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National-scale vulnerability assessment of seawater intrusion: summary report

KM Ivkovic, SK Marshall, LK Morgan, AD Werner, H Carey, S Cook, B Sundaram, R Norman, L Wallace, L Caruana, P Dixon-Jain and D Simon

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- National Centre for Groundwater Research and Training: Adrian Werner

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Abbreviations and acronyms

ABS	Australian Bureau of Statistics
AEM	Airborne Electromagnetic
AHD	Australian Height Datum
ANRA	Australian Natural Resource Atlas
AOI	Area of Interest
APT	Aquifer Parameter Table
BRS	Bureau of Rural Sciences
CD	Collector District
CSA	Case Study Area
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
IPCC	Intergovernmental Panel on Climate Change
KMM	Knowledge Monitoring and Management
NRM	Natural Resource Management
NSW	New South Wales
NT	Northern Territory
NTC	National Tidal Centre
NWC	National Water Commission
PWA	Prescribed Wells Area

QDNRM	Queensland Department of Natural Resources and Mines
Qld	Queensland
RF	Rainfall
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

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

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 sea water into coastal aquifers—which can significantly degrade water quality and reduce freshwater availability. The increasing demands for fresh water 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. Comprehensive investigations of SWI are relatively uncommon and the extent of monitoring and investigations specific to SWI are highly variable across the nation (Werner 2010).

In response to the threat posed by SWI, Geoscience Australia and the National Centre for Groundwater Research and Training, in collaboration with state and territory water agencies, undertook a national-scale assessment of the vulnerability of coastal aquifers to SWI. This assessment aims to identify the coastal groundwater resources that are most vulnerable to SWI, including future consequences of over-extraction, sea-level rise, and recharge–discharge variations associated with climate change. The current study focuses on assessing the vulnerability of coastal aquifers to the landward migration of the freshwater–saltwater interface, rather than surface waterbodies.

To meet the project aims, the study included four main phases:

1. Literature and data reviews provided a baseline assessment of SWI in Australia. This allowed the selection of 27 case study areas (CSAs) where sufficient data existed for detailed technical analyses.
2. Technical assessments analysed various factors contributing to the overall vulnerability of coastal aquifers to SWI. The technical assessments focused on the CSAs, although a selection of SWI vulnerability indicators were examined in other areas around Australia. The following assessments were undertaken:
    - vulnerability factor analysis (VFA)
    - coastal aquifer typology
    - mathematical analysis
    - quantitative and qualitative vulnerability indexing
    - future land surface inundation and population growth analysis.
3. The technical assessments were integrated to provide a final vulnerability analysis of each CSA for both current and future conditions.
4. The suitability of various methods for inferring the level of vulnerability to SWI in data-poor areas outside the CSAs was evaluated. Following this evaluation, a national-scale assessment was made of SWI vulnerability around Australia based on the literature review, integrated vulnerability assessment (phase 3) and VFA.

This report also includes an assessment of the data and knowledge gaps and recommendations for further research and knowledge transfer. In addition to the interpretations of SWI vulnerability arising from the four work phases listed above, the various methodologies developed for SWI vulnerability assessment in phases 2 and 3 provide new tools of investigation that can be applied to other areas; they are key outcomes of this project. These methodologies are briefly outlined in this section, with detailed results included in Chapters 4 and 5.

Literature review of SWI in Australia

The literature review showed that no national-scale SWI studies in Australia were reported until the work of Werner et al. (2008), which focused on the groundwater issues of irrigation areas. The lack of a broader, national-scale assessment covering all of the nation's significant coastal aquifers, and the limited number of detailed SWI studies of Australian aquifers (Werner 2010), emphasised the importance of the project. The literature review, in combination with a stakeholder workshop with state and territory representatives, identified locations around the Australian coast where SWI had been reported or was considered a threat to fresh water quality. This work led to the selection of 27 CSAs for SWI vulnerability investigation using the technical assessments. Site selection was based on the need for sufficient information to allow first-order analyses of SWI vulnerability.

Technical assessments

Five technical assessments were undertaken to provide information on the vulnerability of Australian coastal aquifers to SWI. The results of individual technical assessments were combined to provide an integrated characterisation of SWI vulnerability in the CSAs. The details of technical assessments are discussed in the subsections that follow.

As part of the assessments, existing national and state/territory baseline datasets on groundwater, hydrogeology, hydrology, climate, coastal environments, topography, geology, land use, landscape, tides and population were reviewed and collated. Information was extracted from larger datasets to focus on those areas within 15 kilometres of the coast, since areas further inland were considered less likely to be at risk of SWI.

Vulnerability factor analysis (VFA)

The VFA provided a first-pass, national-scale assessment of SWI vulnerability indicators in Australia's coastal areas based on existing, nationally available datasets. Although additional factors are relevant when assessing vulnerability of groundwater systems to SWI, the VFA was restricted to the following parameters due to limits in the availability of nation-wide datasets:

- groundwater levels
- rainfall
- groundwater salinity
- groundwater extraction (locations and volumes).

Based on the number and range of high SWI vulnerability indicators, VFA priority areas for further assessment were identified where high SWI vulnerability was considered likely.

Coastal aquifer typology

The coastal aquifer typology assessment provides a framework for classifying Australia's coastal aquifers according to their primary hydrological and geological characteristics. The classification was based on principal aquifer types and Köppen-Geiger climate groups. This provided an inventory of aquifer–climate types along the Australian coastline, as a first step towards generalising SWI vulnerability according to typological conditions. Aquifer parameter ranges were derived for each of the 27 CSAs, and simplified hydrogeological cross-sections were catalogued. These were used in the mathematical analyses for vulnerability indexing, and they provided insights into the parametric differences between different typological units.

Mathematical analysis

A mathematical method was developed for this project to provide a first-order assessment of the extent of sea water in a coastal aquifer and the propensity for SWI in response to sea-level rise, recharge change and changes in the seaward flow of groundwater (e.g. due to pumping). The approach considers steady-state conditions and a sharp freshwater–saltwater interface. The method was applied to 28 CSAs (this analysis included Rottnest Island, Western Australia, which was then excluded from the other technical components due to data limitations), using data from the coastal aquifer typology phase of the project. Two measures of SWI were used: the location of saltwater wedge toe and the volume of sea water in the aquifer. Equations were developed for unconfined and confined aquifers and freshwater lenses. SWI in freshwater lens systems was assessed using the maximum freshwater thickness and the freshwater volume. The mathematical analysis allowed for general relationships between seawater landward extent and various aquifer parameters and stresses to be demonstrated.

Vulnerability indexing (quantitative and qualitative)

Indexing approaches were used to rank CSAs in terms of their vulnerability to SWI, whereby causative factors and SWI responses were combined systematically using weightings to distinguish the relative impact of the various vulnerability factors. The indexing methodology consists of two components:

1. quantitative indexing, which considers results from the mathematical analyses of CSAs
2. qualitative indexing, which considers results from the coastal aquifer typology and VFA.

Quantitative and qualitative indices were complementary in that the factors considered in qualitative indexing were mainly those that were not considered due to simplifying assumptions in the mathematical analysis. The scores from both qualitative and quantitative indexing were integrated with the outputs from the other technical assessments to provide a SWI vulnerability assessment for the CSAs.

Future land surface inundation and population growth analysis

A Digital Elevation Model (DEM) was used to identify low-lying areas that may be susceptible to surface inundation by sea water due to sea-level rise. Areas with an elevation less than one metre AHD (Australian height datum, an approximation of mean sea level) were considered highly susceptible to future seawater inundation, which is likely to cause substantial losses to freshwater resources for unconfined aquifer systems.

Population change was analysed using 2001 and 2006 Census data from the Australia Bureau of Statistics (ABS 2007) to identify areas where population changed significantly during this period, and as an indicator for potential future growth in groundwater extraction to meet the associated increase in urban water demands.

Integrated SWI vulnerability assessment for CSAs

The technical assessments described above were unable to provide a full assessment of SWI vulnerability individually. Instead, the technical assessments are complementary and were integrated to collectively assess SWI vulnerability of aquifers in the 27 CSAs. For each aquifer, the results from all technical analyses were considered following a set format to provide an overall vulnerability ranking of low, medium or high. This approach ensured that the myriad of factors relevant to SWI and their inter-relationships were considered consistently when assessing vulnerability. Vulnerability under future predicted conditions was also evaluated. The results for both current and future SWI vulnerability for the CSA aquifers are in the following table.

CSA aquifers and integrated vulnerability rankings

CSA	*Aquifer name*	*State/ territory*	*Current ranking*	*Future ranking*
Bowen	Superficial	Qld	High	High
Burnett Heads (Bargara)	Fairymead Beds	Qld	High	High
Burnett Heads (Bargara)	Elliot Formation	Qld	High	High
Burnett Heads (Moore Park)	Elliot Formation	Qld	High	High
Port MacDonnell	Gambier Limestone	SA	High	High
Derby	Wallal/Erskine Sandstone	WA	High	High
Adelaide	T1	SA	High	High
Adelaide	T2	SA	High	High
Bunbury	Yarragadee	WA	High	High
Esperance	Superficial/Pallinup	WA	High	High
Esperance	Werrilup Formation	WA	High	High
Le Fevre	Q1	SA	High	High
Le Fevre	T1	SA	High	High
Le Fevre	T2	SA	High	High
Perth (Whitfords)	Yarragadee	WA	High	High
Perth (Whitfords)	Superficial	WA	High	High
Perth (Whitfords)	Leederville	WA	High	High
Willunga	Port Willunga Formation	SA	High	High
Willunga	Maslin Sands	SA	High	High
Exmouth	Cape Range Group	WA	High	High
Exmouth	Cape Range Group	WA	High	High
Perth (Cottesloe)	Tamala Limestone	WA	High	High
Uley South	Bridgewater Formation	SA	Moderate	High

CSA	*Aquifer name*	*State/ territory*	*Current ranking*	*Future ranking*
Pioneer Valley	Unconfined	Qld	Moderate	High
The Burdekin	Unconfined	Qld	Moderate	High
Point Nepean	Bridgewater and Wannaeue Formations	Vic	Moderate	High
Broome	Broome Sandstone	WA	Moderate	High
Werribee	Alluvium/Fractured Rock	Vic	Moderate	Moderate
Botany	Botany Sand Beds	NSW	Moderate	Moderate
Stuarts Point	Stuarts Point Coastal Sands	NSW	Moderate	Moderate
Howard Springs	Koolpinyah/Coomalie	NT	Moderate	Moderate
Howard Springs	Koolpinyah/Coomalie	NT	Moderate	Moderate
Albany (Ocean side)	Werillup Formation Sand	WA	Moderate	Moderate
Busselton	Superficial	WA	Moderate	Moderate
Busselton	Leederville	WA	Moderate	Moderate
Carnarvon	Quaternary Riverbed Sand	WA	Moderate	Moderate
Carnarvon	Alluvium	WA	Moderate	Moderate
Stockton	Stockton Coastal Sands	NSW	Moderate	Moderate
Uley South	Wanilla Sands	SA	Low	Moderate
North Stradbroke Island	Dune Sands	Qld	Low	Moderate
Albany (Harbour side)	Superficial	WA	Low	Moderate
Albany (Harbour side)	Pallinup/Werillup	WA	Low	Moderate
Bunbury	Superficial	WA	Low	Moderate
Willunga	Quaternary	SA	Low	Moderate
Port MacDonnell	Tertiary Sands	SA	Low	Low
Hat Head	Coastal Sands	NSW	Low	Low

The results of the CSA vulnerability integration show that of the 46 aquifers assessed (many of the CSAs involve multiple aquifers):

- 22 (47 per cent) were found to have a current vulnerability ranking of high
- 16 (34 per cent) have a vulnerability ranking of moderate
- 8 (17 per cent) have a vulnerability ranking of low.

Future aquifer vulnerability rankings of high, moderate and low were found to be 26 (57 per cent), 18 (39 per cent), and two (4 per cent), respectively.

SWI has already been identified in the CSAs assessed here, and hence the large proportion of moderate and high rankings is not surprising. The integration methodology is considered to provide a useful framework for future assessments in areas outside of the CSAs as further data become available.

National SWI vulnerability assessment

To provide a national summary of locations where existing data suggest high SWI vulnerability of coastal aquifers, information from the following sources was collated:

1. The integrated SWI vulnerability assessments in 27 CSAs in Section 5.1. SWI vulnerability has been evaluated in detail at these locations, thus their SWI vulnerability levels are considered the most reliable of the three information sources.

2. Additional SWI sites identified by the literature review. In total, 20 SWI sites were identified outside the 27 CSAs. Since SWI has been documented in these areas, but no integrated vulnerability assessments were possible due to data availability, the precautionary principle was applied, and they are assumed to have high SWI vulnerability until integrated vulnerability assessments can be undertaken with the same approach used for the CSAs.
3. The VFA priority areas identified in Chapter 4. These include areas outside of the CSAs and SWI sites where high SWI vulnerability is considered likely. Given the limitations of this approach outlined in Section 5.2.2, the VFA parameters are considered to be the least reliable indicators of SWI vulnerability of the three information sources. It is emphasised that much of Australia's coastline is data poor, and lack of VFA SWI indicators should not be taken to imply that areas are not vulnerable to SWI. The VFA priority areas simply highlight those locations where considerable numbers of high SWI vulnerability indicators are present.

Despite differing hydrogeological settings, climate and land use, coastal groundwater resources in all Australian states and the Northern Territory may be highly vulnerable to SWI, and examples of SWI exist in the literature for all of them. Most of the areas identified as vulnerable to SWI or containing indicators of SWI vulnerability (outlined in Section 5.3) have high population densities or intensive groundwater use for agriculture or industry. As such, the consequences of SWI in these areas are likely to be severe.

There were only very limited data from along much of Australia's coast, and no definitive conclusions on the likelihood of high SWI vulnerability in these data-poor areas can be drawn here. The vulnerability of coastal aquifers to SWI varies over time, and SWI-specific monitoring regimes are imperative to facilitate early identification and management of SWI around Australia's coastline.

Outcomes and recommendations

The major outcome of this project was a national-scale assessment of the vulnerability of Australian coastal aquifers to SWI to increase awareness and understanding of regions in Australia that are vulnerable to SWI for federal stakeholders and policy makers. Available data indicate that SWI threatens coastal aquifers in all Australian states and the Northern Territory. The four project phases inform and facilitate this process through identifying, collating and interpreting SWI-related information from available literature and data sources. The project outputs inform on future vulnerability resulting from increased groundwater resource demands, recharge change and sea-level rise associated with climate change.

This project developed and applied a robust method for a first-pass assessment of factors contributing to SWI vulnerability that can be applied to the entire Australian coastline as data become available. This outcome was delivered through five technical assessments that consider various aspects of SWI vulnerability. It was a quantitative advance from the existing, purely qualitative SWI assessment methods present in the literature.

This project also added value to existing data by integrating the five technical components to provide an overall assessment of SWI vulnerability. This integrated assessment of SWI vulnerability was conducted at a CSA level and informs national-scale interpretations of regions with limited data. This was a critical project outcome.

Several opportunities were identified to progress and develop effective resource management and protection of Australia's coastal aquifers through additional monitoring, research, stakeholder education and communication. Recommendations for further work include:

- *Long-term groundwater monitoring*. Consistent, long-term groundwater monitoring at regular intervals is required along the entire Australian coastline at rates and densities commensurate with the likelihood and scale of ongoing and future groundwater use. SWI is often a slow process that requires persistent monitoring that is specifically designed to capture relevant trends to facilitate better understanding of groundwater resources and SWI intrusion processes. It will increase the likelihood of identifying, monitoring, managing and preventing SWI.
- *Prioritisation of regions for active management*. Further total water balance assessment, hydrogeological conceptualisation, hydrochemical analysis and groundwater modelling is needed in areas where the threat of SWI has been identified.
- *SWI-specific climate change research.* The impacts of climate change on coastal groundwater resources are not well understood in Australia due to slow response times and uncertainties in what changes will actually occur. Given that Australian climate variability is high, impacts on coastal aquifers due to changes in climatic averages may be less apparent over short timeframes.
- *Further investigation of the links between coastal aquifer typology and SWI vulnerability and development of a coastal aquifer typology to encompass the entire Australian coastline*. This is crucial to aid in the assessment of SWI vulnerability in undeveloped regions, and it helps to identify appropriate management practices where development is planned.
- *Improved knowledge-sharing and communication*. Individual jurisdictions have varying degrees of SWI assessment and management practices, depending on the development of the particular coastal resource. Several individual state/territory stakeholders developed cutting-edge coastal resource assessment and management practices that can be a shared educational resource on SWI assessment and management fundamentals.
- *Development of national best practice guidelines for SWI assessment, monitoring and management*. Guidelines should be developed to ensure a consistent and pragmatic approach to sustainable coastal resource management and environment protection.

1. Introduction

This chapter provides a brief background to seawater intrusion (SWI) in Australia, the need for a national SWI assessment and the approach taken by this project. This introduction states the project aims, objectives and methods. The purpose and structure of this report and how it relates to the overall project are included.

1.1 Background

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 SWI, which is the landward encroachment of sea water into fresh coastal aquifers. SWI can be caused by hydrological 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. Despite this existing threat, comprehensive investigations of SWI are relatively uncommon and the extent of monitoring and investigations specific to SWI is highly variable across the nation (Werner 2010).

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 fresh water in coastal areas and the anticipated impacts of climate change, such as sea-level rise and variations in rainfall recharge, may result in increases in the incidence and severity of SWI. An assessment is needed to address the paucity of knowledge of SWI vulnerability at the national scale that considers the extensive and diverse aquifer systems of Australia's coastal fringe (Werner 2010). An improved awareness and understanding of the key drivers for SWI, the current and emerging SWI-vulnerable areas and possible future trends in SWI, will benefit decision makers and groundwater stakeholders across local, state/territory and national levels. Development of a consistent approach for the assessment of SWI vulnerability will assist national, state/territory and regional planning and management strategies.

The national vulnerability assessment of SWI that is summarised in this document was developed to address the issues highlighted above. The broader project included a number of technical reports focusing 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 the development of this project.

1.2 Vulnerability concept clarification

Since the principal focus of this project is the vulnerability of coastal aquifers around Australia to SWI, a detailed discussion of the concept of vulnerability is required to provide a background to the project methodology. Vulnerability has numerous definitions, conceptualisations and assessment methods in the literature both between and within disciplines (Füssel 2007). Füssel (2007) reviewed vulnerability definitions and found that four dimensions were fundamental to describe any vulnerable situation. These four dimensions included:

- system—the system of analysis
- attribute of concern—the valued attribute(s) of the vulnerable (susceptible) system that is threatened by its exposure to a hazard
- hazard—a potentially damaging influence on the system of analysis
- temporal reference—the point in time or period of interest (current, future, number of years into the future, etc.).

Applying this vulnerability definition to the current project aim (see Section 1.3), this study could 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*).

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 et al. (2007) notes 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 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) and attribute of concern (position of the freshwater–saltwater interface)
- time (current and future vulnerability)
- adaptive capacity (monitoring and management specific to SWI).

1.3 Project aim and objectives

The aim of this project is to undertake a national assessment of coastal groundwater resources currently vulnerable to SWI and those that may become 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 the factors contributing to the vulnerability of Australian coastal aquifers to SWI incorporating the influences of climate change and sea-level rise;
- 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 Methodology

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 (Figure 1):

Phase 1: Literature and data reviews provided a baseline assessment of the state of SWI investigations in Australia. The literature review is detailed in the technical report by Ivkovic et al. (2012a). This phase was undertaken to meet project objective 1 and is summarised in Chapter 3 of this report. It included:

- An audit of existing SWI investigations in Australia;
- A review of methodologies for assessing SWI vulnerability such as mathematical, typological and indexing approaches;
- An inventory of the available datasets of relevance to a national analysis of SWI as well as additional information gained from project stakeholders regarding jurisdictional perspectives on SWI;
- The compilation of a geographic information system (GIS) database of hydrogeological, climatic, elevation and other key datasets considered relevant to this assessment;
- The selection of 27 case study areas (CSAs) around Australia based on data availability and reported SWI occurrence.

Phase 2: Five technical assessment components were developed to analyse factors contributing to the overall vulnerability of coastal aquifers to SWI. These CSA-focused assessments were undertaken to meet project objective 2 and include:

- Vulnerability factor analysis (VFA): a first-pass, broad-scale methodology to assess key observational elements of SWI vulnerability. This work is detailed in the technical report by Cook et al. (2012) and is summarised in Section 4.2 of this report;
- Coastal aquifer typology: a characterisation of the hydrogeological settings of Australia's coastal aquifers based on principal aquifer types and climate groups. This work is detailed in the technical report by Ivkovic et al. (2012b) and is summarised in Section 4.3 of this report;
- 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 extraction). This work is detailed in the technical reports by Morgan et al. (2011) and Morgan et al. (2012) and is summarised in Section 4.4 of this report;
- SWI vulnerability indexing: qualitative and quantitative SWI vulnerability indexing methodologies developed to rank the relative vulnerability indicators in each CSA or aquifer. This work is detailed in the quantitative indexing technical report by Morgan and Werner (2012) and the qualitative indexing technical report by Norman et al. (2012). Summaries are provided in Section 4.5 of this report;
- Future land surface inundation and population growth analysis: consideration of the impacts of sea-level rise and population growth on SWI in the future. See Section 4.6.

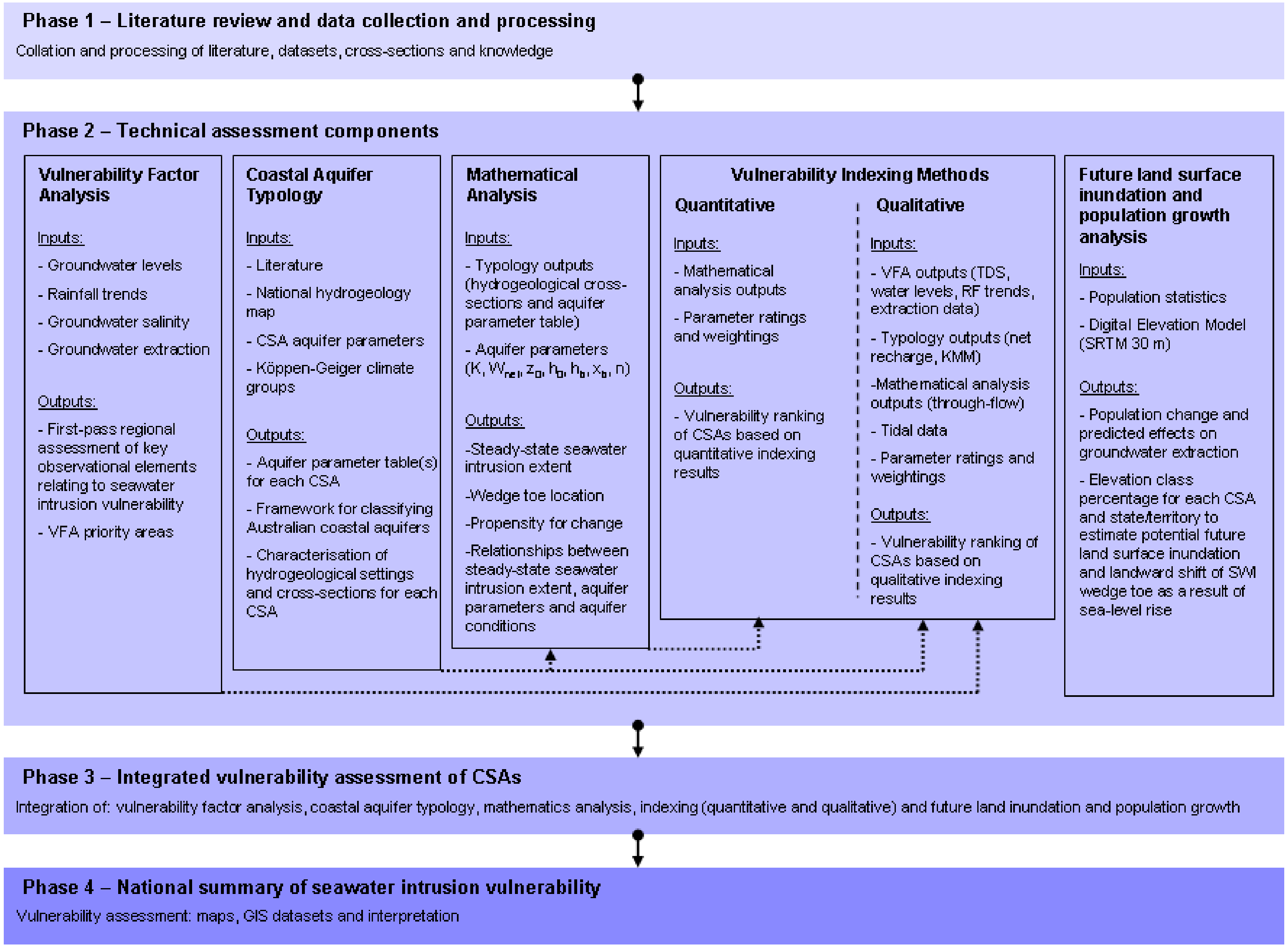
Phase 3: The five technical components in phase 2 were integrated to provide an overall SWI vulnerability assessment. The approach is applied for each CSA for both current and future conditions to meet project objective 3. It is detailed in Section 5.1.

Phase 4: A national summary of SWI vulnerability was prepared. The suitability of various methods for inferring potential vulnerability to SWI in data-poor areas outside of the CSAs was evaluated. Following this evaluation, a national assessment was made of SWI vulnerability around Australia based on the literature review, integrated vulnerability assessment and VFA. This allowed areas that may be vulnerable to SWI at a national scale to be identified. See Sections 5.2 and 5.3.

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

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

Figure 1: National SWI vulnerability assessment methodology



Phase 1 – Literature review and data collection and processing

Collation and processing of literature, datasets, cross-sections and knowledge

Phase 2 – Technical assessment components

Vulnerability Factor Analysis

Inputs:

- Groundwater levels
- Rainfall trends
- Groundwater salinity
- Groundwater extraction

Outputs:

- First-pass regional assessment of key observational elements relating to seawater intrusion vulnerability
- VFA priority areas

Coastal Aquifer Typology

Inputs:

- Literature
- National hydrogeology map
- CSA aquifer parameters
- Köppen-Geiger climate groups

Outputs:

- Aquifer parameter table(s) for each CSA
- Framework for classifying Australian coastal aquifers
- Characterisation of hydrogeological settings and cross-sections for each CSA

Mathematical Analysis

Inputs:

- Typology outputs (hydrogeological cross-sections and aquifer parameter table)
- Aquifer parameters ($K, W_{net}, z_0, h_0, h_b, x_b, n$)

Outputs:

-Steady-state seawater intrusion extent

-Wedge toe location

-Propensity for change

-Relationships between steady-state seawater intrusion extent, aquifer parameters and aquifer conditions

Vulnerability Indexing Methods

Quantitative

Inputs:

- Mathematical analysis outputs
- Parameter ratings and weightings

Outputs:

- Vulnerability ranking of CSAs based on quantitative indexing results

Qualitative

Inputs:

- VFA outputs (TDS, water levels, RF trends, extraction data)
- Typology outputs (net recharge, KMM)
-Mathematical analysis outputs (through-flow)
- Tidal data
- Parameter ratings and weightings

Outputs:

- Vulnerability ranking of CSAs based on qualitative indexing results

Future land surface inundation and population growth analysis

Inputs:

- Population statistics
- Digital Elevation Model (SRTM 30 m)

Outputs:

- Population change and predicted effects on groundwater extraction
- Elevation class percentage for each CSA and state/territory to estimate potential future land surface inundation and landward shift of SWI wedge toe as a result of sea-level rise

Phase 3 – Integrated vulnerability assessment of CSAs

Integration of: vulnerability factor analysis, coastal aquifer typology, mathematics analysis, indexing (quantitative and qualitative) and future land inundation and population growth

Phase 4 – National summary of seawater intrusion vulnerability

Vulnerability assessment: maps, GIS datasets and interpretation

1.5 Report structure

The report has been structured into seven chapters. Chapters 1–3 provide the introduction, background and contextual material for the project. They include SWI concepts (Chapters 1 and 2), and current knowledge of SWI in Australia and the identification of CSAs where the threat of SWI has been reported (Chapter 3). Chapter 4 gives an overview of the national and state/territory datasets used. It provides a summary of the four key project components (VFA, coastal aquifer typology, mathematical analysis, SWI vulnerability indexing) as well as future land surface inundation and population growth analyses.

Chapter 5 integrates the SWI vulnerability findings from all project components for each CSA, evaluates the suitability of the VFA and coastal aquifer typology to infer SWI vulnerability around Australia. This chapter also provides a national summary of SWI vulnerability around Australia. Chapter 6 presents data and knowledge gaps identified in the project. Chapter 7 outlines key project outcomes and recommendations for SWI research and management in Australia.

2. Seawater intrusion concepts

This chapter provides a brief introduction to SWI concepts 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, tides and time scales. For more detailed information on SWI processes, investigation and management, interested readers are referred to Werner et al. (2012a), Cheng and Ouazar (2004), Barlow (2003), Bear et al. (1999), FAO (1997), and Custodio and Bruggeman (1987).

2.1 Introduction to SWI

Seawater intrusion (SWI) is the landward migration of sea water 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 sea water 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 sea water, an interface exists whereby less dense fresh water sits above, and adjacent to, a denser, saltwater wedge (Figure 2). Because salt water has a greater density than fresh water, it moves in the form of a saltwater wedge beneath the fresh water. 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 fresh water and the density of sea water. 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 one metre (m) height of fresh groundwater above sea level translates to 40 m of fresh water 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 freshwater–saltwater 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 freshwater–saltwater interface. In the situation where a land mass is surrounded by sea water (e.g. islands, peninsulas and barrier dunes), opposing saltwater wedges can intersect to isolated freshwater lenses.

Mixing between fresh water and salt water 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 (Figure 2). 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).

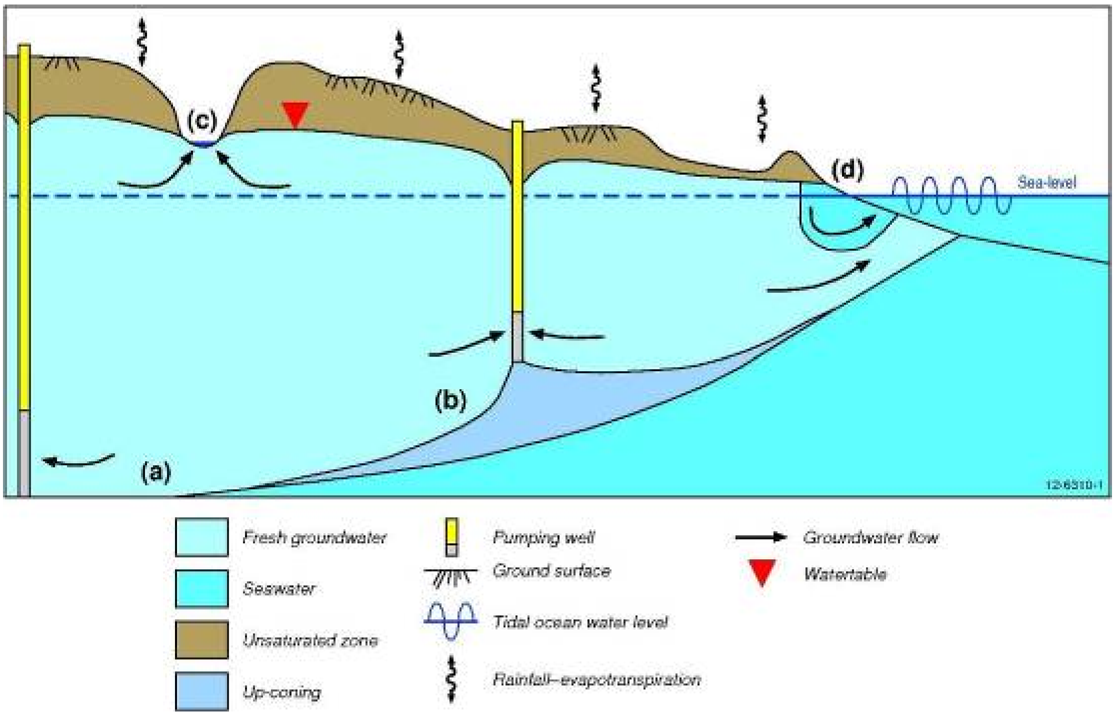


Figure 2: Schematic diagram of a coastal unconfined aquifer

Figure shows (a) the position of the saltwater 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 recirculation of sea water (after Werner et al. 2012a).

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 salt water from a deeper, more saline zone into an upper freshwater aquifer as a consequence of pumping is known as ‘up-coning’ (see Figure 2 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 sea water (Richter and Kreitler 1993). Thus, it is important in any SWI investigation to distinguish sea water 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.

2.2 Factors influencing SWI

There are many factors that can influence the dynamic equilibrium between fresh water and sea water 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 fresh water and sea water 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.

2.2.1 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).

2.2.2 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 the 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.

2.2.3 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 IPCC 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 a 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 salt water 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.

2.2.4 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 sea water within an aquifer. These are important factors when considering the likely extent of SWI.

The mathematical analysis component of the project, discussed in Chapter 4, assesses the influence of aquifer hydraulic properties by providing first-order approximations of the freshwater–saltwater interface for the project CSAs for confined, unconfined and freshwater lens aquifer systems.

2.2.5 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.

2.3 Time scales

The time taken for the freshwater–saltwater 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 in 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 fresh water 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 fresh water to be displaced by sea water. The response of aquifers to the stresses of SWI and any subsequent rehabilitation will depend on the individual hydrogeological setting.

2.4 Summary

For the purposes of this study, SWI is the encroachment of sea water into freshwater coastal aquifers by way of a landward migration of the freshwater–saltwater interface. This interface is typically wedge-shaped, with the toe of the saltwater wedge extending inland. Factors that affect the equilibrium between fresh water and sea water 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. Seawater intrusion in Australia: literature review

The literature for SWI investigations was reviewed at the national and state/territory scale by Ivkovic et al. (2012a). This chapter gives a brief summary of publicly available documented investigations of SWI in Australia. It also serves as an inventory of areas previously investigated or identified as potentially highly vulnerable to SWI.

3.1 National studies

Few national-scale studies on the subject of SWI have been reported in Australia until recently. Driving factors for SWI investigations in Australia are near-coastal groundwater-dependent agriculture and industry and the need for sustainable supply. There is also increased reporting at a national scale due to 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. 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. SWI within coastal aquifers was identified as a likely threat in their gap-analysis, but they made no attempt to highlight areas of likely impact.

Following on from the work of Voice et al. (2006), a report by the Australian Department of Climate Change (DCC 2009) presented the findings of a first-pass national assessment on 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 to assess the potential future risks from climate change. The 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.

Werner et al. (2008) and an unpublished report by Nation et al. (2008) used GIS-based approaches to investigate the current extent of SWI and potential future threats associated with sea-level rise in Australia's coastal irrigation areas. Nation et al. (2008) included a brief overview of management approaches for addressing SWI. Their study brought together a range of datasets, including groundwater salinity and elevation data, surface topography, and land-use information (including crop types and areas under irrigation).

Nation et al. (2008) plotted the maximum total dissolved solids (TDS) concentrations measured in individual coastal aquifer piezometers. The spatial distribution indicated that Queensland had the greatest number of irrigation regions characterised by higher salinity values, with TDS exceeding 6000 milligrams per litre (mg/L) (the area studied included the Bundaberg, Burnett, and The Burdekin and Pioneer Valley irrigation areas). 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 sea water, such as relic sea water, agricultural activities and rock dissolution, since only the TDS values were assessed.

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

Several inundation scenarios were also 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:

- Less than 1 m AHD representing areas most susceptible to SWI and inundation due to sea-level rise
- Less than 5 m AHD representing areas susceptible to inundation due to storm surges
- Less than 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). It was estimated that 46 060 hectares, or 1.4 per cent 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 salinisation. The degree to which productivity of this coastal irrigation is reliant on groundwater supplies, rather than surface water supplies, was not quantified.

Table 1: Summary of a GIS-based analysis of irrigation areas and coastal elevation

State/ territory	*Total irrigation area (hectares)*	*Major land use*	*Area at 0–5 m AHD (hectares)*	*Area at 0–10 m AHD (hectares)*
NSW	867 516	Cropping	7 663	10 198
NT	29 899	Tree fruits	136	402
Qld	1 080 787	Sugarcane	15 706	84 749
SA	271 319	Sown grasses	9 481	16 839
Tas	128 795	Cropping	2 922	6 837
Vic	837 886	Modified pasture	9 624	23 018
WA	55 789	Vine fruits	528	2 814
Total	3 271 991	Cropping	46 060	144 858

Source: After Werner et al. (2008)

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. Some areas within New South Wales, Tasmania and the Northern Territory warranted further assessment because there were signs indicating a vulnerability to SWI, such as lowered groundwater elevations, but no documented evidence of any SWI investigation.

3.2 State and territory studies

The review of literature combined with a stakeholder workshop attended by state and territory representatives, identified a number of locations around the coastline of Australia where the incidence of SWI has been reported (Figure 3). Cases of SWI are reported in each state and the Northern Territory; however, the extent of monitoring and publicly available information specific to SWI is highly variable. Appendix 1 tabulates information from available literature of reported occurrences of SWI or where it has been perceived as a threat in coastal aquifers around Australia. Appendix 1 includes information on the location, key references, aquifer settings, occurrences of SWI, driving factors, remediation strategies and management actions for each site. The tables in Appendix 1 also summarise the perceived level of assessment (Ivkovic et al. 2012b).

A summary of previous Australian studies where SWI impacts have been recognised and the extent of investigations are provided in the following state/territory summaries.

Figure 3: Locations where the threat of SWI has been identified

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. The overall threat 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 (Table 1-1 in Appendix 1). However, the lack of data makes it impossible to be definitive.

3.2.2 New South Wales

Limited information has been published on SWI in New South Wales. SWI was reported in the Botany Sands aquifer near Sydney airport in the 1960s, as a consequence of extracting groundwater for industrial purposes (Timms et al. 2008), and at Stuarts Point, where below average rainfall recharge and increased extraction led to localised increases in aquifer salinity within the coastal sands (DNR 2006) (Table 1-2 in Appendix 1). Other areas that have been reported to be potentially at threat of SWI include the Stockton, Hat Head and Clarence River floodplains.

3.2.3 Victoria

The Werribee River Delta is the only site in Victoria where SWI was found to be documented. It was identified within a bore adjacent to Port Phillip Bay (Table 1-3 in Appendix 1). Seawater influx into the basalt aquifer was reported to have occurred as a consequence of high groundwater demand during a severe drought between 2002 and 2004 (SKM 2005). Other areas in Victoria that are potentially at risk of SWI include Point Nepean, the Gippsland region (Orbost, Sale and Venus Bay) and the Koo Wee Rup, Nullawarre and Yangery areas.

3.2.4 South Australia

The main areas where SWI had been reported in South Australia are the Le Fevre Peninsula suburb of Adelaide and Robinson Basin in the Eyre Peninsula (in which up-coning was identified) (Table 1-4 in Appendix 1); excessive groundwater extractions, coupled with below average rainfall recharge (associated with droughts), are the key drivers of SWI in both areas. There are also concerns of SWI and ongoing investigations in the Port MacDonnell area. Other areas potentially vulnerable to SWI include the Adelaide region's confined aquifers, Willunga Basin, and groundwater basins in Eyre Peninsula hydraulically connected to the sea, such as Uley South.

3.2.5 Western Australia

Western Australia had the greatest number of areas where the occurrence of SWI has been reported, including Perth (Cottesloe Peninsula), Bunbury, Busselton, Carnarvon, Esperance, Cape Range/Exmouth and the coastal Kimberley (Derby and Broome) regions (Table 1-5 in Appendix 1). Other areas potentially vulnerable to SWI include the Northern Swan Coastal Plain (Jurien, Dongara, Leeman), Albany, and Rottnest Island. Groundwater extractions coupled with below average rainfall recharge (associated with droughts) are the key driving factors in all cases.

3.2.6 Northern Territory

No occurrences of SWI were documented for the Northern Territory. The areas potentially at threat of SWI include the Darwin Rural Area (Howard Springs, McMinns and Lambell's Lagoon) and some of the aquifers supplying coastal Aboriginal communities (e.g. Warruwi, Milingimbi, Milikapitia, Ngukurr); however, the investigations specifically into SWI are limited and so it is difficult to gauge the level of threat (Table 1-6 in Appendix 1). All of the aquifers of interest are fractured rock aquifer types, which respond rapidly to seasonal variations in recharge and extraction. In all cases, the main driving factor potentially leading to SWI is dry-season increases in groundwater extraction volumes exceeding the available storage. A current study by Geoscience Australia (Tan et al. 2012) uses airborne electromagnetics to determine areas potentially at risk to SWI in the Northern Territory. The results of this study were not released as at July 2012, when this report was published.

3.2.7 Queensland

Queensland is similar to Western Australia in that it has a large number of documented sites where SWI has been reported, and the literature includes some of the most comprehensive SWI investigations in Australia (Table 1-7 in Appendix 1). The locations where SWI has been reported include Bribie Island, the Pimpana Coastal Plain, The Burdekin River Delta, Pioneer Valley, Bowen and Burnett–Bundaberg irrigation areas. Minor reporting was available for the Mitchell region of Cape York, which is also potentially at threat of SWI.

3.3 Summary

Based on the literature review undertaken for this project (Ivkovic et al. 2012a), it is evident that the most comprehensive SWI investigations have been completed for the coastal aquifer systems in Queensland, and to a lesser degree in Western Australia and South Australia. This is consistent with the findings of Werner et al. (2010).

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 The 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, Albany and Esperance (Western Australia) and Uley South in the Southern Eyre Peninsula (South Australia), as well as other centres reliant on groundwater, are also perceived to be of high value and consequently have been under increasing investigation and monitoring.

In contrast, there have been few investigations where aquifers are perceived to be of lower economic value or where the aquifers may be of low productivity and of localised importance, and yet these aquifers may still be vulnerable. It is noted that many higher economic value aquifer systems at risk of SWI have not been studied in detail.

4. Seawater intrusion vulnerability assessment

A range of data and information was gathered in the course of this project to assess the vulnerability of Australian coastal aquifers to SWI. This SWI vulnerability assessment examines the data to evaluate SWI at national and local scales. National, regional and local datasets were used in the assessment, and the various data sources are summarised in Section 4.2. This chapter summarises the datasets selected and the methods used to produce a first-pass national assessment of SWI in Australia.

While it would be ideal to characterise SWI vulnerability of aquifers for the whole Australian coastline, this was not possible within the project scope since insufficient data are available at both national and local scales to undertake such an analysis. Although some of the technical assessments in this chapter provide information for large parts of Australia's coast (e.g. the VFA, coastal aquifer typology and Digital Elevation Model–DEM), many are restricted to several CSAs where detailed information was available for analysis. Such detail was required for a thorough, integrated assessment of SWI vulnerability that could consequently be undertaken only for the CSAs (see Section 5.1). However, the analytical approaches that provide greater coverage, such as the VFA and coastal aquifer typology, may provide a first-pass analysis of SWI vulnerability indicators outside the CSAs. Where data are available, identification of SWI vulnerability indicators may highlight areas where more intensive local investigations are warranted to allow full assessments of vulnerability.

Local investigations have been used to develop a refined understanding of the major coastal hydrogeology types around Australia in different hydrogeological settings and in areas of varied groundwater uses. Detailed information was available for 27 CSAs, and comprehensive analyses were applied to these individual sites. The CSAs were selected not only to cover different jurisdictions, geologies and land uses but also because there was sufficient data available for the analytical methods presented below. Many of the CSAs have had some prior form of SWI monitoring, or were identified by state/territory agencies as areas potentially vulnerable to SWI. The CSAs are within groundwater management units or equivalent groundwater management areas, as shown in Table 2. Stakeholder communication identified no CSAs in Tasmania, as SWI was not recognised as a current problem at the time of the project and there was limited hydraulic data available to analyse a CSA in the state.

Both the present-day vulnerability to SWI and the possible changes in vulnerability into the future are assessed in this project. As outlined in Chapter 1, the assessment employed five major components of data evaluation:

- Vulnerability factor analysis (VFA): a first-pass, regional assessment of SWI vulnerability from available national data (Section 4.2);
- Coastal aquifer typology: a framework for classifying hydrogeological conditions of Australian coastal aquifers (Section 4.3);

- Mathematical analysis: a first-order mathematical assessment of steady-state SWI extent and propensity for change (Section 4.4);
- SWI vulnerability indexing: qualitative and quantitative SWI vulnerability indexing methodologies developed to assess the key SWI drivers for each CSA (Section 4.5);
- Future influences: an assessment of the future impacts of sea-level rise (based on current land surface elevation) and population growth (Section 4.6).

The outcomes from these five components of evaluation are integrated into an overall assessment of SWI vulnerability in Australia in Chapter 5.

Table 2: Case study areas grouped by state and territory

State/ territory	*Number of areas*	*Case study area locations*	*Groundwater management unit*
SA	5	Adelaide Metropolitan Le Fevre Peninsula Port MacDonnell Uley South Willunga	Central Adelaide PWA Central Adelaide PWA Lower Limestone Coast PWA Southern Basins PWA McLaren Vale PWA
WA	10	Albany (Harbour and Ocean sides) Broome (Cable Beach and Coconut Wells) Busselton Bunbury Carnarvon Cottesloe Peninsula Derby Esperance Exmouth/Cape Range Perth, Whitfords	Albany Broome Busselton-Capel Bunbury Carnarvon Perth Derby Esperance Gascoyne Whitfords
NT	1	Darwin Rural, Howard Springs	Darwin Rural
Qld	5	Bowen The Burdekin Burnett Heads (Moore Park and Bargara) North Stradbroke Island Pioneer	Bowen The Burdekin Bundaberg North Stradbroke Island Pioneer
NSW	4	Botany Hat Head Stockton Stuarts Point	Botany Sandbeds Macleay Coastal Sands Tomago-Tomaree-Stockton Sandbeds Stuarts Point Sandbeds
Vic	2	Point Nepean Werribee	Nepean Deutgam
Tas	0	__	__
Total number of case study areas	**27**		

(PWA, prescribed wells area)

4.1 Summary of national and state/territory data

The existing national and state/territory datasets that have been collected for the project are summarised in Appendix 2. These datasets include information relating to groundwater, hydrogeology, hydrology, climate, coastal environments, topography, geology, land use, landscape, tides and population.

Of the large volume of national and state/territory datasets collected, only selected datasets or parts of datasets have been used in this project. For example, many datasets were clipped to 15 km inland from the coast so that efforts could be concentrated on the coastal interface regions and those most affected by SWI.

4.1.1 National-scale hydrogeology map

National-scale hydrogeology datasets were used from the 1:5 000 000 hydrogeology map of Australia (Jacobson and Lau 1987) that provided information on the principal aquifers. 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. This information was used to inform the aquifer typologies.

4.1.2 Groundwater data

Groundwater data from bores located within 15 km of the coastline were collected from state and territory water agencies. The key datasets included 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 were compiled from Australian Water Resources 2005 (AWR 2006). Groundwater data collected were processed and filtered where possible to remove erroneous measurements for the purposes of GIS and time-series analysis. Most of the high vulnerability category processed groundwater data indicators (see Section 4.2) were validated by the respective state/territory hydrogeologists. Groundwater-related data were used in all components of the project.

4.1.3 Climate data

The Köppen-Geiger system of climate classification (Peel et al. 2007) that was selected for use in this project is based on mean annual precipitation, mean annual temperature and seasonality using historical data collected over the 1930 to 2010 period. The Köppen-Geiger classification is commonly used in climate studies, and it was selected to form part of the coastal aquifer typology applied in the national analysis because rainfall, temperature and associated seasonal patterns can, to varying degrees, influence groundwater recharge and extraction patterns.

4.1.4 Rainfall

Historical monthly rainfall data were 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.

4.1.5 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 km inland buffer to identify flat, low-lying areas below 15 m AHD.

4.1.6 Population

Population Census data were collected from the Australian Bureau of Statistics (ABS) website for locations that represent the SWI CSAs (see ABS 2007).

4.1.7 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 with respect to the CSAs were used in the qualitative indexing method.

4.1.8 Geology

The suitability of national geology datasets from the Geoscience Australia 1:1 000 000 geology map (Raymond and Retter 2010) for identifying principal aquifer types was assessed. However, the geology datasets were found to have shortcomings and were thus unsuitable for this purpose. The national-scale hydrogeology map (Jacobson and Lau 1987) was used instead.

4.1.9 Groundwater salinity

The 1:5 000 000 hydrogeology 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 higher salinity regions along the coast (>5000 mg/L).

4.1.10 Hydrogeomorphic mapping

National-scale geology and landform datasets from the 1:5 000 000 national-scale hydrogeomorphic map of Australia (GA and BRS 2007) were assessed for use in identifying the principal aquifer types. However, the hydrogeomorphic mapping was found to have shortcomings and was thus unsuitable for this purpose. The national-scale hydrogeology map (Jacobson and Lau 1987) was used instead.

4.1.11 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 literature review technical report (Ivkovic et al. 2012a).

4.2 SWI vulnerability factor analysis

The vulnerability factor analysis (VFA) was undertaken to provide a first-pass, regional assessment of SWI vulnerability indicators in Australia's coastal areas based on nationally available datasets. The full VFA is presented in Cook et al. (2012) and reference should be made to that document for a detailed description of methodology, datasets, results and limitations. It is emphasised that the VFA does not contain sufficient information to conclusively determine an area's SWI vulnerability level since such an assessment requires consideration of site-specific factors that is not practical at a national scale. The VFA contributes to the final SWI vulnerability assessment in Chapter 5 where the VFA, coastal aquifer typology, mathematical analysis and both quantitative and qualitative indexing are considered collectively.

4.2.1 Vulnerability factor analysis methodology

The VFA entailed spatial and temporal analysis of state/territory groundwater data to identify locations that may have high SWI vulnerability. Although additional factors are relevant when assessing vulnerability of groundwater systems to SWI, the VFA was restricted to a consideration of the following parameters due to constraints on data availability:

- groundwater levels (minimum groundwater level, inter-decadal changes in groundwater level and groundwater-level trends)
- rainfall trends
- groundwater salinity (maximum salinity and inter-decadal changes in salinity)
- groundwater extraction (locations and rates).

The VFA focused on areas situated within 15 km of Australia's coastline since SWI impacts were considered unlikely to extend further inland in most areas.

The broader SWI VFA study assessed both national and state/territory level data. This summary reports on the national-scale assessment only. Results of both the national-scale and state/territory scale analyses are available in Cook et al. (2012). All data are presented for individual boreholes in the state/territory assessments in Cook et al. (2012) which provides a finer scale assessment than the national approach. The national-scale VFA assessment highlights areas where groups of three or more data points (boreholes) within a 5 km radius satisfied the assessment criteria for groundwater-level and salinity data. This approach was useful for assessing the general vulnerability of large-scale areas and reducing the likelihood of classifications based on single anomalous measurements. The individual VFA parameters are discussed in Sections 4.2.2 to 4.2.5. The results are shown graphically in Appendix 3.

Figure 4 provides a reference map for localities discussed throughout this chapter. Due to the large number of data points in areas along Australia's coast, the place descriptions in Sections 4.2.2 to 4.2.5 are necessarily general; they refer to the locality as well as surrounding areas. Reference should be made to the state/territory analyses in Cook et al. (2012) for more precise locations of vulnerability indicators.

Figure 4: National VFA locality reference map showing the 15 km coastal buffer

4.2.2 Groundwater-level analysis

Groundwater-level data provided by each jurisdiction are analysed below to identify minimum recorded groundwater levels and groundwater-level changes as indicators of SWI vulnerability levels.

4.2.2.1 Minimum groundwater levels

In the VFA, lower groundwater levels are considered to indicate a greater potential for SWI. Minimum groundwater levels measured prior to 2000 and in the decade 2000–2009 are presented in Figures 3-1 and 3-2 respectively (Appendix 3). Groundwater levels are classified according to the following classes (see Cook et al. (2012) for a full justification of these categories):

- <0 m AHD. This is an approximation of mean sea level; it is the highest vulnerability indicator class since freshwater heads may be insufficient to oppose the encroachment of sea water in these areas.
- 0–2.5 m AHD. Most areas in Australia are anticipated to have TWOH (see Chapter 2) below 2.5 m. With TWOH of 2.5 m, migration of water from the coast inland may be possible where water levels inland are below 2.5 m AHD.
- >2.5 m AHD. This is the lowest vulnerability class where SWI is unlikely, noting that this does not take into account up-coning and migration of the wedge toe.

The discussion below focuses on areas showing the highest SWI vulnerability indicator category of water levels <0 m AHD. However, water levels between 0 and 2.5 m AHD in Figures 3-1 and 3-2 may also suggest some vulnerability to SWI in these areas.

Groundwater-level data for the most recent decade (2000 to 2009) were considered separately from pre-2000 data to highlight areas that have recently shown groundwater-level indicators of vulnerability. However, the lack of recent vulnerability indicators cannot be used to infer a reversal in vulnerability trends in many areas since they may in part be due to a lack of recent data. When making such an assessment, Figures 3-1 and 3-2 should be considered together.

Historical minimum groundwater levels

Minimum groundwater levels reported prior to 2000 are summarised in Figure 3-1. Where data were available, the general areas (and surrounds) showing boreholes with groundwater levels <0 m AHD, indicating the possibility of high vulnerability to SWI, included:

- Western Australia: Cambridge Gulf (east head), Derby, Broome, Exmouth (and an area around 50 km south of Exmouth), Carnarvon, Kalbarri, around 15 km south of Dongara, several areas on the Swan Coastal Plain (including several places between Jurien Bay and Mindarie, Perth, Munster, the land around Peel Inlet, Harvey Estuary and Lake Preston, Australind, Eaton, Bunbury, several areas between Capel and Busselton, and several areas between Abbey and Dunsborough), Albany and Esperance
- Queensland: Port Douglas, north of Cairns (Holloways Beach), Innisfail, Kurrimine Beach, Ingham, The Burdekin, Bowen, Proserpine, Pioneer Valley and Mackay, Bundaberg and Burnett Heads, Maryborough, Bribie Island and Brisbane
- New South Wales: Evans Head, around 20 km south-west of Port Macquarie, Taree and surrounds, Botany, Bodalla and Bega
- Victoria: Brooklyn, Koo Wee Rup, Phillip Island and Sale
- South Australia: Streaky Bay, Port Kenny, Venus Bay, Elliston, Coffin Bay and surrounds, Uley South, the Port Lincoln area, Port Germein, Edithburgh, Stansbury, Northern Adelaide Plains, Adelaide, McLaren Vale, Aldinga Beach, Encounter Bay, Goolwa, Narrung, Kingston, the area from Robe to Lake St Clair and around 14 km south-east of Millicent.

Minimum groundwater levels, 2000–2009

Minimum groundwater levels reported for the most recent decade (2000 to 2009) are summarised in Figure 3-2. Where data were available for the period, the areas showing boreholes with groundwater levels <0 m AHD, indicating the possibility of high vulnerability to SWI, included:

- Western Australia: Carnarvon and the Swan Coastal Plain (including Mindarie, Perth, Munster, Peron, the land around Peel Inlet, Harvey Estuary and Lake Preston, Australind, Eaton, Bunbury, Capel, Abbey and Dunsborough)
- Queensland: Port Douglas, north of Cairns (Holloways Beach), Ingham, The Burdekin, Bowen, Pioneer Valley and Mackay, Bundaberg and Bribie Island
- New South Wales: Stuarts Point, Taree and the Myall Lake area
- Victoria: Werribee, Phillip Island, French Island, the Koo Wee Rup area, Venus Bay, Yarram, Sale and Bairnsdale
- South Australia: Streaky Bay, Uley South, Port Lincoln, Northern Adelaide Plains, Adelaide, McLaren Vale, Aldinga Beach, Goolwa, Narrung, Meningie, the area from Robe to Lake St Clair and around 14 km south-east of Millicent.

4.2.2.2 Groundwater-level changes

Declining groundwater levels near the coast may be caused by increases in groundwater extraction or decreases in recharge, or both. They may indicate vulnerability to SWI since, if water levels fall sufficiently where aquifers are connected to the sea, intrusion of sea water may occur.

Changes in groundwater levels were assessed by two different methods in the VFA:

1. Inter-decadal change: the minimum groundwater level measured in the decade 1990–1999 was subtracted from the minimum groundwater level measured in the decade 2000–2009.
2. Linear trend analysis: for boreholes with sufficient time-series groundwater-level data, a straight line was fitted through the data points to provide a measure of yearly level change.

The inter-decadal change analysis is useful since it provides a total estimate of groundwater-level change. However, the linear trend analysis identifies sustained trends in groundwater-level changes, and unlike the inter-decadal change method, it is not based on single extreme measurements that may not be indicative of normal conditions (groundwater levels may display short-term fluctuations in response to a variety of factors including atmospheric pressure changes, rainfall events, changes in surface loading and intermittent pumping). It is therefore useful to consider the results of both analyses together when assessing groundwater-level change as an indicator of vulnerability to SWI.

Inter-decadal changes in minimum groundwater levels

Inter-decadal changes in minimum groundwater levels are presented in Figure 3-3 (Appendix 3). As noted above, this data analysis method is prone to skewing by extreme or anomalous measurements. However, across the relatively large dataset, spatial category clusters are considered likely to be indicative of general area trends.

Figure 3-3 indicates that the greatest inter-decadal declines in minimum groundwater levels (>5 m) occurred in the following areas:

- Western Australia: the Swan Coastal Plain (including from Mindarie to Perth, from the Munster to Peron area and surrounds, and between Abbey and Dunsborough)
- Victoria: Torquay and Yarram
- South Australia: Port Germein, Adelaide, McLaren Vale and Goolwa.

In addition to the above localities, the following areas showed considerable inter-decadal declines in minimum groundwater levels of between 2.5 and 5 m:

- Western Australia: the Swan Coastal Plain (including the area around the Peel Inlet and around Capel)
- Queensland: The Burdekin and North Stradbroke Island
- Victoria: Koo Wee Rup
- South Australia: Uley South, the Northern Adelaide Plains and Aldinga Beach.

Groundwater elevation trends

As outlined above, several factors may result in short-term groundwater-level fluctuations. Such short-term fluctuations make longer term groundwater-level trends difficult to identify at locations where only limited measurements have been made. Consequently, groundwater elevation trends were only included in the VFA where:

- greater than five water level readings existed for a borehole
- monitoring periods were greater than one year
- the correlation coefficient (R^2) between the straight line trend and measured data points was greater than or equal to 0.5.

Groundwater elevation trends are presented in Figure 3-4. In the analysis, decreasing groundwater-level trends are considered to highlight areas that may have high SWI vulnerability or become vulnerable if water levels continue to fall. Under the national analysis, no groundwater elevation trends were available for Tasmania and relatively few data points were present in New South Wales and the Northern Territory, both of which showed increasing groundwater trends. In the remaining states, although some boreholes showed increasing trends in groundwater elevation, most areas where information was available showed decreasing groundwater levels in a number of places. Strong declining groundwater-level trends of more than 0.5 m/year were identified at several locations including:

- Western Australia: Derby (trends >1 m/year were recorded here) and the Swan Coastal Plain (from Mindarie to Perth and surrounds had trends >1 m/year; other areas with trends >0.5 m/year included the area up to 15 km north of Mindarie and from Munster to Peron)

- Queensland: Proserpine, Pioneer Valley and Mackay, and North Stradbroke Island
- Victoria: Brooklyn
- South Australia: Adelaide, Goolwa, and around 15 km south-east of Millicent (trends >1 m/year were recorded here).

Areas with decreasing groundwater-level trends between 0.25 and 0.5 m/year not identified above included:

- Western Australia: the Swan Coastal Plain from Peron to the Peel Inlet
- Queensland: The Burdekin
- Victoria: Koo Wee Rup
- South Australia: the Uley South and Port Lincoln area, Port Germein, Northern Adelaide Plains and McLaren Vale.

Several areas in Figure 3-4 show declining groundwater-level trends <0.25 m/year. Although at the current rates of decline these areas are likely to be more easily managed than areas with greater decreasing trends, such trends may still be indicators of high SWI vulnerability. SWI may become an issue in these areas over a longer timeframe although, if groundwater levels are currently low (see Figure 3-2), they may take on greater significance.

4.2.3 Rainfall trend analysis

Change in rainfall volume over time may be a useful indicator of potential changes to recharge, which can in turn affect groundwater levels. Although it is acknowledged that confined aquifers may have recharge zones distant from the areas they underlie, changes in rainfall volumes in an area commonly affect recharge to underlying aquifers and hence groundwater levels. In addition to directly changing groundwater levels through recharge, changes in rainfall volume can affect the availability of surface water and thereby affect groundwater extraction. In this way, rainfall changes can also indirectly affect groundwater levels. When both direct and indirect impacts are included, it is considered that rainfall may be a useful indicator of stress to groundwater systems.

To assess increasing or decreasing trends in rainfall volumes in Australia’s coastal areas, historical monthly rainfall data were obtained from the Bureau of Meteorology for selected weather stations along the coastal margin. Cumulative deviation of monthly rainfall from long-term average monthly rainfall (calculated as the cumulative sum of monthly rainfall less long-term average rainfall) was plotted for the period 2000 to 2009. An increasing trend to the cumulative plot indicates times when rainfall was greater than average and, conversely, a decreasing trend signifies lower than average rainfall periods.

The results are shown spatially in Figure 3-5 (Appendix 3). It is apparent that most areas around the Australian coast experienced lower than average rainfall during the 2000–2009 period. In these areas, lowered recharge may have contributed to decreasing groundwater levels and may also have resulted in increases in groundwater extraction, leading to further groundwater-level decline. However, it is noted that drought around the country has eased in 2010 and 2011, and a reversal in rainfall trends is evident in some areas. As such, the rainfall trends in Figure 3-5 may not remain good indicators of vulnerability and should be updated in future assessments.

4.2.4 Groundwater salinity analysis

Groundwater salinity data were analysed to identify maximum salinity and changes in maximum salinity as indicators of SWI vulnerability levels. In the VFA, the concentration of TDS in mg/L has been used as a measure of salinity. The methodology to prepare and filter the TDS concentration dataset is outlined in detail in Cook et al. (2012). In most instances, TDS concentrations were estimated from electrical conductivity (EC) measurements using the equation TDS (in mg/L) = 0.64 x EC (in micro-siemens per centimetre, or uS/cm). Although factors such as temperature and ionic composition of groundwater affect EC readings making conversion to TDS concentrations inconsistent, this equation is considered to provide an approximation suitable for the current broad-scale national analysis.

Although average TDS concentration for sea water is typically reported to be around 35 000 mg/L, some authors (e.g. Hoang et al. 2009) suggest it may be as high as 38 500 mg/L in certain areas around Australia. Data from some jurisdictions suggest that a conversion factor for EC to TDS of 0.55 may be appropriate in local areas (Cook et al. 2012). An EC of 70 000 uS/cm equates to a TDS concentration of 38 500 mg/L using a conversion factor of 0.55 but to 44 800 mg/L using a conversion factor of 0.64. On this basis, data on TDS concentration of up to 45 000 mg/L was included in the VFA, since higher values are likely to be either spurious readings or areas where TDS is not indicative of SWI but other salinity concentration mechanisms. It is noted that this approach may result in inclusion of high-salinity water in the VFA that is not sea water and the requirement for site-specific analysis when assessing SWI is emphasised.

4.2.4.1 Maximum salinity measurements

Historical and recent decade maximum groundwater salinity readings are shown in Figures 3-6 and 3-7 (Appendix 3) respectively. On the figures, TDS concentrations are grouped into the following categories (refer to Cook et al. (2012) for further discussion):

- <1000 mg/L: considered to represent relatively fresh water that is suitable for most uses
- 1000–3000 mg/L: generally unsuitable for drinking water but suitable for most stock watering, irrigation of some salt-tolerant crops and some domestic and industrial purposes
- 3000–10 000 mg/L: suitable for limited stock watering and industrial processes
- >10 000 mg/L: unsuitable for most uses with the exception of limited industrial processes and temporary sheep watering.

Historical maximum salinity measurements

Historical maximum TDS concentrations are shown in Figure 3-6. Of particular interest in the VFA are those areas where groundwater has TDS concentrations <3000 mg/L since it is suitable for a wide range of uses. Such groundwater is more likely to be exploited than more saline groundwater and as such it may be more prone to SWI.

Figure 3-6 shows areas where groundwater with low maximum salinity (TDS concentrations <3000 mg/L) is in close proximity to (defined here as within 1 km) groundwater with high maximum salinity (TDS concentrations >10 000 mg/L). Such locations were considered in the analysis to highlight areas that may have high SWI vulnerability since extraction of low-salinity groundwater could cause intrusion of higher salinity water identified nearby. However, this analysis does not include information on whether salinity measurements are within the same aquifer systems or whether migration from an area of high salinity to an area of low salinity is possible. Nearby high- and low-salinity measurements may not indicate high vulnerability to SWI in areas where migration is implausible, and the results should therefore be considered in conjunction with site-specific information to assess vulnerability to SWI.

Areas where groundwater with maximum TDS concentrations <3000 mg/L was within 1 km of groundwater with maximum TDS concentrations >10 000 mg/L included:

- Western Australia: Broome, Karratha, Carnarvon, the Swan Coastal Plain (near Mindarie and Perth and in several areas south of Perth including Munster, Peron, land around the Peel Inlet, Harvey Estuary and Lake Preston, Eaton, Bunbury and Abbey) and Rottnest Island
- Northern Territory: the area south of Keep River, the area north-east of Darwin and in the Baniyala area
- Queensland: Port Douglas, north of Cairns (Holloways Beach), The Burdekin, Bowen, Pioneer Valley and Mackay, Yeppoon, Bundaberg, Burnett Heads, Maryborough, Brisbane and Elanora
- New South Wales: east and west of Taree and south-east of Bega
- Victoria: Sale
- South Australia: Bookabie, Penang and Lake MacDonnell (and surrounding areas, noting that Lake MacDonnell has a history of salt production) typically recorded high maximum TDS concentrations >10 000 mg/L with relatively few maximum TDS concentrations <3000 mg/L. A greater proportion of maximum TDS concentrations <3000 mg/L were present near Streaky Bay, Port Kenny, Venus Bay, in many areas between Elliston and Coffin Bay, Port Lincoln, Tumby Bay inland from Port Gibbon, in the area around Port Germein, Moonta, from the Port Rickaby area in many locations around the peninsular to around 15 km north of Stansbury, from the Northern Adelaide Plains around the coast to Goolwa, Narrung and in the Meningie–Coorong area. The majority of maximum TDS concentrations were <3000 mg/L with relatively few maximum TDS concentrations >10 000 mg/L in Uley South, in the area of Kingston, in several places from Robe to Millicent, Carpenter Rocks and on Kangaroo Island.

Maximum salinity measurements, 2000–2009

Figure 3-7 shows the maximum TDS concentrations measured during 2000–2009. Attention is drawn to those areas displaying groundwater with maximum TDS concentrations <3000 mg/L which is likely to be suitable for a wide range of uses. Areas where groundwater with maximum TDS concentrations <3000 mg/L was within 1 km of groundwater with maximum TDS concentrations >10 000 mg/L included:

- Western Australia: Whim Creek, Exmouth, Carnarvon, the Swan Coastal Plain (including Mindarie, Perth and Lake Preston) and Bremmer Bay
- Queensland: north of Cairns (Holloways Beach), The Burdekin, Bowen, Pioneer Valley and Mackay, Yeppoon, Bundaberg, Burnett Heads and Eli Waters and surrounds
- New South Wales: south-west of Port Macquarie
- South Australia: Streaky Bay, Wallaroo, Northern Adelaide Plains, Adelaide, McLaren Vale, Aldinga Beach, Kangaroo Island, Goolwa and Meningie.

4.2.4.2 Inter-decadal changes in maximum salinity measurements

Increases in groundwater TDS concentrations may indicate the occurrence of SWI in coastal environments. They are considered to serve as indicators of SWI vulnerability level since, if TDS concentrations have increased in an area, further SWI may occur without appropriate management. It is noted that when salinity in groundwater bores increases due to SWI, the bores are often abandoned. This could result in under-reporting of TDS increases.

To provide an indication of the magnitude of recent TDS concentration changes, the maximum TDS concentration measured in the decade 1990 to 1999 was subtracted from the maximum TDS concentration measured in the decade 2000 to 2009 for boreholes where data were available. The results are shown spatially in Figure 3-8 (Appendix 3). As per the methodology for inter-decadal changes in groundwater elevations in Section 4.2.2, this method is prone to being affected by extreme measurements that may not be indicative of normal conditions. However, the national VFA approach of reporting measurements only where three or more boreholes within a 5 km radius fall within the same category will help to remove anomalous readings. The results are therefore considered useful indicators of potential increase in TDS concentrations and therefore vulnerability to SWI.

Only the Mindarie area (Swan Coastal Plain) in Western Australia and Streaky Bay in South Australia showed increases in the maximum TDS concentration by more than 10 000 mg/L. Carnarvon and Perth in Western Australia and The Burdekin, Bowen, Pioneer Valley and Mackay areas of Queensland showed maximum TDS concentration increases in the range 3000 mg/L to 10 000 mg/L.

Maximum TDS concentration increases in the range 1000–3000 mg/L are also considered to be significant and areas showing inter-decadal increases in that range not listed above included:

- Western Australia: the Harvey Estuary area (Swan Coastal Plain)

- Queensland: the Bundaberg and Burnett Heads area
- Victoria: Koo Wee Rup
- South Australia: Northern Adelaide Plains and McLaren Vale.

Although the above areas have shown larger increases in maximum TDS concentrations, even concentration increases of more than 1000 mg/L can be significant since water with TDS concentrations above 1000 mg/L is considered in many areas to be unsuitable for human consumption. The general water use in an area should therefore be taken into account when assessing the significance of the increases in TDS concentration shown in Figure 3-8.

4.2.5 Groundwater extraction

Groundwater extraction rate relative to aquifer recharge is a key indicator of vulnerability to SWI and was included in the qualitative indexing in Section 4.5. Where groundwater is extracted at a rate greater than recharge, groundwater levels will fall and, in coastal areas, SWI may result. Recharge data at a suitable scale were not available nationally for the VFA (local information on recharge is required to assess if local extraction rates exceed recharge volumes). The VFA could therefore only focus on groundwater extraction rate to highlight areas of high groundwater use that could result in SWI. However, the limitations of not incorporating recharge estimates into the VFA assessment are emphasised.

The national VFA focused on groundwater bores classed as “production bores” by jurisdictions. The datasets specifically exclude stock and domestic supply bores, focusing on large volume extractors. Groundwater extraction data provided by the jurisdictions were the least complete and consistent of the data available for the VFA. The time periods that extraction records cover are variable and groundwater extraction data for individual bores were only available for Western Australia, Queensland, Victoria and South Australia. For the purposes of national assessment, extraction volumes for the most recent year when a reasonably complete dataset of groundwater extraction was available were selected for each of the four states considered:

- Western Australia: 2010–11 financial year
- Queensland: 2010 calendar year
- Victoria: 2009–10 financial year
- South Australia: 2007 (Lower Limestone Coast) and 2008 (elsewhere) calendar years.

4.2.5.1 Groundwater extraction rates

Figure 3-9 (Appendix 3) presents groundwater extraction data for production bores in Western Australia, Queensland, Victoria and South Australia. For the purposes of discussion, the bores have been classified according to the following categories:

- <50 megalitres per year (ML/year)
- 50–250 ML/year

- 250–500 ML/year
- 500–1000 ML/year
- >1000 ML/year.

As outlined above, in the context of SWI it is difficult to attach significance to extraction rates in the absence of recharge data. The information presented is best considered at a site-specific level in conjunction with other available information (see Section 5.1). However, the following areas contained individual production bores with particularly high extraction rates >1000 ML/year:

- Western Australia: the area around 20 km north of Dongara, the Swan Coastal Plain (near Mindarie, Perth, Munster, Australind and Eaton)
- Queensland: The Burdekin, Pioneer Valley and Mackay, and Bundaberg
- Victoria: Portland, the area near Torquay, Yarram and Sale
- South Australia: Uley South.

Areas containing production bores with extraction rates in the range 500–1000 ML/year that are not listed above include:

- Victoria: the area between Portland and Port Fairy, and Nullawarre
- South Australia: Port Germein, Le Fevre Peninsular and Adelaide, and the Lower Limestone Coast.

4.2.5.2 Cumulative groundwater extraction rates

The above analysis does not take into account the cumulative impacts of multiple extraction bores. It is apparent from Figure 3-9 that several areas around the coastline contain relatively large numbers of production bores that fall into the lower extraction categories. In Figure 3-10, a 5 km grid has been overlain on the production bore extraction data from Figure 3-9, and the extraction volumes of production bores falling within each grid cell have been summed. The final category that each cell falls into is somewhat dependent on where the grid is positioned, but in general the information shows that the following areas contain cumulative pumping within 25 km^2 grid cells >1000 ML/year:

- Western Australia: Broome, the area around 20 km north of Dongara, the Swan Coastal Plain (near Mindarie, Perth, Munster, Australind, Eaton and Bunbury) and Albany
- Queensland: The Burdekin, Pioneer Valley and Mackay, Bundaberg and Burnett Heads
- Victoria: Portland, the area near Port Fairy, Torquay, Point Nepean, Yarram and Sale
- South Australia: Uley South, Adelaide and the Lower Limestone Coast.

Areas containing 25 km^2 grid cells with cumulative pumping in the range 500–1000 ML/year not listed above include:

- Western Australia: Derby, Dunsborough and Esperance

- Queensland: Bowen
- Victoria: Nullawarre
- South Australia: McLaren Vale and Aldinga Beach.

4.2.6 Vulnerability factor analysis priority areas

There are no or limited VFA data around much of Australia's coast. A single VFA indicator of high vulnerability in an area may correspond to an area with high SWI vulnerability, and some high SWI vulnerability areas may have no data at all. However, it is useful to identify locations where numerous high vulnerability indicators are present as a mechanism to prioritise areas for further investigation and management if groundwater resources are to be developed or groundwater use is to continue.

Given the limitations with respect to rainfall and groundwater extraction data outlined above, only groundwater-level and salinity data were considered in this prioritisation assessment. The following seven categories of VFA parameters were considered to indicate high vulnerability:

1. Historic minimum groundwater levels <0 m AHD, pre 2000
2. Minimum groundwater levels <0 m AHD, 2000–2009
3. Inter-decadal decline in groundwater levels between 1990–1999 and 2000–2009 >2.5 m
4. Groundwater elevation trends >0.5 m/year
5. Historic maximum TDS concentrations >10 000 mg/L located within 1 km of maximum TDS concentrations <3000 mg/L, pre 2000
6. Maximum TDS concentrations >10 000 mg/L located within 1 km of maximum TDS concentrations <3000 mg/L, 2000–2009
7. Inter-decadal increase in maximum TDS concentrations between 1990–1999 and 2000–2009 >1000 mg/L.

Locations showing greater than 50 per cent (4 or more) of the above category indicators and at least one indicator from both groundwater-level (any of the indicators listed in points 1 to 4 above) and salinity (any of the indicators listed in points 5 to 7 above) categories were classified as priority VFA areas containing a significant proportion and range of VFA indicators. Such areas include (place names refer to the general area of interest):

- Western Australia: Carnarvon and the Swan Coastal Plain (including Mindarie, Perth, Munster, Peron, Peel Inlet, Harvey Estuary, Lake Preston and Abbey)
- Queensland: the area north of Cairns (around Holloways Beach), The Burdekin, Bowen, Pioneer Valley and Mackay, Bundaberg and Burnett Heads
- Victoria: Koo Wee Rup
- South Australia: Streaky Bay, Uley South, Northern Adelaide Plains, Adelaide, McLaren Vale, Aldinga Beach and Goolwa.

It is reiterated that there are other areas around Australia showing indicators of high SWI vulnerability and a lack of data in many areas. Omission of locations from the above list should not be taken to imply that they are not significantly vulnerable to SWI. The list simply highlights locations where considerable numbers of high SWI vulnerability indicators are present where data are available around Australia’s coast.

4.2.7 VFA limitations

The VFA is limited spatially and temporally by the availability of relevant groundwater datasets, which are described in detail in Cook et al. (2012). Much of Australia’s coastline is data poor, and the lack of SWI vulnerability indicators in these areas should not be taken to indicate that they are unlikely to be vulnerable to SWI. The figures included in Appendix 3 record where data were available for analysis, and no attempt was made to infer conditions outside these areas. However, it is noted that data-rich regions may coincide with areas of relatively high groundwater use and therefore areas where SWI may be of greater concern.

Data filtering was undertaken to remove obvious outliers and many measurements in the higher vulnerability categories have been verified by state/territory hydrogeologists. However, not all data could be verified due the volume and nature of the measurements. Although the national assessment methodology of removing data where only one or two data points within a 5 km radius fall into the same category will help to remove anomalous readings, caution is required when making assessments based on the data presented since some quality limitations may remain.

The VFA should not be considered in isolation from the other assessments of vulnerability in this report. The vulnerability factors presented in the VFA serve only as indicators of an area’s SWI vulnerability level. It was not possible at a national scale to include information on several important parameters affecting SWI vulnerability, including aquifer geometry, aquifer hydraulic properties, sea–aquifer connectivity and recharge rates. As an example, an aquifer with low water levels that is hydraulically isolated from the sea would not be vulnerable to SWI, but the VFA might identify it as an area containing vulnerability indicators since low groundwater levels suggest that SWI may occur. No distinction has been made between confined and unconfined systems, which may respond differently to stress.

Reference should be made to Cook et al. (2012) and Sections 4.2.2 to 4.2.5 above for further limitations specific to each VFA parameter considered.

4.2.8 VFA summary

The VFA provides a first-pass, regional assessment of SWI vulnerability indicators in Australia’s coastal areas based on nationally available groundwater and rainfall datasets. Although the VFA identifies locations where regionally available data suggests that areas may have high SWI vulnerability, it does not provide sufficient details to conclusively determine if areas are vulnerable to SWI or not. For a full assessment of vulnerability to SWI, additional site-specific factors require consideration. Such an approach is undertaken for the CSAs in Chapter 5 where the VFA, coastal aquifer typology, mathematical analysis and both quantitative and qualitative indexing are considered collectively to determine vulnerability to SWI.

Chapter 5 includes an assessment of how VFA vulnerability indicators for the CSAs compare to the overall CSA vulnerability rankings. Conclusions are drawn on the suitability of the VFA approach as a tool for indicating SWI vulnerability levels and prioritising geographical areas for further SWI vulnerability assessment.

4.3 Coastal aquifer typology

The coastal aquifer typology provides a framework for classifying the hydrogeological conditions of Australia's coastal aquifers in order to assess their vulnerability to SWI. The information contained within this section is a succinct extract of key elements found within the Ivkovic et al. (2012b) technical report where the full details of the coastal aquifer typology are presented.

4.3.1 Elements included within coastal aquifer typology

The coastal aquifer typology took both a top-down and bottom-up approach, utilising national-scale (top-down) and CSA (bottom-up) data. It included:

- a characterisation of the hydrogeological settings of Australia's coastal aquifers based on principal aquifer type and Köppen-Geiger climate groups
- a catalogue of simplified hydrogeological cross-sections, including typical aquifer parameters based on information obtained from 27 CSAs.

The CSAs selected for characterisation are outlined in the introductory paragraphs to Chapter 4. Simplified cross-sections prepared for each of the CSAs are presented in Ivkovic et al. (2012b). An overview of CSA typologies as well as the typical aquifer parameters found in them within 5 km of the coastline is provided in Appendix 4 (Tables 4-1 to 4-8). See Ivkovic et al. (2012b) for further details regarding aquifer conceptualisations and parameterisation.

4.3.2 Principal aquifer types and climate groups

The principal aquifer types identified in the CSAs evaluated were grouped into:

- coastal alluvium: an unconsolidated mix of gravel, sand, silt and clay deposited within the floodplains of current drainage systems
- coastal sands: dune sands of aeolian and marine origin
- sedimentary basins including three sub-types:
  - thick, unconfined, sandstone aquifers
  - deep, multiple-layered, stacked aquifers primarily composed of consolidated sediments
  - shallow, multiple-layered, stacked aquifers primarily composed of unconsolidated sediments.
- carbonates: including deposits such as limestone and dolomite, and commonly exhibiting karstic weathering profiles
- basalt aquifers: layered basalt plains where groundwater is stored primarily in fractures and vesicles

- fractured/undivided classes: older fractured sequences of mixed lithology that have undergone metamorphosis and weathering.

The climate types represented by the CSAs include tropical, arid and temperate Köppen-Geiger climate groups (Peel et al. 2007). The combination of principal aquifer type and climate group formed the basis of the coastal aquifer typology. Table 3 indicates which coastal aquifer typology each CSA is assigned to. The table highlights that currently available groundwater investigations of relevance to SWI with sufficient aquifer parameter data for mathematical analysis (a requirement for CSA selection) are primarily from areas of coastal sands, sedimentary basins and coastal alluvium. Basalt, carbonate and the fractured/undivided aquifer systems are poorly represented. Most of the CSAs are located in the temperate climate zones, reflecting Australia's population distribution and the associated extraction pressures on such groundwater systems.

It is noted that the assessment outlined above covers the CSA aquifer typologies only and is not a national assessment. The work of Ivkovic et al. (2012b) highlights that other aquifer typologies are present in coastal areas around Australia. A national assessment of typology, including a map of coastal aquifer type, would involve identification of the extent of each typology and determination of associated typical parameters. This would in turn allow the implications for SWI to be assessed on a national basis. However, such an assessment was beyond the scope of this project and it is unlikely that sufficient information existed at the time of writing to undertake it.

Table 3: Case study areas grouped by coastal aquifer typology and Köppen-Geiger climate groups using aquifer type sub-groups.

Principal aquifer types		*1) Tropical*	*2) Arid*	*3) Mediterranean Temperate, Summer Dry*	*4) Temperate, Dry Winter*	*5) Temperate, Without Dry Season*
POROUS SEDIMENTARY AND LOW-GRADE METAMORPHIC ROCKS						
Undivided[1]	Coastal Alluvium	Bowen (Qld) The Burdekin (Qld)	Carnarvon (WA)	—	Pioneer (Qld)	Burnett Heads (Qld)
	Coastal Sands	—	—	Perth, Cottesloe Peninsula (WA)	—	Botany (NSW) Hat Head (NSW) North Stradbroke Island (Qld) Point Nepean (Vic) Stockton (NSW) Stuarts Point (NSW)
	Sedimentary Basin – unconfined sandstone	—	Broome (WA) Derby (WA)	—	—	—
	Sedimentary Basin – multi-layered, consolidated, deep	—	—	Adelaide Metro (SA) Le Fevre Peninsula (SA) Bunbury (WA) Busselton (WA) Perth, Whitfords (WA) Willunga (SA)	—	—
	Sedimentary Basin – multi-layered, unconsolidated, shallow	—	—	Albany (WA) Esperance (WA)	—	—
Carbonate		—	Exmouth (WA)	Port MacDonnell (SA) Uley South (SA)	—	—
FRACTURED OR FISSURED ROCKS						
Undivided		Howard Springs (NT)	—	—	—	—
Basalt		—	—	—	—	Werribee (Vic)

[1] The undivided**,** porous sedimentary and low-grade metamorphic rocks principal aquifer class derived from the 1:5 000 000 national-scale hydrogeology map (Jacobson and Lau, 1987) was subdivided into sub-classes based on case study area information.

4.3.2.1 Principal aquifer types – typical characteristics and parameters

Tables 4-1 to 4-9 (Appendix 4) provide an overview of the CSA aquifer parameter values for each coastal aquifer type as utilised in the mathematical analysis outlined in Section 4.4. Reference should be made to Appendix 4 when reading this chapter. The ranges of parameter values provided below relate to the CSAs within each aquifer type and not necessarily to the aquifer type in general which may be present in many places outside the CSAs. In the discussion, 0 m AHD is taken to be the approximate elevation of mean sea level.

Coastal alluvium

The *coastal alluvium* aquifer types include Cenozoic unconfined to semi-confined aquifers associated with current river systems. With the exception of the carbonate aquifers, these aquifers had the highest hydraulic conductivity values in the CSAs; typical values range from 50 to 160 m/day. These aquifers are located in flat, low-lying areas where groundwater elevations are close to, or just below, sea level, with aquifers exposed to tidal influences at the river outlet. In the CSAs, coastal alluvium aquifers are characterised by relatively shallow aquifer depths (<70 m below sea level) and exhibit a relatively thin saturated aquifer thickness (<60 m). The coarse deposits within palaeochannels in the alluvium provide preferential flow paths for sea water to enter the aquifers. Since groundwater recharge in these types of aquifers primarily occurs via rainfall–runoff and associated river losses, they are vulnerable to SWI as a consequence of droughts and a drying climate when net recharge is low and freshwater heads are lowered due to a combination of groundwater extraction and reduced recharge.

Coastal sands

The *coastal sands* aquifer types include Cenozoic (mostly Quaternary), unconfined, sand dune aquifers with a maximum depth of 40 m below sea level. Typical values of hydraulic conductivity in the CSAs within this aquifer type were found to range from 3 to 150 m/day. Groundwater levels were variable, ranging from close to sea level through to >22 m AHD. These aquifers are primarily recharged by diffuse rainfall and they can store only limited amounts of fresh water relative to the amount of rainfall recharge they receive since they are usually relatively thin. Because they store limited amounts of groundwater, these systems may be vulnerable to SWI as a consequence of droughts and a drying climate when net recharge is low and where freshwater heads are lowered due to a combination of groundwater extraction and reduced recharge. These aquifers are often adjacent to lagoons that provide a source of salt water. These aquifer types may include a freshwater lens sitting over saline water, and so they are also vulnerable to up-coning from over-pumping.

Unconfined sandstone

The *unconfined sandstone* aquifer type includes Triassic to Cretaceous sandstone units that are deep (>200 m below sea level) and thick (>190 m). Typical values of hydraulic conductivity in the CSAs within this aquifer type were found to range from 1 to 15 m/day. The CSAs in this aquifer type were all located within an arid climate group setting, and receive relatively low amounts of groundwater recharge. Groundwater elevations are close to sea level. This combination of factors leads to these coastal aquifer types having one of the greatest theoretical inland SWI toe extents of all coastal aquifer types. Mitigating this vulnerability is the considerable aquifer thickness that allows for considerable storage of fresh groundwater resources.

Multi-layered, deep

The *multi-layered, deep* aquifer types include Cenozoic to Jurassic sedimentary sequences of sandstone, coarse silt and sands and minor limestone, with clay aquitards separating the aquifer systems. The upper-most, unconfined sand aquifers in these systems share characteristics with the coastal sands aquifer type. The confined aquifers are deep (100 to more than 1750 m below sea level) and thick (65 to more than 300 m), making them excellent aquifers for large-scale development. Typical values of hydraulic conductivity values in the CSAs in this aquifer type were found to range from 1 to 10 m/day. In many of these systems, the heads have been lowered as a consequence of groundwater extractions – in some cases down to as much as 21 to 24 m below sea level as is seen in the Adelaide and Perth areas where fresh groundwater is ‘mined’. The combination of large aquifer depths and thickness, with relatively low net recharge, makes the theoretical SWI toe extent within the confined aquifers relatively large, particularly in those areas where heads have been drawn down below sea level. An important mitigating factor is that some of these confined freshwater aquifer systems extend some distance out to sea (the extent of which has not been well investigated in Australia), which may result in the SWI interface occurring offshore. However, over-extraction leading to excessive declines in the piezometric surface may eventually lead to SWI onshore.

Multi-layered, shallow

The *multi-layered, shallow* aquifer types include Cenozoic, unconsolidated sediments with multiple aquifers separated by discontinuous clay aquitards. The aquifers in the CSAs within this aquifer type are relatively thin, ranging from 2 to 40 m thick, and shallow (<50 m below sea level in depth). Typical values of hydraulic conductivity in the CSAs in this aquifer type were found to range from 5 to 20 m/day. The unconfined aquifers share common features with the coastal sands aquifer types, and they are replenished by infiltration of rainfall. The deeper, underlying semi-confined aquifers receive considerable net recharge through aquifer leakage, whilst the confined aquifers receive little recharge. Because of the reliance on rainfall recharge, these aquifers are vulnerable to droughts and drying climates. In the CSAs, the deeper, Tertiary sediments are characterised by variable groundwater salinity, including brackish to saline water in some places, and extensive pumping from the upper aquifer can result in up-coning.

Carbonate

The *carbonate* aquifer types have a primary, Cenozoic, carbonate, unconfined aquifer. Hydraulic conductivity in the CSAs with this aquifer type ranged from 45 to 150 m/day. The karstic nature of carbonate aquifers dramatically increases the amount of recharge available to them – especially during intense rainfall events. As a result, groundwater levels can rapidly respond to seasonal, climatic and anthropogenic influences on short time scales. The depth of the carbonate aquifers varied from about 15 to 290 m below sea level and ranged in thickness from 20 to more than 400 m. The theoretical SWI toe extent is expected to be greatest in the deepest and thickest units. Groundwater within the carbonate aquifer type often occurs in freshwater lenses and basins, overlying or adjacent to saline groundwater. The isolated freshwater lenses may be at risk of drawing in saline water, especially where hydraulically connected to sea water or in situations where the overlying freshwater lenses are relatively thin. This is especially the case in areas where net recharge is low. The rapid responses of aquifer storage to changes in climate make these systems susceptible to SWI during drought periods and from a drying climate. In the CSAs, these carbonate aquifers may be underlain by a deeper, confined sand aquifer that is relatively minor in comparison to the upper carbonate aquifer.

Basalt

The coastal *basalt* aquifer types in Australia are Cenozoic in age and generally unconfined. These aquifers are formed by layered basalt plains that primarily store groundwater in fractures and vesicles. Werribee (Victoria) is the only CSA with a basalt aquifer type. In this area, the aquifer was also associated with a river. In the Werribee CSA, the basalt aquifer had a typical hydraulic conductivity value of 5 m/day, aquifer thickness of 50 m, and aquifer depth of 20 m below sea level. Aquifer recharge occurs primarily through rainfall via fractures and river water losses. Groundwater quality can be variable within the basalt aquifers, with fresher groundwater found in areas where there is a greater fracture density and a higher permeability. These fracture openings and higher permeability areas may also provide a preferential flow path for seawater migration. In the CSA, tidal effects along the river may also contribute to ingress of salt water within adjacent aquifers, especially if fracture orientation is perpendicular to estuarine waters.

Fractured/undivided

Howard Springs (Northern Territory) is the only CSA with a *fractured/undivided* aquifer type. It is Proterozoic to Cretaceous in age. This coastal aquifer is characterised by fractured sequences of mixed lithology that have undergone metamorphosis and weathering. In the CSA, a primary carbonate aquifer is included within the mix of lithologies, and so this aquifer shares characteristics in common with other carbonate aquifer systems such as karstic weathering. In the CSA, the aquifers are unconfined to semi-confined, and hydraulic conductivity varies with the degree of fracture density and weathering. A typical hydraulic conductivity value for the aquifer in this CSA was reported to be 40 m/day. The aquifers were relatively deep, at 100 m below sea level, and groundwater levels were around 10 m AHD. Recharge to the aquifer occurs at aquifer outcrops as well as through surficial porous sediments and fractures. Recharge through fractures can be relatively quick. Because of the karstic and fractured nature of the primary aquifer, groundwater levels can rapidly respond to seasonal, climatic and anthropogenic influences on short time scales. Aquifer fractures – especially where fracture orientation is perpendicular to the sea – can provide preferential paths for SWI migration.

4.3.3 Coastal aquifer typology summary

The main characteristics of the principal aquifer types based on the analysis of CSAs is summarised in Table 4-9 (Appendix 4). It is important to note that there can be some degree of overlap in the characteristics of principal aquifer types since some hydrogeological settings will share common elements; for example, the shallow, unconfined sand aquifers found within sedimentary basins have similar characteristics to the coastal sands aquifer type. Furthermore, the fractured, undivided class may contain multiple aquifer types within the broad mix of fractured rock aquifers as found within the Howard Springs (Northern Territory) CSA. Despite these overlaps, the distinct principal aquifer types tend to have specific characteristics and associated implications for SWI.

The ranges of parameter values presented above for each coastal aquifer typology are based on only the 27 CSAs investigated. Some typologies had only one CSA present within them so the ranges of values are unlikely to be fully representative of respective aquifer typologies. The addition of information from other sites around Australia would allow refinement of aquifer parameters characteristic of each typology. Together with identification of where each typology identified in Ivkovic et al. (2012b) exists around Australia's coastline (noting that there are a greater number of typologies than represented by the CSAs above), this would allow extrapolation of likely aquifer characteristics and the associated implications for SWI around Australia.

4.4 Mathematical analysis

This section describes the mathematical analysis component of the project. A method for first-order assessment of steady-state SWI extent under current conditions, and propensity for change in steady-state SWI extent due to various stresses associated with climate change and future extraction, was developed as part of the project. The methodology is an extension to the existing analytical sharp-interface solution of Strack (1976, 1989) and involves the use of partial derivatives to quantify rates of change in SWI extent for the various stresses. The method has been peer-reviewed through the publication by Werner et al. (2012b). The methodology, including detailed description of calculations, has been demonstrated in the report by Morgan et al. (2012) through an application to the Willunga Basin, South Australia.

The mathematical analysis method was applied to 28 CSAs across Australia. The CSAs were identified through literature review and consultation with stakeholders as being at risk of SWI and having sufficient data available for mathematical analysis to be carried out. Using publicly available information, simplified cross-sectional conceptualisations of CSAs were developed, and aquifer parameters (including a base case and likely ranges) were tabled in conjunction with the coastal aquifer typologies (Ivkovic et al. 2012b) component of the project.

Multiple analyses were carried out for some CSAs in order to explore alternate conceptualisations or to account for hydrogeological variability in the area. Also, where stacked aquifers were present, analysis of multiple aquifers was required for the relevant CSAs. Analyses were carried out for 28 unconfined aquifer cases, 17 confined aquifer cases, and four freshwater lens cases. This differs from the number of CSAs that were assigned an overall vulnerability ranking because, after the mathematical analysis was completed, Rottnest Island was excluded due to insufficient data availability.

The extent of SWI was quantified using saltwater wedge toe location and volume of sea water in the aquifer, for unconfined and confined aquifers. For freshwater lens systems, SWI extent was determined using maximum freshwater thickness and freshwater volume.

Under certain conditions, the analytical solution does not achieve a steady-state equilibrium between the seaward flow of fresh water and the density driven influx of sea water, implying the saline wedge is continually migrating inland. For the purposes of this report, such scenarios are termed as unstable conditions.

4.4.1 SWI extent and freshwater–saltwater interface stability under current conditions

For the unconfined aquifer cases, the freshwater–saltwater interface conditions were found to be theoretically unstable for the Derby (Western Australia), The Burdekin (Queensland) and Exmouth (Western Australia) CSAs. Unstable conditions occur where the calculated freshwater discharge to the coast is insufficient for the wedge toe to reach a steady-state location. Under these circumstances, the wedge toe is probably moving inland (although the limitations of the steady-state mathematical analysis preclude confirmation of this). This situation is most likely to result in large-scale SWI problems over long timeframes. For the remaining cases (that were not unstable), the calculated SWI extent was relatively large for the following CSAs: Broome – Cable Beach (Western Australia), Port MacDonnell (South Australia), Broome – Coconut Wells (Western Australia), and Burnett Heads – Moore Park (Queensland). This, and subsequent lists in this section, are in rank order from highest to lowest.

For the confined aquifers, unstable interface conditions were calculated for: Le Fevre [T1 and T2 aquifers] (South Australia), Adelaide Metro [T1 and T2 aquifers] (South Australia), Willunga [Maslin Sands aquifer] (South Australia), Burnett Heads – Bargara (Queensland) and Esperance (Western Australia). Of the eleven remaining confined aquifers (that were not unstable), the toe was greater than 5 km from the coast in the following cases: Bunbury (Western Australia), Perth – Whitfords [Yarragadee aquifer] (Western Australia), Willunga [Port Willunga Formation aquifer] (South Australia), Perth – Whitfords [Leederville aquifer] (Western Australia) and Carnarvon (Western Australia).

For the four freshwater lens systems, maximum freshwater thickness ranged between 7 m (for Perth – Cottesloe in Western Australia) and 67 m (for Point Nepean in Victoria).

Refer to Morgan et al. (2012) for further details of the mathematical analysis for each CSA aquifer, including details of the conceptualisation and parameterisation, interface plots, the range of calculated SWI extent (calculated using estimated parameter ranges), and plots of SWI extent for a range of reduced freshwater discharge to the sea (as might occur under increased extraction).

4.4.2 Propensity for change in SWI due to stresses

The propensity for change in SWI extent due to different stresses (sea-level rise, recharge change and change in inflows at the inland boundary, as might occur under increased extraction inland of the coastal fringe) was calculated using partial derivative equations. The magnitude of the results, termed vulnerability indicators, was used to rank the sensitivity of case study aquifers to the different stresses. The ranking of each aquifer was found to be reasonably consistent across the different stresses. That is, aquifers that rank high (or low) for sea-level rise tended to also rank high (or low) for recharge change and change in inflows at the inland boundary, although some exceptions were observed.

A high vulnerability indicator ranking across the different stresses was determined for unconfined aquifers in the following CSAs: Port MacDonnell (South Australia), Broome – Cable Beach (Western Australia), Esperance (Western Australia), Broome – Coconut Wells (Western Australia), Burnett Heads – Moore Park (Queensland), Perth – Whitfords (Western Australia), Uley South (South Australia) and Bowen (Queensland). Vulnerability indicators could not be calculated for aquifers with unstable interface conditions (these aquifers are noted above). However, it can be inferred that the already potentially unstable inland wedge toe may encroach further inland under increased stress.

For the confined aquifers, a relatively high vulnerability indicator ranking across the different stresses was found for Bunbury (Western Australia), Willunga [Port Willunga Formation aquifer] (South Australia), Perth – Whitfords [Leederville aquifer] (Western Australia), Carnarvon (Western Australia) and Perth – Whitfords [Yarragadee aquifer] (Western Australia). As with unconfined aquifers, vulnerability indicators could not be calculated for confined aquifers with unstable interface conditions.

For the freshwater lens systems, vulnerability indicators for recharge change were used to rank the aquifers. Exmouth (Western Australia) had the highest ranking, followed by Perth – Cottesloe (Western Australia) and Point Nepean (Victoria).

The change in steady-state toe location in each of the case study aquifers (except those with unstable interface conditions) was estimated using normalised sensitivities for the following scenarios:

1. 1 m sea-level rise
2. 25 per cent reduction in recharge
3. 25 per cent reduction in inflows at the inland boundary.

The results provide insight into the potential for change in SWI extent for the given scenarios and allow for a comparison of the sensitivity to the different stresses for each aquifer. Please refer to Morgan et al. (2012) for further details.

4.4.3 General relationships

For the idealised conditions adopted in the mathematical analysis, a number of general relationships between steady-state SWI extent, aquifer parameters and aquifer conditions were demonstrated. For example, steady-state toe location is furthest inland in deep, unconfined aquifers with high hydraulic conductivity, low net recharge and low water levels. In confined aquifers, toe location is furthest inland in deep and thick aquifers, with low net recharge and low heads. SWI extent in confined aquifers is insensitive to hydraulic conductivity. The equations presented in Morgan et al. (2012) can be used to explore these and other SWI relationships.

4.4.4 Limitations

The mathematical analysis approach is limited by the simplification of the conceptual system and the assumptions inherent in the analytical model. These include assumptions of steady-state conditions, a sharp-interface, homogeneous aquifer properties and uniform hydrological stresses. Nevertheless, the approach has the advantage of physical and mathematical justifiability, and is considered an improvement over existing relatively subjective methods for assessing SWI vulnerability over large scales, such as GALDIT (Lobo-Ferreira et al. 2007). Some of the limitations of the current method are countered through the approaches of the VFA, coastal typology assessment and indexing phases of the current project. These are considered as complementary elements that, in combination with the mathematical analysis, allow for the assessment of the vulnerability of the nation’s coastal aquifers to SWI.

4.5 SWI vulnerability indexing: quantitative and qualitative

The SWI vulnerability indexing methodology involves vulnerability factor ratings and weightings to combine both theoretical and subjective elements associated with SWI. The objective of indexing SWI vulnerability is to rate and prioritise regions of the Australian coast by their vulnerability to SWI. As such, the indexing methodology is made up of two components:

1. quantitative indexing, which uses results from the mathematical analysis of CSAs (Morgan et al. 2012)
2. qualitative indexing, which uses results from the coastal aquifer typology and VFA (Norman et al. 2012).

Existing indexing methods used to characterise SWI vulnerability, such as GALDIT (Lobo-Ferreira et al. 2007) and the coastal vulnerability index (Ozyurt 2007), apply a range of SWI vulnerability indicators that are presumed to control SWI. The GALDIT approach, for example, considers aquifer type, distance from the coast, hydraulic conductivity, groundwater level, previous occurrence of SWI and aquifer thickness. While the simplicity of these methods makes them useful for large-scale SWI vulnerability assessments, they lack a theoretical basis because only subjective elements associated with SWI are considered. Also, aquifer fluxes are not accounted for, and SWI vulnerability arising from changes in sea level, recharge or extraction is not captured directly, if at all. The indexing methodology developed as part of the current project improves on existing methods through the use of theoretically justified quantitative factors (taken from the mathematical analysis), as well as a range of qualitative factors, which are able to capture various SWI vulnerability complexities not captured within the mathematical analysis. The indexing was applied to the 27 CSAs listed in Table 2 in this chapter.

4.5.1 Quantitative indexing

4.5.1.1 Quantitative indexing methodology

The quantitative indexing method uses a matrix-style approach to systematically categorise the SWI vulnerability of CSAs. The mathematical analysis considered unconfined aquifers, confined aquifers and freshwater lens systems. Separate indexing matrices were therefore developed for each of these aquifer systems (these are provided within Appendix 5). The range of potential indexing scores is consistent across the different indexing matrices, allowing for comparison between the different systems.

The factors used for each of the unconfined, confined and freshwater lens system indexing matrices are taken directly from results of the mathematical analysis. The mathematical analysis results that were used for factors included:

1. the calculated theoretical steady-state extent of SWI under current conditions – these are scaled wedge toe (unconfined aquifers), wedge toe (confined aquifers), and maximum freshwater thickness (freshwater lenses)
2. the location of the wedge toe relative to extraction bores (for unconfined and confined aquifers)
3. the propensity for change in SWI extent under future stresses (sea-level rise, recharge change and changes in flows at the inland boundary, as might occur under increased extraction).

Details of the mathematical analysis are provided in Morgan et al. (2012). Key tables of mathematical analysis results used for the indexing are provided within Morgan and Werner (2012).

Ratings for each factor were determined by scaling results obtained for all of the case studies considered in the mathematical analysis. Weightings assigned to each factor are a fixed value, which represent the (subjectively determined) relative importance of the factor in terms of SWI vulnerability. Here, the selection of weightings was also guided by the need to have consistent minimum and maximum indexing scores across the different indexing matrices. The minimum indexing score is 5 and the maximum indexing score is 50. An indexing score is obtained by summing the product of the rating and weighting for each factor. A large vulnerability indexing score is presumed to be an indicator of high vulnerability.

4.5.1.2 Quantitative indexing results

The quantitative indexing was applied to 28 CSAs and indexing results are provided in Table 4.

4.5.1.3 Quantitative indexing limitations

The quantitative indexing used outputs from the mathematical analysis and, as such, is subject to the limitations of the mathematical analysis, as reported by Morgan et al. (2012). These limitations arise from the simplification of the conceptual system and the assumptions inherent in the analytical models. The mathematical analysis is heavily reliant on the conceptualisation of the coastal system as well as the availability of data for parameterisation.

Additional limitations of the quantitative indexing arise from the need to develop separate indexing matrices for unconfined, confined and freshwater lens systems, because the mathematical analysis produced different outputs for these systems. The ability of the indexing matrices to effectively compare the potential vulnerability of the different systems requires further detailed assessment. In light of these limitations, it is important to appreciate that the quantitative indexing is complemented by other project components within the final assessment of vulnerability.

Table 4: Ranking of aquifers based on quantitative indexing results

CSA	*Aquifer*	*Indexing score*
Le Fevre, SA	T1 – Confined	50
Le Fevre, SA	T2 – Confined	50
Adelaide Metropolitan, SA	T1 – Confined	50
Adelaide Metropolitan, SA	T2 – Confined	50
Willunga, SA	Maslin Sands – Confined	50
The Burdekin, Qld	Unconfined	50
Esperance, WA	Werillup – Confined	50
Exmouth, WA	Cape Range Group – Unconfined	50
Derby, WA	Wallal/Erskine Sandstone – Unconfined	50
Broome (both locations), WA	Broome Sandstone – Unconfined	47
Port MacDonnell, SA	Tertiary Limestone – Unconfined	47
Esperance, WA	Superficial/Pallinup – Unconfined	43
Exmouth, WA	Cape Range Group – Freshwater lens	41
Perth (Cottesloe), WA	Freshwater lens	38
Rottnest Island, WA	Freshwater lens	38
Bunbury, WA	Yarragadee – Confined	38
Burnett Heads (Moore Park), Qld	Unconfined	36
Willunga, SA	Port Willunga Formation – Confined	35
Perth (Whitford), WA	Yarragadee – Confined	32
Perth (Whitford), WA	Leederville – Confined	32
Perth (Whitford), WA	Superficial – Unconfined	31
Bowen, Qld	Unconfined	30
Carnarvon, WA	Alluvium – Confined	29
Botany Sands, NSW	Botany Sand Beds – Unconfined	28
Point Nepean, Vic	Freshwater lens	26
Carnarvon, WA	Riverbed Sand – Unconfined	25
Uley South, SA	Bridgewater Formation	25
Willunga, SA	Quaternary – Unconfined	25
Port MacDonnell, SA	Tertiary Sands – Confined	20
Werribee, Vic	Unconfined	20
Pioneer Valley, Qld	Unconfined	16
Le Fevre, SA	Semaphore Sands – Unconfined	16
Burnett Heads (Bargara), Qld	Confined	16
Bunbury, WA	Superficial – Unconfined	16
Stockton, NSW	Stockton Sand Beds – Unconfined	16
Howard Springs, NT	Koolpinyah/Coomalie – Confined	14
Busselton, WA	Superficial – Unconfined	13
Hat Head, NSW	Coastal Sands – Unconfined	13
Busselton, WA	Leederville – Confined	10
Stuarts Point, NSW	Coastal Sands – Unconfined	10
North Stradbroke Island, Qld	Unconfined	10
Albany (Ocean side), WA	Werillup Formation Sand – Unconfined	7
Albany (Harbour side), WA	Superficial – Unconfined	7
Albany (Harbour side), WA	Pallinup/Werillup – Confined	7
Uley South, SA	Wanilla Sands	6

4.5.2 Qualitative indexing

4.5.2.1 Qualitative indexing methodology

The qualitative indexing uses a matrix-style approach to systematically categorise a range of datasets to develop a conservative yet robust qualitative indicator of SWI vulnerability. A higher qualitative indicator score is reflective of a greater vulnerability to SWI. In general it was not possible to apply the qualitative indexing method to individual aquifers due to lack of information, so an indexing score was developed for the total CSA only. In some cases, enough information was available to assess the water balance (extraction/net recharge ratio) for individual aquifers.

The factors used in the qualitative indexing method were mostly derived from the coastal aquifer typology and VFA components of the project. The vulnerability parameters that were used in the qualitative assessment included:

- the ratio of groundwater extraction to net recharge of the aquifer(s)
- the minimum groundwater level during 2000–2010 (not aquifer specific) that the minimum water levels in at least 20 per cent of monitoring bores fell below within the 15 km coastal zone
- the current level of SWI-specific knowledge, monitoring and management
- a comparison of the 2000–2010 rainfall against the long-term annual mean rainfall record
- the maximum change in maximum salinity values between the periods 1990–1999 and 2000–2010 that was exceeded by at least 20 per cent of bores
- the tidal setting of the CSA.

Details of the qualitative indexing methodology are provided in Norman et al. (2012).

Ratings for each factor were assigned at each site by using the assessment matrix displayed in Table 5. The weightings assigned to each factor are a fixed value, which represents the (subjectively determined) relative importance of the factor in terms of SWI vulnerability (Table 6). The minimum possible indexing score is 17 and the maximum possible indexing score is 170. An indexing score is obtained by summing the product of the rating and weighting for each factor. The scores are further broken into three vulnerability categories: high, moderate and low vulnerability. A large vulnerability indexing score is presumed to be an indicator of high vulnerability.

Table 5 summarises the weighting and rating rationale of the qualitative indexing method. Table 6 shows an example of the qualitative indexing table that was used to assess the CSAs with the results for Carnarvon (Western Australia).

Table 5: Qualitative indexing method rationale

SWI vulnerability drivers	Parameter	Weighting	Weighting rationale	Rating	Parameter classes	Rating rationale
Sustainable yield	Ratio of groundwater extraction to net recharge	4	Unsustainable yield of coastal groundwater induces SWI	10	>1	The range of rating classes reflects that increasing extraction to recharge ratio results in increasingly unsustainable use of a resource
				8	0.75–1.0	
				5	0.5–0.75	
				3	0.25–0.5	
				1	<0.25	
Coastal head gradients	Minimum groundwater level that at least 20% of monitoring bores fell below during 2000–2010	4	If the head gradient is landwards SWI occurs	10	<0	The range of rating classes reflects that decreasing inland head levels result in increasing vulnerability to SWI
				8	0–1	
				5	1–2.5	
				1	>2.5	
Knowledge, monitoring and management (KMM)	Current level of SWI-specific KMM	3	SWI-specific knowledge and monitoring allows for informed management of SWI risk	10	None	The range of rating classes indicates that increasing levels of KMM reduces the likelihood of unconstrained SWI
				8	Low	
				5	Moderate	
				1	High	
Climate	A comparison of the 2000–2010 rainfall against the long-term annual mean rainfall record	2	Rainfall conditions influence both groundwater extraction behaviour and groundwater recharge	10	Declining	The range of rating classes reflects short-term climatic conditions influence recent extractive behaviours comparative to established extractive patterns
				5	Stable	
				1	Increasing	
Salinity	The value of change in maximum salinity value between the periods 1990–1999 and 2000–2010 that was exceeded by at least 20% of bores	2	SWI causes salinisation of coastal aquifers	10	>2000	The range of rating classes reflects that greater increases in salinity potentially indicate landward movement of sea water
				5	1000–2000	
				1	<1000	
Coastal head gradients	Tidal setting	2	High tides cause elevated time-averaged coastal head conditions, lowering seaward groundwater gradients	10	Macrotidal	The range of rating classes reflects the impact of larger tidal ranges on coastal groundwater head conditions
				5	Mesotidal	
				1	Microtidal	

Table 6: Table summarising the qualitative indexing schema used to derive an index score. The results for Carnarvon are shown below as an example.

	Ratio of groundwater extraction to net recharge	Minimum groundwater level (m) that at least 20% of monitoring bores fell below during 2000–2010	Current level of SWI-specific knowledge, monitoring and management	A comparison of the 2000–2010 rainfall against the long-term annual mean rainfall record	The value of change in maximum salinity (mg/L TDS) value between the periods 1990–1999 and 2000–2010 that was exceeded by at least 20% of bores	Tidal setting
Weighting → Rating ↓	4	4	3	2	2	2
10	>1	<0	Limited	Declining	>2000	Macrotidal
8	0.75–1.0	0–1	Low	NA	NA	NA
5	0.5–0.75	1–2.5	Moderate	Stable	1000–2000	Mesotidal
3	0.25–0.5	NA	NA	NA	NA	NA
1	<0.25	>2.5	High	Increasing	<1000	Microtidal

Index Score	=	Weighting x Rating	+	W x R	+	W x R	+	W x R	+	W x R	+	W x R
111		4 x 10	+	4 x 8	+	3 x 5	+	2 x 10	+	2 x 1	+	2 x 1
		(40)	+	(32)	+	(15)	+	(20)	+	(2)	+	(2)

4.5.2.2 Qualitative indexing results

The qualitative indexing was limited in application to 27 CSAs, with Rottnest Island having insufficient datasets available to provide a meaningful indexing result. The indexing results are provided in Table 7. Table 6-1 (Appendix 6) details the CSA allocations for each of the qualitative indexing parameters.

The combination of rating and weighting allowed comparison and contrast of relative qualitative indexing scores on a national scale. The qualitative indexing scores ranged from a minimum of 17 to a maximum of 170. The qualitative indexing scores were categorised into three categories: Low – 17 to 51, Moderate – 52 to 102, High – 103 to 170.

The scores of the 27 sites fell between 28 and 85 per cent of the maximum qualitative SWI indicator score. Most CSAs (19) had a moderate quantitative indexing score, seven CSAs scored in the highest category and one site scored in the lowest category using this method. This reflects that the sites assessed were chosen because SWI had been previously identified as either an occurring hazard or a potential one.

In order of most vulnerable to least vulnerable, the highest category CSAs were Derby (Western Australia) with 84 per cent; Perth Whitfords (Western Australia) with 78 per cent; Busselton (Western Australia) and Carnarvon (Western Australia) both scoring 73 per cent; Esperance (Western Australia) with 71 per cent; Stuarts Point (New South Wales) with 70.6 per cent; and Adelaide Metropolitan (South Australia) with 70 per cent.

With the exception of Adelaide Metropolitan, high scoring sites all had high ratios of extraction/recharge (>0.75) and low minimum groundwater levels (<1 m AHD).

Several important points are noted from this analysis:

- 35 per cent of sites extract more than half the net recharge
- 67 per cent of sites showed indications of low freshwater heads (20 per cent of bores recorded a height of <1 m AHD during 2000–2010)
- 50 per cent of sites have low knowledge monitoring and management
- 60 per cent of sites showed decreasing cumulative residual rainfall trends during 2000–2010; 2000–2010 was a relatively dry period across most of Australia
- 41 per cent of sites showed indications of considerable salinity increases (20 per cent of bores showed increases of >1000 mg/L TDS between 1990–1999 and 2000–2010)
- the main factors driving the indexing scores in each CSA are variable.

There was no consistent relationship between the qualitative indexing results and the typological setting, primarily due to the fact that parameters assessed in this method were not intrinsic to the aquifer system. Intrinsic aquifer properties were assessed in the quantitative indexing method (Morgan and Werner 2012).

Table 7: Ranking of CSAs based on qualitative indexing results

CSA	*Indexing score*	*Qualitative class*
Derby	128 [2]	High
Perth (Whitfords)	119 [2]	High
Busselton	111	High
Carnarvon	111	High
Esperance	109	High
Stuarts Point	108 [2,3]	High
Adelaide Metropolitan	107	High
Bunbury	100	Moderate
Willunga	100	Moderate
Exmouth (cape range)	100	Moderate
Broome	100	Moderate
Port MacDonnell	98	Moderate
Cottesloe	97	Moderate
The Burdekin	97	Moderate
Point Nepean	92 [2]	Moderate
Le Fevre	92	Moderate
Werribee	91 [2]	Moderate
Albany	89 [2]	Moderate
Bowen	85	Moderate
Uley South	83	Moderate
Hat Head	81 [3]	Moderate
Burnett Heads	79	Moderate
Howard Springs	74	Moderate
Botany	72 [2,3]	Moderate
Pioneer Valley	71	Moderate
Stockton	70 [1,2,3]	Moderate
North Stradbroke Island	45	Low

1 Limited water level data were available for the period 2000–2010

2 No inter-decadal salinity data were available

3 Abstraction data were unavailable so allocation or literature values were used

4.5.2.3 Qualitative Indexing limitations

There are many factors that can influence a location's vulnerability to SWI. Following the vulnerability framework of Füssel (2007), these factors can be categorised as either internal or external to the system and then further classified as either socioeconomic or biophysical.

Many factors have been identified as important contributors to SWI in other SWI qualitative indexing methods (Ozyurt 2007). In an endeavour to create a first-pass assessment of current national SWI vulnerability in this study, the following selection of SWI vulnerability drivers were assessed: sustainable yield; coastal head gradients; the level of SWI knowledge, monitoring and management; local climate and salinity. This method did not assess the potential influence of short-term variations in sustainable yield, climate variability or the spatial distribution of pumping on vulnerability. Detailed discussions of the qualitative indexing limitations are contained within the technical report (Norman et al. 2012).

4.5.3 Indexing summary

Vulnerability indexing allows for the rapid assessment of indicators to SWI vulnerability across a variety of settings. The versatility and adaptability of this tool was highlighted in the fact that two separate indexing approaches were used in this project to address different scales and vulnerability indicators. As tools for a first-pass assessment, the indexing approaches used in this project can be adapted to the level of knowledge of the system, and can be improved upon as more conceptual understanding of SWI in the Australian context becomes available in the future.

4.6 Future land surface inundation and population growth analysis

Future land surface inundation as a result of sea-level rise (Section 4.6.1) and predictions of population growth (Section 4.6.2) were analysed to assess how these factors may influence SWI. These analyses have been used to address coastal aquifer vulnerability to SWI under future predicted conditions using the integrated vulnerability assessment in Section 5.1.

4.6.1 Future land surface inundation due to sea-level rise

Elevation data from the Shuttle Radar Topographic Mission (SRTM) 1 second (30 m) DEM was used to classify the coastal area within the 15 km inland buffer. The purpose was to identify areas that may be susceptible to surface inundation of sea water associated with climate change. As a result of this sea-level rise, permanent inundation of low-lying coastal areas and the migration of the shoreline landwards could occur (IPCC 2007, Nation et al. 2008). This has the potential to shift the saltwater wedge toe landwards, resulting in SWI. The IPCC (2007) has projected a rise in global sea level from 1990 to 2100 of approximately 19 to 58 centimetres, with a possible additional 10 to 20 centimetres due to further melting of ice. Furthermore, the IPCC (2007) has predicted an increase in the frequency and intensity of extreme events such as storms and storm surges associated with climate change.

Coastal areas were categorised into four elevation classes modelled on the ranges used by Nation et al. (2008), who divided elevation data into four categories to consider the impact of climate change on SWI (see Table 8). The four categories consider the impact of surface inundation of sea water as a result of sea-level rise and as a result of storm surges.

Table 8: Elevation classes used for SRTM 30-m DEM mapping

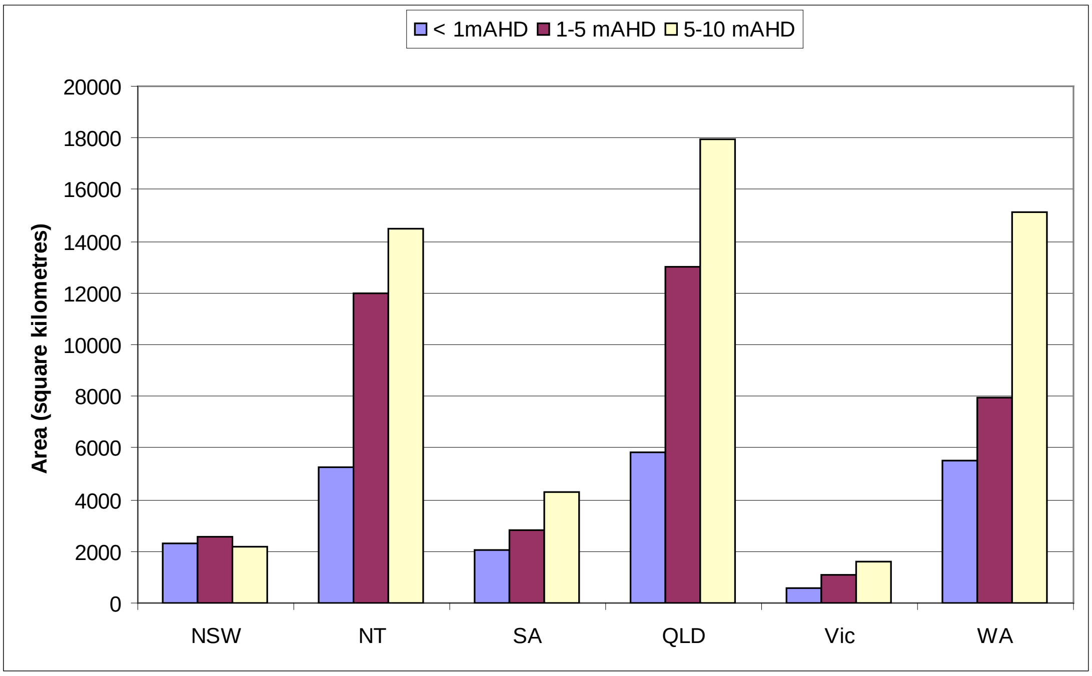
Elevation class	*Elevation classification (m AHD)*	*Characteristics*
1	<1	Represents inundation due to sea-level rise
2	1–5	Represents inundation due to storm surges
3	5–10	Represents maximum height of storm surges
4	>10	Low potential of surface inundation

The four elevation class categories were divided based on the following:

- Areas with elevations <1 m AHD were considered significant as they could be directly inundated as a result of sea-level rise, based on the IPCC's predictions.
- A storm surge height of 5 m AHD has already been recorded in Australia (BoM, 2008, Nation et al. 2008), and this elevation was used to highlight areas that may be susceptible to inundation from storm surges.
- Areas from 5 to 10 m AHD may be affected during extreme storm events.
- Areas with an elevation >10 m AHD are considered to have a lower potential for surface inundation as they are unlikely to be affected by surface inundation associated with sea-level rise or storm surges, based on the IPCC's predictions.

Figure 5 presents the results of the elevation analysis for each state/territory. CSA-specific (Table 7-1) and national-scale (Table 7-2) results tables are included in Appendix 7, with the percentage and area of each elevation class calculated at the CSA and state/territory levels. Each CSA was assigned an elevation class based on the class covering the largest proportion of its area.

Figure 5: Elevation class areas within the 15 km coastal buffer by state/territory

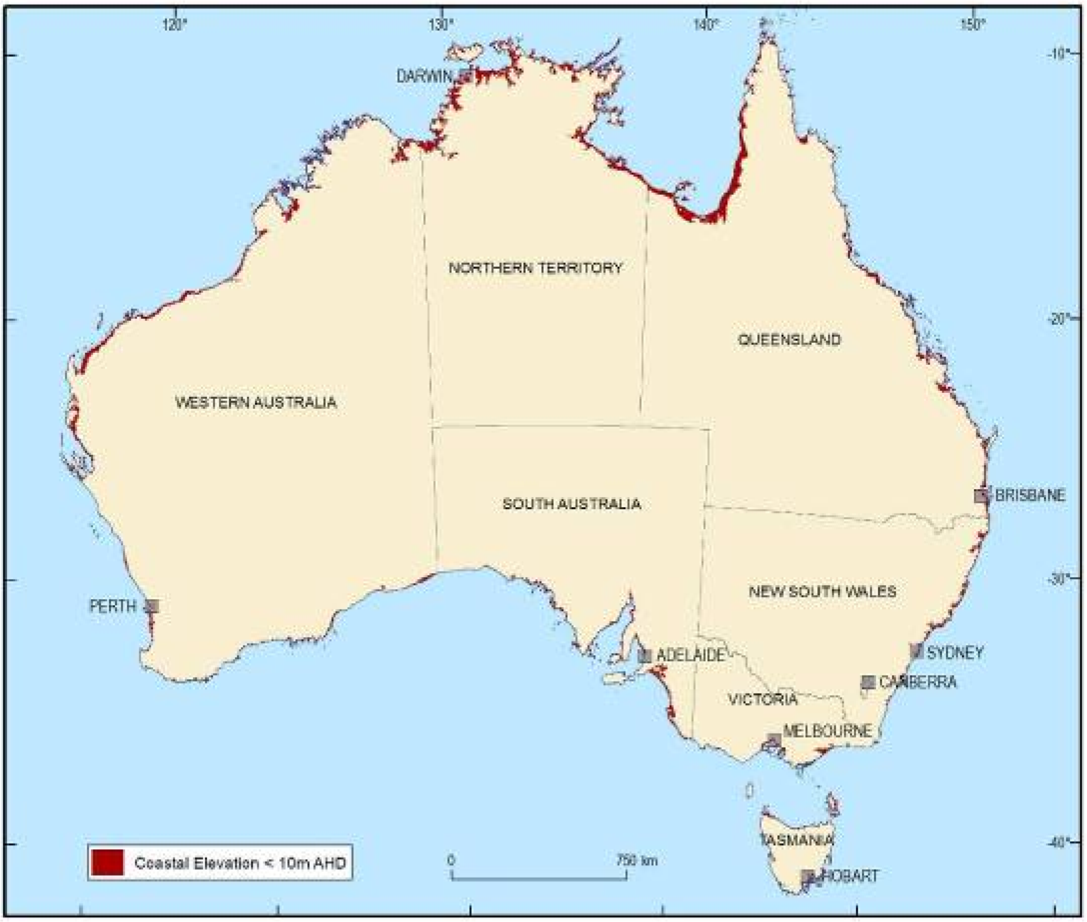


Note: only classes 1 to 3 are presented

The national-scale results show that a significant portion of the Australian coastline has elevations <10 m AHD (as shown in Figure 6). The northern coastlines of Western Australia, Northern Territory and Queensland have particularly large areas <10 m AHD, as do the southern Queensland and northern New South Wales coast, areas adjacent to Melbourne and the Gippsland area in Victoria, and parts of the Fleurieu Peninsula in South Australia. Tasmania’s north-west coast and Flinders Island show large areas with elevations <10 m AHD.

Within the <10 m AHD zone, many areas are present around the Australian coast with elevations <5 m AHD. In Western Australia, these include areas south of Perth along the Swan Coastal Plain, north of Perth, south of Geraldton at the Beekeepers Nature Reserve, and near Exmouth. A large portion of the Northern Territory coastline has areas with elevations <5 m AHD, including south of Darwin and into Western Australia near the Ord River catchment, east of Darwin near Kakadu National Park as well as further east along the Northern Territory and Queensland coastline of the Arafura Sea. Queensland also has areas near Townsville, Curtis Island and south of Brisbane in this category. Large areas of coastline in New South Wales with elevation <5 m AHD include Lennox Head, Evans Head and the coastline from Emerald Beach to Sydney. Areas along the Victorian coast within this category include the Gippsland region, Port Albert, the area south-east of Melbourne (at West Port) and the coastline of Melbourne and west of Melbourne (including Werribee). South Australian areas include the Fleurieu Peninsula, especially around Kingston and surrounding Lake Alexandrina. The coastline from Adelaide to Port Wakefield along the Gulf of St Vincent also contains areas of elevation <5 m AHD, as well as parts of the coastline near Streaky Bay and Fowlers Bay.

Figure 6: Coastal areas in Australia with an elevation of <10 m AHD



Within the <5 m AHD zone, areas with an elevation <1 m AHD are not abundant; they are sparsely scattered around the coastline of Australia. Parts of Australia that have larger areas of land adjacent to the coast with an elevation <1 m AHD include north of Lake Argyle (in the Ord River catchment area), which is in the Northern Territory and Western Australia; parts of the southern Queensland and northern New South Wales coast; and the coastline south-east of Melbourne in the Gippsland area.

The results of the DEM analyses and the figures for each CSA have been summarised in Section 5.1. CSAs that have low-lying areas with more than 10 per cent of the area with elevations <1 m AHD adjacent to the coast include North Stradbroke Island, Stockton and Hat Head. CSAs with more than 30 km^2 of area with an elevation <1 m AHD are North Stradbroke Island (30.94 km^2), Bowen (34.25 km^2), Pioneer Valley (35.69 km^2), Stockton (49.10 km^2), Hat Head (50.86 km^2) and Burnett Heads (51.24 km^2). These CSAs may be particularly susceptible to surface inundation by sea water with sea-level rise and an associated potential landward migration of the saltwater wedge toe.

4.6.2 Population growth

Groundwater extraction is a key driver of SWI, and population growth in groundwater use areas generally coincides with increases in groundwater extraction. In many of the CSAs, groundwater is used heavily for agriculture, horticulture, town water supplies, and the maintenance of golf courses, parks and gardens. Therefore, as population increases, these CSAs may experience associated increases in groundwater use and associated SWI. However, caution is needed when using population growth to estimate future groundwater use, as an increasing population may also result in decreased groundwater use if, for example, an irrigation area is converted to an urban centre that relies on an imported water supply.

Past population change was analysed using Census 2001 and Census 2006 data from the ABS website (ABS 2007) as an indicator of likely future population changes. The extent of Census data collection was unique for each CSA and is reported by the ABS for ‘collector districts’ (CDs). CD extents vary and may be based, for example, on a town boundary, an urban centre, a state/territory suburb, an Indigenous area, a statistical local area or a local government area. The CD scales used for estimating CSA population parameters varied from CSA to CSA as outlined in Table 8-1 (Appendix 8) and were selected to provide the best possible representation of each individual CSA’s population data.

The results of the population change analysis are presented in Table 8-2 (Appendix 8). A number of CSAs experienced population growth exceeding 10 per cent from 2001 to 2006, including Busselton, Howard Springs, Pioneer Valley, Point Nepean, Werribee and Willunga. If population growth continues at the same rates in these areas, it is likely that the associated groundwater stresses will also increase. CSAs that showed a decrease in population included Botany (although Sydney increased), Bowen, Broome, The Burdekin, Carnarvon, Derby, Exmouth, Hat Head, North Stradbroke Island and Stuarts Point. The remaining CSAs showed population increases of less than 10 per cent, indicating some potential increase in groundwater stress and the likelihood of SWI.

Most of the CSAs that showed a decrease in population recorded an increase in number of dwellings; North Stradbroke Island, for example, recorded a 15.73 per cent decrease in population but a 21.91 per cent increase in the number of dwellings. Such demographic changes could be attributed to growth in the number of holiday homes and the presence of a temporary population during some parts of the year. This may result in increased groundwater demands during peak tourism periods. Further, peak tourism periods in Australia often correspond to seasons with low rainfall, such as during summer in the Mediterranean climate types or during the dry season (approximately April–September) in the tropical climate areas. This would add further pressure on the groundwater resource, increasing its vulnerability to SWI.

The only CSAs that showed both a decrease in population and number of dwellings were the Burdekin, Carnarvon, Derby, Exmouth and Stuarts Point. The areas that showed a significant increase in number of dwellings were Burnett Heads, Busselton, Howard Springs, North Stradbroke Island, Perth, Pioneer Valley, Stockton, Werribee and Willunga. The ratio of population to the number of dwellings was also recorded in Table 8-2. This ratio aims to identify areas that may be subject to large tourism-related demands where values are low. The only CSAs that did not show a decrease in this ratio were Perth (Cottesloe), Pioneer Valley, Point Nepean and Port MacDonnell. However, it is noted that there are difficulties and potential ambiguities in data interpretation. Besides relating to an increase in holiday-house ownership in an area, a decrease in population to number of dwellings may simply reflect general decreases in the number of persons per household around Australia.

The 2001–2006 population data were used as indicators for future growth and associated groundwater stress. However, past trends in population growth may not reflect future conditions, so updating of this analysis is important as further information becomes available. Since 2006, the mining boom in particular may have impacted population numbers in regional towns near mines or exploration sites. Also, groundwater use may not be directly linked to population growth in some areas; but rather, affected by factors such as land use, vegetation type, groundwater-dependent ecosystems, surface water supplies, hydrogeology (including the mechanisms of recharge and the amount of storage in the aquifer), seasons, tourism, industries, water management strategies such as desalination plants or storm water harvesting and other social factors.

It was beyond the scope of this study to comprehensively analyse social water-use trends; population growth trends and population to dwelling ratios were taken to be broad indicators of potential increase in future groundwater stress when undertaking the integrated SWI vulnerability assessment of CSAs in Section 5.1. However, the limitations of this analysis method are acknowledged and it is recognised that social trends can exert large influences on an area’s vulnerability to SWI.

5. National summary of seawater intrusion vulnerability

The five technical assessments undertaken during this study are outlined in Chapter 4. Each technical assessment provides information on a variety of different factors that contribute to SWI vulnerability. This complementary information is integrated in Section 5.1 below to determine the overall SWI vulnerability for the aquifers present in each CSA.

Using the integrated SWI vulnerability results from Section 5.1.2, the suitability of the coastal aquifer typology and VFA to highlight areas that may have high SWI vulnerability outside of the CSAs is assessed in Section 5.2. Section 5.3 then provides a discussion of Australia's national SWI vulnerability. All project components are considered in this discussion including the literature review, technical assessments, and the integrated vulnerability assessment from Section 5.1. Locations around Australia where SWI has been reported are identified and the VFA results are used to highlight other areas where indicators of SWI vulnerability are present. Overall, Chapter 5 provides a comprehensive analysis of SWI vulnerability in Australia at both local and national scales.

5.1 Integrated SWI vulnerability assessment in the CSAs

Following integration of the technical assessment outputs to assess overall SWI vulnerability in each CSA, the main drivers of SWI vulnerability are identified below to provide insights for future management. The methodology described in this section is considered to provide a useful framework for determining SWI vulnerability in other areas. It is intended that the methodology be applied to new areas as further data become available.

5.1.1 Integration methodology

The results from all five technical analyses in Chapter 4 were considered to determine an overall vulnerability ranking (low, medium or high) for each aquifer in each CSA. This approach ensured that the myriad of factors relevant to SWI vulnerability and their inter-relationships were considered in a consistent manner. Different rankings were given for each aquifer under current and predicted future conditions.

Marshall et al. (2012) contains the details of the application of the integrated SWI vulnerability assessment methodology to the CSA aquifers. In general, the integrated assessment process is driven by the sequential review of:

- Coastal aquifer typology, topography and demographic settings, including:
    - establishing the physical setting and area of interest
    - defining the hydrogeology, geology and climate of the CSA that collectively comprise its coastal aquifer typology
    - defining characteristics of each aquifer including hydraulic parameters, aquifer depths and thicknesses

  - understanding the aquifer system present in the CSA
  - reviewing existing knowledge of SWI in the area
  - appraising population change and demands on water resources.
- Trends in water level and salinity from the VFA, including:
  - minimum water levels recorded in the CSA from recent and historic periods including inter-decadal comparisons
  - maximum TDS recorded in the CSA for recent and historic periods including inter-decadal comparisons
  - groundwater-level trends.
- Outputs from the quantitative and qualitative indexing, including:
  - aquifer system conceptualisation and assumptions used in the mathematical analysis
  - an evaluation of the quantitative indexing results and ranking for the CSA
  - an evaluation of the qualitative indexing results and ranking for the CSA.
- Possible future impacts relating to climate change, including:
  - propensity for change in SWI for different seaward discharge conditions
  - an assessment of the DEM against future sea-level rise for regions of the CSA with elevations <1 m AHD.

The results of the five technical assessment components have been integrated to assign an overall SWI vulnerability ranking for each CSA. Each of the technical components incorporates a unique suite of analyses relevant to SWI, and therefore each makes a discrete SWI assessment based on the information and data used. To integrate the technical components, each of the results has been standardised and compared to the others. In addition to a direct comparison, an assessment has been made on site-specific factors that may influence the overall SWI vulnerability ranking for any given CSA.

To facilitate integration, the results of each of the five technical components were standardised to three values of high, moderate and low (Table 9). Note that in Table 9, “Aquifer Properties” incorporates the coastal aquifer typology but includes a site-specific analysis of hydrogeological properties influencing SWI such as the presence of preferential flow paths (fully described in Marshall et al. 2012). The standardised technical components were assessed together to identify the number of high, moderate and low values for each site. However, due to the myriad of influences that can affect SWI, the large number of datasets incorporated in the individual components and the potential for site-specific influences, these results cannot simply be added together.

To produce an overall SWI vulnerability ranking, the combined standardised results of the technical components were put into context by considering any site-specific factors that may have a significant contribution to SWI vulnerability. This was assessed CSA-by-CSA by:

1. comparing the values (high, moderate and low) from the individual standardised technical components

2. identifying the main factors that contributed to each individual standardised technical component value
3. evaluating the influence of site-specific factors.

Additionally, future vulnerability was assessed by including factors that are likely to change over time, such as increased groundwater extraction inferred from population growth and land inundation due to sea-level rise. Using this assessment, an overall current and future SWI vulnerability ranking was assigned for each CSA.

The collective values from the standardised technical results agree with the assigned overall current vulnerability ranking (Table 9). This is not the case for all CSAs due to site-specific factors (as indicated above) and these areas are discussed further below. In general, the CSA can be categorised into three overall vulnerability rankings:

1. High: containing three to five high values, zero to three moderate values and zero to one low value from the technical assessments
2. Moderate: containing one to two high values, two to three moderate values and at least one low value from the technical assessments
3. Low: containing zero to one high value, two to three moderate values and at least two low values from the technical assessments.

Note that there is an overlap between moderate and low overall vulnerability rankings where sites have one high value and three moderate values. The line between moderate and low rankings was placed based on higher and lower differentiation within the technical component values.

Relative to current vulnerability rankings, the future vulnerability ranking of each CSA tends to remain the same or increase. No sites decreased in vulnerability ranking under predicted future conditions. This was due to population generally predicted to increase throughout the CSAs with associated predicted increased groundwater demands and the position of the saltwater wedge moving landward as sea-level rises.

As outlined above, not all CSA vulnerability rankings directly reflect the results of the standardised technical components. A number of exceptions are present where a CSA has a high or low vulnerability based on categories 1 to 3 above, but, when assessed for an overall vulnerability ranking, was assigned a lower or higher overall vulnerability. This was primarily due to the consideration of site-specific factors not captured by the individual technical assessment rankings.

Site-specific factors alter the final vulnerability rankings under exceptional conditions. For example, while the maximum possible standardised ‘qualitative indexing’ component value in Table 9 is ‘high’, some CSAs may have such high extraction to recharge ratios (a parameter captured within the qualitative indexing), that additional weighting was given to this category when assigning a total vulnerability ranking. Other examples exist and in the integrated assessment the complex inter-relationships of factors contributing to SWI vulnerability also required consideration. Although this approach introduces further subjectivity to the method, it is necessary to fully describe the unique mix of factors present at each CSA.

Overall CSA vulnerability rankings that deviate from standard implementation of the above three categories due to a consideration of site specific factors include Bowen (Superficial); Perth (Cottesloe – Tamala Limestone Aquifer); The Burdekin (Unconfined); Carnarvon (Alluvium); Stockton (Stockton Coastal Sands); and Port MacDonnell (Tertiary Sands). The details of overall vulnerability ranking are available in Marshall et al. (2012).

Table 9: Integration of technical assessment components to inform the overall current and future vulnerability ranking (full details given in text)

Location		Standardised Technical Assessment Components						Future Projections		Overall Vulnerability	
Aquifer Name	**CSA**	**Aquifer Properties**	**VFA**	**Maths Analysis**	**MA Inland Extent**	**Quantitative Indexing**	**Qualitative Indexing**	**DEM**	**Population**	**Current Ranking**	**Future Ranking**
Werrilup Formation	Esperance	High	High	High	High	High	High	Moderate	Moderate	High	High
T1	Adelaide Metropolitan	Low	High	High	High	High	High	Low	Moderate	High	High
T2	Adelaide Metropolitan	Low	High	High	High	High	High	Low	Moderate	High	High
Superficial/Pallinup	Esperance	High	High	Moderate	Moderate	High	High	Moderate	Moderate	High	High
Superficial	Perth (Whitfords)	Moderate	High	Moderate	High	High	High	Low	High	High	High
Maslin Sands	Willunga	Moderate	High	High	High	High	Moderate	Low	High	High	High
Cape Range Group	Exmouth	Moderate	Moderate	High	High	High	Moderate	Moderate	Low	High	High
Yarragadee	Bunbury	Low	High	High	High	High	Moderate	Moderate	High	High	High
Wallal/Erskine Sandstone	Derby	Moderate	Low	High	High	High	High	Low	Low	High	High
T1	Le Fevre	Low	High	High	High	High	Moderate	High	High	High	High
T2	Le Fevre	Low	High	High	High	High	Moderate	High	High	High	High
Yarragadee	Perth (Whitfords)	Low	High	Moderate	High	High	High	Low	High	High	High
Leederville	Perth (Whitfords)	Low	High	Moderate	High	High	High	Low	High	High	High
Gambier Limestone	Port MacDonnell	Low	High	High	High	High	Moderate	Moderate	Moderate	High	High
Port Willunga Formation	Willunga	Low	High	High	High	High	Moderate	Low	High	High	High
Elliot Formation	Burnett Heads (Moore Park)	High	Moderate	Moderate	Moderate	High	Moderate	High	High	High	High
Superficial	Bowen	High	Low	Moderate	Moderate	Moderate	High	High	Moderate	High	High
Elliot Formation	Burnett Heads (Bargara)	High	Moderate	Moderate	Low	Moderate	Moderate	Moderate	High	High	High
Tamala Limestone Aquifer	Perth (Cottesloe)	High	Moderate	Low	Low	High	Moderate	Low	High	High	high
Q1	Le Fevre	Moderate	High	Low	Low	Moderate	Moderate	High	High	High	High
Unconfined	The Burdekin	High	High	High	High	High	Moderate	High	Moderate	Moderate	High
Alluvium	Carnarvon	Moderate	Moderate	High	High	Moderate	High	High	Low	Moderate	Moderate
Broome Sandstone	Broome	Moderate	Low	Moderate	High	High	Moderate	Moderate	High	Moderate	High
Unconfined	Pioneer Valley	High	Moderate	Moderate	Moderate	Moderate	Moderate	High	High	Moderate	High
Botany Sand Beds	Botany	High	Moderate	Moderate	Moderate	Moderate	Moderate	High	High	Moderate	Moderate
Bridgewater Formation	Uley South	Moderate	High	Low	Moderate	Moderate	Moderate	Low	High	Moderate	High
Bridgewater and Wannaeue Formations	Point Nepean	Moderate	High	Low	Low	Moderate	Moderate	Moderate	High	Moderate	High
Werillup Formation Sand	Albany (Ocean side)	Moderate	High	Moderate	Low	Low	Moderate	Low	High	Moderate	Moderate
Quaternary Riverbed Sand	Carnarvon	Moderate	Moderate	Low	Low	Moderate	High	High	Low	Moderate	Moderate
Koolpinyah/Coomalie	Howard Springs	Moderate	High	Low	Moderate	Low	Moderate	Moderate	High	Moderate	Moderate
Stuarts Point Coastal Sands	Stuarts Point	Moderate	Moderate	Low	Moderate	Low	High	High	Low	Moderate	Moderate
Alluvium/Fractured Rock	Werribee	Moderate	High	Low	Low	Moderate	Moderate	Moderate	High	Moderate	Moderate
Leederville	Busselton	Low	Moderate	Low	Moderate	Low	High	High	High	Moderate	Moderate
Superficial	Busselton	Moderate	Moderate	Low	Low	Low	High	High	High	Moderate	Moderate
Stockton Coastal Sands	Stockton	Moderate	Moderate	Low	Low	Moderate	Moderate	High	High	Moderate	Moderate
Tertiary Sands	Port MacDonnell	Low	High	Low	High	Moderate	Moderate	Moderate	Moderate	Low	Low
Pallinup/Werillup	Albany (Harbour Side)	Moderate	High	Moderate	Moderate	Low	Moderate	High	High	Low	Moderate
Superficial Aquifer	Bunbury	Moderate	High	Low	Low	Moderate	Moderate	Moderate	High	Low	Moderate
Wanilla Sands Aquifer	Uley South	Moderate	High	Low	Moderate	Low	Moderate	Low	High	Low	Moderate
Quaternary	Willunga	Low	High	Low	Moderate	Moderate	Moderate	Low	High	Low	Moderate
Superficial	Albany (Harbour Side)	Moderate	High	Low	Low	Low	Moderate	High	High	Low	Moderate
Dune Sands Aquifer	North Stradbroke Island	Low	High	Low	Low	Low	Low	Moderate	High	Low	Moderate
Coastal Sands Aquifer	Hat Head	Moderate	Low	Low	Moderate	Low	Moderate	Moderate	Moderate	Low	Low

5.1.2 Results

In total, SWI vulnerability was evaluated for 46 aquifer conceptualisations across the 27 CSAs. They were termed ‘conceptualisations’ because, in some instances, the same aquifer was present in different CSAs; however, each conceptualisation is referred to as a separate aquifer in the discussion below. The detailed integrated SWI vulnerability results are included in Marshall et al. (2012) and summarised in Figure 7 (current vulnerability) and Figure 8 (future vulnerability). Table 10 provides details of the key factors driving SWI vulnerability for each aquifer under current and predicted future conditions.

It is apparent from Figure 7 that seven CSAs contained aquifers with low current SWI vulnerability, reflecting the fact that the majority of CSAs selected for analysis had previously been identified by the literature review as potentially vulnerable to SWI. Western Australia, South Australia and Queensland have the greatest number of CSAs with high current SWI vulnerability. Of the 46 aquifers assessed, 22 (47 per cent) were assigned a vulnerability ranking of high, 16 (34 per cent) were assigned a vulnerability ranking of moderate and eight (17 per cent) were assigned a vulnerability ranking of low (under current conditions). Of these 46 aquifers, 26 (57 per cent), 18 (39 per cent) and two (4 per cent) were assigned future vulnerability rankings of high, moderate and low, respectively.

From Figures 7 and 8, it is apparent that current SWI vulnerability is not anticipated to decrease for any aquifers under predicted future conditions, although in some instances increasing SWI vulnerability appears likely (compare Figure 7 with Figure 8):

- The rankings of five aquifers changed from moderate currently to high in the future: Broome Sandstone (Broome), Bridgewater and Wannaeue Formations (Point Nepean), Unconfined (The Burdekin), Unconfined (Pioneer Valley) and Bridgewater Formation (Uley South).
- The rankings of six aquifers changed from low currently to moderate in the future: Wanilla Sands (Uley South), Dune Sands (North Stradbroke Island), Superficial (Albany, Harbour side) Pallinup/Werillup (Albany, Harbour side), Superficial (Bunbury) and Quaternary (Willunga).
- Two aquifers were classified with low current and future rankings: Tertiary Sands (Port MacDonnell) and Coastal Sands (Hat Head).

Table 10 summarises the key drivers of vulnerability under current and predicted future conditions. Some of the key drivers of current SWI vulnerability ranking are:

- high groundwater extraction rates
- low groundwater recharge rates
- declining rainfall.

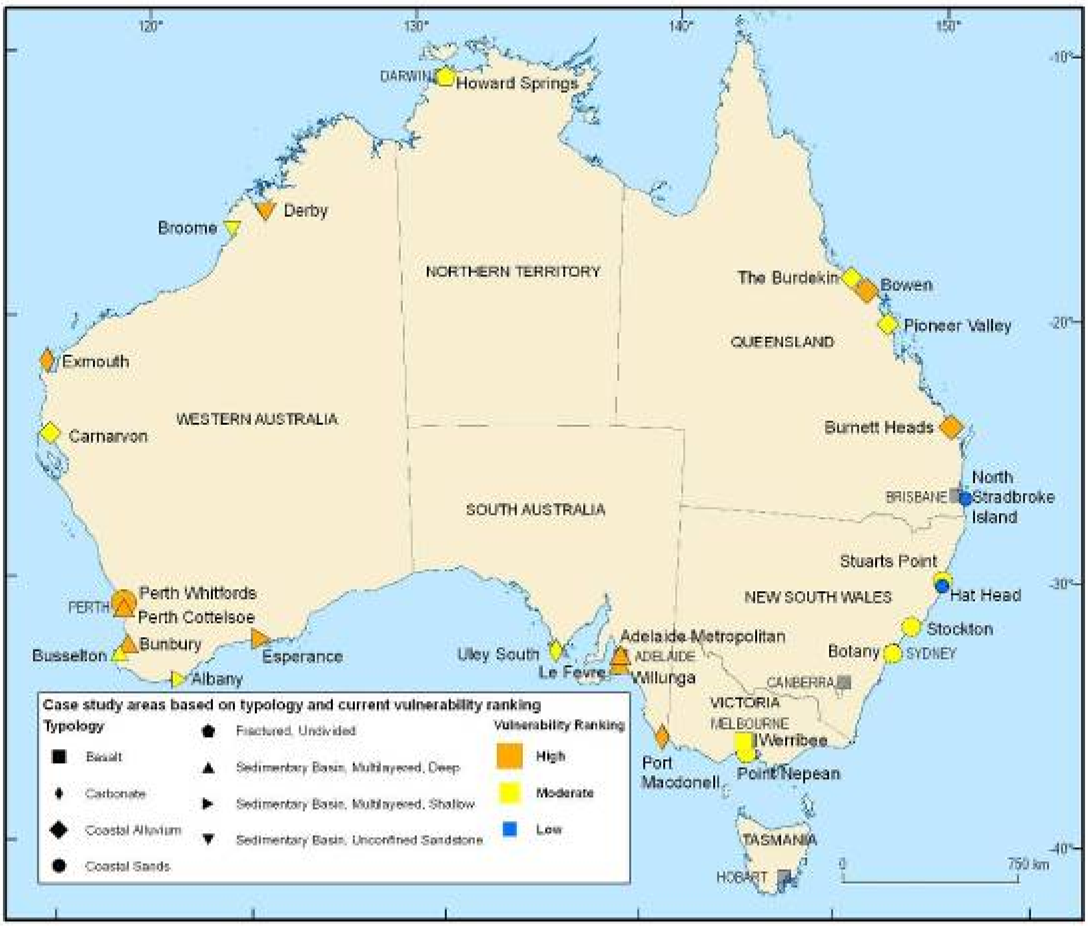
Some of the key drivers to future SWI vulnerability that may exacerbate the above factors include:

- predicted increased groundwater extraction rates due to irrigation and population demand

- reduced rates of groundwater recharge associated with predicted lower than average rainfall
- sea-level rise in low-lying coastal areas.

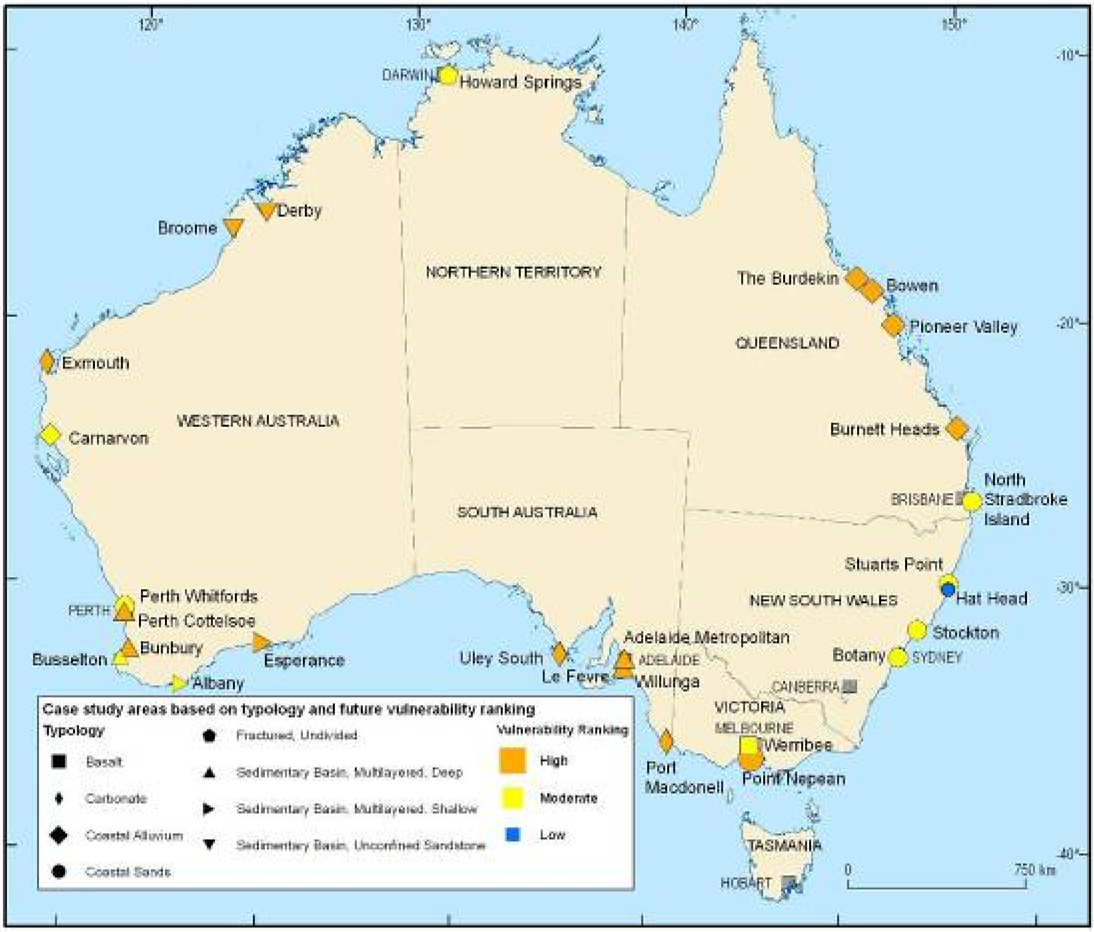
All of the key drivers and many of the less crucial factors contributing to overall SWI vulnerability are subject to change over time. As such, SWI vulnerability may change over time and it is emphasised that the vulnerability rankings should be updated as new data become available to ensure their validity.

Figure 7: Overall CSA current vulnerability ranking results



Note: Results for only the highest vulnerability ranking aquifer for each CSA are displayed on this figure.

Figure 8: Overall CSA future vulnerability ranking results



Note: Results for only the highest vulnerability ranking aquifer for each CSA are displayed on this figure

Table 10: Summary of overall vulnerability rankings and key drivers used to derive these rankings for each CSA

Aquifer name	*CSA*	*State/ territory*	*Type*	*Coastal aquifer typology*	*Current vulnerability ranking*	*Future vulnerability ranking*	*Key drivers to current vulnerability ranking**	*Key drivers to future vulnerability ranking**
Gambier Limestone	Port MacDonnell	SA	Unconfined	Carbonate, Mediterranean, Temperate, Summer Dry	High	High	Declining GWLs; increasing salinities; potentially unstable x_T; high quan. indexing; high E/R; low KMM	High E/R; high propensity to change (maths analysis); low KMM; risk of surface inundation (DEM); potential for inland movement of the interface
Fairymead Beds	Burnett Heads (Bargara)	Qld	Unconfined	Coastal Alluvium, Temperate, Without Dry Season	High	High	Previous incidence; low GWLs; increasing salinities; declining GWLs; potentially unstable x_T; decreasing RF	Moderate propensity to change (MA); GWLs declining; increasing salinity; low-lying (DEM); population increase
Elliot Formation	Burnett Heads (Bargara)	Qld	Unconfined	Coastal Alluvium, Temperate, Without Dry Season	High	High	Previous incidence; low GWLs; increasing salinities; declining GWLs; potentially unstable x_T; decreasing RF	Moderate propensity to change (MA); GWLs declining; increasing salinity; low-lying (DEM); population increase
Elliot Formation	Burnett Heads (Moore Park)	Qld	Unconfined	Coastal Alluvium, Temperate, Without Dry Season	High	High	Previous incidence; low GWLs; increasing salinities; declining GWLs; potentially unstable x_T; decreasing RF	High propensity to change (MA); GWLs declining; increasing salinity; low-lying (DEM); population increase

* DEM, Digital Elevation Model; E/R, extraction to net recharge ratio; GW, groundwater; GWL, groundwater level; KMM, knowledge, monitoring and management; MA, mathematical analysis; RF, rainfall; TWS, town water supply; qual., quality; quan., quantity; x_T theoretical wedge toe location; x_T ' theoretical scaled wedge toe

Aquifer name	*CSA*	*State/ territory*	*Type*	*Coastal aquifer typology*	*Current vulnerability ranking*	*Future vulnerability ranking*	*Key drivers to current vulnerability ranking**	*Key drivers to future vulnerability ranking**
Superficial	Bowen	Qld	Unconfined	Coastal Alluvium, Tropical	High	High	Previous incidence; low GWLs; high qual. and quan. indexing; high salinities; moderate KMM	High propensity to change (MA); KMM not sufficient (drought focused); large population increase which may increase GW usage; significant area <1m AHD; preferential flow via palaeochannels
Wallal/Erskine Sandstone	Derby	WA	Unconfined	Sedimentary Basin, Arid	High	High	Previous incidence; unstable x_T; moderate to low GWLs; high quan. indexing; high E/R; low KMM	Low KMM; some areas low-lying (DEM); arid and highly variable climate; high propensity to change (MA)
T1	Adelaide	SA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Declining GWLs; low GWLs; unstable theoretical wedge toe location; high E/R; decreasing RF; moderate KMM	Low KMM; offshore interface location unknown; increasing population with possibly greater GW reliance; minor low-lying areas (DEM)
T2	Adelaide	SA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Declining GWLs; low GWLs; unstable theoretical wedge toe location; high E/R; decreasing RF; moderate KMM	Low KMM; offshore interface location unknown; increasing population with possibly greater GW reliance; minor low-lying areas (DEM)
Yarragadee	Bunbury	WA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Low GWLs; large x_T; moderate to high E/R; declining GWLs; decreasing RF; low KMM	Low KMM; increasing population and potential GW usage increase; significant low-lying area; high propensity to change

* DEM, Digital Elevation Model; E/R, extraction to net recharge ratio; GW, groundwater; GWL, groundwater level; KMM, knowledge, monitoring and management; MA, mathematical analysis; RF, rainfall; TWS, town water supply; qual., quality; quan., quantity; x_T theoretical wedge toe location; x_T' theoretical scaled wedge toe

Aquifer name	*CSA*	*State/ territory*	*Type*	*Coastal aquifer typology*	*Current vulnerability ranking*	*Future vulnerability ranking*	*Key drivers to current vulnerability ranking**	*Key drivers to future vulnerability ranking**
Superficial/ Pallinup	Esperance	WA	Unconfined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Low GWLs; declining GWLs; large x_T; high quan. and qual. indexing; high E/R	KMM insufficient; monitoring data insufficient; high propensity to change (MA); increasing population; high-dependence on GW for TWS; some low-lying areas in the east
Werrilup Formation	Esperance	WA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Low GWLs; declining GWLs; unstable x_T; high quan. and qual. indexing; high E/R; moderate KMM	KMM insufficient; monitoring data insufficient; high propensity to change (MA); increasing population; high-dependence on GW for town water supply; some low-lying areas in the east
Q1	Le Fevre	SA	Unconfined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Low GWLs; unstable x_T; decreasing RF; low KMM	Limited KMM; increasing population; high propensity to change (MA); low-lying areas <1 m AHD
T1	Le Fevre	SA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Low GWLs; unstable x_T; high quan. indexing	Limited KMM; increasing population; high propensity to change (MA); low-lying areas <1 m AHD
T2	Le Fevre	SA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Low GWLs; unstable x_T; high quan. indexing	Limited KMM; increasing population; high propensity to change (MA); low-lying areas <1 m AHD

* DEM, Digital Elevation Model; E/R, extraction to net recharge ratio; GW, groundwater; GWL, groundwater level; KMM, knowledge, monitoring and management; MA, mathematical analysis; RF, rainfall; TWS, town water supply; qual., quality; quan., quantity; x_T theoretical wedge toe location; x_T ' theoretical scaled wedge toe

Aquifer name	*CSA*	*State/ territory*	*Type*	*Coastal aquifer typology*	*Current vulnerability ranking*	*Future vulnerability ranking*	*Key drivers to current vulnerability ranking**	*Key drivers to future vulnerability ranking**
Yarragadee	Perth (Whitfords)	WA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Declining GWLs; unstable x_T; moderate quan. indexing; moderate KMM	KMM insufficient; very high risk of SWI if interface moves inland; increasing population which may increase GW usage
Superficial	Perth (Whitfords)	WA	Unconfined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Declining GWLs; potentially unstable x_T; moderate quan. indexing; moderate KMM	KMM insufficient; very high risk of SWI if interface moves inland; increasing population which may increase GW usage
Leederville	Perth (Whitfords)	WA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Declining GWLs; unstable x_T; moderate quan. indexing; moderate KMM	KMM insufficient; very high risk of SWI if interface moves inland; increasing population which may increase GW usage
Port Willunga Formation	Willunga	SA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Low GWLs; declining GWLs; high salinities; potentially unstable x_T; moderate quan. and qual. indexing; high E/R; decreasing RF; low KMM	Moderate–high propensity to change (MA); high population growth; low KMM
Maslin Sands	Willunga	SA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	Low GWLs; declining GWLs; high salinities; unstable x_T; high quan. and qual. indexing; high E/R; decreasing RF; low KMM	Moderate–high propensity to change (MA); high population growth; low KMM

* DEM, Digital Elevation Model; E/R, extraction to net recharge ratio; GW, groundwater; GWL, groundwater level; KMM, knowledge, monitoring and management; MA, mathematical analysis; RF, rainfall; TWS, town water supply; qual., quality; quan., quantity; x_T theoretical wedge toe location; x_T ' theoretical scaled wedge toe

Aquifer name	*CSA*	*State/ territory*	*Type*	*Coastal aquifer typology*	*Current vulnerability ranking*	*Future vulnerability ranking*	*Key drivers to current vulnerability ranking**	*Key drivers to future vulnerability ranking**
Cape Range Group	Exmouth	WA	Unconfined	Carbonate, Arid	High	High	Arid climate; high and variable KMM; low GWLs; unstable x_T; high quan. indexing; moderate qual. indexing	Unstable wedge toe; high propensity for change (MA); moderate KMM; significant areas low lying (DEM)
Cape Range Group	Exmouth	WA	Freshwater Lens	Carbonate, Arid	High	High	Arid climate; high and variable KMM; low GWLs; unstable x_T; high quan. indexing; moderate qual. indexing	Unstable wedge toe; high propensity for change (MA); moderate KMM; significant areas low lying (DEM); freshwater lens particularly susceptible to up-coning
Tamala Limestone	Perth (Cottesloe)	WA	Freshwater Lens	Coastal Sands, Mediterranean, Temperate, Summer Dry	High	High	Previous incidence; thin freshwater lens; low GWLs; moderate KMM	High propensity to change (MA); unregulated and unmetered bores
Bridgewater Formation	Uley South	SA	Unconfined	Carbonate, Mediterranean, Temperate, Summer Dry	Moderate	High	Low GWLs; declining GWLs; high salinities; high quan. indexing; moderate qual. indexing; decreasing RF; high E/R	Increasing population may increase GW usage; moderate to high propensity to change; susceptible to drought conditions
Unconfined	Pioneer Valley	Qld	Unconfined	Coastal Alluvium, Temperate, Dry Winter	Moderate	High	Previous incidence; low GWLs; decreasing GWLs; potentially unstable x_T	High extractions; high economic dependence on GW usage; susceptible to drought conditions and highly variable climate; increase in population

* DEM, Digital Elevation Model; E/R, extraction to net recharge ratio; GW, groundwater; GWL, groundwater level; KMM, knowledge, monitoring and management; MA, mathematical analysis; RF, rainfall; TWS, town water supply; qual., quality; quan., quantity; x_T theoretical wedge toe location; x_T ' theoretical scaled wedge toe

Aquifer name	*CSA*	*State/ territory*	*Type*	*Coastal aquifer typology*	*Current vulnerability ranking*	*Future vulnerability ranking*	*Key drivers to current vulnerability ranking**	*Key drivers to future vulnerability ranking**
Unconfined	The Burdekin	Qld	Unconfined	Coastal Alluvium, Tropical	Moderate	High	Low GWLs; high salinities; declining GWLs; high E/R; unstable x_T	High propensity to change (MA); some low-lying areas
Bridgewater and Wannaeue Formations	Point Nepean	Vic	Freshwater Lens	Coastal Sands, Temperate, Without Dry Season	Moderate	High	Low GWLs; declining GWLs; low KMM; decreasing RF	High propensity to change (MA); high population growth which may increase GW use; projected urbanisation may reduce recharge
Broome Sandstone	Broome	WA	Unconfined	Sedimentary Basin, Arid	Moderate	High	Low GWLs; potentially unstable x_T; high quan. indexing; low KMM	High propensity to change; minor low-lying areas
Alluvium/ Fractured Rock	Werribee	Vic	Unconfined	Basalt, Temperate, Without Dry Season	Moderate	Moderate	High salinities; extraction bores near x_T; moderate KMM; moderate quan. and qual. indexing; decreasing RF	Large population growth
Botany Sand Beds	Botany	NSW	Unconfined	Coastal Sands, Temperate, Without Dry Season	Moderate	Moderate	Previous incidence; decreasing RF; potentially unstable x_T; low KMM	Low KMM
Stuarts Point Coastal Sands	Stuarts Point	NSW	Unconfined	Coastal Sands, Temperate, Without Dry Season	Moderate	Moderate	High qual. indexing; high E/R; low GWLs; low KMM	Low KMM

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* DEM, Digital Elevation Model; E/R, extraction to net recharge ratio; GW, groundwater; GWL, groundwater level; KMM, knowledge, monitoring and management; MA, mathematical analysis; RF, rainfall; TWS, town water supply; qual., quality; quan., quantity; x_T theoretical wedge toe location; x_T ' theoretical scaled wedge toe

Aquifer name	*CSA*	*State/ territory*	*Type*	*Coastal aquifer typology*	*Current vulnerability ranking*	*Future vulnerability ranking*	*Key drivers to current vulnerability ranking**	*Key drivers to future vulnerability ranking**
Koolpinyah/ Coomalie	Howard Springs	NT	Unconfined	Fractured, Undivided, Tropical	Moderate	Moderate	Climate variability; x_T close to extraction bores; low KMM; decreasing RF; macrotidal	Localised fractures provide preferential flow paths for SWI; increasing population; KMM insufficient; significant areas low lying
Koolpinyah/ Coomalie	Howard Springs	NT	Confined	Fractured, Undivided, Tropical	Moderate	Moderate	Climate variability; x_T close to extraction bores; low KMM; decreasing RF; macrotidal	Localised fractures provide preferential flow paths for SWI; increasing population; KMM insufficient; significant areas low lying
Werillup Formation Sand	Albany (Ocean side)	WA	Unconfined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	Moderate	Moderate	Low GW levels; declining GWLs; potentially unstable x_T; moderate KMM	Low and declining GWL near the coast; increasing population trend (may increase GW usage); KMM not sufficient; low elevations on harbour side (DEM)
Superficial	Busselton	WA	Unconfined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	Moderate	Moderate	Low GWLs; high qual. indexing; high E/R; decreasing RF	High ratio of extraction to net recharge; population is increasing which may increase GW demand; insufficient KMM
Leederville	Busselton	WA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	Moderate	Moderate	Low GWLs; high qual. indexing; high E/R; decreasing RF	High ratio of extraction to net recharge; population is increasing which may increase GW demand; insufficient KMM
Quaternary Riverbed Sand	Carnarvon	WA	Unconfined	Coastal Alluvium, Tropical	Moderate	Moderate	Arid climate; low GWLs; declining GWLs; high salinities; large x_T	Susceptible to flood and drought conditions; some low-lying areas (DEM)

* DEM, Digital Elevation Model; E/R, extraction to net recharge ratio; GW, groundwater; GWL, groundwater level; KMM, knowledge, monitoring and management; MA, mathematical analysis; RF, rainfall; TWS, town water supply; qual., quality; quan., quantity; x_T theoretical wedge toe location; x_T ' theoretical scaled wedge toe

Aquifer name	*CSA*	*State/ territory*	*Type*	*Coastal aquifer typology*	*Current vulnerability ranking*	*Future vulnerability ranking*	*Key drivers to current vulnerability ranking**	*Key drivers to future vulnerability ranking**
Alluvium	Carnarvon	WA	Confined	Coastal Alluvium, Tropical	Moderate	Moderate	Arid climate; low GWLs; declining GWLs; high salinities; potentially unstable x_T	Susceptible to flood and drought conditions; some low-lying areas (DEM)
Stockton Coastal Sands	Stockton	NSW	Unconfined	Coastal Sands, Temperate, Without Dry Season	Moderate	Moderate	Low KMM; moderate x_T '	Low storage and high hydraulic conductivities; susceptible to dry conditions; increasing populations which may increase GW demand; some low-lying areas (DEM); KMM insufficient
Wanilla Sands	Uley South	SA	Confined	Carbonate, Mediterranean, Temperate, Summer Dry	Low	Moderate	Low GWLs; declining GWLs; high salinities; moderate qual. indexing; decreasing RF	Increasing population may increase GW usage; low propensity to change; susceptible to drought conditions
Dune Sands	North Stradbroke Island	Qld	Unconfined	Coastal sands, Temperate, Without Dry Season	Low	Moderate	No key drivers identified	Potential for increasing extraction; susceptible to drought; population/dwelling increase may increase GW demand
Superficial	Albany (Harbour side)	WA	Unconfined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	Low	Moderate	Low GW levels; declining GWLs; moderate KMM	Low and declining GWL near the coast; increasing population trend (may increase GW usage); KMM not sufficient; low elevations on harbour side (DEM)

* DEM, Digital Elevation Model; E/R, extraction to net recharge ratio; GW, groundwater; GWL, groundwater level; KMM, knowledge, monitoring and management; MA, mathematical analysis; RF, rainfall; TWS, town water supply; qual., quality; quan., quantity; x_T theoretical wedge toe location; x_T ' theoretical scaled wedge toe

Aquifer name	*CSA*	*State/ territory*	*Type*	*Coastal aquifer typology*	*Current vulnerability ranking*	*Future vulnerability ranking*	*Key drivers to current vulnerability ranking**	*Key drivers to future vulnerability ranking**
Pallinup/ Werillup	Albany (Harbour side)	WA	Confined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	Low	Moderate	Low GW levels; declining GWLs; potentially unstable x_T; moderate KMM	Low and declining GWL near the coast; increasing population trend (may increase GW usage); KMM not sufficient; low elevations on harbour side (DEM)
Superficial	Bunbury	WA	Unconfined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	Low	Moderate	Declining GWLs; decreasing RF; low KMM	Low KMM; increasing population and potential GW usage increase; significant low-lying areas
Quaternary	Willunga	SA	Unconfined	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	Low	Moderate	Low GWLs; declining GWLs; high salinities; moderate quan. and qual. indexing; decreasing RF; low KMM	Moderate to high propensity to change (MA); high population growth; low KMM
Tertiary Sands	Port MacDonnell	SA	Confined	Carbonate, Mediterranean, Temperate, Summer Dry	Low	Low	Declining GWLs; increasing salinities; low KMM	Low vulnerability assuming extraction does not increase
Coastal Sands	Hat Head	NSW	Unconfined	Coastal Sands, Temperate	Low	Low	Declining RF; macrotidal	Low-lying areas (DEM)

* DEM, Digital Elevation Model; E/R, extraction to net recharge ratio; GW, groundwater; GWL, groundwater level; KMM, knowledge, monitoring and management; MA, mathematical analysis; RF, rainfall; TWS, town water supply; qual., quality; quan., quantity; x_T theoretical wedge toe location; x_T ' theoretical scaled wedge toe

5.2 SWI vulnerability indicators outside of the CSAs

Section 5.1 focused on the results and vulnerability rankings of 27 CSAs around Australia. Such local-scale, data-intensive studies are essential for accurately assessing SWI vulnerability. As stated by Werner et al. (2012a), *'[Seawater intrusion] research encompasses a multi-disciplinary range of topics due to the complex nature of coastal aquifer flow and transport'*. By adopting a multi-faceted assessment approach, Section 5.1 provided an accurate measure of SWI vulnerability in the individual CSAs. However, since this project aimed to provide a national assessment of vulnerability, a discussion of areas outside of the CSAs is necessary where data availability generally precludes a full assessment of SWI vulnerability.

The VFA and coastal aquifer typology cover substantial portions of Australia's coastline outside of the CSAs and they may be useful indicators of SWI vulnerability levels in these areas. Their suitability as tools for highlighting areas around Australia that may have high SWI vulnerability is thus evaluated below by comparing their outputs to the integrated vulnerability rankings in the CSAs.

5.2.1 Coastal aquifer typology

As outlined in Chapter 3, all coastal aquifer types identified were documented to be at threat of SWI. Although it may be the case that some aquifer types are more likely to be vulnerable to SWI for a variety of reasons, SWI is not unique to any of them and site-specific information is required to make a full assessment of SWI vulnerability.

Figures 9 and 10 summarise the vulnerability rankings from the CSA assessment in Section 5.1 for each aquifer type. Of the coastal aquifer types considered in the CSA assessment, those found to contain the highest numbers of high SWI vulnerability CSA aquifers are the carbonate, coastal alluvium, unconfined sandstones and multi-layered, confined aquifer systems. Aquifers that form a relatively thin lens of fresh water overlying saline water have also been rated as highly vulnerable (e.g. Exmouth, Perth (Cottesloe), Adelaide, Le Fevre and Esperance).

Refer to Section 4.3 which summarises the characteristics of the principal aquifer types and outlines their associated SWI implications. The tables in Appendix 4 are useful for identifying characteristics that might explain why certain aquifer types have been identified as corresponding to the highest vulnerability rated CSAs. In summary, based on the CSAs considered in this study:

- Carbonate and alluvial systems may have highly conductive fractures (carbonate) or palaeochannels (alluvial) which allow for the preferential flow of sea water which has a high propensity for movement in these settings.
- Deep, unconfined sandstones naturally have a large inland extent of the SWI wedge toe that is unstable (i.e. moving inland).
- Multi-layered, confined aquifer systems are commonly mined for groundwater and have the lowest potentiometric surfaces of all aquifer types.
- Thin freshwater aquifers overlying saline groundwater are subject to up-coning.

The future vulnerability of these aquifer types would be expected to rise if extractive and other pressures on these systems, such as droughts, increase.

Figure 9: Aquifer types correlated to current SWI vulnerability rankings in CSAs

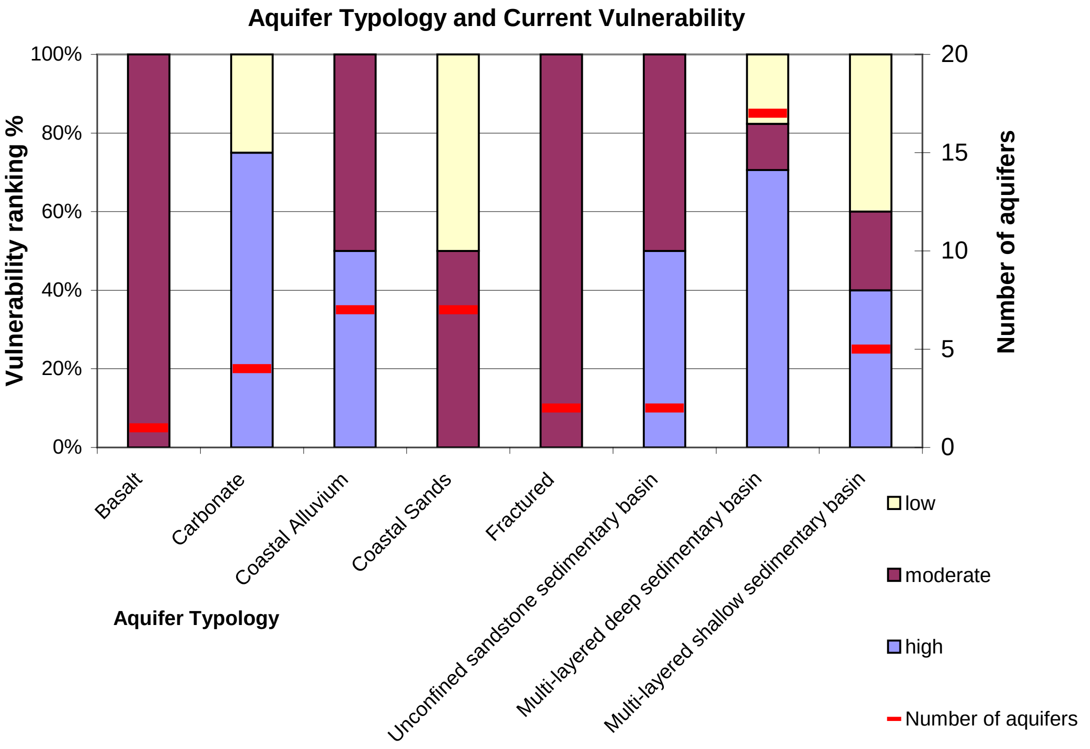
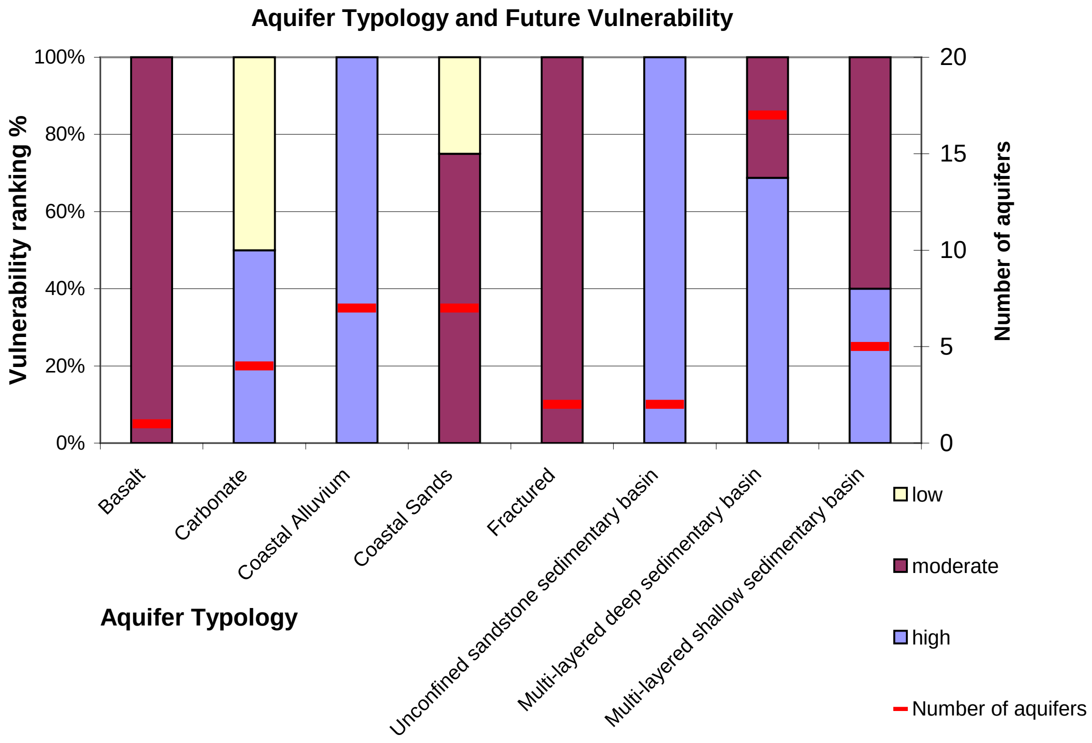


Figure 10: Aquifer types correlated to future SWI vulnerability rankings in CSAs



The role of knowledge, monitoring and management should not be underestimated in terms of moderating the effects of groundwater extraction within the intrinsic vulnerability of a system. Using the coastal alluvium types to illustrate this point, the integrated vulnerability assessment shows that where groundwater has previously been over-allocated and SWI has been identified as an issue in The Burdekin and Pioneer Valley, the vulnerability ranking is only moderate since there is a high level of knowledge, monitoring and management. In contrast, SWI has also been identified in the coastal alluvium CSA of Bowen, but SWI vulnerability is ranked as high due to a lower level of knowledge, monitoring and management.

One could extrapolate the results to areas outside the CSAs to infer that the aquifer types above have some characteristics that make them inherently more vulnerable to SWI than others where they are exploited and not sufficiently characterised, monitored or managed. However, such extrapolation would require further work to correctly classify Australia’s coastal aquifers according to the typology developed in this project. Additional investigations would be required to identify the general characteristics applicable to each aquifer type. However, since extraction relative to recharge is generally the key driver of overall SWI vulnerability, such extrapolation is problematic. Even those aquifer types that may be considered the least inherently vulnerable to SWI may become vulnerable if over-exploited and poorly managed.

5.2.2 Vulnerability factor analysis

A detailed assessment of site-specific information is needed to determine vulnerability to SWI. Much of this information is not available outside of the CSAs and is not captured by the VFA parameters. However, in areas where there is insufficient information to undertake a full assessment of vulnerability following the methodology in Section 5.1, the VFA data presented in Section 4.2 are useful for highlighting locations where there are strong indicators that aquifers may have high SWI vulnerability and require detailed monitoring and careful management if they are to be exploited.

For each CSA, Table 9-1 (Appendix 9) identifies the maximum overall current SWI vulnerability ranking of the aquifers within it and the highest category of SWI vulnerability indicators from the VFA. The table shows that most of the CSAs do contain VFA indicators of high SWI vulnerability, which provides some confidence in using the VFA parameters to highlight other areas that may have high SWI vulnerability. However, this approach has limitations because there is not a direct correlation between the number or density of indicators and the level of vulnerability. This lack of correlation is primarily due to lack of data and the dependency of vulnerability on factors not captured by the VFA.

The discussion on national SWI vulnerability in Section 5.3 highlights areas where there is a comprehensive range of VFA parameters (the VFA priority areas defined in Section 4.2.6), indicating a greater likelihood of high SWI vulnerability. However, for the reasons outlined above, it is stressed that other areas with no VFA data or only low SWI vulnerability indicators may also be vulnerable.

5.3 National SWI vulnerability assessment

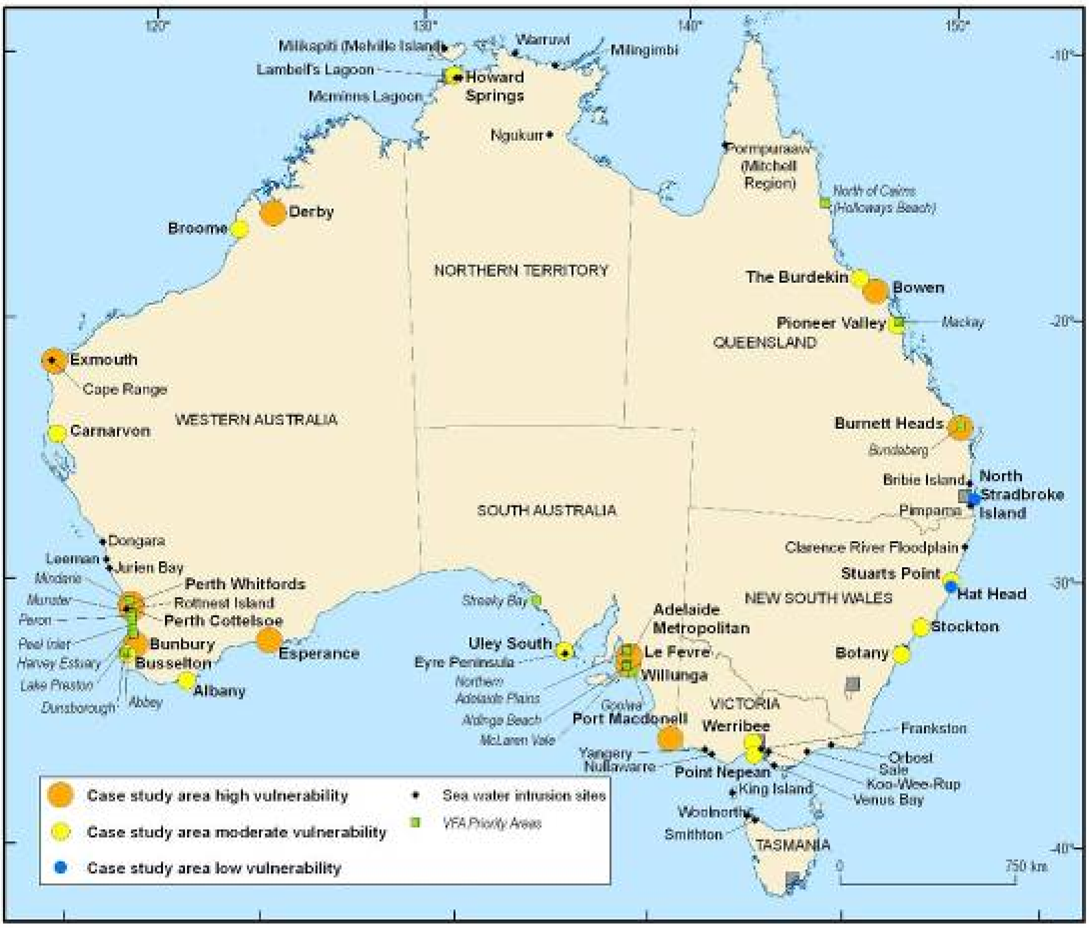
Largely because Australia’s population centres are concentrated along the coast, fresh water stored within Australian coastal aquifers is extensively utilised and relied upon by communities and industry in many areas. Excessive groundwater extraction relative to recharge potentially places these aquifers at risk of SWI and thereby jeopardises the viability of groundwater-dependent activities. Such effects may be exacerbated in the future by climate change, sea-level rise and population growth. It could take many years to reverse the impacts of SWI, so monitoring and managing freshwater coastal aquifers in Australia is vital to protect industry, communities and the environment.

To provide a national summary of locations where existing data suggest high SWI vulnerability of coastal aquifers around Australia, three sources of information presented in this summary report are utilised:

1. The integrated SWI vulnerability assessments in 27 CSAs in Section 5.1: SWI vulnerability has been evaluated in detail at these locations, thus their SWI vulnerability levels are considered the most reliable of the three information sources.
2. The SWI sites identified by the literature review in Chapter 3 (noting that the 27 CSAs are a subset of these): in total, 20 SWI sites were identified in addition to the 27 CSAs (Ivkovic et al. 2012a). Since SWI has been documented in these areas but no integrated vulnerability assessments were possible due to lack of available data, the precautionary principle is applied and they are assumed to have high SWI vulnerability until integrated vulnerability assessments can be undertaken within them following the approach used for the CSAs.
3. The VFA priority areas identified in Chapter 4: areas containing examples of four or more of the seven high category SWI vulnerability indicators. The VFA priority areas highlight places outside of the CSAs and SWI sites where high SWI vulnerability is likely. Given the limitations of this approach outlined in section 5.2.2, the VFA parameters are considered to be the least reliable indicators of SWI vulnerability of the three information sources.

Figure 11 presents the locations of CSAs, SWI sites identified by the literature review and VFA priority areas. The VFA priority areas identified in Figure 11 are general locations and they refer to the particular locality as well as surrounding areas. Reference should be made to Section 4.2 and the figures in Appendix 3 for other areas showing VFA indicators of high vulnerability. It is emphasised that much of Australia’s coastline is data poor and lack of VFA SWI indicators should not be taken to imply that areas are not vulnerable to SWI. The VFA priority areas simply highlight those locations where considerable numbers of high SWI vulnerability indicators are present.

Figure 11: Summary map of CSAs (with current SWI vulnerability ranking), SWI sites and VFA priority areas



The majority of areas identified as having moderate or high SWI vulnerability or containing high category indicators of SWI vulnerability have high population densities or intensive groundwater use for agriculture or industry. The consequences of SWI in these areas are therefore likely to be severe and early monitoring and management are crucial.

This study has confirmed that there are important linkages between land and water use and SWI vulnerability: the extraction rate relative to recharge is the key driver of SWI. Although different aquifer types may respond differently to extraction and have characteristics making SWI less or more likely within them, no aquifer type is immune to SWI. Despite differing hydrogeological settings, climate and land use, all Australian states and the Northern Territory contain areas that may be highly vulnerable to SWI, and examples of SWI exist in the literature for all of them.

Figure 11 focuses only on current and past conditions. Although the impacts of sea-level rise on SWI in low-lying areas have been considered in Section 4.6, the potential impacts on SWI of future changes in other factors such as climate, population and land use are more difficult to predict. The vulnerability level of coastal aquifers to SWI varies over time and SWI-specific monitoring regimes are imperative to facilitate early identification and management of SWI around Australia’s coastline.

6. Data gaps analysis

The national SWI project assessed SWI vulnerability at the regional and local scales, using datasets from national and state/territory agencies. The data sources, methodologies and the results are outlined in Chapters 4 and 5 of this report. The project's comprehensive and national-scale approach enabled the identification of gaps in both data and knowledge. Identification of data and knowledge gaps provides a foundation to improve future studies. An analysis of the gaps in the data used within the project was undertaken to inform the limitations of the study and to inform data collection requirements for future studies. The results of this analysis are summarised in Section 6.1. Knowledge gaps were also analysed and a summary of this work is presented in Section 6.2.

6.1 Data gaps

The current project assessed an array of data sources covering a range of spatial and temporal scales. The differences in length and chronologic availability of data resulted in complex issues with regards to the interoperability and interpretation of these datasets. The variability in data quality and quantity between the various sources added an additional layer of complexity in assessing and comparing the datasets. For brevity, this discussion broadly categorises the data into three major spatial scales as they relate to coastal regions around Australia:

- national: for Australia-wide datasets of consistent quality or generated as a national product, usually from federal data sources, covering thousands of kilometres
- regional: for data products that provide information regarding their specific region. This can be derived from state/territory or federal data sources, covering tens of kilometres
- local: specific information directly related to the interpretation of immediate and adjacent locations or to a scale of tens of metres.

Refer to Section 4.2 which summarises the datasets and describes how they were used in this project. Table 2-1 (Appendix 2) tabulates the datasets from national and state/territory sources in spatial and temporal extent categories.

6.1.1 National-scale data

The national datasets were reliable and consistent datasets that generally encompassed all points of interest in this project. This consistency was achieved at the cost of detail in the data. The loss of detail in these datasets limits their applicability to small areas. The datasets used in this project that fall into the national-scale category include:

Köppen-Geiger Climate of Australia

National climate change investigations were not within the scope of the project and hence pre-existing studies were utilised. We assumed that the approach of Peel et al., (2007) and CSIRO (Barron et al. 2010; Barron et al. 2011) was suitable for use in the project, and these climate groups were selected to be consistent with these other national-scale investigations. Limitations pertaining to the Köppen-Geiger analysis are detailed in the relevant publications (Barron et al. 2010; Barron et al. 2011).

1:5 m Hydrogeology Map of Australia, 1987

Due to the broad generalisations required to reduce complexity in a national map, an immediate shortcoming of the *1:5 000 000 Hydrogeology map of Australia* is the aggregation of many aquifers (coastal and otherwise) into a national category represented by sedimentary and low-grade metamorphic undivided lithology class. A recommendation for future studies is to update the 1987 hydrogeology map to further map the undivided aquifer lithology classes. This redefined map will have greater utility for national groundwater investigations.

1-second Digital Elevation Model

The 1-second Digital Elevation Model (DEM) is the one exception to the limitations of most simplified national datasets. The DEM has detailed and specific information available at a nation-wide scale as well as a local scale of 30-m grids. There are specific caveats with regards to the acquisition and processing of this DEM, which are explored in the technical report associated with the data (Gallant et al. 2011).

6.1.2 Regional-scale data

The use of regional datasets allowed for the infill of data gaps that exist in national data. Regional datasets that were representative of the specific CSAs were chosen for this project. An analysis examined gaps in data for population, tidal range, rainfall, and knowledge, monitoring and management.

Population

The population data were sourced from the ABS 2001 and 2006 Census data, and historical population trends were calculated; these trends do not represent future changes in population. An increase in population can lead to increases in possible water demand and use, but it is not a direct measure of these quantities. As with all statistical data, this information is representative with an unknown accuracy. It is unable to account for fluctuation in temporary population. An additional complexity is that the Census regions do not readily match the specific regions of interest in this project.

Tidal range

The tidal range data were sourced from the National Tidal Centre, which has specific collection and processing requirements. While the tidal data are a point data source, they are used to represent a wider region of coast. Due to the complex interaction of tides, coastal morphology and bathymetry, the calculated tidal range varies with increasing distance from a tide gauge. For much of the Australian coast, there has been consistent long-term tidal gauging for the last 30 years.

Rainfall – A comparison of the 2000–2010 rainfall against the long-term annual mean rainfall record

As with the tidal range data, rainfall is a point dataset used to inform a wider regional area. Where possible, the methodology selected the closest meteorological stations to the regions of interest. The temporal consistency of the data collected varies from rain gauge to rain gauge. The monthly rainfall data sourced from BoM has been selective in using only those meteorological stations with good temporal data consistency.

Knowledge, monitoring and management

Based on information derived from the literature review (Ivkovic et al. 2012a) many of the investigations of relevance at the state/territory scale come from 'grey' literature that is not readily available. Therefore, stakeholders were asked to provide key references in addition to the peer-reviewed journal articles. The degree of SWI assessment is somewhat subjective, and it is based on the perceived degree of knowledge, monitoring and management that was reported in the literature reviewed. These assessments have been validated by stakeholders.

6.1.3 Local-scale data

The project makes use of location-specific, detailed information that is not available in either the national-scale or regional-scale datasets. Implicit in the location-specific nature of these data sources is the poor temporal correlation and comparison against other locations.

Recharge

Recharge was estimated as the volume of freshwater discharge at the coast, which is consistent with the parameters provided for the mathematical analysis (i.e. similar to a Darcy through-flow estimate), plus the volume of net rainfall recharge (obtained from area-specific literature) over the area of interest. In confined aquifers, only the through-flow estimate of recharge was used. The width of the aquifer parallel to the coast through which through-flow occurs was estimated over the portion of the area of interest through which groundwater flows. The aquifers for which through-flow was not included in the recharge estimate were the local flow systems (e.g. coastal sands aquifer type) and freshwater lens situations.

The uncertainty in recharge estimates is large, sometimes as much as ±100 per cent. It was considered beyond the scope of this project to assess uncertainty in both extraction and recharge, and we were reliant on existing data, available reporting and stakeholder input.

Extraction

To assemble a nationally consistent methodology, the extraction dataset is a mixture of metered usage, allocation entitlement, estimated values reported in literature, and estimates from stakeholders (see the VFA and indexing limitations for information for specific areas of interest).

Bore data – water levels and total dissolved solids

Bore data are extensively used in the project to ascertain specific information regarding water levels near the coast and the water quality of coastal aquifers. These bore data have been sourced from the individual state/territory custodians along with relevant bore information where possible (stratigraphy, lithology, screening, and casing information).

The spatial coverage of bores was not consistent either between the areas of interest or from jursdiction to jurisdiction. Some jurisdictions and specific regions had significant volumes of bore data. However, this was a reflection of the level of interest in SWI and its effects on groundwater resources.

The temporal coverage of water level and TDS data varies from bore to bore and from area to area. The temporal discrepancies of the bore data when reviewed at a national scale added significant complexity to interpretation of the bore data.

The inconsistent coverage in spatial and temporal coverage of bore data added complexity to developing a uniform nation-wide assessment methodology on two levels:

- local and regional area of interest: the inconsistent temporal coverage of bore data imposed limitations on creating a small time window for assessment; as a result, decadal windows were chosen
- national scale: the inconsistent spatial coverage leads to considerable portions of Australia's coastline not being able to be assessed as part of this detailed and uniform approach.

These complexities imply that gaps in the bore data can manifest as an interpretation bias, as those jurisdictions and regions with more bore data may be deemed to be more susceptible to SWI. As such, an appreciation of regions where no data is available, as given by the VFA analysis, lends a balance to the understanding of regions or jurisdictions with a greater number SWI-vulnerable locations.

6.2 Knowledge gaps

The project made use of the most recent and accepted existing knowledge about SWI in Australia. Much of this information was sourced from state/territory water resource custodians and peer-reviewed literature. There are significant limitations to the understanding of SWI in Australia.

The overarching drivers of climate change and climate variation and their implications to SWI are not well understood on a national scale. The effects of future sea-level rise, over-extraction and population growth on coastal groundwater resources and the implications for SWI are continuing areas of research. This is relevant to the sustainable use of existing resources where there is limited understanding of groundwater recharge and subsequently the effects of a changing climate.

Current understanding of multi-layered, shallow and sedimentary basins and fractured rock aquifers is detailed in some locations around the coast of Australia but, in general, much of the coastline is extrapolated from existing geology and hydrogeology maps. As such there is no information about offshore hydrogeology, including offshore aquifers. These gaps in knowledge result in a lack of information regarding the detailed coastal aquifer settings around Australia and consequent groundwater–oceanic water interactions in these unknown aquifers.

Where there are detailed studies of coastal hydrogeology, there exist varying levels of detailed investigation from location to location andjurisdiction to jurisdiction. Currently, there is no national, standardised approach to coastal groundwater resource assessment and management. A limitation of these detailed studies is that they are yet to reach beyond currently accessed groundwater resources and investigate untouched groundwater supplies to establish a baseline SWI condition. However, the cost-effectiveness of such baseline studies may limit pre-development monitoring to those regions slated for immediate expansion.

7. Outcomes and recommendations

The national SWI project presented in this summary report provided a detailed analysis of the current state of SWI around the Australian coast and future impacts of sea-level rise associated with climate change and resource demand growth. Key project outputs, recommendations and outcomes are presented in this chapter.

7.1 Key project outputs

The outputs of the national SWI assessment are outlined in Chapters 4 and 5 and detailed in the series of technical reports produced as part of this project. The key outputs include the following:

- Existing SWI investigations in Australia were audited, leading to the identification of areas considered previously to be under threat of SWI (see Chapter 3 and Ivkovic et al. 2012a).
- A GIS database was developed, incorporating hydrogeological information, climatic data, elevation data and other key datasets considered relevant to a national-scale SWI vulnerability assessment (see Cook et al. 2012).
- The VFA was completed, which involved the development and implementation of a first-pass, broad-scale methodology to assess key observational elements relating to SWI vulnerability. The VFA was based on spatial and temporal analyses of the GIS database of available groundwater monitoring datasets (see Section 4.2 and Cook et al. 2012).
- The coastal aquifer typology was completed, which provided a characterisation of the hydrogeological settings of Australia’s coastal aquifers based on principal aquifer types and climate groups. A catalogue of simplified hydrogeological cross-sections and typical aquifer parameters were compiled for the 27 selected CSAs (see Section 4.3 and Ivkovic et al. 2012b).
- The mathematical analysis was undertaken, which provided a unique application of existing methods to aid the understanding of sensitivity of the freshwater–saltwater interface to various hydrogeological parameters and boundary conditions. It led to new tools and methodologies for physically defensible vulnerability quantification. CSAs were analysed using mathematical SWI vulnerability indicators, which were based on first-order assessments of steady-state SWI extent (position of the saltwater wedge toe and seawater volume) under current conditions. The mathematical analysis also assessed the propensity for change due to various stresses associated with climate change, future extraction and sea-level rise (see Section 4.4 and Morgan et al. 2012).
- Qualitative and quantitative SWI vulnerability indexing methodologies within the CSAs were developed and implemented (see Section 4.5, Morgan and Werner 2012 and Norman et al. 2012).
- A brief evaluation of the land surface inundation under sea-level rise (i.e. based on topographic elevations relative to sea level) was completed, along with a preliminary assessment of population growth, to identify areas where future water demands are expected to increase due to urban water requirements (Section 4.6).

- A methodology was developed for integrating the VFA, coastal aquifer typology, mathematical analysis, qualitative and quantitative indexing, the impacts of sea-level rise, and population growth to provide a holistic assessment of vulnerability to SWI. The methodology was applied to each CSA, which allowed a relative ranking of vulnerability to SWI under current and future conditions.
- There was an evaluation of the suitability of the VFA and coastal aquifer typology to infer SWI vulnerability levels outside the CSAs. The VFA was found to be useful as a national, first-pass assessment for decision makers to highlight areas that may have high SWI vulnerability.
- Areas where current VFA data show indicators of high vulnerability were identified for a national summary. It was concluded that the coastal aquifer typology may be useful for identifying particular aquifer types around Australia that are more likely to be vulnerable to SWI than others, but insufficient data currently exist to make this assessment in many areas outside of the CSAs.
- The knowledge and data gaps for SWI vulnerability assessment were identified, and included reliable, detailed investigation and monitoring data and the classification of useful coastal aquifer types around the entire Australian coastline.

This first-pass SWI assessment also provided insights into:

- the variety and complexity of freshwater–saltwater interfaces around the country
- the methods used to analyse SWI vulnerability
- SWI associated with climate change, future extraction and sea-level rise.

7.2 Recommendations

SWI is a national issue that poses a threat to the groundwater resources in all of Australia’s states and the Northern Territory. Despite this, comprehensive investigations of SWI are relatively uncommon at a detailed local level, and a number of knowledge gaps remain. These gaps have important implications for managing SWI and the associated threats to freshwater resources and ecosystems in Australia. The following monitoring, research, education and knowledge dissemination activities are recommended to ensure effective management and protection of coastal groundwater resources.

7.2.1 Key monitoring and research activities

Recommended monitoring and research activities are as follows:

- Long-term groundwater monitoring. Consistent, long-term coastal groundwater monitoring is required in all states and the Northern Territory focusing on the collection of groundwater level, salinity, chemistry and extraction data at regular intervals. Monitoring should occur at rates and densities commensurate with the likelihood and scale of ongoing and future groundwater use. SWI is often a slow process that requires persistent monitoring specifically designed to capture relevant trends. Long-term data collection provides an opportunity for interpretation of trends in water level, salinity and extraction and allows for the development of a better understanding of groundwater resources and SWI intrusion processes. It will increase the likelihood of identifying, monitoring, managing and preventing SWI.
- Further hydrogeological analyses. As a priority, there should be further hydrogeological analyses of areas with significant SWI vulnerability but little to moderate SWI knowledge, monitoring and management activities (as identified in Section 5.1). There should also be further analyses where the VFA has identified indicators of moderate or high level SWI vulnerability. Such analyses may include water balance assessment, hydrogeological conceptualisation, hydrochemical analysis and groundwater modelling.
- Climate change research. The impacts of climate change on coastal groundwater resources are not well understood in Australia due to slow response times and uncertainties in what changes will actually occur. Given that Australian climate variability is high, changes to coastal aquifers due to changes in climatic averages may be less apparent over short time periods. Climate change and climate variability impacts on coastal groundwater and the implications for SWI are continuing areas of research.
- Further characterisation of key SWI processes and features in different hydrogeological and hydrological settings. This includes developing a better understanding of saltwater up-coning processes and time scales, and further characterisation of SWI extent and distinguishing between up-coning and lateral as well as local and more regional types of SWI occurrences.
- Further characterisation of the hydrogeology of the confined aquifer systems that extend offshore and the position of the SWI interface. This is especially critical to the management of the multi-layered, deep aquifer systems which are currently mined for water in Australia.
- Characterisation of the coastal geomorphic settings associated with SWI processes.
- Further classification and subdivision of the ‘undivided’ principal aquifer types within the 1:5 000 000 national-scale hydrogeology map to increase its usefulness for national-scale hydrogeological assessments and allow extension of coastal aquifer typologies around the Australian coast.
- Evaluation of various groundwater assessment tools for their usefulness in assessing and managing SWI issues. These tools may include geophysics (airborne geophysical and associated ground-truthing), hydrochemistry, environmental tracer, and remote sensing.
- Better linking of field processes with models, model calibrations and predictive uncertainty analyses.

- Multidisciplinary research to evaluate interactions between SWI and submarine groundwater discharge, ecosystem health and unsaturated zone processes.
- Developing a better understanding of the relationships between estuarine tidal dynamics of coastal aquifers and SWI.
- Further investigation and research into the use of aquifer storage and recovery to manage SWI in coastal aquifers.

7.2.2 Education and knowledge dissemination activities

Recommended education and knowledge dissemination activities are as follows:

- Development of national best practice guidelines for SWI assessment, monitoring and management.
- A national knowledge adoption workshop focusing on managing coastal groundwater resources. The workshop would build on the investment in this area by facilitating a public exchange of information across the research–management paradigms.
- Development of a SWI website, or a SWI module on the Ozcoast or the National Centre for Groundwater Research and Training websites.
- Improved knowledge-sharing through educational material on SWI fundamentals for researchers, policy makers and management communities.
- Awareness-raising activities to increase uptake of project findings.

7.3 Key project outcomes

The four phases of this project culminated in a national-scale vulnerability assessment of SWI and resulted in the following broad key outcomes:

- *Increased awareness and understanding of the location and magnitude of SWI-vulnerable regions in Australia for state/territory and federal stakeholders, regional managers and policy makers.* The outputs from individual phases identify regions vulnerable to SWI and the likely magnitude of the vulnerability. This can be used to inform and facilitate an increased awareness and understanding of SWI-vulnerable regions by providing a baseline assessment of current vulnerability. The project also informs future vulnerability resulting from resource demand change, recharge change, and sea-level rise associated with climate change.
- *Development and application of a robust method for a first-pass assessment of SWI vulnerability applicable to the entire Australian coast.* The outputs from the five technical assessment components and the integrated vulnerability assessment form the basis of a robust methodology that can be used for the preliminary national-scale assessment of SWI vulnerability. These assessments are conducted for both current and future scenarios. The method builds on previous SWI vulnerability methods by incorporating more quantitative information.

- *Value adding to existing information through integrated vulnerability assessment.* The amalgamation of project outputs through the integrated vulnerability assessment adds value to existing information by assessing the datasets as a whole rather than on an individual basis. The integrated vulnerability assessment is conducted on a CSA level; it helps inform national-scale interpretations of regions with limited information and data.
- *Identification of opportunities to progress and develop effective resource management and protection of Australia's coastal groundwater aquifers through additional research, stakeholder communication and education.* As identified in Section 7.2, the project identifies opportunities to progress and develop resource management and resource protection by informing additional monitoring, research, education and knowledge dissemination activities.
- *Increased awareness and knowledge of priority regions affected by sea-level rise and subsequent inundation*. Sea-level rise associated with climate change will affect coastal Australia in different magnitudes; the project aids in the prioritisation of those low-lying coastal areas most vulnerable to SWI.

It is intended that this project will form the basis for future work in understanding and assessing SWI vulnerability in coastal Australia on a 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.

APT observation bores: The bores used within the *CSAs* to define hydrogeological information that is contained within the *APTs*. The bores used are shown on locality figures.

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

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

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

Area of interest (AOI): This is the area within the *CSAs* from which hydrogeological information was obtained.

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

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: Solid rock present at surface or beneath loose surface cover such as *unconsolidated* sediment, soil or weathered bedrock. *Bedrock* is often composed of crystalline rocks such as granite or *metasediments.*

Case study area (CSA): An area along Australia’s coast assessed by this study for *SWI* vulnerability.

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*

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 is 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 sea water. The depth to which the lens extends below sea level is dependent on the density contrast between the lens fluid and sea water. The approximate maximum depth a lens can extend below sea level is forty times the height of the *watertable* 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: 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 inter-relationship 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 sea water to fresh water.

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

Mean sea level: 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 hydrological 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.*SWI*) 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.

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.*

Primary porosity: See *porosity*

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: Salt water has a greater density than fresh water, and as a result it moves in the form of a saltwater wedge beneath fresh water.

Seawater interface: The front that exists between sea water and fresh water in a coastal *aquifer*, whereby less dense fresh water sits above, and adjacent to, a denser saltwater wedge.

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

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

Secondary porosity: See *porosity*

Sharp-interface: See *transition zone*

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 fresh water and sea water 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 also *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*.

Watertable: 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.

Appendices

Appendix 1 Summary of literature

Table 1-1: 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 use/ 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 groundwater assessment areas (GAAs)	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 GAAs)*	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 Cenozoic 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 few SWI references and little information available

Table 1-2: 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 use/ 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	O'Shea 2005, Department of Natural Resources 2006, Department of Water and Energy 2004	Quaternary sands and alluvium associated with Macleay River	Yes (Department of Natural Resources 2006)	Groundwater extractions; below average rainfall /droughts	Limited hydrochemical and piezometer data	No	No	Low	Domestic
Stockton	Woolley et al. 1995, Woolley et al. 2011, SKM 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	Timms et al. 2008, Bish et al. 2000, Merrick and Knight 1997, Benker et al. 2007	Quaternary sands	Yes, 1960s; 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

Table 1-3: 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 use/ groundwater use
Werribee River Delta	SKM 2005, Leonard 2006, Dahlhaus et al. 2004	Quaternary alluvial delta overlying Quaternary/Tertiary basalt	Yes, in 2005 investigations at one site in basalt adjacent to Port Phillip Bay (SKM 2005)	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 (also applies to Moorabbin)	Parsons Brinckerhoff 2010, Dahlhaus et al. 2004	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 offshore); 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

Table 1-4: 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 use/ groundwater use
Adelaide Metropolitan	Gerges 2006, Gerges 2000, Lamontagne et al. 2005, Jeuken 2005, Zulfic et al. 2008, Osei-Bonsu and Barnett 2008, Hodgkin 2004, Gerges 1996	Tertiary multi-layered aquifers comprising sandstones, limestone (minor sands)	No	Groundwater extractions; groundwater mining; urbanisation	Water level; salinity; flow nets; Ghyben-Herzberg, MODFLOW	No	No	Moderate	Urban; residential; parks and gardens; on occasions used to supplement Adelaide's water supply
Eyre Peninsula (Coffin Bay/Uley)	Auken et al. 2009, Harrington et al. 2006, Alcoe 2009, Harrington and Brown 2002, Brown and Harrington 2003, Zulfic et al. 2006, Eyre Peninsula Natural Resources Management Board 2006, Seidel 2008	Quaternary karst limestone overlying Tertiary sands	No in Uley South, Up-coning in Robinson Basin	Groundwater extractions; below average rainfall/droughts	Water level; salinity; chlorofluorocarbons (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	Electromagnetic (EM) surveys; limited salinity; numerical model	No	No	Moderate	Irrigated agriculture; improved pasture; stock; domestic; industrial; groundwater-dependent ecosystems

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land use/ groundwater use
Le Fevre Peninsula/ Adelaide	Lamontagne et al. 2005, Russell 1996	Quaternary dune sands overlying Tertiary sands, sandstone, limestone	No – but risk is identified	Groundwater extractions; up-coning from underlying saline aquifer	Water level; salinity; flow nets; Ghyben-Herzberg	No	No	Low	Residential; urban; parks and gardens
Willunga	Steward 2006, Lamontagne et al. 2005, Knowles et al. 2007, Herczeg and Leaney 2002, Martin 1998, Harrington 2002, Rasser 2001	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

Table 1-5: 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 use/ groundwater use
Perth (other than Cottesloe)	CSIRO 2009a, Smith et al. 2005, Davidson and Yu 2008, CyMod Systems 2009a, Yesertener 2010a, Rümmler et al. 2005, Yesertener, C 2010, Davidson 1995, Cargeeg et al. 1987	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)	EPA 2005, Appleyard 2004, Blair and Turner 2004	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) – recommendations made to increase coverage	Yes; Managed Aquifer Recharge (MAR)	Moderate	Parks and gardens; golf courses and other recreation
Busselton	Hirschberg 1989, Schafer et al. 2008, Schafer and Johnson 2009, Panasiewicz 1996	Cenozoic superficial sand sediments overlying multi-layered Cretaceous sandstone aquifers	Yes, interface reported as extending up to 4 km inland (Hirschberg 1989, Panasiewicz 1996)	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

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI manage-ment	Level of assessment	Land use/ groundwater use
Albany	Appleyard 1989, URS/Dames & Moore 2010, CyMod Systems Pty Ltd 2010a, Water Corporation 2010, Forth 1973	Cenozoic sands, clays	No	Groundwater extractions; below average rainfall/ droughts	Water levels; salinity; geophysical logging; ground Direct Current resistivity/ Transient electromagnetic investigation; MODFLOW	No	No	Moderate	Town water supply; domestic; agricultural; industrial; parks and gardens
Esperance	Department of Water 2007, Crisalis International Pty Ltd. 2010	Cenozoic sands, clays (relict fluvial and lacustrine sediments)	Yes, in town and twilight groundwater management 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 2009b, 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 manage-ment when salinity reaches 1000 mg/L	Moderate	Town water supply; horticultural

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI manage-ment	Level of assessment	Land use/ groundwater use
Northern Swan Coastal Plain (Jurien, Dongara, Leeman)	Baddock and Lach 2003, Commander 1994a, Commander 1994b, Nidagal 1994	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 inland in the vicinity of Dongara)	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; desalination plant installed in 1995
Bunbury	Commander 1982a, Commander 1982b, 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

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI manage-ment	Level of assessment	Land use/ groundwater use
Broome	Laws 1984, Laws 1985, Laws 1991, Groundwater Consulting Services Pty Ltd. 2008a, Department of Water 2008, Water Authority of Western Australia 1992a, CSIRO 2009c	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 2008b, Laws and Smith 1988, Smith 1992, Water Authority of Western Australia 1992b	Jurassic to Cretaceous sandstone	Yes (Ground-water Consulting Services Pty Ltd 2008b)	Groundwater extractions	Basic hydrogeological characterisation	No	No	Low	Town water supply; gardens; stock; domestic
Cape Range/ Exmouth	Martin 1990, Water and Rivers Commission 1999, Water Corporation 1997, Lee 2004, EPA 1999	Tertiary karst limestone	Yes (Lee 2004)	Groundwater extractions; below average rainfall/ droughts	Water levels; salinity: SUTRA	No	No	Low	Domestic; groundwater-dependent aquatic cave fauna

Table 1-6: 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 use/ groundwater 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)	Yin Foo and Moretti 1991, Pavelic et al. 2002	Weathered Cretaceous sediments	No	Groundwater extractions	Basic hyrogeological characterisation, water banking	No	Yes, water banking and trialling aquifer storage and recovery ASR	None to Very Low	Domestic; small gardens
Milingimbi*	Yin Foo 1980, Martin 1991, Yin Foo 1982	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*	Sumner 2008, Moretti et al. 1992, Jolly 2002, Yin Foo 2002	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

Table 1-7: 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 use/ groundwater use
The Burdekin River Delta	Narayan et al. 2007, Lawrie et al. 2004, Lawrie et al. 2006, Fass et al. 2007, Department of Natural Resources, Mines and Water 2006, McMahon 2004, SKM 2009, O'Shea 1967, Qureshi et al. 2008, Werner 2010, Wang et al. 2012, McMahon et al. 2011, Arunakumaren et al. 2000, McMahon et al. 2000, McMahon et al. 2002	Quaternary alluvial delta	Yes (ANRA 2002, McMahon 2004, Department of Natural Resources, Mines and Water 2006)	Groundwater extractions; below average rainfall/ droughts	Water levels; salinity; theoretical inland extent of SWI using Ghyben-Herzberg; geophysical assessment; geomorphic and sedimentary facies analysis; hydrochemistry (major and minor ion; isotopes); 2D SUTRA	Yes	Yes; artificial recharge; Lower Burdekin Groundwater Science Plan	High	Sugarcane; wetlands; adjacent Great Barrier Reef
Pioneer Valley	Werner and Gallagher 2006, Bedford 1978, Baskaran et al. 2001b, Carey et al. 2009, Werner 2010, Murphy et al. 2005, Cresswell 2008	Quaternary alluvium; palaeo-channels in bedrock	Yes (Bedford 1978, Murphy et al. 2005)	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 1 m AHD; cease pumping at 3000 µS/cm; artificial 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 use/ groundwater use
Burnett Heads/ Bundaberg	Bajracharya et al. 1998, Bajracharya et al. 2006, Dempster 1994, RCC 2004, Zhang et al. 2004, Liu et al. 2006	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 2500 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, Water Resources Commission 1988, Welsh 2002, Welsh 2008	Quaternary alluvium within bedrock palaeo-valleys 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
North Stradbroke Island	EHA 2005b, Laycock 1975, Chen 2001, Laycock 1978, Marshall et al. 2006, Gallagher and Leach 2010	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

Location	References	Aquifer lithology	SWI occurrence reported	Driving factors	Investigations	SWI monitoring	SWI management	Level of assessment	Land use/ groundwater use
Bribie Island	EHA 2005a, Lumsden 1964, Werner 1998, Jackson 2007	Quaternary sand mass	Yes (EHA 2005a)	Groundwater extractions; below average rainfall/droughts	Water levels; salinity; MODFLOW	Yes (but not SWI interface specific), recommendations made to increase coverage	Yes; artificial recharge at southern end of island	Low	Town water supply; wetlands
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

Appendix 1 References

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Appendix 2 Summary of national and state/territory datasets

Table 2-1: Summary of datasets from national and state/territory 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 map of Australia (Jacobson 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, there are few bores in coastal regions that are continuously monitored, with most of these being recently installed. 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 the 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 1-sec coastal elevation	National	2009	Geoscience Australia	The 1-second SRTM derived DEM Version 1.0 is a 1 arc second (~30 m) gridded Digital Elevation Model (DEM). The DEM represents ground surface topography, and excludes vegetation features. This is the best available data and is suitable for national-scale use. *Geoscience Australia and CSIRO Land & Water (2009) 1 Second SRTM Derived DSM and DEM User Guide. Version 1.0. Geoscience Australia.*
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	Geoscience Australia	*Raymond OL & Retter AJ (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 map of Australia (Jacobson and Lau, 1987). National groundwater salinity information has been used in the literature review technical report.
Hydrogeomorphic Mapping	Hydro-geological landforms	National	2007	Geoscience Australia/ Bureau of Rural Sciences	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 combined with three (BoM-Köppen 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.* Hydrogeomorphic mapping information has been used in the literature review technical report.
Coastal Depositional Environments	Clastic coastal depositional environments	National	2007	Geoscience Australia	This data product is available online publicly through the Ozcoasts website (http://www.ozcoasts.org.au/) *Heap A, Bryce S, Ryan D, Radke L, Smith C, Smith R, Harris P & Heggie D, Australian Estuaries & Coastal Waterways: A geoscience perspective for improved and integrated resource management. Australian Geological Survey Organisation, Record 2001/07.* Coastal depositional environments information has been used in the literature review technical report.

Appendix 3 Vulnerability factor analysis figures

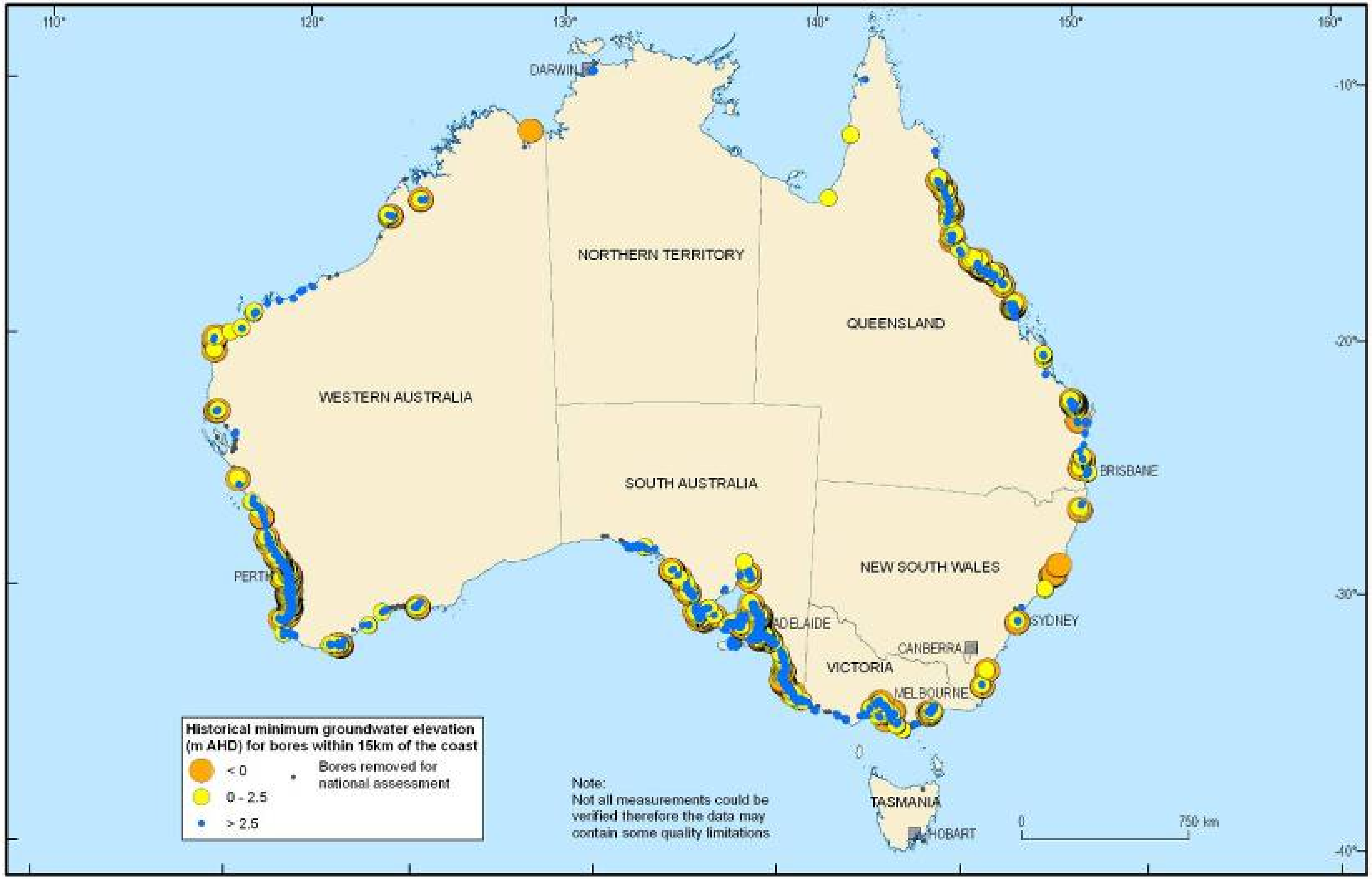


Figure 3-1: Historical minimum groundwater levels measured prior to 2000 (only data points where three or more boreholes within a 5 km radius fall into the same category are classified)

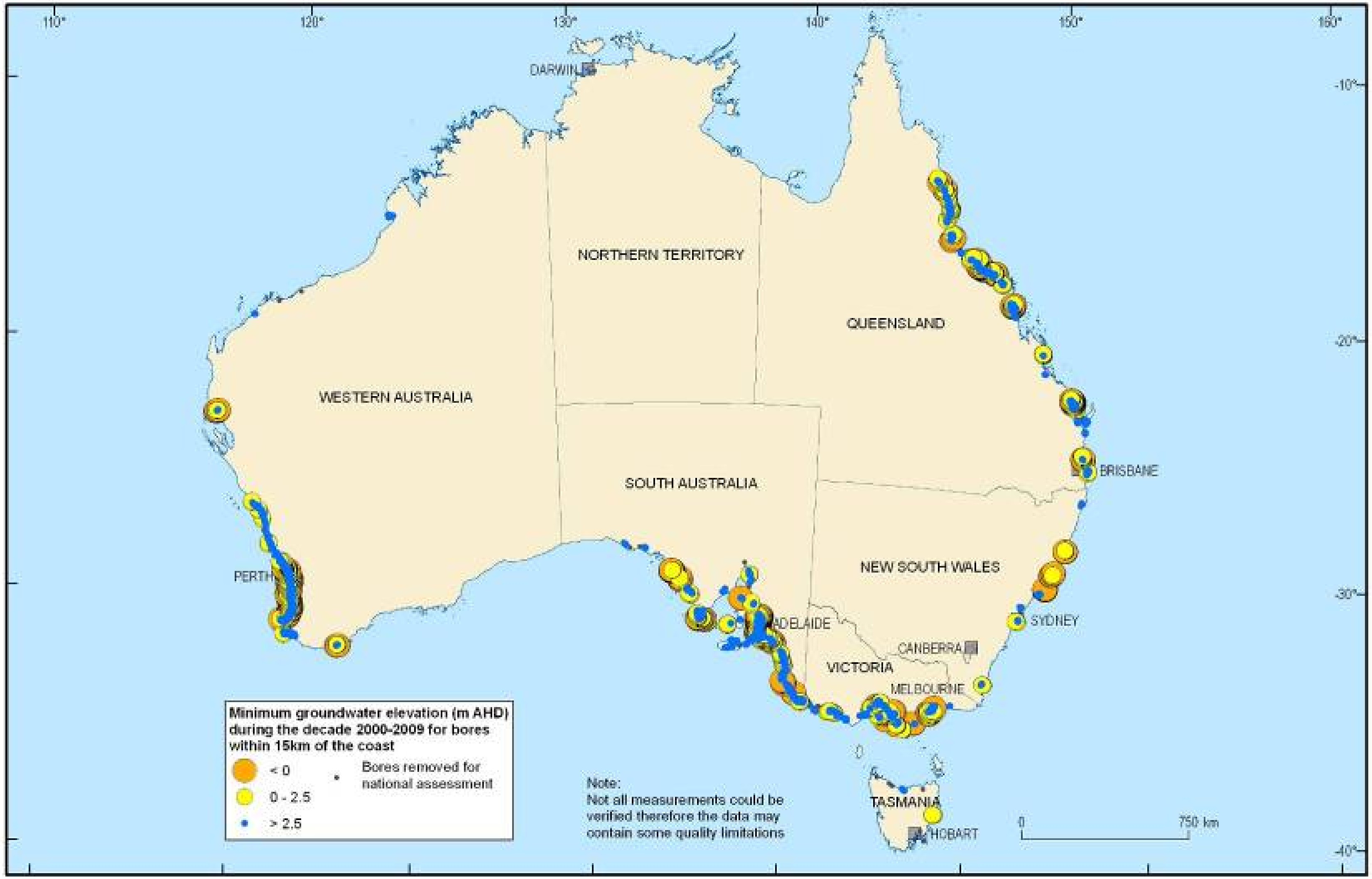


Figure 3-2: Minimum groundwater levels measured between 2000 and 2009 (only data points where three or more boreholes within a 5 km radius fall into the same category are classified)

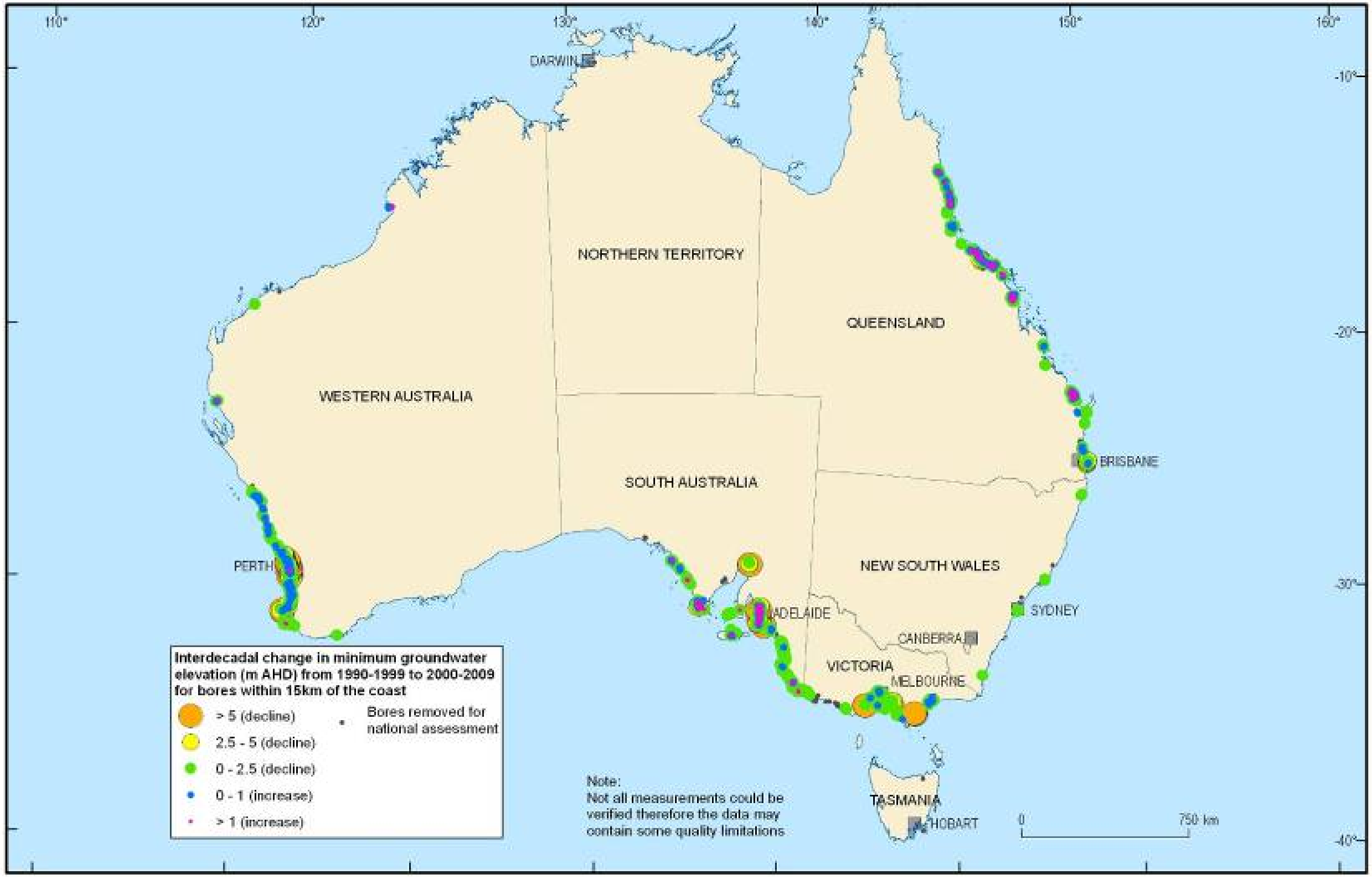
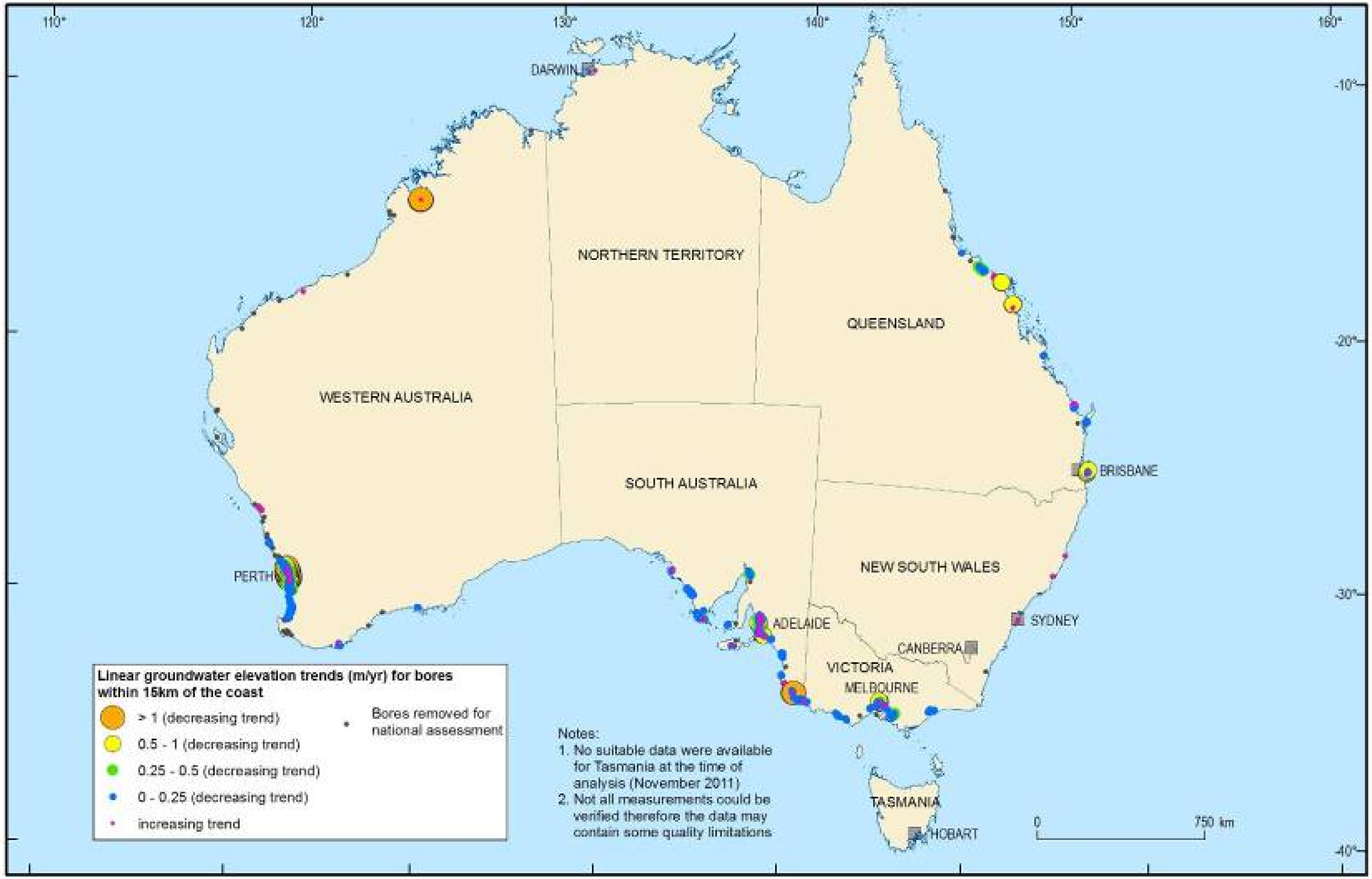


Figure 3-3: Inter-decadal changes in minimum groundwater levels from 1990–1999 to 2000–2009 (only data points where three or more boreholes within a 5 km radius fall into the same category are classified)



Notes:
1. No suitable data were available for Tasmania at the time of analysis (November 2011)
2. Not all measurements could be verified therefore the data may contain some quality limitations

Figure 3-4: Linear groundwater elevation trends (only data points where three or more boreholes within a 5 km radius fall into the same category are classified)

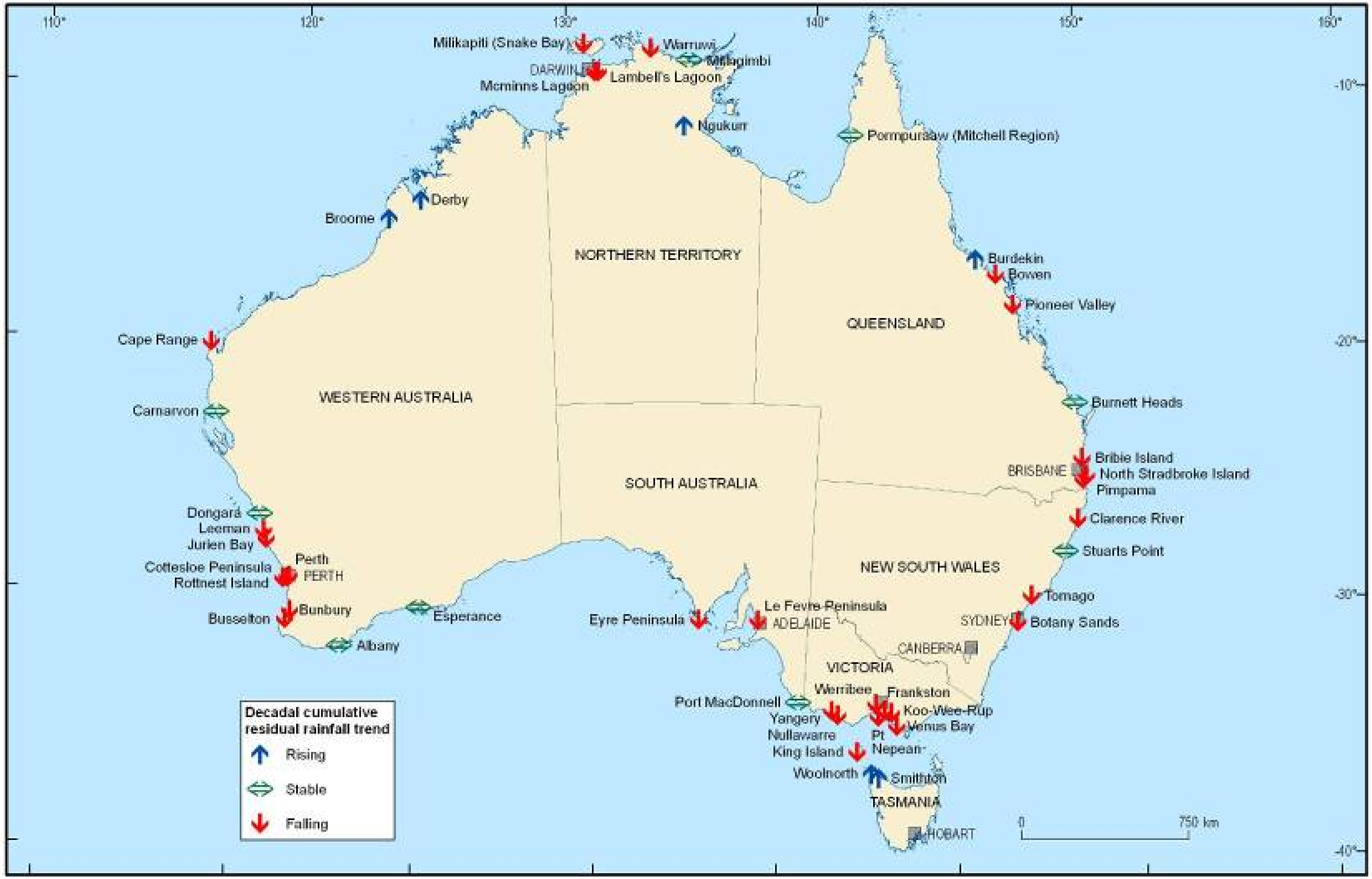
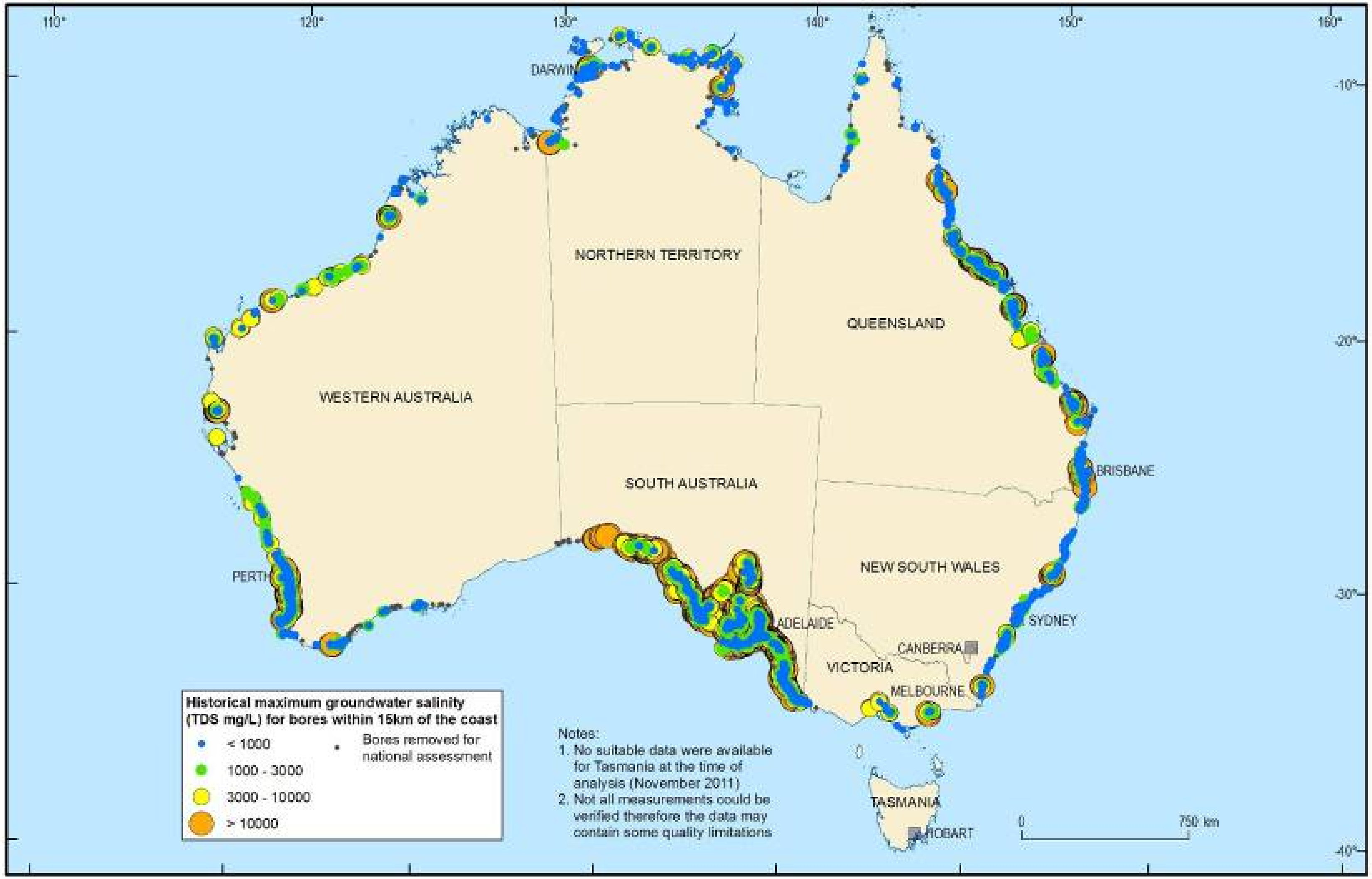


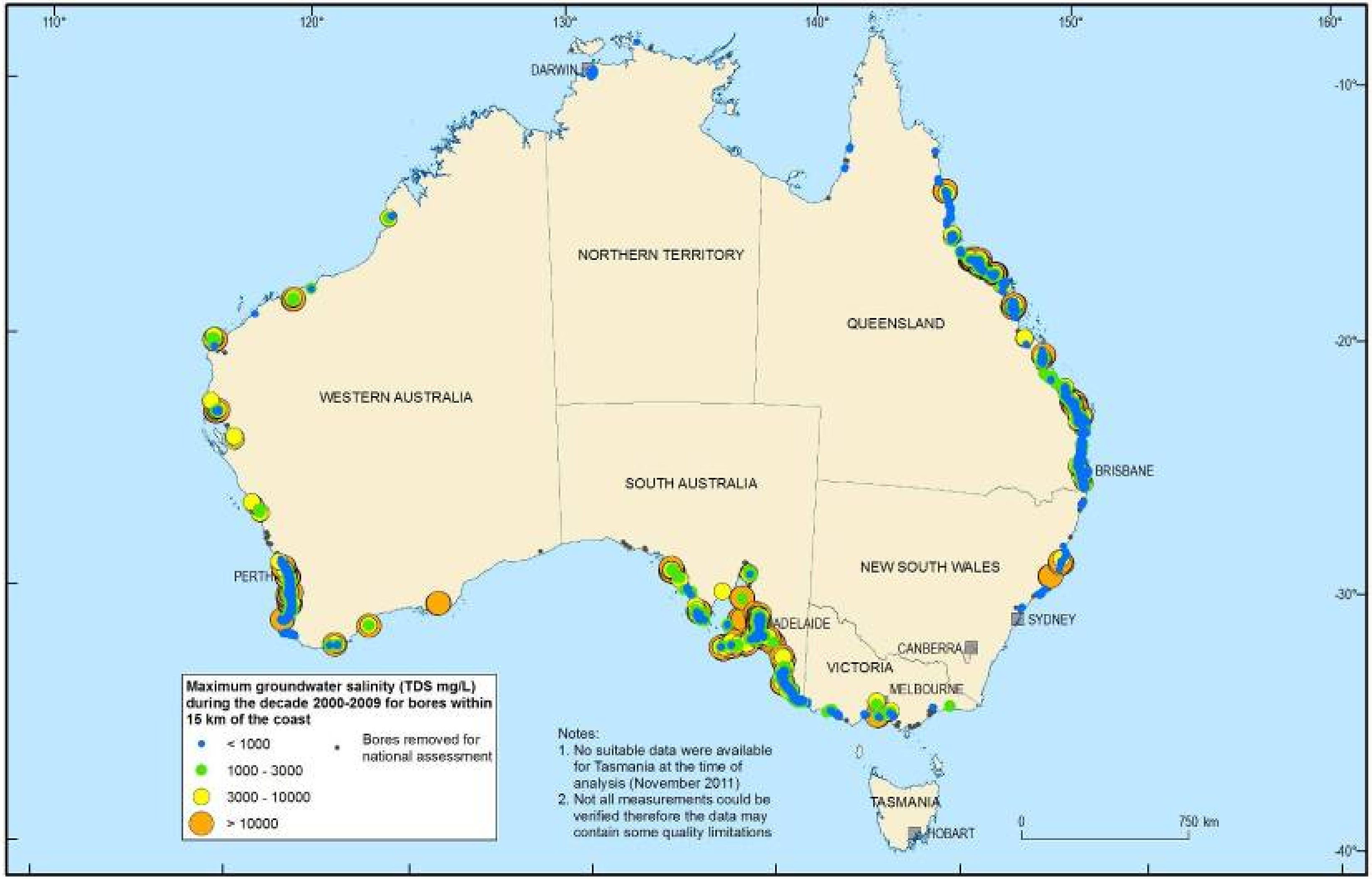
Figure 3-5: Trends in cumulative deviation of monthly rainfall from long-term averages for the period 2000–2009



Notes:

1. No suitable data were available for Tasmania at the time of analysis (November 2011)
2. Not all measurements could be verified therefore the data may contain some quality limitations

Figure 3-6: Historical maximum TDS concentrations measured prior to 2000 (only data points where three or more boreholes within a 5 km radius fall into the same category are classified)



Notes:
1. No suitable data were available for Tasmania at the time of analysis (November 2011)
2. Not all measurements could be verified therefore the data may contain some quality limitations

Figure 3-7: Maximum TDS concentrations for the period 2000–2009 (only data points where three or more boreholes within a 5 km radius fall into the same category are classified)

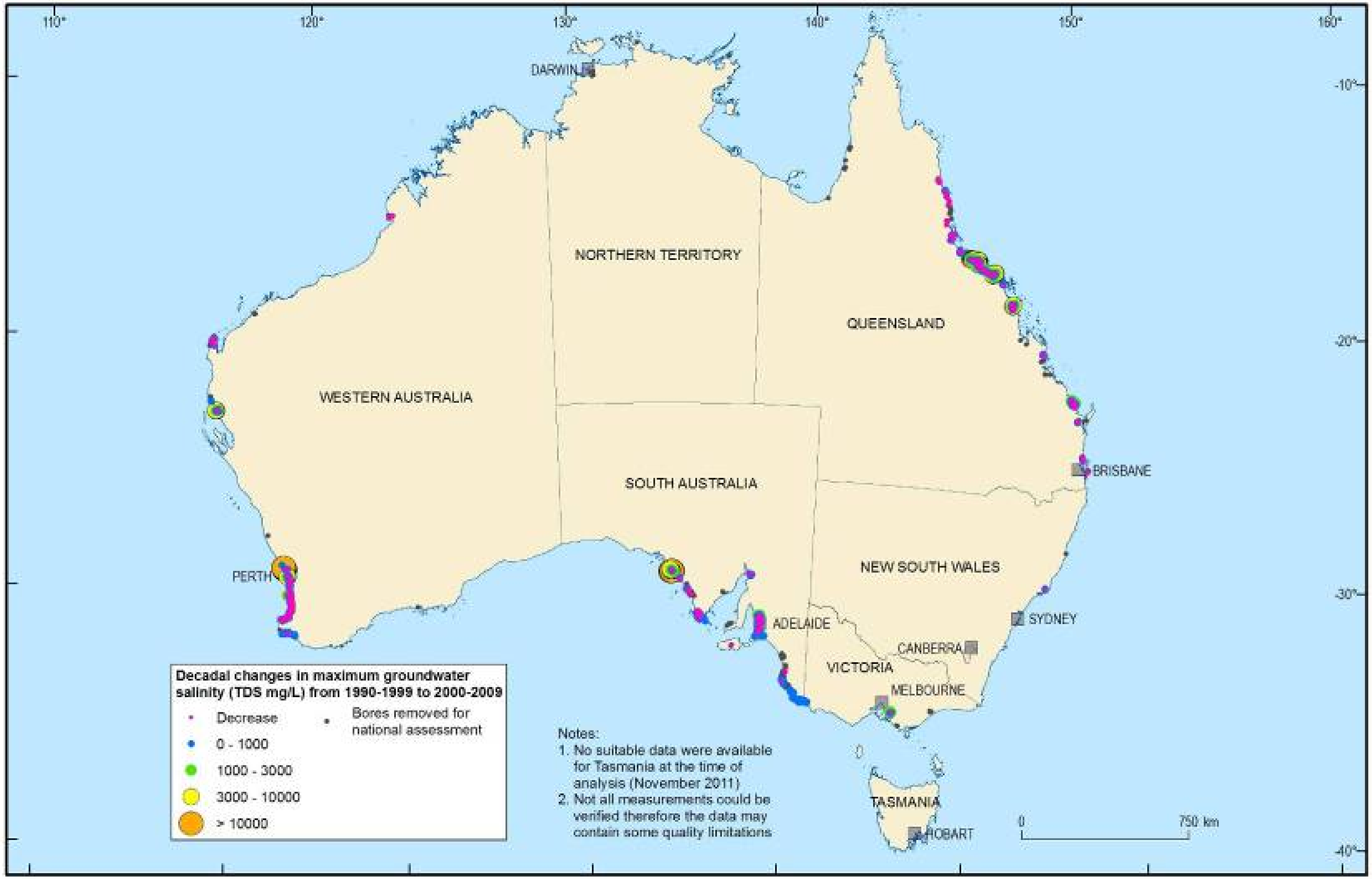
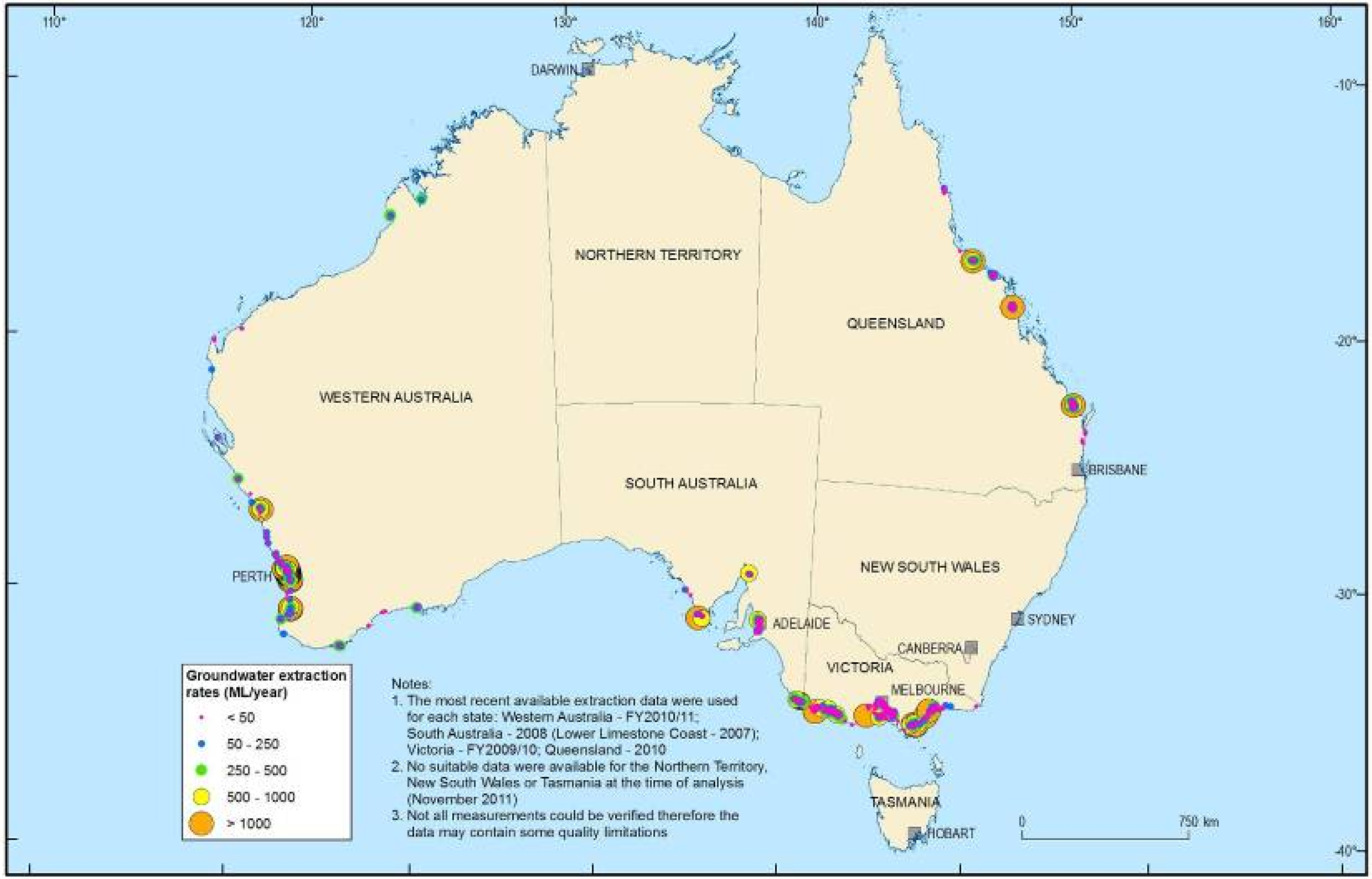


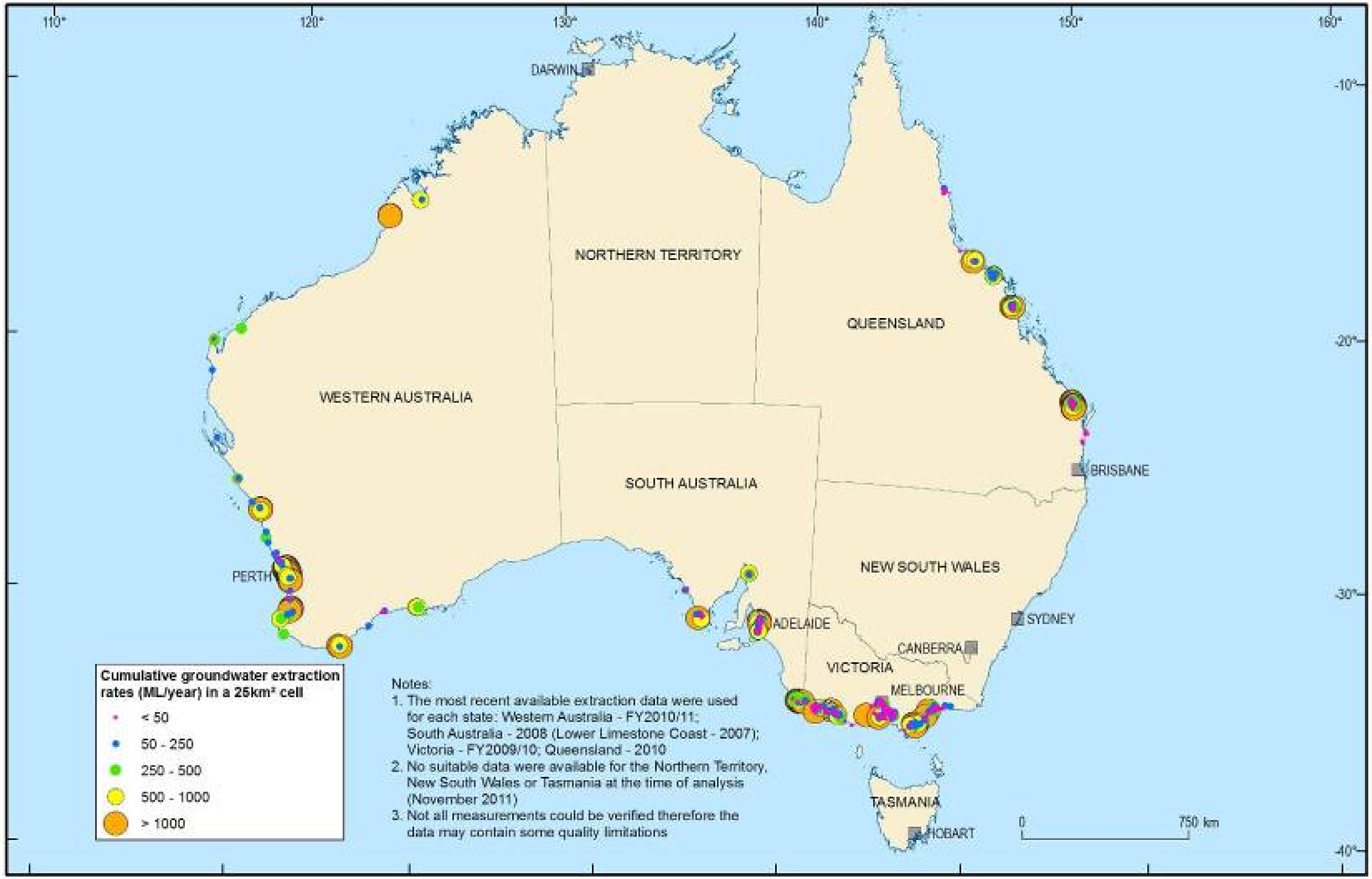
Figure 3-8: Inter-decadal change in maximum TDS concentrations from 1990–1999 to 2000–2009 (only data points where three or more boreholes within a 5 km radius fall into the same category are classified)



Notes:

1. The most recent available extraction data were used for each state: Western Australia - FY2010/11; South Australia - 2008 (Lower Limestone Coast - 2007); Victoria - FY2009/10; Queensland - 2010
2. No suitable data were available for the Northern Territory, New South Wales or Tasmania at the time of analysis (November 2011)
3. Not all measurements could be verified therefore the data may contain some quality limitations

Figure 3-9: Groundwater production bore locations and extraction rates



Notes:

1. The most recent available extraction data were used for each state: Western Australia - FY2010/11; South Australia - 2008 (Lower Limestone Coast - 2007); Victoria - FY2009/10; Queensland - 2010
2. No suitable data were available for the Northern Territory, New South Wales or Tasmania at the time of analysis (November 2011)
3. Not all measurements could be verified therefore the data may contain some quality limitations

Figure 3-10: Cumulative groundwater extraction rates within 5 x 5 km grid cells

Appendix 4 Coastal aquifer typology tables

The following abbreviations are utilised in Tables 4-1 to 4-8 (consistent with the mathematical analysis component of this project):

- hydraulic conductivity (K)
- net recharge (W_{net}) (*Defined as 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 (ET), losses to surface water and groundwater extraction)*
- depth of the aquifer base below sea level (z_0)
- saturated aquifer thickness (h_0)
- inland head (h_b)
- inland distance to inland head (x_b).

Table 4-1: Typical aquifer parameters for coastal alluvium in coastal fringe

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

Unconfined aquifers	Confined/ semi-confined aquifers

1 Value reported within aquifer parameter table (APT); however, zero value assigned to net recharge in confined systems for mathematical analysis

2 Mid-range value reported in APT for unconfined system; this will change with variations in hydraulic head

Q – Quaternary, from 2.5 million years ago to present; T – Tertiary, from 65 million years ago to 2.5 million years ago

Table 4-2: Typical aquifer parameters for coastal sands in coastal fringe

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

🟩 Unconfined aquifer	🟦 Confined/ semi-confined aquifers

1 Not relevant in the case of a freshwater lens

2 Mid-range value reported in APT for freshwater lens thickness

3 Mid-range value reported in APT for unconfined system; this will change with variations in hydraulic head and freshwater lens thickness

Q – Quaternary, from 2.5 million years ago to present; T – Tertiary, from 65 million years ago to 2.5 million years ago

Table 4-3: Typical aquifer parameters for unconfined sandstone, sedimentary basin in coastal fringe

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

🟩 Unconfined aquifers	Confined/ semi-confined aquifers

J – Jurassic, from ~200 million years ago to 145 million years ago; K – Cretaceous, from 145 million years ago to 65 million years ago; T_R- Triassic from 250 Million years ago to 200 Million years ago.

Table 4-4: Typical aquifer parameters for multi-layered, deep sedimentary basin in coastal fringe

Climate Group	*Case study area*	*Aquifer*	*Age*	*K (m/d)*	*W_{net} (mm/a)*	*z_0 (m AHD below surface)*	*h_0 (m)*	*h_b (m AHD)*	*x_b (m)*
Mediterranean	Adelaide Metro (SA)	T1	T	3 (0.1-10)	-4[1]	175 (130-220)	80 (25-120)	-10.0 (-24.0-6.5)	5000
		T2	T	3 (1-10)	-4[1]	290 (260-320)	105 (80-110)	3.8 (2.0-6.0)	5000
	Le Fevre (SA)	Semaphore Sands	Q	8 (4-13)	90	10	11[2]	1.6 (1.3-1.8)	1000
		T1	T	10 (0.5-10)	-4[1]	175 (130-220)	80 (25-120)	-11.0 (-13.0-0)	500
		T2	T	3 (1-10)	-4[1]	290 (260-320)	105 (80-110)	-6.6 (-10.0-1.0)	500
	Willunga (SA)	Quaternary	Q	10 (0.1-10)	20 (15-30)	20	20[2]	3.0 (1.0-6.0)	3500
		Port Willunga Formation	T	10 (0.1-20)	0	120 (80-175)	90 (60-155)	1.5 (0.7-2.0)	3500
		Maslin Sands	T	1 (0.1-1)	0	225 (160-285)	65 (10-70)	2.0 (0-2.5)	3500
	Bunbury (WA)	Superficial	Q	10 (3-16)	30 (10-60)	15 (10-20)	35[2]	6.2 (5.6-6.6)	3000
		Yarragadee	J	20	0	400 (175-700)	300 (175-500)	3.0 (0.5-4.5)	3000
	Busselton (WA)	Superficial	Q	2 (0.5-5)	30 (10-60)	10	5[2]	0.7 (-0.9-2.5)	1500
		Leederville	K	1 (0.2-2)	0	80 (20-100)	65 (25-105)	1.2 (-0.1-2.3)	4300
	Perth, Whitfords (WA)	Superficial	Q/T	15 (8-50)	30	75 (50-100)	75[2]	3.5 (2.2-4.5)	3500
		Leederville	K	1 (0.1-10)	0	275 (250-300)	175 (150-200)	4.2 (-5.0-7.0)	3500
		Yarragadee	J	2 (1-3)	0	1750 (165-1850)	1500 (1450-1550)	17.0 (-21.0-30.0)	4500

Unconfined aquifers	Confined/ semi-confined aquifers

1 Value reported within APT; however, zero value assigned to net recharge in confined systems for mathematical analysis
2 Mid-range value reported in APT for unconfined system; this will change with variations in hydraulic head
J – Jurassic, from ~200 million years ago to 145 million years ago; K – Cretaceous, from 145 million years ago to 65 million years ago; Q – Quaternary, from 2.5 million years ago to present; T – Tertiary, from 65 million years ago to 2.5 million years ago

Table 4-5: Typical aquifer parameters for multi-layered, shallow sedimentary basin in coastal fringe

Climate Group	*Case study area*	*Aquifer*	*Age*	*K (m/d)*	*W_{net} (mm/a)*	*z_0 (m AHD below surface)*	*h_0 (m)*	*h_b (m AHD)*	*x_b (m)*
Mediterranean	Albany, Ocean side (WA)	Superficial/ Pallinup Sandstone/ Werrilup Formation	Q/T	5 (1-50)	160	20 (15-25)	40[1]	6.0 (-0.7-8.8)	1500
	Albany, Harbour side (WA)	Superficial	Q	5 (2-60)	160	5 (5-10)	2[1]	2.0 (1.7-5.5)	250
		Werrilup Formation	T	5	131[2]	25	20	1.4 (-4.8-3.3)	800
	Esperance (WA)	Superficial/Pallinup Sandstone	Q/T	20 (2-40)	15 (2-30)	20 (10-30)	30[1]	0.8 (0.1-3)	1600
		Werrilup Formation	T	10 (8-12)	0	32 (18-46)	10 (0.1-33)	0.5 (0.5-0.7)	300

Unconfined aquifers — Confined/ semi-confined aquifers

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

Table 4-6: Typical aquifer parameters for carbonate in coastal fringe

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

🟩 Unconfined aquifers	🟦 Confined/ semi-confined aquifers

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

Table 4-7: Typical aquifer parameters for basalt in coastal fringe

Climate Group	*Case study area*	*Aquifer*	*Age*	*K (m/d)*	*W_{net} (mm/a)*	*z_0 (m AHD below surface)*	*h_0 (m)*	*h_b (m AHD)*	*x_b (m)*
Temperate without dry season	Werribee (Vic)	Alluvium & Newer Volcanics	Q/T	5 (0.6-23)	85	20 (15-22)	50[1]	7.0 (4.0-9.0)	2500

🟩 Unconfined aquifers	🟦 Confined/ semi-confined aquifers

1 Mid-range value reported in APT for unconfined system
Q – Quaternary, from 2.5 million years ago to present; T – Tertiary, from 65 million years ago to 2.5 million years ago

Table 4-8: Typical aquifer parameters for fractured/undivided in coastal fringe

Climate Group	*Case study area*	*Aquifer*	*Age*	*K (m/d)*	W_{net} *(mm/a)*	z_0 *(m AHD below surface)*	h_0 *(m)*	h_b *(m AHD)*	x_b *(m)*
Tropical	Howard Springs	Fractured Sediments & Koolpinyah/ Coomalie Dolomite	K/P	40 (10-170)	60[1]	100 (55-100)	25 (20-25)	10.0 (8.5-15)	2000

Unconfined aquifer	Confined/ semi-confined aquifers

1 Value reported within APT; however, zero value assigned to net recharge in confined systems for mathematical analysis
K – Cretaceous, from 145 million years ago to 65 million years ago; P - Proterozoic from 2.5 billion years ago to 542 million years ago

Table 4-9: Characteristics of principal aquifer types of Australia’s coastal aquifers

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

Principal aquifer type	Aquifer age	Aquifer description	Aquifer types	Aquifer characteristics	SWI implications
Sedimentary Basins: Unconfined sandstone	Triassic to Cretaceous	• These aquifer types comprise deep (>200 m AHD below sea level), thick (>190 m), unconfined sandstone units	• Unconfined	• Indurated sedimentary aquifers may extend large distances out to sea • Thick sedimentary sequences store large volumes of water • Provide a source of water (town water supply and horticulture) in arid areas • Relatively low recharge rates	• The extension of the unconfined aquifer out to sea may facilitate seawater migration
Sedimentary Basins: Multi-layered, consolidated, deep	Cenozoic through to Quaternary	• Basin thickness thousands of metres • Sedimentary sequences comprising sandstone or multiple-layering of sand, sandstone, coarse silt and minor limestone aquifers, with clay aquitards in between • Commonly mantled by recent sediments, often sands, that form an upper, unconfined aquifer	• Unconfined upper aquifer • Stacked multiple confined aquifers	• Sand veneer upper aquifers share characteristics with coastal sands • Deep, confined aquifers are recharged at aquifer outcrops, usually at higher elevations – generating significant heads • Indurated sedimentary aquifers may extend large distances out to sea • Thick sedimentary sequences store large volumes of water • Large volumes of groundwater stored in confined aquifers make them suited to large-scale development (domestic, parks/gardens, industrial, agricultural) • Intensive development in some areas has led to large piezometric head declines	• Upper unconsolidated aquifer has similar SWI vulnerabilities as coastal sands • The deeper confined indurated aquifers are generally characterised by elevated hydraulic heads which make them more robust to SWI, especially in areas where the freshwater aquifer extends some distance out to sea • The suitability of the deep, thick, confined aquifers for large-scale development means that they are often highly developed with the lowest heads of all coastal aquifer types making them potentially susceptible to SWI • Inter-aquifer contamination of sea water may occur through aquifer leakage

Principal aquifer type	Aquifer age	Aquifer description	Aquifer types	Aquifer characteristics	SWI implications
Sedimentary Basins: Multi-layered, unconsolidated, shallow	Cenozoic	• Shallow sedimentary deposits (<50 m AHD below sea level) of unconsolidated sediments, with multiple aquifers separated by discontinuous clay aquitards •The aquifers are relatively thin, between 2 and 40 m thick • Commonly mantled by sand veneer	• Unconfined upper aquifer • Multiple confined aquifers	• Sand veneer upper aquifers share characteristics with coastal sands • Upper unconfined aquifer recharged by diffuse recharge of rainwater • Semi-confined aquifers are recharged by downward leakage from upper aquifer • Confined aquifers receive little recharge and may be brackish in places • Provide local sources of groundwater that are important for town water supply	• Upper unconsolidated aquifer has similar SWI vulnerabilities as coastal sands • Where underlying aquifers are more saline there is the risk of up-coning through groundwater extraction
Carbonate	Cenozoic	• Carbonate deposits such as limestone and dolomite • Karstic in nature • Primary carbonate aquifer may be shallow or up to several hundreds of metres thick • Often have secondary deeper sand aquifer • There may be a semi-confining/confining layer separating the two aquifer systems	• Unconfined primary carbonate aquifer overlying deeper semi-confining/confining sand aquifer	• Extreme anisotropy in hydraulic conductivity • Porous and fractured rock • Karstic carbonate aquifer dramatically increases amount of recharge available during intense rainfall events • Groundwater levels rapidly respond to seasonal, climatic and anthropogenic influences • Groundwater occurs in freshwater lenses/basins, overlying and/or adjacent to saline groundwater • Freshwater lenses provide water to local towns and for irrigated agriculture	• Isolated lenses at risk of drawing in saline water, especially where hydraulically connected to sea water or where overlying freshwater lenses are relatively thin • Open solutions within karst aquifer provide preferential flow paths • Rapid response of aquifer storage to changes in climate may make these systems susceptible to SWI during drought periods

Principal aquifer type	Aquifer age	Aquifer description	Aquifer types	Aquifer characteristics	SWI implications
Basalt	Cenozoic	• Layered basalt plains storing groundwater primarily in fractures and vesicles • May be overlain by floodplain deposits that are in hydraulic connection with the primary basalt aquifer	• Generally unconfined, although less permeable basalt layers may form semi-confining/confining layers	• Aquifers recharged by rainfall via fractures and surface water losses • Freshest groundwater found in areas where there is a greater fracture density and/or permeability	• Fracture openings and higher permeability areas may provide a preferential flow path for seawater migration
Fractured, Undivided	Cretaceous through to Proterozoic	• Local to broad extent, older fractured sequences of mixed lithology that have undergone metamorphosis and weathering • May be mantled by alluvial, aeolian or colluvial veneer • Aquifers comprise a number of different stratigraphic units with a high degree of interconnection • May include karstic carbonate aquifers within the mix of lithologies, and thus may share characteristics in common with other carbonate aquifer systems	• Unconfined to semi-confining/confining aquifers	• Tend to have variable productivity and salinity • Recharge occurs where aquifer outcrops as well as through via porous sediments and fractures at the surface • Vertical recharge through fractures can be relatively quick • Typically connected with elevated hinterlands and so heads can be comparatively high • Hydraulic conductivity is highly variable, and is dependent on fracture density • Can store large volumes of groundwater in fractures and therefore may provide local supplies of varying yields and quality	• Fracture openings may provide a preferential flow path for seawater migration

Appendix 5 Quantitative indexing tables

Table 5-1: Indexing matrix for unconfined aquifers

	Scaled wedge toe, x_T'	**Wedge toe relative to extraction bores** [1]	**Propensity for change in SWI extent due to sea-level rise** [2]	**Propensity for change in SWI extent due to recharge change** [2]	**Propensity for change in SWI extent due to change in flows at the inland boundary** [2]
Weighting	**1**	**1**	**1**	**1**	**1**
Rating ↓					
1	$x_T' < 0.05$	0	In lowest quarter of ranked results	In lowest quarter of ranked results	In lowest quarter of ranked results
2					
3		0 to 0.25			
4	$0.05 \leq x_T' \leq 0.1$		In lower-mid quarter of ranked results	In lower-mid quarter of ranked results	In lower-mid quarter of ranked results
5					
6		0.25 to 0.5			
7	$0.1 < x_T' < 1$		In upper-mid quarter of ranked results	In upper-mid quarter of ranked results	In upper-mid quarter of ranked results
8		0.5 to 0.75			
9					
10	$x_T' = 1$	≥ 0.75	In highest quarter of ranked results	In highest quarter of ranked results	In highest quarter of ranked results

Score =

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[1] This is the ratio of toe location to distance of extraction bores from the coast.

[2] Derivatives for all unconfined aquifers that were assessed as part of the Math Analysis component of the SWI project were ranked by magnitude. The ranking is used to determine the rating in this indexing table.

Table 5-2: Indexing matrix for confined aquifers

	Inland extent of wedge toe, x_T	**Wedge toe relative to extraction bores**[1]	**Propensity for change in SWI extent due to sea-level rise**[2]	**Propensity for change in SWI extent due to change in flows at the inland boundary**[2]
Weighting	**2**	**1**	**1**	**1**
Rating ↓				
1	$x_T < 2$ km	0	In lowest quarter of ranked results	In lowest quarter of ranked results
2				
3		0 to 0.25		
4	$2 \text{ km} \leq x_T \leq 10$ km		In lower-mid quarter of ranked results	In lower-mid quarter of ranked results
5				
6		0.25 to 0.5		
7	$x_T > 10$ km		In upper-mid quarter of ranked results	In upper-mid quarter of ranked results
8		0.5 to 0.75		
9				
10	Unstable	≥ 0.75	In highest quarter of ranked results	In highest quarter of ranked results

Score =

---

1 This is the ratio of toe location to distance of extraction bores from the coast.

2 Derivatives for all confined aquifers that were assessed as part of the Math Analysis component of the SWI project were ranked by magnitude. The ranking is used to determine the rating in this indexing table.

Table 5-3: Indexing matrix for freshwater lenses

	Maximum freshwater thickness, h_{max} (m)	**Propensity for change in SWI extent due to recharge change** [1]
Weighting Rating ↓	**3**	**2**
1	$h_{max} > 100$ m	In lowest quarter of ranked results
2		
3		
4	$100 \text{ m} \geq h_{max} \geq 50$ m	In lower-mid quarter of ranked results
5		
6		
7	$50 \text{ m} > h_{max} > 20$ m	In upper-mid quarter of ranked results
8		
9		
10	$h_{max} \leq 20$ m	In highest quarter of ranked results

Score =

1 Derivatives for all lens systems that were assessed as part of the Math Analysis component of the SWI project were ranked by magnitude. The ranking is used to determine the rating in the above indexing table.

Appendix 6 CSA qualitative indexing parameters

Table 6-1: Summary of CSA allocations for qualitative index parameters

	Groundwater extraction to recharge ratio	*Minimum groundwater levels during 2000-2010 exceeded by 20% of bores*	*Knowledge, monitoring and management (KMM)*	*Cumulative residual rainfall trend (2000–2010)*	*Change in s 1990–2000 an by 2*
	Weighting = 4	Weighting = 4	Weighting = 3	Weighting = 2	W
Rating =1	<0.25	>2.5 m AHD	High	Increasing	<
	Botany Exmouth Hat Head Howard Springs Le Fevre Nth Stradbroke Pioneer Valley Point Nepean Werribee	Botany Howard Springs Nth Stradbroke Stockton Willunga	The Burdekin Burnett Heads Pioneer Valley	Broome The Burdekin Derby	Adelaide Metr Broome Bunbury The Burdekir Burnett Head Busselton Carnarvon Esperance Exmouth
Rating = 3	0.25-0.5				
	Albany Broome Burnett Heads Stockton Stuart's Point Uley South				
Rating = 5	0.5-0.75	<2.5 m AHD	Moderate	Stable	100
	Bowen Bunbury Cottesloe	Adelaide Metro Bowen Hat Head Port MacDonnell	Adelaide Metro Albany Bowen Busselton Carnarvon Cottesloe Esperance Nth Stradbroke Perth (Whitfords) Uley South Werribee	Albany Bowen Cottesloe Esperance Nth Stradbroke Pioneer Valley Port MacDonnell Stockton	Bowen *No c* Albany Botany Derby Stuart's Point
Rating = 8	0.75-1.0	<1 m AHD	Low		
	Derby	The Burdekin Busselton Bunbury Burnett Heads Carnarvon Le Fevre Uley South Pioneer Valley Point Nepean Perth (Whitfords)	Botany Broome Bunbury Derby Exmouth Hat Head Howard Springs Le Fevre Point Nepean Port MacDonnell Stockton Stuart's Point Willunga		
Rating = 10	>1	<0 m AHD	None	Declining	>
	Adelaide Metro The Burdekin Busselton Carnarvon Esperance Perth (Whitfords) Port MacDonnell Willunga	Albany Broome Cottesloe Derby Esperance Exmouth Stuarts Point Werribee		Adelaide Metro Botany Bunbury Burnett Heads Busselton Carnarvon Exmouth Hat Head Howard Springs Le Fevre Perth (Whitfords) Point Nepean Stuart's Point Uley South Werribee Willunga	

Appendix 7 Summary of CSA and state/territory DEM analysis

Table 7-1: Areas of DEM classes for each CSA

	Total area (km^2)	**Class 1 (<1 m)**		**Class 2 (1–5 m)**		**Class 3 (5–10 m)**		**Class 4 (>10 m)**	
		% area	**area (km^2)**	**% area**	**area (km^2)**	**% area**	**area (km^2)**	**% area**	**area (km^2)**
Hat Head	123.12	**41.31**	50.86	26.26	32.33	16.11	19.84	16.32	20.09
Stockton	374.52	**13.11**	49.10	23.28	87.19	29.26	109.58	34.35	128.64
North Stradbroke Island	262.94	**11.77**	30.94	8.24	21.66	4.94	13.00	75.05	197.35
Bowen	388.49	**8.82**	34.25	15.69	60.97	14.08	54.70	61.41	238.57
Stuarts Point	14.77	**7.49**	1.11	30.77	4.55	52.48	7.75	9.26	1.37
Burnett Heads	711.83	**7.20**	51.24	11.41	81.20	16.46	117.17	64.93	462.22
Pioneer Valley	503.50	**7.09**	35.69	10.99	55.32	18.65	93.92	63.27	318.58
Botany	70.53	**5.20**	3.67	17.57	12.39	18.90	13.33	58.32	41.14
Adelaide & Le Fevre	210.29	**4.18**	8.80	8.44	17.74	27.30	57.41	60.08	126.34
Perth (Cottesloe)	4.90	**3.44**	0.17	2.51	0.12	7.96	0.39	86.09	4.22
Bunbury	397.62	**3.09**	12.31	4.10	16.31	8.98	35.72	83.82	333.28
Albany	49.29	**3.01**	1.48	8.41	4.14	20.94	10.32	67.64	33.34
Howard Springs	565.13	**2.87**	16.21	9.33	52.72	13.84	78.24	73.96	417.96
Exmouth	227.14	**2.74**	6.21	3.33	7.55	5.40	12.27	88.54	201.10
Esperance	56.66	**2.71**	1.53	5.35	3.03	26.14	14.81	65.80	37.28
Busselton	426.40	**2.51**	10.71	7.90	33.70	13.62	58.06	75.97	323.93
The Burdekin	502.07	**1.89**	9.46	14.22	71.37	48.54	243.72	35.35	177.50
Broome	377.33	**1.68**	6.34	3.49	13.19	14.36	54.18	80.47	303.63
Port MacDonnell	356.34	**0.68**	2.44	11.37	40.53	14.89	53.05	73.06	260.32
Perth (Whitfords)	123.99	**0.67**	0.83	0.38	0.47	1.79	2.23	97.16	120.47
Carnarvon	44.75	**0.56**	0.25	6.04	2.70	43.02	19.25	50.38	22.55
Werribee	65.88	**0.42**	0.28	7.26	4.78	28.94	19.07	63.38	41.76
Point Nepean	107.12	**0.28**	0.30	13.87	14.86	25.38	27.19	60.47	64.77
Uley South	128.08	**0.09**	0.11	0.80	1.02	4.52	5.79	94.59	121.16
Willunga	266.03	**0.09**	2.34	0.65	3.69	1.33	5.10	97.93	328.01
Derby	33.78	**0.00**	0.00	0.42	0.14	13.20	4.46	86.38	29.18

Table 7-2: Areas of DEM classes for each state/territory

State/territory	Total area (km^2)	Class 1 (<1 m)		Class 2 (1–5 m)		Class 3 (5–10 m)		Class 4 (>10 m)	
		% area	area (km^2)	% area	area (km^2)	% area	area (km^2)	% area	area (km^2)
NSW	100 542.98	2.27	2281.6	2.53	2541.1	2.14	2147.5	93.07	93 572.8
NT	207 548.37	2.55	5283.1	5.77	11 972.7	6.97	14 456.6	84.72	175 836.0
SA	182 403.68	1.13	2059.3	1.56	2848.0	2.34	4271.0	94.97	173 225.3
Qld	346 782.90	1.69	5854.2	3.75	12 995.5	5.18	17 962.5	89.38	309 970.8
Vic	89 255.43	0.63	558.9	1.23	1094.3	1.80	1605.9	96.35	85 996.3
WA	513 824.76	1.07	5519.7	1.55	7971.1	2.95	15 157.2	94.42	485 176.8
National total	1 440 358.13	**1.50**	**21 556.9**	**2.74**	**39 422.7**	**3.86**	**55 600.6**	**91.91**	**1 323 778.0**

Appendix 8 Summary of population data source

Table 8-1: Collector districts used for population change estimates

Case study area	*2001*		*2006*	
	Collector district	*Location code*	*Collector district*	*Location code*
Adelaide and Le Fevre	Adelaide (Major Statistical Region)	41	Adelaide (Major Statistical Region)	41
Albany	Little Grove (Urban Centre/Locality)	UCL516200	Little Grove (Urban Centre/Locality)	UCL516200
	Albany – Central (Statistical Local Area)	515100081	Albany – Central (Statistical Local Area)	515100081
Botany	Botany (State Suburb)	SSC11316	Botany (State Suburb)	SSC11133
	Sydney (Statistical Division)[1]	105	Sydney (Statistical Division)	105
Bowen	Bowen (Statistical Local Area)	340100950	Bowen (Statistical Local Area)	340100950
Broome	Broome (Urban Centre/Locality)	UCL502400	Broome (Urban Centre/Locality)	UCL502400
Bunbury	Bunbury (Statistical Local Area)	510031190	Bunbury (Statistical Local Area)	510031190
	Dardanup (Urban Centre/Locality)	UCL506220	Dardanup (Urban Centre/Locality)	UCL506220
The Burdekin	Home Hill (Urban Centre/Locality)	UCL327600	Home Hill (Urban Centre/Locality)	UCL327600
	The Burdekin (Statistical Local Area)	345151900	The Burdekin (Statistical Local Area)	345151900
Burnett Heads	Bundaberg (Statistical Subdivision)	31505	Bundaberg (Statistical Subdivision)	31505
	Moore Park (Urban Centre/Locality)	UCL340200	Moore Park (Urban Centre/Locality)	UCL340200
Busselton	Busselton (Statistical Local Area)	510151260	Busselton (Statistical Local Area)	510151260
Carnarvon	Carnarvon (Statistical Local Area)	535051540	Carnarvon (Statistical Local Area)	535051540
Derby	Derby (Urban Centre/Locality)	UCL507000	Derby (Urban Centre/Locality)	UCL507000
Esperance	Esperance (Urban Centre/Locality)	UCL508800	Esperance (Urban Centre/Locality)	UCL508800
Exmouth	Exmouth (Statistical Local Area)	535053360	Exmouth (Statistical Local Area)	535053360
Hat Head	Crescent Head (Urban Centre/Locality)	UCL123400	Crescent Head (Urban Centre/Locality)	UCL123400
	Hat Head (Urban Centre/Locality)	UCL138600	Hat Head (Urban Centre/Locality)	UCL138600
Howard Springs	Howard Springs (Urban Centre/Locality)	UCL702870	Howard Springs (Urban Centre/Locality)	UCL702870
	Palmerston (Urban Centre/Locality)	UCL705500	Palmerston (Urban Centre/Locality)	UCL705500
	Virginia-Bees Creek (Urban Centre/Locality)	UCL707020	Virginia-Bees Creek (Urban Centre/Locality)	UCL707020
North Stradbroke Island	Dunwich (Urban Centre/Locality)	UCL318200	Dunwich (Urban Centre/Locality)	UCL318200
	Amity Point (Urban Centre/Locality)	UCL301200	Amity Point (Urban Centre/Locality)	UCL301200
	Point Lookout (Urban Centre/Locality)	UCL346600	Point Lookout (Urban Centre/Locality)	UCL346600
Perth (Cottesloe)	Cottesloe (State Suburb)	SSC51331	Cottesloe (State Suburb)	SSC51346
	Peppermint Grove (State Suburb)	SSC52106	Peppermint Grove (State Suburb)	SSC52146
Perth (Whitfords)	Perth (Major Statistical Region)	51	Perth (Major Statistical Region)	51
Pioneer Valley	Half Tide Beach (Urban Centre/Locality)	UCL325800	Half Tide Beach (Urban Centre/Locality)	UCL325800
	Mackay (Statistical District)	3054	Mackay (Statistical District)	3054

Case study area	*2001*		*2006*	
	Collector district	*Location code*	*Collector district*	*Location code*
Point Nepean	Cape Schanck (Urban Centre/Locality)	UCL208100	Cape Schanck (Urban Centre/Locality)	UCL208100
	Portsea (State Suburb)	SSC22276	Portsea (State Suburb)	SSC21549
	Sorrento (State Suburb)	SSC22426	Sorrento (State Suburb)	SSC21617
	Blairgowrie (State Suburb)	SSC21206	Blairgowrie (State Suburb)	SSC21089
	St Andrews Beach (Urban Centre/Locality)	UCL246640	St Andrews Beach (State Suburb)	SSC26653
	Rye (State Suburb)	SSC22356	Rye (State Suburb)	SSC21581
Port MacDonnell	Port MacDonnell (Urban Centre/Locality)	UCL422000	Port MacDonnell (Urban Centre/Locality)	UCL422000
Stockton	Boat Harbour (Urban Centre/Locality)	UCL110000	Boat Harbour (Urban Centre/Locality)	UCL110000
	Anna Bay (Urban Centre/Locality)	UCL101200	Anna Bay (Urban Centre/Locality)	UCL101200
	Corlette (Urban Centre/Locality)	UCL122660	Corlette (Urban Centre/Locality)	UCL122660
	Fingal Bay (Urban Centre/Locality)	UCL130170	Fingal Bay (Urban Centre/Locality)	UCL130170
	Medowie (Urban Centre/Locality)	UCL151400	Medowie (Urban Centre/Locality)	UCL151400
	Lemon Tree Passage (Urban Centre/Locality)	UCL147400	Lemon Tree Passage (Urban Centre/Locality)	UCL147400
	Salamander Bay–Soldiers Point (Urban Centre/Locality)	UCL168250	Salamander Bay–Soldiers Point (Urban Centre/Locality)	UCL168250
	Nelson Bay (Urban Centre/Locality)	UCL160000	Nelson Bay (Urban Centre/Locality)	UCL160000
	Newcastle (Urban Centre/Locality)[3]	UCL160400	Newcastle (Urban Centre/Locality)[3]	UCL160400
Stuarts Point	Stuarts Point (Urban Centre/Locality)	UCL170800	Stuarts Point (Urban Centre/Locality)	UCL170800
Uley South[2]	Port Lincoln (Urban Centre/Locality)	UCL421800	Port Lincoln (Urban Centre/Locality)	UCL421800
Werribee	Werribee (State Suburb)	SSC22676	Werribee (State Suburb)	SSC21725
	Werribee South (Urban Centre/Locality)	UCL256450	Werribee South (Urban Centre/Locality)	UCL256450
Willunga	McLaren Vale (Urban Centre/Locality)	UCL413600	McLaren Vale (Urban Centre/Locality)	UCL413600
	Sellicks Beach (Urban Centre/Locality)	UCL424000	Sellicks Beach (Urban Centre/Locality)	UCL424000
	Aldinga Beach (State Suburb)	SC41041	Aldinga Beach (State Suburb)	SC41041
	Willunga (Urban Centre/Locality)	UCL428800	Willunga (Urban Centre/Locality)	UCL428800

1 The population of Sydney wasn't added to that of Botany, but was analysed separately.

2 Port Lincoln is not located within the Uley South area of interest (AOI) boundary but is the nearest major town.

3 Newcastle's population was not added to that of Stockton but is a major town directly adjacent to the AOI.

Table 8-2: Results of population change analysis for each CSA

Case study area	*Population*			*Number of dwellings*			*Population to dwellings ratio*	
	2001	*2006*	*% Change*	*2001*	*2006*	*% Change*	*2001*	*2006*
Significant[4] increase in population from 2001 to 2006								
Willunga	10 558	12 615	19.48	5018	6136	22.28	2.10	2.06
Pioneer Valley	63 411	73 584	16.04	26 060	29 051	11.48	2.43	2.53
Busselton	21 868	25 355	15.95	10 938	12 863	17.60	2.00	1.97
Point Nepean	12 322	13 879	12.64	15 255	16 074	5.37	0.81	0.86
Howard Springs	26 433	29 513	11.65	9880	11 154	12.89	2.68	2.65
Werribee	33 715	37 297	10.62	12 126	14 427	18.98	2.78	2.59
Increase in population from 2001 to 2006								
Stockton	31 887	34791	9.11	16 636	18 671	12.23	1.92	1.86
Perth (Whitfords)	1 325 392	1 445 078	9.03	552 006	608 721	10.27	2.40	2.37
Burnett Heads	56 674	61 366	8.28	23 998	26 728	11.38	2.36	2.3
Perth (Cottesloe)	8173	8646	5.79	3931	3897	-0.86	2.08	2.22
Sydney[1]	3 948 015	4 119 190	4.34	1 546 691	1 643 675	6.27	2.55	2.51
Bunbury	28 918	30 072	3.99	12 540	13 578	8.28	2.31	2.21
Port MacDonnell	600	623	3.83	421	433	2.85	1.43	1.44
Adelaide & Le Fevre	1 066 103	1 105 839	3.73	458 002	480 429	4.90	2.33	2.30
Newcastle[3]	278 773	118 196	3.57	288 732	123 008	4.07	2.36	2.35
Port Lincoln[2]	12 630	13 044	3.28	5474	5922	8.18	2.31	2.20
Albany	16 804	17 340	3.19	7719	8145	5.52	2.18	2.13
Esperance	9365	9536	1.83	4146	4350	4.92	2.26	2.19
Decrease in population from 2001 to 2006								
Botany	7466	7455	-0.15	2840	2944	3.66	2.63	2.53
The Burdekin	21 141	19 927	-5.74	9090	9070	-0.22	2.33	2.20
Stuarts Point	778	724	-6.94	417	412	-1.20	1.87	1.76
Hat Head	1491	1374	-7.85	959	1001	4.38	1.55	1.37
Bowen	13 436	12 377	-7.88	6186	6290	1.68	2.17	1.97
Significant[4] decrease in population from 2001 to 2006								
Derby	3662	3093	-15.54	1300	1279	-1.62	2.82	2.42
North Stradbroke Is.	2232	1881	-15.73	1511	1842	21.91	1.48	1.02
Broome	15 242	11 547	-24.24	5458	5983	9.62	2.79	1.93
Carnarvon	8941	5682	-36.45	3684	3638	-1.25	2.43	1.56
Exmouth	4092	2063	-49.58	1853	1836	-0.92	2.21	1.12

1 Sydney is not a CSA but was analysed in reference to population change for Botany.
2 Port Lincoln is not a CSA but was analysed in reference to population change for Uley South.

3 Newcastle is not a CSA but was analysed in reference to population change for Stockton.

4 A significant increase/decrease in population was defined at >10% for the purpose of this study.

Appendix 9 Summary of vulnerability factor analysis parameters

Table 9-1: Summary of VFA parameters in case study areas (see table notes for category classes. All available VFA data were used to compile Table 9-1 as per the state and territory assessments in Cook et al. (2012))

CSA	Current vulnerability ranking from integrated vulnerability assessment	Typology	Minimum water level category			Ground-water level trends	2000–2009 Rainfall trend	Maximum TDS concentration category			Extraction category	
			2000–2009	Pre 2000	Inter-decadal change			2000–2009	Pre 2000	Inter-decadal change	Maximum	Cumul-ative
*Adelaide Metro	High	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	High	Moderate	Decline	High	High	High	Moderate	High
Bowen	High	Coastal Alluvium, Tropical	Low	Low	Low	Increasing	Decline	High	High	Moderate	Moderate	Moderate
*Bunbury	High	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	Low	High	ND	Low	Decline	ND	High	ND	High	High
*Burnett Heads	High	Coastal Alluvium, Temperate, Without Dry Season	High	High	Moderate	Low	Stable	High	High	High	High	High
Derby	High	Sedimentary Basin, Arid	ND	High	ND	High	Increasing	ND	Low	ND	Moderate	Moderate
*Esperance	High	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	ND	High	ND	Moderate	Stable	ND	High	ND	Moderate	Moderate
*Exmouth (Cape Range)	High	Carbonate, Arid	ND	High	ND	ND	Declining	High	High	Moderate	Low	Moderate

*Multiple aquifers were present in these CSAs. The table presents the aquifer with the highest vulnerability ranking for each CSA. VFA parameters are not aquifer specific.
ND = No data
Minimum water levels: High <0 m AHD, Moderate 0–2.5 m AHD, Low >2.5 m AHD.
Inter-decadal decline in minimum water levels: High >5 m, Moderate 2.5–5 m, Low 0–2.5 m, increases are marked.
Declining groundwater elevation trends: High >1 m/year, Moderate 0.25–1 m/year, Low 0–0.25 m/year, increasing trends are marked.
Maximum TDS: High >10 000 mg/L within 1 km of <3000 mg/L, Moderate >10 000 mg/L within >1 km of <3000 mg/L, Low all <10 000 mg/L.
Inter-decadal increase in TDS: High >10 000 mg/L, Moderate 1000–10 000 mg/L, Low <1000 mg/L.
Extraction: High >1000 ML/year, Moderate 250–1000 ML/year, Low <250 ML/year.

CSA	Current vulnerability ranking from integrated vulnerability assessment	Typology	Minimum water level category			Ground-water level trends	2000–2009 Rainfall trend	Maximum TDS concentration category			Extraction category	
			2000–2009	Pre 2000	Inter-decadal change			2000–2009	Pre 2000	Inter-decadal change	Maximum	Cumul-ative
*Le Fevre	High	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	High	High	Declining	Low	High	Low	Moderate	Moderate
Perth (Cottesloe)	High	Coastal Sands, Mediterranean, Temperate, Summer Dry	ND	High	ND	ND	Declining	ND	High	ND	ND	ND
*Perth (Whitfords)	High	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	High	High	Declining	ND	Low	ND	High	High
*Port MacDonnell	High	Carbonate, Mediterranean, Temperate, Summer Dry	High	High	Low	Low	Stable	High	High	Low	Moderate	High
*Willunga	High	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	High	High	High	High	Declining	High	High	ND	Low	Moderate
*Albany	Moderate	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	ND	High	ND	Moderate	Stable	Low	Low	ND	Moderate	High
Botany	Moderate	Coastal Sands, Temperate, Without Dry Season	Moderate	High	ND	Low	Declining	ND	High	ND	ND	ND
Broome	Moderate	Sedimentary Basin, Arid	Moderate	High	Increase	Increasing	Increasing	Low	Moderate	Low	Moderate	High

*Multiple aquifers were present in these CSAs. The table presents the aquifer with the highest vulnerability ranking for each CSA. VFA parameters are not aquifer specific.
ND = No data
Minimum water levels: High <0 m AHD, Moderate 0–2.5 m AHD, Low >2.5 m AHD.
Inter-decadal decline in minimum water levels: High >5 m, Moderate 2.5–5 m, Low 0–2.5 m, increases are marked.
Declining groundwater elevation trends: High >1 m/year, Moderate 0.25–1 m/year, Low 0–0.25 m/year, increasing trends are marked.
Maximum TDS: High >10 000 mg/L within 1 km of <3000 mg/L, Moderate >10 000 mg/L within >1 km of <3000 mg/L, Low all <10 000 mg/L.
Inter-decadal increase in TDS: High >10 000 mg/L, Moderate 1000–10 000 mg/L, Low <1000 mg/L.
Extraction: High >1000 ML/year, Moderate 250–1000 ML/year, Low <250 ML/year.

CSA	Current vulnerability ranking from integrated vulnerability assessment	Typology	Minimum water level category			Ground-water level trends	2000–2009 Rainfall trend	Maximum TDS concentration category			Extraction category	
			2000–2009	Pre 2000	Inter-decadal change			2000–2009	Pre 2000	Inter-decadal change	Maximum	Cumul-ative
The Burdekin	Moderate	Coastal Alluvium, Tropical	High	High	Low	Low	Increasing	High	High	High	ND	ND
*Busselton	Moderate	Sedimentary Basin, Mediterranean, Temperate, Summer Dry	ND	High	ND	Low	Declining	ND	High	ND	Moderate	Moderate
*Carnarvon	Moderate	Coastal Alluvium, Tropical	High	High	Low	Moderate	Stable	Low	High	Moderate	ND	ND
*Howard Springs	Moderate	Fractured, Undivided, Tropical	Low	Low	Moderate	ND	Declining	Low	High	ND	ND	ND
Pioneer Valley	Moderate	Coastal Alluvium, Temperate, Dry Winter	High	High	High	Moderate	Declining	High	High	High	High	High
Point Nepean	Moderate	Coastal Sands, Temperate, Without Dry Season	High	High	High	Low	Declining	Moderate	Moderate	ND	Moderate	High
Stockton	Moderate	Coastal Sands, Temperate, Without Dry Season	ND	Low	ND	ND	Declining	Low	Low	ND	ND	ND
Stuarts Point	Moderate	Coastal Sands, Temperate, Without Dry Season	High	High	ND	ND	Stable	High	High	ND	ND	ND

*Multiple aquifers were present in these CSAs. The table presents the aquifer with the highest vulnerability ranking for each CSA. VFA parameters are not aquifer specific.
ND = No data
Minimum water levels: High <0 m AHD, Moderate 0–2.5 m AHD, Low >2.5 m AHD.
Inter-decadal decline in minimum water levels: High >5 m, Moderate 2.5–5 m, Low 0–2.5 m, increases are marked.
Declining groundwater elevation trends: High >1 m/year, Moderate 0.25–1 m/year, Low 0–0.25 m/year, increasing trends are marked.
Maximum TDS: High >10 000 mg/L within 1 km of <3000 mg/L, Moderate >10 000 mg/L within >1 km of <3000 mg/L, Low all <10 000 mg/L.
Inter-decadal increase in TDS: High >10 000 mg/L, Moderate 1000–10 000 mg/L, Low <1000 mg/L.
Extraction: High >1000 ML/year, Moderate 250–1000 ML/year, Low <250 ML/year.

CSA	Current vulnerability ranking from integrated vulnerability assessment	Typology	Minimum water level category			Ground-water level trends	2000–2009 Rainfall trend	Maximum TDS concentration category			Extraction category	
			2000–2009	Pre 2000	Inter-decadal change			2000–2009	Pre 2000	Inter-decadal change	Maximum	Cumul-ative
*Uley South	Moderate	Carbonate, Mediterranean, Temperate, Summer Dry	High	High	High	Moderate	Declining	Moderate	High	ND	High	High
Werribee	Moderate	Basalt, Temperate, Without Dry Season	High	High	ND	Low	Declining	High	High	ND	Low	Low
North Stradbroke	Low	Coastal Sands, Temperate, Without Dry Season	Moderate	Moderate	High	Moderate	Declining	Low	Low	ND	ND	ND
Hat Head	Low	Coastal Sands, Temperate	ND	Moderate	ND	Increasing	Declining	Low	Low	Low	ND	ND

*Multiple aquifers were present in these CSAs. The table presents the aquifer with the highest vulnerability ranking for each CSA. VFA parameters are not aquifer specific.
ND = No data
Minimum water levels: High <0 m AHD, Moderate 0–2.5 m AHD, Low >2.5 m AHD.
Inter-decadal decline in minimum water levels: High >5 m, Moderate 2.5–5 m, Low 0–2.5 m, increases are marked.
Declining groundwater elevation trends: High >1 m/year, Moderate 0.25–1 m/year, Low 0–0.25 m/year, increasing trends are marked.
Maximum TDS: High >10 000 mg/L within 1 km of <3000 mg/L, Moderate >10 000 mg/L within >1 km of <3000 mg/L, Low all <10 000 mg/L.
Inter-decadal increase in TDS: High >10 000 mg/L, Moderate 1000–10 000 mg/L, Low <1000 mg/L.
Extraction: High >1000 ML/year, Moderate 250–1000 ML/year, Low <250 ML/year.