) with 133 records collected between 22/03/1969 and 04/07/1998; Trendline: $y= -3.96E^{-2}x+4.60$, $R^2=0.05$

[10] Refer to reported range of porosity values for sandstone in Freeze and Cherry (1979); Other water balance information: The Derby town water supply borefield comprises 12 production bores with a total abstraction of $1.15x10^6$ m^3/yr or 1150 ML/yr (in explanatory notes)

Table 36 *Aquifer parameter table for Adelaide Metropolitan, South Australia*

Aquifer Layer[1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Porosity	Net Recharge (mm/yr)
1	Clay aquitard with six interbedded minor aquifers all grouped together as one layer with Hindmarsh clay followed by Carisbrook sand at base	Quaternary	Aquitard with minor aquifers	-80 to -100 [2]	55 to 70 [3]	—	—	—	—	—
2	T1: mixed sands, sandstone, minor limestone Includes Hallet Cove SS and Upper Port Willunga	Tertiary	Confined	-130 to -220 [2]	80 (25-120) [4]	-18.22 to 2.46 (Avg - 4.82; Med -4.10) [7]	650	2.46 (0.15-8.88) [11]	0.05-0.3 [14]	-4 [12]
						-24.40 to 2.94 (Avg - 6.29; Med -4.83) [8]	5000			
3	Munno Para Clay	Tertiary	Aquitard	-130 to -220 [2]	12 [5]	—	—	—	—	—
4	T2: mixed sands, sandstone, minor limestone of Lower Port Willunga	Tertiary	Confined	-260 to -320 [2]	105 (80-110) [6]	-6.99 to 8.16 (Avg 2.40; Med 2.05) [9]	650	2.81 (0.97-9.6) [11]	0.05-0.3 [14]	-4 [13]
						1.89 to 9.29 (Avg 4.47; Med 4.19 [10]	5000			

Notes:

[1] Aquifer parameters derived primarily for the area within 5km of the coast in the Adelaide Metropolitan Region, Zone 3

[2] Refer to Figure 3 in Osei-Bonsu and Barnett (2008) for the area to the west of Adelaide

[3] Refer to Tables 2 and 5 in Zulfic et al. (2008)

[4] Refer to Tables 7 and 8 in Zulfic et al. (2008)

[5] Refer to Tables 3 and 5 in Zulfic et al. (2008)

[6] Refer to Tables 9 and 10 in Zulfic et al. (2008) for zone 3

[7] Refer to Obswell Obs. no. YAT037 with 264 records collected between 01/06/1936 and 01/03/2011; Trendline: $y = -1.21E^{-2} + 5.80$, $R^2 = 0.28$

[8] Refer to Obswell Obs. no. YAT031 with 271 records collected between 01/12/1945 and 01/03/2011; Trendline: $y = -7.1E^{-3}x + 0.071$, $R^2 = 0.05$

[9] Refer to Obswell Obs. no. YAT099 with 96 records collected between 01/10/1983 and 01/05/2011; Trendline: $y = -7.7E^{-3}x + 11.75$, $R^2 = 0.16$

[10] Refer to Obswell Obs. no. ADE146 with 97 records collected between 01/10/1983 and 01/05/2011; Trendline: $y = -1.36E^{-2}x + 21.16$, $R^2 = 0.77$

[11] Refer to Table 1 in Osei-Bonsu and Barnett (2008)

[12] Refer to Table 8 in Osei-Bonsu and Barnett (2008): Leakage inflows [5631 ML/yr] minus leakage [846ML/yr] and extraction [7043ML/yr] losses over area of 560 km^2 gives -4 mm

[13] Refer to Table 9 in Osei-Bonsu and Barnett (2008): Leakage inflows [596 ML/yr] minus leakage [846 ML/yr] and extraction [1824 ML/yr] losses over area of 560 km^2 gives -4 mm

[14] Refer to reported range of porosity values for sandstone in Freeze and Cherry (1979)

Table 37 *Aquifer parameter table for LeFevre Peninsula, South Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Porosity	Net Recharge (mm/yr)
1	Semaphore sands aeolian dunes (Q1a)	Quaternary	Unconfined	-10 [2]	11 (7-20) [4]	0.7-1.1 [8]	500	4.3-13.0 [12]	0.27 [17]	90 [14]
						1.3-1.8 [9]	1000			
2	Clay aquitard with interbedded minor aquifers grouped as one layer	Quaternary	Aquitard with minor aquifers	-80 to -100 [3]	55 to 70 [3]	—	—	—	—	—
3	T1: mixed sands, sandstone, minor limestone Includes Hallet Cove SS and Upper Port Willunga.	Tertiary	Confined	-130 to -220 [3]	80 (25-120) [5]	-10.21 to -2.56 (Avg -5.98; Med -5.80) [10]	500	2.46 (0.15-8.88) [13]	0.05-0.3 [18]	-4 [15]
4	Munno Para Clay	Tertiary	Aquitard	-130 to -220 [3]	12 [6]	—	—	—	—	—
5	T2: mixed sands, sandstone, minor limestone of Lower Port Willunga	Tertiary	Confined	-260 to -320 [3]	105 (80-110) [7]	-9.6 to 1.0 [11]	500	2.81 (0.97-9.6) [13]	0.05-0.3 [18]	-4 [16]

Notes:

[1] Aquifer parameters derived primarily for the area within 1km of the coast in the LeFevre Peninsula, Adelaide Metropolitan Region. A groundwater divide exists within the shallow aquifers approximately 1km inland to the west of Gulf St. Vincent. To the east of the divide shallow groundwaters flow to the Port Adelaide River.

[2] Refer to Figure 2.1 in Russell (1996)

[3] Refer to Figure 3 in Osei-Bonsu and Barnett (2008) for the area to the west of Adelaide

[4] Refer to Figure 2.6 and Pg 52 in Russell (1996)

[3] Refer to Tables 2 and 5 in Zulfic et al. (2008)

[5] Refer to Tables 7 and 8 in Zulfic et al. (2008)

[6] Refer to Tables 3 and 5 in Zulfic et al. (2008)

[7] Refer to Tables 9 and 10 in Zulfic et al. (2008) for zone 3

[8] Refer to piezometer T1-762 in Russell (1996)

[9] Refer to piezometer T3-768 in Russell (1996)

[10] Refer to Obswell Obs. no. PTA062 with 69 records collected between 01/09/1979 and 01/04/2011; Trendline $y = -1.07E^{-2}x + 6.8$, $R^2 = 0.54$

[11] Refer to Obswell Obs. no. PTA040 with 272 records collected between 01/05/1974 and 01/05/2011; Trendline $y = -1.65E^{-2}x + 15.05$, $R^2 = 0.55$

[12] Refer to Table 2.2 in Russell (1996) for piezometers T1-762 and T3-768

[13] Refer to Table 1 in Osei-Bonsu and Barnett (2008)

[14] Refer to water balance figures in Russell (1996). Values reported include those for vertical recharge (pg 130) [115 mm/yr] minus losses arising from extractions (pg 134) [285 ML/yr] over an area of 11.2 km^2.

[15] Refer to Table 8 in Osei-Bonsu and Barnett (2008): Leakage inflows [5631 ML/yr] minus leakage [846ML/yr] and extraction [7043 ML/yr] losses over area of 560 km^2 gives -4 mm

[16] Refer to Table 9 in Osei-Bonsu and Barnett (2008): Leakage inflows [596 ML/yr] minus leakage [846 ML/yr] and extraction [1824 ML/yr] losses over area of 560 km^2 gives -4 mm

[17] Refer to porosity value from Pg 52 of Russell (1996)

[18] Refer to reported range of porosity values for sandstone in Freeze and Cherry (1979)

Table 38 *Aquifer parameter table for Willunga, South Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)[3]	Inland Head Distance (m)[3]	K (m/d)[2]	Porosity	Net Recharge (mm/yr)
1	Quaternary (Qa) aquifer: comprising sands and gravels, interbedded clays, inferred to be separated from PWF by increasing clay content	Quaternary	Unconfined	up to -20 m AHD	10 to 30	2 to 5	1250	10 to 0.1 (assuming more uniform beach sand texture at coast) [5]		15 to 30
2	Port Willunga Formation (PWF) aquifer: comprising loosely consolidated sand and indurated limestone	Tertiary	Confined at coast, unconfined further up catchment	up to -120 m AHD (say -90 m AHD)	60 to 100 (say 70 m)	0.5 to 2	1250	10 to 0.1		0
3	Maslin Sands (MS) aquifer: comprising very fine to coarse sands, separated from PWF by the Blanche Point Formation Aquitard	Tertiary	Confined at coast, unconfined further up catchment	up to -190 m AHD (say -160 m AHD)	10 to 70 (say 40 m)	0 to 1	3500	0.01 to 1		0
4	Fractured Rock (FR) aquifer: comprising fractured basement rock	Proterozoic	Confined at coast, unconfined further up catchment and at eastern boundary at Willunga Fault	up to approximately-360 m AHD	say 150	1 to 5	1250	0.1 to 10		0

Notes:

[1] Aquifer parameters derived primarily for the area within 3.5 km of the coast, south of Willunga township; Key references used:

[2] Hydraulic conductivity estimates used in the conceptual hydrogeological box model were based on a combination of literature values (Fetter, 2001 and Driscoll, 1986) assigned to lithological descriptions and personal experience of realistic ranges of K values.

[3]Hydrogeological unit	Description of Data Source	Inland head range (m AHD)
Qa	Stewart (2006), Figure 6 Obswell data for WLG135 located approximately 1.25 km inland of the coast within the boundary of the study area	2 to 5
PWF	Stewart (2006), Figure 7 Lamontagne et al (2005), Figure 1.8 Obswell data for WLG087 and WLG088 located approximately 2.5 km and 1.25 km, respectively, inland of the coast within the boundary of the study area	0.5 to 2
MS	Stewart (2006), Figure 8 Lamontagne et al (2005), Figure 1.7	0 to 1
FR	Stewart (2006), Figure 9 (updated with current reduced water level information) Obswell data (not density corrected) for WLG040 located approximately 1.25 km inland of the coast within the boundary of the study area	1 to 5

***Table 39** Aquifer parameter table for Perth (Whitfords subregion), Western Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Superficial sediments (sand, siltstone, limestone, clay); may also include other localised aquifers above aquitard layer including permeable King's Park (eg Mullaloo and Como sandstone members) and Mirrabooka Aquifer	Quaternary/ Tertiary	Unconfined	-50 to -100 [2]	60 to 90 [3]	0.87-1.61 (Avg 1.24; Med 1.23) [14]	900	8-50 and 100-1000 (Avg 15) [4]	0.2 [24]	120 (rainfall recharge only approximatelypre-development) [20] 31 [21]
						2.22-4.60 (Avg 3.59; Med 3.69) [15]	3600			
2	Kardinya Shale (siltstone, shales, sandstone) and impermeable King's Park and Lancelin Fms, Osborne Clay	Tertiary/ Cretaceous	Aquitard/ discontinuous	-50 to-100 [5]	0 to 50 [6]	—	10^{-2} - 10^{-6} [13]	—	—	
3	Leederville, including Henley ss, Pinjar, Wanneroo and Maringiniup Members (discontinuous interbedded sandstone, siltstone, shale, conglomerate)	Cretaceous	Semi-confined to Confined	-250 to -300 [7]	150 to 200 [8]	-5.18 to 7.08 (Avg 3.21; Med 4.21) [16]	3439	0.1-10 [13]	0.05-0.3 [25]	-1 [22]
						-0.89 to 5.02 (Avg 2.76; Med 3.59) [17]	4610			
4	South Perth Shale	Cretaceous	Aquitard	-300 to -350 [9]	100 [10]	—	10^{-4} - 10^{-5} [13]	—	—	
5	Yarragadee and Gage Fm aquifers (discontinuous interbedded sandstone, siltstone, shale)-alternatively Cattamarra Coal measures if present within 5km of coast	Cretaceous/ Jurassic	Confined	-1650 to -1850 [11]	1450 to 1550 [12]	-26.1 to 24.96 (Avg 14.36; Med 17.71) [18]	3439	1-3 [13]	0.05-0.3 [25]	0 [23]
						-21.51 to 30.43 (Avg 14.26; Med 22.03) [19]	4610			

Notes:

[1] Reference used for parameters (with the exception of net recharge) is Davidson and Yu (2008) for the area up to 10 km inland for the Whitfords subarea north of Perth. The confined aquifers extend out to sea at least as far as 20 km (model boundary used by Davidson and Yu, 2008); additional data would be required to estimate the aquifer position and extension below the ocean.

[2] Refer to Fig 13 and Fig 107; note that the thickness also considers localised aquifers above the aquitard that may not traditionally be considered part of the Superficial aquifer system, eg permeable members of the Kings Park Formation and the Mirrabooka Aquifer.

[3] Depth to watertable presented in Fig 79

[4] Refer to pg 36, 37 and 57; averages for the Safety Bay and Becher Sands and Tamala Limestone which are found along the coastal plain; note that the Tamala Limestone values range from 100-1000 m/d. See Appendix Table 2.

[5] Refer to Fig 108

[6] Refer to Fig 38

[7] Refer to Fig 43

[8] Refer to Fig 44

[9] Refer to Fig 55

[10] Refer to Fig 56

[11] Refer to Fig 97

[12] Refer to Fig 98

[13] Refer to Appendix Table 2

[14] Refer to DoW observation bore 61620102 in the Whitfords area with 57 records collected between 19/05/1992 and 28/09/2010; Trendline: $y= -8E^{-5}x+3.97$, $R^2=0.49$

[15] Refer to DoW observation bore 61620110 in the Whitfords area with 55 records collected between 11/05/1992 and 28/09/2010; Trendline: $y= -3E^{-4}x+14.73$, $R^2=0.88$

[16] Refer to DoW observation bore 61615006 in the Whitfords area with 255 records collected between 03/06/1975 and 10/05/2010; Trendline: $y= -7E^{-4}x+27.14$; $R^2=0.68$
note, The bore logs are unclear and suggest that the Leederville aquifer is unconfined in this area; however, Davidson and Yu (2008) report the aquifer is confined.

[17] Refer to DoW observation bore 61615065 in the Whitfords area with 414 records collected between 14/08/1973 and 15/09/2010; Trendline: $y= -4E^{-4}x+16.0$; $R^2=0.72$
note, The bore logs are unclear and suggest that the Leederville aquifer is unconfined in this area; however, Davidson and Yu (2008) report the aquifer is confined.

[18] Refer to DoW observation bore 61615007 in the Whitfords area with 171 records collected between 17/01/1983 and 10/05/2010; Trendline: $y= -3.7E^{-3}x+142.07$; $R^2=0.63$

[19] Refer to DoW observation bore 61615063 in the Whitfords area with 433 records collected between 23/10/1973 and 15/09//2010; Trendline: $y= -3.7E^{-3}x+137.92$, $R^2=0.80$

[20] Value of 120 mm/yr of rainfall recharge obtained from estimating 15 % (Fig 81 for Whitfords area) of long term average annual rainfall of 800 mm/yr (Fig 1).

[21] Value of 31 mm/yr derived from rainfall recharge value in footnote 20 (120 mm/yr) and minus the extraction values reported in Appendix D of CyMod Systems (2009) typical of the 1992-1997 period for the Whitfords (123.99 km^2) subarea estimated as 6300 ML/yr (or 51 mm/yr) of licensed and 4700 ML/yr (or 38 mm) of unlicensed groundwater extraction.

[22] Value of -1mm derived from Appendix D in CyMod Systems (2009) and is typical of the 1992-1997 period for the Whitfords (123.99 km^2) subarea estimated as 100 ML/yr of groundwater extraction (approximately1 mm) and zero rainfall recharge.

[23] No extractions reported within the Yarragadee Aquifer in Appendix D of CyMod Systems (2009) within the Whitfords subarea

[24] Avg specific yield value reported on pg 58 of Davidson and Yu (2008)

[25] Refer to reported range of porosity values for sandstone in Freeze and Cherry (1979)

Table 40 Aquifer parameter table for Busselton Western Australia

Aquifer Layer	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield/ Porosity	Net recharge (mm/yr)
1	Superficial clay, sand	Quaternary	Unconfined	30 to -10 [2]	0 to 5 [3]	-0.92 to 2.52 (Avg 0.70; Med 0.41) [13]	1650	0.5-5 [4]	0.2 [11]	8 to 61 (Avg 33) [9]
2	Leederville interbedded sandstone, siltstone, shale	Cretaceous	Confined	-20 to -100 [5]	25 to 105 [6]	-0.13 to 2.34 (Avg 1.24; Med 1.35) [14]	1650	0.01 to 10 (typical 0.2-2.1) [7]	0.03-0.5 [12]	0 [10]
3	Sue coal Measures sandstone, shale, coal	Permian	Confined/fractures	—	up to 1838 [8]	0.14 to 2.51 (Avg 1.15; Med 1.07) [15]	1650	—	—	—

Notes:

[1] These parameters are derived for the area between the Dunsborough Fault (to the west) and the Wirring Fault (to the east), as shown in Fig 2 of Hirschberg (1989) between Dunsborough and Busselton. Conceptualisation assumes no groundwater extractions within the approximately1.7 km coastal fringe.

[2] Refer to Fig 4 of Hirschberg (1989)

[3] Refer to pg 27 of Hirschberg (1989)

[4] Refer to pg 28 of Hirschberg (1989)

[5] Refer to Fig 3 and Fig 13 of Hirschberg (1989)

[6] Refer to pg 29 of Hirschberg (1989) for average values of Leederville thickness

[7] Refer to pg 47 of Schafer and Johnson (2009)

[8] Refer to Table 2 of Hirschberg (1989) and Table 2 of Schafer et al. (2008). Insufficient data to characterise aquifer in more detail.

[9] No values of groundwater recharge reporting found. Assume same recharge as for the Bunbury area parameter table extrapolated from Commander (1982) which assumes a range of recharge estimates ranging from 1 % (8mm) 4 % (31mm) and 8 % (62mm) of long term average annual rainfall of 825mm/yr as cited in Hirschberg (1989).

[10] Assumes zero recharge in the coastal fringe

[11] Value commonly reported for Superficial Formation in literature such as Davidson and Yu (2008)

[12] Refer to reported range of porosity values for sandstone in Freeze and Cherry (1979)

[13] Refer to DoW observation bore 61030048 (BN16S) with 60 records collected between 15/03/1984 and 14/09/2010; Trendline: $y= 3E^{-5}x-0.34$, $R^2=0.01$

[14] Refer to DoW observation bore 61030049 (BN16I) with 37 records collected between 15/03/1984 and 14/09/2010; Trendline: $y= 9E^{-5}x-2.06$, $R^2=0.06$

[15] Refer to DoW observation bore 61030050 (BN16D) with 56 records collected between 21/02/1984 and 14/09/2010; Trendline: $y= -6E^{-5}x+3.51$, $R^2=0.08$

Other information:

Seawater intrusion noted to have occurred to a distance of at least 4km inland within the Permian Sue Coal Measures and along the coast within the Leederville and Superficial aquifers as indicated on pg 36 and shown in Fig 13 of Hirschberg (1989)

***Table 41** Aquifer parameter table for Bunbury, Western Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Porosity	Net Recharge (mm/yr)
1	Superficial Fms (sands, clays, limestone)	Quaternary	Unconfined	-10 to -20 [2]	20-50 [3]	2.48 - 4.26 (Avg 3.17; Med 3.16) [13]	870	3-16 [4]	0.2 [11]	8 to 61 (Avg 33) [9]
						5.64 - 6.64 (Avg 6.18; Med 6.20) [15]	3047			
2	Yarragadee Fm (sand, minor shale)	Jurassic	Semi-confined to Confined	-175 to -700 [5]	175-500 [6]	-1.29 to 3.23 (Avg 1.72; Med 1.93) [14]	870	18-21 (Avg 20) [8]	0.03-0.5 [12]	0 [10]
						0.40 to 4.55 (Avg 2.89; Med 3.02) [16]	3047			
3	Cockleshell Gully Fm (upper portion grouped with layer 4 above)	Jurassic	Confined	>/= -755	>580 [7]	—	—	—	—	—

Notes:

[1] Bunbury is located in the Bunbury Trough subdivision of the Southern Perth Basin on eastern limit of anticline. Parameters derived for approximately3km coastal fringe and assume no groundwater extraction in this area.

[2] Refer to Pg 5 of Commander (1981)

[3] Refer to Fig 9 and pg 27 of Deeney (1988); maximum thickness obtained from Table 1 in Commander (1981)

[4] Refer to Table 2 of Deeney (1988)

[5] Refer to Plate 1, Section D in Commander (1982); the thickness is highly variable. On Pg 10 of Commander (1981) max depth reported as -700m AHD in Bunbury area.

[6] Minimum thickness estimated from Plate 1, Section D in Commander (1982); maximum thickness obtained from Table 1 in Commander (1981); this aquifer tends to be grouped with the Cockleshell Gully Fm giving a combined freshwater thickness of 500 m in the sand aquifer (refer to pg 12 in Commander (1981)).

[7] Maximum thickness obtained from Table 1 in Commander (1981); freshwater component of aquifer can be grouped with upper Yarragadee Fm

[8] Refer to pg 12 in Commander (1981)

[9] Refer to Superficial aquifer characteristics for Area 6 in Commander (1982) using estimated recharge over the areas with a salinity <3000 mg/L. These estimates provide values of 62 mm/yr in the areas with groundwater salinity <500 mg/L; 31 mm/yr in the areas with salinity ranges between 500-1000 mg/L and 8 mm/yr in the areas with salinity ranges from 1000-3000 mg/L.

[10] No recharge data reported. Assume zero pumping and no downward recharge in coastal fringe.

[11] Value commonly reported for Superficial Formation in literature such as Davidson and Yu (2008)

[12] Refer to reported range of porosity values for sandstone in Freeze and Cherry (1979)

[13] Refer to DoW observation bore 61118024 with 163 records collected between 04/12/1975 and 10/09/2010; Trendline: $y= -3E^{-5}x+4.11$, $R^2=0.12$

[14] Refer to DoW observation bore 61118023 with 191 records collected between 04/12/1975 and 10/09/2010; Trendline: $y= 7E^{-6}x+1.48$, $R^2=0.00$; note: Leederville Fm absent above at this location.

[15] Refer to DoW observation bore 61118013 with 192 records collected between 26/07/1977 and 10/09/2010; Trendline: $y= -2E^{-5}x+6.75$, $R^2=0.09$

[16] Refer to DoW observation bore 61118012 with 187 records collected between 26/07/1977 and 10/09/2010; Trendline: $y= -1E^{-4}x+6.27$, $R^2=0.11$

Other Information:

North of Bunbury there are a number of important lakes and swamps covering large areas of the coastal plain that are inland from the coastal dunes; These include Lakes Clifton and Preston. The lagoons of Leschenault and Peel inlets are to the north. Salt water intrusion is reported along the shore of Leschenault Inlet and reported for the underlying aquifers at depths ranging from 45 to 100 m (refer to Figs 5 and 7 in Commander (1981)).

Table 42 *Aquifer parameter table for Albany (Princess Royal Harbour Side), Western Australia*

Aquifer Layer[1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Superficial aquifer; surficial sands and Tamala Limestone	Quaternary	Unconfined	0 (5 to -10) [2]	2 (0 to 10) [3]	2.34 [21]	140	5 (2-60) [10]	0.05-0.15 [14]	160 [17]
						1.69-5.79 [22]	260			
2	Superficial clay	Quaternary	Aquitard	42 (40-45) [17]	10 (5-15) [18]	—	—	0.001-0.2 [11]	—	—
3	Pallinup Basal Middle Sands	Tertiary	Unconfined in coastal fringe	-25 (-10 to -30) [4]	30 (20-40) [7]	— [23]	—	5 (2-18) [12]	0.05-0.15 [15]	131 [19]
4	Werillup Fm Clay	Tertiary	Aquitard (discontinuous)	-30 (-10 to -40) [5]	0 (0-25) [8]	—	—	0.005-0.2 [11]	—	—
5	Werillup Fm Sand	Tertiary	Unconfined in portions of coastal fringe – not present in far southeast	-20 (-20 to -40) [6]	15 (0; 5-30) [9]	-0.59 to 1.43 (Avg 0.73; Med 0.80) [24]	30	7 (0.1-15) [13]	0.05-0.15 [16]	131 [20]
						-1.90 to 2.35 (Avg 1.48; Med 1.60) [25]	160			
						-4.82 to 3.28 (Avg 1.41; Med 1.88) [26]	800			
5	Granite Basement	Precambrian	Aquitard	—	—	—		—		

Notes:

[1] Aquifer parameters derived primarily for the area within 1.5 km of the coast along the Princes Royal Harbour Racecourse Borefield. It is assumed that no groundwater extractions occurs within the 800 m coastal fringe. The width of the peninsula is approximately 5 km.

[2] Refer to Figs 5.1 and 5.10 in Water Corporation (2010)

[3] Refer to Fig 6.1 in Water Corporation (2010)

[4] Refer to Fig 5.8 in Water Corporation (2010)

[5] Refer to Fig 5.5 in Water Corporation (2010)

[6] Refer to Fig 5.4 in Water Corporation (2010)

[7] Refer to Fig 6.5 in Water Corporation (2010); Middle Sands Aquifer absent in eastern Sandpatch area.

[8] Refer to Fig 6.6 in Water Corporation (2010); Werillup Formation Clay mostly absent in Sandpatch wellfield.

[9] Refer to Fig 6.7 in Water Corporation (2010); Werillup Sands Aquifer absent in eastern Sandpatch area.

[10] Refer to Table 6 in CyMod Systems Pty Ltd (2010a). note, on pg 56 of Water Corporation (2010) that the Superficial aquifer is not particularly permeable.

[11] Refer to Table 6 in CyMod Systems Pty Ltd (2010a).
[12] Refer to Table 6 in CyMod Systems Pty Ltd (2010a) and pg 56-57 Section 6.3.2 of Water Corporation (2010)
[13] Refer to Table 6 in CyMod Systems Pty Ltd (2010a) and pg 56-57 Section 6.3.3 of Water Corporation (2010)
[14] Refer to Fig B16 in CyMod Systems Pty Ltd (2010a)
[15] Refer to Fig B18 in CyMod Systems Pty Ltd (2010a)
[16] Not reported, but assume similar to that reported for other sand layers
[17] Refer to Fig 5.9 in Water Corporation (2010)
[18] Refer to Fig 6.3 in Water Corporation (2010)
[19] Assumes a mean recharge rate of 21 % of average annual rainfall of 900 mm/yr – refer to pg 64 of Water Corporation (2010)
[20] Assumes a mean recharge rate of 14.5 % of average annual rainfall of 900 mm/yr from leakage through Superficial Clay – refer to pg 64 and 65 of Water Corporation (2010)
[21] Refer to DoW observation bore 60210185 with 1 record collected on 26/05/1997. note there is little observation data for the Superficial Aquifer.
[22] Refer to DoW observation bores 60210184 and 60210187 each with 1 record collected on 26/05/1997; assume that these two values represent the range of heads in this area due to limited data.
[23] No observation bore data screens this aquifer within the coastal fringe
[24] Refer to Water Corp observation bore 60218121 screening Werillup Fm with 128 records collected between 5/9/1973 and 1/2/1985; Trendline: $y= 2E^{-4}x-5.06$, $R^{2}=0.28$
[25] Refer to Water Corp observation bore 60218120 screening Werillup Fm with 262 records collected between 5/9/1973 and 30/12/1998; Trendline: $y= -4E^{-5}x+2.72$, $R^{2}=0.05$
[26] Refer to Water Corp observation bore 60218136 screening Werillup Fm with 205 records collected between 5/9/1973 and 30/12/1998; Trendline: $y= -3E^{-4}x+10.67$, $R^{2}=0.16$

Other water balance information:

The current total licensed water allocations for all borefields is 3.95 GL/yr which has been fully utilised in recent years. Demand for projected water increases is by 5 GL in the next 30 years (Water Corporation, 2010); Note: A geophysical resistivity survey of the shoreline area along Princess Royal Harbout has defined a zone of high electrical conductivity in the upper littoral zone at Pelican Point and extending approximately 80 m inland which suggests the presence of a saltwater interface – refer to pg 80 of Water Corporation (2010).

***Table 43** Aquifer parameter table for Albany (Ocean Side), Western Australia*

Aquifer Layer[1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Superficial aquifer; surficial sands and Tamala Limestone	Quaternary	Unconfined	-10 (20 to -30) [2]	15 (0 to 30) [3]	1.19-3.14 (Avg 1.99; Med 1.73) [20]	750	5 (2-60) [10]	0.05-0.15 [14]	160 [17]
2	Superficial clay	Quaternary	Aquitard (discontinuous)- not present along coastal fringe	—	—	—	—	0.001-0.2 [11]	—	—
3	Pallinup Basal Middle Sands	Tertiary	Unconfined in coastal fringe	-20 (0 to -40) [4]	10 (0; 5-30) [7]	— [21]	—	5 (2-18) [12]	0.05-0.15 [15]	160 [18]
4	Werillup Fm Clay	Tertiary	Aquitard (discontinuous)- not present along portions of coastal fringe	-30 (-10 to -40) [5]	0 (0-25) [8]	—	—	0.005-0.2 [11]	—	—
5	Werillup Fm Sand	Tertiary	Unconfined Aquifer in portions of coastal fringe – not present in far southeast	-20 (-20 to -40) [6]	15 (0; 5-30) [9]	2.76-3.68 (Avg 2.85; Med 2.79) [22]	1300	7 (0.1-15) [13]	0.05-0.15 [16]	160 [19]
						-0.72 to 8.78 (Avg 5.95; Med 6.28) [23]	1500			
5	Granite Basement	Precambrian	Aquitard	—	—	—		—		

Notes:

[1] Aquifer parameters derived primarily for the southern peninsula coast along the Werillup, Prison and Sandpatch Borefields. It is assumed that no groundwater extraction occurs within the 1.5 km coastal fringe. The width of the peninsula is approximately 5 km.

[2] Refer to Fig 5.10 in Water Corporation (2010)

[3] Refer to Fig 6.1 in Water Corporation (2010)

[4] Refer to Fig 5.8 in Water Corporation (2010)

[5] Refer to Fig 5.5 in Water Corporation (2010)

[6] Refer to Fig 5.4 in Water Corporation (2010)

[7] Refer to Fig 6.5 in Water Corporation (2010); Middle Sands Aquifer absent in eastern Sandpatch area.

[8] Refer to Fig 6.6 in Water Corporation (2010); Werillup Formation Clay mostly absent in coastal fringe except for in the western Werillup area.

[9] Refer to Fig 6.7 in Water Corporation (2010); Werillup Sands Aquifer absent in eastern Sandpatch area.

[10] Refer to Table 6 in CyMod Systems Pty Ltd (2010a). note on pg 56 of Water Corporation (2010) that the Superficial aquifer is not particularly permeable.

[11] Refer to Table 6 in CyMod Systems Pty Ltd (2010a).

[12] Refer to Table 6 in CyMod Systems Pty Ltd (2010a) and pg 56-57 Section 6.3.2 of Water Corporation (2010)

[13] Refer to Table 6 in CyMod Systems Pty Ltd (2010a) and pg 56-57 Section 6.3.3 of Water Corporation (2010)

[14] Refer to Fig B16 in CyMod Systems Pty Ltd (2010a)

[15] Refer to Fig B18 in CyMod Systems Pty Ltd (2010a)

[16] Not reported, but assume similar to that reported for other sand layers

[17] Assumes a mean recharge rate of 21 % of average annual rainfall of 900 mm/yr – refer to pg 64 of Water Corporation (2010)

[18] Assume that the middle sands are hydraulically connected with the Superficial aquifer within the coastal fringe

[19] Assume that the Werillup Fm Sands are hydraulically connected with the Superficial and Middle aquifers within the coastal fringe

[20] Refer to DoW observation bore 60218111 with 47 records collected between 21/01/1976 and 02/08/1980; Trendline: $y=-3E^{-4}x+9.13$, $R^2=0.03$

[21] No observation bore data screens this aquifer within the coastal fringe

[22] Refer to DoW observation bore 60218105 (W15) screening Werillup Fm with 16 records collected between 9/04/1975 and 23/12/1976; Trendline: $y= 4E^{-4}x-7.49$, $R^2=0.10$

[23] Refer to Water Corp observation bore 60218167 screening Werillup Fm with 211 records collected between 21/01/1976 and 15/11/1995; Trendline: $y= 2E^{-4}x-1.09$, $R^2=0.08$

Other water balance information:

The current total licensed water allocations for all borefields is 3.95 GL/yr which has been fully utilised in recent years. Demand for projected water increases is by 5GL in the next 30 years (Water Corporation, 2010).

***Table 44** Aquifer parameter table for Esperance, Western Australia*

Aquifer Layer[1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Porosity	Net Recharge (mm/yr)
1	Superficial (dune sands, interbeds of sandy limestone, siltstone)	Quaternary	Unconfined	-9 to -32 [2]	2-45 (Avg 20-30) [3]	-1.79 to 2.63 (Avg 1.16; Med 1.19) [7]	760	2-43 [4]	0.15 [11]	1.7 to 31 [5]
						0.11 to 3.26 (Avg 0.91; Med 0.80) [8]	1600			
2	Pallinup Siltstone, Plantagenet Group (silty sandstone with clay at base)	Tertiary	Unconfined/ Semi-confined minor aquifer lumped with layer 1 note: Aquifer becomes aquitard at base	-18 to -35 [2]	1-39 (Avg 16-20) [3]	— [9]	—	0.8-10 [4]	—	1.7 to 31 [6]
3	Werillup Fm, Plantagenet Group (fluvial and lacustral)	Tertiary	Confined	-18.1 to -46.5 [2]	0.1-33 [3]	0.49 to 0.68 [10]	295	8-12 [4]	0.25-0.5 [12]	0
4	Weathered Zone and Basement (granite, gneiss, quartzite and mafic rock)	Proterozoic	Aquitard	—	—	—	—	—	—	—

Notes:

[1] The primary reference used is Crisalis International Pty Ltd. (2010) and is focused on the Town sub-area within the Esperance Groundwater Area; note that saline wetlands such as Pink Lake and Lake Warden are found approximately4 km inland from the coast, and are thought to provide a source of saline water to the underlying Pallinup aquifer that is mobilised through over-abstraction. This conceptualisation assumes that there are no extractions within the 1.6 km coastal fringe.

[2] Refer to Figure 3 in Crisalis International Pty Ltd. (2010)

[3] Refer to Section 2 and Table 1

[4] Refer to Table 1 values converted from m/s to m/d

[5] The lower value of net recharge assumes rainfall recharge of 1.73 mm/yr (refer to Fig 4 recharge estimates in coastal area for zone 5) and the upper value of net recharge assumes rainfall recharge that 5 % of the long term average annual rainfall (623 mm/yr) or approximately31 mm/yr recharges the aquifer (refer to Pg 3 where it is stated that a study indicated that between 5 and 25 % of average annual rainfall was estimated to recharge aquifers in this region.)

[6] Assume that same volume of recharge occurs in the upper aquifer as for the hydraulically connected Superficial aquifer.

[7] Refer to WaterCorp observation bore 60118001 with 193 records collected between 01/01/1963 and 05/10/1998; Trendline: $y= 5E^{-5}x - 0.37$, $R^2=0.04$

[8] Refer to WaterCorp observation bore 60118008 with 107 records collected between 11/12/1965 and 30/03/1998; Trendline: $y= -3E^{-4}x + 9.27$, $R^2=0.59$

[9] Insufficient stratigraphic data to determine heads for this minor aquifer

[10] Refer to WaterCorp observation bore 60119520 with 2 records collected on 31/10/1997 and 01/05/1998

[11] Refer to pg 20, section 4.2 for specific yield of layer 1

[12] Refer to reported range of porosity values for sand in Freeze and Cherry (1979)

Other water balance information:
Approximately 2930 ML/yr is allocated for abstraction within the Twilight and Town GMUs.

***Table 45** Aquifer parameter table for Exmouth, Western Australia*

Aquifer Layer [1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Porosity	Net Recharge (mm/yr)
1	Cape Range Group aquifers Trealla, Tulki and Mandu (karstic limestones, marl, interbedded sands)	Tertiary (with minor overlying Quaternary sediments near coast)	Unconfined to semi-confined	-50 to -120 (and up to -600) [2]	60 to 120 [3]	-0.49 to 1.08 (Avg 0.59; Med 0.63) [6]	2200	8.64 x10^{-2} to 864 (Avg range 23 to 45) [4]	0.05-0.5 [8]	25 [5]
						-1.43 to 1.37 (Avg 0.67; Med 0.67) [7]	2700			
2	Giralia calcarenite	Tertiary	—	—	—	—	—	—	—	—

Notes:

[1] Parameters determined for the Exmouth Town sub-area the eastern coastal part of the Cape Range Peninsula which is 96 km in length and 21 km from east to west (Martin, 1990). Fresh groundwater occurs as a lens overlying saline water. It is assumed that no groundwater extractions occur within the approximately2.8km coastal fringe.

[2] The base of the Mandu Limestone is considered as the base of the Cape Range Group. Refer to Fig 2, within a 7 km distance of the East coast, and Table 2 in Martin (1990) for overall maximum estimated depths to base of Mandu

[3] Saturated thickness estimated from Fig 3; note that freshwater sits upon saline water, so that the aquifer thickness of the freshwater portion is much less than the overall aquifer thickness

[4] Refer to typical range of generic values for Karst systems in Table 2.2 of Freeze and Cherry (1979). Transmissivity reported as 2720 m^2/d on page 9 of Water and Rivers Commission (1999), and over an aquifer thickness of 60 to 120 m gives average hydraulic conductivity values that range from 22.7 to 45.3 m/d

[5] Refer to pg 9 of Water and Rivers Commission (1999) where groundwater recharge estimated to be about 10 % of average annual rainfall (250 mm/yr)

[6] Refer to WaterCorp observation bore 70519001 (Exmouth TWS) with 179 records collected between 02/06/1974 and 17/01/1996; Trendline: y= -3E^{-5}x + 1.38, R^2=0.04

[7] Refer to WaterCorp observation bore 70519014 (Exmouth TWS) with 211 records collected between 27/08/1973 and 13/05/1996; Trendline: y= -3E^{-5}x + 1.65, R^2=0.05

[8] Refer to reported range of porosity values for karst limestone in Freeze and Cherry (1979)

Water balance information:

The Water Corp abstraction volumes range from 177 and 298 ML/yr and private use is reported to be on the order of 133 ML/yr (Water and Rivers Commission, 1999).

Other information:

Note that the seawater interface has been reported by Martin (1990) on pg 9 to extend up to 5 km inland on the eastern side of the peninsula and ranges from negligible thickness near the coast to 200 m thick inland.

Table 46 *Aquifer parameter table for Port MacDonnell, South Australia*

Aquifer Layer[1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Porosity/ Specific Yield	Net Recharge (mm/yr)
1	Gambier Limestone	Tertiary	Unconfined	-290	300 (100-340) [2]	2.67-2.97 (Avg 2.76; Med 2.75) [3]	500	5-90 [5]	<0.1 to 0.25 (Avg 0.1) [13]	29 (5-90) [6]
						2.31-5.46 (Avg 3.64; Med 3.54) [4]	3000			
2	Dilwyn Formation Clay	Tertiary	Aquitard	-330	40 (20-50) [7]	—	—	$1x10^{-6}$ [8]	—	—
3	Dilwyn Formation Sand	Tertiary	Confined	-780	400 (350-500) [9]	14.21-19.43 (Avg 18.49; Med 18.59) [10]	370	0.5-10 [12]	0.25-0.5 [14]	0
						20.5 [11]	5000			

Notes:

[1] Aquifer parameters derived primarily for the area within 5 km of the coast near Port MacDonnell; Key reference used is Stadter and Yan (2000)

[2] Refer to Fig 5

[3] Refer to Obswell Unit No 7021-03085 (Obs. no. MAC054) with 31 records collected between 6/05/1981 and 13/03/2001; Trendline: $y=-9E^{-6}x + 3$, $R^2=0.063$

[4] Refer to Obswell Unit No 7021-01005 (Obs. no. MAC045) with 126 records collected between 01/09/1971 and 17/03/2010; Trendline: $y=2E^{-5}x + 2.80$, $R^2=0.02$

[5] Refer to Fig 12

[6] Refer to Fig 14; assumed that no extraction is occurring within 5km boundary; water balance figures from Appendix G1 suggest that inflows (vertical recharge [35,409 ML/yr] plus upward leakage [805ML/yr]) minus ET [4,932 ML/yr] over an area of 1087.2 km^2 gives a recharge estimate of 29 mm/yr. Note extraction values reported as 24,593 ML/yr (or 23 mm/yr) have not been included within the net recharge water balance since there is limited extraction within the coastal fringe.

[7] Refer to Fig 6

[8] Refer to pg 10

[9] Refer to Fig 7

[10] Refer to Obswell Unit No 7021-01347 (Obs. No. MAC077) with 49 records collected between 13/03/1998 and 17/03/2010; Trendline: $y=5E^{-5}x + 16.74$, $R^2=0$

[11] Refer to Refer to Fig 11

[12] Refer to Fig 13

[13] Refer to specific yield values reported on pg 10; value of 0.1 was used by the authors within their model

[14] Refer to reported range of porosity values for sand in Freeze and Cherry (1979)

***Table 47** Aquifer parameter table for Uley South, South Australia*

Aquifer Layer[1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Bridgewater Fm Limestone	Quaternary	Unconfined	-10 to -20	10-20 (max of 130m) [2]	0.86-1.80 (Avg 1.27; Med 1.26) [3]	1500	5-1400 (100-150 Avg) [9]	0.1-0.3 [12]	50-150 (Avg 100) [10]
						1.07-4.00 (Avg 2.38; Med 2.54) [4]	2200			
						0.94-2.52 (Avg 1.56; Med 1.37) [5]	2200			
2	Uley Formation Clay	Tertiary	Aquitard	-20 to -40	5-25 [2] (discontinuous)	—	—	0.0048-10 [9]	—	—
3	Wanilla Sands	Tertiary	Confined	-25 to -65	30-40 (up to 60) [2]	0.52-0.63 (Avg 0.58; Med 0.58) [6]	1500	20-150 [9]	—	0 [11]
						1.35-4.41 (Avg 2.75; Med 2.86) [7]	2800			
Combined 1 & 3 without aquitard	As above	Quaternary and Tertiary	Unconfined to semi-confined	-10 to -65	45-85 [2]	0.86-1.80 (Avg 1.27; Med 1.26) [8]	1500	20-150 [9]	0.15 [12]	50-150 [10]

Notes:

[1] Aquifer parameters derived primarily for the area within 5 km of the coast in Uley South; conceptualisation assumes little extraction occurs within the 2.5 km fringe

[2] Refer to pg 11 of Seidel (2008)

[3] Refer to Obswell SLE009 with 303 records collected between 1/4/1963 and 1/11/1996; Trendline: $y= -6E^{-4}x + 1.84$, $R^{2} = 0.17$

[4] Refer to Obswell ULE134 with 379 records collected between 26/4/1961 and 14/6/2011; Trendline: $y= -1E^{-4} x + 5.89$, $R^{2} = 0.76$

[5] Refer to Obswell ULE194 with 170 records collected between 3/5/1991 and 14/6/2011; Trendline: $y= -2E^{-4} x + 8.16$, $R^{2} = 0.79$

[6] Refer to Obswell ULE133 and ULE206 with 271 records collected between 23/5/1962 and 1/6/2011; Trendline: $y= -2E^{-5}x + 1.45$, $R^{2} = 0.39$

[7] Refer to Obswell ULE135 with 371 records collected between 1/4/1961 and 1/6/2011; Trendline: $y= -3.1E^{-3} x + 5.85$, $R^{2} = 0.67$

[8] Assume the same as for layer 1

[9] Refer to pg 14 of Seidel (2008) and Figs 9-11 in Zulfic et al. (2006)

[10] Refer to pg 26 of Seidel (2008) who cites the work of (Evans, 1997); Avg net recharge value for coastal fringe derived from Fig 12 of Zulfic et al. (2006).

[11] Refer to pg 88 of Harrington et al. (2006) who states that there is no downward leakage

[12] Refer to Table 4 in Zulfic et al. (2006)

Other water balance information:
Approximately 7,200 ML/yr extracted in Uley South (pg 50 of Harrington et. al, 2007)

Table 48 *Aquifer parameter table for Werribee (parallel to the Werribee River), Victoria*

Aquifer Layer[1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Werribee River Delta sand and gravel lenses within clay, silt alluvium deposits	Quaternary	Unconfined to semi-confined	-15 to -10 [2]	8 to 25 [2]	0 - 1.28 (Avg 0.56; Med 0.58) [6]	400	5 (0.6-23) [3]	0.04 (0.1-0.2) [4]	85 [10]
2	Newer Volcanics multi-layer fractured rock with basalt layering	Quaternary & Tertiary	Unconfined to semi-confined	-22 to -15 [2]	2 to 23 [2]	-0.37 to 0.89 (Avg 0.17; Med 0.17) [7]	400	5 [5]	0.1 [5]	
						3.28-8.94 (Avg 6.76; Med 7.00) [8]	2500			
						5.69-11.96 (Avg 9.33; Med 9.44) [9]	3800			
3	Brighton Group clay, silt, fine sand	Tertiary	Unconfined-semi-confined-confined minor aquifer	-35 to -22 [2]	8 to 20 [2]	—	—	0.3 [5]	0.1 [5]	—
4	Fyansford Fm (also referred to as Newport Fm) marine mudstone, clay, silt	Tertiary	Aquitard	—	—	—	—	—	—	—

Notes:

[1] Aquifer parameters derived primarily for the area within 5 km of the coast in the Werribee Delta irrigation district. The observation bore transect from which data was obtained is parallel to the Werribee River at an approximate distance of 2.5 km.

[2] Refer to Fig 5 showing the stratigraphy of the Werribee Delta in SKM (2002)

[3] Refer to values reported on pg 71 Leonard (2006) and within Table 8 in SKM (2005)

[4] Refer to values reported on pg 3 of SKM (2002) for mix of sediment types

[5] Refer to values reported within Table 8 in SKM (2005)

[6] Refer to GMS observation bore 59520 with 367 records collected between 12/3/1985 and 15/2/2010; Trendline: $y= -4E^{-5}x + 2.20$, $R^2 = 0.29$

[7] Refer to GMS observation bore 59521 with 364 records collected between 12/3/1985 and 15/2/2010; Trendline: $y= 2E^{-6}x + 0.10$, $R^2 = 0.00$; Refer to log within SOBN database which indicates alluvium rather than Basalt

[8] Refer to GMS observation bore 59526 with 368 records collected between 12/4/1985 and 15/2/2010; Trendline: $y= -4E^{-4}x + 19.75$, $R^2 = 0.46$

[9] Refer to GMS observation bore 59538 with 357 records collected between 30/1/1986 and 15/2/2010; Trendline: $y= 4E^{-4}x + 22.23$, $R^2 = 0.41$

[10] Value derived by assuming 4 % of average rainfall recharge of 550 mm/yr (22 mm/yr), a deep drainage value of 113 mm/yr and extractions of 50 mm/yr. Rainfall recharge reported to be about 4 % of long term average value of 550 mm/yr (Fig 6, pg 23 and pg 47 of SKM (2005)) report. Deep drainage estimated as 170 mm/yr over the 8 month irrigation season, which equates to about 113 mm/yr over the year (pg 47 of SKM (2005)). Extractions range from 1000 to 8000 ML/yr, with about 2000ML/yr generally used (Fig 9, pg 27 of SKM (2005)). If we assume extraction occurs within the Deutgam Irrigation Area over 40 km^2 this equates to between 25 and 200 mm/yr of groundwater extraction, with 50mm/yr generally used. These values apply to lumped alluvium and basalt aquifers, although one might expect the deeper fractured rock to receive less recharge.

Other water balance information:

Tidal range is approximately 4 km inland along the Werribee River from the river mouth according to pg 17 of SKM (2005)

Table 49 *Aquifer parameter table for Werribee (perpendicular to the Werribee River), Victoria*

Aquifer Layer[1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance from River (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Werribee River Delta sand and gravel lenses within clay, silt alluvium deposits	Quaternary	Unconfined to semi-confined	-15 to -10 [2]	8 to 25 [2]	0.42 - 1.56 (Avg 0.86; Med 0.79) [6]	70	5 (0.6-23) [3]	0.04 (0.1-0.2) [4]	85 [9]
						2.06 - 6.14 (Avg 3.80; Med 3.70) [7]	600			
2	Newer Volcanics multi-layer fractured rock with basalt layering	Quaternary & Tertiary	Unconfined to semi-confined	-22 to -15 [2]	2 to 23 [2]	3.28-8.94 (Avg 6.76; Med 7.00) [8]	2500	5 [5]	0.1 [5]	
3	Brighton Group clay, silt, fine sand	Tertiary	Unconfined-semi-confined-confined minor aquifer	-35 to -22 [2]	8 to 20 [2]	—	—	0.3 [5]	0.1 [5]	—
4	Fyansford Fm (also referred to as Newport Fm) marine mudstone, clay, silt	Tertiary	Aquitard	—	—	—	—	—	—	—

Notes:

[1] Aquifer parameters derived primarily for the area within 5 km of the coast in the Werribee Delta irrigation district. The observation bore transect from which data was obtained is perpendicular to the Werribee River at an approximate distance of 2.5 km inland from the coast in order to assess seawater intrusion to the aquifer via the river.

[2] Refer to Fig 5 showing the stratigraphy of the Werribee Delta in SKM (2002)

[3] Refer to values reported on pg 71 Leonard (2006) and within Table 8 in SKM (2005)

[4] Refer to values reported on pg 3 of SKM (2002) for mix of sediment types

[5] Refer to values reported within Table 8 in SKM (2005)

[6] Refer to GMS observation bore 145271 with 219 records collected between 2/1/2002 and 15/2/2010; Trendline: $y= -1E^{-4}x + 6.29$, $R^2 = 0.17$

[7] Refer to GMS observation bore 112802 with 281 records collected between 12/7/1992 and 15/2/2010; Trendline: $y= -5E^{-4}x + 21.24$, $R^2 = 0.5$

[8] Refer to GMS observation bore 59526 with 368 records collected between 12/4/1985 and 15/2/2010; Trendline: $y= -4E^{-4}x + 19.75$, $R^2 = 0.46$

[9] Value derived by assuming 4 % of average rainfall recharge of 550 mm/yr (22 mm/yr), a deep drainage value of 113 mm/yr and extractions of 50 mm/yr. Rainfall recharge reported to be about 4 % of long term average value of 550 mm/yr (Fig 6, pg 23 and pg 47 of SKM (2005)) report. Deep drainage estimated as 170 mm/yr over the 8 month irrigation season, which equates to about 113 mm/yr over the year (pg 47 of SKM (2005)). Extractions range from 1000 to 8000 ML/yr, with about 2000 ML/yr generally used (Fig 9, pg 27 of SKM (2005)). If we assume extraction occurs within the Deutgam Irrigation Area over 40 km^2 this equates to between 25 and 200 mm/yr of groundwater extraction, with 50 mm/yr generally used. These values apply to lumped alluvium and basalt aquifers. Note that the same net recharge estimates are used within both of the Werribee conceptual models, although one might expect greater recharge to the aquifers via the river in this conceptual model. Given the uncertainty in net recharge estimates, it is reasonable to assume the same net recharge volumes for this analysis.

Other water balance information:

Tidal range is approximately 4km inland along the Werribee River from the river mouth according to pg 17 of SKM (2005)

Table 50 Aquifer parameter table for Howard Springs, Northern Territory

Aquifer Layer[1]	Aquifer Lithology	Aquifer Age	Aquifer Type	Base of Aquifer (m AHD)	Saturated Aquifer Thickness (m)	Inland Head (m AHD)	Inland Head Distance from River (m)	K (m/d)	Specific Yield	Net Recharge (mm/yr)
1	Laterite with preferential flow (intertidal muds and sands adjacent coast not parameterised)	Cenozoic	Unconfined	8 to -5 [2]	0-12 [2]	—	—	50 [11]	0.01 [11]	200 [10]
2	Darwin Member of Bathurst Island Formation fine sandstones, claystones, minor conglomerate and weathered Koolpinyah/ Coomalie Dolomite	Cretaceous and Lower Proterozoic	Semi-confined	-30 to -75 [2]	30 (25-70) [2]	—	—	3 [8]	0.06 [3]	60 [10]
3	Fractured Koolpinyah/Coomalie Dolomite, karstic with chlorite schist	Lower Proterozoic	Semi-confined	-55 to -100 [2]	20-25 [2]	10.48-16.56 (Avg 12.74; Med 12.44) [5]	7,500	36 (9-168) [9]	0.05-0.3 [4]	
						8.60-15.21 (Avg 10.61; Med 9.83) [6]	9,500			
						7.22-21.62 (Avg 16.77; Med 16.28) [7]	16,500			
4	Hard Koolpinyah/Coomalie Dolomite	Lower Proterozoic	—	—	—	—	—	—	—	—

Notes:

[1] Aquifer parameters derived primarily for the area around Howard Springs to the west of the Howard River at a distance of 18 km inland. This conceptualisation assesses SWI from the north in the direction of Hope Inlet. Conceptualisation assumes little to no groundwater extractions within the coastal fringe.

[2] Refer to Fig 37 for schematic cross-section found in EHA (2007).

[3] Refer to aquifer parameter values for specific yield reported in section 2.2 of Jolly (1983)

[4] Refer to typical porosity values reported for karst limestone/dolomite in Freeze and Cherry (1979)

[5] Refer to observation bore RN035864 with 15 records collected between 3/4/2008 and 10/5/2011; Trendline: $y= 1.74E^{-3}x – 58.38$, $R^2 = 0.10$

[6] Refer to observation bore RN009421 with 279 records collected between 30/8/1980 and 19/7/2011; Trendline: $y= -4E^{-5}x + 12.09$, $R^2 = 0.00$

[7] Refer to observation bore RN007424 with 310 records collected between 4/4/1973 and 28/4/2011; Trendline: $y= 2E^{-4}x + 22.34$, $R^2 = 0.06$

[8] Average value assuming approximately 10m of sandstone and 20m of claystone using the upper range of representative values reported in Domenico and Schwartz (1990)

[9] Refer to pumping test data transmissivity values reported in Table 2.2 of Jolly (1983) which range from 233 to 4200, with an average of 908 m^2/d. Assuming that the aquifer thickness is 25 m, the range and average K values are provided.

[10] Refer to pg 3 in Cook et al. (1998) where the mean groundwater recharge rate beneath the eucalypt savannah was estimated to be 200 mm/yr. Of the 200 mm only about 60 mm is expected to reach the aquifer at the base of layer 2 and in layer 3 after surface losses to streams (D. Yin Foo, personal communication, 1 Dec 2011).

[11] Indicative aquifer parameter values suggested by stakeholders (D. Yin Foo, personal communication, 31 Oct 2011)

Additional information:
The max tidal inundation is about 8 km inland from the coastline; Preliminary AEM results give indication that SWI has occurred via the dolomite at the base of the Bathurst Island Formation.