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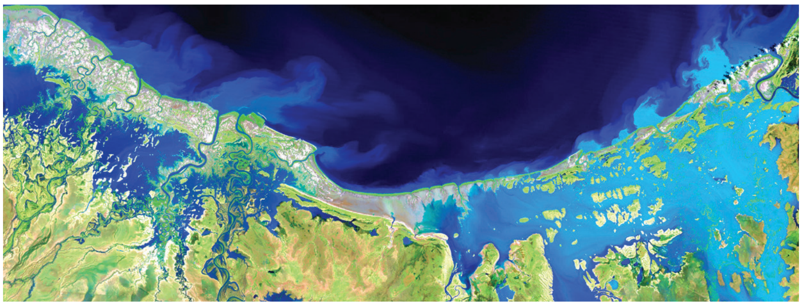

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Literature review, data review, and method development

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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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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.

In response to 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 the potential future consequences arising from 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 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.

To achieve a national-scale assessment of vulnerability to SWI for both current and future scenarios, the project adopted a method comprising four work phases: a literature review, data review and method development (Phase 1); five technical assessments (Phase 2); integration of technical assessments (Phase 3); and, finally an evaluation and assessment of national SWI vulnerability (Phase 4).

This report provides details for Phase 1 of the study which includes a ‘literature review, data review, and method development’.

Some key outputs from Phase 1 of the project have included:

- Provision of background information on SWI concepts
- A literature review and baseline assessment of information relating to SWI in Australia
- An audit of sites identified as being vulnerable, or potentially vulnerable to SWI in Australia
- A literature review of international SWI investigations conducted at the regional-scale, and review of concepts of vulnerability and vulnerability assessment;
- A data review evaluating what data is required, and available, for an assessment of SWI in Australia;
- The collection, compilation and evaluation of key datasets for use in the current project; and,
- The development of a method, based on the findings from the literature review and utilising the data required and available from the data review, that is appropriate to assess SWI vulnerability in Australia.

The literature review showed that few national-scale SWI investigations have been conducted within Australia until relatively recently (in 2008), and that these investigations were focused only on the groundwater resources in irrigation areas. Moreover, these investigations did not provide comprehensive assessments of SWI vulnerability.

The literature review in combination with contributions from stakeholders identified numerous locations around the Australian coast, including sites within each of the states and Northern Territory, where SWI has been reported or is considered a serious threat to water security (Figure 1).

***Figure 1** Locations where the threat of SWI has been identified.*

The literature review also evaluated international SWI publications, and these highlighted that SWI has a long history of investigation internationally, with a number of regional-scale overviews on SWI having been published for North America, South America, Europe and Africa.

The data review showed that there are numerous datasets able to be utilised in Australia for SWI vulnerability analysis, including a range of hydrologic, hydrogeologic and physiographic datasets which have been discussed within this report. The review of literature provided by stakeholders added a critical additional source of information and data for the project.

Method investigation and development showed that the integration of the large quantities of data required to achieve an overall assessment of SWI vulnerability for Australia's coastal aquifers is not straightforward. Previous regional-scale methods were reviewed within the literature and evaluated to determine whether they might be applicable to Australia's national situation. This review led to the selected method development for the project which proposed five streams of technical assessments 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 for subsequent integration to provide an overall assessment of SWI vulnerability.

This report provides an overview of Phase 1 activities including 'literature review, data review and method development', and addresses the first phase of this four-phase project. The findings from this report have been integral to laying the foundations to achieving the overarching project objective of assessing the vulnerability of Australian coastal aquifers to SWI.

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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.

To meet the project objectives and to achieve a national-scale assessment of vulnerability to SWI for both present and future scenarios, the project adopted a method consisting of four work phases: a literature review, data review and method development (Phase 1); technical assessments (Phase 2); integration of technical assessments (Phase 3); and an evaluation and assessment of national SWI vulnerability (Phase 4).

This report represents the culmination of Phase 1 of this investigation: the ‘literature review, data review, and method development’. Some key outputs from Phase 1 of the project have included:

- Provision of background information on SWI concepts
- A literature review and baseline assessment of information relating to SWI in Australia
- An audit of sites identified as being vulnerable, or potentially vulnerable to SWI in Australia
- A literature review of international SWI investigations conducted at the regional-scale, and review of concepts of vulnerability and vulnerability assessment;
- A data review evaluating what data is required, and available, for an assessment of SWI in Australia;
- The collection, compilation and evaluation of key datasets for use in the current project; and,
- The development of a method, based on the findings from the literature review and utilising the data required and available from the data review, that is appropriate to assess SWI vulnerability in Australia.

The current 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; 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

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, 2010b). As Werner (2010b) 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, 2010b). 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. Project funding was provided through the Raising National Water Standards program, which is administered by the National Water Commission, 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 2). 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 (this report)

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 (Ivkovic et al., 2012a)
- Mathematical Analysis (Morgan et al., 2012)
- 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 a succinct 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 Case Study Area (CSA) 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.

1.5 Literature review, data review and method development aims and objectives

The purpose of this technical report is to provide an overview of: the literature pertaining to SWI in Australia as well as international investigations at the regional-scale; existing datasets and published methods for assessing SWI vulnerability. An earlier version of this report was presented in 2010 as a Phase 1 interim output (Dixon-Jain et al., 2010); the current report builds upon the previous literature review and provides a more complete and updated review of literature, data and methods pertaining to SWI assessment.

1.6 Report Structure

The structure of this report follows the sequence of literature review, data review and lastly method review and development. This chapter has provided an introduction to the overarching project aims and objectives, and places the current report within the larger project context. Chapter 2 presents foundational SWI concepts. Chapters 3 and 4 provide national and international SWI literature reviews, respectively, in order to provide an overview the status of SWI in Australia and internationally as a starting point for the current study. Chapter 5 provides a data review, containing details of what data are both required, and available, for the project. Chapter 6 then provides a review of methodologies that have previously been used to assess SWI vulnerability and a description of how SWI vulnerability will be assessed in this project. The purpose of Chapter 6 has been to inform the development of the project methodology. Chapter 7 briefly summarises the key outputs from Phase 1 of the project. It is important to note that SWI vulnerability has not been assessed in this report, rather, vulnerability assessments are reported within the series of project publications listed below.

1.7 Associated publications

Additional reports associated with the 'A national-scale vulnerability assessment of seawater intrusion' project include:

- Final summary report (Ivkovic et al., 2012b)
- Literature review, data review and method development (the current report)
- Vulnerability factor analysis (Cook et al., 2012)
- Coastal aquifer typology (Ivkovic et al., 2012a)
- Mathematical analysis (Morgan et al., 2012)
- Quantitative indexing (Morgan and Werner, 2012)
- Qualitative indexing (Norman et al., 2012)
- Integrated SWI vulnerability assessment (Marshall et al., 2012)

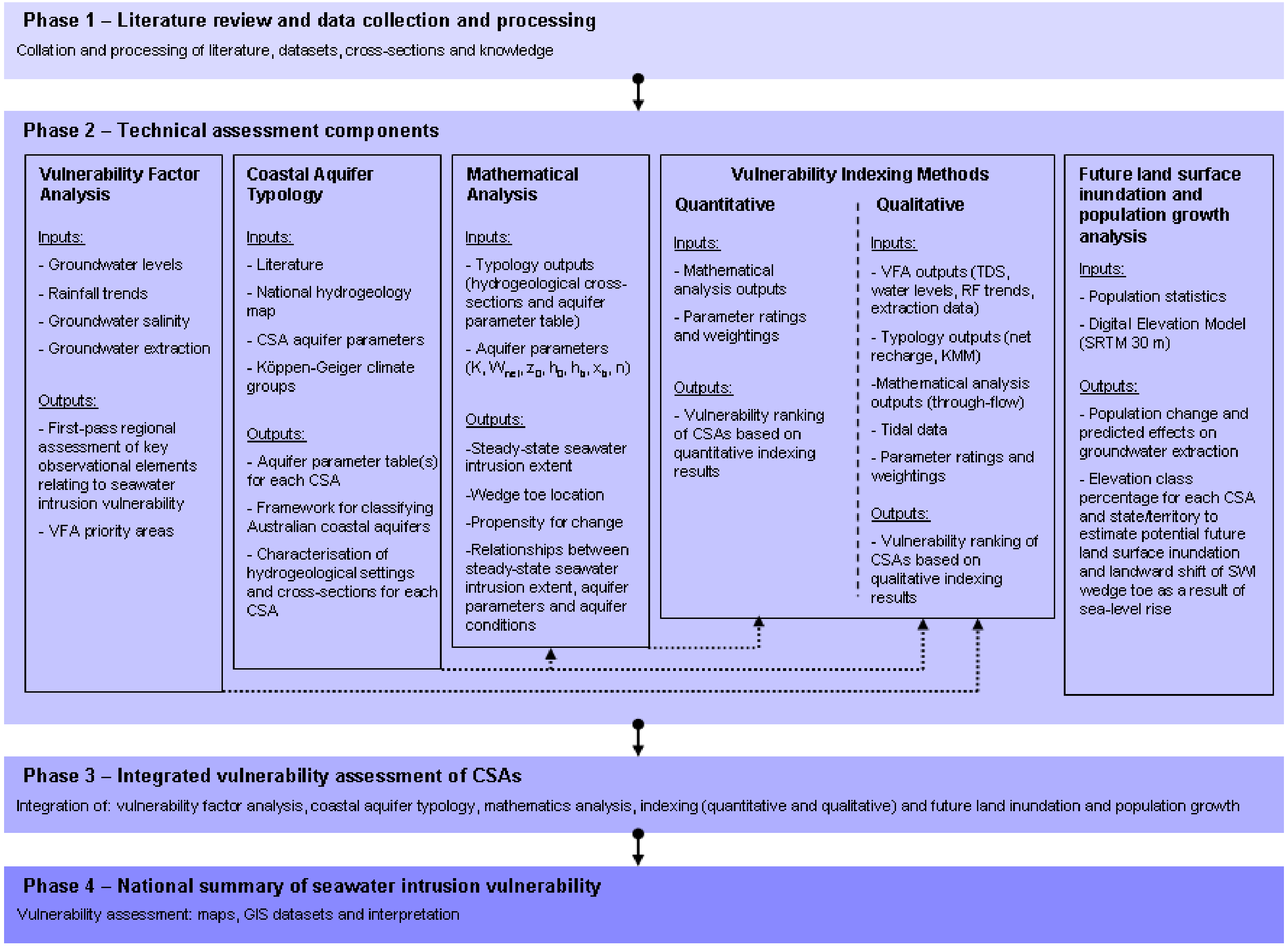


Figure 2 *Methodology of overarching project, 'A national-scale vulnerability assessment of seawater intrusion'.*

2. Seawater intrusion concepts

This chapter provides a brief introduction to the subject of SWI and gives background information on some of the factors influencing SWI that have been considered within this project. These factors include groundwater extraction, recharge, sea-level rise, aquifer hydraulic properties and tides. For more detailed information on SWI process, investigation and management interested readers are referred to Werner et al. (2012), Cheng and Ouazar (2004), Barlow (2003), Bear et al. (1999), FAO (1997) and Custodio and Bruggeman (1987).

2.1 Introduction to seawater intrusion

Seawater intrusion (SWI) is the landward migration of seawater into freshwater coastal aquifers. The current study focuses on assessing the SWI vulnerability of coastal aquifers rather than surface waterbodies.

Freshwater resources stored within coastal aquifers are particularly susceptible to SWI due to their proximity to seawater and the intensive water demands that occur when population pressures exist along the Australian coast. SWI most often occurs in coastal aquifer systems as a consequence of groundwater extraction for agricultural, industrial, recreational, domestic and other purposes (Barlow, 2003). However, other anthropogenic disturbances to hydrological systems, such as those that occur through urbanisation, land reclamation and development of drainage canals, can also contribute to SWI. SWI may also result from natural processes, including geological coastal evolution and long-term historic sea-level changes, tsunamis, flooding, and climate variability, all of which can alter the hydrology of an aquifer system.

Climate variations, groundwater pumping and fluctuating sea levels impose dynamic hydrological conditions that influence salinity and density in coastal aquifers (Custodio and Bruggeman, 1987). When coastal aquifers are in hydraulic contact with seawater, an interface exists whereby less dense freshwater sits above, and adjacent to, a denser, saltwater wedge (Figure 3). Because saltwater has a greater density than freshwater, it moves in the form of a saltwater wedge beneath the freshwater. This wedge often occurs on the landward side of the coastline and can potentially extend from tens of metres through to several kilometres beneath freshwater reserves in some types of systems.

The Ghyben-Herzberg principle is often used as a first approximation when estimating the depth to the saltwater interface. This relationship estimates the depth to the saltwater interface based on the difference in the density of freshwater and the density of seawater. This relationship is described for a steady-state system by the equation:

$$z = 40h$$

where z is the depth to the interface below sea level and h is the freshwater head above sea level. According to this density relationship, a 1 metre (m) height of fresh groundwater above sea level translates to 40 m of freshwater below sea level. The leading edge of the saltwater wedge is referred to as the toe, and it is located at the bottom of the aquifer, marking the maximum extent of SWI. The position of the seawater–freshwater interface can shift in response to changes in hydrological conditions between the aquifer and the sea. For a freshwater aquifer, the Ghyben-Herzberg principle indicates that a 1 m decline in fresh groundwater level could potentially result in a 40 m rise in the position of the seawater-freshwater interface. In the situation where a land mass is surrounded by seawater (e.g. islands, peninsulas and barrier dunes), opposing saltwater wedges can intersect to isolated freshwater lenses.

Mixing between freshwater and saltwater by mechanical dispersion and molecular diffusion results in a 'transition zone' of salinity around the interface, which can range from a few metres to kilometres in width. The position and width of the transition zone, and hence the extent of the saltwater wedge, is highly variable and changes with particular hydrogeological and hydrological circumstances (Custodio and Bruggeman, 1987).

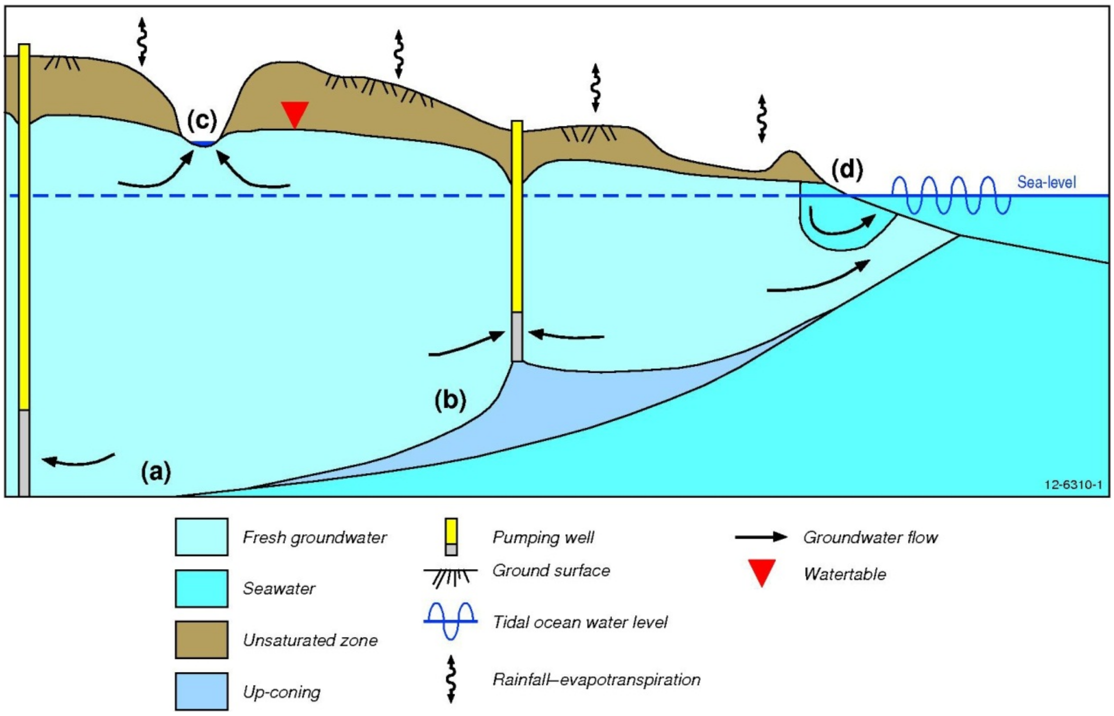


Figure 3 *Schematic diagram of a coastal unconfined aquifer, including (a) the position of the seawater wedge toe, (b) seawater up-coning as a result of groundwater extraction from a bore, (c) head-controlled surface expression of groundwater and (d) coastal fringe processes, including reticulation of seawater, (after Werner et al., 2012).*

Dynamic forces such as daily tidal oscillations, seasonal and annual variations in groundwater recharge and extraction rates, and long-term changes in sea levels will cause the transition zone to fluctuate landward and seaward over time (Barlow, 2003).

SWI can occur through several pathways including: lateral intrusion from the ocean; upward intrusion from deeper, more saline zones of a groundwater system; and downward intrusion from coastal waters (Barlow, 2003). SWI involving a vertical rise of saltwater from a deeper, more saline zone into an upper freshwater aquifer as a consequence of pumping is known as 'up-coning' (see Figure 3 above).

SWI is not the only way coastal groundwater can become saline as salt can come from other sources. For example, salinity can increase due to dissolution of basement rock by fluids, inflow of agricultural waste products, and inflow from another aquifer containing relic seawater (Richter and Kreitler, 1993). Thus it is important in any SWI investigation to distinguish seawater from other sources of salinity.

SWI may produce aquifer degradation that can be difficult or impossible to reverse, and so it is generally accepted that SWI avoidance should be the objective of coastal aquifer management strategies.

2.1.1 Factors influencing seawater intrusion

There are many factors that can influence the dynamic equilibrium between freshwater and seawater and contribute to SWI in a coastal aquifer. These influences include both natural variations and anthropogenic activities. A change in the hydraulic head difference between freshwater and seawater is the principal driver for movement of the transition zone. The influences of groundwater extraction, recharge, sea-level rise, aquifer hydraulic properties and tides will all influence hydrodynamics associated with SWI. A brief overview of some of these key aspects follows.

2.1.1.1 Groundwater extraction

Groundwater extraction reduces coastal freshwater discharge and therefore alters the position of the freshwater and seawater interface (Custodio and Bruggeman 1987). The decrease in groundwater head due to extraction can produce an equivalent localised rising (up-coning) of the underlying saltwater wedge as well as a more regional shift in the position of the saltwater wedge landward. If the landward migration of the saltwater wedge is to be managed to protect existing production bores, a freshwater groundwater discharge must be maintained (Custodio and Bruggeman, 1987).

2.1.1.2 Recharge

Groundwater recharge is a primary control on the movement and position of the interface. Aquifers with high recharge volumes can have a transition zone that extends seaward of the coastline, while lower recharge areas can have a transition zone that extends for kilometres inland. Any changes to the water balance of an aquifer as a consequence of groundwater recharge or extraction will result in a change in the position of the interface.

Groundwater recharge can occur in several ways, including infiltration of rainfall, river recharge, flooding, inter-aquifer leakage, return irrigation flows, leaky drains and artificial recharge. Low recharge rates are an important factor for consideration in a relatively arid and drought-prone country such as Australia. An important consideration is that the impacts of reduced groundwater recharge may intensify in future as a consequence of the anticipated climate change-induced reductions in rainfall in some areas (Pittock, 2003). The adverse effect of low groundwater recharge rates on an aquifer’s water quality will be exacerbated by groundwater extractions, which tend to increase during dry periods.

2.1.1.3 Sea-level rise

Sea-level rise, in response to a changing global climate, can also change the position of the transition zone. Climate change predictions by the Intergovernmental Panel on Climate Change indicate a possible rising sea level of 59 centimetres (plus 10–20 centimetres for ice sheet melt) by 2100 (IPCC, 2007), which would lead to the inland migration of the freshwater-saltwater interface (Werner and Simmons, 2009). In order to re-establish equilibrium with fresh groundwater in response to rising sea-levels, the transition zone is expected to move landward and intrude coastal aquifers. Based on prehistoric cases of the influence of sea level rise, SWI may cause a landward shift in the transition zone that does not return to its original position and may be difficult to remediate, emphasising that prevention of SWI is better option than post-intrusion remediation (Barlow, 2003).

In addition to the subsurface impacts, sea-level rise may also result in the permanent surface inundation of low-lying coastal regions and increase the frequency and intensity of temporary inundation through the occurrence of storm surges. This could result in the intrusion of saltwater into freshwater reserves by movement of the interface, similar to tidal changes (discussed below), or by downward seepage. However, downward seepage is not within the scope of this project and is not discussed further.

2.1.1.4 Aquifer hydraulic properties

The extent of seawater penetration into the aquifer is highly dependent on the aquifer's hydraulic properties. According to Custodio and Bruggeman (1987), the equilibrium conditions representing the inland penetration distance of the saltwater wedge can be measured as a first approximation by the following equation:

$$L = \frac{1}{2a}\frac{kb^2}{qo}$$

Where:

L = the distance of inland penetration of the saltwater wedge toe for a sharp-interface for a homogeneous and isotropic aquifer

a = density ratio based on Ghyben-Herzberg relation (1.025 in most cases)

k = aquifer hydraulic permeability

b = aquifer thickness

qo = freshwater discharge per unit of coast length

From the equation, it is evident that the saltwater wedge toe penetration is proportional to aquifer permeability and the square of aquifer thickness, but inversely proportional to freshwater discharge.

Heterogeneities in aquifer properties will result in a variable inland penetration of the saltwater wedge toe. The inland extent of the toe may be minimal in shallow, low permeability formations and much greater in thick permeable formations, despite the fact that these areas might have larger volumes of groundwater discharge (Custodio and Bruggeman 1987). Multi-layered aquifer systems will have varying SWI inland extents due to varying aquifer properties. 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 likely extent of SWI.

The mathematical analysis component of the current project assesses the influence of aquifer hydraulic properties by providing first-order approximations of the freshwater-saltwater interface for selected project case study areas for confined, unconfined and freshwater lens aquifer systems (Morgan et al., 2012).

2.1.1.5 Tides

The tidal rising and falling of ocean water levels can 'push and pull' the freshwater-saltwater interface in a landward direction at high tides and in a seaward direction at low tides (Barlow, 2003), thus contributing to mixing of fresh and saline water within the transition zone.

The influence of tides leads to elevated time-averaged watertable heights above the mean sea level in the near-shore area. The tidal watertable over-height (TWOH) is defined by Carey et al. (2009) as 'the tide-induced increase in the time-averaged watertable height above mean sea level at the spatial location of highest astronomical tide'. The TWOH is predominantly influenced by the sloping beach surface, non-linearity of tidal groundwater waves, and formation of seepage faces (Carey et al., 2009).

In addition to tides, waves and storms will also have an influence on near-shore groundwater and influence the TWOH. When defining coastal boundary conditions, e.g. in the development of conceptual and mathematical models, the analysis of TWOH is an important consideration in achieving a robust estimation of groundwater heads and hydraulic gradients in the coastal zone.

2.1.1.6 Time scales

The time taken for the freshwater–seawater transition zone to reach equilibrium can vary significantly, and it depends on the processes of disturbance to the state of dynamic equilibrium (e.g. extraction, recharge variations, sea-level rise, and tidal influences), magnitude and location of the disturbance, the local hydrogeological setting and boundary conditions. Transition zones within highly permeable aquifers can have a quick response time in areas where groundwater flows and solute transport occur rapidly from a hydrogeological point of view. Nonetheless, even in these rapid systems, the time-scale will still be on the order of years to decades for a new dynamic state of equilibrium to be reached. Barlow (2003) found that SWI from past sea-level fluctuations have not yet reached equilibrium even after periods as long as 100 000 years.

In general, it takes considerable time for new states of equilibrium to be reached within aquifer systems because very large volumes of freshwater must be displaced by saline water in order for SWI to occur (FAO, 1997). The distinction needs to be made between local and regional effects of SWI, with the latter requiring a much greater volume of freshwater to be displaced by seawater. The response of aquifers to the stresses of SWI and any subsequent rehabilitation will depend on the individual hydrogeological setting.

2.1.2 Summary

For the purposes of this study, SWI is the encroachment of seawater into freshwater coastal aquifers by way of a landward migration of the freshwater-seawater interface. This interface is typically wedge-shaped, with the toe of the saltwater-wedge extending inland. Factors that affect the equilibrium between freshwater and seawater also affect the position of the interface and have the potential to induce SWI. The principal factors that control the position of the interface are groundwater extraction, recharge, sea-level rise, aquifer hydraulic properties and to a lesser extent, tides. The time scales during which the position of the interface can change vary depending on the processes and the aquifer but, in the case of SWI, may be difficult and expensive to reverse.

3. National SWI literature review

In order to develop an overview of the coastal resources currently affected by, and vulnerable to, SWI, the literature pertaining to SWI investigations has been reviewed at the national and state/territory-scale. The literature review serves to provide a summary of publicly available documented investigations of SWI in Australia, as well as an inventory of areas previously investigated and regions identified as potentially vulnerable to SWI. Any documented SWI management and monitoring considerations within these identified areas are also provided. In addition to documented studies of SWI, areas of potential SWI are highlighted based on information presented at the Stakeholder Workshop (see Appendix 2). The review is based on publicly available reports and journal articles, as well as documents and presentations (at the stakeholder workshop) provided by the states and territories.

3.1 National-Scale Studies

Few national-scale studies on the subject of SWI have been reported in Australia until recently. The main driving factor in the increased reporting at a national-scale seems to be the perceived threat of climate change and sea-level rise on the Australian coastal zone.

Voice et al. (2006) presented a national-scale assessment of the potential impacts of climate change on coastal systems as a consequence of sea-level rise. SWI into coastal aquifers was identified as a likely threat in their gap-analysis. The open beach, coastal lake beach and sand island geomorphic settings were highlighted by Voice et al. (2006) as being particularly vulnerable to the saline intrusion of their freshwater aquifers as a consequence of sea-level rise, but no quantitative analyses were undertaken of the extent and likelihood of impacts. Their greater vulnerability was reported to be due to their higher potential for erosion and the resultant loss of beach width. The loss of beach width would expose more inland areas to inundation, potentially impacting on the freshwater aquifer systems. The main objective of the Voice et al. (2006) report was to highlight the gaps in the current extent of knowledge and to identify and prioritise future research needs in climate change threat assessments and adaptation in Australia's coastal zone. A staged approach was recommended to further identify, categorise and map coastal components and the potential threats as a first-pass assessment, and later to undertake more comprehensive assessments at a range of scales.

Following on from the Voice et al. (2006) recommendation, a report by the Australian Department of Climate Change (***DCC***, 2009) presented the findings of a first pass national assessment of the threats associated with climate change in Australia's coastal zone. Datasets pertaining to climate change research, remote sensing, inundation modelling and coastal zone ***geomorphology*** were brought together in order to assess the potential future ***risks*** from climate change. Their assessment primarily focused on risks to settlements, infrastructure, ecosystems and industries as a consequence of sea-level rise and shoreline erosion, and there was little mention of groundwater systems. It was summarised that sea-level rise would lead to inundation in the lower lying parts of the coastal zone, accelerated erosion, and saline intrusion into coastal waterways and ***wetlands***. The areas most vulnerable to sea-level rise were reported to be the low-elevation coastal deltas, floodplains and estuaries, and the most vulnerable ecosystems were identified as seagrasses, mangroves and saltmarshes. The only mention of groundwater pertained to the beaches along the mainland coast behind the Great Barrier Reef, which are sediment deficient compared to the beaches further south (no particular beaches were specified in the report). It was reported that these beaches will have the potential to recede at higher rates under the influence of locally generated winds and irregular tropical cyclones associated with climate change. The ***delta*** systems behind the Great Barrier Reef, such as the Burdekin River Delta in Queensland, would experience greater levels of seawater inundation during the dry season, potentially impacting on the groundwater resources unless deltaic accretions were to keep up with sea-level rise.

An unpublished report by Nation et al. (2008) used a GIS-based approach to investigate the current extent of SWI and potential future threats associated with sea-level rise in Australia's coastal irrigation areas, and they also provided a brief overview of management approaches for addressing SWI. Their study brought together a range of datasets, including groundwater salinity and groundwater elevation data, surface topography, and land use information (including crop types and areas under irrigation). Groundwater information was extracted from the ***NAMS*** (National Agricultural Monitoring System) database; topographic information was obtained using the NASA ***SRTM*** (Shuttle Radar Topographic Mission) 90 metre digital elevation model; and land use types were defined according to the Bureau of Rural Sciences data as at January 2007.

Nation et al. (2008) plotted the maximum TDS (mg/L) values for individual coastal aquifer piezometers. The spatial distribution indicated that Queensland had the greatest number of irrigation regions characterised by higher salinity values (TDS > 6000 mg/L) (including the Bundaberg, Burnett, Burdekin and Pioneer Valley irrigation areas) (Figure 4; after National et al., 2008). Other areas of high groundwater salinity included the Werribee irrigation area in Victoria, the Adelaide coastal plain in South Australia and Stuarts Point in New South Wales. It was acknowledged within their report that the sources of salinity could be other than seawater, such as relic seawater, agricultural activities and rock dissolution, since only the TDS values were assessed.

Several inundation scenarios were investigated by Nation et al. (2008) to highlight the low lying coastal areas most vulnerable to surface inundation associated with sea-level rise; they included the following elevation classes:

- < +1 m ***AHD*** representing SWI and inundation due to sea-level rise;
- < +5 m AHD representing inundation due to storm surges; and
- < +10 m AHD representing the maximum height of storm surges.

Although low lying elevations are found along most of the Australian coast, the lowest lying coastal irrigation areas were found mostly in Queensland followed by Victoria and South Australia (Table 1; after (Werner et al., 2008). It was estimated that 46 060 hectares or 1.4 % of Australia's irrigation area is coastal land lying less than 5 m above sea level (i.e. between 0 and 5 m AHD) and is therefore potentially at threat from seawater salinisation. The degree to which productivity of this coastal irrigation is reliant on groundwater supplies is yet to be fully quantified. Whilst the data listed in Table 1 suggests that about 3 271 991 ha of land are irrigated in coastal Australia, the Australian Bureau of Statistics reported that in the 2009-10 year, a total of 1 840 610 ha of crops and pastures were irrigated throughout Australia (ABS, 2011); these possible discrepancies require further investigation.

Groundwater elevation data were also evaluated in the Nation et al. (2008) study in order to identify coastal irrigation areas most vulnerable to SWI (Figure 5). The lowest groundwater elevations - below mean sea level, and hence of greater vulnerability - were found in several of the Queensland irrigation areas, as well as areas in Victoria, South Australia and Western Australia.

The combined GIS-based assessment by Nation et al. (2008) concluded that the vulnerability to SWI was greatest in the Queensland irrigation areas, with smaller areas also identified in Victoria, South Australia, and Western Australia. Werner (2010b; 2008) compared the areas highlighted within the Nation et al. (2008) study to areas that had documented cases of SWI in order to cross-validate the vulnerability assessment; the assessment and reporting were broadly consistent. According to Werner (2010b; 2008), areas within New South Wales, Tasmania and the Northern Territory warrant further assessment because there are signs indicating a vulnerability to SWI, such as lowered groundwater elevations for example, but no documented evidence of any SWI investigation.

Werner (2010a) reported that comprehensive SWI investigations had only been completed for coastal systems in Queensland, and to a lesser degree in Western Australia and South Australia. The location and degree of SWI assessments appeared to be linked to the perceived economic value of the groundwater resource. For example, the aquifer systems in the sugarcane growing regions of Queensland (Pioneer Valley, Burnett and Lower Burdekin Basins), which are heavily reliant on groundwater resources to supply irrigation water, have been subject to considerable hydrogeological investigations and targeted monitoring for SWI. Similarly, the aquifers which are used to supply water for population centres, such as in Perth, and more recently the Southern Eyre Peninsula and Darwin peri-urban areas, are also perceived to be of high value and consequently have also been under investigation and monitoring. In contrast, there have been few investigations where aquifers are perceived to be of lower economic value, and yet these aquifers may still be vulnerable, for example where these resources are used for domestic water supply in unmanaged quantities within coastal settlements.

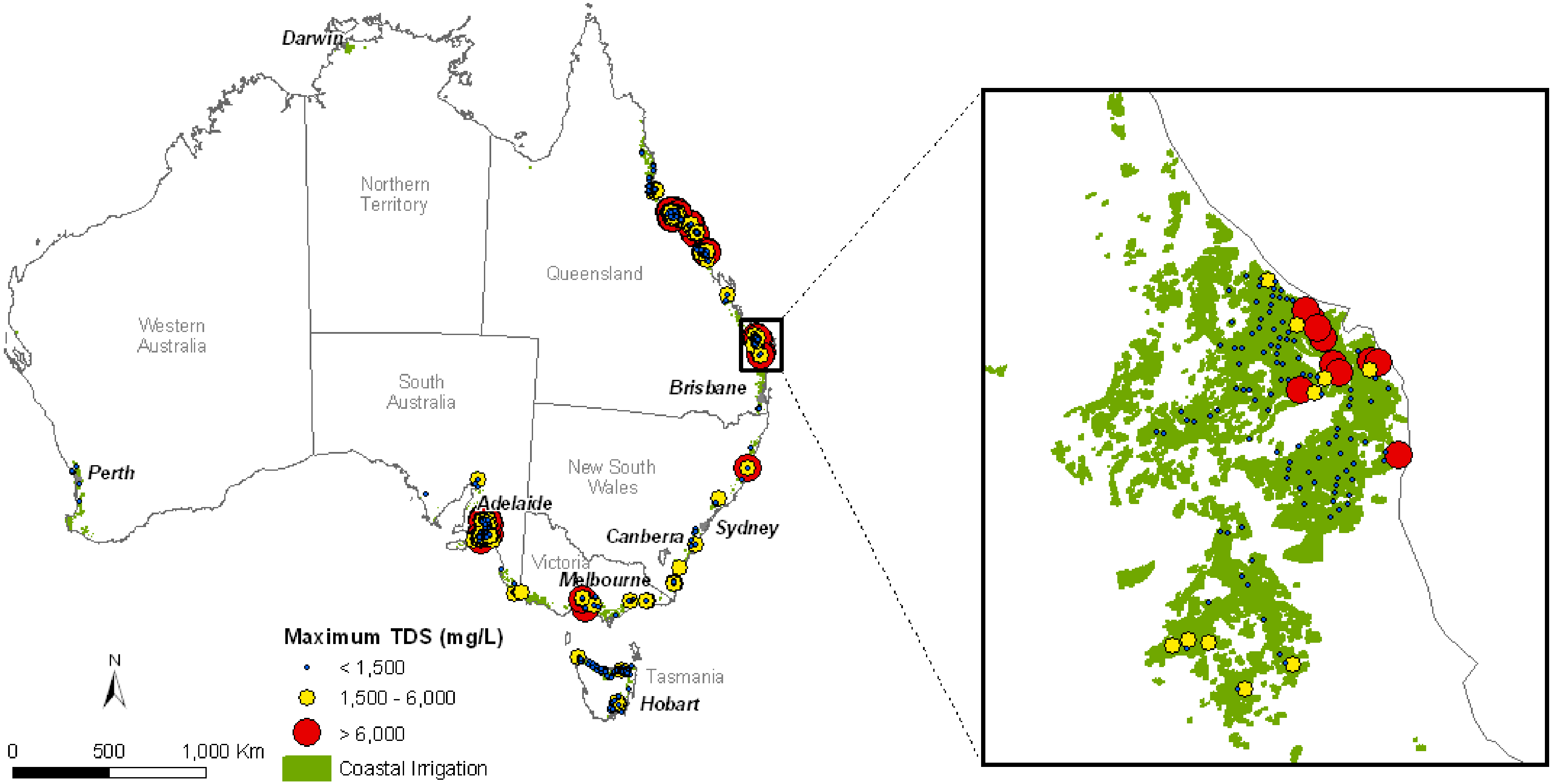


Figure 4 *Maximum TDS (mg/L) of groundwater in Australia's coastal irrigation areas. Inset: Bundaberg Irrigation Area; Note: no groundwater data was available for the Northern Territory (after Nation et al., 2008).*

Table 1 *Summary of a GIS-based analysis of irrigation areas and coastal elevation, after Werner et al. (2008).*

State	Total irrigation area (ha)	Major Land-use	Area at 0–5 mAHD (ha)	Area at 0–10 mAHD (ha)
NSW	867 516	Cropping	7663	10 198
NT	29 899	Tree fruits	136	402
Qld	1 080 787	Sugar cane	15 706	84 749
SA	271 319	Sown grasses	9481	16 839
TAS	128 795	Cropping	2922	6837
Vic	837 886	Modified pasture	9624	23 018
WA	55 789	Vine fruits	528	2814
Total	3 271 991	Cropping	46 060	144 858

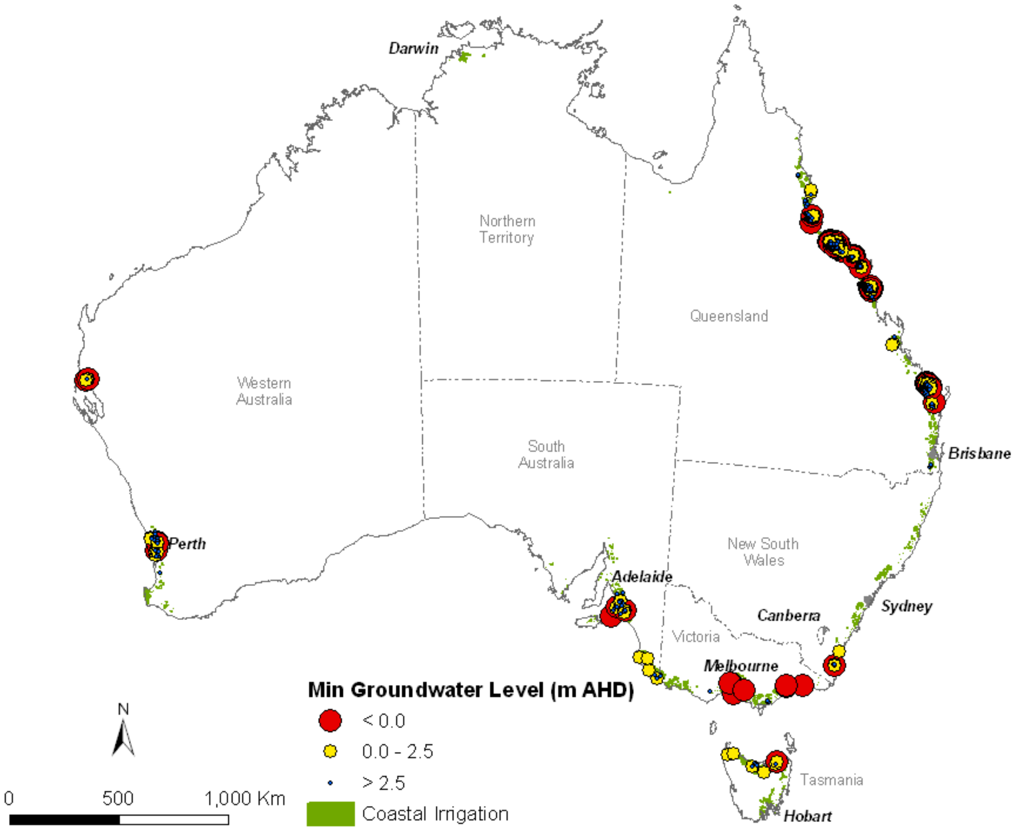


Figure 5 *Irrigation areas vulnerable to SWI based on the lowest minimum groundwater level (m AHD) recorded for each bore. Note: data not available for the Northern Territory (after Nation et al., 2008).*

A summary of Australian sites where the threat of SWI has been recognised is shown below in Figure 6 and also listed in Table 2. Further details on these areas follows in Chapter 3.2.

Figure 6 *Locations where the threat of SWI has been identified.*

Table 2 *Distribution of previous Australian studies that identify the threat of SWI.*

Location	SWI Incidence Reported	SWI Monitoring	Degree of SWI assessment[1]
South Australia			
Eyre Peninsula	Yes	Yes, but not SWI interface specific	Moderate
Le Fevre 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

Location	SWI Incidence Reported	SWI Monitoring	Degree of SWI assessment[1]
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
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

Location	SWI Incidence Reported	SWI Monitoring	Degree of SWI assessment[1]
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*

[1]**Degree of assessment**
None to Very Low: Few to no hydrological investigations have been undertaken or made publically available. No monitoring, management or modelling assessments undertaken to inform the threat of SWI.
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.

3.2 State and Territory Studies

The main objective of this section is to give a general overview of the locations, geological and geomorphic settings, aquifer types, extent of investigations, driving factors, remediation strategies and management actions for sites where SWI has occurred, or has been reported to be at risk of occurring, within Australian coastal aquifers. Literature reviews are provided on a State and Territory basis, with the exception of the Australian Capital Territory, whose coastline is restricted to Jervis Bay. The reviews are based on the readily available published information, including those references provided by the state and territory governments and/or Geoscience Australia. It is important to keep in mind that the available literature does not always provide the latest status of areas because the available literature can be sparse and difficult to obtain, and reports are not always written to document activities.

3.2.1 Tasmania

The water resources in Tasmania are generally plentiful, and therefore, groundwater management has not traditionally been a high priority for the State. As a result, little information exists on Tasmania's groundwater resources. For details of all Tasmanian sites where SWI threat has been acknowledged, refer to Table 3. Groundwater monitoring data is limited to 34 monitoring bores and 2903 production bores across the whole state, and they do not represent a structured sampling of Tasmania's hydrogeology. Groundwater abstraction data is not collected nor are the groundwater resources formally allocated (Australian Water Resources Assessment, 2000; Resource Planning and Development Commission, 2003).

A review of Tasmania's groundwater resources by Bacon and Latinovic (2003) indicated that 'coastal influences' were observed in the northwest of the State and that these influences appear to have contributed to an increase in salinity in near-coastal bores compared to those located further from the coastline. The Woolnorth region, in the northwest of the State, is the only area where SWI is reported to have occurred within the Tertiary limestone aquifer as a consequence of groundwater extractions (Cradle Coast NRM Committee, 2005).

Two risk analysis studies were conducted on King Island – one by Ezzy (2003) and a second by Dyson (2006). Ezzy (2003) investigated the regional groundwater resources of King Island where he identified that the Quaternary, unconsolidated and unconfined aquifers within the dune sands were at risk of SWI. These aquifers are used to provide drinking water for towns, such as Currie. In particular, the low hydraulic gradients and the palaeo-erosion channels existing within the Pleistocene dunes, which have been in-filled by more permeable Holocene dune sands, potentially allowed for seawater to extend some distances inland. The Yellow Rock River estuary was given as an example area that had these characteristics. In contrast, Ezzy (2003) described the larger unconsolidated basins with larger volumes of stored groundwater as having sufficient hydraulic force to limit SWI (e.g. Tuffa Terraces). His conclusions were based on 15 sites which were drilled for the study and included pumping tests, water levels and major ion chemistry.

Dyson (2006) undertook a desktop study of the Grassy scheelite mine site in order to assess the impacts of mine de-watering within the fractured-rock, metasediment aquifers. He reported that large shear zones, such as occur along the Grassy Fault near the mine site, had the potential to behave as major groundwater conduits and that there was a risk of SWI where mine workings extended below sea level.

Highlighted in the Stakeholder Questionnaire were a number of heavily utilised groundwater basins in the far northwest coast of Tasmania, near Smithton. These are the Duck, Montague, and Welcome River catchment areas. Data on these appears limited; groundwater recharge is from alluvial aquifers into fractured bedrock.

The overall risk of SWI appears to be low in Tasmania, with the possible exception of some regions such as King Island, Woolnorth and potentially some of the more heavily exploited coastal aquifer systems near Smithton. However, the lack of data makes it impossible to be definitive.

Table 3 *Summary of literature for areas identified as being vulnerable, or potentially vulnerable, to SWI in Tasmania.*

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land / groundwater use
Woolnorth	(Cradle Coast NRM Committee, 2005)	Tertiary limestone	Yes (e.g. Cradle Coast NRM Committee, 2005)	Groundwater extractions; “saline coastal influences”	Limited data	No	No	None to Very Low	Not reported
King Island	(Ezzy, 2003)	Quaternary dune sands	No	Groundwater extractions	Limited data	No	No	None to Very Low	Town water supply
King Island, Grassy scheelite mine site	(Dyson, 2006)	Proterozoic fractured metasediments	No	Faults intersected by mining operations at depths below sea level	Limited data	No	No	None to Very Low	Mine de-watering
Duck River Catchment (Mella /Smithton Syncline GAA)*	Unknown	Alluvium over fractured to karstic Proterozoic dolostone	No	Groundwater extractions	Unknown	No	No	None to Very Low	Agricultural irrigation
Montagu River Catchment (Togari/Smithton Syncline GAA)*	Unknown	Alluvium over fractured Proterozoic sediments	No	Groundwater extractions	Unknown	No	No	None to Very Low	Agricultural irrigation
Welcome River Catchment (Smithton Syncline)*	Unknown	Alluvium over Cainozoic sediments and volcanics	No	Unknown	Unknown	No	No	None to Very Low	Agricultural irrigation

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

3.2.2 New South Wales

New South Wales SWI studies are relatively recent, and were not available when this literature review was initially conducted (Dixon-Jain et al., 2010). Since then, a series of reports have become available and have been included in this section. The locations include Clarence River Floodplain, Stuarts Point, Botany Sands, Stockton and Hat Head. Additional details follow in the subsections below. For details of all New South Wales sites where SWI threat has been acknowledged, refer to Table 4.

3.2.2.1 Clarence River Floodplain

A study by Johnston et al. (2005) looked at the effects of opening tidal barriers in a coastal floodplain setting. The study assessed water levels and salinity data along piezometer transects at two sites (Romiaka and Shark's Creek) in the Clarence River coastal floodplain. This research showed that when tidal pressures signalled floodgates to open, seawater entered the drains and recharged the shallow, Quaternary, unconsolidated aquifers. The Shark Creek site, with the highest hydraulic conductivity soils and lowest hydraulic gradients, showed a tidal forcing of saline water into the aquifers a distance of more than 80 metres from the drain. Shark Creek is located in an acid sulphate backswamp (estuarine in-filled), and when the groundwater gradients reversed with lower tidal pressures, acid groundwater flowed laterally into the drain. The Romiaka site, with the lower hydraulic conductivity soils and steeper hydraulic gradients, showed a lateral movement into the aquifer of less than 10 metres. This study demonstrated the importance of considering soil properties when constructing floodgates in order to prevent unintended saline intrusion into shallow aquifers. This is particularly important in acid sulphate soil backswamps where acid groundwater drainage has implications for ecosystem health.

3.2.2.2 Stuarts Point

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. The area experiences a temperate climate.

The area surrounding Stuarts Point is a sand plain with a generally flat to gently undulating slope. The 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 Paleozoic 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.

The aquifers at Stuarts Point comprise dominantly sands. They can also contain muds and clays when associated with the Macleay River or estuarine deposits.

Groundwater within the aquifer exists either as a perched aquifer system or within a shallow, unconfined aquifer. The perched aquifers are extensive but not entirely laterally extensive. In parts they are supported by an almost impermeable coffee rock layer, which is only locally extensive. 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. 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.

In the Stuarts Point area, groundwater is used for individual domestic use, town supply as well as for horticulture.

A status report by DNR (2006) found there was clear evidence of seawater intrusion at Stuarts Point based on observed salinity increases. However, it 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.

An investigation of the effects of changing groundwater pumping, recharge conditions and sea level on the position and movement of the freshwater/saltwater interface was undertaken by SKM (2011). They used an existing 3-D groundwater flow model and associated 2D slice variable-density solute transport models of the North Stockton Sandbeds developed with FEFLOW and constructed as vertical slices using appropriate properties and boundary conditions obtained from the 3D MODFLOW model (SKM, 2005a). These models were used as a base for predictive scenario runs to help quantify the long term sustainable yield of the aquifer corresponding to the quantity of water that can be extracted from the aquifer without inducing unwanted impacts on groundwater salinity and groundwater dependent ecosystems. The scenario results considered the hydraulic heads and the TDS concentrations at observation points and their distributions in the slices. Based on the outcomes of these models, the abstraction rate was found to have the biggest impact on salt water intrusion into the aquifer. 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 also found to have little impact on the salt water intrusion compared to changes induced by groundwater abstraction.

3.2.2.3 Botany Sands

The Botany Sands Aquifer near Sydney airport 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, situated within the Quaternary unconsolidated and unconfined sand aquifer, were shut down as a consequence of SWI, and usage from the aquifer subsequently moved inland from Botany Bay.

Given the pressures associated with increasing population developments and tourism along the New South Wales coast and islands (e.g. Lord Howe Island), it is likely that there are risks of SWI which up to now, with the lack of publicly available data and reporting, have remained unidentified. There are, however, a couple of newly-funded NWC projects that will investigate coastal aquifer systems. These include:

1. Sustainable management of coastal groundwater resources (GHD Hassall): This project aims to improve the management of groundwater in the coastal dune aquifers that are used to

supply water for coastal communities in the Mid North Coast region. The key objective of this project is to develop an integrated approach for managing the availability and quality of coastal groundwater resources, and to ensure that coastal aquifers do not become over allocated, depleted or degraded as a consequence of increasing demand from rapidly expanding urban centres such as South West Rocks. The project will use socioeconomic assessment and new state of the art groundwater and SWI modelling tools to ensure the long term availability and quality of groundwater in coastal sand dune aquifers. The Macleay Coastal Sands Aquifer will be used as a case study area.

2. Coastal groundwater quality and groundwater dependent ecosystems (NSW Office of Water): This project will improve the understanding of how pumping and tidal patterns in NSW coastal sand and alluvial aquifers affect groundwater quality and dependent ecosystems. The project will model how groundwater and the ocean interact in a number of coastal aquifers. A field program will sample groundwater quality, conduct geophysical surveys during a tidal cycle, and identify vegetation that depends on groundwater.

The results of the above two current projects will be considered within the current national-scale investigation as results become available.

3.2.2.4 Stockton

Stockton is located immediately northeast of the city of Newcastle on the Newcastle Bight on the NSW coast. The area experiences a temperate climate.

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 from 0.5 to 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.

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. At the base of these aquifers the Medowie Clay member forms a continuous ***aquitard*** and the base is 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. 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.

Groundwater is used for stock and domestic activities, sand mine and mineral processing, small scale irrigation and industry.

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 coastline (SKM, 2011).

3.2.2.5 Hat Head

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. The area experiences a temperate climate with no dry season.

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 35 m below sea level to 50 m, due to dune systems. The plain has been dissected by the Macleay River, running from the southwest to the northeast and discharging ~ 20 km to the north of Hat Head at South West Rocks. The plain surrounding Hat Head includes minor tributaries associated with this major river and is underlain by marine and estuarine deposits of clay and silt, with minor layers of marine sand. There is a thin layer of alluvial and aeolian deposits, of which the alluvium is thicker in the vicinity of the Macleay River, overlying the marine sediments. 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 (GWCD).

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 resulted from sea level fluctuations, transgression and regression during the late Quaternary Period. Continuity between the dunes has been interrupted in parts by estuarine and alluvial material that was deposited during the late Pleistocene decline in sea level (Woolley, 2011) The dunes are 30 to 45 m deep and overly mostly estuarine clay and silts but can also overlie weathered Palaeozoic rocks (Woolley, 2011).

Marine clay basement material contains saline water. It is also 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.

Hat Head is a town of approximately 300 people (Australian Bureau of Statistics, 2007) and close to the town is Hat Head National Park, which contains 7220 hectares of coastal land. The Kempsey Municipal Council uses groundwater from a number of borefields within the national park, and groundwater is also used for urban use.

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. It 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 whilst the groundwater is mostly fresh, some of the deep bores have higher salinities and ionic ratios similar to seawater, which could indicate a higher risk of seawater intrusion resulting from high extractions.

Table 4 *Summary of literature for areas identified as being vulnerable, or potentially vulnerable, to SWI in New South Wales.*

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land / groundwater use
Hat Head	(Ecoseal, 2011; Woolley et al., 2011)	Quaternary sands	No	Groundwater extractions;, below average rainfall/droughts	Water levels; salinity; water chemistry; SEAWAT (combines MODFLOW code with MT3DMS	Yes (loggers installed July 2008)	No	Moderate	Domestic
Stuarts Point	(DNR, 2006; Government NSW., 2004; O'Shea, 2005)	Quaternary sands and alluvium associated with Macleay River	Yes (DNR, 2006)	Groundwater extractions; below average rainfall/droughts	Limited hydrochemical and piezometer data	No	No	Low	Domestic
Stockton	(SKM, 2011; Wooley et al., 1995; Woolley et al., 2011)	Quaternary sands	No	Groundwater extractions; below average rainfall/droughts	Water levels; salinity; water chemistry; 3D MODFLOW groundwater flow model; four 2D FEFLOW models	No	No	Low	Stock, domestic, mine & mineral processing, small-scale irrigation, industry
Botany Sands, Sydney	(Benker et al., 2007; Bish et al., 2000; Merrick and Knight, 1997; Timms et al., 2008)	Quaternary sands	Yes, 1960's; bores shut down and usage moved inland (e.g. Timms et al., 2008)	Groundwater extractions; below average rainfall/droughts	Limited; No SWI specific studies	No	No	None to Very Low	Industry, chemical manufacturing, recreation
Clarence River Floodplain	(Johnston et al., 2005)	Quaternary alluvium associated with Clarence River; estuarine deposits	Yes, minor local	Drains	Limited hydrochemical and piezometer data	No	No	None to Very Low	Sugarcane

3.2.3 Victoria

The State of Victoria has only one reported SWI site, but several anecdotal accounts of SWI. The locations include the Werribee Irrigation District and Gippsland. Additional details follow in the subsections below. For details of all Victorian sites where SWI threat has been acknowledged, refer to Table 5.

3.2.3.1 Werribee

The Werribee Irrigation District is the only location in Victoria where SWI is reported to have occurred. This region experiences a Mediterranean-type of climate, with hot, dry summers and cool, wet winters. However, the recent climate has been uncharacteristically dry since 2002. Both groundwater and surface water resources are used within the Werribee Irrigation District to support a major horticultural industry on the eastern portion of the Werribee Delta, and shallow bores also provide stock and domestic supplies.

The Werribee Delta was formed by the accumulation of sediments carried by the Werribee River and its tributaries. The sediments are of mixed provenance and represent Quaternary flood plain deposits, alluvium, colluvium and gully alluvium, as well as lagoon and swamp deposits (Dahlhaus et al., 2004). These sediments are hydraulically connected to the underlying basalts. The unconsolidated alluvial sediments and underlying fractured basalt form the unconfined to semi-confined aquifer of the Werribee River Delta. The aquifer is generally less than 50 metres thick, and the most permeable horizons are believed to be the fractured basalts and the coarser sediments immediately overlying the basalts. The Werribee River is tidal, and tidal influences are evident up to 4 km upstream from the river mouth, based on the rise and fall of river water levels (SKM, 2005b).

Surface water is fed from a weir on the Werribee River and is distributed through a channel system within the irrigation district to provide water for irrigation. The channel system and irrigation water also provides recharge to the underlying aquifer in addition to rainfall, with the amount of surface water available for delivery through the network dependent upon rainfall and river flows. Groundwater is used to provide supplementary irrigation water during drier periods. According to a study by SKM (2005b), between 2002 and early 2004, the aquifer had experienced unparalleled demand from the irrigators in the district as a result of on-going drought conditions. Increased groundwater demands and reduced groundwater recharge (both rainfall, river and irrigation accessions) during this period 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.

The study by SKM (2005b) included an assessment of bore monitoring data of water levels; geophysical logging of observation bores; and the collection of water samples from both the observation bore network and the river. The water samples were analysed for major ion chemistry, selected metals, and bacterial analysis over the 2002-2003 period. Only one bore site showed an impact from seawater influx based on hydrochemistry - a deeper aquifer within the basalt (screened 26-28 metres) located immediately adjacent to Port Phillip Bay. However, there were a number of additional factors that pointed to a high level of risk of SWI.

A comparison was made of the potentiometric surfaces for 2002 and 2003. Comparisons showed a drop in groundwater water levels of up to 4 metres over this period and a large increase in the area to the east of the river where groundwater levels had fallen below sea level. The presence of tidal influences in the river adjacent to the region where groundwater levels had fallen below sea level and a reduction in the hydraulic gradient to the coast indicated a high risk of SWI. This led to a ban on groundwater extractions within the irrigation district that continues through to the present day due to ongoing drought conditions.

The investigations by SKM (2005b) culminated in the development of a MODFLOW 2000 finite-difference groundwater model. One of the main objectives of the modelling exercise was to help define a series of trigger levels that could be applied to key monitoring bores which would indicate the potential onset of saline water fluxes into the aquifer. A range of scenarios were modelled in order to assist in the management of groundwater extractions, and model development is still on-going.

3.2.3.2 Other Victoria

While no regions other than the Werribee Irrigation District have reported incidences of SWI, a study by Dahlhaus et al. (2004) used the groundwater flow system (***GFS***) approach of Coram et al. (2001a) to classify catchments according to their salinity risks. The Dahlhaus et al. (2004) investigation highlighted a number of groundwater flow systems within the Port Phillip and Westernport regions that might be vulnerable to SWI. These regions included the Nepean Bay Bar Barrier Dunes (local flow system, e.g. Nepean GMA) and the Swamp and Back-Dune Wetlands (local and intermediate flow systems, e.g. Kooweerup GMA). The Werribee Delta (local and intermediate flow system) was also identified, and the risk has been corroborated by the SKM (2005b) findings.

A general management action was suggested for the Nepean Bay Bar GFS, which was to ensure that SWI did not contaminate the shallow groundwater water resources used for stock and domestic water supply as a consequence of over-pumping. The management action suggested for the Swamp and Back-Dune Wetlands, where groundwater is extracted from the more productive aquifers at depth, was to not over-pump the deeper aquifers.

Parsons Brinkerhoff (2010) conducted an extensive reappraisal of groundwater resources in Southeast Melbourne and highlighted that the Nepean and Frankston areas were at risk of SWI. No long-term monitoring data were found to be available in the Mornington, Dromana and Moorabbin areas by which to evaluate the water balance of aquifers.

There are considerable groundwater reserves that are used for irrigation, stock and domestic supplies in the East Gippsland region coastal areas. According to EGCMA (2005) there is currently no evidence that saline water from the sea or Gippsland Lakes has intruded into the groundwater reserves; however, saline intrusion remains a threat to the aquifers in the Sale region, where groundwater levels have been drawn down below sea level, adjacent to the lakes, and in the Orbost region, given its proximity to the sea (EGCMA, 2005). The two main aquifer systems utilised within the East Gippsland region are the Boisdale Formation used within the Sale Water Supply Area, and the Curlip Gravel aquifer used within the Orbost Groundwater Management Area (EGCMA, 2005). The Boisdale aquifer system is composed of Upper Tertiary, non- marine, fluviatile deposits consisting of sand, clay and minor brown coal. It is generally found at depths between 50 and 200 metres below natural surface and is confined (***ANRA***, 2002). The Curlip Gravel comprises Quaternary alluvial, fluvial sandstones and thin fine-grained clastic beds associated with the Snowy River floodplain and these are found at depths of 20-45 metres (SKM, 2001).

The EGCMA (2005) report also stated that offshore extractions could lead to SWI within the Stratford Groundwater Management Area. Groundwater levels are expected to continue falling in the Lower

Tertiary Latrobe Group Aquifers (sands, clay, brown coal) at a rate of 1 m/yr as long as oil and gas extraction continues in Bass Strait (ANRA, 2002).

In the stakeholder workshop (Appendix 3) the GMA's of Moorabbin (sand plain aquifer), Yangery (limestone province) and Nullawarre (limestone province) were also identified as potential areas for SWI. A study is currently in progress in the Moorabbin area.

Table 5 *Summary of literature for areas identified as being vulnerable, or potentially vulnerable, to SWI in Victoria*

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land / groundwater use
Werribee River Delta	(Dahlhaus et al., 2004; Leonard, 2006; SKM, 2005b)	Quaternary alluvial delta overlying Quaternary/Tertiary Basalt	Yes, in 2005 investigations at one site in basalt adjacent Port Phillip Bay (SKM, 2005b)	Groundwater extractions; below average rainfall/droughts; shortfall in channel deliveries	Water level; salinity; major ions, metals, bacteria; geophysical logging; MODFLOW 2000	Yes (but not SWI interface specific)	Yes – exploring trigger levels and reducing extraction volumes	Moderate	Horticulture
Point Nepean (same references apply to Moorabbin*)	(Dahlhaus et al., 2004; Parsons Brinckerhoff, 2010)	Quaternary sands overlying mixed alluvial/fluvial	No	Groundwater extractions; below average rainfall/droughts	Reappraisal of groundwater resources conducted	No	No	Low	Stock; domestic; gardens; recreational
Gippsland (Sale/Orbost region and Venus Bay dune sands)	(ANRA, 2002; EGCMA, 2005)	Tertiary non-marine fluviatile sand, silt, clay, minor gravel and coal overlain by local thin Quaternary sands and alluvium; multi-layered aquifers	No	Groundwater extractions (including off-shore); below average rainfall/droughts	Limited data	No	No	None to Very Low	Irrigation; town water supply
Koowerup*	(ANRA, 2002)	Tertiary sediments	No	Groundwater extractions	Unknown	No	No	None to Very Low	Vegetables/ horticulture
Nullawarre*	(ANRA, 2002)	Tertiary Limestone	No	Groundwater extractions	Unknown	No	No	None to Very Low	Agricultural irrigation
Yangery*	(ANRA, 2002)	Tertiary Limestone	No	Groundwater extractions	Unknown	No	No	None to Very Low	Agricultural irrigation

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

3.2.4 South Australia

The main area where SWI has been reported in South Australia is within the Adelaide Plains, and to a lesser extent the Eyre Peninsula. There are also concerns and on-going investigations in the Port MacDonnell area, Willunga and the Adelaide Metropolitan area. These areas are discussed in further detail below. For details of all South Australia sites where SWI threat has been acknowledged, refer to Table 6.

3.2.4.1 Eyre Peninsula

Eyre Peninsula experiences a semi-arid climate, and groundwater is the main source of potable water in the region. Groundwater resources are used to provide domestic supplies to the town of Port Lincoln and other townships, and they are also used for irrigation (recreational grounds, improved pasture, horticulture, and cropping) and industrial purposes. The major fresh groundwater resources are located in two principal areas; the southern tip of Eyre Peninsula and along the western side of the Peninsula. Below-average rainfall and increased demands for water have led to concerns regarding the sustainability of the groundwater resources and the risks of SWI.

Tertiary and Quaternary age sediments form the major low salinity aquifers within the region, and these overlie the crystalline basement rocks and volcanics of the Gawler Craton. The groundwater basins consist of a series of palaeovalley depressions within the ***fractured*** basement which have been in-filled with Tertiary aeolian, sand-sized shell fragments and clays, and which have been overlain by the Quaternary Bridgewater Formation limestone. The ***karstic*** nature of the limestone dramatically increases the amount of recharge available to the underlying aquifers during intense rainfall events, and the volumes of groundwater recharge are much higher than would normally be expected within an arid area.

A number of groundwater basins are presently used for water supply on Eyre Peninsula, including the Musgrave Prescribed Wells Area, located near the town of Elliston, and the Southern Basins Prescribed Wells Area, located southwest of Port Lincoln. Other smaller lenses are also used to supply small coastal townships on the western side of the Peninsula (Streaky Bay, Port Kenny).

3.2.4.1.1 Robinson Basin

According to the Department of Water, Land, and Biodiversity Conservation (DWLBC Factsheet), the first groundwater lens to have been utilised for potable water supplies was obtained from shallow trenches dug within the Robinson Basin and was used to supply water to the coastal town of Streaky Bay. The water supply from the Robinson Basin failed during the prolonged droughts of 1949 and 1976/77 when major increases in groundwater salinity were observed. The Harrington and Brown (2002) investigation on the groundwater resources of the Robinson Basin reported that the monitoring bore network was in poor condition (clogging) and that the previous recordings, including salinity, were likely to be flawed. This is because after further purging and development of the bores, the electrical conductivity measurements were significantly higher than previously recorded (Harrington and Brown, 2002). Additional concerns were raised regarding the sustainability of the resource given the increases observed in the salinity measurements.

Further investigations by Brown and Harrington (2003) assessed groundwater hydrographs and chemical trends, including distributions of ***CFC*** ages and salinity measurements, and these data suggested that the hydrodynamics of the Robinson Lens were “completely controlled by rare, episodic recharge events and subsequent pumping of the fresh groundwater resource". The expected life of the resources under the extraction rates at that time was estimated to be approximately 10 years. Trench #1 was also predicted to become permanently dry by 2010 and reach a salinity (electrical conductivity) of around 3500 µS/cm. There have not been any recent reports by which to assess if the predictions made by Brown and Harrington (2003) for the Robinson Lens were valid. The water supply for Streaky Bay is now provided by the Southern Basins Prescribed Wells Area, discussed further below, as well as the Robinson Basin, which would have addressed some of the reported sustainability concerns.

The groundwater resources contained within the Musgrave Prescribed Wells Area and the Southern Basins Prescribed Wells Area are discussed in further detail as follows.

3.2.4.1.2 Musgrave Prescribed Wells Area

The groundwater resources within the Musgrave Prescribed Wells Area (***PWA***) have been described by Evans (2002a) as being primarily contained within the Quaternary Bridgewater Formation Limestone and the Tertiary Sand Aquifers. The resources found within the Quaternary limestone are held in separate geologically controlled structures that include the Bramfield, Kappawanta, Polda, Polda North, Talia and Sheringa A and B Lenses. These lenses yield good quality supplies of groundwater with a concentration less than 1000 mg/L TDS. The Polda lens contributes to the reticulated water supply for upper Eyre Peninsula via the major Tod River to Ceduna pipeline and the Bramfield lens is the source of water for the township of Elliston.

The Quaternary Limestone Aquifer is unconfined and occurs where the underlying formations are either confining in nature or where they are saturated and connected by continuous moisture. The depth to the watertable varies widely across the region. The Tertiary Sands Aquifer receives lateral flow and recharge via downward leakage from the Quaternary Limestone Aquifer. The Tertiary Sands Aquifer is considered to be confined where it underlies the saturated Quaternary Limestone Aquifer and elsewhere is considered as unconfined. The salinity of the groundwater in the Tertiary Sands Aquifer ranges from 500-5500 mg/L TDS and exhibits poor to moderate yields (1-10 L/s). Groundwater monitoring in the Musgrave PWA began in the 1960s and 132 bores are regularly observed for water level (monthly) and salinity (six monthly). Despite the relatively large volumes of groundwater extracted from some lenses, groundwater quality has only fluctuated within a small range since monitoring began. This is likely to be because the groundwater lenses tend to be isolated from the adjoining saline waters that could mix under the stress of pumping. The freshwater-saltwater interface was not defined in the Evans (2002a) report.

3.2.4.1.3 Southern Basins Prescribed Wells Area

The region around the Southern Basins Prescribed Wells Area is described by Evans (2002b) 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 metres high coastal cliffs and ***bedrock*** highs of up to 200 metres, through to inland depressions at sea level containing saline lakes. The Southern Basins PWA region includes both national and conservation parks. As is the case within the Musgrave PWA, the groundwater resources are primarily contained within the Quaternary Limestone Aquifer and the Tertiary Sands Aquifer. The groundwater resources found within the Quaternary Limestone Aquifer are also stored in separate geologically controlled structures, including Coffin Bay A–C; Wanilla; Uley Wanilla, Uley East and Uley South; and Lincoln A–D and D West Lenses.

The South Australian Water Corporation (SA Water) is the largest groundwater user within the Southern Basins PWA. Groundwater extractions were reported by Evans (2002b) to have notably increased in the 1970's with the commissioning of the Uley South borefield, which is used to provide more than 70 % of the reticulated public water supply for Eyre Peninsula. Groundwater monitoring in the Southern Basins PWA began in the late 1930's, and 103 bores are monitored for their water levels. Only a subset of these, 63 bores, are monitored for TDS at 6 monthly intervals or longer.

According to the Government of South Australia Factsheet entitled "The water resources in the Eyre Peninsula", there are currently about 60 wells that are monitored for groundwater levels and 30 that are monitored for groundwater quality within the Uley Basin. Water levels are recorded monthly throughout the year and water quality measurements are monitored daily by SA Water at the major pumping stations. The noticeable declines in groundwater levels from the Uley Basin due to over-extractions have resulted in reduced groundwater withdrawals to ensure the sustainable development of the resource. However, due to the extended periods of below-average rainfall, the groundwater levels within the Uley Basin have continued to decline irrespective of pumping. This has resulted in the deepening of many wells. Many of the fresh groundwater systems are surrounded by brackish or saline groundwater, and there is the potential that the deepening of wells may eventually draw the saline water towards the pumped wells. Since salinity measurements began, no significant increases in TDS have been reported. However, the monitoring has not been seawater interface specific and the investigations into SWI have been limited.

The Uley Basin Groundwater Modelling Project was initiated by SA Water and the Eyre Peninsula Natural Resources Management Board in September 2005 as a result of the concerns over the high dependency on groundwater in the regions and the limited state of hydrogeological and other knowledge gaps in the face of a varying climate and climate change (Harrington et al., 2006). The main focus of the project according to Harrington et al. (2006) was to determine a sustainable groundwater extraction regime for the Uley South groundwater lens, as well as to develop a conceptual and numerical ***model*** for the entire Uley Basin, including the Uley Wanilla, Uley East and Uley South lenses. Harrington et al. (2006) reported on the initial conceptual model development. The second part of the project outlined the modelling results (Zulfic et al., 2006) using MODFLOW2000 to simulate both the steady state and transient flow aquifer responses to variable pumping and climatic regimes. SWI processes were not simulated and there has been little work to date on SWI within the Uley Basin and within the Eyre Peninsula more generally.

A review and rehabilitation of the Uley Basin observational bore network was reported by Clarke (2005). Pressure transducers and data loggers were installed within two of the new bores to better assess the impact of rainfall on groundwater recharge. Surface geophysical surveys and salinity profile measurements were also conducted as part of the monitoring bore network review in order to establish the existence and position of the saltwater interface. The position of the saline interface and zone of diffusion was observed within two coastal bores located about 600-700 metres in from the coast, and it was recommended that these are monitored every 2 to 3 months for the first year to document the movement of the interface. The installation of additional monitoring bores and pluviometers was also recommended.

The available groundwater resources in the Eyre Peninsula are primarily rainfall-recharge controlled and a strong relationship exists between groundwater levels and the amount of rainfall. It is estimated that between 10 and 30 % of the rainfall recharges the Quaternary Limestone Aquifer (Evans, 2002b). Groundwater monitoring has indicated that water levels are near their lowest point on record, with the last major recharge event recorded in 1993 (DWLBC Factsheet) at the time this report was written in

December 2009. Monitoring data over the last 60 years had indicated that during periods of below-average rainfall, groundwater levels declined irrespective of groundwater pumping as a result of natural groundwater discharges and losses. Historic extraction has at times exceeded sustainable use of the groundwater resources, such as during the prolonged droughts of 1949/50 and 1976/77. Groundwater levels have been dropping at an average rate of around 0.2 m/year since the last major recharge event of 1992/93 (DWLBC Factsheet). The on-going below-average rainfalls have led to increased concerns of SWI.

Concerns over SWI have more recently led to increased funding for hydrogeological investigations. In September 2006, about 1000 km lines of TEMPEST ***AEM*** data were acquired over the Southern Eyre Peninsula in order to assist in the definition of freshwater lens systems and aquifer bounds as part of a resource definition project (Auken et al., 2009).

Alcoe (2009) more recently assessed SWI risk within the Uley South Basin by developing a lumped parameter water balance model with a first-order approximation of SWI extent. The model was used to compare trigger-level to flux-based management for a coastal aquifer system. A “hybrid” approach that integrates pumping protocols common to both trigger-level and flux-based management was shown to provide optimal risk reduction in the migration of the toe of the saltwater interface.

The Eyre Peninsula Groundwater Project has recently been established and has the objective of improving the scientific understanding that underpins the sustainable management of the region’s groundwater resources (http://www.epnrm.sa.gov.au/Water/Groundwater.aspx, cited 3 March 2010). This project will be a collaborative effort resulting in contributions over the next two years from the NWC (Australian Government), SA Water, the Eyre Peninsula ***NRM*** Board and the South Australian Department of Water, Land and Biodiversity Conservation. Technical investigations are being undertaken by a team of scientists from the Board, Flinders University, SA Water, CSIRO and private consultants. According to Werner (personal communication, 2009) the newly formed Australian National Centre for Groundwater Research and Training will include a number of research projects to assess the groundwater resources of the region as part of a larger Eyre Peninsula Groundwater Project.

3.2.4.2 LeFevre Peninsula (Adelaide Metropolitan and Northern Adelaide Plains)

The Adelaide region experiences a Mediterranean-type of climate with hot dry summers and cool, wet winters. However, climatic conditions have been drier than average conditions over recent years putting greater stress on the groundwater resources. The hydrogeological setting of the Adelaide Coastal Plains is complex. The Quaternary and Tertiary sediments within the Adelaide Geosyncline are up to 600 metres thick, containing up to ten semi-confined to confined aquifer systems. These sediments overlie a Precambrian fractured rock aquifer. Prior to development the Quaternary and Tertiary aquifers were artesian.

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, such as in the LeFevre Peninsula which has experienced SWI (see below).

The main groundwater resources in the Adelaide Plains are contained in the four, confined Tertiary aquifers (T1-T4). The Tertiary sands, sandstones and limestone form the aquifer units, white clay, chert and marl form leaky confining beds. 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. On several occasions since 1915 the uppermost Tertiary aquifer (T1) was used to supplement the Adelaide metropolitan water supply (Gerges, 1996). 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).

A hydrogeological investigation by Gerges (1996) of the Adelaide metropolitan region included the drilling and installation of monitoring bores, geophysical logging, pump tests and the collection of water level and salinity measurements. The risk of SWI, based on salinity and groundwater level data, was identified by Gerges (1996) for the LeFevre Peninsula area. Higher salinities were observed within the Quaternary coastal aquifers in the LeFevre Peninsula in areas where it was noted the ***potentiometric surface*** was being drawn down below sea level (by as much as 20 metres) due to large extractions of groundwater from the underlying Tertiary aquifer and over-pumping of the Q1 aquifer.

In the LeFevre Peninsula the uppermost Q1 aquifer is overlain by dune sands which store good quality water due to local direct recharge from rainfall. The Q1 aquifer/dune sands in this area are used extensively for watering gardens and recreational parks. The Q1 sediments are underlain by the hydraulically connected Q2 aquifer which has a salinity of up to 21 000 mg/L. Over-pumping of the Q1 aquifer has the potential to cause up-coning from the underlying salty aquifer. Moreover, heavy pumping from the underlying Tertiary aquifer in this area has led to an expanding ***cone of depression*** that has induced downward leakage and the lowering of the watertable in the Q1 aquifer.

Another investigation conducted by Lamontagne et al. (2005) assessed the volumes of groundwater being discharged to coastal waters between Port Gawler to Sellicks Beach in the Gulf St Vincent. The aim of the study was primarily to determine nitrogen loads which were implicated with the decline in native sea grasses in the region. The groundwater investigations included the construction of flow nets and the collection of salinity measurements and naturally occurring radioisotopes (radon and radium). The flow nets suggested that intrusions of seawater may be more widespread than previously thought along the length of the Adelaide coastline, although it was acknowledged that the poor bore monitoring network along the coastal fringe made the potentiometric surface somewhat uncertain. Measurements in coastal monitoring bores showed an increasing salinity trend for both Quaternary and Tertiary aquifers and a general decline in groundwater levels. The areas of the LeFevre Peninsula (confirming the findings of Gerges (1996)) and the region to the south of Point Blanche were highlighted by Lamontagne et al. (2005) as regions at particular risk of SWI. In these areas the zero potentiometric surfaces were up to 6 km inland of the coast. Lamontagne et al. (2005) compared their flow net results to the calculations made by Martin (1998b) who used the Ghyben-Herzberg principle to investigate the length of the seawater wedge inland, and similar results for the extent of the seawater wedge inland were found.

The main driving factors associated with SWI have been reported as below-average rainfall and recharge, increased groundwater extractions, the practise of lining surface water drainage features with concrete (which reduce recharge), aquifer leakage into corroded sewer pipes and urbanisation. The Gerges (1996) report recommended upgrading the monitoring bore networks, particularly in areas under heavy and continuous stress. The report also recommended comprehensive water and salt balance studies and the development of a groundwater model to assist in managing extractions. He also advocated the use of aquifer storage and recovery (ASR) as a means to maintain the groundwater reserves. A number of ASR case study areas have since been implemented to inject storm water into stressed aquifer systems (Gerges, 2000).

3.2.4.3 Port MacDonnell

The Port MacDonnell region experiences a Mediterranean-type of climate with hot dry summers and cool, wet winters. It is situated within the Gambier Basin, where groundwater resources are extracted from the unconfined, Tertiary Gambier Limestone Aquifer. Groundwater is used for irrigated agriculture, improved pasture, and for industrial, domestic and stock water supplies. The groundwater resources within this region also support groundwater-fed springs and wetland habitats such as the Ewens Ponds Conservation Park. The Gambier Limestone ranges in thickness from 100 to 300 metres and the watertable is at ~3 metres (King and Dodds, 2002).

An investigation was conducted by Barnett (1976) in order to establish a potable groundwater supply within the Carpenter Rocks area. Two production bores were drilled, one was located 350 metres inland from the coast, and the second one was located 500 metres inland. The bore closest to the coast (at 17 metres depth) was abandoned due to high salinity as a consequence of up-coning during the pump test, while the second production bore (drilled to 25 metres depth) continued to yield good quality water throughout the test. A salinity profile was obtained from an observation bore, also located 350 metres from the coast, which was drilled to a depth of 40 metres. The salinity profile was noted to be in the range of 600-700 mg/L TDS at 12 metres in depth and the salinity increased to 23 610 mg/L at 40 metres in depth; the saltwater interface was noted at approximately 25 metres. The interface was not encountered 500 metres inland during drilling to a depth of 25 metres. A resistivity survey was subsequently undertaken to determine the position of the saltwater interface, and the results suggested that the interface was located at a depth of 40 metres at a distance of 500 metres inland from the coast. According to Barnett (1976) the cavernous nature of the limestone aquifer resulted in high transmissivity values on the order of 12 560 m^3/d/m , and a safe yield of 120 L/s was determined for further development of the site 500 metres inland. Numerical modelling investigations reported by Stadter and Yan (2000) indicated that the risk existed for saline groundwater to be extracted if over pumping occurred (King and Dodds, 2002).

King and Dodds (2002) conducted a transient electromagnetic survey to determine the presence of and depth to the saltwater interface over 5 traverse lines in a northerly direction from the coast. The results showed the presence of a strong conductor below the watertable at depths of around 200 metres, which was likely to represent the saltwater interface. Considerable irregularity in the shape of the assumed interface was noted, and this was presumed to be due to the variations in aquifer permeability and localised volcanic intrusions. Additional drilling was recommended to confirm the relationship between geophysics and ***hydrogeology***.

3.2.4.4 Willunga

The Willunga Basin is located in South Australia, approximately 40 km south of Adelaide. It experiences a Mediterranean-type climate with hot dry summers and cool, wet winters.

The Willunga Basin is a sub-basin of the larger St. Vincent Basin. It is sedimentary, characterised by mostly mid- to late-Tertiary and Quaternary sediments. 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 included slates, quartzites and dolomites that have been interbedded and experienced low to moderate levels of metamorphism (Martin, 1998b).

The Willunga Basin is a complex multi-aquifer system (Board, 2007). 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).

The Quaternary aquifer is largely unconfined, comprising 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 becomes 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.

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, 1998b).

In the Willunga Basin, analysis of hydrographs show that more than half of all monitored wells have a declining water level trend. Salinity is increasing in the centre of the basin and along the northern and coastal margins (Lamontagne et al., 2005).

3.2.4.5 Adelaide Metropolitan

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. The region experiences a Mediterranean-type climate with hot dry summers and cool, wet winters.

The hydrological setting of the Adelaide Coastal Plains is complex. 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.

The majority of Quaternary aquifers (Q1-Q6) tend to be insignificant due to their low yields and high salinity. These aquifer units vary greatly in thickness (from 1-18 m), lithology and hydraulic conductivity (Lamontagne et al., 2005). There are, however, localised areas that provide good quality water. 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, whilst 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).

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 second-most upper Tertiary aquifer is used by industry and for irrigating recreational areas such as Parks and golf courses. The uppermost Tertiary aquifer is on occasions used to supplement Adelaide metropolitan water supply.

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. 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).

In order to effectively manage the groundwater resources in the two main Tertiary aquifers (T1 and T2 aquifers) beneath the Adelaide Metropolitan Area, the Adelaide and Mount Lofty Ranges Natural Resources Management Board (AMLRNRMB) engaged the Department of Water Land and Biodiversity Conservation (DWLBC) to develop and construct a groundwater flow simulation model. The three-dimensional groundwater flow model was developed using MODFLOW 2000 (Osei-Bonsu and Barnett, 2008). Zulfic et al. (2008) reported that although groundwater monitoring is currently conducted on a six monthly basis, it would be beneficial to monitor water level fluctuations on a quarterly basis because of the industrial nature of groundwater abstractions. They also stated that the existing monitoring network needs to be reviewed and assessed, with recommendations made for the upgrade of the network (rehabilitation, backfilling, new wells). Salinity monitoring and regular reviews of sampling trends were considered necessary in order to enable more vigorous management of the resource, along with an improved spatial distribution and greater number of sampling sites across different zones.

Table 6 Summary of literature for areas identified as being vulnerable, or potentially vulnerable, to SWI in South Australia

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land / groundwater use
Adelaide Metropolitan	(Gerges, 1996; Gerges, 2006; Gerges, 2000; Hodgkin, 2004; Jeuken, 2005; Lamontagne et al., 2005; Osei-Bonsu and Barnett, 2008; Zulfic et al., 2008)	Tertiary multi-layered aquifers comprising sandstones, limestone (minor sands)	No	Groundwater extractions; groundwater mining; urbanisation	Water level; salinity; flownets; Ghyben-Herzberg, MODFLOW	No	No	Moderate	Urban, residential; parks and gardens; on occasions used to supplement Adelaide water supply
Eyre Peninsula (Coffin Bay/Uley)	(Alcoe, 2009; Auken et al., 2009; Brown and Harrington, 2003; Eyre Peninsula Natural Resources Management Board, 2006; Harrington and Brown, 2002; Harrington et al., 2006; Seidel, 2008; Zulfic et al., 2006)	Quaternary karst limestone overlying Tertiary sands	No in Uley South, Yes in Robinson's Basin	Groundwater extractions; below average rainfall/droughts	Water level; salinity; CFCs; geophysical (AEM and surface); lumped parameter model for Uley South Basin	Yes (but not SWI interface specific); infrequent	No – exploring trigger level management	Moderate	Town water supply; irrigation, industry
Port MacDonnell	(Barnett, 1976; King and Dodds, 2002; Stadter and Yan, 2000)	Tertiary limestone	No	Groundwater extractions	EM; limited salinity; numerical model	No	No	Moderate	Irrigated agriculture; improved pasture; stock; domestic; industrial; groundwater dependant ecosystems
Le Fevre Peninsula/ Adelaide	(Lamontagne et al., 2005; Russell, 1996)	Quaternary dune sands overlying Tertiary sands, sandstones, limestone	Yes (e.g. (Gerges, 2006)	Groundwater extractions; up-coning from underlying saline aquifer	Water level; salinity; flownets; Ghyben-Herzberg	No	No	Low	Residential; urban parks and gardens

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land / groundwater use
Willunga	(Harrington, 2002; Herczeg and Leaney, 2002; Knowles et al., 2007; Lamontagne et al., 2005; Martin, 1998a; Rasser, 2001; Steward, 2006)	Multi-layered aquifer comprising Quaternary sands overlying Tertiary sands and limestone	No	Groundwater extractions	Water levels; salinity; Numerical model developed to investigate sustainable yields (Rasser 2001)	No	No	Low	Viticulture, almonds, stock, industrial

3.2.5 Western Australia

SWI has been reported in the Perth, Bunbury, Busselton, Albany, Esperance, Carnarvon, Cape Range, the coastal Kimberley regions, Northern Swan Coastal Plan, Cottesloe Peninsula and Rottnest Island. These areas are further discussed in the subsections below. Note that some of the information provided in this section on the WA case studies is based on unpublished hydrogeology reports of the Western Australian Geological Survey and successor organisations which cannot be specifically cited without written permission. For details of all Western Australia sites where SWI threat has been acknowledged, refer to Table 7.

3.2.5.1 West Kimberley Coast

The West Kimberly Coast region has a hot tropical climate with a distinct wet and dry season. The Water Authority reported SWI in the Triassic, unconfined Upper Erskine Sandstone aquifer and confined Lower Erskine Sandstone aquifer in Derby in 1992 (Water Authority of Western Australia, 1992b). It also documented SWI in the Jurassic – Cretaceous, unconfined Broome Sandstone aquifer; and Jurassic, confined Alexander Formation and Wallal Sandstone aquifer in Broome in 1994 (Water Authority of Western Australia, 1994). The Broome and Derby water supply areas were briefly reported by CSIRO (2009c) as having induced SWI as a consequence of groundwater extraction from the Jurassic – Cretaceous unconfined sandstone aquifers of the Canning Basin. Limited groundwater elevation and salinity data are available and no published reports were noted for this region that specifically address SWI.

3.2.5.2 Cape Range (Exmouth)

The Cape Range Province has coral reef contained within the Ningaloo Marine Park and limestone karst formations that support diverse subterranean fauna. The Province draws tourism and recreational activities, and supports fishing, mining and pastoral industries. Cape Range experiences an arid climate, and potable water is limited to groundwater which is carefully harvested from within the sensitive karst system (EPA, 1999). 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). SWI is of concern in the area not only because of its potential impact upon the potable groundwater resources for domestic use, but also because of the groundwater dependent aquatic cave fauna.

The Cape Range area geomorphology consists of an uplifted and highly dissected karst terrain flanked by coastal plain sediments and a series of wave-cut uplifted reef terraces. The coastal plain aquifers are comprised of alluvial fan units that hold little to no freshwater other than for intermittent periods of times after cyclonic rains. The main freshwater groundwater resources are located in the hinterland within the Tertiary limestone which has been karstified to depths of 50 metres. The fresh groundwater within the hinterland overlies a saltwater wedge that extends about 5 km inland from the coast, and the diffusion zone is approximately 20-30 metres thick (Lee, 2004; Water Corporation, 1997). Aquifer recharge occurs from direct rainfall and through the beds of ephemeral streams which carry storm runoff from the range. However, recharge is limited and results in the thinness of the freshwater lens. The watertable lies a couple of metres above sea level near the coast and rises to 15 metres in elevation towards the inland part of the Water Corporation borefield (EPA, 1999).

Lee (2004) applied the SUTRA modelling code to investigate the effects of dewatering and to predict the movement of seawater inland under various recharge and extraction scenarios. The results of his work have been used to inform the management and allocation of the groundwater resources in the region.

3.2.5.3 Carnarvon

The town of Carnarvon experiences a semi-arid climate, and the town's population and horticultural industries are completely reliant on the groundwater resources found within the fluviatile sediments laid down by the Gascoyne River. The flows in the Gascoyne River are intermittent, and during periods of river flow the aquifer systems are usually fully replenished. The groundwater resource is bound to the west, on the coast, by a saltwater interface and to the east, inland, by a geological anticline. Droughts and over extraction of groundwater have led to rising salinity levels presumed to be a consequence of SWI (WRC, 2004).

The WRC (2004) report provides a good overview of the hydrogeology and groundwater management issues for the Carnarvon region, and the following information has been summarised from this report.

The regional unconfined to semi-confined aquifer systems are separated into two Quaternary-aged aquifers: the upper riverbed sand aquifer, in the immediate vicinity of the Gascoyne river bed, and the older, deeper alluvium comprised of discontinuous channel beds of sediments ranging from coarse gravel to clays. The two aquifers are hydraulically connected and are divided into 11 arbitrary groundwater basins for water management. Basin A contains groundwater resources which are obtained predominantly from the riverbed sands; these resources are used mostly for horticulture. Basins B-L, located further upstream, provide groundwater resources from the older alluvium as part of the Water Corporation's well field for domestic use and industry. The deeper alluvium holds a much greater volume of water than the riverbed sand; however, the salinity levels and water quality are highly variable.

During periods of river flow licensees in Basin A are provided with unrestricted access to both groundwater and surface water. During no-flow periods, licensees are restricted to their licensed annual entitlement. The groundwater allocations are based on groundwater models that simulated two years without river flow, which was the longest no-flow period since records began in the mid 1950's.

Monitoring of groundwater levels and TDS in a network of observation bores takes place quarterly, or monthly during no-flow periods. The bore observation data for Basin A, located closer to the sea, shows an increasing salinity trend to brackish water during no-flow periods, which is presumed to be a consequence of SWI. When groundwater salinity reaches a TDS value exceeding 1000 mg/L, pumping is ceased until the salinity measurements are reduced, generally after the next river flow event recharges the groundwater system. In the interim, during dry periods, farmers have a choice to cease irrigation or to purchase water from the Water Corporation's well field that utilises groundwater from Basins B-L. Annual aquifer status reports are prepared, and according to the WRC (2004) report, no well has experienced any long-term elevated salinity trend when using the cease to pump trigger of 1000 mg/L.

3.2.5.4 Northern Swan Coastal Plain (other than Perth metropolitan)

The large extent of the Swan Coastal Plain, along some 600 km of coastline, has meant that studies of SWI have focused on specific sites within the aquifer, rather than assessing the aquifer as a whole.

In the southern part of the Swan Coastal Plain (between Mandurah and Dunsborough) a saltwater interface is present within the Superficial and Leederville Aquifers, along the coast and coastal lakes and inlets. Within the Superficial Aquifer the interface is typically situated close to the coast, but extends for several kilometres inland associated with the Leschenault Inlet and Peel-Harvey, Wonnerup and Vase Estuaries, and saline lake Clifton and Preston (Commander, 1982; Deeney, 1988; Hirschberg, 1989). In the Leederville Aquifer the interface tends to occur as several tongues of saline water separated by intervening clay beds within the aquifer. About the Peel Inlet, saltwater intrudes the upper part of the Leederville Formation, but is separated from the underlying low salinity groundwater by a green clay marker horizon (Commander, 1974).

In the Bunbury area a saltwater interface intrudes up to 3 km inland within the Yarragadee Formation where the aquifer subcrops the Superficial Formations offshore and is in hydraulic connection with the ocean (Wharton, 1989). Recent observations of increased groundwater salinity within the Yarragadee aquifer have been documented in the Bunbury area. In order to provide information to manage the saltwater-freshwater interface the DoW installed a purpose-built interface monitoring bore in Bunbury.

Near Busselton, unpublished data indicate that strong hydrologic heads result in the saltwater interface occurring offshore. The interface extends inland for 4-5 km, forming a wedge that increases in depth to the south. The interface cuts across the older sedimentary succession of Jurassic (Leederville Formation) and Permian (Sue Coal Measures) age (Panasiewicz, 1996c). The area is being actively monitored.

In the northern portion of the Swan Coastal Plain, a wedge of saltwater extends inland from the coast below an interface with fresh groundwater within the Superficial Aquifer. Due to the high transmissivity of the Quaternary Tamala Limestone, there is a mixing zone between the saltwater and freshwater that extends up to 4 km at Jurien (Baddock and Lach, 2003a). A similar SWI will be associated with coastal lakes east of Leeman – Green Head (Commander, 1994b; Commander, 1994d). Around Dongara, the SWI has been identified 7-8 km inland in the Yarragadee aquifer (Nidagal, 1994a).

3.2.5.5 Perth Metropolitan

The Perth region experiences a Mediterranean-type of climate with hot dry summers and cool, wet winters. A reduction in rainfall since the mid 1970's, coupled with an increased reliance on groundwater resources, has led to a decline in groundwater levels and increased concerns regarding resource sustainability and the risk of SWI. More than half of Perth's water supply is obtained from the groundwater resources found within the Swan Coastal Plain aquifers. Groundwater is also utilised by industry, horticultural developments and other rural supply, pine plantations, recreational areas, gardens and wetland habitat.

The superficial aquifers within the Swan Coastal Plain are comprised of Quaternary and Late Tertiary sediments that extend from Geraldton in the north to Busselton in the south. The sediments most exploited for groundwater resources within the Perth region are the quartz sands (Bassendean Sand Formation), and calcareous sands and limestone (Tamala Limestone) which reach a maximum thickness of about 70 metres. These are referred to collectively as the Superficial Aquifer. The Gnangara and Jandakot groundwater mounds within these sediments are the main sources of Perth's water supply.

A study by Smith et al. (2005) assessed the opportunity for increased self-supply of groundwater from the Superficial Aquifer in the Perth region with a view to reducing the growing pressure on drinking water supplies. They analysed the 10 year trend in groundwater level monitoring data from the 1995-

2004 period and applied linear regression models. The fitted slopes were used to estimate the 10 year trend in the freshwater thickness, using the Ghyben-Herzberg approximation, which was used as a surrogate for aquifer storage. Declining groundwater trends and the risk of SWI was identified for the Safety Bay and Stakehill Mounds, as well as the deeper bores located within the Superficial Aquifer located closest to the coast in the Rockingham-Warnbro area and northern coastal strip between Whitfords and Yanchep.

SWI has been documented in the Cottesloe Peninsula in Perth. The entire Peninsula is underlain by saline water upon which a lens of freshwater floats within the aeolian sediments of the Tamala Limestone aquifer. The lens has a maximum thickness of 20 metres and thins to less than 5 metres near the coast.

An investigation by Appleyard (2004) estimated that the amount of freshwater beneath the Cottesloe Peninsula had been reduced by about 40 % due to groundwater abstractions for golf courses, gardens and other recreational reserves. This approximation was made applying a simple analytical model that assumed an elongated oceanic island in order to calculate the depths of the saltwater interface. The depths calculated were similar to those measured in the local monitoring bores in the 1980's, and suggested that the interface may not have changed much since that period. However, EPA (2005) reported that the salinity values in the area have been showing a marked increase over time. The salinity reached an average value of 1460 mg/L TDS in 2003 and a maximum value of 2600 mg/L TDS (January 2003). These were the highest salinity values recorded since monitoring began in the Peninsula in 1996.

These elevated salinity values prompted investigations to assess the feasibility of using reclaimed wastewater for aquifer recharge in the Cottesloe area. A three-dimensional SWI model was developed for the Cottesloe/Mosman Peninsula using a model based on MODFLOW/MT3DMS, called SEAWAT (Blair and Turner, 2004). Initial scenario modelling indicated that aquifer recharge would secure sufficient groundwater resources to meet current requirements, with a small amount of future growth in water use. The lack of comprehensive groundwater level and quality data meant that there were few data with which to calibrate the model. Nonetheless, the assessment highlighted that the area would make a good test case for managed aquifer recharge. A project has recently been funded by the Australian Government Water fund for the Cottesloe Peninsula area in order to replenish the aquifer using treated wastewater.

Recommendations have been made by Smith et al. (2005) to increase the monitoring bore network spatial coverage, and to establish a dedicated network of bores for monitoring SWI in the susceptible coastal areas.

The Perth Regional Aquifer Modelling System (PRAMS) was jointly developed by the Western Australia Water Corporation and Department of Water Western Australia (DoW) for the purpose of simulating regional groundwater flows in the Central Perth Basin (Davidson and Yu, 2006) . The model has been continuously improved over time and the latest version (3.2) has been calibrated and validated to 2008 (CSIRO, 2009a). PRAMS is based on the MODFLOW code and was coupled with vertical flux recharge modelling as part of the CSIRO (2009a) South-West Western Australia Sustainable Yields Project. According to the CSIRO (2009a) report, modelling scenarios suggest that by 2030, under the drying climate predictions, that the average groundwater discharge to the ocean will decline from 225 ***GL***/year to between 180 and 220 GL/year. These modelled reductions suggest that a drying climate will potentially increase the possibility of saltwater intrusion.

3.2.5.6 Cottesloe Peninsula

Cottesloe Peninsula is located north of the Port of Fremantle in Perth, Western Australia where the Swan River reaches the Indian Ocean. It experiences a Mediterranean climate with cool, wet winters and hot, dry summers.

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).

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 underneath the entire peninsula. The lens has been described as having a maximum thickness of approximately 20 metres, thinning towards the coast with a thickness of less than 5 metres in many coastal areas (Appleyard, 2004).

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).

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

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.

3.2.5.7 Rottnest Island

Rottnest Island is an offshore extension of similar sediments to 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 island is extensively used for recreational purposes by the inhabitants of Perth and tourists from more distant locations. The hydrogeology was investigated by Leech (1976). Drilling indicated that the freshwater lens was less than 9 metres thick and sustainable yields were high; however, because of the highly porous nature of the aquifer, sustainable yields greatly exceeded predicted usage. 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.

3.2.5.8 Bunbury

Bunbury is located on the western coast of Australia approximately 120 kilometres south of Perth within the Swan Coastal Plain. It experiences a Mediterranean climate, with hot dry summers and cool wet winters.

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).

Bunbury contains aquifers within the Superficial formations, Leederville Formation, Bunbury Basalt, Yarragadee Formation and Cockleshell Formation. The Superficial sediments, consisting predominantly of clay and sand in the east and of sand and limestone in the west, form an unconfined aquifer. Watertable ranges from 1-30 metres deep. The aquifer is anisotropic and heterogeneous due to lithological variability and stratification of the sediment. The aquifer is recharges 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, with a minor portion coming 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 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).

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).

In the Bunbury area a saltwater interface intrudes up to 3 kilometres inland within the Yarragadee Formation where the aquifer subcrops the Superficial Formations offshore and is in hydraulic connection with the ocean (Wharton, 1989). Recent observations of increased salinity in the Yarragadee aquifer have been documented in the Bunbury area.

3.2.5.9 Busselton

The Vasse Shelf area is located immediately to the west of Busselton, approximately 200 kilometres south of Perth, and is situated on the south-western coast of Australia on what is known as the Swan Coastal Plain. The area experiences a Mediterranean climate with cool wet winters and hot dry summers.

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).

On the Vasse Shelf area there are two regional aquifers known as the Superficial and Leederville aquifers. 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).

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, 1996b).

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.

On the Vasse Shelf, the interface extends 4-5 kilometres 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, 1996b).

3.2.5.10 Albany

The town of Albany is a growing tourist and retirement town that is built on the more traditional fishing, whaling, and agriculture sectors. The region experiences a Mediterranean-type of climate with hot dry summers and cool, wet winters. Groundwater is used for town water supply, domestic, agricultural and industrial supply, as well as for irrigating recreational areas, parks and gardens. There is also extensive urban use of rainwater. The region is growing rapidly, putting pressure on the available groundwater resources.

The Quaternary and Tertiary sediments along the coastline are part of the most western extent of the Eucla Basin (Clarke et al., 2003). Unpublished data indicate that these sediments form the regionally significant surficial and sedimentary aquifers. The Quaternary coastal sediments are approximately 5-100 metres thick and comprise dune sands and shelly limestone. These sediments are highly permeable and store good quality water from rainwater recharge; however, due to high transmissivities the water table in these unconfined aquifers is relatively subdued, with a saturated aquifer thickness ranging from 5-30 metres. Tertiary fluvial and lacustrine sediments of the Lower Werillup Formation form important aquifers in the Albany groundwater area. These aquifers contain good quality water where they are hydraulically linked to the overlying Quaternary aquifers (URS, 2000).

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 an inland toe in some areas, but this was thought to be due to brackish to saline water within the clay aquitard.

3.2.5.11 Esperance

Although more remote than Albany, the town of Esperance is a growing tourist and retirement town that traditionally has been based on fishing and agriculture. The region has a Mediterranean climate with hot dry summers and cool, wet winters. Groundwater is used for town water supply, domestic, agricultural and industrial supply, irrigating recreational areas, parks and gardens. The town of Esperance is reliant on groundwater for its drinking water supply. Continued growth is expected for the region, placing further pressure. Moreover, like many Australian cities, the region has been experiencing lower than average rainfall over recent years.

The stratigraphy is similar to that encountered at Albany. Quaternary and minor Tertiary sediments along the coastline form the regionally significant surficial aquifers (Department of Water, 2007). The Quaternary coastal sediments, comprised of dune sands and limestone, are approximately 10-30 metres thick, are highly permeable, and store good quality water from rainwater recharge. Brackish to saline groundwater (hypersaline in the vicinity of Pink Lake) is resident in the underlying Tertiary sediments. Extensive pumping can result in up-coning. 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, and an escarpment, probably an ancient erosional shoreline, marks the inland extent of the coastal plain.

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 Pink Lake. The risks to groundwater dependent ecosystems have also been identified as a consequence of deepened groundwater levels and salinisation around wetlands.

In order to manage SWI, groundwater allocations have been reduced, pumping rates have also been reduced near the coast and a new network of production bores has expanded within the region in order spread the stresses on the groundwater aquifer systems. The Water Corporation, which supplies groundwater resources in the region, is required to undertake regional-scale monitoring of water level and water quality, including measurements from seawater interface monitoring bores. An annual report is provided to the Department of Water Resources and any increase in groundwater salinity above 1000 mg/L must be reported within 7 days.

Table 7 *Summary of literature for areas identified as being vulnerable, or potentially vulnerable, to SWI in Western Australia.*

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land/water use
Perth (other than Cottesloe)	(Cargeeg et al., 1978; CSIRO, 2009a; CyMod Systems, 2009; Davidson, 1995; Davidson and Yu, 2008; Rümmler et al., 2005; Smith et al., 2005; Yesertener, 2010a; Yesertener, 2010b)	Cenozoic superficial sand sediments overlying multi-layered sandstone aquifers	No	Groundwater extractions; below average rainfall/droughts ; groundwater mining	Water levels; theoretical inland extent of SWI using Ghyben-Herzberg; PRAMS/MODFLOW	Yes (but not SWI interface specific)	No	Moderate	Domestic; urban, horticulture; parks and gardens; plantations
Cottesloe Peninsula (Perth)	(Appleyard, 2004; Blair and Turner, 2004; EPA, 2005)	Quaternary carbonate eolianite sands	Yes, elevated salinity values reported by EPA	Groundwater extractions; below average rainfall/droughts	Water levels; salinity; analytical model; SEAWAT numerical model	Yes (but not SWI interface specific) – recommend ations made to increase coverage	Yes; MAR	Moderate	Parks, gardens, golf courses and other recreation
Busselton	(Hirschberg, 1989; Panasiewicz, 1996a; Schafer and Johnson, 2009; Schafer et al., 2008)	Cenozoic superficial sand sediments overlying multi-layered Cretaceous sandstone aquifers	Yes, interface reported as extending up to 4 km inland (Hirschberg, 1989; Panasiewicz, 1996a)	Groundwater extractions; below average rainfall/droughts	Water levels; salinity; water chemistry; flow net development; geophysical logging; pumping tests; groundwater dating; 3D model using MODFLOW	Yes, but not SWI interface Specific	No	Moderate	Urban and rural; mixed horticulture, viticulture, olives, plantation forestry, dairy
Albany	(Appleyard, 1989; CyMod Systems Pty Ltd, 2010a; Forth, 1973; URS/Dames & Moore, 2010; Water Corporation, 2010)	Cenozoic sands, clays	No	Groundwater extractions; below average rainfall/droughts	Water levels; salinity; geophysical logging; ground DC resistivity/TEM investigation; MODFLOW	No	No	Moderate	Town water supply; domestic; agricultural; industrial; parks and gardens

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land/water use
Esperance	(Crisalis International Pty Ltd., 2010; Department of Water, 2007)	Cenozoic sands, clays (relict fluvial and lacustrine sediments)	Yes, in Town and Twilight gw mgmt areas, especially south of Pink Lake wetland (Department of Water, 2007)	Groundwater extractions; below average rainfall/droughts	Water levels; salinity; geophysical logging; ground TEM investigation; FEFLOW model	No	No	Moderate	Town water supply; domestic; agricultural; industrial; parks and gardens
Carnarvon	(CyMod Systems Pty Ltd, 2009; CyMod Systems Pty Ltd, 2010b; WRC, 2004)	Quaternary alluvium associated with Gascoyne River	Yes (WRC, 2004)	Groundwater extractions; below average rainfall/droughts	Water levels; salinity	Yes (but not SWI interface specific)	Yes; trigger level management when salinity reaches 1000 mg/L	Moderate	Town water supply; horticultural
Northern Swan Coastal Plain (Jurien, Dongara, Leeman)	(Baddock and Lach, 2003b; Commander, 1994a; Commander, 1994c; Nidagal, 1994b)	Cenozoic superficial sand sediments overlying multi-layered sandstone aquifers separated by clay aquitards	No (but SWI interface reported ~4 km inland at Jurien and ~7-8 km)	Groundwater extractions; below average rainfall/droughts ; groundwater mining	Water level; salinity (at Jurien)	No	No	Low	Town water supply, agricultural
Rottnest Island	(Leech, 1976; Playford and Leech, 1977)	Quaternary carbonate eolianite sands	No	Groundwater extractions; below average rainfall/droughts	Resource estimation	No	No	Low	Parks, and recreation; Desalinatio n plant installed in 1995

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land/water use
Bunbury	(Commander, 1981; Commander, 1982; Deeney, 1988)	Cenozoic superficial sand sediments overlying multi-layered Jurassic sandstone aquifers separated by clay aquitards	Yes, interface reported as extending up to 3 km inland	Groundwater extractions; below average rainfall/droughts	Water level, salinity monitoring, geophysical logging	Yes	No	Low	Urban and rural; irrigation
Broome	(CSIRO, 2009c; Department of Water, 2008; Groundwater Consulting Services Pty Ltd., 2008; Laws, 1984; Laws, 1985; Laws, 1991; Water Authority of Western Australia, 1992a)	Jurassic to Cretaceous Sandstone	Yes (Laws, 1991; Water Authority of Western Australia, 1992a)	Groundwater extractions; below average rainfall/droughts	Basic hydrogeological characterisation	No	No	Low	Town water supply; horticulture; parks/gardens; industry
Derby	(CSIRO, 2009c; Groundwater Consulting Services Pty Ltd, 2008; Laws and Smith, 1988; Smith, 1992; Water Authority of Western Australia, 1992c)	Jurassic to Cretaceous Sandstone	Yes (Groundwater Consulting Services Pty Ltd, 2008)	Groundwater extractions	Basic hydrogeological characterisation	No	No	Low	Town water supply; gardens; stock; domestic
Cape Range/Exmouth	(EPA, 1999; Lee, 2004; Martin, 1990; Water and Rivers Commission, 1999; Water Corporation, 1997)	Tertiary karst limestone	Yes (Lee, 2004)	Groundwater extractions; below average rainfall/droughts	Water levels; salinity: SUTRA	No	No	Low	Domestic; Groundwater dependant aquatic cave fauna

3.2.6 Northern Territory

The Northern Territory has a number of SWI investigations. The locations include McMinns-Howard East, Lambells Lagoon, Milikapiti, Warruwi, Millingimbi, Ngukurr. Additional details follow in the subsections below. For details of all Northern Territory sites where SWI threat has been acknowledged, refer to Table 8.

3.2.6.1 McMinns/Howard East

Current groundwater extraction in the Darwin Rural Area (McMinn's-Howard East Section) horticultural area is estimated to be in excess of 36 GL/year, and the dry season minimum groundwater levels for this dolomite aquifer have been declining for many years. CSIRO (2009c) used the FEFLOW groundwater models that were previously developed for the Darwin Rural Area (EHA, 2007; EHA, 2009) as part of their sustainable yields reporting for the Northern Rivers Region. Their assessment indicated that groundwater levels will continue to decline under current and future climate regimes with the current level of development. In particular, the groundwater levels in the eastern section of Lambells Lagoon regularly approached or dropped below mean sea level throughout the simulation period (2007 to 2030), posing a risk of SWI.

A NWC funded project was led by Geoscience Australia within the Darwin peri-urban area (Tan et al., 2012). This project used airborne electromagnetic data (AEM) combined with additional geophysical, geologic and hydrogeological datasets to assess the occurrence and potential risk of SWI into the coastal aquifers in this area. The report found that there are serious potential implications of a potential threat from seawater intrusion in the Howard East area. It found that the saltwater interface extends up to 10 km inland at Howard Springs. The highly saline water was found to have intruded along structural corridors of high transmissivity.

The CSIRO (2009c) report also mentioned a theoretical risk of SWI into the coastal dolomite aquifer near the Adelaide River if aquifer levels were being drawn down below sea level and if there were hydraulic connection between the aquifer and river system. However, there was insufficient data to establish this risk.

3.2.6.2 Lambells Lagoon

Lambells Lagoon in the Darwin Rural Area experiences marked wet summers and dry winters, is the only region in the Northern Territory where the risk of saltwater intrusion has been reported (CSIRO, 2009c). The main driving factors are groundwater extractions for horticultural and domestic use during the dry season. The groundwater resources are obtained from Proterozoic carbonate sediment aquifers, primarily from the McMinn's-Howard East borefield. The amount of dry season extraction is close to the long-term extraction limit, and a moratorium has been placed on future groundwater development. The aquifers exhibit strong seasonal variability, and groundwater levels have been observed to rise and fall by up to 17 m/year. Although the aquifers are recharged during the wet season, they become depleted during the dry season (CSIRO, 2009c).

3.2.6.3 Milikapiti

Coastal aboriginal communities are often situated in low lying land and often rely heavily on poorly defined/monitored aquifers. The potential for SWI is unknown but possibly high, and of considerable significance to the local communities. Examples of such communities include Warruwi on Goulburn Island (Pavelic et al., 2002a), Milingimbi (Foo, 1980a), Milikapiti on Bathurst Island (Chin, 1991), and Ngukurr in eastern Arnhem Land (Summer, 2008). Although not yet documented to be a threat of SWI, other island communities like Umbakumba (Groote Eylandt (Tyson and Foo, 1991)), Wurankuwu (Bathurst Island (Moser and Chin, 1994)) and Galiwinku (Elcho Island (Foo, 1984)) are potentially vulnerable. Many of these aquifers show strong seasonal variation in groundwater levels, indicating rapid responses to changes in the hydrological balance and high sensitivity to perturbation.

The aquifers supporting the Milikapiti settlement on Bathurst Island currently discharge to the sea (Chin, 1991). However, population pressures within this developing area will require ongoing monitoring to prevent lateral SWI.

3.2.6.4 Warruwi

At Warruwi on Goulburn Island, the main aquifers are weathered Cretaceous sediments and permeable beds within the Cretaceous sediments themselves. The aquifers are the main water supply for the community and have been investigated for managed aquifer recharge to increase storage in the dry season (Pavelic et al., 2002a). Brackish water at depth has been related to the marine water (Foo, 1991); displacement of brackish water during injection trials has led to clogging via a clay dispersal mechanism. Sustainability of the water supply depends on the management of the fresh/brackish water interface.

3.2.6.5 Millingimbi

The aquifer supporting the Milingimbi settlement (Foo, 1980a; Foo, 1982a) poses a number of challenges to management, and the seawater interface is only one of them. Contamination of the aquifer from septic tanks is an immediate problem. Water quality is seasonal, and capping of water extraction is in place to reduce the incursion of saline water.

3.2.6.6 Ngukurr

At Ngukurr in eastern Arnhem Land the main aquifer is fractured Proterozoic bedrock (Summer, 2008). Lateral and vertical SWI is a major issue, requiring immediate reduction in groundwater extraction. Although the aquifer consists of fractured bedrock, incursion is controlled by palaeochannel systems (Summer, 2008).

Table 8 *Summary of literature for areas identified as being vulnerable, or potentially vulnerable, to SWI in the Northern Territory.*

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land/water use
Howard Springs, McMinns & Lambell's Lagoon (Darwin Rural Area)	(EHA, 2007; EHA, 2009; Haig and Townsend, 2003)	Cretaceous metasediments overlying weathered and fractured Proterozoic dolomite	No	Dry season Groundwater extractions exceeding wet season recharge	Water levels; salinity; FEFLOW	No	No	None to Very Low	Domestic; public water supply; horticulture; agriculture
Warruwi* (Goulburn island)	(Foo and Moretti, 1991; Pavelic et al., 2002b)	Weathered Cretaceous sediments	No	Groundwater extractions	Basic hyrogeological characterisation, water banking	No	Yes, water banking and trialing ASR	None to Very Low	Domestic; small gardens
Milingimbi*	(Foo, 1980b; Foo, 1982b; Martin, 1991)	Fractured laterite and Cretaceous sandstone	No	Groundwater extractions	Basic hydrogeological characterisation and simple numerical model; geophysical	No	No	None to Very Low	Domestic; small gardens
Ngukurr*	(Foo, 2002; Jolly, 2002; Moretti et al., 1992; Sumner, 2008)	Fractured Proterozoic bedrock	No	Groundwater extractions; tidal influences	Basic hydrogeological & hydrochemical characterisation	No	No, but considering ASR	None to Very Low	Domestic; small gardens
Milikapiti* (Melville Island)	(Chin, 1992)	Tertiary & Cretaceous sandstones	No	Groundwater extractions	Basic hydrogeological characterisation	No	No	None to Very Low	Domestic; small gardens

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

3.2.7 Queensland

The State of Queensland has by far the greatest number of documented sites where SWI has been reported, including some of the most comprehensive SWI investigations in Australia. The locations include Bribie and Stradbroke Islands, and the Pimpama Coastal Plain, Burdekin River Delta, Pioneer Valley, Bowen and Burnett/Bundaberg irrigation areas. Minor reporting was available for the Mitchell region of Cape York. Additional details follow in the subsections below. For details of all Queensland sites where SWI threat has been acknowledged, refer to Table 9.

3.2.7.1 Mitchell Region of Cape York Peninsula

The Mitchell region traverses the base of Cape York Peninsula. The coastal Tertiary limestone Wyaaba Beds of the Karumba Basin along the western coast of this region were reported by CSIRO (2009b) as having a risk of SWI. The Wyaaba Beds contain limestone aquifers up to 50 metres thick along the present day coastline. According to the CSIRO (2009b) report the community of Pormpuraaw sources its water supply from the Wyaaba Beds, as do several community outstations and cattle stations for domestic and stock water supplies. The Wyaaba Beds aquifers are hydraulically connected to seawater under the Gulf of Carpentaria and tidal influences on the coastal groundwater aquifers were noted by Horn et al. in 1995 (CSIRO, 2009b) suggesting that the coastal aquifers are vulnerable to SWI should groundwater levels continue to decline. The Wyaaba Beds aquifers are confined and receive limited fresh groundwater recharge other than lateral inflow from the east. The current levels of extraction for water supply may be 'mining' the aquifer and promoting SWI, particularly if the groundwater levels of the aquifer were to continue to decline (CSIRO, 2009b). Very little data is available for the region, with few groundwater levels and salinity measurements and monitoring is not routinely undertaken. So there is insufficient data to establish the presence of SWI.

3.2.7.2 Burdekin River Delta

The Burdekin River Delta is located along the central Queensland coastal plain, approximately 80 km south east of Townsville where the Burdekin River enters the Coral Sea (ANRA, 2002). It experiences a tropical climate, with highly variable rainfall that primarily occurs during the summer months. The Burdekin Irrigation area is one of Australia's foremost users of groundwater for irrigation, and is 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 value (SKM, 2009). This site also represents one of Queensland's earliest groundwater irrigation efforts, with the first wells recorded as having been dug in 1884 (http://www.clw.csiro.au/naif/casestudies/ burdekin.html, cited 10 Dec 2009). The region is also unique in that it has a high concentration of wetlands, including the Ramsar–listed Bowling Green Bay Wetland, and it is located adjacent to the World Heritage listed Great Barrier Reef.

Heterogeneous, unconsolidated alluvial and deltaic sediments in excess of 100 metres collectively form the shallow, unconfined aquifer body. These Quaternary-aged sediments comprise a mixture of discontinuous lenses of inter-bedded gravel, channel sands, silt, mud and clay. The lenses are vertically connected and the hydraulic gradient of the watertable is flat (Narayan et al., 2007). Underlying the alluvial and floodplain deposits is the predominantly granitic basement rock. Estuarine deposits with mangrove and tidal muds dominate the marine deposits closer to the present day coastline.

The combined impact of low rainfall and intense groundwater pumping has led to watertables dropping below sea level during drought periods (McMahon, 2004). The areas most under threat of SWI are those closest to the shoreline or tidal estuaries. According to the ANRA (2002) report, saltwater intrusion within the Burdekin River Delta groundwater management unit was highlighted as a problem in 1935 following an extended drought that lasted from 1930 to 1935. This early 1930's drought resulted in extreme reductions in groundwater levels below mean sea level due to excessive extractions, and increased salinity concentrations were noted in the groundwater. The groundwater overdraft situation was finally addressed with the implementation of an artificial groundwater recharge scheme during the severe drought in 1965.

Natural flows along the Burdekin River have been extensively modified for irrigation diversions and returns. Floodplain watercourses and artificial channels are used to reticulate surface water to irrigators and to artificially recharge aquifers with river water; the replenishment of groundwater through artificial recharge has a long history of investigation in the region which is discussed in O'Shea (1967). Although the artificial groundwater recharge scheme has resulted in reducing the over use of groundwater, the groundwater system remains threatened by saltwater intrusion. Tidal barrages have been constructed on the lower delta to restrict the effects of saltwater intrusion into the aquifer and to enable agricultural expansion into formerly tidal areas (NRMW, 2006). An extensive amount of groundwater is extracted from the underlying aquifers and more than 1800 production bores are currently in use for irrigation in the Burdekin Delta; production bores are not metered for use but estimates suggest about 210-530 GL/yr is extracted (Narayan et al., 2007).

An extensive monitoring bore network exists throughout the delta with some records going as far back as 1940. The current monitoring network for the Burdekin River Delta groundwater management unit consists of 268 observation bores (ANRA, 2002). These are currently measured for water level and water quality at 3 monthly intervals. Some bores are monitored more frequently at one month intervals. The monitoring network within the delta is comprised mostly of single and multi-pipe bores drilled to various depths. In the coastal areas, a number of fully screened wells have been installed to define the position of the seawater interface. Current monitoring bore data suggests that the seawater interface extends kilometres inland, placing some inland pumping bores under threat (NRMW, 2006).

McMahon (2004) analysed 30 years of bore monitoring data and used EC data to reconstruct the position and depth of the seawater interface using the 5000 µS/cm isochlor to represent the top of the mixing zone. The data from four continuously slotted observation bores in the delta region were also assessed for an 8 year period in order to evaluate the vertical movement of the seawater interface. The range of vertical movement of the top of the mixing zone was found by McMahon (2004) to vary between 2 to 6 metres. Based on the regional salinity mapping, the interface gradient for bores screened between 10 and 40 metres was typically around 1:200. Accordingly, McMahon (2004) inferred that the horizontal component of SWI could range from 400 to 1200 metres using the Ghyben-Herzberg relationship. The interface was described as sharp (< 7 metres thick) and the toe of the wedge extended up to 15 km inland from Bowling Green Bay to less than 10 km inland from the eastern shoreline. Studies by Lawrie et al. (2004; 2006) gave more spatial detail to the saltwater interface through the use of geophysical data (resistivity and natural gamma electric) collected for 73 bore holes, with additional geomorphic and sedimentary analysis from recently constructed boreholes.

A 2-D vertical cross-sectional SUTRA model was developed by Narayan et al. (2007) in order to define the current and potential extent to SWI in the Burdekin Delta under various pumping and recharge conditions. The results of the study demonstrated the effects of variations in pumping, net recharge rates, hydraulic conductivity and tidal fluctuations on the dynamics of SWI. Their analysis suggested that SWI is far more sensitive to pumping and recharge rates than aquifer hydraulic conductivity. The tidal influence on groundwater levels was limited to very close to the coast and was considered to be a minor influence compared with the effects of groundwater pumping. It was recommended that pumping rates be kept to less than 5-10 L/s in the delta region under the current climatic conditions. The deficiencies in monitoring bores along the saltwater interface were highlighted, which made model validation difficult.

A hydrochemical study by Fass et al. (2007) investigated the origins of saline water from selected monitoring bores. High salinity groundwaters with chloride concentrations up to almost three times that of seawater were found to occur up to 15 km from the present coastline. Carbon isotope analysis indicated that the high salinity waters were between 4000 and 6000 years old. These very saline waters were attributed to transpiration by mangrove forest vegetation during periods of previously higher sea levels. These hypersaline waters, due to their higher density, moved downward through the aquifer and formed a layer of highly saline groundwater at the bottom of the unconfined aquifer. This study highlighted the importance of distinguishing the sources and origins of saline water when conducting SWI investigations.

The Lower Burdekin Initiative (LBI) was formed in 2000 to provide a framework for coordination of the water related research activities that were being undertaken in the Burdekin region by a range of organisations. The Burdekin Water Futures (BWF) group, representing key groundwater management stakeholders, recognised the need to address the emerging threats to the region by underpinning planning and decision-making with sound science. This has led to the development of the Lower Burdekin Groundwater Science Plan, which forms the framework for future investment (SKM, 2009). The science plan identifies key assets and articulates core knowledge needs required to provide a coordinating approach to ensuring lasting economic, environmental and social outcomes in the region. SWI is one of the identified risks, and a number of knowledge needs have been identified within the science plan (SKM, 2009), including to:

- Improve the 3-D understanding of the stratigraphy and salt storages, including the delineation of the SWI boundary (spatially and at depth).
- Develop a set of operational bore field management rules, such as the distance from the coast that production bores are located and their depths and pumping rates, in order to avoid increasing advancement of SWI and to avoid ***upconing***.
- Develop improvements to numerical models, including finer-scale model/s, to assess SWI, up-coning and transport of salts (and agrichemicals).
- Inform a strategic monitoring program, particularly with regards to the location of bores that are used to assess actual water level outcomes against targets and groundwater quality within the coastal SWI/groundwater interface.

The Queensland Department of Environment and Resource Management (DERM) is developing a groundwater modelling toolkit to support the decision making process for water management in the Lower Burdekin. The toolkit will be designed to provide a framework on which various environmental resource management scenarios can be modelled. The toolkit will be based on the MODFLOW 2000 software platform and make use of a range of additional packages as described in Wang et al. (2012). The development of the groundwater flow model for the Lower Burdekin catchment is based on the conceptualisation detailed in the McMahon et al. (2011) report.

3.2.7.3 Bowen Irrigation Area

The Bowen Irrigation Area is located between Townsville and Mackay on Queensland's central coast near the town of Bowen. Situated in the dry tropics, the rainfall is much lower when compared to both Mackay and Townsville. Most of the rainfall occurs between December and March, and exceptionally high rainfall occurs at times as a result of cyclonic influences, leading to periodic flooding of the Don River/Euri Creek delta. The area is also regularly affected by drought.

The regional land use is primarily horticulture and a wide range of crops are grown. The volumes of groundwater used for irrigation far exceed that of surface water because of the unreliability of stream flows. Irrigation is the largest consumer of groundwater in the Bowen area, followed by residential, stock and industry which are relatively minor users. The expansion of horticultural land use around the Bowen area has led to increased groundwater demand and allocation pressures, particularly during the prolonged dry periods. The potential water demand exceeds the available groundwater resources, which are fully committed (Sundaram et al., 2001a; Water Resources Commission, 1988). The potential for overpumping leading to SWI has been identified as a major groundwater management issue (Welsh, 2002).

Sundaram et al. (2001a) summarised a Water Resources Commission (1988) report on the geology, hydrogeology and water resources of the region, and their descriptions follow. The Bowen region is covered by the Cainozoic fluvio-deltaic sediments of the Don River/Euri Creek drainage system, and these sediments overlie a granitic basement that has incised palaeochannels containing highly transmissive sediments. The unconsolidated, Quaternary sediments form the most significant aquifers and they are generally unconfined; sandy; found 4-12 metres below the land surface; and can be up to 18 metres thick, especially within the palaeochannels. Nearer to the mouth of the Don River, a deltaic pattern is evident with mangrove muds in the estuarine coastal zone. Aquifer recharge occurs via direct rainfall accessions, floods and irrigation.

A network of about 260 piezometers has been established by the Queensland Department of Natural Resources and Mines (***QDNRM***) to monitor watertable and salinity levels, including multi-piped bores near the coast to monitor SWI. Water level and electrical conductivity are routinely measured 4 to 5 times a year, increasing in frequency during periods of pumping restrictions. Major ion chemistry is analysed on samples taken on a less regular basis (Baskaran et al., 2001a).

Sundaram et al. (2001b) also assessed hydrogeological, hydrochemical and isotopic data from 41 observation bores and two private bores in the Bowen Irrigation Area, as well as a few samples from the upper and lower reaches of the Don River and Euri Creek during low flows. This investigation confirmed that the highly saline groundwaters near the coast were of seawater origin. Major salinity fluctuations in the near-coastal monitoring bores were noted within the data giving evidence of the historical incidences of SWI. These results provided sufficient evidence to prompt controls on pumping in order to minimise the watertable declines leading to SWI.

According to Sundaram et al. (2001a), there are several management actions currently in place in the Bowen Irrigation Area. These include the licensing, allocation and metering of all bores used for irrigation and stock water, and the subdivision of groundwater management zones according to their hydrogeological characteristics. In addition, groundwater restrictions have been imposed on several occasions to avoid over-pumping. For example, during extended dry periods between 1969 and 1987 groundwater pumping ceased for periods totalling 32 months in order to maintain watertable levels at critical heights to prevent SWI.

A conceptual hydrogeological model was prepared by Welsh (2002) for the Bowen Irrigation area that comprised water balance estimates based on Darcy's Law. The water balance accounting included estimates for: groundwater discharge to the sea, bore water use, river leakage into and out of the aquifer, evapotranspiration, rainfall and irrigation deep drainage, lateral groundwater inflow and groundwater in storage. The area covered approximately 200 km^2, and included most of the Don River Delta and the floodplain. Estimates were made for 28-day periods from July 1989 to the extent of the available data, which varied from 1997 to 2000. Groundwater pumping was reported by Welsh (2002) to be about six times greater than the volume of fresh groundwater that flows out to the sea. During July 1989 to May 1997, the year 2000 groundwater allocation for irrigation of 1600 ***ML*** was exceeded on average by over 11 000 ML per year. Welsh (2002) stipulated that these figures may not accurately reflect current usage because flood irrigation ceased in about 1996 and groundwater usage data were not available beyond 1997.

3.2.7.4 Pioneer Valley

The Pioneer Valley experiences a wet tropical climate with a distinct summer wet season. The land use since the 1980's has been primarily for sugarcane growing, with the major of groundwater irrigation used to supplement rainfall. The groundwater resources are also used by the sugar-milling industry and for urban water supply, stockwater, and farm and rural residential domestic water supplies.

The regional geology comprises Quaternary fluviatile deposits overlying a mostly Palaeozoic basement; sand dunes and marine mud deposits occur near the coastline and estuarine fringes. The coastal plain covers an area of approximately 24 000 ha, and it stores significant groundwater resources within the alluvial sediments deposited by the Pioneer River, Sandy Creek, Baker's Creek and their tributaries. Both Baker's Creek and Sandy Creek are tidal to about 8-10 km inland (Murphy and Sorensen, 2000). The unconsolidated alluvial aquifers are unconfined, show up to three fining-upward sequences and are relatively thin (less than 40 metres in thickness) (Bedford, 1978). Rainfall recharge is the primary source of recharge to the aquifers, with watertables rapidly responding to rainfall events. During reduced periods of groundwater abstraction, groundwater mounds are seen to develop. Excessive groundwater extractions between Sandy Creek and the Pioneer River have altered the hydrology. A large numbers of observation bores have their lowest minimum water level reported to be below mean sea level, increasing the susceptibility of the aquifers to SWI (Murphy and Sorensen, 2000; Werner and Gallagher, 2006). The large tides (6 metres range in spring) and flat topography of the coastal plain have resulted in the tidal limits extending up to 16.5 km inland, and as a result estuarine SWI contributes significantly to coastal aquifer salinisation (Werner and Gallagher, 2006).

The alluvial aquifer system of the Pioneer Valley has palaeochannels in the bedrock which are generally filled with highly permeable, water-bearing deposits, and as such are considered to be preferential groundwater flow pathways (Bedford, 1978; Murphy and Sorensen, 2000). It has been suggested that these palaeochannels may influence saltwater intrusion processes (Werner et al., 2005).

SWI was first recognised in 1975 within the coastal aquifers of the Pioneer Valley, and this led to a regional study of the groundwater resources by Bedford (1978). SWI became a more serious concern in the mid 1990's as a result of below-average rainfalls between 1991 and 1997 and the large increases in irrigation demands. The combination of these factors together with the location of pumping bores close to areas with tidal influence, such as tidal streams, resulted in the deterioration of the groundwater quality in a number of observation bores, particularly to the east of the Bruce Highway which has been labelled a Saltwater Intrusion Area. These concerns led to increased resources being put into groundwater resource and SWI investigations (Cresswell, 2008a; Murphy et al., 2005b; Murphy and Sorensen, 2000; Werner et al., 2005). Pumping restrictions were placed on bores where groundwater levels dropped below 1 m AHD in 1992, and these areas demonstrated increased aquifer recharge during the 1999-2000 wetter years. Despite the increase in aquifer recharge during these years, seawater encroachment is reported to have expanded.

A study by ***AGSO*** (Sundaram et al., 2001b) assessed the hydrochemistry of the Lower Pioneer Valley and their data was incorporated into a broader groundwater study by Murphy and Sorensen (2000) which was focused on developing a groundwater management plan for the Mackay coastal aquifer system in the Eastern Pioneer Valley (data from Sundaram et al. 2001b was made available before their report was completed). Murphy and Sorensen (2000) analysed water level readings and hydrochemical analysis for 72 monitoring bores. Bi-monthly readings were collected in this study for water level and hydrochemical data (field parameters, major and minor ions, and age dating). Murphy and Sorensen (2000) reported that the 1000 µS/cm boundary between 1997 and 2000 had moved further inland, although it was acknowledged that this could be due to the increased data definition from analysing a greater number of monitoring bores and more frequent data collection. They also found that increased EC values were associated with higher groundwater level drawdowns in some areas closer to the coast. Werner and Gallagher (2006) also reported an advancing landward extent of SWI.

In 2005, the Queensland Department of Natural Resources and Mines (NR&M) undertook a groundwater investigation in the Pioneer Valley to develop a framework for the allocation and management of the groundwater resources. One component was to conceptualise SWI in the Pioneer coastal aquifers for the purpose of developing saltwater intrusion models (Werner et al., 2005). Werner et al. (2005) analysed historical water quality monitoring data (e.g. EC, major and minor ions) stored on the NR&M groundwater database to conceptualise groundwater salinisation processes and sources, extents and trends from a regional perspective. The study found that saline groundwater in the Pioneer coastal plain originates principally from marine sources, encompassing both modern SWI and relic seawater. Furthermore, SWI was reported to be characterised by a slow inland movement of highly saline groundwater and a more rapid inland movement of lower salinity groundwater, producing an expanding dispersion zone of brackish water. The areas considered more prone to SWI were situated at the fringes of SWI extent. Werner et al. (2005) also provided recommendations for monitoring and numerical modelling. Cresswell (2008a) reviewed the study by Werner et al. (2005) and refined the position of the SWI interface in the Pioneer Valley based on additional hydrochemical analyses.

A three-dimensional SWI model was developed by Werner and Gallagher (2006) using the MODHMS code to explore regional-scale processes and to aid assessment of water management strategies in the Pioneer Valley. Prior to model development, hydrochemical analysis was used to distinguish the various sources of salinity such as relic or non-marine sources from seawater. A SWI potential map based on hydrochemical mapping, aquifer basement morphology and modified groundwater hydrology as a result of anthropogenic influences was prepared prior to model development, and provided an interpretation of SWI susceptibility that was independent of the modelling (Werner and Gallagher, 2006). The model scenarios developed by Werner and Gallagher (2006) indicated that the assignment of trigger levels (whereby pumping restrictions are based on groundwater salinity and/or elevation levels) required an estimation of tidal over-height forcing of the ocean in order to correctly estimate the coastal hydraulic gradients. This was because of the 6 metres tidal range and shallow beach slope that characterise the area. The influence of tidal over-height and other model parameters were further assessed by Carey et al. (2009) where they reported on the importance of incorporating appropriate near-shore and near-estuary boundary conditions in models of regional groundwater flow in coastal aquifers.

The finite-element SUTRA code was used by Werner and Lockington (2006) to predict density-dependent variably saturated groundwater flow and salt transport in a two-dimensional representation of an estuary–aquifer system. The model was applied to the Sandy Creek alluvial aquifer. The influence of a range of factors was explored, such as aquifer and soil materials, tidal amplitudes, and regional groundwater hydraulic gradients. They found that the density contrast between estuarine water and the fresh groundwater primarily drove saltwater penetration within the aquifer, even in the case of a marked groundwater hydraulic gradient towards the estuary. The tidal fluctuation in the estuary was also shown to influence the groundwater salinity distribution within the aquifer system, and demonstrated that salinity was advection driven. The shape of the dense saltwater wedge propagating into the adjacent groundwater system was also modified by the estuarine tidal signal, although this effect appeared to have only minor influence on the maximum distance penetrated into the aquifer (i.e. location of the 'toe' of the wedge).

The water management plan developed by Murphy and Sorensen (2000) provided a number of recommendations for managing SWI. Some of the key remediation strategies were to:

- Define separate management rules based on trigger points for groundwater level and quality within the designated SWI area (defined where bedrock is located below 0 m AHD in the coastal plain);
- Restrict pumping where the water level drops below 1 m AHD;
- Cease pumping where groundwater salinity reaches a threshold of 3000 μS/cm ;
- Restrict the construction of new bores and the allocation of groundwater in SWI risk areas;
- Abandon bores already affected by intrusion;
- Review the current monitoring networks for location, frequency of sample collection and sampling parameters; and
- Explore artificial recharge and the feasibility of using effluent water from urban and industrial sources as an irrigation water supply.

Water trading also has potential for the management of SWI, and according to Werner (2010a) the groundwater trading rules established by the Queensland Government for the Pioneer Valley will promote the reduced abstraction of groundwater from areas known to be at threat of SWI.

3.2.7.5 Burnett Heads/Bundaberg

The coastal Burnett region is located near the town of Bundaberg, and is situated within the sub-tropics with hot summers and mild winters. Rainfall occurs mostly over the summer months. The dominant land use in the area is sugarcane, as well as associated industries (sugar refining, rum). Horticultural activities are also prominent. Groundwater is the main source of reliable water supply and is used for irrigation, industrial purposes and urban water supply. The Burnett and Elliott Rivers dissect the region into areas referred to as Gooburrum, Woongarra and Barns for water management purposes. To the east is the Coral Sea, the Kolan River to the north and the Gregory River partly bounds the south (Bajracharya et al., 2006).

Groundwater occurs in two main aquifers, the upper Elliott Formation and the underlying Fairymead Beds. The aquifers are comprised of Tertiary unconsolidated to semi-consolidated alluvial sediments unconformably overlying the Lower Cretaceous Burrum Coal Measures basement (Bajracharya et al., 2006). A leaky, aquitard clay layer of variable thickness and distribution lies between the two aquifers and creates a spatially variable hydraulic connection. Rainfall is the primary source of recharge to the unconfined to semi-confined aquifer systems and the quality of the groundwater is generally excellent, 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, with the deepest section being about 80 metres below mean sea level near the coast (Zhang et al., 2004). Accordingly, the risk of SWI is greater within the Fairymead Beds.

The coastal Burnett alluvial aquifer system has supplied water for irrigation and domestic uses since the late 1800's. SWI was first reported in the 1960’s when the high price of sugarcane led to the intense use of the groundwater resources for irrigation. The 1960’s also coincided with drought conditions which led to declining groundwater levels in excess of 5 metres below sea level around the Burnett Heads area (Bajracharya et al., 2006). Zhang et al. (2004) and Dempster (1994) reported that during the period of 1977-79, when rainfall was well below-average, groundwater levels were drawn to levels in excess of 3 metres below mean sea level for a period lasting over 15 months. During this time considerable SWI occurred with increases in salinity up to 50 000 µS/cm observed in some areas. Since the 1988 there have been a succession of drought years and SWI was detected over a greater area. Since the 1960’s it is estimated that 12,500 hectares of land in the Gooburrum area have been lost to SWI and the interface is estimated to be moving at 100 metres per year, primarily within the highly permeable aquifer channels that are in hydraulically connection to the sea (Bajracharya et al., 1998).

In 1970, the Bundaberg Irrigation Scheme was established to provide both surface and groundwater to areas within the defined Bundaberg Sub-Artesian Area in order to reduce the demands on groundwater use; however, despite the overall reduction in groundwater demand as a result of the scheme providing additional surface water supplies, groundwater levels were and are still pumped below sea level in some areas, resulting in ongoing risk of SWI (Bajracharya et al., 2006).

A number of SWI models have been developed for the region in order to assist with assessing groundwater management options. These include a two-dimensional density-dependent, saturated and unsaturated flow and transport model using SUTRA (Bajracharya et al., 1998); a two-dimensional, variable density groundwater and solute transport model using the 2DFEMFAT code (Zhang et al., 2004); two different two-dimensional volume finite-element models (Liu et al., 2006); and a pseudo-three-dimensional, two-layered numerical model using the MODHMS code (Bajracharya et al., 2006).

According to Bajracharya et al. (2006) salinity monitoring began in the mid 1980’s for 146 bores. Additional monitoring bores were installed in 1992 to assess the movement of the saltwater intrusion front in more detail. There is still difficulty in interpreting the SWI in the central Woongarra area due to the poor distribution of monitoring bores. An important consideration in SWI investigations within this area is to distinguish sources of salinity originating from seawater from other sources such as magnesium salts.

The position of the depth-averaged 2,500 µS/cm conductivity contour (the salinity threshold for irrigating sugarcane) for the years 1996, 2000 and 2003 were drawn by Bajracharya et al. (2006) for the upper and lower aquifers respectively, and these have been used to give an indication of the depth averaged concentration SWI front movement. An analysis of the variation in the location of 2,500 µS/cm conductivity contour suggested that the seawater interface has been relatively stable since the announced groundwater allocation system (Bajracharya et al., 2006).

The groundwater reserves within the Bundaberg Irrigation Area are currently over-committed, and this has led to saltwater intrusion into the aquifers close to the coast adjacent to the Elliott River and the Burnett River Delta (RCC, 2004). SWI has been managed in the region in a number of ways over the last 15 years. Annual groundwater extraction volumes have been restricted and are now based on groundwater modelling results with permissible annual limits announced by the Queensland Department of Mines, Energy and Water. In recent years, pumping rates for individual bores have also been limited. According to the RCC (2004) report, this allocation system has been largely effective in controlling SWI, although there have been some instances of increased SWI due to local effects. Further monitoring and modelling are on-going in order to effectively manage the groundwater resources and the use of additional surface water resources has been suggested to replace groundwater use in salt intrusion areas.

3.2.7.6 Bribie Island

Bribie Island is a Quaternary age sand mass aquifer covering 144 km^2 and is located 65 km north of Brisbane. The land use on Bribie Island consists of a National Park, forestry plantations, and residential developments. There are also a number of coastal wetlands nestled within the dune swales. Groundwater extractions for town water supply commenced in 1962 and by 1964 incidences of SWI were reported (EHA, 2005a).

The island consists of a blanket of Holocene to Pleistocene age sand deposits that overlie an eroded surface of Mesozoic sandstone. Groundwater occurs within the unconsolidated sands that range in thickness from 5 to 41 metres. The sand aquifer is generally unconfined, although there are local semi-confining to confining conditions in some areas associated with humicrete layers. The watertable is encountered between 0-1 metres in depth and has a maximum elevation of 6 metres above mean sea level. The salinity values are low apart from near coastal locations or adjacent to waterways with tidal influence. Like all coastal aquifers, Bribie Island is subject to the impact of SWI where the groundwater elevations are reduced by pumping to levels below mean sea level between the coast and extraction site (EHA, 2005a).

EHA (2005a) conducted a desk top study review of the Bribie Island groundwater resources and summarised publicly available information. According to their review, as early as 1964 saline groundwater was noted at depth in the observation bores located closest to the coast, which highlighted the importance of managing groundwater extractions (Lumsden, 1964). Since the Lumsden (1964) study, salinity levels have been steadily increasing in observation bores located adjacent to town water supply pumping bores and trenches where groundwater levels have been dropping in response to extraction.

An artificial recharge scheme using treated sewage effluent was specifically established to prevent SWI at the southern end of Bribie Island. A series of MODFLOW-based groundwater models were been developed to manage the groundwater resources and to assess extraction rates and volumes; this work is on-going. According to the EHA (2005a) report, there is a limited spatial coverage of groundwater monitoring bores from which water level and salinity data is collected on Bribie Island, and this makes it difficult to validate modelling investigations. It was recommended that a network of SWI monitoring bores be established along the western and eastern coasts to augment the existing network and to better define the edge of seawater influence on the aquifer system.

The Bribie Island bore field was relocated to the central part of the island in 2007 and consists of approximately 22 bores that are spread out and extract water at low rates. The old bores field/trench system at the southern part of the island has been abandoned, but sewerage disposal continues in that southern area. This has resulted in overall increased groundwater levels as the recharge mounds limits drainage to the sea (J. Hillier, personal communication, August 2012).

3.2.7.7 Stradbroke Island

Stradbroke Island is dominated by Quaternary unconsolidated sediments, including extensive elevated sand dunes. The Quaternary sediments form a blanket over the Mesozoic sedimentary and volcanic rocks and the Palaeozoic ***metasediments***. The island has a land area of about 267 km^2 (Chen, 2001; EHA, 2005b). The land use is characterised by settlements, sand mining, reserves, and the island is notable for its significant wetlands, lakes and lagoons. Groundwater is used to provide town water supplies, including additional off-island water supply (the island is located about 5 km from the mainland) and it is also used to support sand mining activities. Similar to the situation on Bribie Island, Stradbroke Island is subject to the impact of SWI.

The hydrogeology of Stradbroke Island is described by Laycock (1975) and Chen (2001), and EHA (2005b) conducted a desk top study review of the groundwater resources and summarised publicly available information. These studies indicate that good quality groundwater is stored within the Quaternary dune sands, which can be quite thick and elevated in places reaching a height of 76 metres above sea level. The average depth to groundwater on the island is 16 metres, and the maximum elevation of the groundwater is 50-60 m AHD in the central north of the island, forming a groundwater mound. 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 extractions.

The risks of SWI have been primarily assessed by modelling, with Chen (2001) having developed a model for the whole island using the MODFLOW code. He noted that centralised groundwater extractions from the central groundwater mound would have the least impacts on groundwater levels in coastal areas, but that there was still a risk of SWI in the coastal area due to decreased discharges. The Redland Council production bore fields in the south of the island that extract groundwater for off-island export have shown a downward trend in water levels that are attributed to below-average rainfall conditions. Modelling by Chen (2001) has indicated that if this trend does not alter due to reduced pumping or a major recharge event, then groundwater levels will be drawn down to mean sea level within 8 to 12 years.

Another modelling study by Kaegi (2006) applied the SUTRA code and also analysed hydrochemical data to assess the potential for increased groundwater developments along the eastern shoreline of Stradbroke Island. The results indicated if the swamps in the area were modelled as a permanent feature, they would act as a hydraulic barrier to SWI.

EHA (2009) noted that the island had an insufficient number of suitably constructed groundwater monitoring bores to allow delineation of the seawater interface. The report recommended as a matter of some urgency that the groundwater monitoring system, particularly between the western coast and the Redland Shire Council bore field, be improved for SWI monitoring purposes. The potential use of artificial recharge was also discussed as a management option for SWI.

3.2.7.8 Pimpama Coastal Plain

The Pimpama coastal plain is located between Brisbane and the Gold Coast in southeast Queensland. The region is experiencing a growing population, which is placing increased pressures on the water resources. Groundwater extractions are used for domestic and stock use, as well as irrigation for sugarcane. The low-lying, flat plain has had a number of flood mitigation surface drainage features constructed, such as channelised streams and tidal gates.

The geology has been described in Harbison (2007) as a fluviatile-estuarine plain where unconsolidated, heterogeneous river deposits have in-filled bedrock palaeovalleys. Estuarine and lagoonal muds have been deposited closer to the coast in the region of the flood-tide delta. The combination of sediment heterogeneity, low hydraulic gradients and drainage modifications make this area hydrogeologically complex. Harbison (2007) undertook drilling, geophysical surveys (downhole gamma log, electromagnetic induction, magnetic susceptibility), hydrochemical analysis for major ion chemistry and stable isotopes, and developed a MODFLOW model to further characterise this system. The aquifer systems were separated into an upper unconfined aquifer and a lower semi-confined aquifer located within the gravel and sand river deposits, with little interaction between the two systems. The depth to bedrock is about 60 metres. The elevated potentiometric surface in the deeper semi-confined aquifer suggests upward movement of both saline and hypersaline water, for which provenance was distinguished through their hydrochemistry. Two sources of saline water were identified including a recent seawater source and a relic salinity source presumed to be from Holocene mangrove forests.

Surawski et al. (2005) developed a field-scale SWI simulation model using SALTFLOW for a one dimensional transect. The simulations assessed the impact of groundwater extractions on future chloride concentrations, and they also incorporated physical forcing in the sensitivity analysis for variations in freshwater inflow, sea-level rise and groundwater extractions. The simulations suggested that a serious SWI is predicted to occur near the coastal boundary of the Pimpama coastal plain over the next 20 years.

Table 9 Summary of literature for areas identified as being vulnerable, or potentially vulnerable, to SWI in Queensland.

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land/water use
Burdekin River Delta	(Arunakumaren et al., 2000; Fass et al., 2007; Lawrie et al., 2004; Lawrie et al., 2006; McMahon, 2004; McMahon et al., 2000; McMahon et al., 2002; McMahon et al., 2011; Narayan et al., 2007; NRMW, 2006; O'Shea, 1967; Qureshi et al., 2008; SKM, 2009; Wang et al., 2012; Werner, 2010b)	Quaternary alluvial delta	Yes (ANRA, 2002; McMahon, 2004; NRMW, 2006)	Groundwater extractions; below average rainfall/droughts	Water levels; salinity; theoretical inland extent of SWI using Ghyben-Herzberg; geophysical (resistivity and gamma); geomorphic and sedimentary facies analysis; hydrochemistry (major and minor ion; isotopes); 2D SUTRA; MODFLOW 2000	Yes	Yes; artificial recharge; Lower Burdekin Groundwater Science Plan	High	Sugarcane; wetlands; adjacent Great Barrier Reef
Pioneer Valley	(Bedford, 1978; Carey et al., 2009; Cresswell, 2008b; Murphy et al., 2005a; Sundaram et al., 2001b; Werner, 2010b; Werner and Gallagher, 2006)	Quaternary alluvium; paleochannels in bedrock	Yes (Bedford, 1978; Murphy et al., 2005a)	Groundwater extractions; below average rainfall/droughts; flat topography; large tides (6 m in spring) and estuaries/tidal streams 16.5 km inland	Water levels; salinity; hydrochemistry (major and minor ions; isotopes); mapping of 1000 μS/cm boundary between 1997 and 2000; 3D MODHMS; 2D SUTRA	Yes	Yes; rules based on trigger points for groundwater level and quality within the SWI area; pumping restricted where water levels drop below 1m AHD; cease pumping at 3000 μS/cm; artifical recharge explored	High	Sugarcane; industry (sugar mill) stock, residential domestic

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land/water use
Burnett Heads/ Bundaberg	(Bajracharya et al., 1998; Bajracharya et al., 2006; Dempster, 1994; Liu et al., 2006; RCC, 2004; Zhang et al., 2004)	Tertiary alluvial sediments	Yes (Bajracharya et al., 2006; Dempster, 1994; Zhang et al., 2004)	Groundwater extractions; below average rainfall/droughts; over-allocation of groundwater resources	Water levels; salinity; 2D SUTRA; 2DFEMAT; 2D finite-element models; quasi 3D MODHMS; mapping of 2,500 µS/cm for 1996, 2000, 2003.	Yes	Yes, annual permissible groundwater extraction volumes announced annually; pumping rates limited; further modelling	High	Sugarcane and associated industries
Bowen	(Baskaran et al., 2001a; Baskaran et al., 2001b; Water Resources Commission, 1988; Welsh, 2002; Welsh, 2008)	Quaternary alluvium within bedrock paleovalleys and delta	Yes (Baskaran et al., 2001a)	Groundwater extractions; below average rainfall/droughts; over-allocation of groundwater resources	Water levels; salinity; hydrochemistry (major and minor ion; isotope); water balance calculations based on Darcy's Law	Yes	Yes, Groundwater pumping restrictions during droughts; review of water allocation volumes	Moderate	Horticulture
Stradbroke Island	(Chen, 2001; EHA, 2005b; Gallagher and Leach, 2010; Laycock, 1975; Laycock, 1978; Marshall et al., 2006)	Quaternary sand blanket over Mesozoic and Palaeozoic basement rock	No	Groundwater extractions; below average rainfall/droughts	Water levels; salinity; MODFLOW; SUTRA	Yes (but not SWI specific) – recommend ations made to increase coverage	No, but artificial recharge proposed	Moderate	Town water supply, including off-island; wetlands, lakes, and lagoons; sand mining
Bribie Island	(EHA, 2005a; Jackson, 2007; Lumsden, 1964; Werner, 1998)	Quaternary sand mass	Yes (EHA, 2005a)	Groundwater extractions; below average rainfall/droughts	Water levels; salinity; MODFLOW	Yes (but not SWI interface specific), recommend ations made to increase coverage	Yes; artificial recharge at southern end of island	Low	Town water supply; wetlands

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land/water use
Mitchell region, Cape York	(CSIRO, 2009b)	Tertiary limestone; carbonate massif	No	Excessive groundwater extractions/Groundwater mining	Limited data	No	No	None to Very Low	Domestic supplies for isolated communities and stock water supplies

4. International SWI Literature Review

SWI has a long history of investigation internationally. The earliest documented studies include those by Ghyben (1888) within the Netherlands, and Herzberg (1901) along the North Sea coast in Germany. According to Barlow and Reichard (2010a), Back and Freeze (1983) reported that SWI was recognised as a problem in the United States as early as 1854 on Long Island, New York. Since these first documented studies, incidences of SWI have been reported within all continents (with the exception of Antarctica) and have been observed within numerous countries. Interested readers are referred to Custodio and Bruggeman (1987), FAO (1997), Bear et al. (1999), Cheng and Ouazar (2004) and Werner et al. (2012) for excellent overviews of the international literature pertaining to SWI investigation, modelling, monitoring, and control, with case study examples provided from around the world.

This portion of the literature review is not meant to be an exhaustive review of documented cases of SWI internationally, but rather, it has the specific purpose of providing an overview of international perspectives on the manifestation of SWI and aquifer vulnerability at the regional-scale. In particular, any hydrogeological characterisation or other key system aspects noted within the international literature that might guide the future development of generic typological conceptual models of coastal aquifer settings and aquifer vulnerability at the larger-scale are highlighted.

4.1 Regional-Scale Perspectives

A number of regional-scale reviews of coastal aquifer systems and SWI have been recently published for North America (Barlow and Reichard, 2010b), South America (Bocanegra et al., 2010), Europe (Custodio, 2010) and Africa (Steyl and Dennis, 2010). These papers are summarised below since they provide valuable insights into the larger-scale perspectives on the manifestation and characterisation of SWI within coastal aquifer systems.

4.1.1 North America

A review by Barlow and Reichard (2010b) reported that saltwater has intruded into many of the coastal aquifers of the United States, Mexico and Canada, and that the extent of intrusion and its mechanisms varied with locality and hydrogeological setting. The main aquifer units in the coastal regions of North America were identified as unconsolidated and semi-consolidated silts, sands and gravels of both marine and continental origin; and consolidated rock aquifers such as carbonates (generally limestone), sandstones and fractured crystalline rocks. The coastal groundwater flow systems were found to vary considerably in their climatic setting, areal and volumetric dimensions, length of the flowpaths, number of aquifer layers, and hydraulic connection/disconnection (via confining layers), and accordingly, SWI was reported in widely varying physical settings and contexts. The authors did not attempt to classify the typological settings where SWI was occurring. Rather, the objective of their paper was stated as being to summarise the extent and modes of SWI; to describe the many approaches and tools used to manage SWI; and to comment on the future directions to assess the problem. They provided four case study examples to illustrate the varying hydrogeological settings, causes, and modes by which SWI occurs; the case studies included:

- Lateral encroachment of saltwater into confined freshwater aquifers from surrounding saline zones;
- Vertical migration along fractures and other preferential flow conduits in a carbonate aquifer;
- Regional saltwater intrusion due to large-scale drainage and pumping; and
- Regional intrusion into multi-layer unconsolidated/semi-consolidated aquifer systems.

A number of factors were found by Barlow and Reichard (2010b) to influence the seaward limit of freshwater; the transition zone between fresh and saline water; and the extent of SWI. They also identified varying modes of SWI.

The seaward limit of freshwater in the coastal aquifers was reported by Barlow and Reichard (2010b) to be primarily controlled by: the amount of freshwater flowing through each aquifer; the thickness and hydraulic properties of each aquifer and confining units; the current geographic distribution of saline surface water; and the geological history of global sea-level fluctuations. For example, the confined aquifers along the Atlantic Coast have fresh groundwater that has been found to extend tens of kilometres offshore, and this has been attributed to recharge over the past 900 000 years when sea levels were lower than at present. In contrast, the confined aquifers in southern Florida, exhibit sluggish groundwater flow, and have large inland areas of residual seawater that entered the aquifers during the Pleistocene when sea levels were higher. Inland areas of saline water have also been found near tidal estuaries, where SWI naturally occurs.

The transition zone between fresh and saline water was found to vary from less than 30 metres thick in thin aquifers to as much as 670 metres thick and 60 km wide in confined aquifers along the North Atlantic Coastal Plain where global sea-level fluctuations have caused repeated advance and retreat of the freshwater-saltwater interface. Mixing within the transition zone between fresh and saline water was stated by Barlow and Reichard (2010b) to be caused by hydrodynamic dispersion, which is driven by the spatial heterogeneity in aquifer properties and dynamic forces including tides, groundwater recharge rates and global sea levels, which occur on a range of time-scales from daily to millennial.

The variability in hydrogeological settings and three-dimensional distribution of saline water, as well as the history of groundwater extraction and drainage modification, has resulted in a variety of modes of SWI. These have been categorised by Barlow and Reichard (2010b) as lateral intrusion from the ocean; upward intrusion from deeper, more saline zones of a groundwater system; and downward intrusion from coastal waters (embayments and estuaries), and storm or tidal driven saltwater flooding of coastal lowlands. Saltwater contamination was also reported to occur as a consequence of open boreholes, improperly constructed and corroded wells, and drainage channels, all of which provide pathways for the vertical migration between aquifer systems.

Several factors were noted by Barlow and Reichard (2010b) to influence the extent of SWI into an aquifer, and these included: the total amount of groundwater extraction relative to freshwater recharge to the aquifer; the distance between the locations of pumped wells and drainage channels from the source(s) of seawater; the geological structures of the aquifer system (faults, folds, submarine canyons); the distribution of hydraulic properties and aquifer interconnectivity; and the presence of confining units that may prevent the vertical movement of saltwater.

Groundwater pumping was the main cause of SWI in the North American coastal aquifers, with SWI particularly noted in the areas where groundwater resources are heavily exploited for agricultural or urban/town water supply. Other lesser causes of SWI included the lowering of watertables by drainage canals and urbanisation (paving of drainage features and installation of pipes which reduce groundwater recharge).

A range of actions to manage SWI have been undertaken and can be broadly grouped into scientific monitoring and assessment, engineering techniques, and regulatory approaches. Due to the often complex pathways of saltwater movement, Barlow and Reichard (2010b) stated that in the future more accurate three-dimensional system characterisation and modelling will be required to predict and manage the dynamics of SWI. Further investigations into how SWI may be affected by potential rises in sea level due to climate change will also need to be undertaken and addressed by water managers.

4.1.2 South America

A comparative analysis of 15 coastal aquifers in South America was undertaken by Bocanegra et al. (2010) in order to gain insights into the current state of knowledge in terms of hydrogeological characteristics, identified problems, extent of studies, and management efforts to guide sustainable groundwater management. These sites were selected based on the available published literature as a desk top study, and form part of the IGCP 519 UNESCO funded project still underway on the hydrogeology, hydrochemistry and management of coastal aquifers on the Atlantic Coast of South America.

Similar to the cases reported within Australia , there were widely varying degrees of information available and documented management practices for their coastal aquifer systems - ranging from no data and no management (the most common case in South America), to considerable data, robust aquifer characterisation and conceptualisation, and sound groundwater management practices. The better studied and managed coastal aquifer systems were those perceived as having the greatest economic importance because they provide urban and peri-urban water supplies and/or provide irrigation water for agriculture.

Three main types of groundwater bodies were identified by Bocanegra et al. (2010): 1) large-extent, coastal aquifers of regional importance; 2) small, clastic aquifers of local interest; and 3) small island aquifers. A table was prepared that summarises the main aspects of the 15 aquifer systems investigated, and it included information on the aquifer location, hydrogeological characteristics, identified problems, and management actions. Nine of the 15 aquifers studied reported problems due to SWI, and were found amongst all three types of groundwater bodies. A description of the characteristics of the three main aquifer systems follows.

The large-extent coastal aquifers are found within coastal sedimentary basins and have a mixed depositional environment characterised by numerous aquifer units. The units tend to comprise: 1) multi-layer, unconsolidated sands, silts, clays and carbonates; 2) unconfined to confined sandstones (with clay and calcareous horizons); and 3) alluvium of variable depth with confined sands and gravels. The main feature of these systems is the competition for water (and land) between urban, industrial and agricultural uses, particularly in the more populated areas. These aquifers are commonly intensively exploited and they are subject to SWI of varying modes and pollution. However, due to the large extent of the aquifer systems they tend to be poorly studied.

The small clastic aquifers of local interest tend to have the greatest perceived economic and social importance. These aquifer systems are generally found in shallow, dune sand and beach deposits; silty-sandy loessic sediments; unconfined alluvial deposits underlain by a thick sedimentary sequence. Given the local importance of these aquifers and their compact size, they tend to be well studied in terms of their hydrodynamics, groundwater quality and aquifer vulnerability. Aquifer management programmes such as the use of treated waste-water for artificial recharge and irrigation, as well as pumping controls have been carried out in some areas to manage SWI.

The small island aquifers are also intensively exploited for water supply, commonly for tourism. Their small dimensions make it difficult to define the aquifer boundaries, particularly because of the intense water use that mobilises water from a range of formations. These aquifer systems include vulcanites, karstified limestone and consolidated calcareous silts. Common to these islands are the intensive groundwater use; SWI; and a lack of resource planning and management. Although, in some island areas groundwater management actions to address SWI have been undertaken, detailed hydrogeological information is still often scarce.

The use of groundwater in South America is irregularly distributed throughout the continent. In areas where groundwater is intensively used by the local population and/or for tourist developments, groundwater levels have been drawn down in the coastal aquifer systems and this has led to SWI. In the more intensively developed regions, particularly within the small clastic aquifer systems, actions to address the remediation of SWI have included artificial recharge, modifications of pumping regimes and water supply bore relocations. In the scarcely inhabited coastal areas, few studies exist. The lack of pressure on these more remotely located groundwater resources suggests that they are unlikely to experience any major SWI problems in the near future as a consequence of human activity.

According to Bocanegra et al. (2010), some of the challenges in the management of the South American coastal aquifers include the lack of policy and regulatory frameworks by which to manage the groundwater resources, as well as the lack of funding for hydrogeological investigations and education. Within the review, no mention was made of the potential risks of climate change and rising sea levels on SWI and aquifer vulnerability.

4.1.3 Europe

Europe has a long history of investigating SWI since the late 19th century. The lengthy European coastline is heavily populated and many of its coastal aquifers are intensively developed. The heavy use of groundwater resources has led to the reporting of SWI in many locations. The European coastal aquifers are used to provide domestic, urban and industrial water supplies, and during the summer months the aquifers may become highly stressed, particularly in the Mediterranean region, as a consequence of the use of groundwater for seasonal irrigation and domestic water supply for tourists (Wriedt and Bouraoui, 2009). Because of the importance in maintaining their coastal aquifer systems, annual saltwater intrusion meetings have been held in Europe since 1968. Some of the best studied European aquifers in terms of SWI investigations are found in the Netherlands, Belgium, southern Italy and northeastern Spain (Custodio, 2010).

The Custodio (2010) overview of European coastal aquifers describes the regional geology as variable and complex, and accordingly, a wide range of hydrogeological settings, scales and modes of SWI were reported. This was also the case for the North American and South American coastal aquifer systems. In order to illustrate some of the common characteristics of Europe’s coastal aquifer systems, Custodio (2010) presented four hydrogeological type settings. These included: 1) deltaic areas; 2) detritic coastal formations; 3) carbonate coastal massifs and 4) small islands. A brief overview follows.

The deltaic areas are found in the lower reaches of rivers where the rate of river-contributed sediments exceeds their dispersion by the sea tides and current. Eustatic changes in sea level have highly influenced the hydrogeological characterisation of these systems, particularly in terms of the varied depositional environments due to the sea-level fluctuations associated with glacial-interglacial events. A number of significant aquifer formations of deltaic origin were deposited during the last low sea-level stand, when sea levels were between 100-120 metres below present day levels. During periods of seawater regression, river flows began to erode the underlying rocks and sediments and created river valleys. These river flows led to the deposition of alluvial sediments and they become freshwater aquifers under low sea level conditions. During periods of transgression, with rising sea levels, coastal sediments were often deposited under saline water conditions. These transgressive and regressive sequences alternated throughout the Quaternary, and led to the development of aquifers of varying salinity – from freshwater aquifers through to saline and hypersaline brine aquifer systems. These, often juxtaposed, aquifer systems of varying salinity are prone to SWI under poor groundwater management practices. Intensive groundwater development, land subsidence and land reclamation drainage schemes have all contributed to SWI.

The detritic coastal formations include those systems other than the deltaic and carbonate systems. They include Quaternary to Mesozoic age formations that comprise coral-reef deposits, coarse piedmont and alluvial fan deposits and palaeodune sands. The aquifer systems vary in size from small, localised units through to large formations. As is the case for the deltaic systems, sea-level fluctuations have also influenced the hydrogeology of the detritic systems. Consequently, the detritic coastal formations may hold palaeowaters, including both freshwater and relic seawater, in addition to recently recharged freshwater and seawater. In the piedmont and alluvial fan coastal deposits, seawater may form wedges that deeply penetrate the coarser, more permeable sediments that outcrop at sea. This may occur under natural conditions and/or as a result of groundwater pumping. SWI primarily tends to occur in the low elevation aquifer units that are intensively exploited; or else in aquifer units that are close to the shore, or disturbed by dewatering civil works.

Carbonate massifs of Mesozoic and Cainozoic age are commonly found along the Mediterranean coast. These formations may be karstified with enlarged cavities extending down to 100 metres below present day sea level or more. Groundwater commonly discharges at the shore or offshore at shallow depths, and large springs are often found along these coastal systems. Incidences of SWI within carbonate massifs are well documented. The hydrogeology of carbonate systems is often complex, and similarly, so are the variation in the modes of SWI. Groundwater development of carbonate massifs tends to be concentrated in the more permeable regions of the massif, as otherwise the yields may be too low. In order to avoid saline water upconing, groundwater bores are commonly drilled or excavated to depths that only just penetrate the watertable, and the pumping rates are kept low. Horizontal drilling is commonplace in order to skim the fresh groundwater that sits at watertable level above the underlying saline layer. Because surface supplies of freshwater are often scarce in karstic areas, the groundwater resources tend to be overexploited. This is particularly the case when the groundwater resources are exploited for irrigation, as well as to meet the demands of a large, seasonal influx of tourists.

The geological setting of the islands comprises volcanic, crystalline and metamorphic rocks, as well as carbonate dominated islands. The island settings often support large populations and intense agricultural and tourist activities. In some areas, they may also have significant industrial activity. The presence of surface water is often limited on islands, and consequently the groundwater resources are heavily exploited, especially near the shore. The sustainability of the groundwater resources is a key management issue because extractions are usually excessive, often leading to SWI. Various management options have been implemented to reduce the pressure on the island groundwater resources, including the reuse of treated wastewater and desalinisation of seawater and brackish water in order to provide an alternate water supply to groundwater. In some cases, freshwater may be piped from the mainland where the island is located close by.

A range of locally varying actions have been taken to manage SWI in Europe including scientific, engineering and regulatory approaches. The European Union Water Framework Directive, including the 2006 Daughter Groundwater Directive (European Commission, 2000), makes it a legal requirement for aquifer systems within the EU Member states to achieve the good quantitative and qualitative status by 2015. This will require well-documented studies, including those pertaining to SWI as a result of human activity. In some areas such as southern Europe, the Atlantic Ocean archipelagos and the Mediterranean islands, where the pressures on the groundwater resources are large as a consequence of agricultural activity and tourism, and where there may not have traditionally been much understanding of resource sustainability, this poses a serious challenge.

Wriedt and Bouraoui (2009) undertook large-scale screening of SWI risk along the Spanish Mediteranean coast. Their two-tiered approach involved an assessment of the balance of recharge and extraction, followed by application of the methods of Strack (1976) to calculate steady-state SWI responses to pumping stresses. As geological data did not support an assessment of individual 'true' coastal aquifers, a calculation of abstractions and recharge was carried out for a set of hypothetical aquifer domains of different size and repeated in regular intervals along the coastline.

4.1.4 Africa

Africa shares a number of similar characteristics to Australia. Both continents have most of their population clustered within major cities located along the coast, and both have a highly spatially and temporally variable rainfall pattern that includes extended periods of droughts.

Unlike Australia, the instability of the governments within many African countries has led to poor water management practices and the failure to meet the basic human needs for freshwater. The instabilities have also resulted in disputes over water supply amongst neighbouring states and the severe over-exploitation of water resources as a consequence of war. For example, the war in Somalia destroyed a considerable amount of wells and water supply infrastructure. Consequently, the supply of water from the few remaining intact wells in the capital city of Mogadishu was distributed by entrepreneurs using a donkey car system which led to the over-exploitation of the groundwater resources and led to the occurrence of SWI within the local aquifer system (Steyl and Dennis, 2010).

The coastal aquifer systems within Africa are described by Steyl and Dennis (2010) as having developed according to their tectonic and climatic environments, and consist of folded, continental and alluvial deposits. These are described below:

Folded zone aquifers: The folded zone aquifer areas occupy 3 % of the continent but support 10 % of its population. These aquifers types are found in South Africa, where they are composed of Palaeozoic limestones, sandstones, quartzites and shales; and they are also found in the northwest of the continent in the Atlas fault zone where they comprise Jurassic and Cretaceous aged limestone and dolomite carbonate aquifers.

Continental aquifers: The continental aquifer systems are found over an extensive area within the African platform and interact with the coastal regions. Six major aquifer systems were identified according to their lithology including: continental sandstone, carbonate, sandstone-carbonate, alluvial, basaltic and crystalline basement aquifers.

Alluvial aquifers: The alluvial aquifers are of Neogene and Quaternary age and occur in the sedimentary and coastal basins. The Congo basin and Nile River alluvial deposits are examples of these types of aquifer systems.

There was no attempt by Steyl and Dennis (2010) to further characterise the aquifers and associated management problems according to hydrogeological type-setting. Rather, the continent of Africa was divided into four main sections (north, east, south and west) consistent with regional characteristics and local cooperation agreements in order to facilitate discussion of the region in a systematic way.

According to Steyl and Dennis (2010), the more arid regions within Africa, particularly in the north, south and eastern Horn of Africa regions, have a high reliance on the groundwater resources in order to meet their domestic, urban-industrial and agricultural requirements. For example, some areas within Tunisia and Eritrea obtain more than 95 % of their water from groundwater sources, and the rate of groundwater abstraction often far exceeds the amount of freshwater recharge. In Egypt and Libya, for example, where the groundwater resource is mined, the rate of extraction exceeds recharge by more than 400 %. Not surprisingly, the over-development of aquifer systems has led to widespread SWI throughout much the coast of Africa, leading to a substantial loss of well production in some areas; although, in many cases no substantial information exists due to the lack of financial, technical and social resources.

Some of the key factors noted in leading to SWI within Africa's coastal aquifer systems include the over extraction of groundwater resources as a consequence of climatic factors - such as droughts, low rainfall recharge, and the high reliance on groundwater resources within an arid region - together with increasing and unfettered rates of groundwater development for urbanisation and agricultural expansion leading to a decline in groundwater levels. For example, a lowering of the watertable on the order of 20-50 metres per decade has been noted in the Algerian coastal aquifers. More generally throughout the Maghreb countries (Morocco, Algeria, Tunisia), groundwater levels have been reported to be reaching 'alarming levels' of drawdown. The damming of river systems, such has occurred in Kenya and Tanzania to provide water and electrical supplies, has also been implicated with SWI along the lower reaches of coastal river systems (Steyl and Dennis, 2010).

According to Steyl and Dennis (2010) the importance of protecting groundwater aquifers within the coastal zone and cross boundary cooperation is becoming recognised amongst the African nation states. Groundwater monitoring programs are becoming more commonplace in some of the coastal cities in order to intervene if water quality deteriorates, and a national monitoring network has been established in South Africa. Several artificial recharge schemes are being implemented to address SWI in South Africa and Namibia. The African Union has committed itself to addressing the water security issues of the continent and is working towards establishing national strategies on water management and monitoring, which have been lacking for most of the countries.

5. National and state data review

5.1 Data required

An important component of the project is to review and collate the existing national and state baseline datasets that are of relevance to a national-scale vulnerability assessment of SWI. This can be time-consuming and resource-intensive, as data requirements are comprehensive and need to be sourced from multiple agencies. Typical datasets and their sources have been provided in Table 10 as an initial starting point to investigate the datasets required for the project. After a comprehensive data review, much data appropriate for the project was found to be available. An outline of all datasets available and their sources follows in the subsections below, and is summarised in Appendix 1.

Table 10 *Typical datasets and sources.*

Hydrologic	
• Climate (e.g. rainfall, evapotranspiration, zones) • Groundwater elevation • Tidal information • Groundwater quality (e.g. salinity and major ion chemistry) • Groundwater recharge/discharge • Groundwater extraction and sustainable yield information	• Climate databases • Groundwater monitoring databases • Coastal and climate databases • Water quality databases • Scientific literature, unpublished reports • Unpublished reports and other publically available resources
Hydrogeologic	
• Bore survey (e.g. location, elevation, construction, intake screen depth, stratigraphic logs, aquifer extent and thickness) • Aquifer properties (e.g. hydraulic conductivity, saturated aquifer thickness, ***porosity***) • Geology • Geophysics (airborne radiometrics, magnetics, gravity, downhole conductivity and gamma logs, AEM)	• State agency groundwater databases • Hydrogeological maps, scientific literature, unpublished reports • Geological maps • Reports, state agency databases
Physiographic	
• Geomorphology • Soils • Beach slope • Topography/ bathymetry • Surface water features • Land use and water infrastructure • Vegetation maps (e.g. mangroves) • Ecosystem maps	• Coastal geomorphic maps • Soil maps • Coastal mapping (OzCoasts) • Topographic maps, Spot heights, DEM's, LiDAR • Drainage, streams and waterbody datasets • Land use and topographic maps, remote sensing, State agency databases, catchment authorities, unpublished reports • Stage agencies, consultant reports • Stage agencies, consultant reports

5.2 Datasets available

As mentioned above, fundamentally, the first step in assessing SWI vulnerability is to collect the datasets that are considered to be of critical importance to a SWI investigation. The existing national and state datasets collated for the project are summarised in Appendix 1. In some instances, only selected datasets or parts of datasets may be required for analyses. For example, datasets can be clipped to 15 kilometres inland from the coast, where regions are most affected by SWI. The datasets available for use in the project, as well as additional datasets identified for further investigations, are outlined below.

5.2.1 National-scale hydrogeology map

National-scale hydrogeology datasets are available from the 1:5 000 000 hydrogeology map of Australia (Jacobson and Lau, 1987b). Principal aquifers have been classified within the national-scale hydrogeology map as either porous or fractured types, depending on whether the porosity is primarily inter-granular or fractured; the aquifers have also been subdivided into their extent and productivity.

5.2.2 Groundwater data

Groundwater data from bores located within 15 kilometres of the coastline have been collected from state and territory water agencies. The key datasets include groundwater monitoring information such as bore survey data (e.g. coordinates, surface and reference elevation), groundwater levels, groundwater salinities, and groundwater extraction information (licensing and extraction volumes). The length of record of time-series groundwater-level, salinity and extraction data varies across the states and the Northern Territory. In addition, extraction and sustainable yield information has been compiled from Australian Water Resources 2005 (AWR, 2006). The collected groundwater data has been processed and filtered where possible to remove erroneous measurements for subsequent use within all project components.

5.2.3 Climate data

The Köppen-Geiger system of climate classification (Peel et al., 2007) 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 was made available for the typological development component of the project.

5.2.4 Rainfall

Historical monthly rainfall data has been collected from the Bureau of Meteorology website (http://www.bom.gov.au/climate/data/index.shtml) for rainfall stations that represent the CSAs. The annual rainfall and the calculated cumulative deviation from the mean monthly rainfall were plotted for the selected sites over the historical record to further investigate the impacts of rainfall on groundwater levels.

5.2.5 Digital Elevation Model data

National-scale Shuttle Radar Topographic Mission (SRTM) 1-second (30 m) digital elevation model (DEM) data have been collected in this project for use to classify the coastal area within the 15-kilometre inland buffer to identify flat, low-lying areas below 15 m AHD.

5.2.6 Population

Population census data were collected from the Australian Bureau of Statistics (ABS) website for locations that represent the SWI case study areas (Australian Bureau of Statistics, 2007).

5.2.7 Tidal range

National tidal records were collected from the National Tidal Centre (NTC). The following three tidal ranges were considered in this project:

- microtidal range = < 2 m
- mesotidal range = between 2 and 4 m
- macrotidal range = > 4 m.

These tidal ranges were assessed within the development of the qualitative indexing method.

5.2.8 Geology

National geology datasets were collected from the Geoscience Australia 1:1 000 000 geology map (Raymond and Retter, 2010) in order to identify principal aquifer types. The geology datasets were found to have shortcomings when used to identify the principal aquifers and were therefore not used in the coastal aquifer typology.

5.2.9 Groundwater salinity

The 1: 5 000 000 hydrogeological map of Australia (Jacobson and Lau 1987) included a groundwater salinity map of the principal aquifer systems. The groundwater salinity datasets have been used to identify the more elevated salinity regions along the coast (> 5000 mg/L).

5.2.10 Hydrogeomorphic mapping

National-scale geology and landform datasets were collected from the 1:5 000 000 national-scale hydrogeomorphic map of Australia (GA and BRS, 2007) in order to identify the principal aquifer types. The datasets were found to have shortcomings when used to identify the principal aquifers and were therefore not used in the coastal aquifer typology.

5.2.11 Additional datasets

The following datasets were identified in Phase 1 of the project (Dixon-Jain et al., 2010), and were incorporated into the final methodology to varying extents. These are presented below to introduce possible extensions to the approach in the future.

- Coastal depositional environment: national-scale coastal geomorphology data have been accessed through the Ozcoasts website (http://www.ozcoasts.org.au/). Coastal depositional environments information has been used in the development of a coastal aquifer typology to a limited extent (Ivkovic et al., 2012a).
- Detailed bore data (some of which was incorporated into the coastal aquifer typology assessment (Ivkovic et al., 2012a) and vulnerability factor analysis (Cook et al., 2012): construction information; bore location and elevation; intake screen depth)
- Land use and surface features, e.g. extent of urban areas, forestry, agriculture, vegetation, location of drains and other relevant infrastructure. The land/groundwater use has been briefly described within the SWI state and territory reviews in this report (refer to Tables 3 to 9).
- Groundwater usage volumes and general dependency of communities and ecosystems on coastal groundwater systems. Extraction to recharge ratios have been assessed within the qualitative indexing component of the project (Norman et al., 2012).
- Aquifer status such as sustainable groundwater yield assessments
- Geophysics, remote sensing, refer to Lawrie et al., (2012)
- Hydrogeologic classification of the coast: this information is very useful to understand SWI vulnerability but was not incorporated into the final methodology. Appendix 5 provides a comprehensive examination of coastal hydrogeologic classifications in Australia and how they may impact on SWI vulnerability.

6. Method Development

The aim of this project is to assess the vulnerability of coastal aquifers in Australia to SWI. To achieve this aim, an appropriate and robust method is required. The previous chapters in this report have described the concepts of SWI, the current status of SWI knowledge in Australia and internationally, and the datasets that are available to be utilised for SWI investigation in Austraila. The assessment of SWI vulnerability is not straightforward, because there is often confusion concerning the precise definition of the term 'vulnerability' and there is no single way of conceptualising and assessing vulnerability (Hinkel and Klein, 2006). This chapter will define vulnerability, discuss stakeholder engagement input to the project and provide details of some of the ways in which aquifer vulnerability to SWI has been assessed within the existing literature. The vulnerability assessment approaches evaluted include: using a vulnerability factor analysis, typological approaches, mathematical analysis and SWI vulnerability indexing. The culmination of this chapter 'Summary of method development' outlines the suggested approach, based on the investigation of previous methods, suitable for assessing SWI in Australia.

6.1 Definition of Vulnerability

A definition of vulnerability used by the United Nations International Strategy for Disaster Reduction (UN***ISDR***) is 'the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard' (http://www.unisdr.org/eng/terminology/terminology-2009-eng.html; cited February 2010). The word 'hazard' has been defined by the UNISDR as 'a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage'. The 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). Vulnerability is stated as being a function of exposure, sensitivity and adaptive capacity, and for a 'complete' assessment the values of items, systems, infrastructure, etc., should also be taken into consideration and assessed (Voice et al., 2006).

The use of the term 'vulnerability' in the field of hydrogeology was originally used by Margat (1968) in the context of assessing the potential for groundwater contamination, and consequently, much of the groundwater literature on vulnerability assessment pertains specifically to aquifer contamination. Vrba and Zaporozec (1994) defined vulnerability in relation to groundwater systems as the intrinsic properties of a groundwater system and its susceptibility to natural and/or human impacts. A similar definition was proposed by Chachadi et al. (2003) for the specific case of SWI. They proposed that the vulnerability of groundwater to seawater 'pollutants' or intrusion be defined in agreement with the recommendations of the International Conference on the Vulnerability of Soil and Groundwater to Pollutants, held in The Netherlands in 1987 (van Duijvenbooden and van Waegeningh, 1987), as: 'the sensitivity of groundwater quality to an imposed groundwater pumpage and/or sea-level rise in the coastal belt, which is determined by the intrinsic characteristics of the aquifer'. This definition has not been uniformly accepted, and according to Gogu and Dassargues (1998), 'hydrogeologists have failed to reach a consensus concerning the definitions of and reference terms for groundwater vulnerability assessment.' 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".*

As one can see from the range of definitions above, the term vulnerability encompasses a broad spectrum that could include communities, as well as the systems and assets susceptible to an adverse effect/hazard. As Klein and Nicholls (1999) have stated, "vulnerability to impacts is a multi-dimensional concept, encompassing biogeophysical, economic, institutional and socio-cultural factors".

There are numerous definitions of vulnerability, ways of conceptualising vulnerability, and methods for assessing vulnerability described within the journal literature, and variations exist amongst different research communities and even within the same research community (Füssel, 2007). The different terminologies and conceptualisations of vulnerability have become confusing and problematic, particularly in climate change research for example, where collaboration occurs amongst different research traditions. Such problems arise because there may not be a shared or comparable framework or assessment methodology and this can lead to misunderstandings and the inability to compare research findings.

In order to ensure clarity about the current project goals and objectives, it is worth making clear the proposed definition and conceptual framework regarding vulnerability for use in this investigation. Moreover, this clarity will be required to ensure that this investigation is comparable to other SWI vulnerability investigations at regional/State scales.

6.2 Vulnerability Framework

The vulnerability framework proposed for this project is based on the work of Füssel (2007), who after reviewing a broad range of vulnerability definitions and concepts developed a generally applicable framework of vulnerability that included six dimensions. The first four dimensions were considered to be fundamental to *describing* any vulnerable situation and include (Füssel, 2007):

i. **System**: The system of analysis.
ii. **Attribute of concern**: The valued attributes of the vulnerable system that is threatened by its exposure to a hazard.
iii. **Hazard**: A potentially damaging influence on the system of analysis.
iv. **Temporal reference**: The point in time or period of interest (current, future, number of years into future etc.).

In the context of the current project, the specific vulnerability that will be assessed is the vulnerability of Australian freshwater coastal aquifers (*system*) to water quality salinisation (*attribute*) as a consequence of the position of the freshwater-saltwater interface (*attribute*) in the present, and into the future as a consequence of climate change (e.g., sea-level rise and recharge-discharge variations) and groundwater extraction (*hazards*).

The following two dimensions according to Füssel (2007) are used to describe the vulnerability factors (or risk factors) when *conceptualising* vulnerability. These additional two dimensions include:

i. **Sphere**: Whether the vulnerability factors are internal to the system itself, and are therefore intrinsic properties of that system, or whether the factors are external to the system.
ii. **Knowledge domain**: The origin of knowledge from socioeconomic and/or biophysical factors.

The sphere and knowledge domain are interdependent and can be combined into four categories which comprise the key factors considered important to assessing the vulnerability profile of a particular system at a given point in time. These are shown in Table 11 (adapted from Füssel (2007)), which provides some examples of the vulnerability factors that might be of relevance in a SWI vulnerability assessment. Assessing the vulnerability of Australia's coastal aquifers to SWI is inherently linked to the availability of coastal aquifer data at appropriate temporal and spatial resolutions. The specific vulnerability factors selected for inclusion within this project require were outlined in Figure 2.

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).

Table 11 *Examples for each of the four categories of vulnerability factors according to the sphere and knowledge domains (after Füssel, 2007)*

Sphere	KNOWLEDGE Domain	
	Socioeconomic	Biophysical
Internal	Community income dependant on groundwater use; population density; access to information; social networks; community values of coastal groundwater and understanding of SWI drivers/consequences	Coastal topography; aquifer properties; groundwater elevation; distance from coast; recharge/climate; land use (i.e. natural vegetation, farming, urban areas)
External	National policies; catchment management plans; best-practice guidelines; economic factors	Climate change-induced recharge variations and sea-level rise; pumping infrastructure; extraction; management and operation of bore fields; land management practices

6.3 Stakeholder engagement

To develop the most appropriate method for assessing SWI vulnerability in Australia, engagement with our project stakeholders was both necessary and desirable. Hydrogeologists and natural resource managers from representative state/territory agencies and from the National Water Commission provided input into the development of this project. Stakeholders also provided some essential feedback that led to the refinement of the project methodology, for example by guiding the selection of case study areas and validating the interpretation of hydrogeological data within the project, throughout each phase. The result of a stakeholder workshop, conducted in May 2010, is provided in Appendix 2.

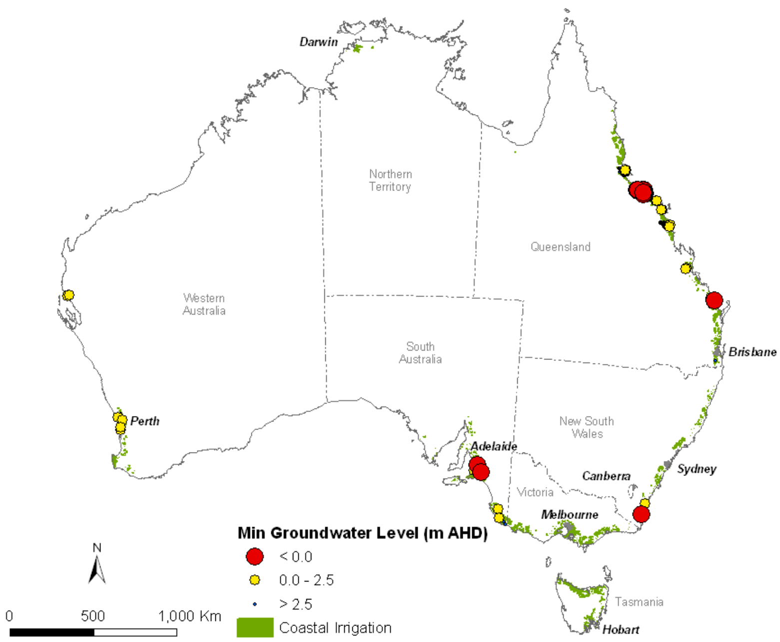
6.4 Methodologies to assess coastal aquifer vulnerability

Many different methodologies can be utilised to assess vulnerability and the utilisation of multiple methods enables a myriad of SWI-related processes to be considered. The project ultimately proposed five streams of 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. These are discussed further below.

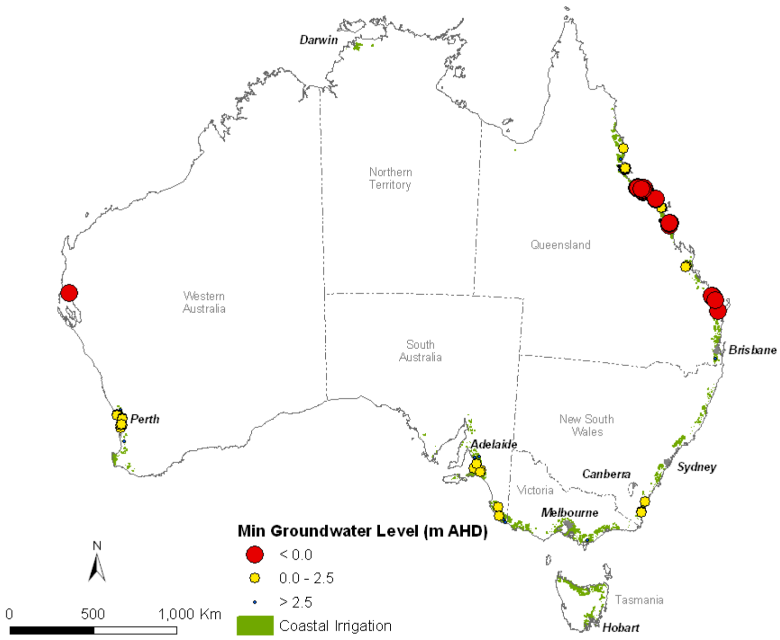
6.4.1 Vulnerability Factor Analysis

Fundamentally, the first step in assessing SWI vulnerability is to collect the datasets that are considered to be of critical importance to a SWI investigation. These datasets may be analysed in various ways, e.g. to obtain both spatial and temporal trends, to inform the vulnerability of the system to SWI. The first stream of technical assessment was to undertake a vulnerability factor analysis (VFA).

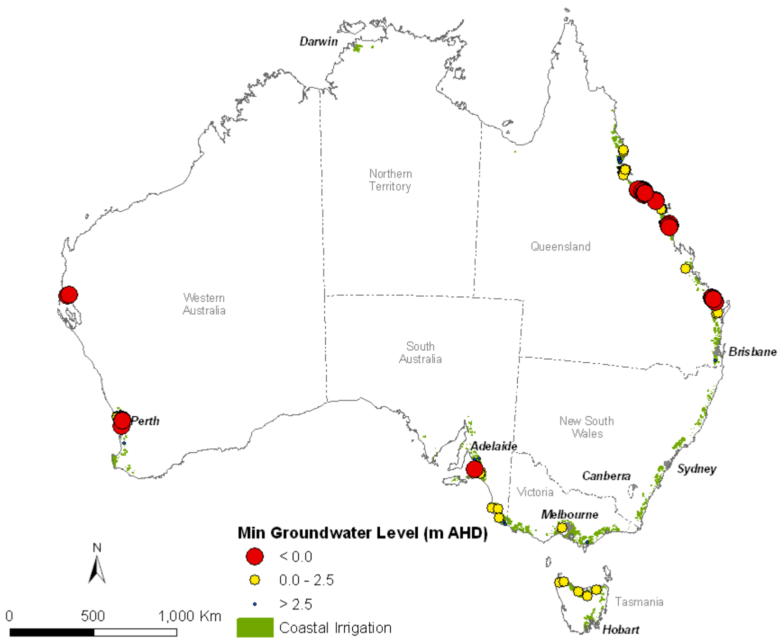
Many of the datasets collected for the project (outlined in Chapter 5.2 and summarised in Appendix 1) are able to be analysed within a GIS, using a similar approach to that adopted by Nation et al. (2008) who spatially analysed point data pertaining to minimum groundwater elevation and maximum groundwater salinity to infer SWI vulnerability in Australian coastal aquifers used for irrigation supplies. This analysis was based on groundwater levels, salinities and other selected vulnerability factors. Certain vulnerability factors may be analysed to assess temporal trends, e.g., decadal changes in water level or salinity, in order to better understand historical aquifer behaviour and the associated SWI threat. Simple examples of vulnerability factor mapping are shown below in Figure 7. These examples assume that trends of decreasing groundwater elevation, or groundwater levels at or below sea level, are associated with an elevated threat of SWI. This approach was extended by Cook et al. (2012), within the VFA technical component of the project.



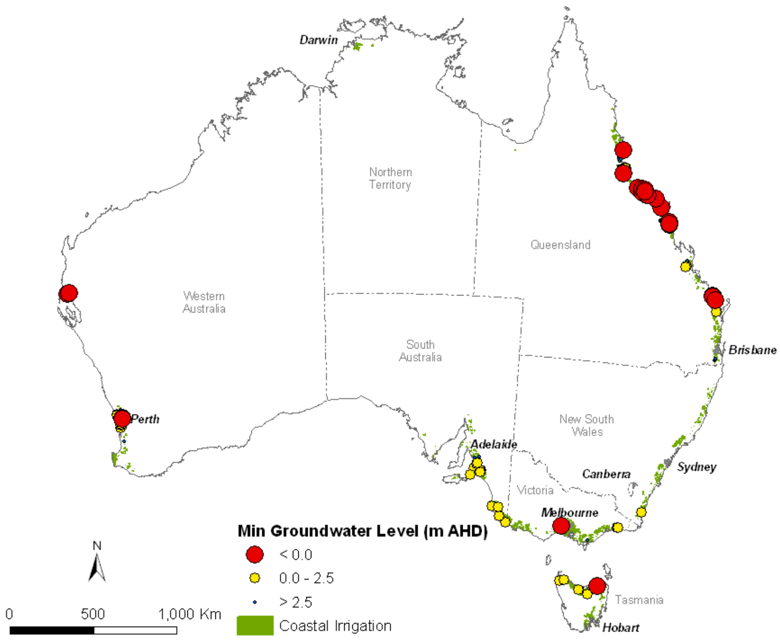
1970-1979



1980-1989



1990-1999



2000-2008

Figure 7 *Decadal changes in groundwater heads (results from Nation et al., 2008)*

6.4.2 Coastal Aqufier Typology

The second stream of technical assessment for the project was to develop a coastal aquifer typology. 'Typology' is the study, analysis or classification based on type (Bokuniewicz et al., 2003). A typological assessment is typically undertaken in an attempt to classify environments into groups based on physical, structural or other functional similarities. After developing a systematic categorisation, a typology should allow for a framework that can be used for scaling local investigations to the larger regional-scale where direct observations may be lacking (Bokuniewicz, 2001) using surrogate information to infer processes. The purpose for developing a coastal aquifer typology for 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. In order to evaluate how such an approach might be taken within Australia, some pre-existing typological conceptualisations are reviewed. This section includes general typological approaches and provides a description of a groundwater flow systems approach and hydrogeomorphic mapping approach.

FAO (1997) stated that various classifications of coastal aquifers can be made, but that a general classification system was difficult to give. Custodio and Bruggeman (1987) reported upon a study undertaken by Luk'yanova and Kholodilin in 1975 that classified coasts according to morphological origin, including the percentage coastal area of: mountain, tablelands and plateau, glaciated, alluvial, marine and others (FAO, 1997). Another typological approach is to characterise the aquifer systems where fresh groundwater resources are exploited. For example deltaic systems, coastal sand dunes and barrier islands have been described by Custodio (2010) for European coastal aquifers (refer to Section 0). Bocanegra et al. (2010) used a different typology and categorised the groundwater bodies of South America into large-extent coastal aquifers of regional importance; small, clastic aquifers of local interest; and small island aquifers (refer to Section 0).

The attempt by Bokuniewicz (2001) to develop a coastal typology for estimating the volumes of potential submarine groundwater discharge (SGD) along the world's coasts is also of relevance to the current study. Bokuniewicz (2001) envisaged three approaches to the development of a typology based on 1) physical/climatological parameters (e.g. precipitation, soil type etc.); 2) geomorphic-geologic classes (e.g. karst, coastal plain etc.); and 3) a collection of state parameters (aquifer thickness, hydraulic gradient, anisotropy etc.). This research was undertaken as part of the Land–Ocean Interactions in the Coastal Zone (LOICZ) Program, which is a core project of the International Geosphere-Biosphere Programme. Some of the preliminary results based on cluster analysis of various selected variables for the development of a SGD typology are presented in Bokuniewicz (2003). There are clear links between SGD and SWI, because SGD is arguably the primary factor controlling the extent of the freshwater-saltwater interface, and therefore a typology of SGD has considerable relevance to the current project, which also attempts to classify coastal hydrogeological systems. Further, considering SGD within the context of SWI vulnerability may offer advances in coastal aquifer management practices, because the rate of SGD has a major bearing on the influence of groundwater pumping on the freshwater-saltwater interface position, and subsequently on the volumes of groundwater available for pumping. Therefore, SWI management could consider the maintenance of SGD rather than only considering coastal aquifer recharge volumes, although SGD management would be a paradigm shift for coastal aquifer management in Australia.

Additional information contribute to the development of a coastal aquifer typology could include the geological settings and geomorphic depositional environments of the Australian coast (discussed further in Appendix 3). The hydrogeological characteristics and other knowledge gained from the review of Australian SWI case studies (Section 3.2) would ideally be combined with hydro/geological characteristics, coastal zone geomorphic attributes, and other key factors, to build an understanding of Australian coastal aquifer systems. These possibilities were further explored within the first and second phases of the project.

There were two existing typological approaches developed for use in groundwater investigations within Australia. These include the Groundwater Flow Systems approach, which was adopted by the National Land and Water Salinity Audit, and the Hydrogeomorphic Mapping approach which has been proposed by GA to map potential surface-groundwater connectivity across Australia. These are further discussed in the sections below because of their potential relevance to the development of a typological approach for classifying Australian coastal aquifers, in the second phase of this project.

6.4.2.1 Groundwater Flow Systems approach

The Groundwater Flow Systems (GFS) classification (Coram et al., 2000) is based on recharge and flow behaviour, and uses measures such as length of flow paths through aquifers, aquifer permeability and driving pressure gradients to assess groundwater flow systems. The framework characterises 'similar landscapes in which similar groundwater processes contribute to similar salinity issues, and where similar salinity management options apply' (Coram et al., 2001b). Twelve GFS have been mapped in Australia based on nationally distinctive geological and geomorphological characteristics such as elevation, geology and landform.

GFS can be classified as local, intermediate or regional based on their spatial extent and influence and flow paths (Figure 8). This terminology should not be confused with that used in classic groundwater textbooks for the nested flow systems of groundwater basins. Rather, local, intermediate and regional GFS are described by their response rate to hydrological change caused by alteration to the natural environment (http://new.dpi.vic.gov.au/vro, cited 7 April 2010).

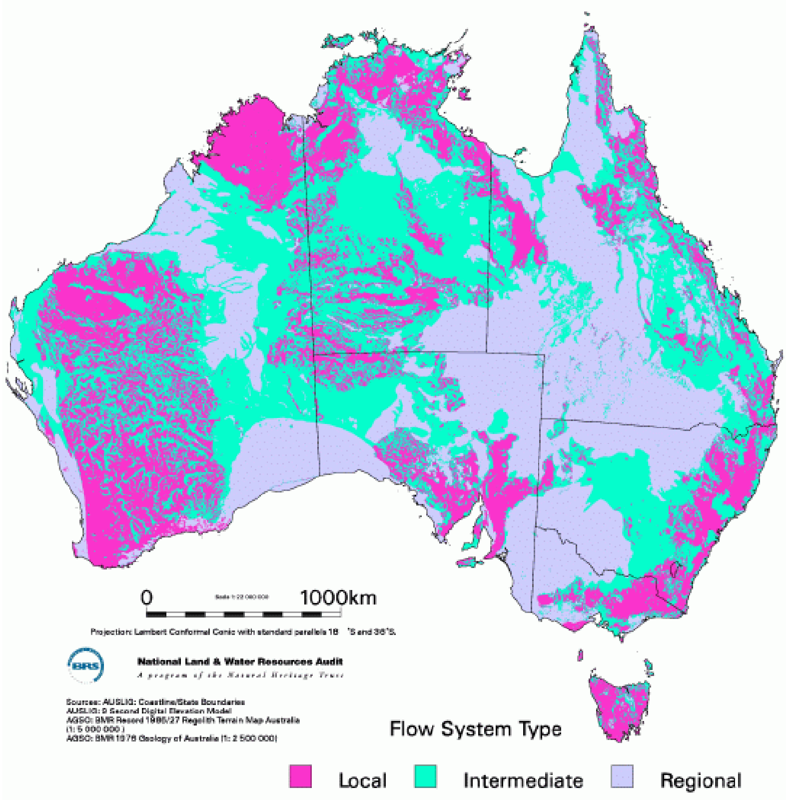


Figure 8 *Australian Groundwater Flow Systems classifications (after Coram et al., 2000).*

The extent of the system has implications for its responsiveness to a change in the water balance and therefore influences the types of management options that are appropriate for modifying the water balance. In some areas, flow systems may be superimposed or physically linked. Each system has a unique combination of attributes, and yet each system is composed of different landscapes with other variable characteristics.

Local groundwater flow systems have recharge and discharge areas within a few kilometres of one another and tend to occur in areas of high relief such as foothills to ranges. These systems respond rapidly to increased groundwater recharge; watertables rise rapidly and saline discharge typically occurs within 30 to 50 years of clearing of native vegetation for agricultural development. These systems can also respond relatively rapidly to salinity management practices, and afford opportunities to mitigate salinity at a farm-scale.

Intermediate groundwater flow systems have a greater storage capacity and generally higher permeability than local systems. These systems tend to occur in valleys and typically extend for 5-10 km horizontally. They take longer to 'fill' following increased recharge. Increased discharge typically occurs within 50 to 100 years of clearing of native vegetation for agriculture. The extent and responsiveness of these groundwater systems present much greater challenges for dryland salinity management than local groundwater flow systems.

Regional groundwater flow systems are characterised by laterally extensive aquifers (recharge and discharge areas separated by > 50 km) and have a high storage capacity and permeability. They occur in areas of low relief such as alluvial plains. The aquifers are usually wholly or partly confined, and can be overlain by local and intermediate flow systems. They take much longer to develop increased groundwater discharge than local or intermediate flow systems – as great as 100 years after clearing of native vegetation; the full extent of change may take thousands of years. The scale of regional systems is such that farm-based catchment management options are ineffective in re-establishing an acceptable water balance. These systems require widespread community action and major land use change to secure improvements to the water balance.

While the GFS approach was primarily developed for assessing land-based salinity risk and management, the methodology considers hydrogeological, topographical and responsiveness to recharge/climatic factors – which are also important in the assessment of SWI vulnerability. An example of the application of the GFS within Victoria is provided below because, in addition to providing a land-based salinity risk assessment, the GFS approach was used to highlight flow systems at risk of SWI.

The GFS approach (Coram et al., 2000) was applied to a study in the Port Phillip and Westernport Catchment Management Authority region in Victoria (Dahlhaus et al., 2004) to characterise landscapes in which similar groundwater processes contribute to similar salinity risks. In order to conceptualise groundwater flow in each GFS, the Victorian study devised a classification system based on the GFS definition in the Audit (NLWRA, 2001), the Evaluation Framework (Coram et al., 2001b), and additional descriptive information, to provide an historical and landscape context to each system. The four broad categories considered in the classification included:

1. Landscape (geology, topography, land systems, regolith, annual rainfall, dominant vegetation, dominant land uses);
2. Hydrogeology (aquifer type, hydraulic conductivity, aquifer transmissivity, aquifer storativity, hydraulic gradient, flow length, catchment size, recharge estimate, temporal distribution of recharge, spatial distribution of recharge, aquifer uses);
3. Salinity (groundwater salinity, salt store, salinity occurrence, soil salinity rating, salt export, salt impacts); and
4. Risk (soil salinity hazard, water salinity hazard, assets at risk, responsiveness to land management).

The Victorian study identified a number of GFS in coastal settings that might be prone to SWI. These regions included the Nepean Bay Bar Barrier Dunes (local flow system); the Swamp and Back-Dune Wetlands (local and intermediate flow systems); and the Werribee Delta (local and intermediate flow system) (Figure 9). While the original GFS classification and the more holistic method exemplified by the Victorian GFS study were primarily developed for assessing terrestrial or landscape salinity risk and management, the framework could also be modified and applied to characterise coastal aquifers in the context of SWI vulnerability.

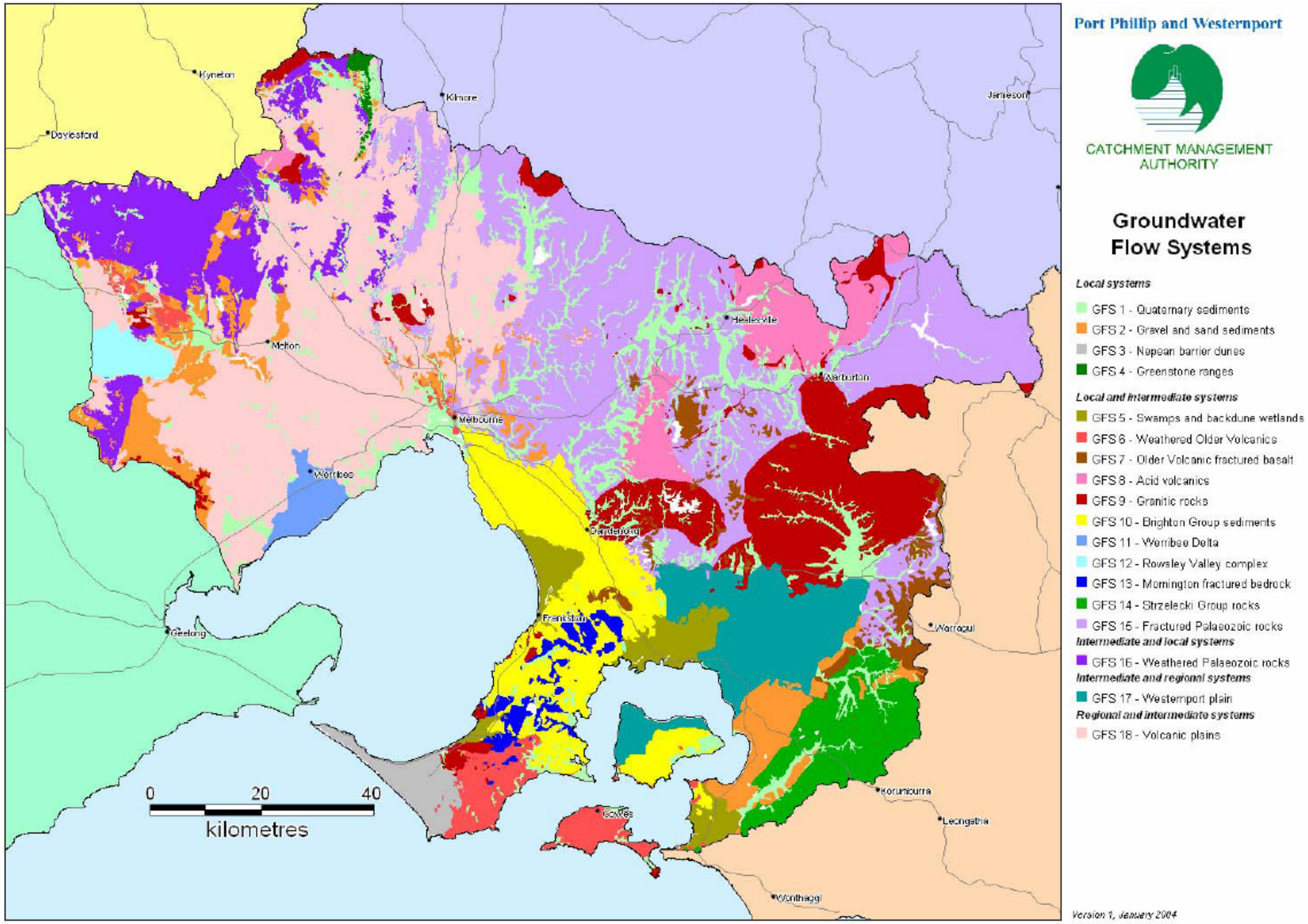


Figure 9 *Groundwater flow systems in the Port Phillip and Westernport Catchment Management Authority region (after Dahlhaus et al., 2004).*

6.4.2.2 Hydrogeomorphic mapping approach

The hydrogeomorphic mapping approach (GA and BRS, 2007) is based on the three variables of geology, landform (topography) and climate. At a national level this approach effectively captures the continental variation in hydrogeology, topography and climate. The lithological characteristics of the aquifer and its hydraulic properties are critical in controlling the magnitude and dynamics of groundwater systems. Topography is a key driver that influences the scale of the groundwater flow systems and the hydraulic gradient. Climate controls the volume and seasonality of recharge to the aquifer. This mapping approach has been developed for mapping potential groundwater-surface water connectivity in Australian catchments, and of course, would require modification for a SWI typology.

Table 12 summarises the broad-scale hydrogeomorphic framework proposed for the range of geological, climatic and landform characteristics across Australia (GA and BRS, 2007) for the specific purpose of assessing connectivity between surface water and groundwater systems (i.e., excluding seawater-groundwater interactions and SWI). The framework is presented in matrix form, where geology and landform are combined into geomorphic categories and correlated with each climate zone. At the national-scale, the resulting 21 combinations of geomorphology and climate represent unique hydrogeomorphic settings (HGM).

Table 12 *Matrix of Australian hydrogeomorphic settings based on climate, geology and landform (after GA and BRS, 2007).*

	Temperate	(Semi) Arid	(Sub)Tropical
Fractured Rock Upland	Temperate Fractured Rock Upland	(Semi) Arid Fractured Rock Upland	(Sub) Tropical Fractured Rock Upland
Deeply Weathered Terrain	Temperate Deeply Weathered Terrain	(Semi) Arid Deeply Weathered Terrain	(Sub) Tropical Deeply Weathered Terrain
Contained Sediment Valley	Temperate Contained Sediment Valley	(Semi) Arid Contained Sediment Valley	(Sub) Tropical Contained Sediment Valley
Broad Sediment Plain	Temperate Broad Sediment Plain	(Semi) Arid Broad Sediment Plain	(Sub) Tropical Broad Sediment Plain
Layered (Volcanic) Complex	Temperate Layered (Volcanic) Complex	(Semi) Arid Layered (Volcanic) Complex	(Sub) Tropical Layered (Volcanic) Complex
Sedimentary Basin	Temperate Sedimentary Basin	(Semi) Arid Sedimentary Basin	(Sub) Tropical Sedimentary Basin
Karst	Temperate Karst	(Semi) Arid Karst	(Sub) Tropical Karst

The seven geomorphic categories are broadly representative of the key geological and topographic provinces across the continent, and are mappable at a national-scale using consistent datasets. The seven categories are:

1. *Fractured rock upland* - steeply sloping to undulating eroded bedrock hills, ranges and plateaus, with narrow stream valleys and minor floodplains;
2. *Deeply weathered terrain* - bedrock hills, plateaus or undulating terrain with extensively developed weathering profiles; may be mantled by aeolian deposits;
3. *Contained sediment valley* - relatively narrow (typically < 10km) alluvial floodplains and terraces commonly bounded by fractured or weathered upland basement;
4. *Broad sediment plain* - flat to gently undulating expansive depositional plains, commonly with large low-angle alluvial fans and meandering or deltaic distributary drainage;

5. *Layered (volcanic) complex* - layered, multiple or geologically complex systems such as volcanic plateaux and plains;
6. *Sedimentary basin* - large sedimentary sequences with regional groundwater flow systems. Commonly mantled by alluvial, aeolian or colluvial veneer; and
7. *Karst* - landscape formed by the dissolution of carbonate deposits such as limestone or dolomite, characterised by sinkholes and underground drainage.

Figure 10 shows the spatial distribution of hydrogeomorphic settings across Australia based on the matrix of hydrogeomorphic classes in Table 12 above. At the broadest level, the national hydrogeomorphic map represents the variation in landform, hydrogeology and climate across Australia.

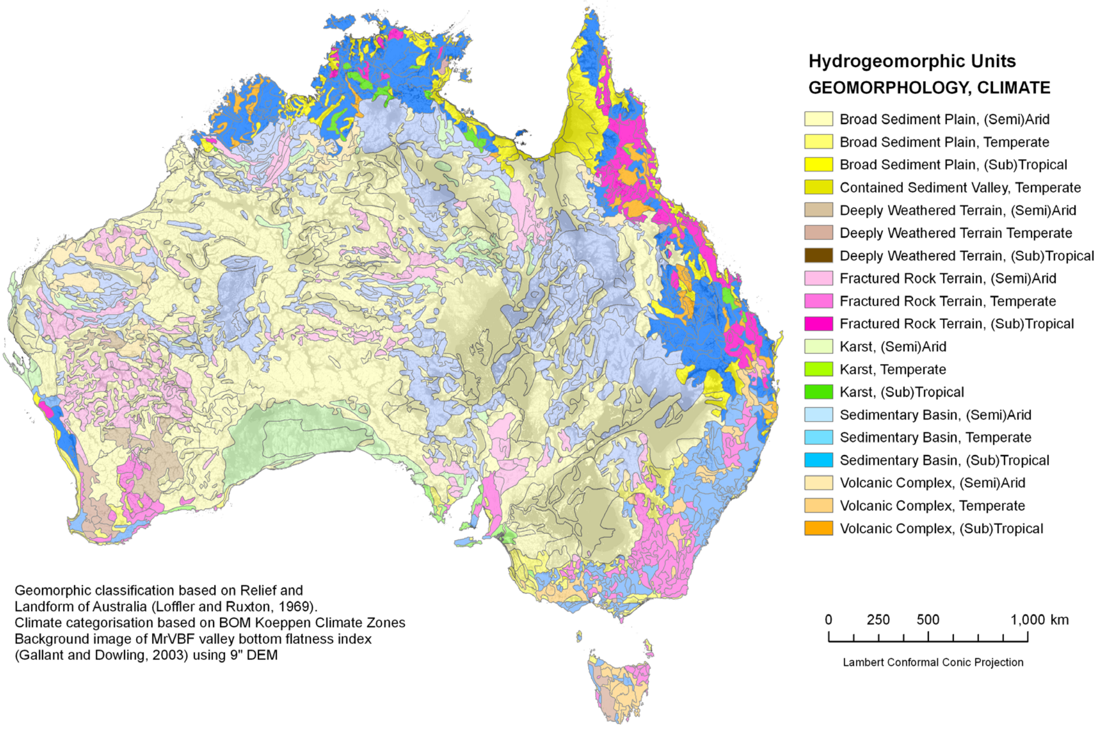


Figure 10 *National hydrogeomorphic settings for Australia*

While the hydrogeomorphic mapping approach described above was specifically developed for mapping potential groundwater-surface water connectivity, this type of approach gives an example of how a typological framework might be applied within an assessment of SWI vulnerability at a national-level. The proposed methodology for assessing SWI vulnerability in the current project aims to utilise a geological and geomorphological characterisation as the basis for subdividing the coastal zone into unique aquifer settings, for the purposes of comparing and contrasting SWI vulnerability in a range of typical Australian conditions. These concepts were further developed, as discussed in Ivkovic et al. (2012a).

6.4.3 Mathematical Analysis

The third stream of technical assessment for the project was mathematical analysis of SWI vulnerability. Quantitative methods for interpreting coastal aquifer data to infer freshwater-saltwater interface characteristics and changes, and also for predicting future SWI trends, can be subdivided into categories of:

1. Sharp-interface approaches
    1.1. steady-state analyses by application of analytical solutions and
    1.2. transient analyses using numerical methods;
2. Dispersive interface approaches using numerical methods.

The approaches under (1) typically presume vertical homogeneity within hydrostratigraphic units and are therefore considered quasi-3D/2D and 1D (i.e. the vertical dimension contains only an interface depth and not vertical gradients). Sharp-interface methods often depend on the Ghyben-Herzberg approximation, which presumes that saline groundwater within the wedge is motionless and that pressures along the interface equate to the forcing hydrostatic loading of the ocean (i.e. there are no head losses within the saline wedge). Strack (1987) offers comprehensive coverage on sharp-interface approaches to SWI assessment. Codes like SWI (Bakker and Schaars, 2005) allow for simplified modelling of transient SWI using the sharp-interface approximation combined with MODFLOW analysis of groundwater flow aspects.

There are many codes that simulate dispersive SWI. Leaders in the field include FEFLOW (Diersch, 2002), and SEAWAT (Langevin et al., 2003). Considerations in the selection of dispersive SWI simulators include the code's capacity to simulate unconfined aquifers (i.e. and associated unsaturated zones), numerical robustness and stability, access to graphical user interfaces as well as model accuracy and software support availability. Models that are based on MODFLOW (e.g. SEAWAT, MODHMS) are typically designed to simulate large-scale SWI, although the predictability of dispersive SWI and the associated pollution of production bores at the regional-scale is somewhat unknown (Sanford and Pope, 2010).

Ultimately, the selection of a quantitative method for SWI analysis will depend on available resources, time and expertise. The complexity of the coastal aquifer will also impact on model choice, because some situations are not amenable to the application of highly simplified approaches (e.g. methods assuming homogeneity may not apply to karst aquifers involving strong preferential salinisation pathways). SWI is a complicated process, and therefore a simple method that builds intuition is encouraged in the first instance prior to complicated investigations that potentially incur substantial investments of time from suitably qualified hydrogeologists/modellers. Investment in complex modelling efforts and associated programs of monitoring and field-investigation should be guided by preliminary simple sharp-interface analysis as a minimum. Where water resources management is involved, SWI modelling requires strong field-based interpretation of salinity and water level trends, across space and time domains, above and beyond that of most other hydrogeological investigations. Importantly, a conceptualisation of SWI is needed that identifies the key coastal aquifer processes leading to changes in freshwater-saltwater interface positions, including both lateral movements and up-coning, and also the sources of groundwater salts, i.e. modern versus relic seawater, terrestrial versus marine salt sources. As such, modelling may be used to assist in elucidating SWI processes at the local-scale prior to embarking on a regional SWI assessment, because the latter may have limited local-scale resolution of salinity dynamics (include saline groundwater influx into individual bores), but rather may serve to offer basin-scale trends of interface movements and also allow for estimates of the volumetric influx of seawater into the coastal aquifer under different pumping regimes. It is uncommon that the salinisation of individual bores can be accurately simulated for large coastal aquifers involving expansive bore fields, and so localised modelling, perhaps developed using localised meshrefinement methods may serve to assist in the management of high value infrastructure and water resources.

The reader is referred to various key texts on SWI investigation that include guidance on SWI modelling. These include Custodio and Bruggeman (1987), FAO (1997), Bear et al. (1999) and Cheng and Ouazar (2004).

The mathematical component of the project was further developed for use in the project as discussed in Morgan et al. (2012).

6.4.4 SWI Vulnerability Indexing

The fourth stream of technical assessment for the project was to incorporate qualitative and quantitative SWI vulnerability indexing. The datasets and factors contributing to SWI vulnerability discussed in previous sub-sections largely coincide with the factors considered important within the FAO (1997) report on characterising the vulnerability of coastal aquifer systems to SWI, namely:

- Coastal evolution: sea-level transgressions and regressions and subsidence
- Sea behaviour: storm surges, wave action, tidal regimes, sedimentation
- Climate and hydrological regimes
- Occurrence of freshwater resources
- Socio-economic activities
- Distance between the coastline and vulnerable areas
- Time lag (for example between sea-level rise or groundwater pumping and SWI)
- Geometry of aquifer and its characteristics

Data pertaining to the groundwater conditions and other vulnerability factors need to be analysed giving due consideration to the complex nature of SWI. That is, SWI manifests differently across the broad range of geological settings, and SWI occurs through varying modes. For example, the processes that lead to up-coning and lateral SWI have uniquely different salinisation mechanisms, and accordingly the spatial and temporal scales may also be very different. One also needs to consider that the salinisation of a single bore may be indicative of a localised influence rather than more regional aquifer salinisation due to SWI. These types of considerations will need to be taken into account in designing and applying the proposed vulnerability methodology. Further, the design and application of the project's vulnerability methodology will be underpinned by the evaluation of the hydrogeological conditions (including the results of typological and modelling analyses) of Australia's coastal aquifers.

There is a number of vulnerability indexing approaches that have been published for use within SWI vulnerability assessments. These are outlined in the section below as a starting point for achieving the current project's objectives of assessing SWI vulnerability.

Some of the methods for vulnerability evaluation include computing a vulnerability rank and index from hydrogeological, morphological and other aquifer characteristics in some well-defined way (Lobo-Ferreira, 2000). These approaches have the potential advantage of minimising the subjectivity in ranking the vulnerability of regions (Lobo-Ferreira, 2000) and could be used within this project to evaluate the influences of a number of selected vulnerability factors.

6.4.4.1 Classical approaches to vulnerability mapping

A range of vulnerability mapping approaches based on indices have traditionally been used to map the vulnerability of groundwater to contamination, such as DRASTIC (Aller et al., 1987) and GOD (Foster, 1987). The DRASTIC method, which is one of the most widely used groundwater vulnerability mapping methods, assesses: **D**epth to watertable; net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone, Hydraulic **C**onductivity. The GOD method assesses the **G**roundwater occurrence (i.e., whether the aquifer is unconfined, semi-confined, confined, etc.); **O**verall aquifer class in terms of degree of consolidation and lithological character; **D**epth to groundwater table or strike (Lobo-Ferreira, 2000). The thickness and properties of the unsaturated zone, amongst other hydrogeological factors, are important factors in assessing the likelihood of a contaminant reaching groundwater when using the DRASTIC or GOD method. However, these classical groundwater vulnerability approaches are challenging to apply in the case of a SWI vulnerability investigation. This is because although SWI can be considered as the contamination or pollution of a freshwater aquifer, the processes that lead to the migration of the freshwater-saltwater interface are different to the processes that lead to the migration of a contaminant such as fertilisers or pesticides from the land surface through to the subsurface and into an aquifer. However, either the DRASTIC or GOD method could be modified to include other parameters of relevance to a SWI investigation, for example, by replacing depth to groundwater with groundwater elevation as in the case of the GALDIT method described below.

6.4.4.2 GALDIT indexing method

The GALDIT indexing method was specifically developed by Chachadi and Lobo-Ferreira (2001) for the purpose of assessing the spatial vulnerability of hydrogeological settings to SWI. This method was originally developed for use in India in order to assess the vulnerability of their coastal aquifer systems to SWI. Many of the coastal aquifer systems of the Indian sub-continent have been under considerable stress as a consequence of agricultural, industrial, urban and tourist related activities. Groundwater withdrawals have led to continually declining groundwater levels within many regions, and SWI has been reported within the maritime states of Andhra Pradesh, Gujarat, Orissa, Tamil Nadu and West Bengal (Chachadi et al., 2003).

The acronym GALDIT is formed from the parameters used within this index-based assessment method, and they include:

- **G**roundwater occurrence (aquifer type; unconfined, confined and leaky confined);
- **A**quifer hydraulic conductivity;
- Groundwater **L**evel relative to sea level;
- **D**istance of site from seawater;
- **I**mpact of existing status of SWI in the area (defined by the hydrochemical ionic ratio of $Cl/(HCO_3+CO_3)$; and
- **T**hickness of the aquifer system being mapped.

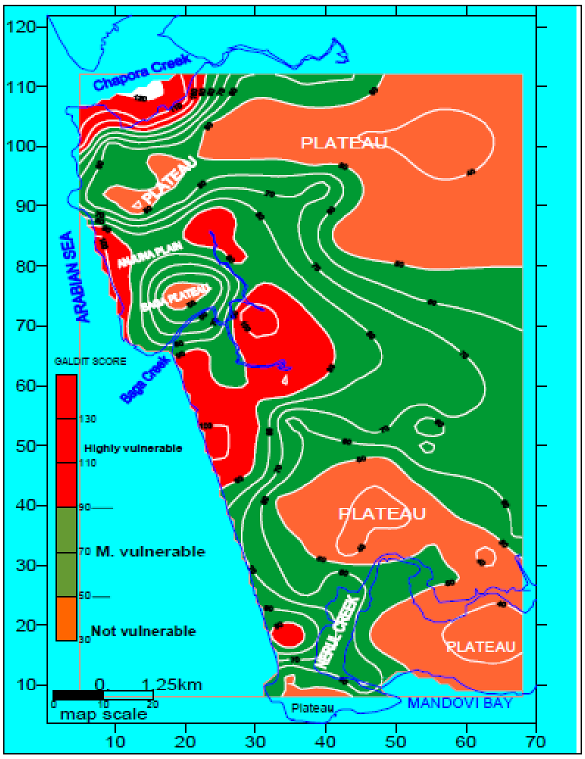


Figure 11 *GALDIT vulnerability map for the North Goa Coast (after Chachadi et al., 2003)*

These parameters, in combination, were reported by Chachadi et al. (2003) to comprise the key factors required to assess SWI potential within a hydrogeological setting. Each factor is assigned a relative weighting and a rating. The weightings are pre-determined, and given a value from 1 to 4. The ratings, ranging from 1 to 10, are obtained from a look-up table. The data values for the area of investigation are used to assign the rating, whereby the lower the value of the weighting and rating, the lower is the influence of the factor. A local index of vulnerability is calculated by multiplying each rating by their weighting and summing all six products. The indices range from a minimum value of 13 to a maximum value of 130, and the GALDIT index score corresponds with one of four vulnerability classes ranging from not vulnerable to highly vulnerable.

The GALDIT method was applied to the coastal region of North Goa (Figure 11) in order to assess the impact of a 0.5 metre sea-level rise on the extent of the SWI area (Chachadi et al., 2003), and more recently has been applied by the same authors to the Portuguese Monte Gordo aquifer (Chachadi and Ferreira, 2007; Ferreira et al., 2007).

The GALDIT method is a somewhat subjective method in terms of the applied ratings, weightings and assignment of vulnerability index, and the authors themselves state that the index provides a relative tool rather than absolute answers. A number of the factors selected for the GALDIT method correspond with the factors identified by Barlow and Reichard (2010b) that influence the extent of SWI, such as the aquifer type and its properties, and the distance from the seawater source. However, the rate of groundwater withdrawal relative to the amount of total freshwater recharge to the aquifer does not form part of the GALDIT assessment and yet is clearly a key driver of SWI. The simplicity of the GALDIT method makes it attractive for mapping SWI vulnerability; however, its applicability within Australia at a national-scale would require further investigation and modification to meet this project's objectives.

6.4.4.3 Other Coastal Vulnerability Indices

A coastal vulnerability index approach was implemented for three coastal regions in Turkey in order to assess their vulnerability to the local effects of sea-level rise (Özyurt and Ergin, 2009). The study considered both physical and socioeconomic factors. The particular impacts assessed included: coastal erosion, flooding due to storm surge, inundation, saltwater intrusion to groundwater resources and saltwater intrusion to river/estuarine areas.

The physical parameters considered by Özyurt and Ergin (2009) within the assessment of SWI included: rate of sea-level rise, proximity to coast, type of aquifer, hydraulic conductivity and elevation of groundwater above sea level. The socioeconomic factors included groundwater consumption and land-use pattern.

Similar to the GALDIT approach, each parameter was assigned a vulnerability ranking, in this case ranging from very low (1) to very high (5) vulnerability. The coastal vulnerability index (CVI) to sea-level rise was calculated based on the ratio of the total value of the parameter value ranks to the sum of the least vulnerable value ranks; weighting factors were also considered. According to Özyurt and Ergin (2009), the CVI approach applied was based on the concept that was used by Thieler and Hammar-Klose (1999) to assess the vulnerability of the US coasts to rising sea levels at a national-scale (http://woodshole.er.usgs.gov/project-pages/cvi/; cited 24 February 2010). However, some additional factors such as the Bruune Rule for predicting coastal erosion and the Ghyben-Herzberg principal in the case of SWI were also considered by Özyurt and Ergin (2009), although the paper didn't discuss how this information was incorporated within their vulnerability assessment.

The vulnerability score ranking for each of the risk factors was derived by Özyurt and Ergin (2009) based on the ranking according to the 'distribution of available data related to each parameter at locations around the world'. Unlike with the GALDIT method, no look-up table was provided within the paper, so there is some lack of clarity as to how the ranking was assigned. The vulnerability scores of the Özyurt and Ergin (2009) investigation are presented for three geologically different regions within Turkey in table format.

While it would be necessary to gather further details in order to more clearly understand the specific methods used by Özyurt and Ergin (2009) in order to assess their potential applicability within this project, the paper does provide an example of the potential use of calculating vulnerability indices for coastal regions and is an example of how the vulnerability of Australia's coastal aquifers to SWI might be mapped.

Both qualitative and quantitative indexing approaches were further developed for the project as discussed by Norman et al. (2012) and Morgan and Werner (2012).

6.4.5 Future Land Surface Inundation and Population Growth Analysis

The fifth stream of technical assessment for the project was to consider assessing future land surface inundation as a result of sea level rise and predictions of population growth in order to evaluate how these factors may influence SWI. This aspect of the project is discussed within the final summary report (Ivkovic et al., 2012b).

6.5 Summary of method development

This section describes the methodological approach developed for use within this project to assess SWI vulnerability of Australian coastal aquifers. The method is based on foundational information provided within the sections above, based on literature review and data inventory. As previously mentioned, the project proposed five streams of technical assessments in order to analyse the SWI vulnerability of coastal aquifers. These five streams included: (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. These five technical assessments have been integrated to achieve an overall assessment of current SWI vulnerability.

To assess SWI vulnerability, both ‘top-down’ (national-scale) and ‘bottom-up’ (local-scale) methods have been considered. Using a top-down approach, national-scale datasets such as hydrogeological and climate mapping, bore data and DEM data are utilised. Using a ‘bottom-up’ approach, local scale datasets based on case study areas are used to further characterise local conditions for the vulnerability assessment. The project has been developed according to four phases, as described below.

Phase 1: A literature review, data review and method development. This phase provides a baseline assessment of the state of knowledge of SWI investigation in Australia, with literature review informing project method development. The information pertaining to Phase 1 of the project is contained within this report.

Phase 2: Five technical assessment streams undertaken to analyse factors contributing to the overall vulnerability of coastal aquifers to SWI. The technical assessments include:

i. Vulnerability factor analysis (VFA): a first-pass, broad-scale methodology to assess key observational elements (eg based on spatial and temporal data trends) of SWI vulnerability. The results of this assessment are reported in Cook et al. (2012).
ii. Coastal aquifer typology: a characterisation of the hydrogeological settings of Australia’s coastal aquifers based on principal aquifer types and climate groups. This assessment led to the selection of 28 case study areas which had sufficient hydrogeological data to parameterise conceptual models for subsequent mathematical analysis. The results of this assessment are reported in Ivkovic et al. (2012a).
iii. Mathematical analysis: a theoretical first-order assessment of steady-state SWI extent under current conditions, as well as the propensity for change due to various future stresses (i.e. climate change and groundwater extraction). This component is based on the analysis of data from selected case study areas. The results of this assessment are reported in Morgan et al. (2012).
iv. SWI vulnerability indexing: qualitative and quantitative SWI vulnerability indexing methodologies developed to provide a relative rank of aquifer vulnerability to selected indicators found within selected case study areas. The results of this component can be found, for the quantitative indexing, in Morgan and Werner (2012) and, for the qualitative indexing, in Norman et al. (2012).
v. Future land surface inundation and population growth analysis: considers the impacts of sea-level rise and population growth on SWI vulnerability in the future. The results of this analysis can be found in Ivkovic et al. (2012b), which is the project summary report, as the analyses were not presented in a separate report.

Phase 3: The five technical assessment streams in phase 2 are integrated to provide an overall SWI vulnerability assessment, with case study areas ranked according to ‘high’, ‘moderate’ or ‘low’ vulnerability. The integration is discussed by Marshall et al. (2012).

Phase 4: A national summary of SWI vulnerability is provided. The suitability of various methods for inferring potential vulnerability to SWI in data poor areas outside of the case study areas is also evaluated. The results of the assessment summary are reported in Ivkovic et al. (2012b).

7. Phase 1 Project Outputs - Overview

This report has provided an overview of Phase 1 activities including ‘literature review, data review and method development’, and addresses the first phase of this four-phase project. The outputs from this phase of the project have been integral to laying the foundations for achieveing the overarching project objective to assess the vulnerability of Australian coastal aquifers to SWI.

Some key outputs from Phase 1 of the project have included:

- Provision of background information on SWI concepts
- A literature review and baseline assessment of information relating to SWI in Australia
- An audit of sites identified as being vulnerable, or potentially vulnerable to SWI in Australia
- A literature review of international SWI investigations conducted at the regional-scale, and review of concepts of vulnerability and vulnerability assessment;
- A data review evaluating what data is required, and available, for an assessment of SWI in Australia;
- The collection, compilation and evaluation of key datasets for use in the current project; and,
- The development of a project methodology, informed by the literature and data review, which is appropriate for assessing SWI vulnerability in Australia at the national-scale.

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Glossary

Note: Words in italics are cross-referenced

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.

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.

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

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*.

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.

Geological Time Scale

Ka = thousand years Ma = million years

Eon	Era	Period	Epoch
Phanerozoic 0-542 Ma	Cenozoic 0-65.5 Ma	Quaternary 0-2.6Ma	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 55.8-65.5 Ma
	Mesozoic 65.5-250 Ma	Cretaceous 65.5-145.5 Ma	
		Jurassic 145.5-199.6 Ma	
		Triassic 199.6-250 Ma	
	Palaeozoic 250-542 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			

Appendix 1 Summary of National and State datasets collected to date

Table 13 *Summary of datasets from national and state sources*

Datasets	Type	Extent		Source	Comments
		Spatial	Temporal		
Hydrogeology of Australia	Hydrogeology	National	1987	Bureau of Mineral Resources	Principal aquifer types based on the Hydrogeological Divisions of Australia, produced from the 1:5 000 000 scale Hydrogeology of Australia map (Jacobsen and Lau, 1987).
Groundwater	Groundwater bore data	Regional	various	State and territory agencies	Groundwater borehole data collected from various state and territory water agencies resulting in an extensive amount of data; however, few continuously monitored bores in the coastal regions. Datasets contain bore survey data, standing water level, groundwater quality (TDS, EC, pH) and limited extraction data.
Köppen-Geiger Climate of Australia	Climatic variations	National	2007	University of Melbourne	Climatic codes based on updated Köppen-Geiger climate map of the world. *" Peel MC, Finlayson BL & McMahon TA (2007), Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633-1644."* Web: http://people.eng.unimelb.edu.au/mpeel/koppen.html
Rainfall	Historical monthly rainfall	Case study area	historical	Bureau of Meteorology	Historical monthly rainfall data were obtained from the Bureau of Meteorology website (http://www.bom.gov.au/climate/data/index.shtml) for rainfall stations that represent the case study areas.
Digital Elevation Model (DEM)	SRTM 1sec-Coastal elevation	National	2009	GA	The 1 second SRTM derived DEM Version 1.0 is a 1 arc second (~30m) gridded digital elevation model (DEM). The DEM represents ground surface topography, and excludes vegetation features. This is the best available and is suitable for national-scale use. *"Geoscience Australia and CSIRO Land & Water (2009) 1 Second SRTM Derived DSM andDEM User Guide. Version 1.0. Geoscience Australia."*

Datasets	Type	Extent		Source	Comments
		Spatial	Temporal		
Population	Population census - Online database, accessed through QuickStats	Collector districts and statistical local areas	Data accessed for 2001 or 2006	ABS	Australian Bureau of Statistics (ABS) Census Data, accessed through Quickstats: http://www.abs.gov.au/websitedbs/censushome.nsf/home/data?opendocument#from-banner=LN
Tidal Range	Point tidal gauge measurement	National	2011	National Tidal Centre	Tidal ranges estimated from highest astronomical tide (HAT) to lowest astronomical tide (LAT) and categorised into micro, meso and macro tides.
Geology	Simplified geology	National	2010	GA	*Raymond, O.L., Retter, A.J., (editors), 2010. Surface geology of Australia 1:1 000 000 scale, 2010 edition [Digital Dataset] Geoscience Australia, Commonwealth of Australia, Canberra. http://www.ga.gov.au* The Surface Geology of Australia (2010 edition) is a seamless national coverage of outcrop and surficial geology, compiled for use at or around 1:1 000 000 scale. Geological units are represented as polygon and line geometries, and are attributed with information regarding stratigraphic nomenclature and parentage, age, lithology, and primary data source.
Groundwater Salinity	Salinity	National	1987	Bureau of Mineral Resources	Salinity based on the Hydrogeological Divisions of Australia, produced from the 1:5 000 000 scale Hydrogeology of Australia map (Jacobsen and Lau, 1987). National groundwater salinity information has been used in the literature review technical report.
Hydrogeomorphic Mapping	Hydrogeologic landforms	National	2007	GA/BRS	The hydrogeomorphic mapping approach combines the three key variables which affect stream-aquifer connectivity, namely hydrogeology, landform and climate. The combination of hydrogeology and landform produces the broad seven geomorphic classes and these are combines with three (BOM-Koppen classified) general climate categories to give 21 unique hydrogeomorphic units at national-scale. *"GA and BRS, 2007. Mapping potential surface water-groundwater connectivity across Australia, draft version 1.5, Geoscience Australia and Bureau of Rural Sciences."*

Datasets	Type	Extent		Source	Comments
		Spatial	Temporal		
Coastal Depositional Environments	Clastic Coastal depositional environments	National	2007	GA	This data product is available online publicly through the Ozcoasts website (http://www.ozcoasts.org.au/) *"A.Heap, S.Bryce, D.Ryan, L.Radke, C.Smith, R.Smith, P.Harris & D.Heggie. Australian Estuaries & Coastal Waterways: A geoscience perspective for improved and integrated resource management. Australian Geological Survey Organisation, Record 2001/07."*
Australian Land Management Classification	Land use	National and regional	1997 - 2006	Bureau of Mineral Resources	Australian Land Management Classification version 6 was downloaded from the BRS website by state and is a very comprehensive data capture. Coastal and/or populated regions were derived from 25k – 100k mapping, SPOT imagery and various other sources. National coverage is almost complete except a few areas in NSW.
Geotechnical Landscape Map	Landscape and soil data	National	1984	NRIC	A geotechnical map including landforms, regolith, underlying lithology and soil type: captured at 2.5M scale
Soil landscapes	Landscape	National	1960-1968	Australian Soil Resources Information Systems (ASRIS)	Soil landscape maps, derived from CSIRO 2M scale maps

Appendix 2 Stakeholder Workshop Overview

A2.1 Purpose of workshop

The SWI project stakeholder workshop was held in Canberra on the 5th-6th May 2010. The purpose of the workshop was to:

- Formally introduce stakeholders to the objectives of the SWI project;
- Present findings from National SWI literature review;
- Hear from Jurisdictions on perceptions/actions towards SWI;
- Gain feedback on approach of SWI project towards a national vulnerability assessment; and
- Communicate/identify what data is needed/available.

This section of the report summarises the outcomes of the workshop. The agenda and stakeholder questionnaire for the workshop follow.

A2.2 Workshop participants

- National Water Commission - Peter Hyde, Cynthia Maher (NWC);
- Jurisdictions - Michael Williams (NSW); Chris O'Boy, Seth Johnson (WA); Steve Barnett (SA); Des Yin Foo (NT); Chris McAuley (VIC); Don Rockliff (TAS); Leon Leach (QLD);
- CSIRO - Richard Cresswell (CSIRO);
- Geoscience Australia - Chris Pigram, Jane Coram, Steven Lewis;
- SWI Project team - Baskaran Sundaram, Prachi Dixon-Jain, Luke Wallace, Jon Clarke (GA); Karen Ivkovic (Naiades Hydrogeology); Adrian Werner (NCGRT)

A2.3 Workshop structure

Day 1 consisted of four sessions. The opening session was held in plenary and consisted of a welcome, an introduction to the topic, purpose and structure of the workshop. Session 2 provided an overview of the project and SWI approaches, and this was followed by a discussion session. In Session 3 stakeholders perspectives on SWI issues in various jurisdictions were presented by jurisdiction delegates. Sessions 4 comprised brake-out sessions: one with a SWI vulnerability factors focus, the other with typological approaches focus. Each break-out session was overseen by a convenor and supported by discussion group.

Break-out sessions opened in plenary with the convenor providing an introduction to the topics. The plenary group then broke into designated discussion groups to address prescribed tasks associated with their relevant discussion topic. Break-out session leaders met at the conclusion of Day 1 to collate and summarise discussion findings.

Day 2 of the workshop was held in plenary and was devoted to recap the proceedings of Day 1 followed by project deliverables. The participants then discussed the datasets that are relevant to a national-scale vulnerability assessment of SWI. This session provided an opportunity to identify data gaps. Jurisdictions agreed to provide support to access the state datasets for the project and also nominated a representative for each jurisdiction a key point of contact for accessing the datasets. Opportunity was provided for each jurisdiction delegate to seek their expectations on outputs of the project. Finally the day ended with consensus on key achievements and directions for achieving the SWI project objectives and the way forward.

A2.4 Project approach to SWI

The approach of the SWI project (discussed in detail in the literature review) was presented and discussed with stakeholders. The major discussion points for each presentation are outlined below.

A2.4.1 Understanding SWI

The presentation of SWI fundamentals brought up two main discussion points from stakeholders of 1) how SWI is distinguished from other forms of salinity and 2) what action/management should take place when SWI is suspected.

1. Stakeholders noted caution is needed when mapping SWI in groundwater using salinity as seawater is not the only source of salts. The source of salinisation needs to be distinguished as different mechanisms of salinisation require different management responses. For these reasons, the presenter explained, seawater is typically identified from other sources of salinity by the characteristic ratio of calcium to carbonate [Ca/(HCO3 + CO3)] by analysis of groundwater.
2. When seawater is identified as a source of salinity within an aquifer, the management response will need to vary depending on the mechanisms driving the SWI (e.g. up-coning, lateral movement of seawater/freshwater interface) and aquifer characteristics (unconfined vs confined aquifers, hydraulic conductivity). Due to these issues, it was pointed out by stakeholders that, a blanket 'Trigger Level' management approach to indications of SWI may cause unnecessary 'red-tape', expense and restrictions to water users depending on which of the driving forces of SWI are operating. It was suggested by stakeholders that rather than Trigger Levels (imposing an automatic restriction on groundwater extraction etc) that a step-wise approach is used prompting further investigation. An example of this would be if seawater salinity was identified in a coastal bore that a follow up with further investigations is prompted (i.e. water levels AHD relative to sea level, installation of more monitoring bores, more frequent monitoring of bores etc) rather than prescribed changes in groundwater extraction.

A2.4.2 Project outline and strategy

The purpose, aims and objectives and how this project responds to our current understanding of SWI was introduced without any specific questions.

A2.4.3 SWI case studies – a literature review

The focus of discussion regarding the literature review pertained to the range of case study settings available in Australia. With the relatively small number of detailed SWI studies documented around Australia not all environments have been assessed in detail. For Australian settings, many of the SWI have been in sedimentary aquifers with less information available for fractured rock aquifers. To cover these less studied settings the case study section of the literature review incorporates international literature focusing on regional studies.

A2.4.4 Vulnerability assessment frameworks

After an outline of the existing vulnerability assessment frameworks found in the literature, the discussion focused on 1) what should/shouldn't be incorporated in this study, and 2) definitions of risk and vulnerability.

1. Currently, the existing SWI vulnerability assessment frameworks may not be suitable at a national-scale. Many frameworks currently do not incorporate geology and this information will need to be added, to incorporate the typological approach, to this investigation. A number of the current frameworks also do not incorporate changes in salinity or surface water salinity which could be included in the current study. Additionally, there is no index in current frameworks to say if SWI is happening, that is, it is assumed that SWI is occurring. These points, raised during the workshop, support the literature review findings that the current frameworks will need to be built upon to reflect a national-scale vulnerability assessment of this study.
2. The word vulnerability has a number of definitions. It was discussed that it will be important for this project to not only articulate how vulnerability is being used, but also be clear how this is different to related factors not being assessed, such as risk.

A2.4.5 Typological approach

An outline of the typological approach suggested for this study led to discussions ranging from the broad assumptions of the approach to the detailed data inputs required. Questions raised included whether the approach should use 1) case studies to generalise how geology influences SWI or 2) an analysis of SWI data to inform the importance of geology/geomorphology. This study will have an iterative approach between these two research methods.

A2.4.6 Modelling approach

The modelling approach presentation covered the background, existing studies and potential uses of numerical modelling for SWI. Questions that were raised included: what will the model say, and how will the results be used? The numerical modelling will be used to make first approximations of the potential extent of SWI under different scenarios and to test the sensitivities of typology parameters.

A2.5 Jurisdiction approach to/information on SWI

The following information is drawn from presentations and responses to questionnaires (the questionnaire sent out is given below) from jurisdictions regarding SWI for the workshop. The questionnaire provided an opportunity for the jurisdictions to provide feedback on the importance of seawater (SWI) within jurisdictions and also issues on emerging SWI issues and any recommendations for future directions and research on assessment and management of SWI in Australia.

A2.5.1 Queensland

This information has been drawn from a presentation given by the Queensland delegate.

How much of a problem?

SWI has been recorded since 1926. However, due to salinity also coming from ancient marine sediments, the amount SWI will depend on whether the definition includes 'non-current SWI'. This is because SWI is a product of analysis rather than monitoring.

Which basins are at risk?

Many areas are monitored and numerous basins have been identified with an amount of SWI. Monitored coastal basins potentially at risk of SWI currently and in the future include:

- Mossman River,
- Barron River,
- Herbert River;
- Black River;
- Burdekin;
- Bowen;
- Proserpine;
- Pioneer;
- Yeppoon;
- Gladstone;
- Bundaberg;
- Bribie Island;
- North Stradbroke Island and
- Gold Coast.

What are the drivers?

- Groundwater use
- Movement of saline groundwater
- Land use, urbanisation and drainage
- Canal development

What are the management strategies?

- Monitoring conceptualisation and Model Development (saltwater movement)
- Education and information transfer
- Identify Environmental Performance Indicators
- Identify Water Security Objectives
- Consultation
- Implement Compulsory Reduction

- Monitoring and adaptive groundwater management

Management due to climate change?

- Monitoring Conceptualisation and Model Development
- Predictive uncertainty of groundwater model
- Assess sensitivity of change in recharge with respect to change in daily rainfall
- Implement through the Water Planning Processes.

More specifically the management approach can be broken into:

Rainfall Variability

- Derive modified daily recharged from historic rainfall (by varying duration of rainfall events and/or magnitude)
- Use a stochastic approach to derive daily rainfall files from decadal climate change models.

Sea-level rise

- Alter the model boundary conditions to reflect the change in coastal head.
- North Stradbroke no measurable response due to very steep gradient
- Pioneer little response due to groundwater gradient
- Bribie important due low relief and flat gradient
- Drains and canals will allow for landward penetration

Groundwater protection guidelines?

- Each aquifer system has its own characteristics and management requirements
- Use with caution
- Monitoring lateral or vertical movement
- Understanding, identifying and relating change in groundwater chemistry with groundwater movement
- Jurisdictional limitations
- Basic intent is to limit further movement of saline groundwater

What future directions for SWI?

- Monitoring
- Assumptions and limitations
- Model uncertainty
- Chemistry mass balance ion exchange, crystallisation and remobilisation
- Dispersion and molecular diffusion Big picture small picture

A2.5.2 Northern Territory

These are responses by the Northern Territory representative to the SWI questionnaire.

How much of a problem?

SWI is generally considered to not represent a significant problem in the NT at this present time as there are only few areas where susceptibility or even vulnerability is recognised to exist (ranking 2, Section A11). However, where SWI has been identified and a threat to the integrity of the resource does exist, it would not be treated with any less importance than any other groundwater issue (ranking 5, Section A11). SWI in the affected areas will result in a reduction to regional abstraction, potentially damage environmental assets and limit any new development (ranking 5, Section A11).

Which basins are at risk?

There are four aquifer systems in the NT where there are indications of SWI. Three are aquifers representing the water supply source for the communities of (a) Warruwi (on Goulburn Island), (b) Milingimbi and (c) Ngukurr, and the fourth is (d) the McMinns / Howard East groundwater system underlying the peri urban area to the east of Darwin. This system represents the water source to an estimated 30,000 residents, a horticultural industry, market gardens and a public utility augmenting Darwin's municipal supply. With the exception of the latter, when assessment of the aquifer systems indicated that SWI was occurring, subsequent management actions were proposed to address this issue. With regards to the latter, prior to a recent AEM survey, no evidence had been available to suggest SWI was occurring (although it was suspected as highly possible).

What are the drivers?

In all cases, over extraction would be the likely cause. Climate change is not considered to be a possible cause as the Top End of the NT is experiencing a period of significantly above average rainfall and SWI is unlikely to occur under this circumstance.

What are the management strategies?

In two of the areas cited above (a and b), the borefield was developed so as to spread the pumping effect across the aquifer and minimise any concentration of drawdown. It should be noted that no management plans exist in any of the areas above at the present time. Therefore, with regard to monitoring, this is the role of the water supply provider (Power and Water Corporation) - the only monitoring undertaken is the sampling of the production bores. I believe this is done annually and can only speculate that the parameters analysed includes salinity (because this data is not shared). Likewise, there is no regulation of pumping and therefore pumping rate cut-backs are not enforced.

Management due to climate change?

No management plans exist for any of the areas above. A plan for the (d) McMinns / Howard East groundwater system is expected to be developed in the next 2-3 years. A numerical model of the groundwater system is available to assist in the development of the plan and various recharge scenarios would be expected to be applied as part of this process.

Groundwater protection guidelines?

Neither of the guidelines has been applied.

What future directions for SWI?

As the SWI path and process is specific to each aquifer system, it is difficult to generalise. However, cost effective remotely sensed detection and tracking of the interface, and aid in the parameterisation for numerical modelling purposes would seem to be a useful direction to follow. This may already be available through AEM but this technique is costly and generally not justifiable.

A2.5.3 Western Australia

This information has been drawn from a presentation given by the Western Australia delegate.

How much of a problem?

No comment provided

Which basins are at risk?

Population centres:

- Derby (confined & unconfined aquifers)
- Broome, Exmouth, Canarvon, Perth, Albany, Esperance (unconfined aquifers)
- Mandurah, Bunbury (confined aquifers)
- Canarvon – model GASVANS?, upcoming, not a SWI problem, not well monitored
- Bunbury – rapidly expanding population, BAMS model used to predict movement of SWI, SWI noted ~ 30 yrs ago linked to production bores, Yarragadee aquifer (source MWH 2007)
- Perth – lots of aquifers, Perth groundwater atlas, saltwater wedge offshore
- Exmouth – limestone, being carefully managed to avoid bores becoming saline
- Pilbara – geophysics on 4 palaeochannels for potential water supply (wetting iron ore)
- Broome – expansion due to oil and gas, vulnerable to upcoming
- Albany and number of south coastal towns

What are the drivers?

No comment provided

What are the management strategies?

Reactive management in response to development.

Management due to climate change?

No comment provided

Groundwater protection guidelines?

No comment provided

What future directions for SWI?

No comment provided

A2.5.4 Tasmania

These are responses by the Tasmanian representative to the SWI questionnaire.

How much of a problem?

The Department of Primary Industries, Parks, Water and Environment is not aware of any areas of widespread SWI. Anecdotal evidence from a limited number of landowners suggests that some individual bores may have suffered from reduced water quality however this has not been formally reported to the department.

In recognition of the growing importance of conjunctive water management the state has made considerable steps forward in managing and regulating groundwater. In the previous two years a licence system has been introduced to licence all water well drillers and a permit to drill system has been introduced. Following on from this work the department is now developing a framework to allocate and licence commercial groundwater extraction.

In addition to the establishment of a groundwater management and regulation framework, technical studies have included numerical and conceptual modelling of key agricultural catchments, database development and catchment specific studies.

As SWI has not been identified as a major issue as yet, and given the considerable ongoing task of establishing sustainable groundwater management in Tasmania, SWI is considered a lower priority at this point in time.

Which basins are at risk?

As mentioned above, SWI has not at this stage been recognised as an issue in Tasmania. There are however catchments that due to the increasing reliance on groundwater for agricultural production may be at risk of SWI. Such catchments may include the Duck, Montagu and possibly the Welcome in the Northwest of the state. Due to the limited availability of the surface water resource, these catchments have seen an significant increase in drilling for groundwater in recent years.

What are the drivers?

Given that in most catchments high reliability surface water systems are fully allocated it is likely that commercial and agricultural water users will increasingly turn toward groundwater as their means of securing high reliability water. It would be expected therefore that unless carefully managed over extraction would be the key SWI driver.

What are the management strategies?

There are currently no SWI specific management strategies in place. Tasmania has a limited groundwater monitoring network that monitors regional groundwater levels and water quality. The monitoring network does not provide adequate coverage to be used for SWI specific monitoring.

Management due to climate change?

As stated above, Tasmania is in the process of developing a system to licence and allocate groundwater extraction, climate change will be taken into account with respect to future allocation however currently it is not taken into consideration with respect to coastal aquifer management.

Groundwater protection guidelines?

Unable to provide comment at this stage.

What future directions for SWI?

In the Tasmanian context, additional project funding is required that will enable the detailed investigation of catchments that are considered at high risk of SWI. The investigations should at a minimum enable the establishment of suitable monitoring networks that will enable long term monitoring of groundwater quality.

A2.5.5 Victoria

This information has been drawn from a presentation given by the Victorian delegate.

How much of a problem?

SWI is considered consistently across VIC but generally not looked at in detail. SWI is not considered to be a major driver for groundwater management as are other groundwater issues are seen to be greater.

Which basins are at risk?

In the East Coast (VIC) the fluvial aquifers form the principal aquifers, with the coastal dune sands and dune-barrier systems providing minor sources of groundwater.

The East Coast aquifers include:

- Gippsland Lakes
- Latrobe Group Aquifers (SWI observed)
- Coastal dunes (lower yielding, domestic use, potential use in Kooweerup)
- Nepean region (Increase in salinities)
- Morrabbin sand plain aquifer (SWI could be a problem and a study in progress due to be completed in June).

West Coast aquifers include:

- Werribee delta (most significant example and intensive study of SWI in VIC)
- Yangery and Nullawarre Limestone province

What are the drivers?

No comment provided

What are the management strategies?

Each Water Supply Protection Area (WSPA) has/should have a groundwater management plan. Currently Groundwater Management Areas (GMA) do not have specific management plans but will do in the future for the whole state.

Around 30% of the state is under management. SWI is managed within existing management plans with ~3000 mg/L salinity at the high-end of usable water. Currently SWI is managed based on salinity prompting further investigation in the first instance rather than using 'trigger levels' to impose water restrictions. Management strategy will depend on findings of investigation in that area. For example, Werribee is currently under a zero-use policy for groundwater use (horticulture and market gardens) due to SWI.

Management due to climate change?

No comment provided

Groundwater protection guidelines?

No comment provided

What future directions for SWI?

No comment provided

A2.5.6 New South Wales

New South Wales is currently undertaking a state-wide study of groundwater resources including the vulnerability of SWI. The NSW study highlights that SWI is seen as a management issue that requires a plan of action. The current investigation will work to compliment any SWI investigation such as the NSW example.

A2.5.7 South Australia

These are responses by the South Australian representative to the SWI questionnaire.

How much of a problem?

Not really significant- about a 2. It is more a risk than a direct threat.

Which basins are at risk?

Otway Basin (SouthEast) and Uley South/Coffin Bay Basins (Eyre Peninsula). No to both

What are the drivers?

Risk due to groundwater extraction

What are the management strategies?

Sondeing and salinity sampling at 6 monthly intervals at Uley South

Management due to climate change?

Not all at the moment – adaptive management approach adopted with monitoring

Groundwater protection guidelines?

Didn’t know they exist!

What future directions for SWI?

Modelling techniques to determine critical trigger levels for water levels and extractions.

A2.5.8 General information drawn from jurisdiction responses

How much of a problem?

SWI is largely not perceived to be a major problem for groundwater management until it is present. That is, SWI is generally seen to be preventable by informed management of groundwater extraction (providing a level of detailed understanding of the groundwater resources water balance is known). However, SWI is perceived as the major water management issue where it does occur, resulting in the reduction or prevention of groundwater extraction.

The perception of the future risk of SWI may increase if factors other than groundwater extraction, the ‘less manageable’ aspects of the water balance such as raised sea level or reduced recharge (climate change scenarios), become the main driving forces of SWI.

Additionally, the lack of spatially extensive SWI studies, both detailed and regional, makes the risk of SWI unknown. Without the information available to assess how vulnerable groundwater resources are to SWI, the perception of SWI importance may be not as well informed as other groundwater issues.

Which basins are at risk?

A number of groundwater basins experiencing some form of SWI or at risk of SWI were identified from jurisdictions during the workshop that were not available in the literature. This highlights the importance of the knowledge and data that are only available from the jurisdictions and the need for cooperation from stakeholders to fulfil the current project.

What are the drivers?

Over extraction of groundwater was primarily identified as the driver for SWI from a management perspective. However, the sustainable amount of groundwater that can be extracted into the future will depend on groundwater recharge and storage which will inturn be affected by climate change scenarios. Therefore sustainable groundwater extraction management plans will need to incorporate a temporal component; what amount of groundwater can be extracted and when.

What are the management strategies?

SWI is largely incorporated into existing groundwater management strategies and monitoring networks. There are generally no specific SWI management strategies unless SWI is identified as occurring. Once identified, SWI is managed with reduced groundwater extraction. The management of SWI tends to be reactionary in response to development and other changing groundwater stresses.

Management due to climate change?

Management of SWI in response to climate change is variable between jurisdictions. Management plans range from using existing models for different recharge scenarios, plans to incorporate climate change into future management plans, and conceptualisation of specific groundwater resources in response to predicted sea-level rise and rainfall scenarios.

Groundwater protection guidelines?

No national SWI guidelines currently exist for Australia. Jurisdictions appear to use existing groundwater quality guidelines for SWI. SWI developed for international settings are not applied by jurisdictions in Australia.

What future directions for SWI?

The suggested future directions for SWI in Australia were based around understanding the driving processes and how to monitor these for management. The suggestions include: further research (funding, modelling and the physical and chemical processes); guidance in how to monitor/manage; modelling/conceptualisation for trigger levels/tracking of the SWI interface.

A2.6 Typology and Vulnerability discussion sessions

Discussion sessions were provided to gain feedback on the projects approach on typologies and vulnerability (outlined in detail in the above report). Feedback was largely supportive of the approach and advice was given and discussed on how to achieve the required outputs for the next phose of the SWI project. The discussions were centred on what data sets should be used for outputs to be indicative of SWI. Discussions included: 1) the need for nationally consistent parameters, 2) the need to compare the simple solutions produced by the project with existing detailed case-studies for comparison; and 3) the need for SWI indicators to reflect the driving processes.

Two concurrent discussion sessions on typologies and vulnerability indicators were held with each session reporting back to the group as a whole. The outputs of these discussion sessions were lists of the relevant information/data sets to inform the development of national-scale typology and vulnerability indicators as follows.

A2.6.1 Typologies

Matrix table incorporating factors that influence SWI (SWI version of GFS approach), as discussed in breakout session & team debrief:

- Geology/geomorphology
- Topography

- Climate
- Recharge
- Evapotranspiration
- Temperature
- Climate change
- Sea-level rise/inundation
- Tidal magnitude (inland limits of estuaries) + watertable over-heights
- Water use (high, med, low)
- Hydrogeology/aquifer properties (porosity, K, aquifer saturation depth, degree of heterogeneity)
- Anthropogenic (e.g. canal developments) – population density
- Water level trends/gradient
- Salinity trends
- Knowledge (management, monitoring, assessment)
- Chemistry (source of salinity)

A2.6.2 Vulnerability indicators

As discussed in breakout session & team debrief:

- Water level trend analysis (surrogate for storage in the aquifer)
- Salinity trend analysis
- Levels of stress (pumping vs recharge; estimated usage relative to maximum allocations; water level analysis)
- Population stress (surrogate for extraction data) – refer to ABS data
- Aquifer’s responsiveness to stress

A2.7 Datasets

The project team presented a list of datasets that are considered to be of critical importance to a national-scale SWI investigation. Some of the datasets required are grouped into (details in literature review):

- Physiographic;
- Hydrogeologic; and
- Hydrologic.

The presentation reported the lists of datasets that have already been accessed but also highlighted some of the data gaps including:

- Aquifer properties (hydraulic conductivity, storativity, anisotropy);
- Groundwater chemistry (major ions);
- Groundwater extraction volumes;
- Groundwater recharge & discharge estimates; and
- Aquifer status relative to sustainable yield assessments.

Opportunity was also provided for stakeholders to incorporate other datasets they considered useful for the project. Discussion focused around: what data is useful; what data is available; and how the relevant data will be obtained. The majority of relevant publicly available national datasets have been collected by the project team. The majority of the remaining relevant datasets are to be provided by the States and Northern Territory.

A2.8 Communication/data-sharing plan

It was agreed that the project team would be responsible for collecting the existing datasets from each jurisdiction with the help of the relevant State/Territory representative.

A2.9 Concluding comments/major workshop outputs

The primary outcomes of the workshop were:

- In general supportive of the project objectives and approach;
- An offer by jurisdictions to provide logistical support to the project (i.e. data availability and knowledge and information sharing);
- Agreement to work collaboratively with other existing SWI projects (eg. NSW SWI project); and
- Suggestions for improvement of the delivery of the project outputs (Including maintaining the focus of the project deliverables on client (NWC) needs.

A2.10 Agenda for Stakeholder Workshop

Stakeholder Engagement Workshop, National Seawater Intrusion Project
Geoscience Australia, 5th-6th May 2010

DAY 1 – 5th May – Geoscience Australia – Room G.118 (Scrivener)

Session 1: Welcome and introduction	*10:00-10:30*
1. Welcome – Chris Pigram, GA	
2. Opening – Peter Hyde, NWC	
3. Overview of workshop – Jane Coram, GA	
Session 2: Project overview: Information sharing session	*10:30-12:30*
1. SWI fundamentals – Adrian Werner, NCGRT (30 mins)	
2. Project outline and strategy – Baskaran Sundaram, GA (15 min)	
3. Key project activities (10 min talks, 5 min Q each)	
i. SWI case studies – Karen Ivkovic, Naiades Geohydrology (NG)	
ii. Vulnerability assessment frameworks – Luke Wallace, GA	
iii. Typological approach – Karen Ivkovic, NG and Jon Clarke, GA	
iv. Modelling – Adrian Werner, NCGRT	
Discussion (15 mins)	
Lunch	*12:30-1:15*
Session 3: Stakeholder perspectives on SWI: Information sharing session	*1:15-3:00*
1. Synthesis of stakeholder questionnaire (15 min)	
2. Beyond the questionnaire - presentations from jurisdictions (15 min each)	
Afternoon tea	*3:00-3:20*
Session 4: Defining generic typologies: Discussion session	*3:20-5:30*
1. Vulnerability factors and typological approaches – breakout session (1h)	
2. Data availability – Prachi Dixon-Jain + participants (30 min)	
3. Project modelling approach (30 min)	
Dinner	*6:30*

DAY 2 – 6th May – Geoscience Australia – Room 1.024 (Seminar)

Session 1: Project deliverables and next steps: Discussion session	*8:40-10:30*
1. Recap on previous day (15 min)	
2. Recap of SWI project deliverables (15 min)	
3. What outputs of the project are stakeholders most interested? – breakout session (45 min)	
4. Consensus on key achievements and directions for achieving the SWI project (45 min)	
Morning tea	*10:30-10:50*
Closing summaries: Using workshop outputs	*10:50-11:30*
1. Next steps post-workshop (SWI project phase 1)	
2. Future activities of the SWI project (SWI project phases 2 and 3)	
3. National groundwater conference & next steering committee meeting	

A2.11 Questionnaire on SWI and Management in Australia

The following questionnaire is to gain feedback and gauging the importance of SWI (SWI) within jurisdictions across Australia. The questionnaire also encourages additional feedback on emerging

SWI issues and any recommendations for future directions and research on assessment and management of SWI. For each question we are seeking around a paragraph summary to provide a snapshot of SWI issues.

We would appreciate receiving your comments by 26th April 2010 so that these can be compiled and used as the basis for discussions during the Stakeholder workshop to be held on 5-6 May 2010 in Canberra. The workshop will provide an opportunity for SWI knowledge-sharing and for establishing a national perspective of jurisdictional views on the extent of SWI issues. The responses will eventually be documented in an appendix of a technical report on the perceived importance of SWI across Australia.

Survey questionnaire

In your jurisdiction:

1. How much of a problem is SWI? (i.e. How does SWI compare with other groundwater issues across the State/Territory? What threat does SWI pose to assets and water resources?; in addition to written answers please rank your answers from: 1 – not significant to 5 – most significant)
2. Which basins are thought to be at risk of water quality degradation due to SWI? Have these basins shown signs of SWI previously?
3. What are thought to be the key SWI drivers (i.e. climate change/sea-level rise, over-extraction, change in land-use)?
4. What are the management strategies adopted in areas subject to SWI? (i.e. Are there examples where SWI-specific monitoring is undertaken? If so, how often the bores in the coastal regions are monitored and which parameters are monitored in SWI areas? Are pumping cut-backs enforced to combat the threat of SWI?)
5. How are the issues of climate change (sea-level rise and changes in recharge etc) accounted for in current coastal aquifer management regimes?
6. Are the current Groundwater Quality Protection Guidelines adequate for managing groundwater quality from SWI? Are the FAO Guidelines on Seawater Intrusion in Coastal Aquifers (FAO, 1997) adopted and thought to be useful in guiding SWI investigation, monitoring and remedial measures?
7. What future directions would you like to see for SWI research and investigation?
8. Please provide any further comments on issues not covered by the above questionnaire.

Appendix 3 Hydrogeologic Classification of Australian Coastal Environments

This appendix provides a brief overview of Australian coastal aquifers and introduces twelve typical coastal deposition environments that are found in Australia. This overview was first presented in the Dixon-Jain et al. (2010) report. The descriptions of these environments include geomorphologically informed descriptions that are able to provide insights into the implications of these typical settings for SWI.

A3.1 Hydrogeology of Australian Coastal Aquifers

The hydrogeology of Australia has previously been described in terms of its principal aquifers, defined as those producing the best-quality water at highest yield from the shallowest depths (Lau et al., 1987). Aquifers were classified lithologically by Lau et al. (1987) as comprising sedimentary and low-grade metamorphic rocks, or igneous and medium- to high-grade metamorphics; they were also defined as being porous or fissured and subdivided in terms of their extent and productivity (Figure 12). The salinity of groundwater in the principal aquifers was also mapped for the continent (Figure 13). The major hydrogeological divisions across Australia included large sedimentary basins, fractured-rock provinces, and the overlying surficial aquifers. Australia's coastal aquifers encompass the spectrum of aquifer types characterised for the continent. In broad terms, the coastal hydrogeology of Australia can be summarised as follows (Jacobson and Lau, 1987a):

West coast - extensive porous sedimentary aquifers of high productivity and local igneous/medium-high grade metamorphic aquifers of low productivity;

North coast - extensive porous sedimentary aquifers of high/low-moderate productivity and extensive fractured sedimentary aquifers of low-moderate productivity;

East coast - extensive fractured igneous/sedimentary aquifers of low-moderate productivity and extensive porous sedimentary aquifers of low-moderate productivity; and

South coast - extensive porous sedimentary (limestone) aquifers of low-moderate/high productivity, weathered rock aquifers of low-moderate productivity, and local igneous/medium-high grade metamorphic aquifers of low productivity.

Australian coastal aquifers comprise unconfined, confined, semi-confined and multilayered types. The composition of the aquifers ranges from ***uncemented*** to poorly cemented sediments of Quaternary depositional environments; aquifers in the relic primary porosity of partially cemented sedimentary rocks; karstic aquifers formed by the partial dissolution of limestone sediments; and fractured rock aquifers in fully indurated rocks of sedimentary, igneous, and metamorphic origin. The storage capacity and flow rates of groundwater, and thus the position of the transition zone, are dependent on the geometry and extent of geological formations, collectively known as architecture. Coastal geological formations can also consist of multiple aquifers with varying degrees of interconnection, both within a single aquifer class, such as coastal sediments, and between different types of aquifers, such as where coastal sediments overlie karstified sediments.

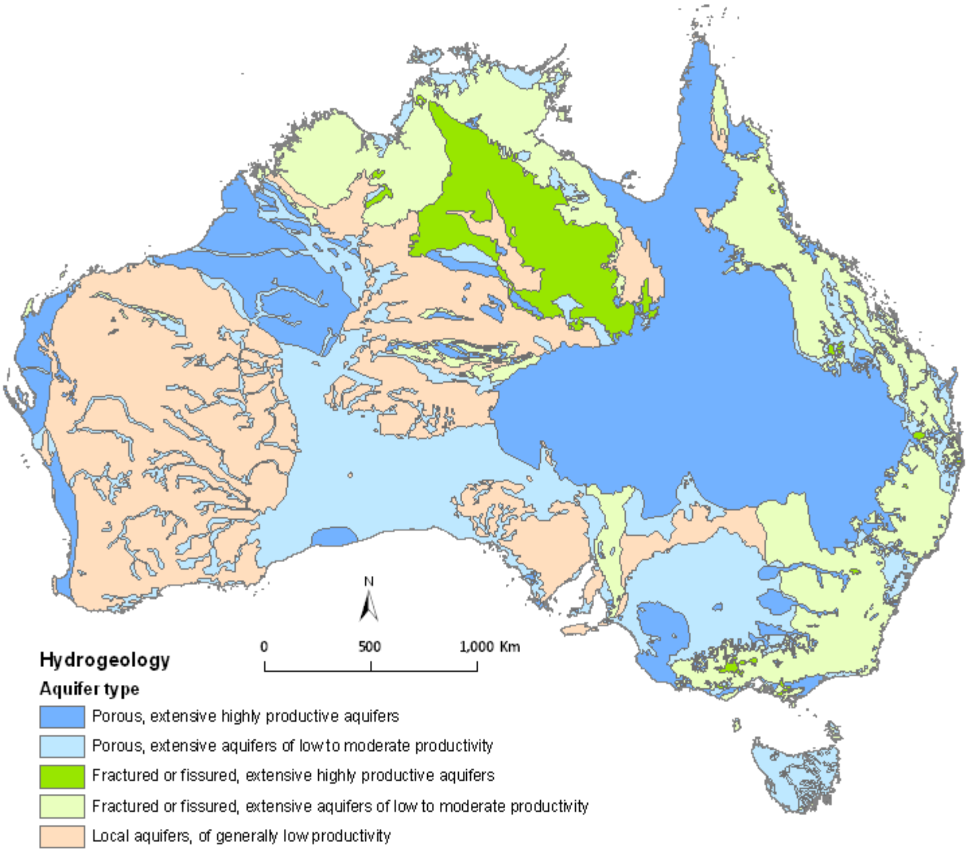

Figure 12 *Hydrogeology of Australia (after Jacobson and Lau, 1987).*

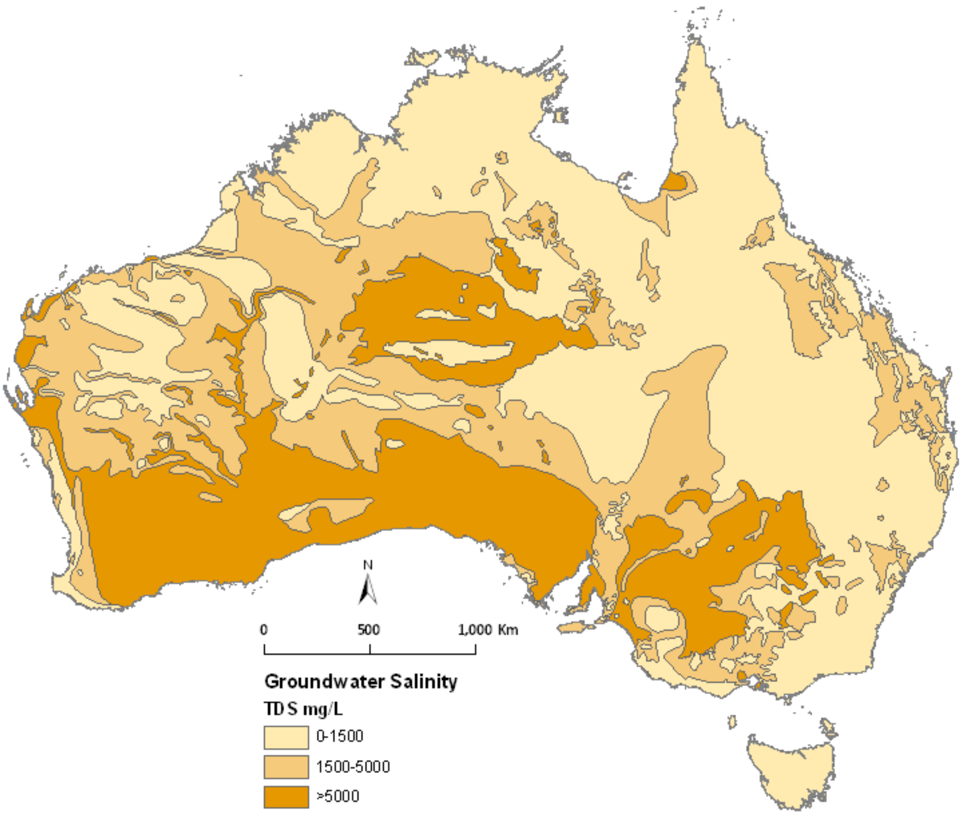

Figure 13 *Groundwater salinity in the principal aquifers of Australia (after Jacobson and Lau 1987).*

A3.1.1 Hydrogeological Settings and Conceptual Models

To a hydrogeologist, a conceptual model encapsulates factors that establish what the setting is, such as for example the geological and geomorphic framework; the location, types and characteristics of the aquifers in the study area; the identification of recharge and discharge sites; the direction of groundwater flow; and, the water balance for the region to be modelled. There are many additional types of information that could be considered when developing a conceptual model with the selection of factors consistent with the purpose for the model development.

The development of coastal conceptual models is important in three main ways. Firstly, conceptual models provide a setting and framework for the contextualisation of datasets such as groundwater elevations, water chemistry and other factors that will be assessed within the project to assess aquifer vulnerability. The same numerical value for a particular dataset, for example standing water level or ionic composition, may have a different interpretation in different contexts, such as if they occur at a recharge or discharge site or are found within a fractured bedrock or in an alluvial aquifer, or in sediments from distinct types of sedimentary environments, for example a barrier island sand or a lagoonal mud. Understanding the context of these data is critical to their correct interpretation.

Secondly, conceptual models – particularly those that incorporate geomorphic information – can provide a degree of 'predictive' information based upon the inferences which can be made regarding the hydrogeological setting. For example, a strandline geomorphic conceptual model can provide predictive capability regarding the distribution and geometry of aquifer and aquitard bodies which will be distinct to those predicted by a delta type of conceptual model. This predictive quality also applies to a range of depositional environments, such as those responsible for the formation of sedimentary rock aquifers. For example, a fluvial sandstone aquifer will have quite different characteristics to an aquifer composed of a marine siltstone; and karstic and fractured bedrock types of aquifers will also differ markedly in their properties. The predictive ability of conceptual models incorporating geomorphic attributes may also provide useful information for consideration in the development of mathematical models, the planning of new data acquisition programs, and the design of both monitoring and mitigation schemes for SWI.

Lastly, having an understanding of the different types of hydrogeological conceptual models when they include representations for typical coastal depositional environments, and which also include information about the actual configurations of real world aquifers, may allow for more informed mapping and interpretation within these coastal aquifer type settings. This too is critical in the development of mathematical models, the planning of new data acquisition programs, and the layout of monitoring and mitigation schemes for SWI.

Given the importance outlined above for the development of hydrogeological conceptual models that incorporate geomorphic characteristics, it would be useful to advance our understanding of such settings within the coastal zone for the current project.

The influence of different hydrogeological architectures to the patterns and processes of SWI has been extensively reviewed for a wide range of settings worldwide by Custodio & Bruggeman (1987). Unless otherwise stated, much of the following information in this appendix is summarised from their report.

A3.2 Porosity Types

Water in aquifers is contained in a range of different porosity types (Figure 14). The five major ones are:

Primary porosity is the porosity that occurs between the original grains of a sediment, such as a sand.

Remnant primary porosity occurs when the original intergranular porosity has been partly, but not completely filled in by cements; porosity occurs in the remnant intergranular spaces.

Secondary porosity related to grain and/or cement dissolution occurs when the grains are dissolved out but the cement remains intact. It is most common in carbonate rocks but can also occur in clastic rocks with more easily dissolved components.

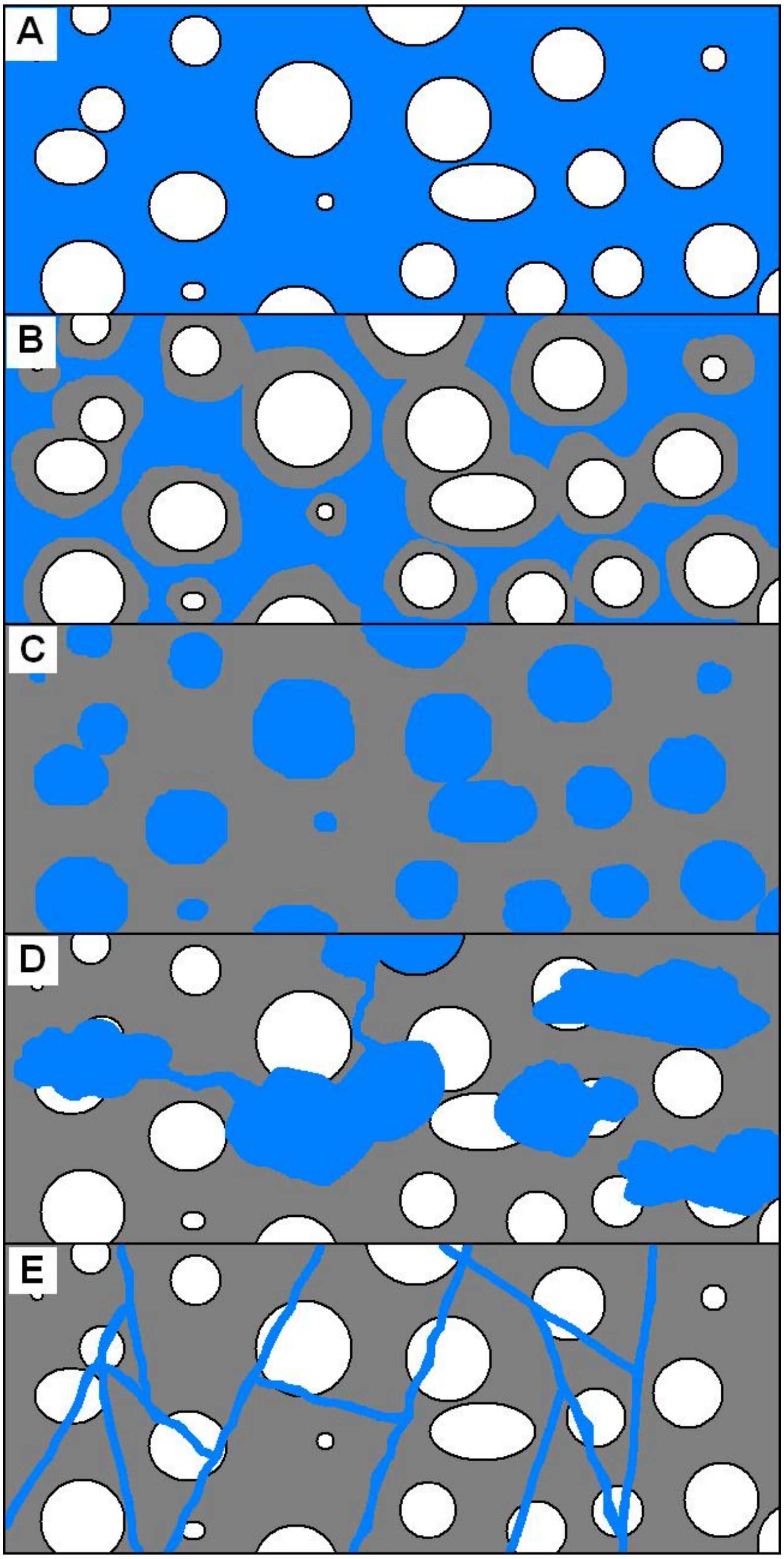

Figure 14 *Schematic diagram of porosity types. Original grains are outlined in black, cements in grey, and water-filled porosity in blue. A: Primary porosity in unconsolidated sediment. B: Remnant porosity in partly cemented sediment. C: Secondary porosity formed by solution of original grains. D: Karstic porosity. E: Fracture porosity.*

Karstic porosity can be considered a type of secondary porosity that occurs in carbonate rocks. The secondary porosity is enlarged into voids and caverns causing strong anisotropy in the hydraulic properties.

Fracture porosity is formed by cross-cutting structural features such as faults, joints, and cleavage.

Most of these porosity types are not mutually exclusive except for the first – unconsolidated sediments are unable by their basic character to host secondary, karstic or fracture porosity. Hence, a rock with remnant primary porosity may also have some fracture porosity; there is a complete spectrum between inter and intra-granular secondary and karstic porosity in carbonate rocks, and some karstic porosity may occur along solution enlargement of fractures. For further information on the nature of different generations of cements the reader is referred to the relevant literature on porosity classification evolution (Choquette and James, 1987; Choquette and Pray, 1970; Hutcheon, 1983; James and Choquette, 1983; James and Choquette, 1984).

A3.3 Geomorphology and Sedimentology of Australian Coastal Aquifers

Australian clastic coastal sediments span a diverse range of depositional environments. The evolution of coastal sedimentary facies is controlled by sediment supply, sea-level and a number of physical processes. The geomorphology of these facies types are most commonly related to the relative influence of wave, tide and river power in a ternary classification. The variable influences of wave, tide and river power results in the formation of deltas, estuaries, barriers lagoons, strand plains and ***tidal flats***.

Australian depositional coasts have been classified by Harris et al. (2002a). Depositional environments occur where tectonic subsidence allows for the accumulation of sediments and they contrast with rocky coasts which have been uplifted and where erosional processes dominate. Coastal depositional environments can be classified into a ternary diagram according to the dominant physical processes influencing their morphology, be it waves, rivers, or tides (Figure 15). Their distribution around the Australian coast is shown in Figure 16 and Figure 17.

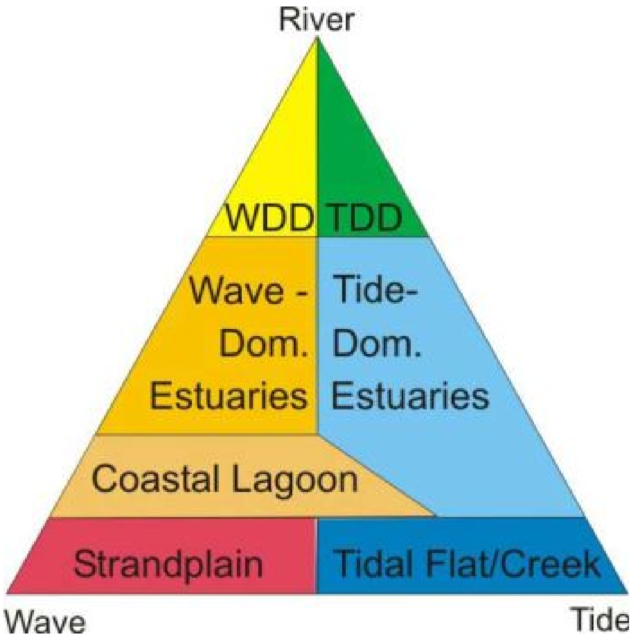

Figure 15 *Coastal depositional environments (after Boyd et al. (1992) and Dalrymple et al. (1992)). WDD = Wave-Dominated Deltas; TDD = Tide-Dominated Deltas*

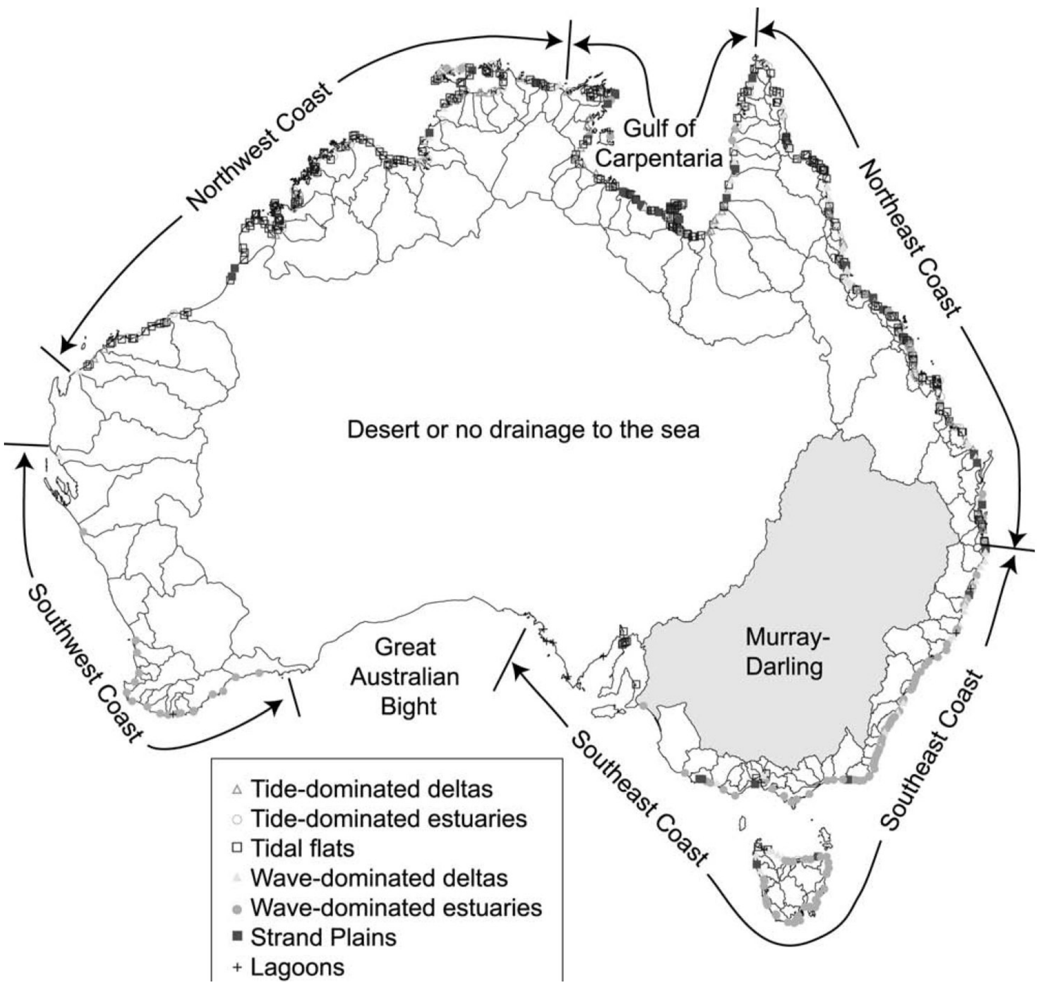

Figure 16 *Australian coastal environments, after Harris et al. (2002b).*

River dominated coasts are characterised by tide or wave-dominated deltas. Reduced riverine and increasing wave and tide influence leads to the formation of estuaries. Like deltas, estuaries are also divided into tide and wave-dominant categories. Complexes of tidal flats and creeks form where tidal currents dominate. Wave-dominated coasts form ***strandplains*** where successive shorelines form an amalgamated plain. Wave-dominated environments, where there is still some fluvial influence, form barrier and lagoon coasts.

A second important parameter is whether the coastline is prograding or transgressive. Prograding coastlines are where sediment supply exceeds sediment removal and the coastline progrades out to sea. Transgressive coastlines occur where the rate of sediment removal exceeds the rate of supply and the coastline is drowned. The expression of this parameter in coasts of different wave and tide energy is shown diagrammatically in Figure 18.

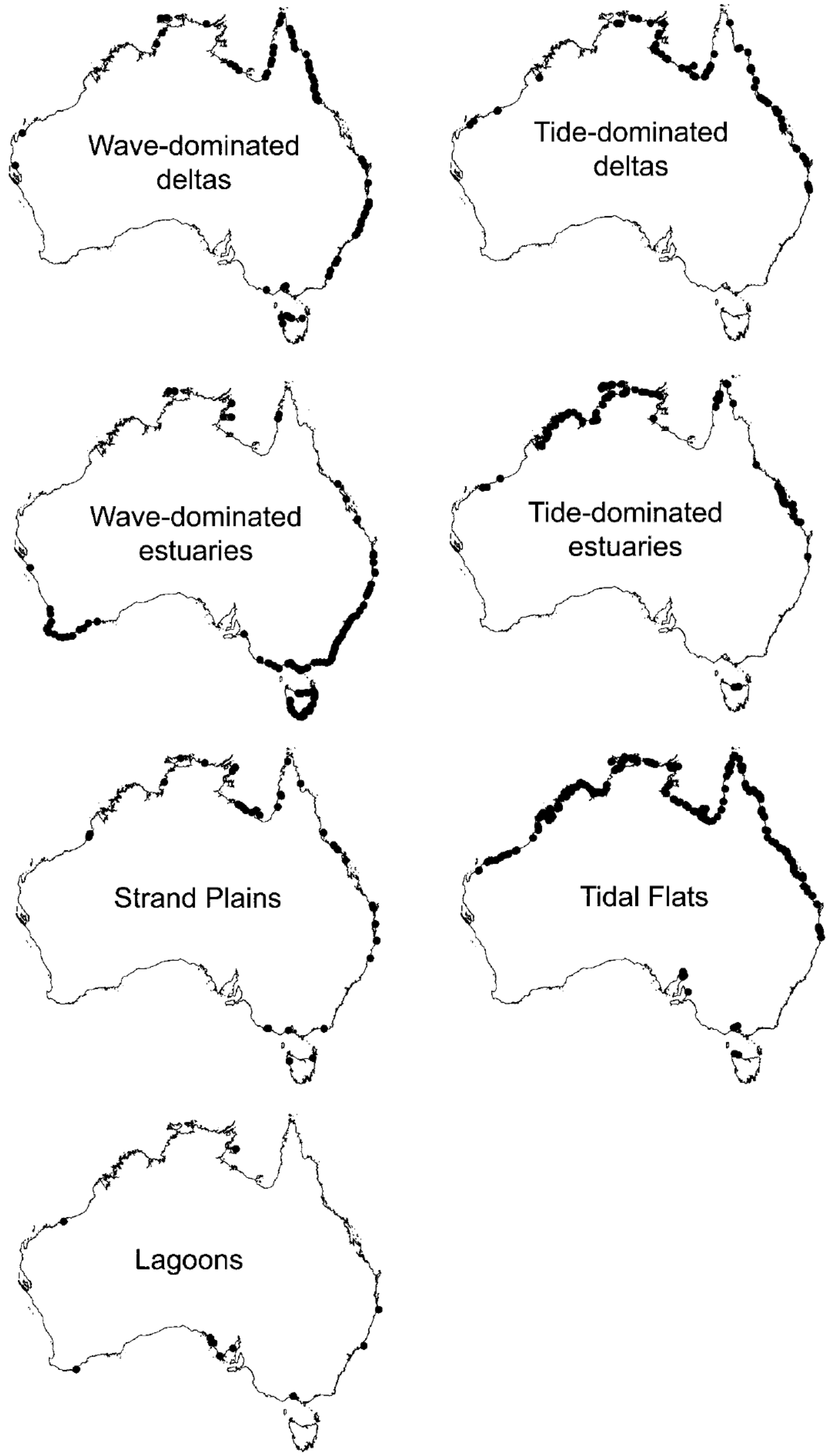

Figure 17 *Distribution of different depositional coast types round the Australian coastline, after Harris et al. (2002b).*

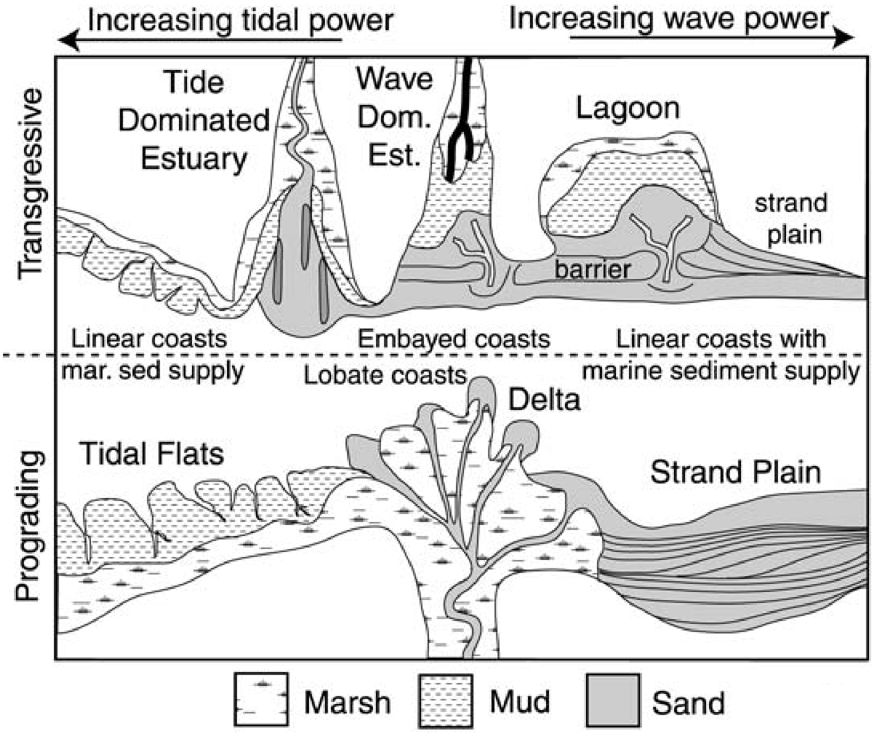

Figure 18 *Representative of wave and tide dominated coastlines in prograding and transgressive settings, after Harris et al. (2002b).*

A3.4 Deltas

A3.4.1 Definition

Deltas are prograding river-dominated coastal depositional systems where sediment supply from the river exceeds the rate of sediment removal by wave and tide-driven current. Rivers forming deltas vary markedly in their flow styles, including flow velocity (which determines grainsize and sorting), and seasonal variability. For example the Burdekin and Ord Rivers are strongly seasonal, with most flow occurring during the monsoon. As a consequence, their bedload sediments are composed of coarse-grained material (gravel to cobble) that moves only through peak flow events. Fine-grained sediments (muds, silts) remain suspended and are deposited in the estuary or out at sea. Less seasonally affected rivers, for example the Murray, move sediment constantly as both bed and suspended load, subject to long term drought cycles.

Typically, deltas form triangular or fan-shaped accumulations of sediments that built out into the sea. Australian rivers build comparatively few deltas as most have relatively limited sediment supply. Instead, most enter the sea through estuaries.

A3.4.2 Facies characteristics

Australian coastal deltas range in size from the Gilbert in Queensland, as one of the largest, to the King in Tasmania, as one of the smallest. The King River delta is anomalous as it owes its formation to a pulse of mining-related anthropogenic sediment. Deltas are of two main types: classic deltas and fan deltas. Each of these occurs as wave or tide-dominated forms.

Classic deltas are mud-rich and their aquifers consist of comparatively narrow, more-or-less radial sand bodies formed by the distributary channels of the delta surrounded by muddy delta plain and lagoon deposits (Figure 19). Some shore-parallel sand bodies are formed by offshore bars and by beaches. Through coastal progradation these shore-parallel units can be found at considerable distances inland from the present shoreline. Aquifers are unconfined at the surface but confined at depth when buried by delta accretion. Larger deltas can persist through several eustatic depositional cycles and therefore can contain multiple stacked confined aquifers.

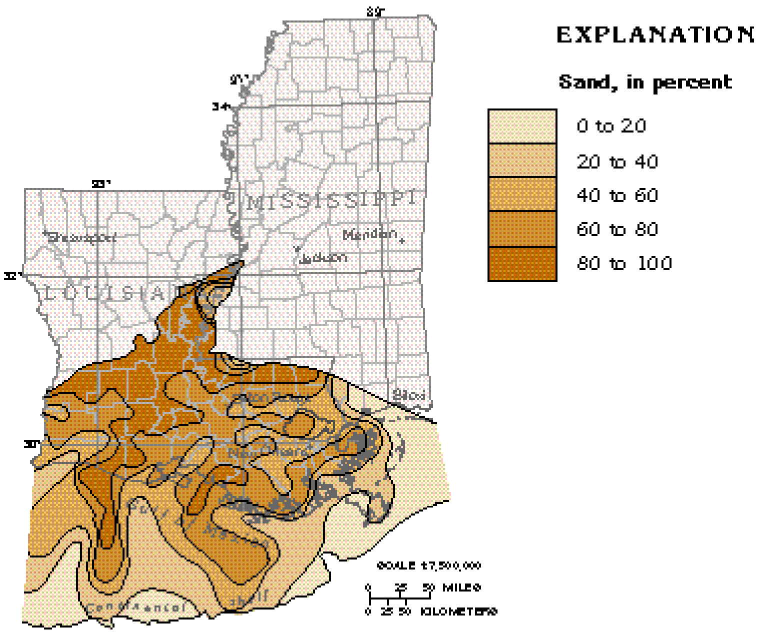

Figure 19 *Sand percentages in the Mississippi Delta showing predominance of muddy facies over sand and the more or less radial distribution of the sandy units, after Weiss (1992).*

Fan deltas are sand dominant and can contain gravels. Muddy units are comparatively minor and do not greatly compartmentalise the aquifer units. Aquifers are therefore unconfined to semi-confined and show high connectivity. The Burdekin Delta (Figure 20) is an excellent example of an Australian fan delta. Like classic deltas, facies aquifer architecture of fan deltas is dominated by more or less radial channels with some shore parallel aquifers formed by beach and offshore bar deposits.

Wave-dominated deltas, for example the Burdekin, have well developed beaches and strandlines developed along their seaward margins. Conversely tide-dominated deltas have wider, more funnel-shaped distributary channels, and well developed offshore bars.

A3.4.3 Examples

The Burdekin is the best-studied example of a delta in Australia (see Fielding et al. (2006) for a summary). It is also the site of managed aquifers and previous studies of SWI risk (Narayan et al., 2002). Some other coastal systems have been called deltas (e.g. the Ord, see (Coleman and Wright, 1978)) but more closely resemble estuaries (below). The Burdekin illustrates several features characteristic of deltas in relation to SWI, as discussed in the next section.

Figure 20 *Google Earth image of the fan-delta of Burdekin River, Queensland, dominated by sand and gravel*

A3.4.4 Implications for SWI

The major implications for SWI of deltaic facies include:

- Hydrochemical structure consists of saline water to seaward, with freshwater to landward. Locally saline waters of continental derivation may also occur to landward.
- The predominantly radial geometry of the principle aquifer units formed by the distributary channels.
- A strong textural contrast between the channel sands and the fine-grained floodplain and lagoon facies, especially in classic deltas.
- The presence of confined and semi-confined aquifers where channels are surrounded by fine-grained floodplain and lagoon facies.
- The likely presence of multiple stacked delta successions, some of which may contain fossil saline waters from previous phases of high sea level.

A3.5 Estuaries

A3.5.1 Definition

Estuaries are embayed, transgressive coasts that have semi-enclosed bodies of water and adjacent wetlands which have input both from marine inundation and terrestrial runoff (Pritchard, 1967). They can be tide or wave-dominant (Harris et al., 2002a) with a complete spectrum between them (Figure 16 and Figure 17). Tide-dominated estuaries have bars parallel to the axis of the estuarine funnel, for example, in the mouth of the Ord estuary where it enters Cambridge Gulf (Figure 22). Wave-dominant estuaries have a shore-parallel bar at their mouth, more or less normal to the estuarine funnel. An example of this is provided by Port Sorell, Tasmania. Where wave energy is even higher, the estuary becomes a lagoon and barrier system (see Figure 23 and also Figure 19).

Figure 21 *Google Earth image of the Ord River estuary, WA, a typical tide-dominant estuary. Note funnel-parallel bars near the mouth*

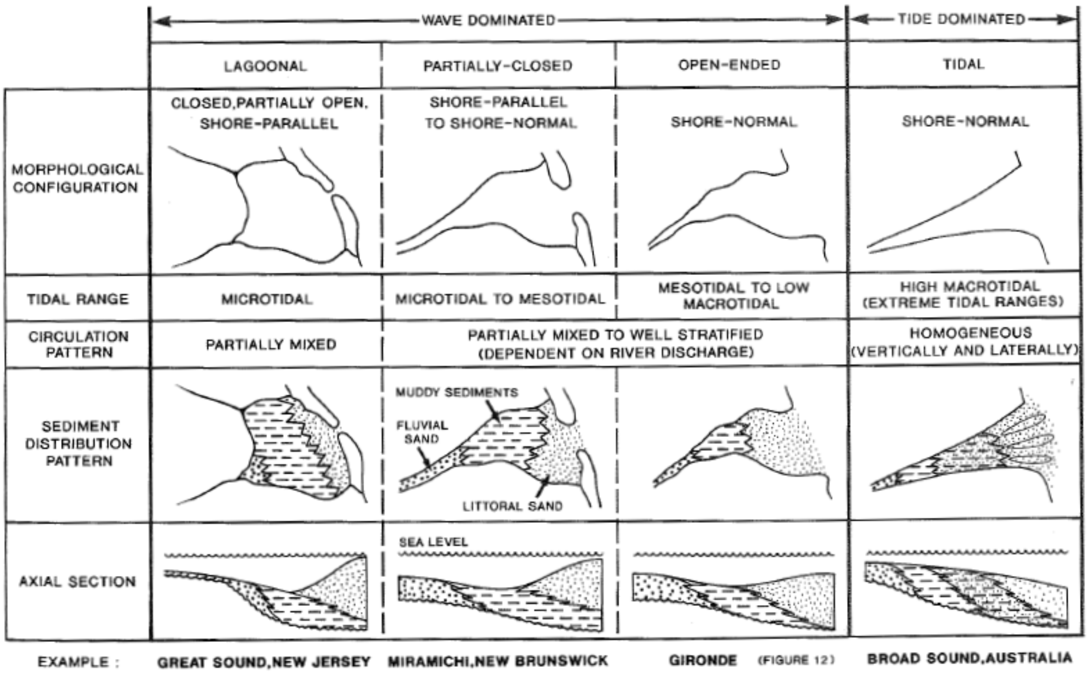

Figure 22 *Estuary classification, after Reinson (1992).*

Estuary scale varies considerably. One of the largest is Cambridge Gulf in WA, which is more than 100 km long and more than 20 km wide. By contrast one of the smallest is Northwest Bay estuary in Tasmania, less than 1 km in length and 200 metres in width. The thickness of estuarine sediment in such estuaries varies from less than 10 metres to more than 40 metres. The thickness is a combination of the depth to which the ancestral river was originally able to excavate a valley in the bedrock and extent to which the Holocene sedimentation rate has filled the available accommodation space.

The architecture of a tide-dominated estuary is simple, with aquifers forming a main axial sandy channel, tributary sandy channels and intervening fine-grained sediments forming the aquitards. Aquifers are likely to be unconfined. With increasing wave dominance the architecture becomes more complex. The main aquifers are increasingly associated with the sandy barrier system, which stores most of the sand, and the channel becomes less important. The orientation of the channel may increasingly deviate from the axis of the estuary because of the reduction from strong tidal influence. As with the tide-dominated estuary, the wave-dominated estuary is characterised by unconfined aquifers. Complexity can be introduced with the relics of former barrier and estuary complexes formed during previous high sea-levels (Roy, 1999). These may contain both unconfined and semi-confined aquifers as well as host fossil saline groundwater.

A3.5.2 Facies characteristics

Estuaries are typically funnel-shaped and often rock-bound. In a tide-dominated estuary, sediments accumulate along the margins and at the mouth. Marginal sediments are typically fine-grained muds and silts, whereas those of the estuary mouth are sands. Sands and gravels may also accumulate along the axis of the estuary. As the estuary fills, secondary tidal channels form, draining the marginal tidal flats and resulting in a dendritic tributary pattern that feeds into the main channel.

Wave-dominated estuaries have the entrance barred by a sand barrier, the degree to which the estuary behind the barrier is closed depends on the degree to which the tidal energy is able to keep a channel open. Behind the barrier the sandy tidal channel of the estuary may take a complex path to the sea with marginal flats of silt and mud and dendritic tributary tidal channels. The barrier architecture will consist of well sorted medium to coarse sands of the beach topped by fine-grained sands of the dunes.

A3.5.3 Examples

As previously noted a prime example of a tide-dominated estuary is that of the Ord in Western Australia (Figure 21). The Ord estuary is more than 10 km long and approximately 10 km wide, including a large bedrock island that divides it into two. The Ord itself is but one arm of the large estuarine complex of Cambridge Gulf, which includes the false estuary of the Ord and the Pentecost estuary.

Port Sorell in northern Tasmania is a good example of a wave-dominant estuary. The estuary is more than 12 km long and 6 km wide and is formed where the Rubicon River enters Bass Strait. A well-developed barrier complex formed by longshore drift from the east has deflected the main tidal channel to the west.

A3.5.4 Implications for SWI

The major implications for SWI of estuarine facies include:

- Hydrochemical structure
  - In tide-dominated estuaries generally decreasing salinities up the estuary and behind the barrier. If in an arid environment, the tidal flats may be hypersaline through evaporative concentration. Locally saline waters of continental derivation may also occur to landward.
  - In wave-dominated estuaries freshwater will occur along the seaward margin in the barrier; the estuary will show decreasing salinities up the estuary and behind the barrier. But, if in an arid environment, the tidal flats may be hypersaline through evaporative concentration. Locally saline waters of continental derivation may also occur to landward.
- For tide-dominated estuaries
  - Aquifers will be orientated approximately shore normal and coincident with the original drainage pattern.
  - The main aquifers will be the tidal channel and former channel mouth bars. Secondary aquifers will be formed by tributary channels
  - Aquitards will be formed by the fine-grained beds that progressively enclose the channel facies from the sides of the estuary.
  - Aquifers will be mostly unconfined, older aquifers may be semi-confined.
- For wave-dominated estuaries
  - Aquifer distribution will be complex and consist of:
    - The shore-parallel barrier complex dominated by sands
    - The tidal channel of the estuary proper, this may be quite narrow and displaced significantly from the original drainage thalweg by the development of the barrier.
    - Minor aquifers formed by tributary channels.
  - Aquitards will consist of the fine-grained beds that progressively enclose the channel facies from the sides of the estuary. Lower tidal energy may result in rapid infill of the back ***barrier lagoon*** by fine-grained sediments.
  - There is ***considerable*** potential for older aquifer units hosted by former barrier-estuary and lagoon complexes deposited during period sea-level highstands.
  - Aquifers will be mostly unconfined, older aquifers may be semi-confined.

A3.6 Barrier and Lagoon Coasts

A3.6.1 Definition

Barrier and lagoon coasts are transgressive coastlines (see Figure 18 and Figure 22) dominated by wave energy (see Figure 15 and Figure 16). Sand barriers build up across the mouths of embayments, trapping a lagoon behind them. A river may, or may not enter into the embayment. Barrier coastlines can evolve into strandplains (see below) if sediment supply is sufficient to allow coastal progradation to occur.

A3.6.2 Facies characteristics

Barrier and lagoon complexes vary widely in scale. At the largest scale there is the Mouth of the Murray, with the barrier more than 100 km in length and 1 km wide. The lagoons are the lakes of the Coorong and lakes Alexandrina and Albert; these extend up to 50 km inland from the coast (Figure 23). At the smallest scale are complexes such as Tomakin Beach in NSW, where the barrier and lagoon are of approximately 1 km in size. Despite the differences in scale, common architectural features are evident to both.

Barrier and lagoon coasts have two dominant facies, those of the barrier and those of the lagoon. The barrier facies are almost exclusively sandy, whereas those of the lagoon are mostly fine-grained. Barrier architecture along lagoon coasts is very similar to that in wave- dominated estuaries, consisting of well sorted medium to coarse sands of the beach topped by fine-grained sands of the dunes. The lagoon will be mostly fine-grained, but if open to tidal influence may have sandy flats and tidal channels. Breaches in the barrier by storms will lead to sand sheets deposited as wash over fans from the reworked barrier.

Because they are transgressive systems, sediment thicknesses of barrier and lagoonal complexes are generally thin, of the order of a few metres. The primary exception is the barrier itself, where the sand may achieve thicknesses in excess of 10 metres. The main aquifer will be the barrier complex itself, followed by the sandy channels in the lagoon. Water quality will vary immensely, generally fresh in the barrier and from fresh to hypersaline in the lagoon. Like wave-dominated estuaries, barrier and lagoon costs may contain much older coastal features from older highlands.

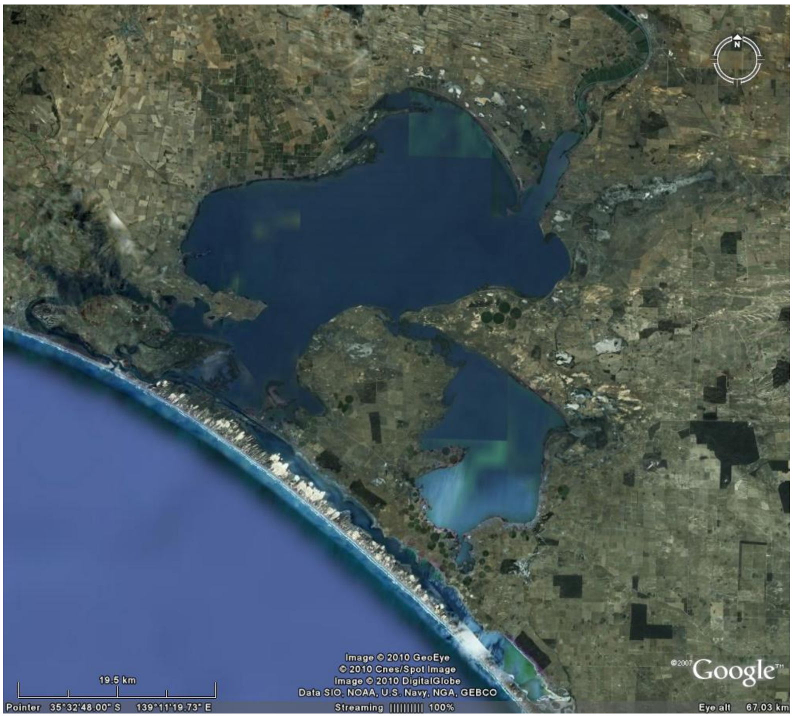

Figure 23 *Google Earth image of the lower Murray, showing the barrier formed by Younghusband Peninsula, and the lagoonal complex of the Coorong and lakes Alexandrina and Albert.*

A3.6.3 Examples

In addition to the Coorong and Murray Mouth and Tomakin Beach, discussed earlier, a good example is provided by Merimbula on the south coast of NSW Figure 25. Merimbula also shows the tendency of barrier and lagoon coastlines to be extensively settled and developed. This results in them being high risk areas for SWI impacts. There are a diversity of small to medium-scale barrier and lagoon coastal deposits along the southern coast of NSW; these were reviewed by Thom et al. (1978) and provide a good illustration of the variations in style shown by such features.

A3.6.4 Implications for SWI

The major implications for SWI of lagoon and barrier facies include:

- Freshwater will occur along the seaward margin in the barrier; lagoon aquifers will be of varying salinity, depending on degree of freshwater influx and evaporative concentration.
- The main freshwater lens will be shore parallel.
- SWI will occur along the sandy channels in the lagoon, however the orientation of these will be highly complex.
- Aquifers will be largely unconfined.
- There is potential for complexity in SWI patterns if older (pre Holocene) lagoon and barrier sediments are present.

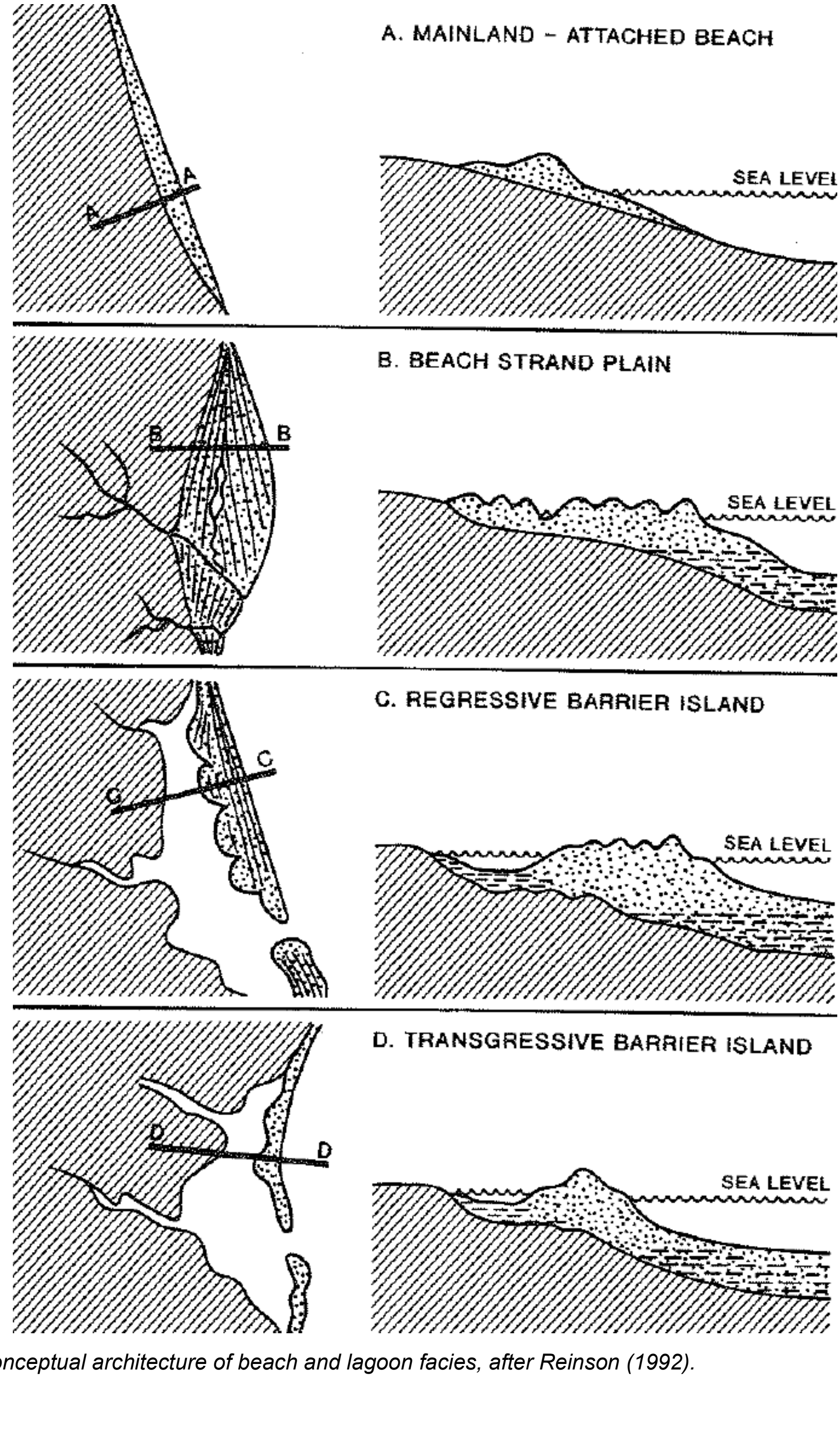

Figure 24 *Conceptual architecture of beach and lagoon facies, after Reinson (1992).*

Figure 25 *Google Earth image of the barrier and lagoon complex at Merimbula, south coast of NSW. Note extensive shallow sand flats in the lagoon.*

A3.7 Strandplains

Figure 26 *Massacre Inlet area on the southern shores of the Gulf of Carpentaria, just on the Queensland side of the Queensland/NT border. Well developed small strand plains are broken up and separated by tidal flats.*

A3.7.1 Definition

Strandplains are prograding coastlines dominated by wave energy and minimal tide or river input. They exhibit progressive accretion of more or less parallel beach ridges, for example in Figure 26. Strandplains are generally large-scale features, many km in width and hundreds of km long. They can be associated with other sedimentary environments such as tidal flats or deltas.

A3.7.2 Facies characteristics

Strandplains, such as the Swan Coastal Plain, can be 10's of km wide and 100's of km in length. Individual strand ridges can be 10's of metres in thickness. Strands are shore parallel and consist of well sorted medium to coarse sands of the beach topped by fine-grained sands of the dunes. Narrow corridors between dunes may contain fine-grained lagoonal facies. Aquifers are largely unconfined but may be laterally compartmentalised into specific strands by the inter-strand fine-grained sediments. The well sorted and sandy character of the aquifers results in good connectivity along the length of individual strands.

Other facies associated with strandplains are marine deposits, deltas, estuarine sediments, and tidal flats. Because they are prograding depositional systems, strandplains are built out over older and usually finer-grained marine sediments deposited in shallow coastal environments. These may be hydrologically continuous with the strandplain deposits. Estuary, delta, and tidal flat deposits may compartmentalise the strandplain. More or less shore-normal channel deposits associated with these depositional environments may provide corridors for saltwater intrusion.

A3.7.3 Examples

A prime example of an Australian strandplain is the Swan coastal plain on the southwestern coast of Western Australia (Figure 27). The strandplain has a long history back into the Pliocene. Inter-strand corridors contain lakes, often saline in composition. Because of the limited supply of clastic sediments to the western Australian coastline the sediments of the strandplain are rich in carbonate. Carbonate is particularly common in the most recent and aeolian-dominated parts of the strands. They have been variably leached and cemented as a result of carbonate remobilisation. In the southern part of the area caves are common and host karst aquifers.

A smaller example of a strandplain is on Robbins Island, on the coast of northwest Tasmania. On Robbins Island the strand ridges are only a few 10's of metres apart and less than 2 km long.

A3.7.4 Implications for SWI

The major implications for SWI of strandplain coasts include:

- Aquifers are highly permeable because of their well-sorted composition.
- The highest permeability is parallel to shore because the orientation of the strands. Permeability between strands may be impeded by finer-grained lagoonal deposits.
- Strandplains are often underlain by marine facies, because of their sheet-like geometry these may offer good permeability in all directions and be good paths for the intrusion of saline water.
- Strandplains are locally cut by drainage features and associated tidal, estuarine, or deltaic deposits. Sandy channel facies in these breaks in the strandplain may also offer potential invasion pathways for saline water.

Figure 27 *Google Earth image of the Swan coastal plain showing parallel strandline ridges and inter-strand corridors with finer grained sediments deposited in lagoons.*

A3.8 Tidal Flat Coasts

A3.8.1 Definition

Tidal flats are a class of prograding coastline found in environments dominated by wave energy and with very low river input of wave energy.

A3.8.2 Facies characteristics

Tidal flats are very low relief features, sloping gently to seaward. They are composed of thin beds of silt, sand, and mud, generally flooded each tidal cycle. Tidal flats are broken up by tidal channels; these typically are oriented roughly shore normal and branch inland, forming a dendritic pattern. The rising tide floods the flats along the channels and the falling tides drains off through them (Figure 28). Sand lobes at the mouths of tidal channels are sometimes described as tidal deltas, but this is a misnomer as their form is rarely deltaic and, there is no river influence. Furthermore it can cause confusion with tide-dominated deltas, and this therefore is best avoided.

Aquifers in tidal flat environments range from brackish, in areas of high terrestrial runoff, to hypersaline, where there is little or no runoff and evaporative concentration of seawater is high. Because aquifer systems are thin and either laterally extensive, in the case of sandy tidal flats, or penetrate a considerable distance inland, the potential for saltwater intrusion is high. Interbedding of sandy and muddy facies in the tidal flats and lateral migration of the tidal channels leads to common development of semi-confined aquifers. Due to their progradational nature, tidal flats overlie more marine coastal facies. These are most commonly shallow marine sands.

The salinity and frequent inundation of tidal flats poses significant hazards to land use even before considering saltwater intrusion. Land use examples include: as salt evaporation ponds, such as in Shark Bay or at Adelaide; where construction of dykes and land reclamation allows construction of infrastructure, such as the smelter, port and town of Port Pirie; or for canal developments, such as at West lakes in Adelaide.

Figure 28 *Google Earth image of tidal flats and dendritic tidal channels at the mouth of the Victoria River, northern Territory.*

A3.8.3 Examples

Extensive stretches of tidal flats are found along the northern coastline of Australia in the King Sound, Gulf of Carpentaria, Joseph Bonaparte Gulf, and Van Diemen's Gulf. Smaller examples are found elsewhere, for example in Shark Bay, WA, and in Spencer Gulf and Gulf St. Vincent. In these last three examples the tidal flats are dominated by carbonate sediments. Corner Inlet in Victoria is another example from southern Australia.

In addition to these relatively extensive to very extensive areas of tidal flats, many small examples of tidal flats are known in embayments protected from wave energy, often associated with coastal barriers.

A3.8.4 Implications for SWI

The major implications for SWI of tidal flats include:

- Rapid inundation potential from storm surges and minor sea-level rise.
- Thin and laterally extensive aquifers with low storage capacity provide potential for rapid SWI.
- Tidal channel facies oriented roughly shore-normal allow for rapid ingress of saline waters.

- Basal high permeability marine sand sheets may also offer favourable pathways for saltwater incursion.

A3.9 Older Sedimentary Coasts

A3.9.1 Definition

Many rocky coasts are composed of older (pre-Quaternary) sedimentary successions from which continental water can discharge and into which seawater can intrude. The coastal geometry of these areas is controlled by erosion, rather than by on-going sedimentation. Although variably indurated, groundwater flow is still primarily through remnant intergranular primary porosity, rather than through secondary porosity from fractures or solution. It is this characteristic that distinguishes this type of sedimentary aquifer from karst and fractured bedrock aquifers.

A3.9.2 Hydrologic characteristics

Like younger aquifers, those developed in older sedimentary successions are dominated by variably indurated sands to coarse silts, with fine silts and mudrocks acting as aquitards. The scale of intersection between these sedimentary basins and the coastline varies significantly. The smallest are only a few km in width, while the largest can extend for more than 1000 km.

Aquifer architecture is as highly variable as the depositional environments represented in the basin sediments. They can range from fluvial to deeper marine. The aquifers may be highly structured with channelised sediments or laterally continuous and sheet-like. Basin margin sediments may be broken up by basement highs and locally deepened by the presence of incised palaeovalleys. The sedimentary basin aquifers tend to be thick, hydraulically continuous over large areas, and contain multiple stacked aquifer systems that are confined.

A3.9.3 Examples

A smaller example of an older sedimentary succession is the Cainozoic embayment at Wynyard in NW Tasmania, which is only a few km in width. The largest, such as the Eucla Basin along the margins of the Great Australian Bight, and the Perth Basin extend for more than 1000 km. The Eucla Basin is, it should be noted, a special case, as it features both intergranular and karstic aquifers (see following section).

Coastal basins of older sediments can vary from fluvial (e.g. the Triassic of the Sydney Basin), deeper marine clastic rocks (such as the Cretaceous sediments of the Darwin area), or marine carbonates (in the Great Australian Bight). Both the eastern and western margins of the Great Australian Bight on Eyre Peninsula and near Esperance and Albany in WA, respectively (Clarke et al., 2003), provide examples of the complex architecture that can arise at basin margins, with basement highs forming bedrock hills rising through the basin sediments. Palaeovalleys along the base form locally thicker successions that can extend inland for hundreds of kilometres. Other examples include the Carpentaria Basin in the NT and Queensland and the Canning Basin in WA.

A3.9.4 Implications for SWI

Older sedimentary successions show similar same facies control on aquifer geometry as that shown by modern coastal sediments. Some additional environments may be represented in the older sediments that are not observed in present-day Australian depositional environments. Several other complicating factors occur with these aquifers that are not present with those in Quaternary aquifer systems. Firstly, because they represent a much greater range of depositional environments, including offshore and non-marine environments, not found in coastal successions, the range of possible geometries is much greater. Secondly, because they are often buried by younger coast sediments, their stratigraphy, extent, and architecture is quite poorly known and cannot be predicted from the modern geomorphology. Thirdly, because their original porosity has been partly filled by cements, porosity, permeabilities and transmissivities may be much lower than for their modern counterparts. Fourthly, because some of these older sedimentary successions may be affected by tectonism, the recharge areas for their groundwater systems may be elevated some height above sea level, generating significant hydraulic heads in confined sediments. Lastly, many of these basins are very large and can have regional groundwater flow systems influenced by features occurring at considerable distances from the coast.

A3.10 Karstic Coasts

A3.10.1 Definition

Karst aquifers are those formed by the dissolution of limestone, dolomite or gypsum. Because of this, karst aquifers can be very complex and variable at all scales.

When first deposited, carbonate sediments are dominated by primary intergranular porosity. This porosity is occluded over time by cementation, often also of carbonate. However, because the calcium carbonate that makes up the sediments and their cements is soluble, the movement of water that is undersaturated with respect to calcium carbonate results in the dissolution of the carbonate material (e.g. limestone etc.). Not all carbonate minerals are equally soluble; aragonite, common in the skeletons of many marine organisms such as molluscs and corals as well as in tropical marine cements, is more soluble than calcite. Nor are the solubilities of all calcite compositions equal; calcite with high magnesium contents are more soluble than those with low magnesium contents. Through the process of diagenesis other carbonate minerals can form, in particular dolomite, which is less soluble than carbonate. Carbonate dissolved from one part of the rock may be precipitated elsewhere in the system, or flushed out to surface water in rivers, lakes, and the ocean.

As a result of these complex processes of dissolution and precipitation, carbonate rocks evolve towards having highly anisotropic aquifer structures. Primary porosity is first partly filled by aragonite and high magnesium carbonate, which are then partly removed by dissolution, along with the more soluble fossils, leaving irregular and interconnected voids. Remnant primary porosity continues to be plugged by reprecipitation of dissolved carbonate. Dissolution voids are highly effective at focussing groundwater flow and become progressively enlarged to form complex cavern systems. Even when fully lithified and subject to fracturing, dissolution remains important and will operate along the fracture planes.

A further complication with karstic aquifers is that the patterns of dissolution and reprecipitation vary significantly above and below the watertable, and between fresh and saline groundwaters.

Consequently, karstic systems are often divided into distinctive vadose and phreatic karst styles, and meteoric and burial karst.

A3.10.2 Hydrologic characteristics

The scale of karstic aquifers is controlled by the extent of the carbonate unit. Karstic aquifers can be relatively small, less than 100 km in length, to up to almost 1000 km. They are characterised by extreme anisotropy in flow for two reasons: the tendency of karstic porosity to be controlled by structural features such as solution enlarged fractures and joints, and because of the extreme focussing of fluid flow into the caverns and passages. As a result, groundwater flow in karstic aquifers tends to be stratabound (confined to a single stratigraphic unit) rather than stratiform (confined to one or more stratigraphic layers), as is generally the case in other sedimentary aquifers.

Karstic aquifers can be both confined and unconfined. Aquitards within the aquifer unit tend to be broken up by cross stratal flow, and are significant only as upper and lower confining beds, if present. Even in this larger-scale case, the efficacy of overlying aquitards can be disrupted by gravitational collapse of the aquitard into caverns in the underlying aquifer. This can result in windows into otherwise confined aquifers and cause large-scale cross-stratal flow. A further complexity can be introduced by the fact that the hosting unit may be so impermeable away from the karstic porosity that it acts as both an aquifer and an aquitard. A consequence of this is the common association of onshore freshwater springs in karstic coastlines.

Unlike other sedimentary aquifer types, grainsize is not a major factor in most karst aquifers except those in the very youngest sediments. This is because the secondary porosity formed by dissolution rapidly exceeds any relic primary porosity in significance. Under favourable conditions karst aquifers can form very rapidly, with significant karst aquifers being found in the Pleistocene Tamala Limestone south of Perth.

Some karstic aquifers are also associated with more diffuse intergranular flow. In these examples, typically chalks, the rocks preserve exceptional primary porosity, are composed of carbonate mineralogies that resist differential solution, and have low fracture densities. Arid climatic conditions and sluggish groundwater flow rates can also further impede karst development in such basins.

Lastly, karstic porosity is characterised by clogging. In addition to carbonate precipitation, karstic cores and caverns can be clogged by clays and other fine-grained – non calcareous sediments. These can cause deviations in hydrological flow from that predicted by structural analysis of karstic aquifers.

A3.10.3 Examples

Karst aquifers are extremely important in many locations in the world and have been extensively described from the coast of the Mediterranean and the Caribbean in particular. SWI is a major issue in the karstic limestone aquifers of Florida. These aquifers are less common in Australia, but are locally present in the Eyre Peninsula of South Australia and in the Cape Range of Western Australia. The Eucla coastline of southern Australia is composed of carbonate sediments but these karstic aquifers are poorly developed because of a combination of the chalky composition of the main aquifer unit (the Wilson Bluff Limestone), low fracture densities, and arid climate conditions. The aquifer therefore is primarily intergranular in nature, locally overprinted by the development of karst. Another example is the Otway Basin in South Australia where Oligo-Miocene sediments have extensive karstic and primary porosity.

A3.10.4 Implications for SWI

The main implication for SWI of a karst-dominated aquifer system is the extreme anisotropy imposed on the groundwater flow by the distribution of the karstic porosity. This can be very difficult to predict without detailed use of tracers, although a good understanding of lithological and structural controls can help. Because karstic porosity can consist of large, well interconnected caverns, responses to perturbations in groundwater flow can be extremely rapid, responding to season, climatic, or anthropogenic influences on very short time-scales. An example of SWI in a karstic aquifer system in illustrated in Figure 29.

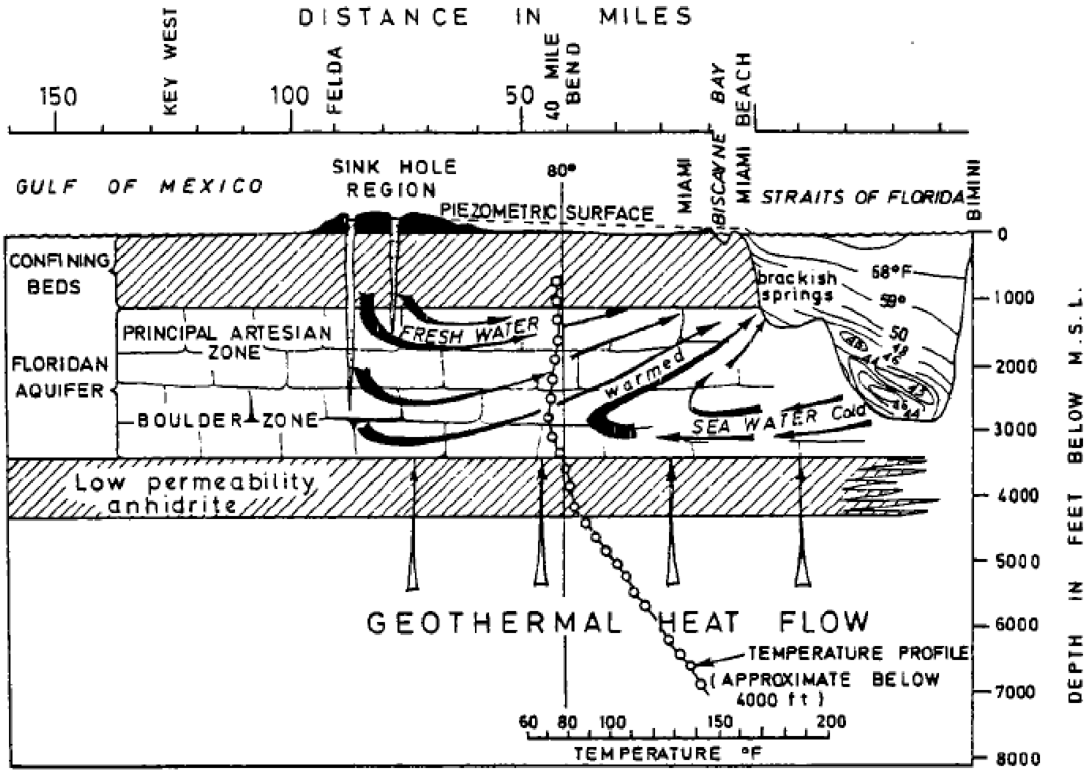

Figure 29 *Hydrogeologic structure of the karst aquifer of Florida, after Custodio and Bruggeman (1987).*

A3.11 Fractured and Weathered Bedrock Aquifers

A3.11.1 Definition

Fractured bedrock aquifers occur in fractures in fully lithified rocks, be they igneous, metamorphic or sedimentary rocks lacking primary porosity. The style of fractures, their density, and the nature of their interconnectedness will vary from lithology to lithology. In addition, thick profiles of weathered bedrock (10's to 100's of metres in thickness) can substantially influence bedrock aquifers. Weathered mantles can have significant secondary porosity of their own through dissolution of soluble minerals. However, structural features that form groundwater conduits in fresh rock may be obliterated or variably occluded by deposition of secondary minerals such as clays. The interface between fresh and weathered bedrock is highly variable, and weathering can penetrate downwards along joints and fractures to depths of 10's to 100's of metres below the average depth of the weathering front.

A3.11.2 Hydrologic characteristics

The scale of bedrock aquifers is determined by the scale of the host rock units. Imposed on the lithological variation are second order variations in structural density brought about by overprinting features such as weathering, small intrusions, and hydrothermal alteration. As with karst systems, there is significant anisotropy in fractured rock aquifers. Depending on connectivity, different fracture systems intersected by adjacent bores may have quite different characteristics. Because the fractures are smaller than karstic fissures their overall hydraulic transmissivities are typically lower, except where large and dense fracture systems are encountered. Because fractured bedrock coastlines are typically connected with elevated hinterlands, hydraulic heads are often comparatively high. The groundwater flow systems relate to topography, and the groundwater systems tend to be unconfined.

A3.11.3 Examples

Fractured rock coastlines occur in all Australian coasts where igneous, metamorphic and older sedimentary rocks make up erosional coastlines. Noteworthy examples include the southwest of Western Australia and much of the eastern seaboard.

A3.11.4 Implications for SWI

Transmissivity of fractured rock aquifers is highly variable, dependent on fracture density. Because of their common association with high relief, areas of fractured bedrock aquifers often have high hydraulic heads. SWI is often minor in such environments. However, because of the anisotropic hydraulic properties of fractured rocks there may be significant small- to medium-scale variability, with areas subject to SWI because of the nature of zones with high fracture density occurring next to areas with minimal SWI because of low fracture density.

A3.12 Hydrogeologically Complex Coasts

Hydrogeologically complex coasts are those where there are multiple and interconnected aquifers of the types summarised above. These multi-layer aquifer systems occur at a range of scales and introduce considerable complexity.

A good example of such a hydrogeologically complex coast is that which occurs at Esperance in southwest Western Australia. In this area multiple aquifers exist with varying compositions. Shallow aquifers ranging from fresh to hypersaline occur in Quaternary sediments of a lagoon and barrier coastline. These occur as numerous small depositional systems overlying more extensive, but still somewhat compartmentalised Cainozoic sediments consisting of marine spongolites and minor limestones overlying palaeovalley fills of sand, lignite, and clay. Aquifers in these sediments range from brackish to saline.

A3.12.1 Implications for SWI

Such hydrogeologically complex coastal systems have the potential to introduce considerable complexity to the pattern of SWI. Seawater may intrude more rapidly along some horizons than others and either flow down or upwards into aquifers that might otherwise be isolated from the sea by permeability barriers. Conversely, upwards discharge of groundwater from a confined and transmissive aquifer into overlying units can act as a hydraulic barrier to seawater encroachment. In such environments it is important that the hydrogeologic architecture is adequately known to predict and then map such occurrences.

A3.13 Anthropogenic Coasts

Some coasts, not all in urban areas, have been extensively modified by human activity, mostly by drainage or infill. Anthropogenic coasts will also be subject to SWI, but they will have modified and completely different architectures to those found in undisturbed depositional coastlines. Although their areas may be small, the extremely high dollar value for area means that any saltwater intrusion impact on infrastructure will have high societal costs. Some examples include city waterfronts, such as Hobart, and the Stanley wharf and esplanade in Tasmania (http://soer.justice.tas.gov.au/2009/indicator/98/index.php, cited April 2010).

Anthropogenic coasts will be characterised by deposits of strongly contrasting hydrological properties (sand, mud, crushed building materials) deposited on top of, or excavated into a pre-existing geological substrate. SWI pathways and hydrological characteristics cannot be predicted from general models in these settings, but only from detailed site investigations. These coasts will not be assessed in this investigation.

A3.14 Conceptualising Coastal Aquifers at a National-Scale

Twelve typical coastal depositional environments that are found in Australia have been described in the sections above. A summary of their characteristics follow in the tables below. Table 14 lists the characteristics of depositional coasts while Table 15 looks at other coastal types. These were initially considered for use in developing a coastal aquifer typology in Phase 2 of the project but ultimately were excluded from the analyses due to the complexity of this type of assessment for application at the national-scale.

Table 14 Summary of key aquifer characteristics in different coastal depositional environments

Depositional environment	Dominant physical processes	Coastline type	Aquifer material	Aquifer architecture	Aquifer characteristics	Examples	Other
Classic delta	River	Prograding	Mud-rich with narrow sand bodies	Narrow, radial sand bodies surrounded by muddy delta plain & lagoon deposits; some shore-parallel sand bodies	Unconfined at surface but confined at depth; can contain multiple stacked aquifers	Gilbert (QLD), King (TAS)	Influenced by wave and tide energy
Fan delta	River	Prograding	Sand dominant, can contain gravel; minor mud units	Radial channels; some shore-parallel units	Unconfined to semi-confined; high connectivity; can contain multiple stacked aquifers	Burdekin (QLD)	Influenced by wave and tide energy
Wave-dominated estuary	Wave	Transgressive	Barrier consists of well sorted medium to coarse sands topped by fine-grained sands	Shore-parallel sand bar normal to estuarine funnel	Unconfined aquifers associated with sand barrier (main) and tributary channels (minor); intervening fine-grained beds form aquitards	Port Sorell (TAS)	Higher wave energy forms a lagoon & barrier system
Coastal lagoon	Wave	Transgressive	Well sorted medium to coarse sands topped by fine grained sands (barrier); fine-grained (lagoon)	Sand barrier parallel to coast with lagoon trapped behind	Unconfined aquifers associated with barrier complex (main) and sandy channels of lagoon (secondary)	Mouth of River Murray (SA), Tomakin beach, Merimbula (NSW)	Evolve into strandplain with sufficient sediment supply for coastal progradation
Strandplain	Wave	Prograding	Well sorted medium to coarse sands topped by fine-grained sands; underlain by finer-grained marine sediments	Large shore-parallel strands	Unconfined but may be laterally compartmentalised by inter-strand fine-grained sediments; high permeability along length of strands and lower between strands; good permeability in underlying marine aquifer	Massacre Inlet (QLD), Swan Coastal Plain (WA), Robbins Island (TAS)	

Depositional environment	Dominant physical processes	Coastline type	Aquifer material	Aquifer architecture	Aquifer characteristics	Examples	Other
Tidal flat/creek	Wave	Prograding	Thin beds of silt, sand and mud; carbonate sediments	Tidal channels oriented shore-normal and branching inland, forming a dendritic pattern	Semi-confined where sand and mud are interbedded; thin and laterally extensive; high permeability basal marine sediments	King Sound, Joseph Bonaparte Gulf (WA), Van Diemen Gulf, Victoria River (NT), Shark Bay (WA), Spencer Gulf, Gulf of St Vincent (SA), Corner Inlet (VIC)	
Tide-dominated estuary	Tidal	Transgressive	Sands at mouth; marginal sediments are fine grained muds & silts; sands & gravel along estuary axis	Sand bars parallel to axis of estuarine funnel; dendritic tributary pattern	Unconfined aquifers associated with the tidal channel (main) and tributary channel (secondary); intervening fine-grained sediments form aquitards; older aquifers may be semi-confined	Ord River (WA)	

***Table 15** Summary of key aquifer characteristics of coastal aquifers in older rocks and other settings*

Depositional environment	Dominant physical processes	Coastline type	Aquifer material	Aquifer architecture	Aquifer characteristics	Examples	Other
Older sedimentary coasts	Erosion	Depositional or erosional	Variable; can range from fluvial to deeper marine deposits; dominated by sands to coarse silts, with fine silts and mudrocks acting as aquitards	Sedimentary basin aquifers tend to be thick, hydraulically continuous over large areas, and contain multiple stacked aquifer systems that are confined	May be highly structured with channelised sediments or laterally continuous and sheet-like	Sydney Basin (NSW); Darwin area (NT); Perth Basin (WA)	Basin margin sediments may be broken up by basement highs and locally deepened by the presence of incised palaeovalleys
Karstic coasts	Dissolution	Erosional	Limestone, dolomite or gypsum that has been affected by dissolution	High anisotropic aquifer structures	Confined or unconfined; characterised by sinkholes, caves and underground drainage; prone to clogging by fine grained non-calcareous deposits	Cape Range (WA); Eyre Peninsula (SA)	Patterns of dissolution and reprecipitatio n vary above/below watertable & with fresh/saline water
Fractured bedrock		Erosional	Aquifers occur in fractures in fully lithified rocks (non-porous sedimentary, igneous or metamorphic)	High anisotropic aquifer structures	Variable characteristics as a function of rock type and fracture structure. The groundwater flow systems relate to climate and topography. aquifers tend to be unconfined.		

Depositional environment	Dominant physical processes	Coastline type	Aquifer material	Aquifer architecture	Aquifer characteristics	Examples	Other
Typically occur in elevated hinterlands thus hydraulic heads are often comparatively high.	Southwest WA and eastern seaboard						
Hydrogeologically complex			Varying compositions comprising several depositional environments	Multiple and interconnected aquifers at a range of scales	Varying characteristics	Esperance (WA)	
Anthropogenic	Human alteration through engineering works		Sand, mud, crushed building materials) deposited on top of, or excavated into a pre-existing sedimentary substrate	Extensively modified by human activity, mostly by drainage or infill	Deposits of strongly contrasting hydrological properties	Hobart waterfront; Stanley wharf and esplanade (TAS)	