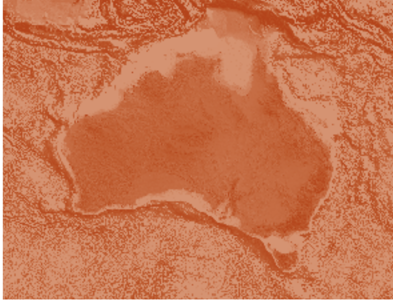
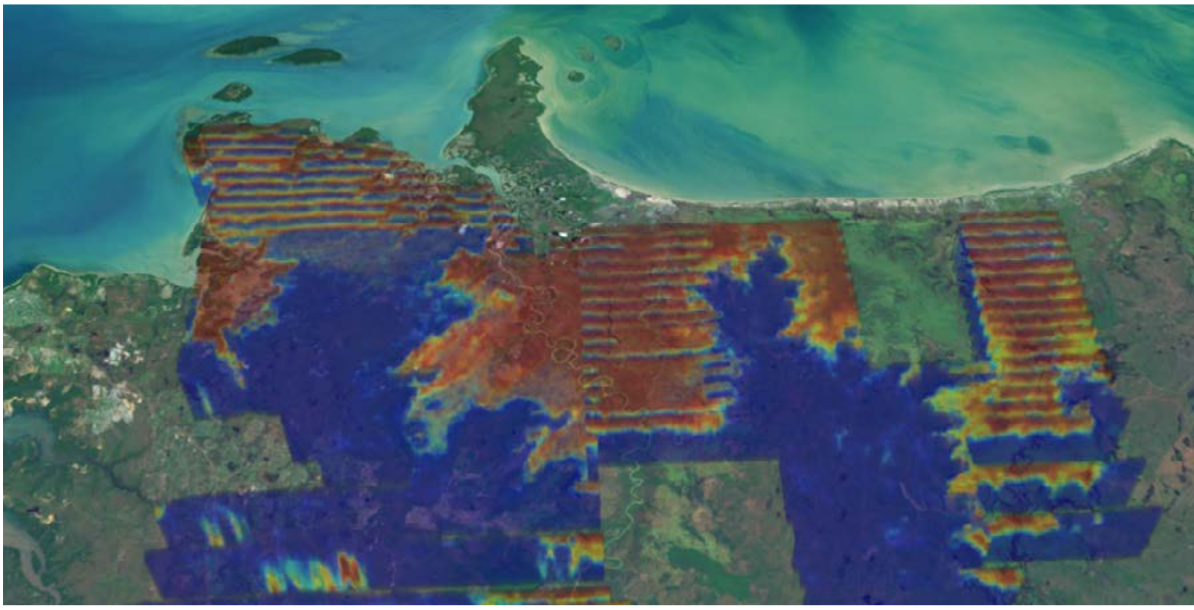
Australian Government
Geoscience Australia





Record 2012/42 | **GeoCat** 74101

Evaluating the Role of Airborne Electromagnetics in Mapping Seawater Intrusion and Carbonate-Karstic Groundwater Systems in Australia

Prepared for the National Water Commission, May 2012

Lawrie, K.C., Carey, H., Christensen, N.B., Clarke, J., Lewis, S., Ivkovic, K.M. and Marshall S.K.

Evaluating the Role of Airborne Electromagnetics in Mapping Seawater Intrusion and Carbonate-Karstic Groundwater Systems in Australia

Prepared for the National Water Commission, May 2012

GEOSCIENCE AUSTRALIA
RECORD 2012/42

Lawrie, K.C.[1], Carey, H.[1], Christensen, N.B.[2], Clarke, J.[1], Lewis, S.[1], Ivkovic, K.M.[3], and Marshall S.K.[1]

Australian Government
Geoscience Australia

1. Geoscience Australia
2. Aarhus University, Denmark
3. Naiades Geohydrology

Department of Industry
Minister for Industry: The Hon Ian Macfarlane MP
Parliamentary Secretary: The Hon Bob Baldwin MP
Secretary: Ms Glenys Beauchamp PSM

Geoscience Australia
Chief Executive Officer: Dr Chris Pigram
This paper is published with the permission of the CEO, Geoscience Australia

ISSN 2201-702X (PDF)

ISBN 978-1-922103-29-1 (PDF)

GeoCat 74101

Bibliographic reference: Lawrie, K.C., Carey, H., Christensen, N.B., Clarke, J., Lewis, S., Ivkovic, K.M. & Marshall S.K., 2012, *Evaluating the Role of Airborne Electromagnetics in Mapping Seawater Intrusion and Carbonate-Karstic Groundwater Systems in Australia*. Record 2012/42, Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2012.042

Contents

Executive Summary....1
Principal Findings....2
Recommendations....2
1 Introduction....4
1.1 Seawater Intrusion....5
1.2 Carbonate-Karstic Groundwater Systems....7
2 The Use of Airborne Electromagnetics (AEM) for Groundwater Mapping and Management....10
2.1 Airborne Electromagnetic Surveying....10
2.2 AEM Data Processing, Inversion And Interpretation....14
2.3 The Use of AEM for Mapping Hydrogeological Systems in Australia....15
2.4 Assessment Guidelines for Using AEM Systems For Groundwater System Mapping....18
3 Review of Existing Studies that Utilize AEM to Map Seawater Intrusion....20
3.1 Everglades, Florida, USA....20
3.2 Aceh, Indonesia....22
3.3 Galápagos Islands, Ecuador....25
3.4 Karstic Aquifers, Tulum, Yucatan, Mexico....28
3.5 Robe River, Pilbara, Western Australia....30
3.6 Coorong, Lakes Albert and Alexandrina, South Australia....33
3.7 Coffin Bay/Uley South, Eyre Peninsula, South Australia....35
3.8 Ord River, Western Australia....39
4 Review of Existing Studies that Utilize AEM to Map Carbonate-Karstic Aquifer Systems....41
4.1 Copper Ridge Dolomite, Tennessee, USA....41
4.2 Edwards Aquifer, Texas, USA....41
4.3 Camp Crowder, Missouri, USA....45
4.4 Oak Ridge National Laboratory, Tennessee, USA....47
4.5 Northern Territory Coastal Plain, Northern Territory, Australia....48
4.6 Daly Basin, Northern Territory, Australia....51
5 Preliminary Assessment of AEM Suitability for Assessing Seawater Intrusion Hazard in Australian Coastal Aquifers....54
5.1 Queensland....54
5.1.1 Burdekin River....54
5.1.2 Burnett Heads....56
5.1.3 North Stradbroke Island....57
5.1.4 Pioneer Valley Aquifer....58
5.2 South Australia....60
5.2.1 Adelaide Coastal Plains....60
5.3 Northern Territory....62
5.4 Western Australia....62
5.4.1 Bunbury....62
5.4.2 Busselton....64

5.4.3 Broome ... 66
5.4.4 Carnarvon ... 68
5.4.5 Derby ... 69
5.4.6 Esperance ... 70
5.4.7 Perth ... 72
5.4.8 Fortescue Swamp ... 73
5.5 Victoria ... 74
5.5.1 Point Nepean ... 74
5.6 New South Wales ... 75
5.6.1 Stockton ... 75
5.6.2 Stuart's Point ... 77
6 Preliminary Assessment of AEM Suitability for Mapping Australian Carbonate-Karstic Aquifer Systems ... 79
6.1 Lower Limestone Coast, South Australia ... 79
6.2 Exmouth (Cape Range), Western Australia ... 81
6.3 Rottnest Island, Western Australia ... 82
6.4 Daly Basin, Northern Territory ... 84
6.5 Georgina Basin, Northern Territory/Queensland ... 85
6.6 Smithton Dolomite, Tasmania ... 85
7 Conclusions ... 86
8 Recommendations ... 87
Acknowledgements ... 89
References ... 90

Executive Summary

Australia has witnessed a boom in the development of groundwater resources over the past 40 years. This rapid development has been driven by population pressures in coastal areas, with increasing use of groundwater in coastal aquifers leading to seawater intrusion in many sites. Likewise, many of the carbonate-karstic groundwater systems in Australia are assessed as over-allocated, or at risk from contamination.

To better quantify the hydrogeological cycle and to identify, assess and manage hazards to these groundwater systems holistic systems approaches are required. These integrate the use of the latest remote sensing and airborne geophysical mapping technologies with hydrogeochemical and hydrogeological investigations and modelling studies. Such approaches are increasingly being adopted internationally and within Australia.

In 2005, a review facilitated by the Australian Academy of Sciences and the Australian Academy of Technological Sciences and Engineering for the Australian Federal Government's Natural Resource Management Ministerial Council found that in the Australian landscape context airborne electromagnetics, (AEM) combined with ground and borehole control, was the only technique capable of mapping groundwater systems and groundwater salinity to depths of 200-300 m, at a variety of scales (Spies & Woodgate, 2005). A wide range of AEM systems and acquisition platforms are available (Allen, 2005; Spies & Woodgate, 2005), and the now-mature technology is capable of mapping complex groundwater salinity relationships in a variety of landscape and hydrogeological settings.

AEM systems cover large areas rapidly and generally penetrate to significant depths, providing important broader contextual information on hydrogeological systems. AEM systems also provide a logistical advantage in being able to acquire data systematically over difficult or inaccessible terrain. Given the increasing use of AEM technologies for a wide range of hydrogeological applications, the Australian Government's National Water Commission (NWC) approached Geoscience Australia to review the available literature to:

- Summarise the results of previous investigations that have used AEM data to map and characterise SWI and carbonate-karstic groundwater systems, documenting both international and Australian examples.
- Describe the key hydrogeological characteristics of the coastal groundwater systems in Australia that are most at-risk from adverse SWI impacts. These data are crucial for initially evaluating whether AEM systems may be of use in characterising the key elements of these groundwater systems.
- Provide recommendations on AEM technical risk assessment processes that could be employed to assess AEM system suitability for further surveys.

Principal Findings

1. AEM has been used successfully in many landscape and hydrogeological settings to map SWI. In the past decade, AEM has been used to map the SWI interface in increasingly complex geological environments. These include coastal alluvial sediments, fractured rock aquifers, and coastal carbonate-karstic systems.
   - International examples include the Everglades (USA), Denmark, Galapagos Islands (Ecuador), Malaysia, Venice (Italy) and Aceh (Indonesia).
   - Australian examples include Coffin Bay-Uley South, and the Coorong, and Lake Albert and Alexandrina (South Australia); the Roper and Ord Rivers (Western Australia), Northern Territory Coastal Plain (Northern Territory).
2. AEM has also been used in many case studies internationally to map the hydrogeology of carbonate and dolomitic sediments of varying age and character, as well as to the mapping and characterisation of karstic groundwater systems developed within these lithology types.
   - International examples include Edwards Aquifer, Cooper Ridge, Camp Crowder and at the Oak Ridge National Laboratory (USA), Denmark and Yucatan (Mexico).
   - Australian examples include Northern Territory Coastal Plain and Daly Basin (Northern Territory), and Renmark Group Limestones (South Australia).
3. AEM has the potential to be applied to the mapping and characterisation of additional SWI and carbonate-karstic groundwater systems in a wide-range of additional landscape and hydrogeological settings in Australia.
   - AEM may be of use in mapping SWI hazard in a number of priority sites identified as part of a national-scale vulnerability assessment (Ivkovic et al., 2012). However, a full hydrogeological and geophysical technical risk evaluation is required at each of these sites.
   - AEM may also be of use in mapping and characterising the groundwater system in Australian carbonate-karstic systems, with a full hydrogeological and geophysical risk evaluation required for each candidate site. However, unlike successful applications internationally, many Australian examples are complicated by having to discriminate between variations in lithology/porosity and groundwater salinity. This makes mapping of karstic systems more problematic in many settings. In general, higher resolution surveys may be required to map karstic porosity, which is typically smaller scale than SWI interfaces.

Recommendations

1. As with several earlier AEM-based studies (Lawrie et al., 2009, 2010a, 2011), a phased or staged approach should be employed for future AEM-based SWI and/or carbonate-karstic groundwater systems. Integrated assessments should be phased, and include:
   - Collation and review of existing information for the purpose of identifying critical knowledge gaps.
   - Scoping and technical risk evaluation to assess the methods and technologies best suited to addressing identified knowledge gaps.
   - A comparative system resolution analysis to determine the optimal AEM system for particular survey aims (Christensen & Lawrie, 2012). The resolution of an AEM system depends critically on the achievable signal-to-noise ratio, and this must be factored in to any technical assessment.

- An assessment of the scale of the groundwater systems and key elements to be mapped to ascertain the area to be flown and the appropriate flight-line spacing.
- Integrated geoscientific studies to enable key elements of the hydrogeological system to be mapped, and groundwater flow and hydrogeochemical processes to be understood.
- Data synthesis and interpretation using contemporary 'systems' approaches (Lawrie et al., 2000; Lane et al., 2004a, b; Spies & Woodgate, 2005; Lawrie, 2008; Lawrie et al., 2008, 2009, 2010, 2011, 2012), with an emphasis on delivering products that address specific issues and assist with the improved parameterisation of hydrogeological models.
- Groundwater, surface-groundwater modelling and land use modelling to ascertain the sustainability of proposed developments. Modelling should use the best available climate data and modelling scenarios.

2. In considering AEM technology suitability for a particular mapping task, a range of parameters and their influence on the modelled ground response should be considered. Such approaches include inversion analysis that is capable of comparing systems. A pragmatic approach may include:
    - Theoretical analysis based on noise figures that have been deemed reasonable by the analyst.
    - Test lines of field data for all systems in a range of hydrogeological settings.
    - Comparison of the contractors' own inversion of their test line data.
    - Inversion with a GOOD inversion program of all datasets for comparison.
3. The acquisition of AEM data for SWI and carbonate-karstic groundwater system mapping should only be considered within the context of the broader, integrated, hydrogeological assessment of an area (Lawrie et al., 2010; 2012). Technical risk evaluation is required to gauge the merits of employing different geophysical approaches and technologies.
    - Acquisition of AEM data should only proceed after completion of scoping studies to assess the likelihood of success arising from their acquisition.
    - Scoping studies are required to identify target aquifers and groundwater systems, and the scale, depth and orientation of target objectives (where possible). This should then be followed by completion of a technology suitability assessment exercise in each area. Technology selection should include forward modelling of system responses, and should follow the best practice procedures developed by the Commonwealth, taking particular note of the ability of AEM system to map key elements of relevant elements of the hydrogeological system.
    - AEM data analysis and interpretation should follow a 'hydrogeological systems' approach based on the methodology recommended by the Joint Academies of Science Review of Salinity Mapping Methods in the Australian Landscape Context (Spies & Woodgate, 2005). Based on these recommendations, AEM-based projects need to incorporate a drilling program, complementary ground investigations and hydrogeochemical studies to ensure appropriate survey calibration, validation and interpretation.
4. Future AEM surveys should carefully consider the merits of using calibrated AEM systems and inversion software that can significantly shorten data acquisition and delivery timeframes. These technologies and methods can significantly shorten overall project timeframes and potential costs.

1 Introduction

There has been a boom in the development of groundwater resources in Australia over the past 40 years. This rapid development has been driven by population pressures in coastal areas (e.g. Perth, Queensland), and a need to secure new water supplies for regional communities and agriculture in the face of drought conditions and reductions in surface water licences (e.g. the Murray-Darling Basin). Through direct and indirect contributions, groundwater is thought to contribute >50 % of Australia’s water supplies, making it a critical component of national water security (Lawrie et al., 2011).

In this environment of rapid resource development, ‘sustainable’ groundwater management faces many challenges. It is estimated that one third of existing groundwater management units (GMUs) are ‘over-allocated’ (NWC, 2007). Others remain poorly understood, with identified resources under increasing pressure not only from an expanding population, but also from increased demands from the energy, mining and agricultural sectors. Of particular concern for this study, coastal groundwater resources are being heavily exploited in many areas, leading to an increased threat of seawater intrusion (Dixon-Jain et al., 2010). The groundwater resources in many of our carbonate-karstic aquifer systems (in inland and coastal regions) are also thought to be over-allocated, or at risk from contamination or over-extraction (NWC, 2007).

The Australian Government has provided leadership in addressing many of these issues through a program of National Water Reform. One consequence of this is that new investments on major water security infrastructure at State and Federal level require high levels of certainty before committing to decisions. This has seen decisions in coastal areas to progress energy-intensive and expensive desalination plants as insurance against water scarcity. Groundwater suffers in this space because of acknowledged information gaps, due in large part to a systemic lack of investment in resource quantification and monitoring. As a result, poor groundwater model parameterisation produces large uncertainties in hydrological predictions, leading to a reluctance to rely on ‘less certain’ groundwater solutions. This is exacerbated by perceptions that “groundwater is at least an order of magnitude more difficult to quantify than surface water”, or “is too technically challenging”, while the need to provide alternative water supplies in short timeframes means there is often insufficient time and resources to fill key hydrogeological knowledge gaps using traditional methods. Paradoxically, uncertainty in understanding groundwater systems also provides policy makers with increased leeway to continue with or to develop groundwater extraction policies that are unsustainable in the longer term.

Demand for higher certainty in model predictions and rapid characterisation and quantification of resources, has provided an impetus for new hydrogeological research directions beyond conventional discipline boundaries, with a marked increase in multi-disciplinary systems approaches (Lawrie, 2008; Lawrie et al., 2012). New approaches have incorporated the use of improved geospatial mapping technologies that enable key elements of the hydrogeological system to be mapped and characterised with greater certainty more rapidly. In the sub-surface, these approaches map and characterise key elements of the hydrogeological system critical to the storage and movement of water, salts and other solutes and nutrients. The approaches rely on the use of technologies and methodologies developed largely for the minerals and petroleum exploration sectors, and integrate a variety of airborne and ground geophysical techniques and other remotely sensed datasets with information on landscape evolution and sedimentology validated by drilling (Lawrie et al., 2009, 2010a, 2012). These approaches enable the creation of 3-D mapping constructs that provide a framework within which hydraulic and chemical processes can be considered, uncertainties in model parameterisation and outputs reduced, and targeted conjunctive water and environmental management strategies and actions developed (Lawrie et al., 2009, 2010a, 2012).

Airborne electromagnetics (AEM) is one of the key technologies now being used internationally and within Australia to fill knowledge gaps of our shallow (<300 m depth) groundwater systems (Lawrie, 2008; Lawrie et al., 2009, 2010, 2012; Munday, 2008). A wide range of AEM systems and acquisition platforms are available (Allen, 2005; Spies and Woodgate, 2005; Auken et al., 2006; Kirsch, 2006). The technology is now recognised as mature, capable of mapping complex hydrostratigraphy and groundwater quality (salinity) relationships in a variety of Australia's unique landscape and hydrogeological settings (Lawrie et al., 2000, 2009, 2009, 2010a, b; 2011, 2012; Munday, 2008; Fitzpatrick et al., 2009). AEM systems cover large areas rapidly and generally penetrate to significant depths depending on the ground conductivity, often providing important broader contextual information on hydrogeological systems. AEM systems also provide a logistical advantage over ground-based methods in being able to acquire data systematically over difficult or inaccessible terrain, and areas where ground access is difficult for cultural, heritage or environmental reasons.

This study aims to:

- Summarise the results of previous investigations that have used AEM data to map and characterise SWI and carbonate-karstic groundwater systems, documenting both international and Australian examples.
- Describe the key hydrogeological characteristics of the coastal groundwater systems in Australia that are most at-risk from adverse SWI impacts. This data is a crucial initial step in evaluating whether AEM systems may be of use in characterising the key elements of these groundwater systems.
- Provide recommendations on AEM technical risk assessment processes that could be employed to assess AEM system suitability for further surveys.

1.1 Seawater Intrusion

Seawater intrusion (SWI) is the influx of seawater into an area, such as an aquifer or a body of surface water, where freshwater normally dominates. SWI most commonly occurs in coastal aquifer systems as a consequence of groundwater extraction (Barlow, 2003). However, other anthropogenic factors including urbanisation, land reclamation and development of drainage canals can also contribute to SWI.

SWI may also be caused by natural processes such as coastal evolution, long-term sea-level change, tsunamis, and natural climate variability. These factors can all lead to altered water balances within an aquifer system. Projected sea-level rises in response to a changing global climate may also vary the dynamic balance of the transition zone between fresh groundwater and seawater. The basic principles of SWI are further discussed below.

Coastal aquifers which are hydraulically connected to seawater commonly develop an interface in which fresh groundwater sits above, and adjacent to, seawater (Figure 1.1). As saltwater is more dense than freshwater a wedge-like zone of seawater develops beneath fresher groundwater on the landward-side of the coast. The leading edge of the seawater wedge, which occurs where the seawater interface intersects the bottom of the aquifer, is known as the toe.

The saltwater toe marks the maximum extent of SWI. The position of the seawater–freshwater interface can shift in response to changes in flow conditions between the aquifer and the sea. The seawater wedge decreases in thickness landward from the coast, with the toe of the wedge potentially extending several kilometres inland beneath the fresh groundwater resource. In situations where the land mass is partly or totally surrounded by seawater (e.g., islands, peninsulas and barrier dunes), opposing seawater wedges can intersect to isolate freshwater from the regional groundwater system. This may result in development of subsurface freshwater lenses.

Mixing between freshwater and saltwater by mechanical dispersion and molecular diffusion results in a 'transition zone' of salinity around the interface, which can range from a few metres to kilometres in width (Figure 1.1). Dynamic temporal forces such as daily tidal oscillations, seasonal and annual variations in rates of groundwater recharge and extraction, and long-term sea-level change may all cause the position of the transition zone to fluctuate between landward and seaward positions (Barlow, 2003).

Groundwater recharge and pumping primarily control the transience and position of the saltwater–freshwater interface. Aquifers with high recharge volumes can have a transition zone that is laterally seaward of the coastline, whereas aquifers with lower recharge rates may develop a transition zone that extends for several kilometres inland. Any change in groundwater recharge or extraction volumes will shift the relative position of the interface. The interface will gradually translate its position until it matches the new inflow–outflow regime and associated hydraulic head condition, although the time required for the interface to assume a new steady-state position after a persistent disturbance has occurred is not easily assessed or generally understood. It likely occurs over timeframes of years to centuries.

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

SWI is not the only mechanism by which coastal groundwater can become saline. Salt can also be derived from other sources. For example, salinity can increase due to: dissolution of basement rock by fluids; inflow of agricultural waste products; and inflow from another aquifer containing relic seawater (Richter & Kreitler, 1993). Thus, it is important in any SWI investigation to distinguish seawater from other sources of salinity.

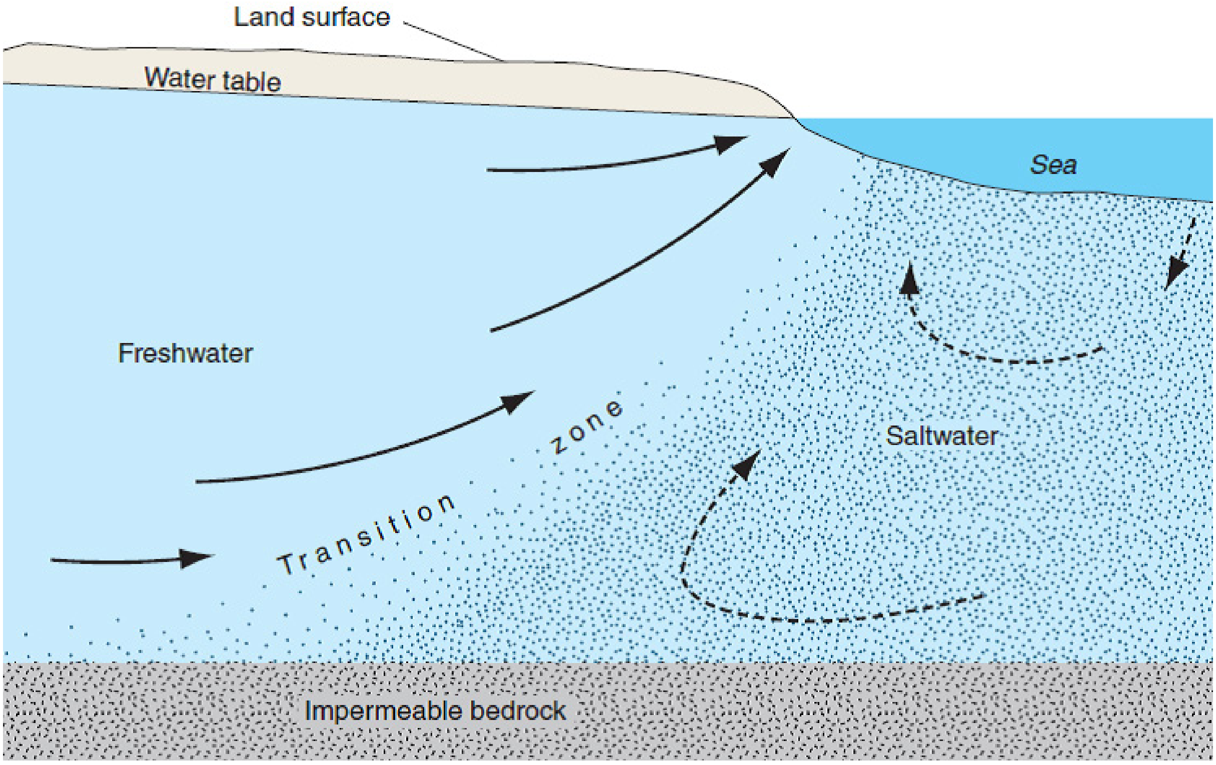


Figure 1.1 Schematic of the transition zone between freshwater and saltwater in coastal aquifers (Barlow 2003).

Seawater intrusion may alter the composition of groundwater in an aquifer to such an extent that it can be difficult (even practically impossible) to reverse. Consequently, an important objective of coastal aquifer management is to avoid or minimise the impact of actions that may exacerbate SWI. A foundation principle that can be used by managers of coastal aquifer systems for first-order analysis of SWI is the Ghyben-Herzberg Principle (Ghyben, 1888; Herzberg, 1901).

In Australian coastal aquifers, fresh groundwater constitutes an important resource for the natural environment, as well as urban, agricultural, rural residential and industrial activities. It is expected that the vulnerability of Australia’s coastal aquifer systems to SWI will increase into the future as a consequence of population growth, an expansion in groundwater development, as well as due to a drying climate characterised by periods of below-average rainfall and reduced groundwater recharge and discharge (Dixon-Jain et al., 2010). Moreover, climate change predictions suggest a possible rising sea level of more than 50 cm by 2100 which would lead to the inland migration of the freshwater-saltwater interface. Each of these factors will contribute to putting increased pressures on the available fresh groundwater resources in coastal areas. The sites of current sea water intrusion and those areas thought to be at high hazard are shown in Figure 1.2 (Dixon-Jain et al., 2010).

1.2 Carbonate-Karstic Groundwater Systems

More than 25 % of the world's population either lives on or obtains its water from karst aquifers in carbonate terranes. Groundwater management in these environments can be particularly challenging due to the heterogeneity of the aquifers. In Australia, carbonate, dolostone and karst aquifers are less important overall, but form key aquifers in the Northern Territory, South Australia and Western Australia, and locally in the other States.

Carbonate and dolostone aquifers generally have a relatively low porosity, with groundwater storage and flow largely in a dual porosity system where fractures are particularly important. In these cases, carbonate and dolostone aquifers are generally electrically resistive, although AEM methods are sensitive to porosity, clay content and groundwater salinity, hence it is often possible to map subtle variations in dolostone and carbonate hydrostratigraphy. In karstic terranes developed in these lithologies, porosity is commonly enhanced and occurs at a range of scales, from cavernous sink holes, dolines, and connected underground channels, to epikarsts, palaeo-epikarsts, vughs and fracture zones. While only the larger variations in porosity can be mapped directly using AEM methods, particularly at depth, many variations in karst hydrostratigraphy can often be detected indirectly by mapping variations in water quality and porosity fill materials. Identifying karstic aquifers is also aided by mapping the irregular topography (commonly buried) produced by karst dissolution, and infill by overlying units.

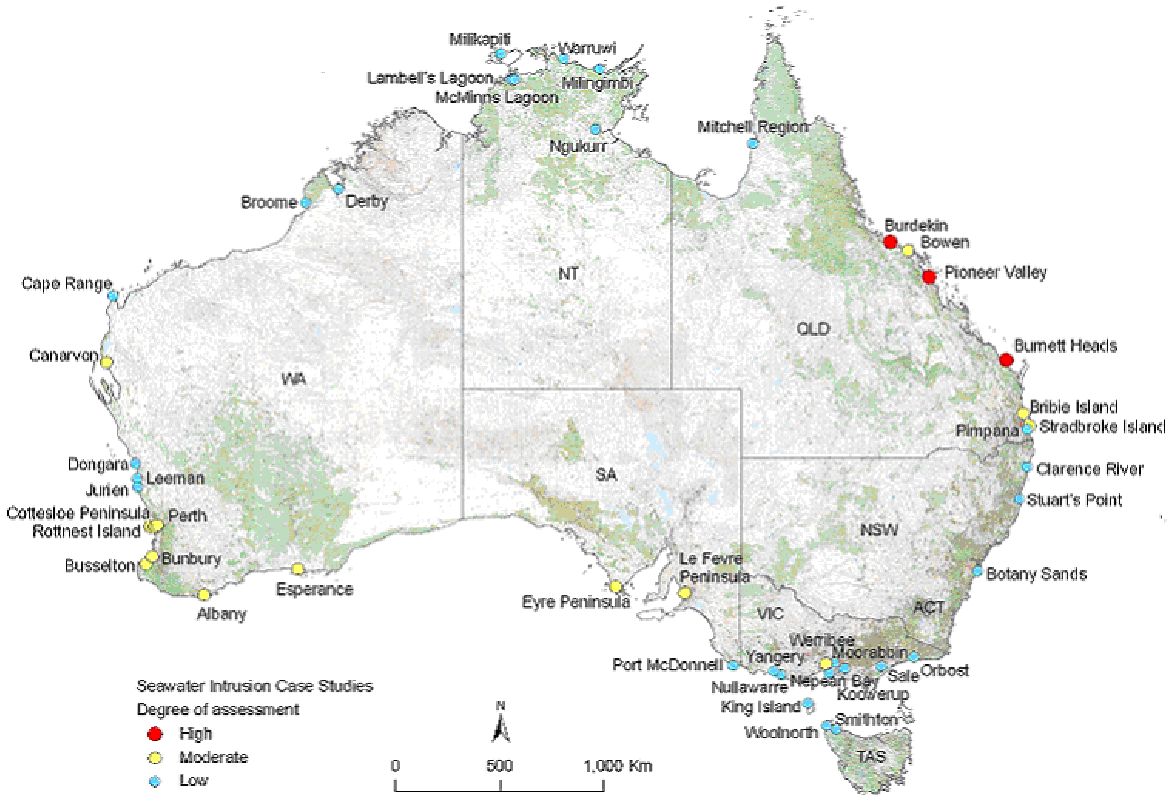


Figure 1.2 Seawater Intrusion Locations in Australia. From Dixon-Jain et al., (2010).

Karstic aquifers are of comparatively minor importance in Australia compared to other continents. Many are of limited extent or occur in areas of saline groundwater. Those of importance all lie in coastal or near-coastal areas and are therefore potential candidates for SWI (Figure 1.3). The six main aquifers discussed in this report are: the Gambier Limestone in the Otway Basin of SA and Victoria; the Bridgwater Formation aquifers, which occur discontinuously along the southern coast of Australia from Coffin Bay in SA to Cape Otway in Victoria; the Tamala Limestone southwest WA; the Cape

Range Group of the Cape Range area in WA; the Smithton Dolomite near Smithton Tasmania; and the largest inland karstic basin with usable groundwater in Australia, the Georgina Basin.

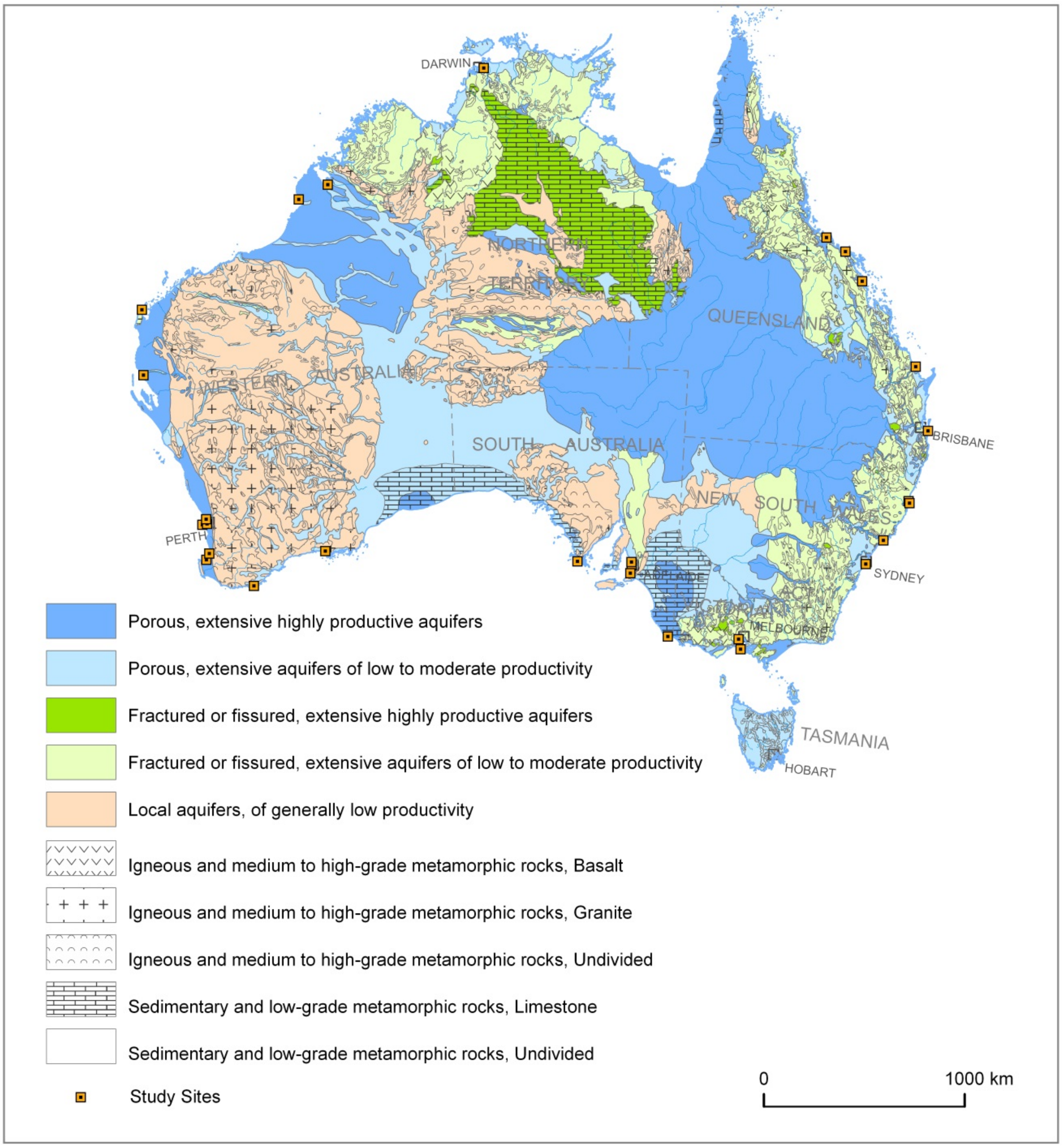


Figure 1.3 Map showing Australian groundwater basins. Those including karstic characteristics are included under the broader classification “Sedimentary and low-grade metamorphic rocks, Limestone”. Significant known SWI sites are indicated. Modified from Jacobson (1987)

2 The Use of Airborne Electromagnetics (AEM) for Groundwater Mapping and Management

Electromagnetic (EM) surveying techniques involve the measurement of the varying response of the ground due to the propagation of electromagnetic fields. Ground and borehole electrical and electromagnetic (EM) methods, have been successfully used in hydrogeologic investigations over the past few decades (Kirsch, 2006). A variety of electrical and EM technologies have been used to map hydrostratigraphy, hydraulic properties, and the chemical composition of groundwater, e.g., salinity, contamination plumes etc. (Kirsch, 2006).

The techniques have been particularly successful in mapping SWI interfaces in many coastal zones, due to the marked contrast that commonly exists between highly saline groundwater wedges associated with SWI, and fresh ambient groundwater. Similarly, ground electrical and EM methods have been successful in providing high-resolution imaging of porosity and water quality variability (salinity) in many carbonate-karstic terranes. Although ground (and borehole) techniques are particularly useful in mapping local scale variability at high resolution they are relatively time consuming and expensive to use over large areas.

Electromagnetic methods can very effectively be used to map variations in conductivity of subsurface features. However, these variations reflect a number of factors that make the interpretation of electromagnetic data complex. For example, electrical conductivity is affected in different ways by lithologies, with quartz sands and gravels electrically resistive, and clays generally conductive. However, electrical conductivity is also affected by pore fluid factors and the percentage of pore space relative to mineral grains. Clays typically contain ~70-80 % porosity, while sands have 20-35 % porosity. Pore fluid saturation also varies significantly above and below the watertable. Electrical conductivity responses are also influenced significantly by pore fluid salinity, with saline groundwater being conductive and fresh groundwater resistive. Compared to many landscapes and hydrogeological systems in more temperate climates in northern Europe and North America, the interpretation of electrical and EM data in Australia is made more complex by the significant salt stored in our ancient landscapes, and the more recent salinisation of many of our groundwater systems (Lawrie et al., 2000, 2002).

In summary, electrical conductivity responses are influenced by a range of factors, with results ideally constrained and validated by drilling, and expert interpretation of a range of additional information, particularly relating to the geological and hydrochemical characteristics of the system being considered.

2.1 Airborne Electromagnetic Surveying

AEM systems utilising frequency-domain and time-domain (transient) methods have progressively developed from minerals exploration tools to systems that are well suited to hydrogeological applications (Fountain, 1998). In airborne electromagnetic surveying primary fields are generated by passing a current through a loop or coil positioned in the air (Figure 2.1). A secondary field is induced in the ground and these fields are detected by the alternating currents that are induced to flow in a receiver coil, positioned at the rear, and offset from the transmitter loop (Figure 2.2), by a process known as electromagnetic induction. As the induction of current flow results from the magnetic component of the electromagnetic field, there is no need to have physical contact between transmitter or receiver and the ground. Consequently, EM surveys can proceed effectively both on the ground and in the air.

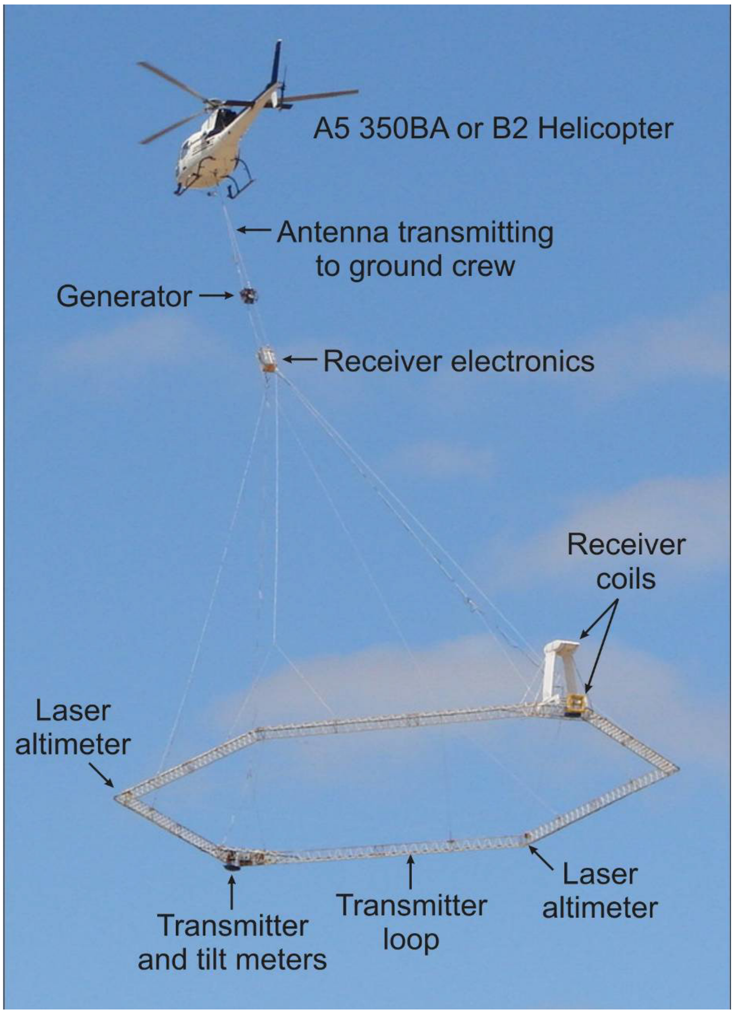


Figure 2.1 The SkyTEM airborne electromagnetic system in flight mode

The primary field travels from the transmitter to the receiver via paths above and below the ground surface (Figure 2.1). In the presence of a conducting body (for example, conductive soils), the magnetic component of the electromagnetic field penetrating the ground induces eddy or alternating currents to flow in the conductor. These eddy currents generate the secondary electromagnetic field which is measured by the receiver (Peters, 2001). The receiver coils record the response of a decaying signal in the ground at various times after the transmitter pulse has been switched off.

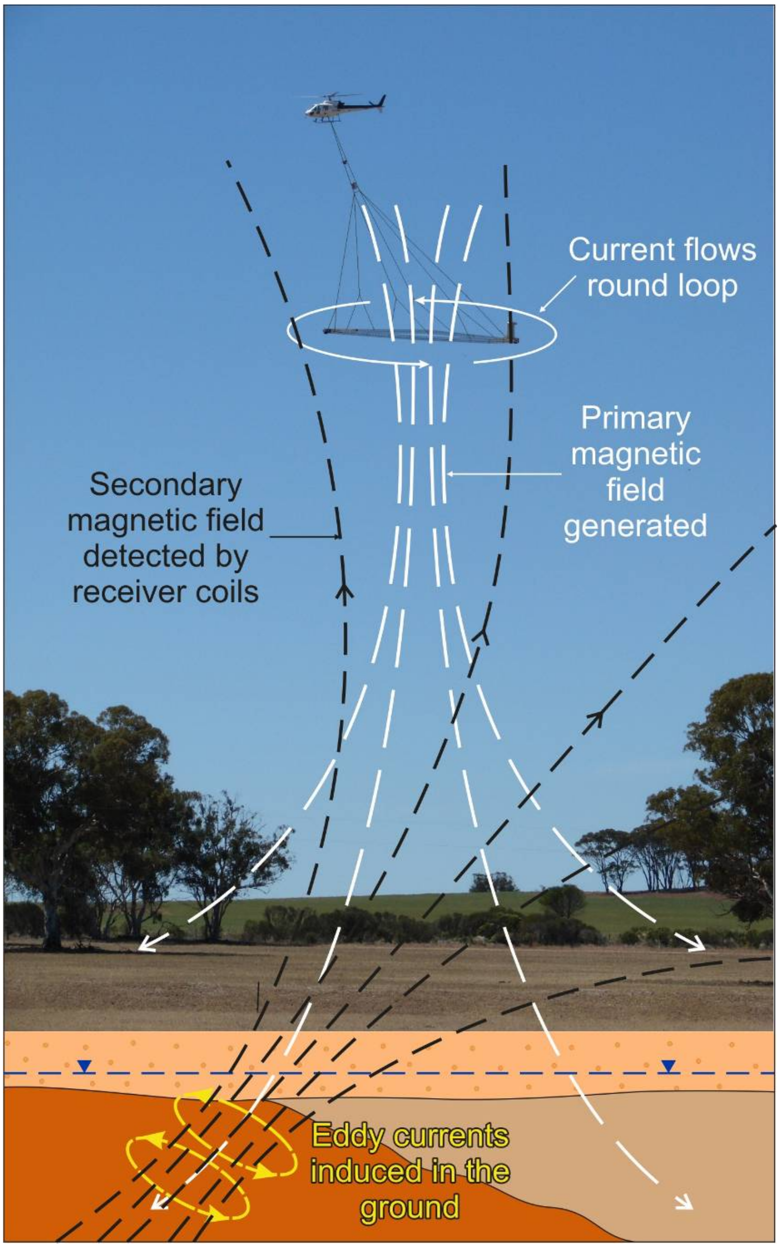


Figure 2.2 Operating principles of the SkyTEM AEM system.

The difference between the transmitted (primary) and received (secondary) electromagnetic fields is determined by the geometry and electrical properties of conductors in the ground. Materials that are highly conductive produce strong secondary electromagnetic fields. Sediments, soils or other regolith materials that contain saline pore water generate such fields. The shape of the decaying signal provides information about the conductivity structure of the ground.

AEM systems can be mounted below helicopters or mounted in fixed wing aircraft (Lane, 2002). AEM systems are capable of rapid systematic coverage of large areas at relatively low cost, and data can be acquired in areas of difficult ground access. More detail on AEM technologies are summarised by Thompson et al., 2007 and Macnae (2007). Systems currently available commercially are summarised by Munday (2008). These include time domain fixed wing systems (e.g. TEMPEST, GEOTEM), time domain helicopter systems (e.g. SkyTEM, HOISTEM, VTEM and REPTEM), and frequency domain systems (e.g. DIGHEM, Resolve, and Hummingbird).

The depth of investigation and spatial resolution of these AEM systems varies significantly with system type and depends on ground conditions (Spies & Woodgate, 2005; Sorensen & Auken, 2004). A summary of these differences can be found in Munday (2008). Kirsch (2006) provided a summary of the optimal specifications for some of the common fixed wing and helicopter-borne AEM systems for investigations of different depths. Frequency-domain AEM systems that are applicable to hydrogeological surveying are listed in Table 2.1. These systems are predominately deployed on rigid boom arrays towed by a helicopter. Fixed-wing platforms for time-domain AEM systems are more cost effective due to their increased acquisition speed and wider spatial coverage. Table 2.2 lists specifications of some time-domain AEM systems currently available for deployment.

Table 2.1 Helicopter and fixed-wing frequency-domain systems (#F: no. of frequencies f, #x: no. of coils, coil orientation: hor: horizontal, vert: vertical, copl: coplanar, coax: coaxial, r: coil separation). After Kirsch (2006).

Method	System	System Properties
Helicopter	AWI	2F, f = 3.7 / 112 kHz, 2x hor copl, r = 2.1 / 2.8 m
Helicopter	Impulse	6 F, f = 870 Hz – 23 kHz, 3x hor copl / 3x vert coax, r = 6.5 m
Helicopter	Humming-bird	5 F, f = 880 Hz – 35 kHz, 3x hor copl / 2x vert coax, r – 4.7 m
Helicopter	GEM2-A	6F, f = 300 Hz – 48 kHz, 1x hor copl, r =5.1 m
Helicopter	Dighem[V]	5F, f = 400 Hz – 56kHz, 5x hor copl, r = 6.3 / 8 m
Helicopter	RESOLVE	6F, f = 380 Hz – 101 kHz, 5x hor copl / 1x vert coax, r = 7.9 – 9 m
Helicopter	Dighem-BGR	5F, f = 385 Hz – 195 kHz, 5x hor copl, r = 6.7 m
Fixed-wing	GSF-95	2F, f = 3.1 / 14.4 kHz, 2x vert copl, r = 21.4 m
Fixed-wing	Hawk	1 – 10F, f = 200 Hz – 12.5 / 25 kHz, 1x hor copl / 1x vert copl, r = wingspan

Table 2.2 Key parameters of some helicopter and fixed-wing time-domain systems. After Kirsch (2006).

Method	System	Moment/waveform	Configuration and measured components
Fixed-wing	GEOTEM	450 kAm^2/ half-sine	Offset-loop, Z and X
Fixed-wing	MEGATEM	1500 kAm^2/ half-sine	Offset-loop, Z and X
Fixed-wing	TEMPEST	55 kAm^2/ trapezoid	Offset-loop, Z and X
Helicopter	AeroTEM	40 kAm^2/ triangular	Central-loop, coplanar, Z and X
Helicopter	HoisTEM	120 kAm^2/ trapezoid	Central-loop, coplanar, Z
Helicopter	VTEM	400 kAm^2/ trapezoid	Central-loop, coplanar, Z
Helicopter	SkyTEM	120 kAm^2/ trapezoid	Central-loop, coplanar, Z and X

AEM methods for near-surface investigations have undergone rapid improvements over the past few decades (Auken et al., 2006; Macnae, 2007; Lawrie, 2008). The inclusion of microprocessors in survey instruments, development of new interpretation algorithms, and easy access to powerful computers has supported significant innovation (Auken et al., 2006). However, it is the development of continuous-measurement systems that generate large, dense datasets efficiently being of particular importance to AEM surveys, as these allow measurements over wide areas without sacrificing lateral resolution (Auken et al., 2006).

Overall, the trend is clearly toward dense surveying over larger areas, followed by highly automated, post-acquisition processing and interpretation to provide improved resolution of the shallow subsurface in a cost-effective manner (Auken et al., 2006).

2.2 AEM Data Processing, Inversion And Interpretation

In order to map ground conductivity it is necessary to convert measurements of the ground electromagnetic response, through a process of inversion, into an estimate of this parameter. Through the application of approximate transforms or layered inversions, conductivity-depth values can be calculated for each observation or sounding made by the AEM system, and then stitched together into sections to provide a representation of the 2D variation of conductivity. This is sometimes referred to as a 'parasection' (Lane, 2002). Further, the conductivity depth profiles can be combined into a 3D gridded volume from which arbitrary sections, horizontal depth slices (or interval conductivity images) and isosurfaces can be derived. The schematic in Figure 2.3 summarises the process of acquiring AEM data, inverting the resulting data, and presenting the results as conductivity images.

The representation of essentially continuous and gradational conductivity distributions as discrete conductive 'units' or bounding layers is an effective way to summarise information from large AEM surveys. This is particularly so when the application calls for mapping the conductivity, depth to top and or the thickness of a semi-continuous layer of sediments or in situ regolith. The processing and presentation of AEM data as maps or sections is an effective way of displaying conductivity data.

AEM data acquired for exploration or environmental applications are commonly modelled using algorithms such as conductivity depth transforms (CDT's) or Layered Earth Inversions (LEI's) that assume a 1D earth (Sattel, 2005). To date, full 2.5 or 3D inversion of AEM data remains limited, and in many respects unrealistic and unnecessary particularly for hydrogeological investigations in Australian basins where the assumption that the sub-surface can be represented as a series of horizontal layers holds reasonably well, particularly at the footprint scale of most AEM systems (Lane, 2000; Sattel, 1998). The 1D model assumption is also legitimate in sub-horizontal, layered sedimentary areas where it produces results that are only slightly distorted by 2D or 3D effects induced by faults, fractures, or other geological phenomena (Auken et al., 2005; Newman et al., 1987; Sengpiel & Siemon, 2000).

The availability of these datasets has in turn spurred development of interpretation algorithms, including: Laterally constrained 1D inversion as well as innovative 2D- and 3D-inversion methods, and rapid approximation methods (Christensen, 2008; Lawrie et al., 2012). There are several approaches to inversion methods which are detailed in the literature (Lane et al., 2000; Lane et al., 2001; Smith, 2001; Brodie & Sambridge, 2006; Johnson & Mifflin, 2006; Auken et al., 2009a). The information derived from AEM surveys, particularly with regards to the structural and hydrogeological data, can be used to inform hydrogeological modelling (Johnson & Mifflin, 2006).

Strong correlations between AEM data and conductivity data from borehole surveys provide greater confidence in the validity of the AEM data and its suitability for mapping subsurface conductivity variations across wider regions (Lane et al., 2004a; Lawrie et al., 2009, 2010a, 2012).

2.3 The Use of AEM for Mapping Hydrogeological Systems in Australia

In 2005, a review facilitated by the Australian Academy of Sciences and the Australian Academy of Technological Sciences and Engineering for the Australian Federal Government's Natural Resource Management Ministerial Council found that in the Australian landscape context, airborne electromagnetics, combined with ground and borehole control, is the only technique capable of mapping groundwater systems and groundwater salinity to depths of 200-300 m, at a variety of scales (Spies & Woodgate, 2005). A wide range of AEM systems and acquisition platforms are available (Allen, 2005; Spies & Woodgate, 2005), and the technology is now recognised as mature, capable of mapping complex groundwater salinity relationships in a variety of landscape and geological settings.

AEM systems cover large areas rapidly and generally penetrate to significant depths, often providing important broader contextual information on hydrogeological systems. AEM systems also provide a logistical advantage in being able to acquire data systematically over difficult or inaccessible terrane. Borehole EM technologies provide important constraints on sub-surface salinity distribution and are an essential component in calibration and validation of AEM inversions. Ground-EM and in-river EM systems are particularly effective at mapping near-surface salinity with high resolution (Allen, 2005; Spies & Woodgate, 2005).

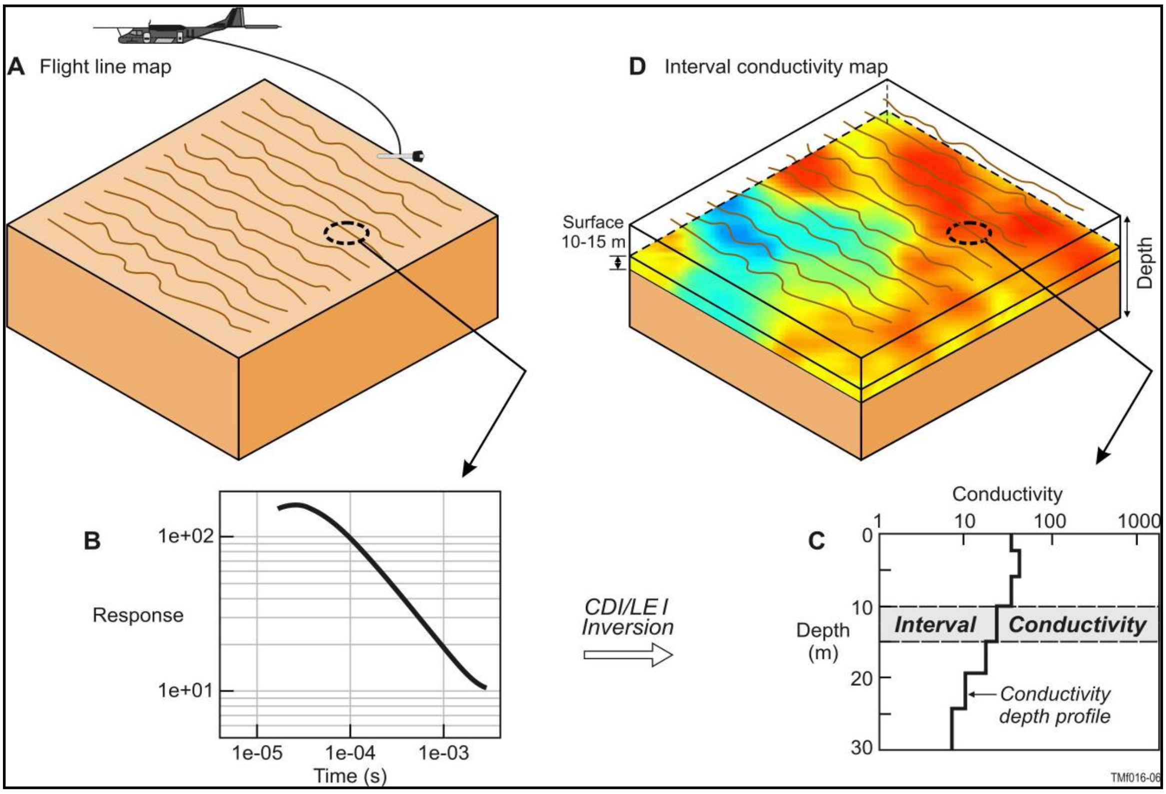


Figure 2.3 This figure shows the processes involved from data collection to generation of conductivity images. (A) AEM survey along flight lines. Electromagnetic data from each fiducial point (B) is processed using specific inversion technique to derive the conductivity depth model. (D) Generation of interval conductivity map from inversion model. From Lane (2002; Munday, 2008).

The benefits from AEM surveys are maximised when these technologies are employed within multi-disciplinary, systems-based approaches to the analysis of problems and the development of customised interpretation products (Lawrie et al., 2000; Lawrie et al., 2003a, b; Spies & Woodgate, 2005). Systems-based approaches incorporate an understanding of landscape evolution and scale, utilise modern investigative approaches to the conceptualisation of aquifer systems, and incorporates data on water, salinity and vegetation dynamics to provide key constraints on aquifer systems (Lawrie et al., 2000, 2008, 2009a).

Over the past 5 years, a staged approach to survey design combined with forward modelling studies have ensured that appropriate AEM technologies are selected to match the target objectives (Green & Munday, 2004; Lawrie, 2006; Munday et al., 2007, 2008d; Lawrie et al., 2009a, b). In Australian landscape settings AEM-based products are particularly effective at providing high resolution baseline data on the spatial distribution of aquifers and aquitards as well as water quality and salt stores in shallow (<120 m) floodplain sediments (Mullen et al., 2007; Tan et al., 2005; Munday et al., 2006, 2007; Lawrie et al., 2009a). However, while these datasets and information products address specific gaps in the biophysical knowledge framework, addressing salinity and land management questions usually requires an understanding of underlying biophysical processes and dynamics that generally cannot be determined from analysis of spatial patters of conductivity alone (Cresswell et al., 2007).

While increasing sophistication of AEM-derived products (e.g. porosity-corrected lithology products, maps of salt load, salt hazard etc; Tan et al., 2009) has improved their utility and up-take by land managers, much of the success of AEM surveys in the past 5 years has come from demonstration of relevance through incorporation of AEM-derived products in regional planning and decision support tools and in groundwater modelling frameworks (Chamberlain & Wilkinson, 2004; Walker et al., 2004). The high resolution (in 2D and 3D) afforded by AEM datasets enables key elements of the hydrogeological system to be mapped and characterised with greater certainty. This has contributed to improved parameterisation of models, and enables more reliable quantitative assessments to be made of the uncertainties and confidence levels in model predictions. It is the adoption of these multi-disciplinary, multi-scale system approaches that underpin the development of more effective salinity and groundwater management strategies, and enable more targeted salinity management actions (Lawrie, 2008; Lawrie et al., 2009a).

George et al., (2003) emphasised the need to match the appropriate technology to the groundwater salinity management issues to be addressed, and articulated a phased methodology to achieve successful management outcomes using airborne geophysics. To date, a large variety of modelling approaches have incorporated AEM-derived products, reflecting the diversity of salinity management questions tackled. The approaches vary from GIS-based modelling platforms to fully distributed groundwater flow models. For example, building on the availability of a number of AEM surveys that have been conducted along the River Murray, modelling studies include: the impacts of broad-scale land use planning including land clearing along the River Murray (RCSM: Walker et al., 2005; Doble et al., 2005, 2008); salt loads in the Murray River (SIMPACT; Wang et al., 2005); the links between groundwater processes, evapo-transpiration and vegetation health (WINDS; Munday et al., 2008c); leakage from salinity disposal basins (Munday et al., 2008), and the potential impacts of flooding and environmental watering in the River Murray Corridor using fully distributed finite difference (MODFLOW) groundwater models (Richardson et al., 2007; Yan & Howe, 2008; H. Middlemass, pers. com. 2008).

In particular, new insights into the lateral and vertical connectivity of the aquifer systems are required to assist with groundwater management. Similarly, new insights into distribution of sand and gravel aquifers in 3D are required to better understand the extent of surface-groundwater interactions, and to identify preferential recharge and infrastructure leakage in the landscape. These are essential to improve the management of surface water, groundwater, salinity, and broader environmental management. To constrain the hydrogeological models it is necessary to better map water quality (salinity), aquifer boundaries, and elements of the sedimentary system, particularly the upper and lower gravels and their connectivity, as groundwater flow is highest through these units. Gaining a better understanding of where the potential increased evaporation and or discharge zones occur is also desirable. Ultimately, it is necessary to construct an improved 3D map of the aquifer systems.

The power and long-term value of AEM-based datasets for groundwater management lies largely in providing stakeholders with a range of customised information products that help address specific groundwater and land management questions (George et al., 2003). This necessitates translating conductivity measurements to estimates of salinity extent, salt hazard and ‘loads’ and groundwater quality, and requires the differentiation of host lithologies and other hydraulic parameters (such as texture and porosity) acquired through drilling.

To address most questions other than those related simply to salinity extent, it is also necessary to relate these map-based products to an understanding of salinity dynamics and processes by carrying out hydrogeochemical studies and incorporating the AEM-derived products within hydrogeological and land use models (Walker et al., 2004; Cresswell et al., 2007).

2.4 Assessment Guidelines for Using AEM Systems For Groundwater System Mapping

Previous AEM-based studies (Lawrie, 2008; Lawrie et al., 2010, 2011), have concluded that a phased or staged approach should be employed for future AEM-based hydrogeological investigations, including the mapping of SWI and/or carbonate-karstic groundwater systems. Integrated assessments should be phased, and include:

- Collation and review of existing information for the purpose of identifying critical knowledge gaps.
- Scoping and technical risk evaluation to assess the methods and technologies best suited to addressing identified knowledge gaps (Lawrie, 2006; Lawrie et al., 2009, 2010a).
- A comparative system resolution analysis should be carried out to determine the optimal AEM system for particular survey aims (Christensen & Lawrie, 2012). The resolution of an AEM system depends critically on the achievable signal-to-noise ratio, and this must be factored in to any technical assessment.
- An assessment of the scale of the groundwater systems and key elements to be mapped to ascertain the area to be flown and the appropriate flight-line spacing (Lawrie et al., 2003a, b; Munday, 2010).
- Integrated geoscientific studies to enable key elements of the hydrogeological system to be mapped, and groundwater flow and hydrogeochemical processes to be understood.
- Data synthesis and interpretation using contemporary ‘systems’ approaches (Lawrie et al., 2000; Lane et al., 2004a, b; Spies & Woodgate, 2005; Lawrie et al., 2008, 2010a, 2012), with an emphasis on delivering products that address specific issues and assist with the improved parameterisation of hydrogeological models.
- Groundwater, surface-groundwater modelling and land use modelling to ascertain the sustainability of proposed developments. Modelling should utilise the best available climate data and modelling scenarios.

In considering AEM technology suitability for a particular mapping task, a range of parameters and their influence on the modelled ground response should be considered in comprehensive modelling study (Lawrie et al., 2010a; Christensen & Lawrie, 2012). Such approaches include inversion analysis that is capable of comparing systems.

It has become common practice to quantify the system resolution for a series of models relevant to the survey area by comparing the sum over the data of squares of noise-normalised derivatives. However, a resolution analysis based on the posterior covariance matrix of an inversion formulation must be preferred because it takes parameter coupling into account. The comparative analysis depends critically on the noise model of the compared systems, and can preferably be supplemented with inversion of both theoretical data and field data. However, it is often not apparent how the noise levels supplied by contractors are derived, as data processing methods are proprietary, as are is the modelling of the system response. While there are excellent inversion analysis methods available, we may never know if the comparative analysis is performed on a reasonable basis. However, it is suggested that a pragmatic way forward may include:

- Theoretical analysis based on noise figures that have been deemed reasonable by the analyst.
- Test lines of field data for all systems in a range of hydrogeological settings.

- Comparison of the contractors' own inversion of their test line data.
- Inversion with a GOOD inversion program of all data sets for comparison.

The acquisition of AEM data for SWI and carbonate-karstic groundwater system mapping should only be considered within the context of the broader, integrated, hydrogeological assessment of an area (Lawrie et al., 2010a; 2012). Technical risk evaluation is required to gauge the merits of employing different geophysical approaches and technologies. Specifically:

- Acquisition of AEM data should only proceed after completion of scoping studies to assess the likelihood of success arising from their acquisition.
- Scoping studies are required to identify target aquifers and groundwater systems, and the scale, depth and orientation of target objectives (where possible). This should be followed by completion of a technology suitability assessment in each area. Technology selection should include forward modelling of system responses, and should follow the best practice procedures developed by the Commonwealth, taking particular note of the ability of AEM systems to map key elements of relevant elements of the hydrogeological system.
- AEM data analysis and interpretation should follow a 'hydrogeological systems' approach based on the methodology recommended by the Joint Academies of Science Review of Salinity Mapping Methods in the Australian Landscape Context (Spies & Woodgate, 2005). Based on these recommendations, AEM-based projects need to incorporate a drilling program, complementary ground investigations and hydrogeochemical studies to ensure appropriate survey calibration, validation and interpretation.

Future AEM surveys should also carefully consider the merits of using calibrated AEM systems and inversion software that can significantly shorten data acquisition and delivery timeframes (Christensen, 2008; Lawrie et al., 2010a, 2012). These technologies and methods can significantly shorten overall project timeframes and potential costs.

The choice of an appropriate AEM system for a given task should be based on a comparative analysis of candidate systems, consisting of both theoretical considerations and field studies including test lines. In the first instance, an initial assessment needs to be made of whether an AEM survey is the most suitable approach for investigating a groundwater issue.

3 Review of Existing Studies that Utilize AEM to Map Seawater Intrusion

AEM data can be particularly useful in helping to map the distribution and extent of seawater intrusion (SWI) in near-coastal aquifers due to the elevated sub-surface conductivity contrasts that exist between saline and fresh groundwater. Internationally, SWI investigations using AEM data cover a wide range of geological settings, including the Everglades in USA (Fitterman & Deszcz-Pan, 1998), Aceh in Indonesia (Siemon & Steuer, 2011), Mexico (Supper et al., 2009) and the Galapagos Islands (D'Ozouville et al., 2008). Prior to this study AEM has been used to map SWI in Coffin Bay, South Australia (Munday et al., 2007; Auken et al., 2009a; Ward et al., 2009; Fitzpatrick et al., 2009), Robe River in the Pilbara (Munday et al., 2010), and in the Northern Territory Coastal Plain (Tan et al., 2012).

This section provides selected case studies to illustrate the way that AEM surveying can be used to detect and map zones of saline groundwater or seawater intrusion, and improve the overall understanding of the hazards posed by SWI. The examples included here cover SWI in diverse near-coastal aquifers including alluvial sediments, fractured rock and karstic systems.

3.1 Everglades, Florida, USA

The Everglades National Park (NP) stretches from the south shore of Lake Okeechobee to Florida Bay, a distance of 170 km. The groundwater system has been impacted by canals, levees and roads. The hydrogeology underlying the Everglades NP consists of highly permeable karst aquifers known as the Biscayne Aquifer system including the overlying Miami Oolite (Fish & Stewart, 1991). This unconfined aquifer merges with the floor of the Biscayne Bay and is susceptible to rapid seawater intrusion due to over-extraction. The Biscayne Aquifer system is a primary source of fresh water for most of South Florida.

To rapidly cover large areas of the Florida Everglades where ground access is often very difficult, an AEM survey was deployed (Figure 3.1). A measurement was made every 10 to 15 m along flight lines that were typically spaced 400 m apart. The high sampling density provides a detailed picture of aquifer resistivity that is not readily available by other means. The extent of saltwater intrusion can be interpreted from conductivity models (Figure 3.2, Figure 3.3).

A DIGHEM[v] Helicopter EM survey was conducted for the purpose of mapping saltwater intrusion into the Biscayne Aquifer (Fitterman & Deszcz-Pan, 1998). The study concluded that coastal seawater/freshwater interface could be effectively mapped using the Helicopter EM (HEM) system as well as the imprint of anthropogenic activity. The depth slices clearly indicate both natural and anthropogenic features which could be used as a basis for constructing hydrologic models (Fitterman & Deszcz-Pan, 1998).

The technique worked well in the Everglades region which has sub-horizontally layered rock types and minimal clay. However, similar surveys could be of use in many coastal aquifers, even where the geology is more complicated, because of the tendency of saltwater intrusion to overprint geologic boundaries and to dominate the electromagnetic response. (Fitterman & Deszcz-Pan, 1998).

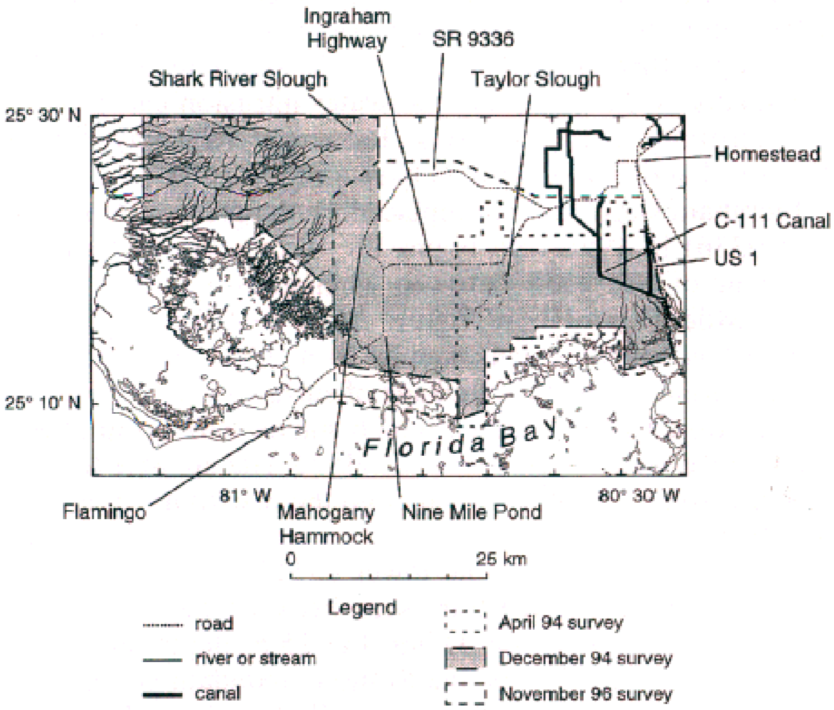


Figure 3.1 Location map of the Florida Everglades showing the HEM survey area.

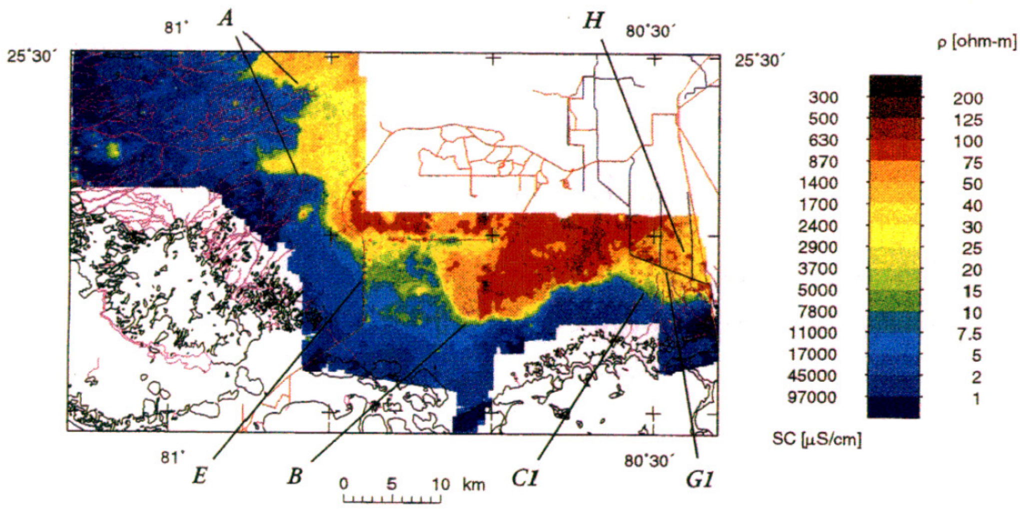


Figure 3.2 Map of 1m resistivity depth slice for Florida Everglades HEM survey.

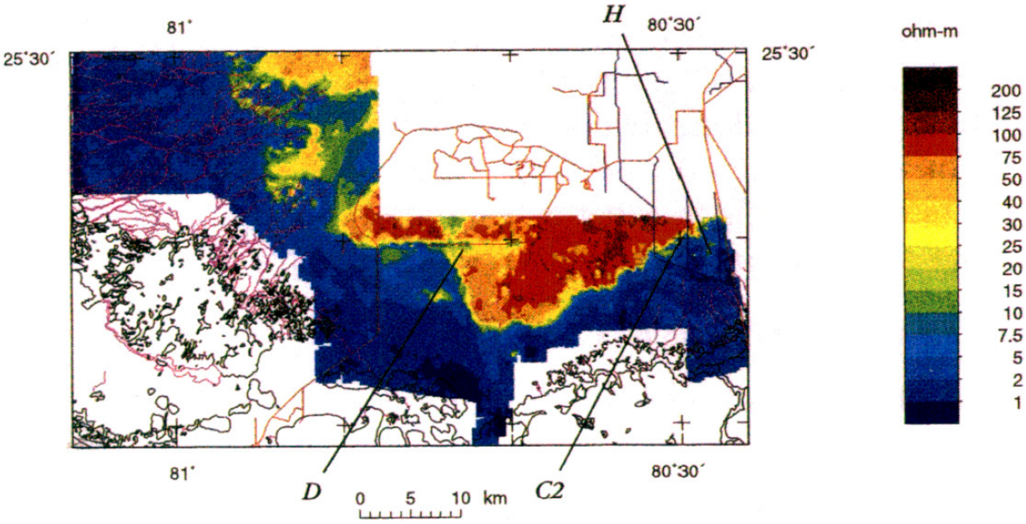


Figure 3.3 Map of a 30 m resistivity depth slice for Florida Everglades HEM survey.

3.2 Aceh, Indonesia

The December 26th, 2004 earthquake and tsunami event introduced the large scale intrusion of saltwater along the coastal regions of the Province of Nanggroe Aceh Darussalam in northern Sumatra. The supply of sufficient potable water was limited as a result of the earthquake damaging infrastructure and the tsunami destroying shallow water wells. A fast overview of remaining freshwater resources was required with the German Federal Institute for Geosciences and Natural Resources (BGR) conducting airborne geophysical surveys in the joint Indonesia-German HELP-ACEH project. The BGR system employed the Fugro RESOLVE© helicopter based AEM system (Figure 3.4).

The HELP-ACEH project covered three localities along the northern Sumatran coast. The primary site of evaluation for this study was the alluvium along the coast of Banda Aceh. This aquifer is the main productive unit for the region. The top 20 m of the alluvium is considered a traditional source of domestic water supply, consisting of sandy clays and sands to gravels which are recharged directly from rainfall (Siemon & Steuer, 2011).

On the north coast (survey area Banda Aceh) shallow salt water was found in a broad strip (about 3 km) whereas deep salt water occurred at around 30 m depth up to more than 10 km inland. On top of these deep salt-water occurrences potential freshwater lenses were mapped in an area 5-10 km from the coast (see Figure 3.5, Figure 3.6) and in the palaeoriver bed of the Krueng Aceh. The salt-water occurrences along the west coast (survey area Calang-Meulaboh) were mostly restricted to a small strip close to the shore line or some river valleys flooded by the tsunami, and thus, shallow freshwater occurrences could be expected in the entire survey area. (Siemon & Steuer, 2011).

On the north-east coast (survey area Sigli) seawater intrusion appeared to be not strengthened by the tsunami event (Siemon & Steuer, 2011) (Figure 3.7, Figure 3.8). The reason for that may be that in the central part of the shoreline groundwater flow from the hinterland is supposed to strongly push back seawater even to off-shore areas. A major potential freshwater occurrence was located beneath the central Sigli plain from the hilly hinterland down to the coast.

In summary, the AEM data indicated the salinisation of shallow groundwater in the region of Banda Aceh for several kilometres inland. This salinisation was still apparent in the AEM data nine months after the tsunami event (Siemon & Steuer, 2011). This is in comparison to other survey sites in the project which showed less impact from the tsunami inundation. A significant outcome of the HELP-ACEH project was better delineation of remaining freshwater resources to assist aid organisations with the targeting of water wells (Siemon & Steuer, 2011).

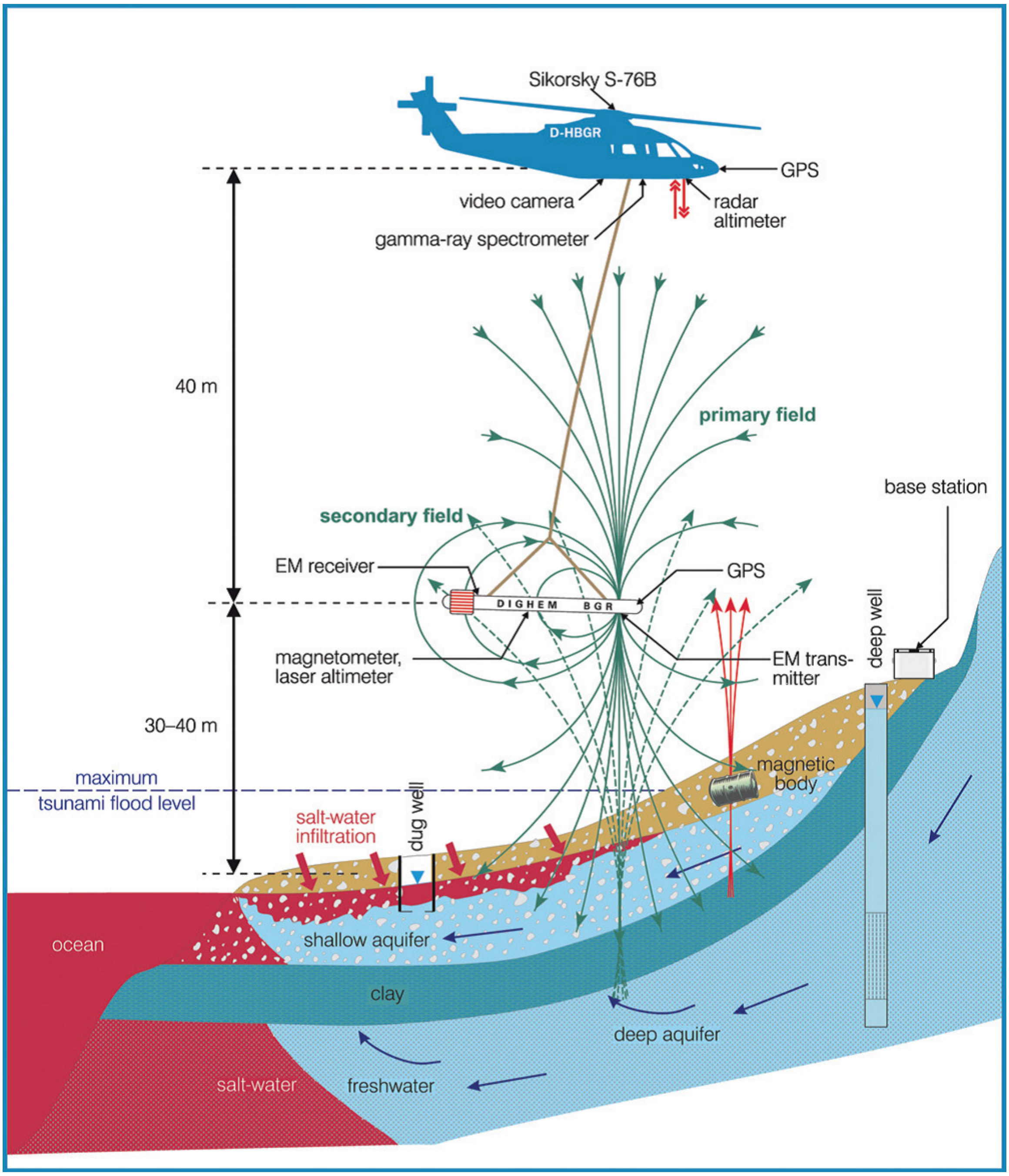


Figure 3.4 Sketch of the BGR helicopter-borne geophysical system and the hydrogeological situation expected along the coasts of northern Sumatra.

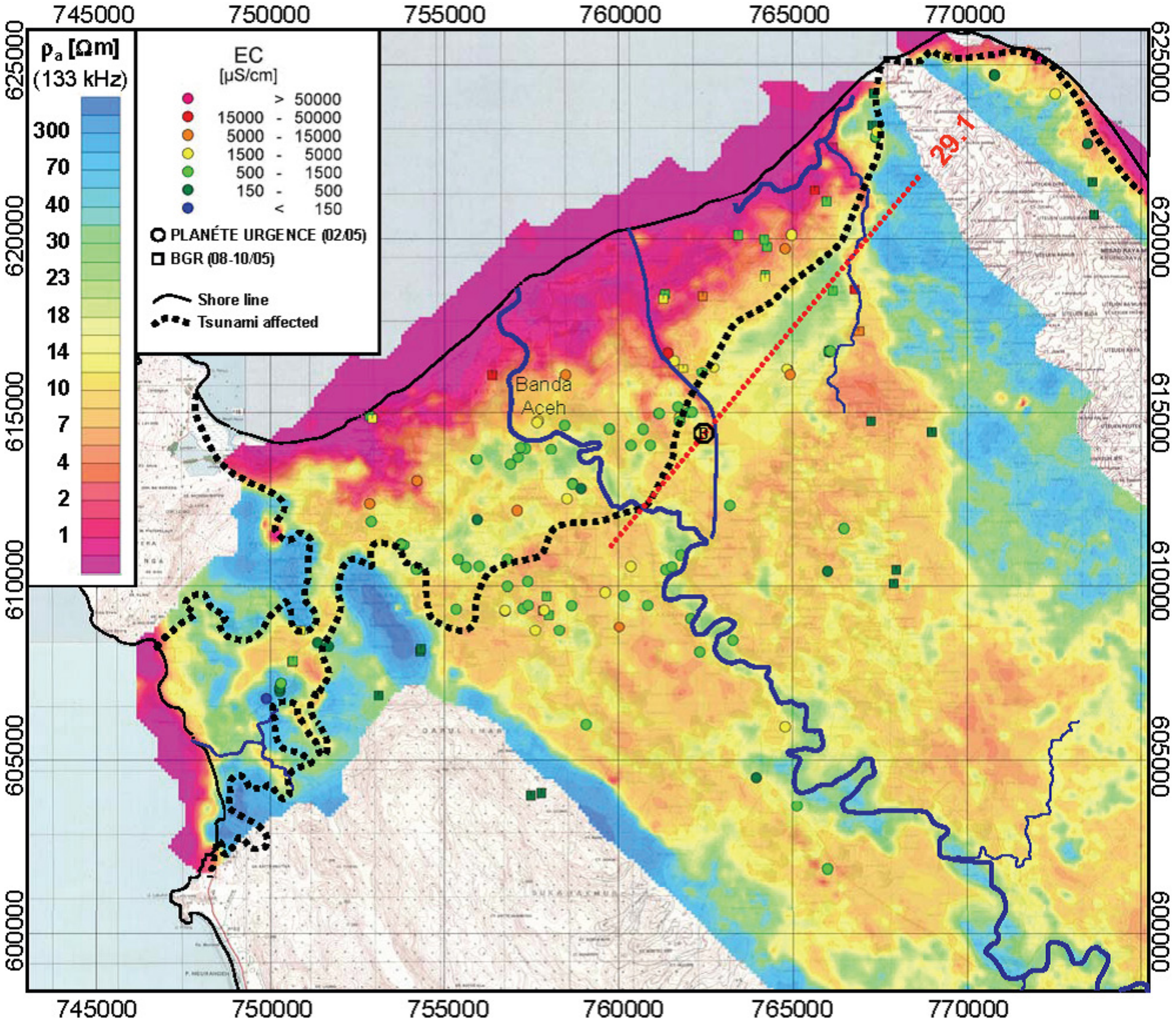


Figure 3.5 Apparent resistivity at a frequency of 133 kHz revealing the lithology and the salinisation of the shallow groundwater in the northern part of the Banda Aceh survey area. Water conductivity samples (coloured dots and squares), maximum extent of the tsunami flooding (dashed black line) and main rivers (blue lines) are plotted on top.

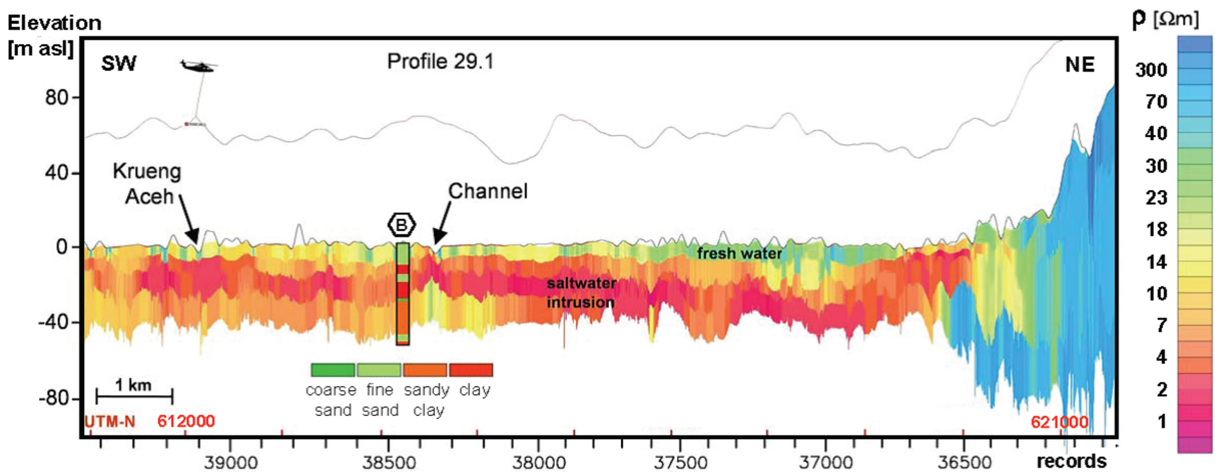


Figure 3.6 Resistivity section along a profile 29.1 (cf.Figure 3.5) showing a freshwater lens on top of salt-water saturated sediments; simplified lithology of a borehole (B) is plotted on top.

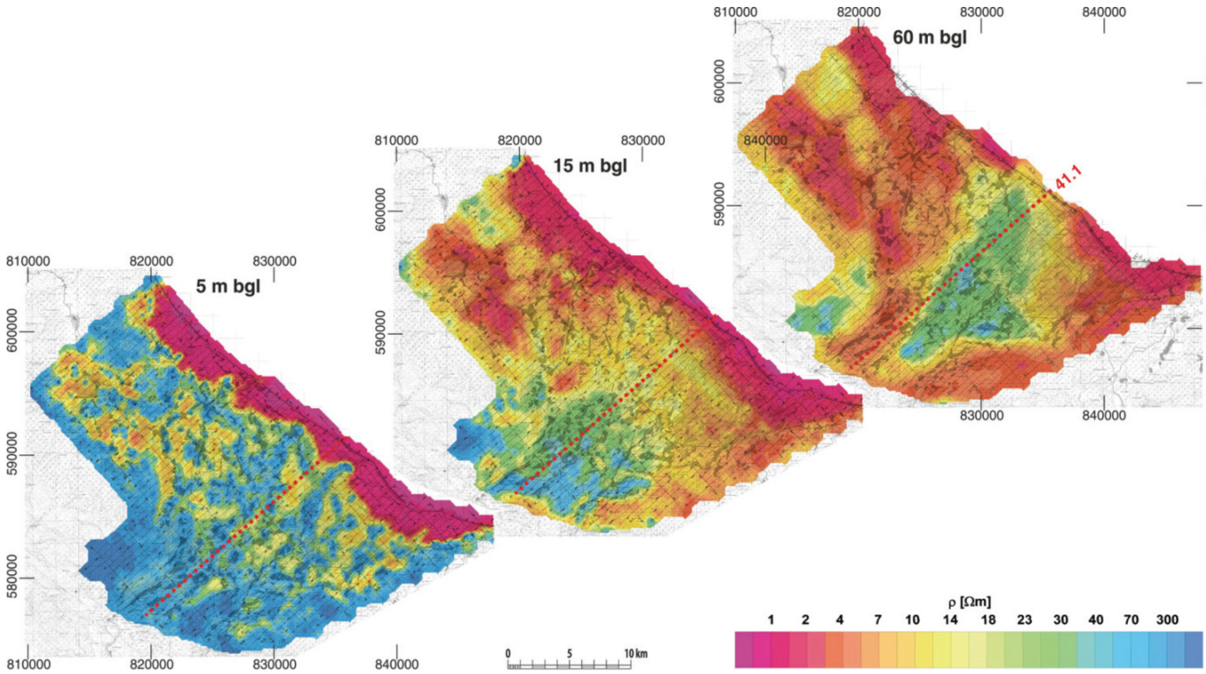


Figure 3.7 Resistivity maps at selected depth levels of 5, 15 and 60 m mbgl derived from HEM 1D inversion models. Additionally flight line 41.1 (cf.Figure 3.7) is indicated by red dots. Background: TMI (1978).

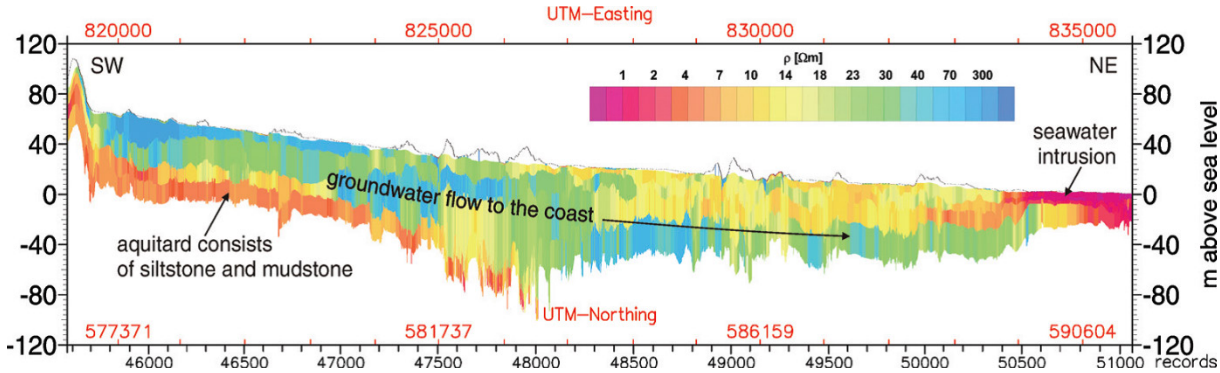


Figure 3.8. The vertical resistivity section along profile 41.1 (cf. Figure 3.7) crossing the central part of the plain indicates a strong groundwater flow to the coast.

3.3 Galápagos Islands, Ecuador

D'Ozouville et al*.,* (2008) highlighted the stresses placed on water resources as a result of increasing human habitation of the island of Santa Cruz in the Galápagos Archipelago. This island was previously thought to have limited fresh water supply, but the use of AEM identified a new perched aquifer system.

There is limited information available regarding the geology and hydrogeology for the volcanic island due to its listing as an Endangered World Heritage area. Only one bore exists on the island at 5 km inland, which shows a repetitive series of basalt lava flows (Auken et al*.,* 2009b). There are no perennial creeks and the groundwater potential prior to the AEM survey was limited to a tidally influenced brackish basal aquifer (d'Ozouville et al*.,* 2008). A concentric loop airborne EM (SkyTEM) device was flown over Santa Cruz Island, acquiring non-invasive measurements over inaccessible terrain. The method is sensitive to low-resistivity layers of hydrogeological interest [50-200 ohm-m] to a depth of approximately 300 m.

The SkyTEM system allowed for the non-invasive investigation of hydrogeological features of Santa Cruz. The system identified regions of the island that are potentially weathered zones or fractured basalts saturated with freshwater. The system has also mapped a surrounding seawater intrusion wedge that sits below the island as a result of lateral seawater flowing through fractured basalts below the basal aquifer (d'Ozouville et al*.,* 2008; Figure 3.9, Figure 3.10).

The low resistivity Unit II (b10 Ωm shown as dark blue) is located near sea level on all sides of the volcano (Figure 3.9). It represents the salt-water wedge beneath the island, formed by lateral seawater intrusion into the fractured basalts below the basal aquifer. The unit slopes inland from the coast on the eastern and southern sides and is no longer detected when its distance from the ground surface exceeds the maximum penetration depth of the SkyTEM system (300 m) approximately 9 km inland. This shows how the highly fractured nature of the basalts allows continuous seawater intrusion and gives an unprecedented view of the geometry of the salt-water wedge beneath an island. The inverse hydraulic gradient of 0.004 at the top of the saltwater wedge on the southern side of the volcano (Figure 3.9) is consistent with the known presence of a thin fresh-water lens on top of the salt-water. It is in close agreement with the Ghyben-Herzberg formula stating that the salt-water/fresh-water interface is located at a depth below sea level of forty times the elevation of the head above sea level. This result allows an extrapolation of this water lens to the whole island, whereas previously water levels were only known where they had been measured, i.e. in the bore well and in coastal fractures connected to the sea (d'Ozouville et al*.,* 2008).

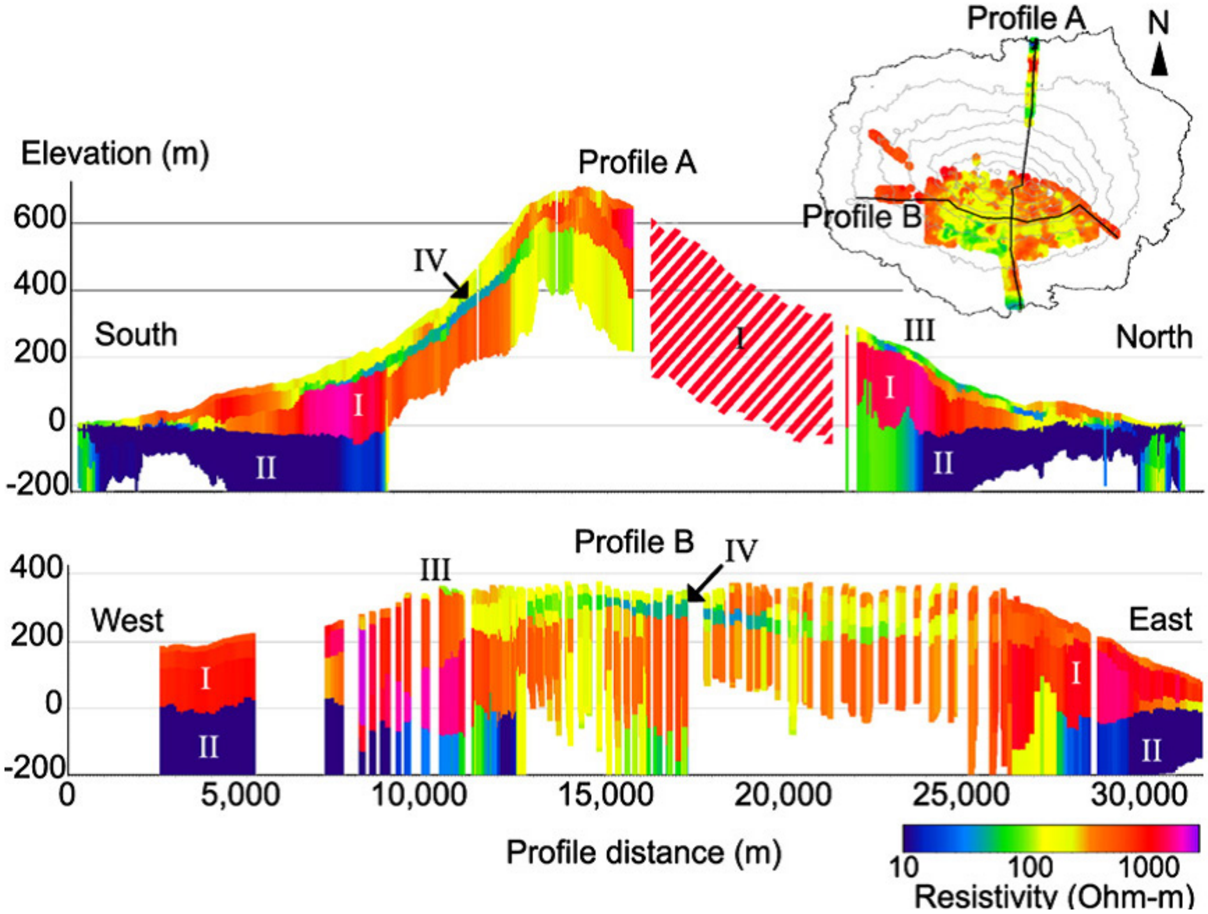


Figure 3.9. Two cross-sections reveal the internal structure of Santa Cruz Island and four units of hydrogeological interest. The positions of the south-north and west-east profiles across the island are shown on the inset over a background of near-surface average resistivity showing extent of mapped area. The profiles show the density of data generated and the penetration depth of between 200 and 300 m. The four units of hydrogeological interest are: (I) High-resistivity unsaturated basalts; (II) Seawater intrusion wedge underlying the brackish basal aquifer; (III) Near-surface, low-resistivity units consisting of colluvial deposits; (IV) Internal, low-resistivity unit of saturated basalts overlying an impermeable stratum.

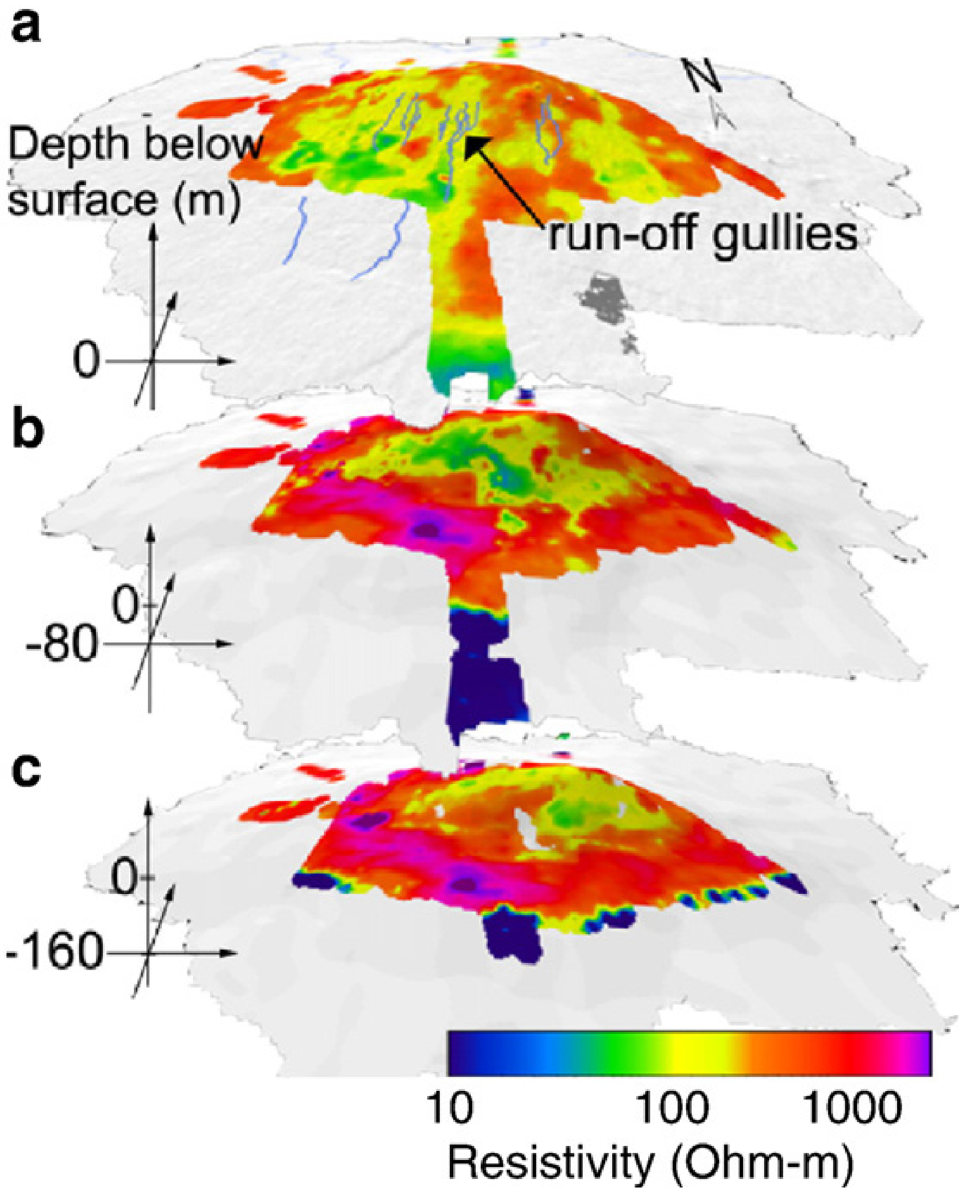


Figure 3.10. Three-dimensional visualization of the internal resistivity structure of Santa Cruz Island. a) 0-20m near-surface average resistivity map draped over the surface topography shows the coincidence of low-resistivity zones with run-off gullies. b) 80-100 m below surface average resistivity map shows the extent of the internal low-resistivity unit on the windward side of the volcano, surrounded by unsaturated basalts; the inland extent of the seawater wedge is clearly visible as the dark blue area. c) 160-180m below surface average resistivity map shows the disappearance of the low-resistivity unit to the east and the further inland extent of the seawater wedge.

3.4 Karstic Aquifers, Tulum, Yucatan, Mexico

The Yucatán Peninsula (YP) is an extensive limestone platform consisting of limestones, dolomites and evaporates, reaching 1500 m in thickness. Flow paths within the YP exist at a variety of scales from regional fracture zones (10-100s of kilometres) to dissolution conduits (1-10s of kilometres) down to small-scale fractures and cavities (10s of m) (Bauer-Gottwein et al*.,* 2011).

An AEM survey for spatially mapping submerged cave systems was conducted on the east coast of the YP in an area north of Sian Ka'an Reserve (Supper et al*.,* 2009). The results of a homogenous half-space inversion indicated good correlation with seawater intrusion along the karstic coast. The AEM survey also identified and delineated known cave systems mapped through conventional means as well as identifying previously unknown/unmapped cave systems.

A complex survey in the coastal karst system of Yucatan proved the capability of airborne electromagnetics to detect submerged karst systems (Figure 3.11). Although many features related to the caves system could be detected in the single phase components, inversion of the results only showed the main dominating karst structures. Therefore, further work has to be focused in refining inversion procedures in order to derive data for size and depth of the karst system. Moreover, field verification of results using ground geophysics, drillings and borehole geophysics is necessary to understand the source of the electric anomaly generated by a cave.

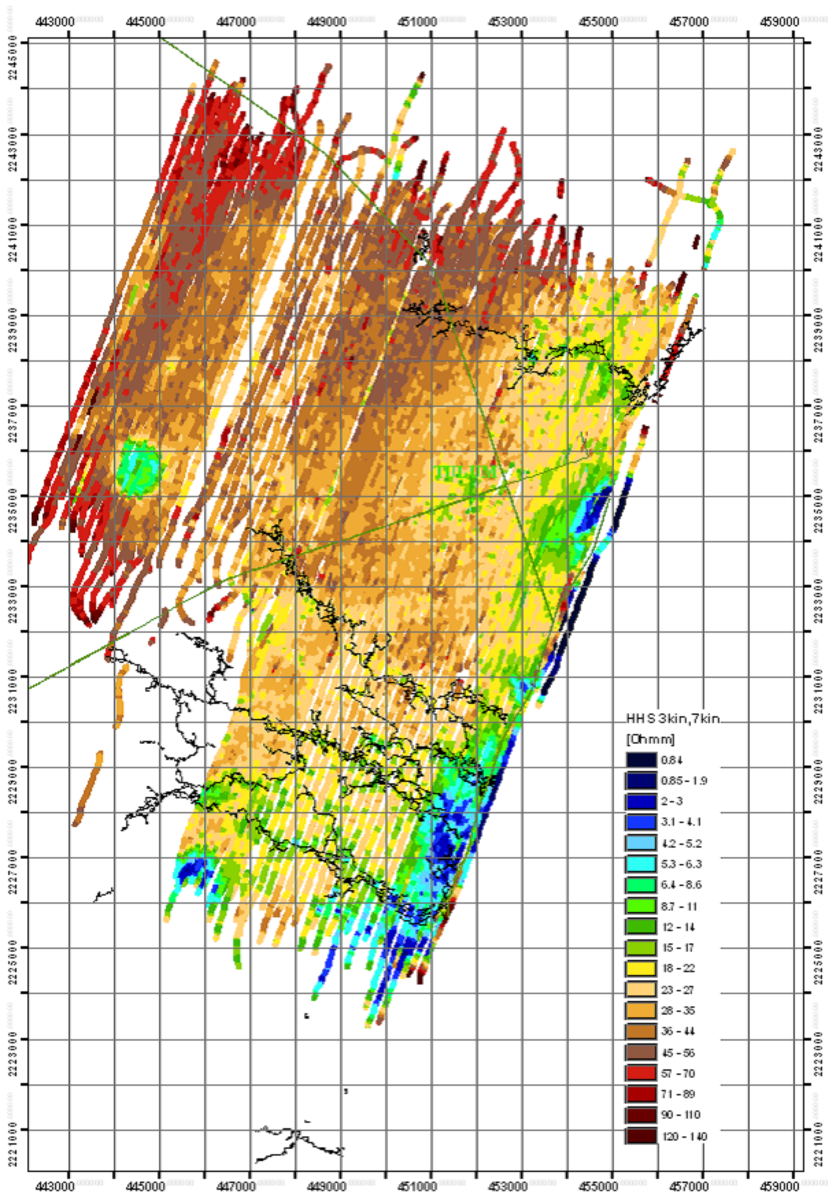


Figure 3.11. Resistivity depth slice for the Yucatan AEM survey.

3.5 Robe River, Pilbara, Western Australia

The Robe River drains part of the Hamersley region of Western Australia (Figure 3.12, Figure 3.13). The coastal zone is macrotidal, with a range of ±5 m. High tides reach ~ 4 km inland. A 2 km-spaced AEM survey (Munday, 2010) suggested that the salt-water interface occurs as much as 6 km inland, along an approximately vertical front (Figure 3.14). The geology hosting the saline water zone is extremely complex, consisting of fractured basement aquifers (fractured rock and minor intergranular aquifers) in flat-lying Cretaceous sediments, intergranular porosity aquifers in Cenozoic sediments, including the complexly ferruginised Robe Pisolite, and Quaternary fluvial and coastal sediments (Figure 3.15). Flush zones are associated with the present course of the Robe River (Figure 3.16).

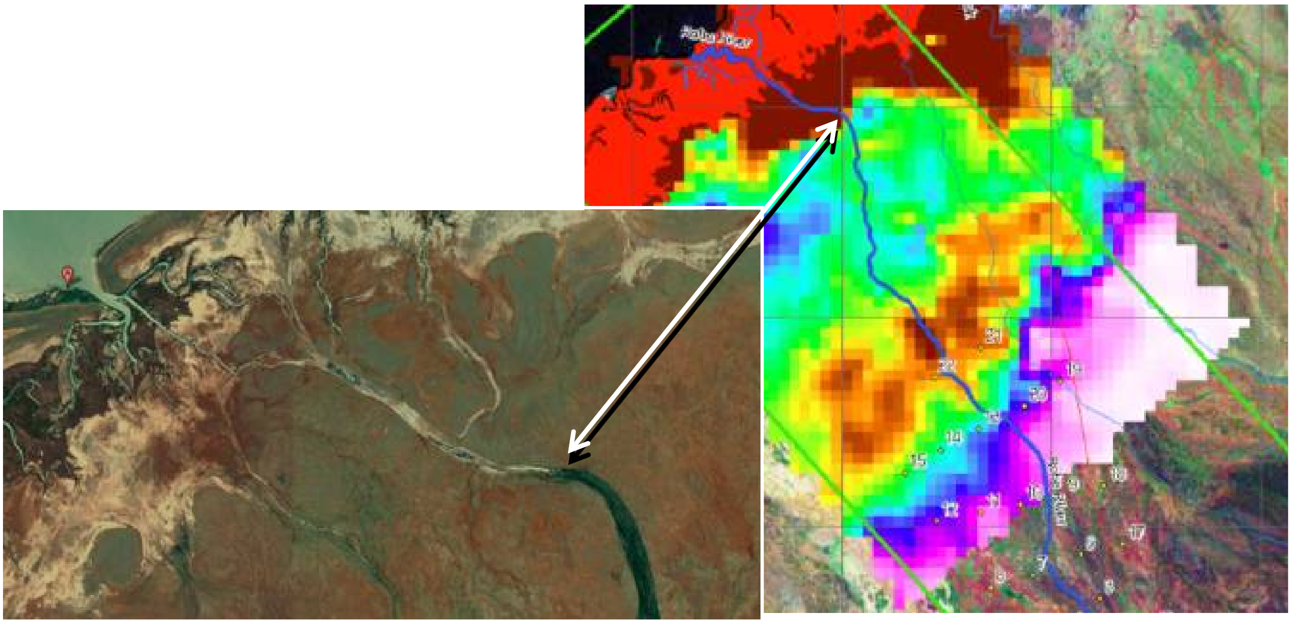


Figure 3.12. AEM survey for the Robe River. Top left: Landsat location map. Top right: sea water intrusion shown in red.

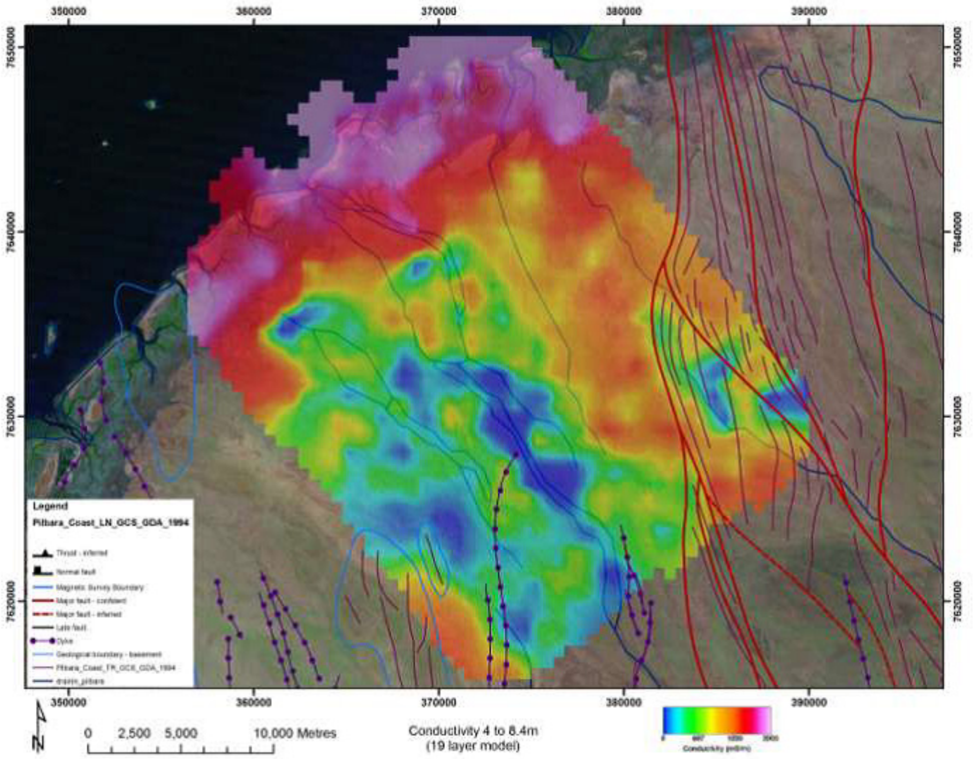


Figure 3.13. AEM survey for the Robe River. Conductivity depth slice for 4 to 8 m interval.

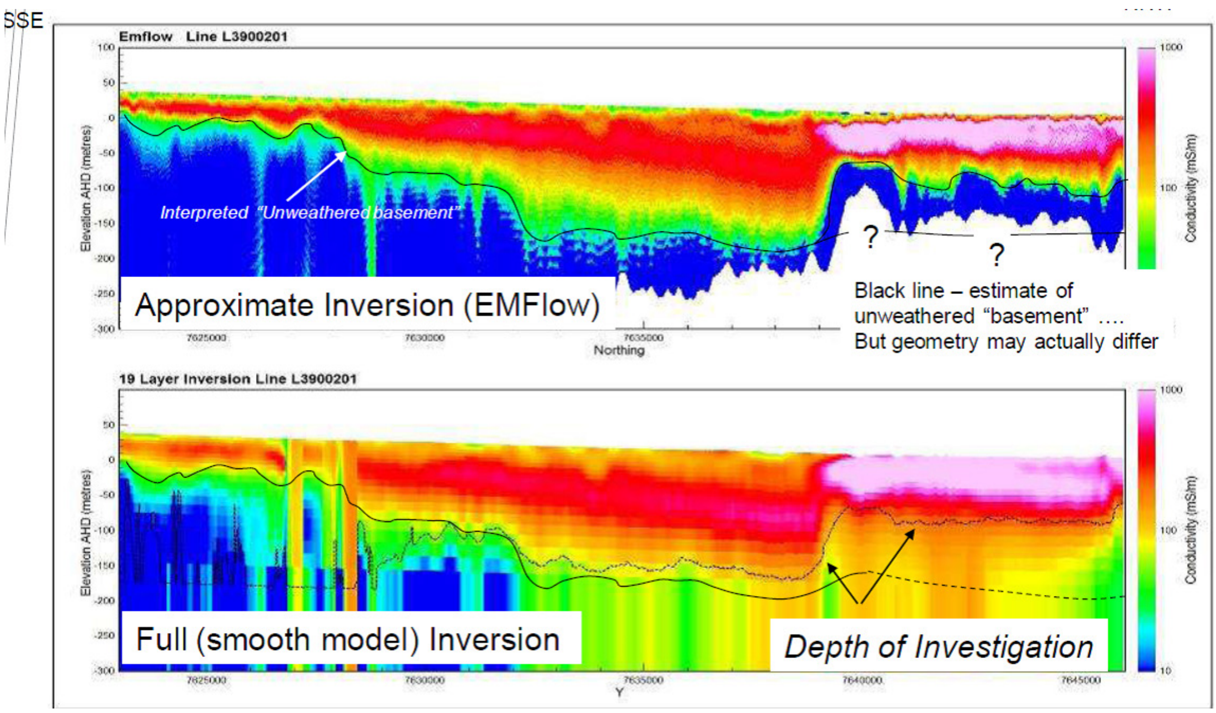


Figure 3.14. Conductivity depth section for the Robe River survey. The pink colour is SWI, with resistive basement (blue) and saline groundwater in alluvial aquifers in red-yellow.

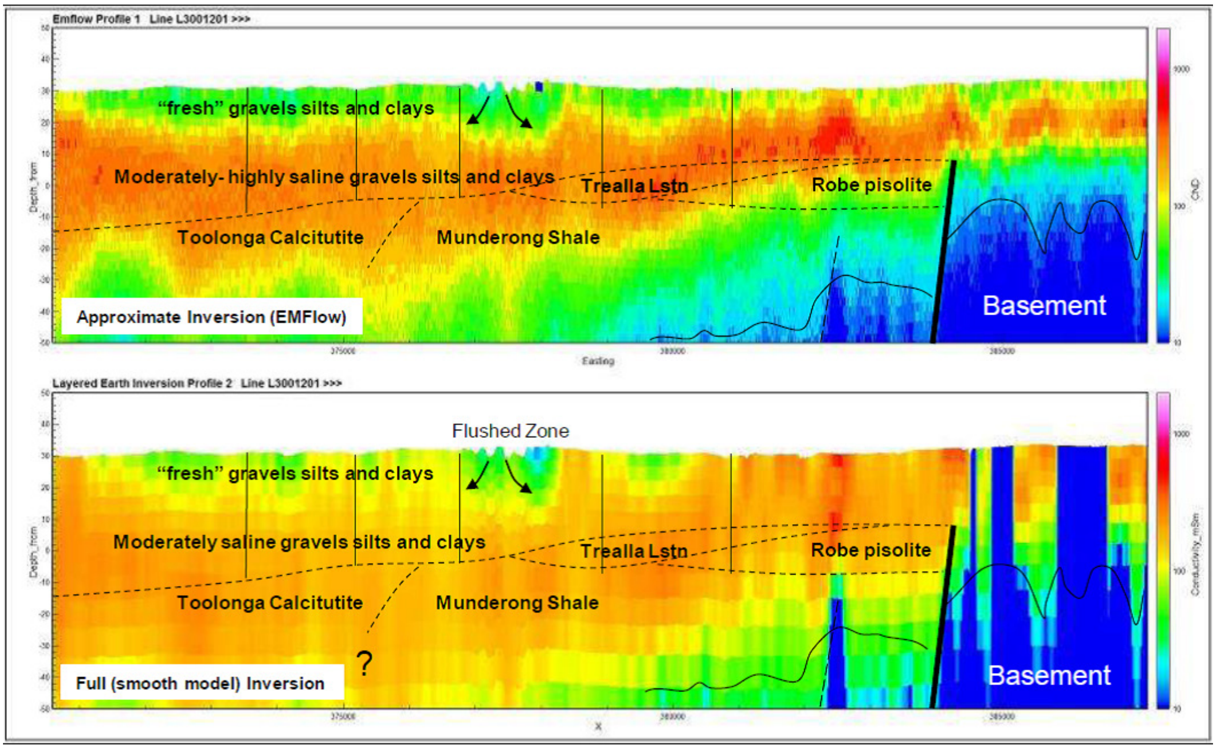


Figure 3.15. Conductivity depth section for the Robe River survey showing water quality aquifer lithological boundaries.

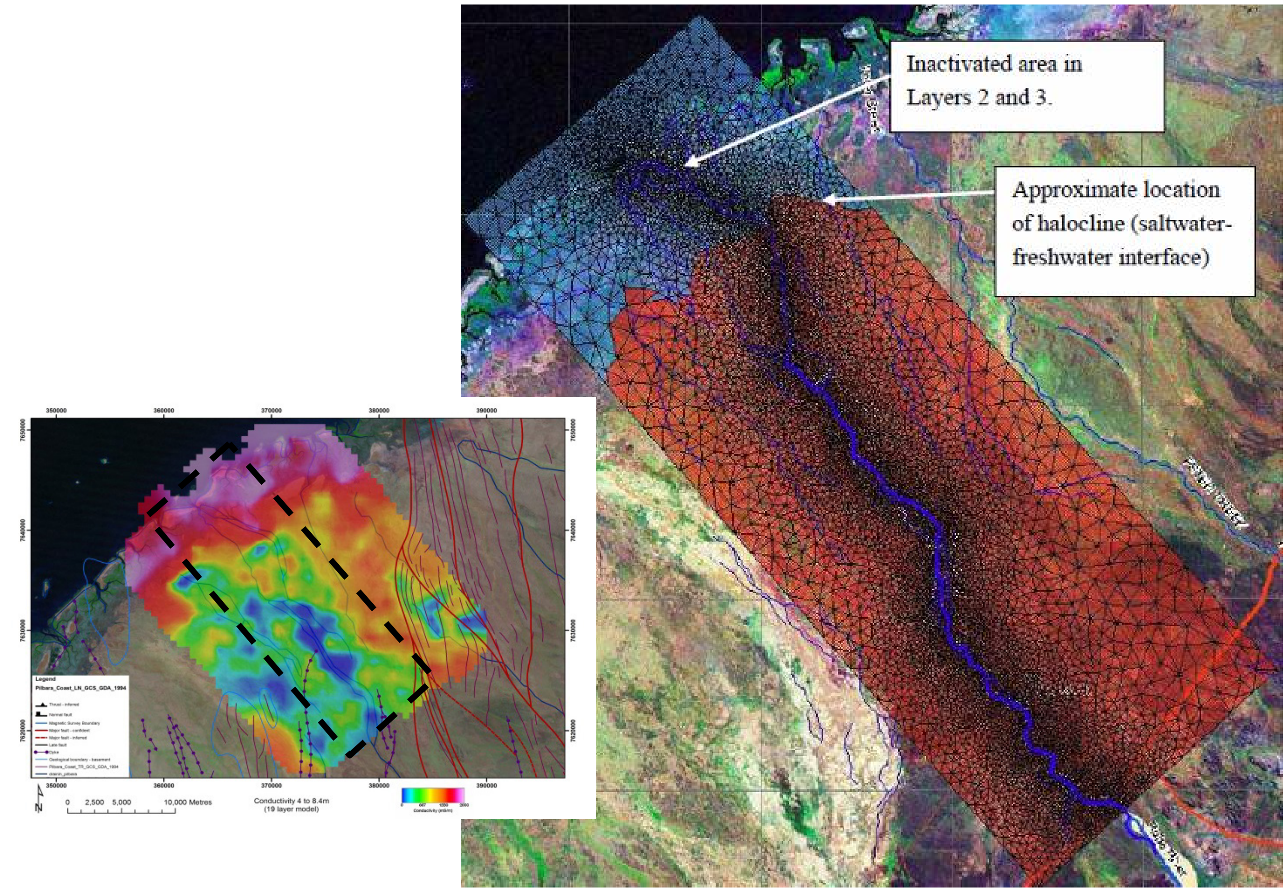


Figure 3.16. Robe River survey demonstrating use of AEM data within a calibrated groundwater model which is used to model saltwater-freshwater interface.

3.6 Coorong, Lakes Albert and Alexandrina, South Australia

The Coorong region of southeast South Australia is a complex set of coastal environments formed at the mouth of the Murray River. The environments include large estuarine lakes, artificially managed by barrages to be filled by fresh water (Lakes Albert and Alexandrina), a long coastal beach-dune barrier complex (Younghusband Peninsula) and a brackish to saline back barrier coastal lagoon (The Coorong), filled by mixed continental and marine waters (von der Borch 1965). The region is of considerable importance to indigenous culture, agriculture and as coastal habitat.

A single AEM flight line (Figure 3.17) was discussed by Munday (2010) and has delineated the hydrogeological features well, with the high conductivity sea water and Coorong lagoonal waters separated by the highly resistive sands of the Younghusband Peninsula (Figure 3.18). These contain a lens of fresh water floating above the saline zone. The saline water is further depressed beneath the fresher waters of Lakes Albert and Alexandrina and decrease in conductivity landwards as they become mixed with continental waters flowing seaward. Also visible on the landward size is the highly resistive zone associated with the Pleistocene dune systems with contained perched freshwater lenses.

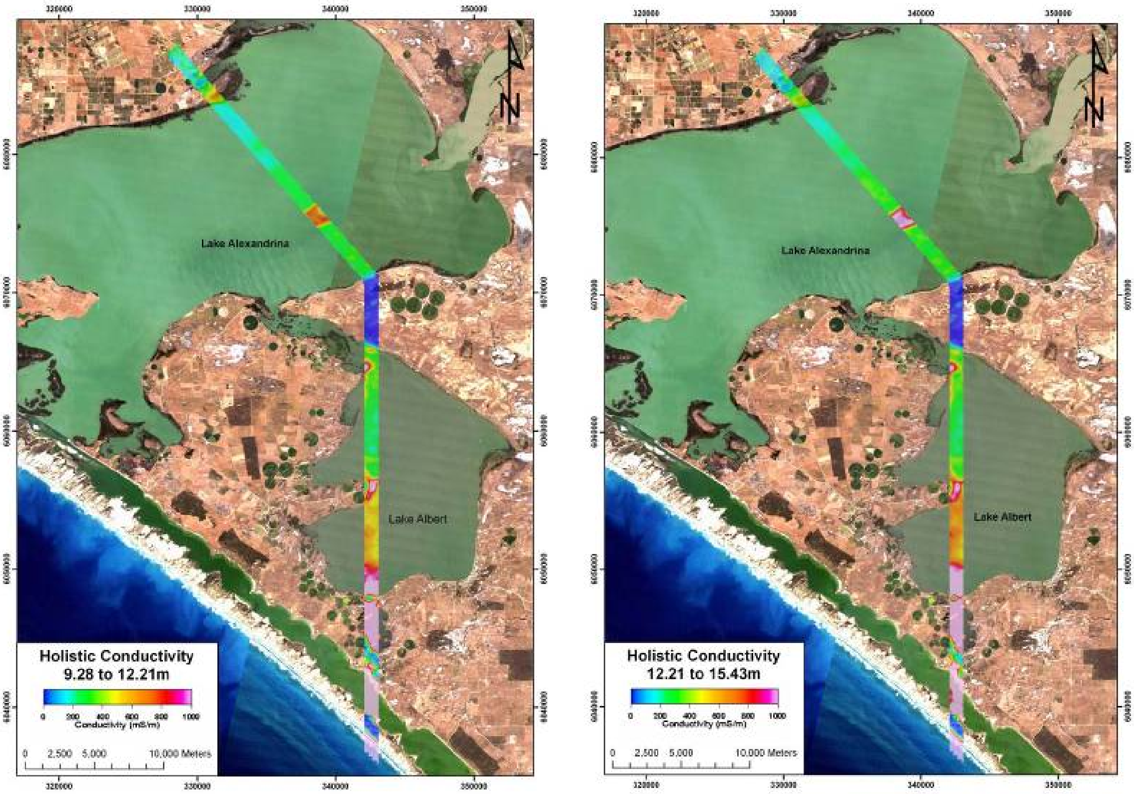


Figure 3.17. AEM map of Coorong and Lower Lakes showing conductivity in flight lines for the 9-12 m depth slice (left) and 12-15 m (right). Highly conductivity groundwater (sea water intrusion) shown in red.

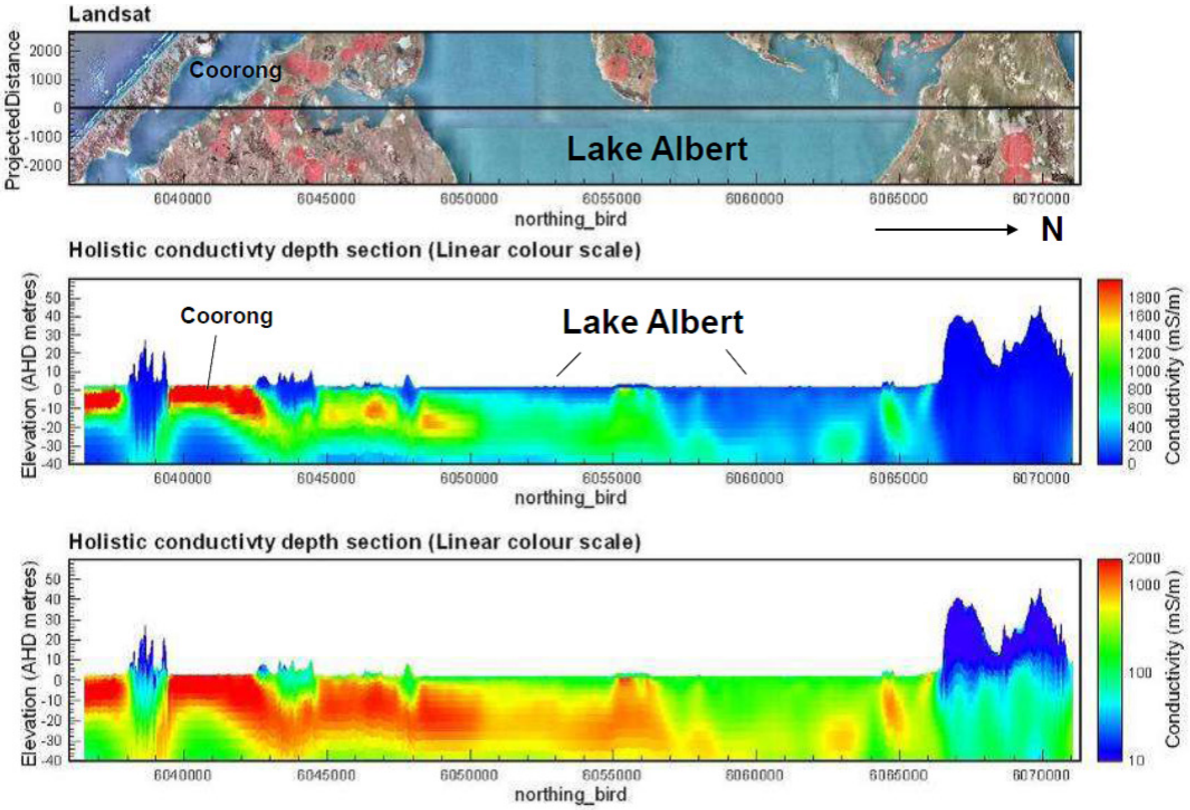


Figure 3.18. Conductivity depth sections for the Coorong and Lower Lakes. Highly conductivity groundwater (sea water intrusion) shown in red.

3.7 Coffin Bay/Uley South, Eyre Peninsula, South Australia

Uley South is located on the southern coastline of the Eyre Peninsula, South Australia, approximately 30 km west of Port Lincoln (Figure 3.19). Coffin Bay is situated north-west of Uley South and the Southern Basins Prescribed Well Areas GMU. Groundwater is the main source of potable water on the Eyre Peninsula and the South Australian Water Corporation (SA Water) is the largest user. Groundwater is used to provide domestic supplies to the town of Port Lincoln and other smaller communities, as well as for industrial and irrigated agriculture use.

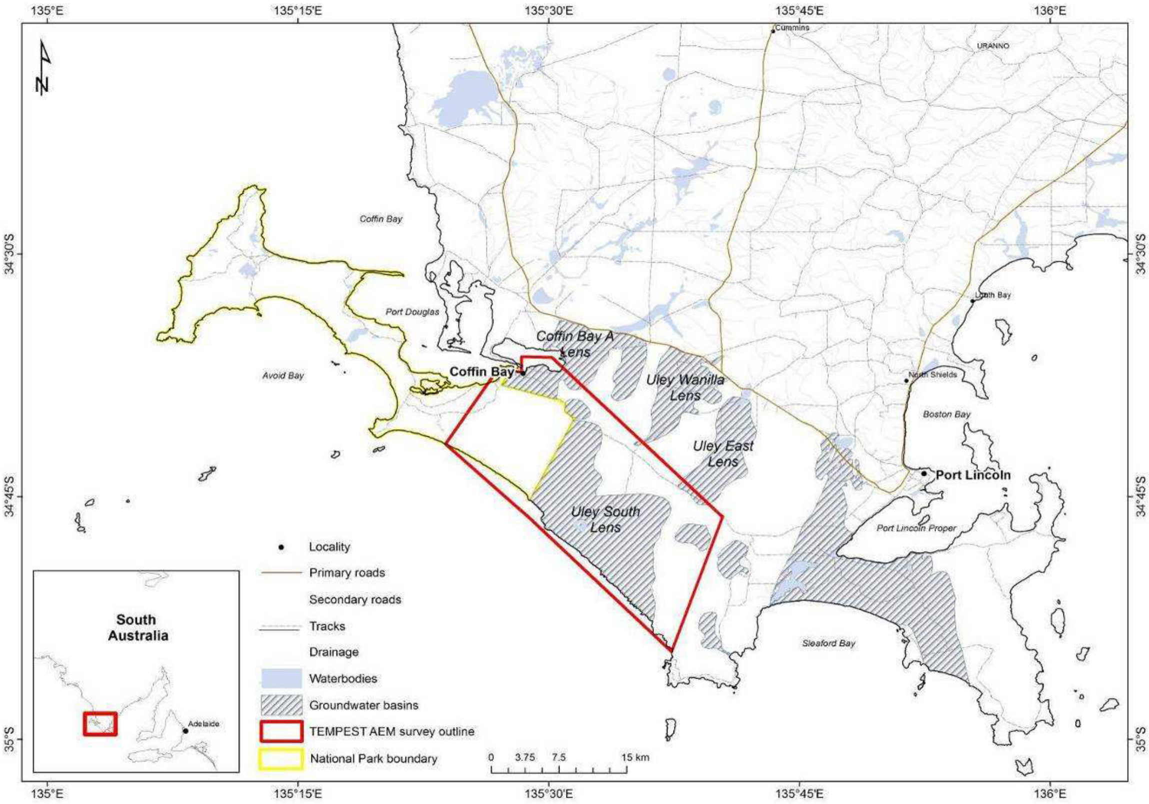


Figure 3.19. Map showing the location of the study area, and the known extent of the groundwater lens systems of the Southern Basins on the Eyre Peninsula. The area surveyed by the TEMPEST AEM system is also defined. (Data courtesy of SA Water and DWLBC). From Fitzpatrick et al, (2010).

Groundwater in the Uley Basin mainly occurs in three aquifers: the Quaternary Bridgewater Formation, the Paleogene Wanilla Formation and fractured volcano-metasedimentary basement rocks of the Gawler Craton (Figure 3.20). The Paleogene and Quaternary age sediments are the main source of low salinity groundwater. A number of groundwater basins, such as Uley South, occur within north–south trending palaeovalley depressions incised into the fractured basement rock sequences. These depressions have been filled by sands, clays and carbonaceous sediments, and generally have a basal sand-rich aquifer zone capped by an overlying clayey aquitard. However, the clay layer is discontinuous and there are areas of effective hydraulic connection between the Quaternary and Paleogene sandy sediments through the clay (Zulfic et al*.,* 2006).

The Tertiary sediments have been overlain by the Quaternary Bridgewater Formation. The karstic nature of this aquifer dramatically increases the amount of recharge available to the underlying aquifers during intense rainfall events and the volumes of recharge are much higher than would normally be expected. The underlying Tertiary Wanilla Sands Aquifer is mostly adjacent to the Southern Ocean coastline. This aquifer is mostly confined, but in some parts is unconfined and has poor to moderate yields.

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

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

Ongoing concerns over the potential impacts of SWI resulted in acquisition of AEM surveys of the southern basins. In September 2006 ~1000 km of TEMPEST AEM data were acquired over the Southern Eyre Peninsula to help define the freshwater lens systems and aquifer bounds as part of a resource definition project (Auken et al*.,* 2009a; Ward et al., 2009). The TEMPEST fixed-wing time domain EM system consists of a transmitter employing a nominally horizontal loop of wire slung between wing-tips and the fuselage around the aircraft, and a receiver employing vertical and horizontal coils of wire housed in a “bird” towed behind and below the aircraft (Fitzpatrick et al*.,* 2009). The system transmits a square waveform and the receiver employs fast sampling across a wide bandwidth of 25 Hz to 37500 Hz. This allows the system to operate well in both resistive and conductive terrains and at a range of depths.

As Fitzpatrick et al. (2009) concluded, the resulting AEM survey was able to map the significant hydrogeological bounding surface, including the base and thickness of the Bridgewater Formation, and the base and thickness of the Tertiary aquifer. The AEM study and known groundwater levels suggest the Uley South groundwater lens is connected with a freshwater lens system that underlies the Coffin Bay National Park and is connected to the Coffin Bay groundwater lens. Both the upper and lower surface of the seawater intrusion has been inferred for the Uley South Lens from the AEM survey (Figure 3.20, Figure 3.21).

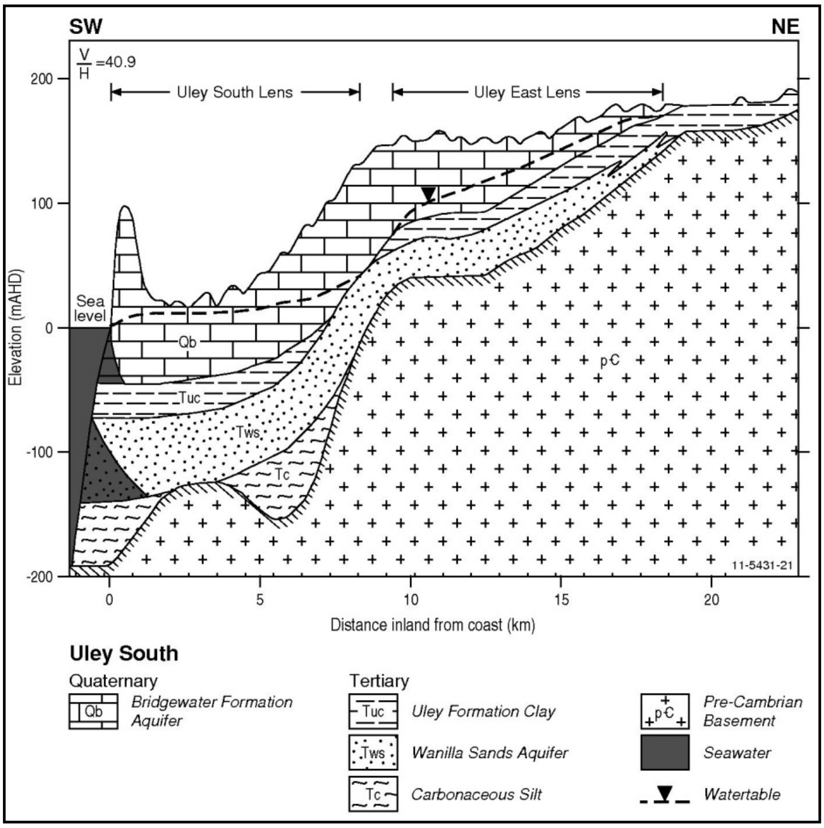


Figure 3.20. Cross-section through the Uley South area, adapted from Fig. 2 of Evans (2002).

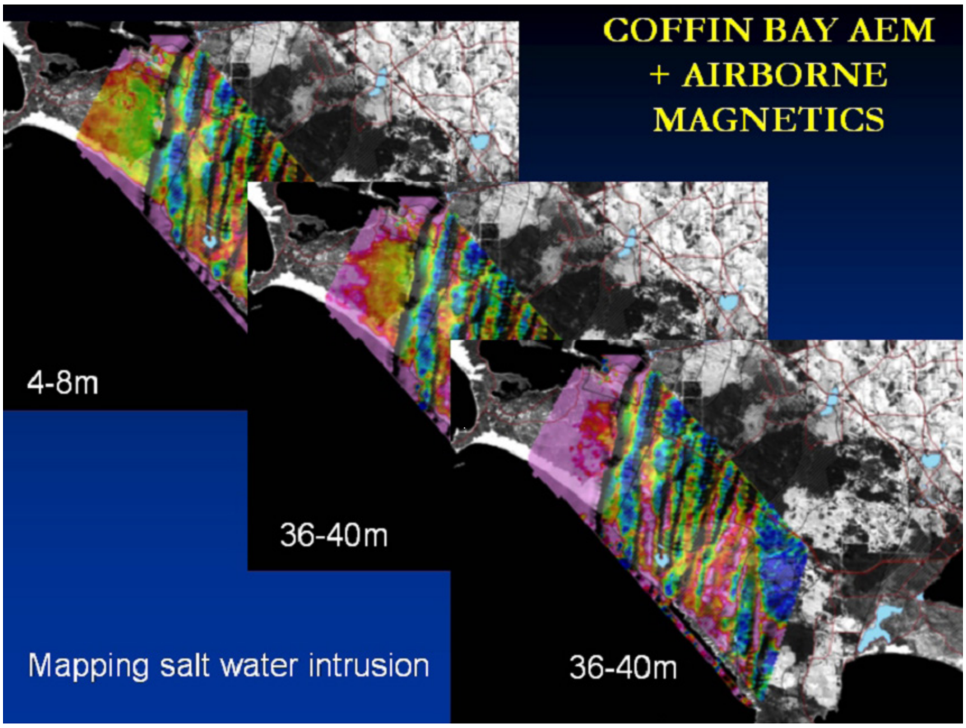


Figure 3.21. Three stacked conductivity depth slices for the Coffin Bay AEM survey. Images show AEM draped over airborne magnetics. Reds and pinks indicate sea water intrusion. Blues are resistive bedrock ridges.

A low resolution TEMPEST fixed wing time domain airborne electromagnetic survey was undertaken over the Eyre Peninsula region of South Australia to provide additional information on aquifer geometry and characteristics. The resulting data have been inverted using a constrained inversion approach to generate an enhanced ground electrical conductivity model. The modelled conductivity was assessed against available borehole conductivity data. The resulting conductivity model mapped important elements of the Quaternary and Tertiary aquifer systems in the area. Hydrogeologically significant bounding surfaces were defined, specifically:

- Elevation of the base of the Quaternary limestone aquifer (Bridgewater Formation).
- Elevation of the base of the Tertiary aquifer (combined with the in situ regolith layer).
- Thickness of the Tertiary aquifer.
- Thickness of the Quaternary and thickness of saturated Quaternary.

This area is underlain by a highly conductive aquifer and interpretation of the base of the Tertiary was not possible.

Overall, the study found that the mapped aquifer bounds compare well with those generated from the borehole data alone and give confidence in the extrapolation of those surfaces into areas where bore data is absent or limited. A comparison of these surfaces with known groundwater levels in the unconfined Bridgewater Formation aquifer, which hosts the groundwater lens systems, suggests that the Uley-South groundwater lens is connected (through a gap in a basement ridge) with a freshwater lens system that underlies the National Park and is itself connected to the Coffin Bay A lens system. These products provided a sound basis for the enhanced constraint of groundwater models, particularly where bore data is absent or limited.

3.8 Ord River, Western Australia

Geoscience Australia and its partners carried out an extensive AEM survey using the SkyTEM system of the lower Ord River as part of a groundwater assessment for the Ord Phase 2 expansion (Lawrie et al*.,* 2010a; Figure 3.22). Part of the survey overflew an area of salt water intrusion associated with an infilled Quaternary embayment that predated the modern Ord estuary. The saline wedge in this area is stable at present due to the lack of significant extraction. However due to its proximity to the surface, the saline wedge has considerable potential to effect surface vegetation should the saline groundwater rise or the wedge migrate further inland in response to groundwater extraction. A number of environmental assets, such as Marglu Billagong, are adjacent to the saline wedge, and are sustained only by the surface freshwater lens.

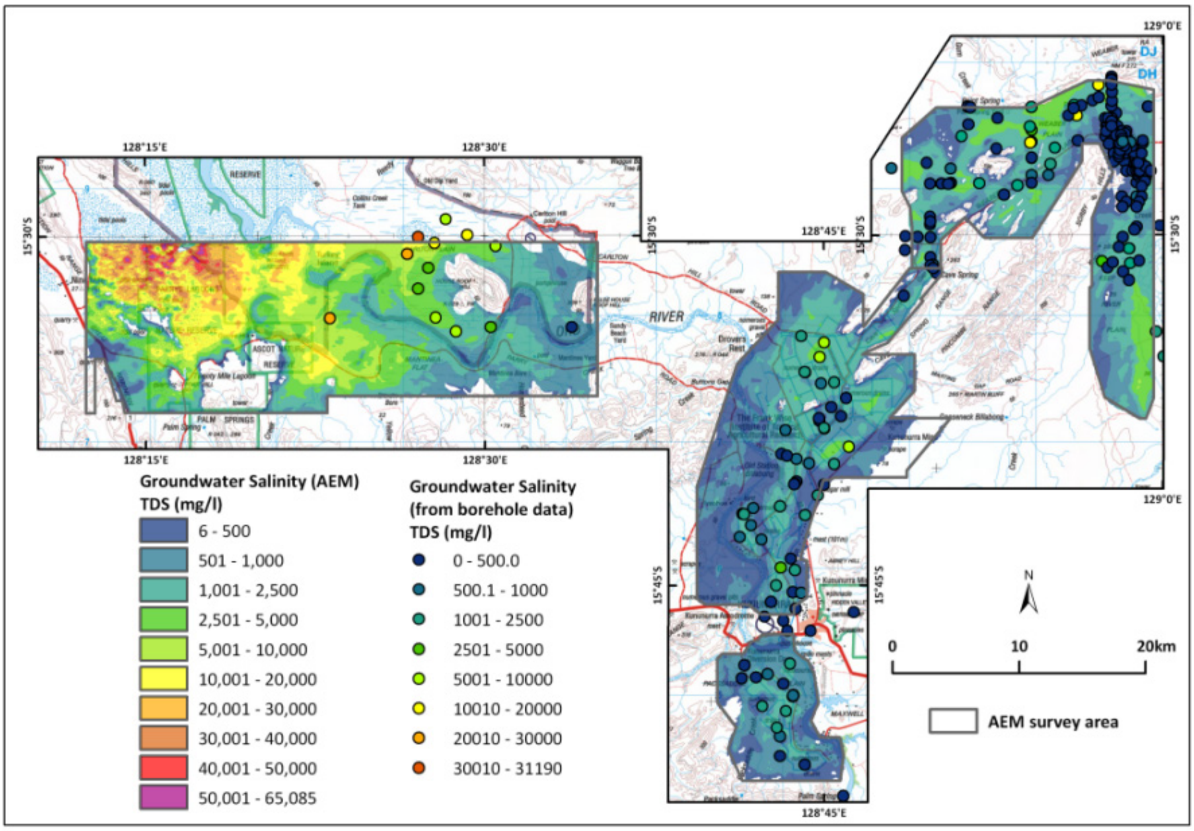


Figure 3.22. Groundwater salinity from the Ord Irrigation area and proposed extensions, mapped from AEM and validated from bores. Note saline zone in the north-western corner associated with seawater intrusion.

4 Review of Existing Studies that Utilize AEM to Map Carbonate-Karstic Aquifer Systems

4.1 Copper Ridge Dolomite, Tennessee, USA

Doll et al. (2000) assessed AEM data used for characterising a hazardous waste site on the Oak Ridge Reservation, Tennessee. Due to the nature of the subject matter, limited information was available in the public domain. Doll et al. (2000) noted the ability of the AEM survey to map geology and for locating karst features within the Copper Ridge Dolomite. Low apparent resistivity data in the Copper Ridge Dolomite survey corresponded to known karst areas with additional previously unknown karst regions mapped by the AEM surveys. The AEM surveys were able to prioritise areas for further geologic mapping and added to the mapping of folding and faulting in the area.

4.2 Edwards Aquifer, Texas, USA

The Edwards aquifer system in Texas, USA is the subject of several airborne geophysical surveys, including AEM. This aquifer is the designated sole source of water for the city of San Antonio, TX and is one of the most permeable aquifers in the United States. The Edwards aquifer consists of the Georgetown Formation and the Edwards Limestone. These carbonate rocks underlie the Gulf Coastal Plain and are regionally extensive with thickness between 120 m and 240 m. Many wells in the aquifer can flow in excess of 4500 L/min. The hydrogeology of the Edwards aquifer is detailed in Maclay (1995) and shown in Figure 4.1.

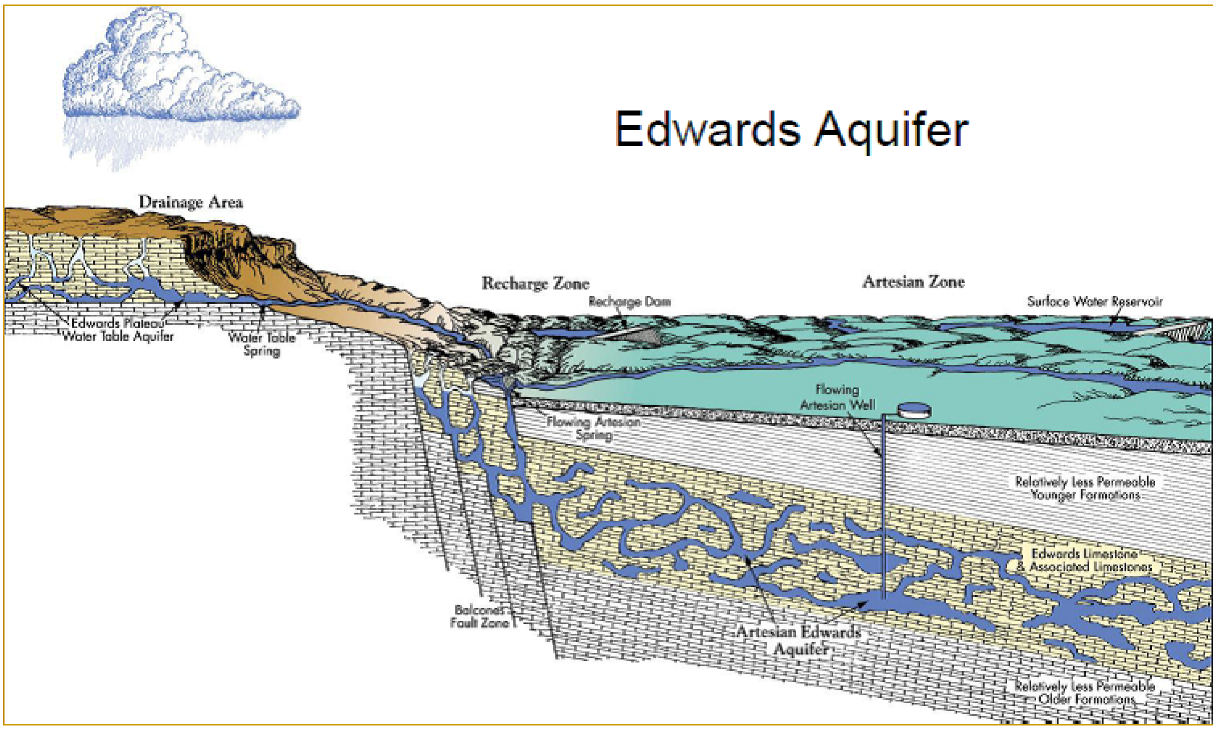


Figure 4.1 Schematic cross section showing the Edwards Aquifer, Carbonate-Karstic groundwater system

Following the high resolution airborne magnetic surveys, AEM surveys were conducted to map and image subsurface features that were important in understanding groundwater resources (Smith et al., 2003; Smith et al., 2005). Earlier Helicopter EM surveys around the Seco Creek area (Smith et al., 2003) mapped both the electrical and magnetic characteristics of the central Edwards aquifer system and the underlying confining Trinity group (Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5).

The massive limestones of the Edwards Group are generally associated with high resistivity values (hundreds of ohm-meters). The depths of investigation of these hydrogeologic features have been surveyed from the near surface to ~100 m deep. The acquisition of these feature maps is important to the understanding and modelling of the hydrology of each of the catchment, recharge and confining zones for the regions of the Edwards aquifer under study (Smith et al., 2003; Smith et al., 2005).

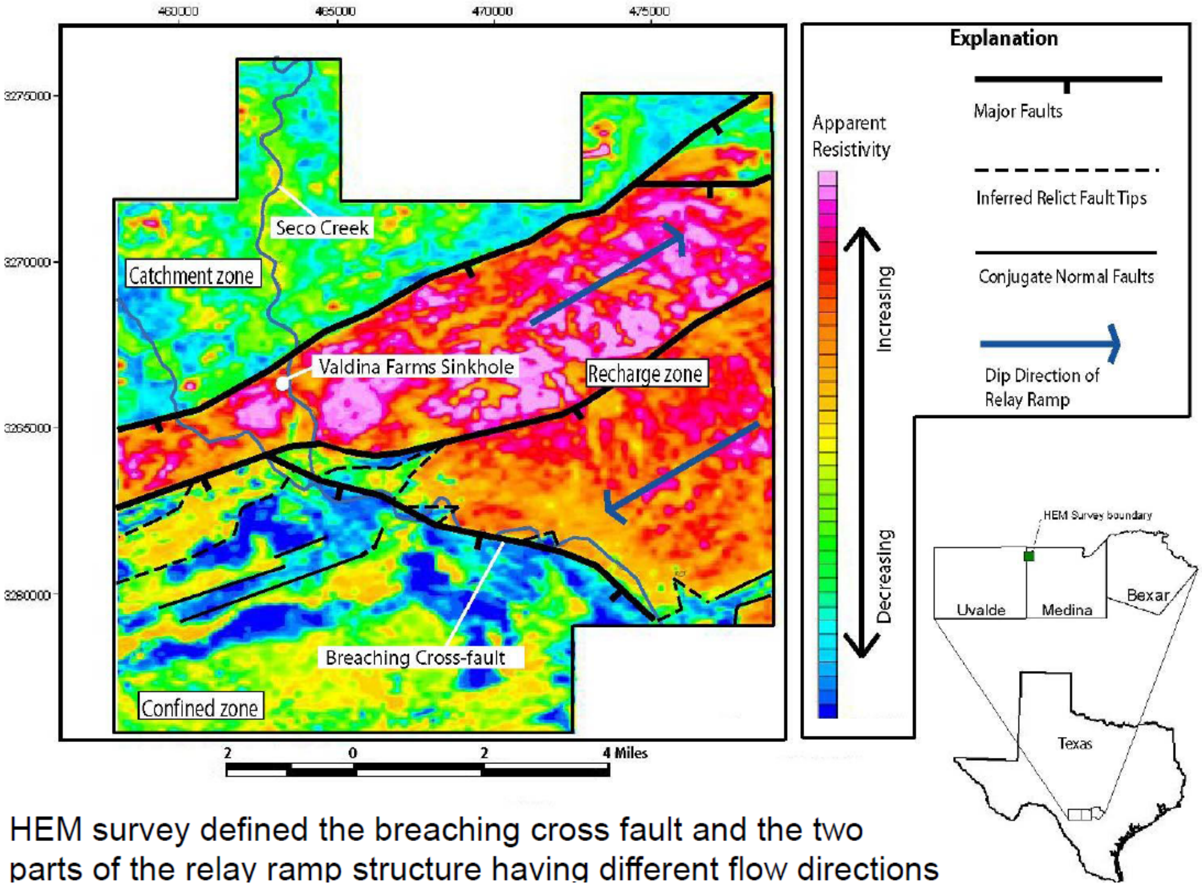


Figure 4.2. HEM survey of the Edwards Aquifer. This survey defined structural features that exert a very significant influence on resistivity and groundwater behaviour.

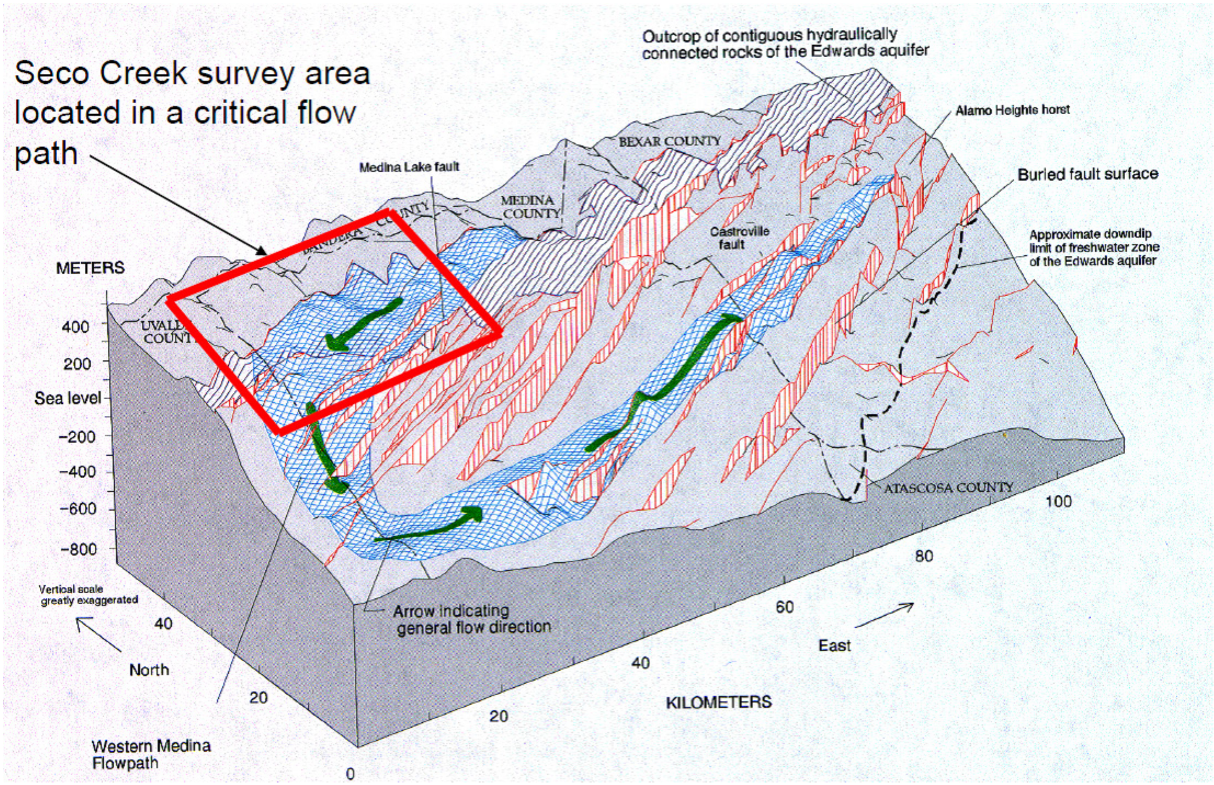


Figure 4.3. Helicopter EM surveys around the Seco Creek area (Smith et al., 2003) showing strong structural control on resistivity.

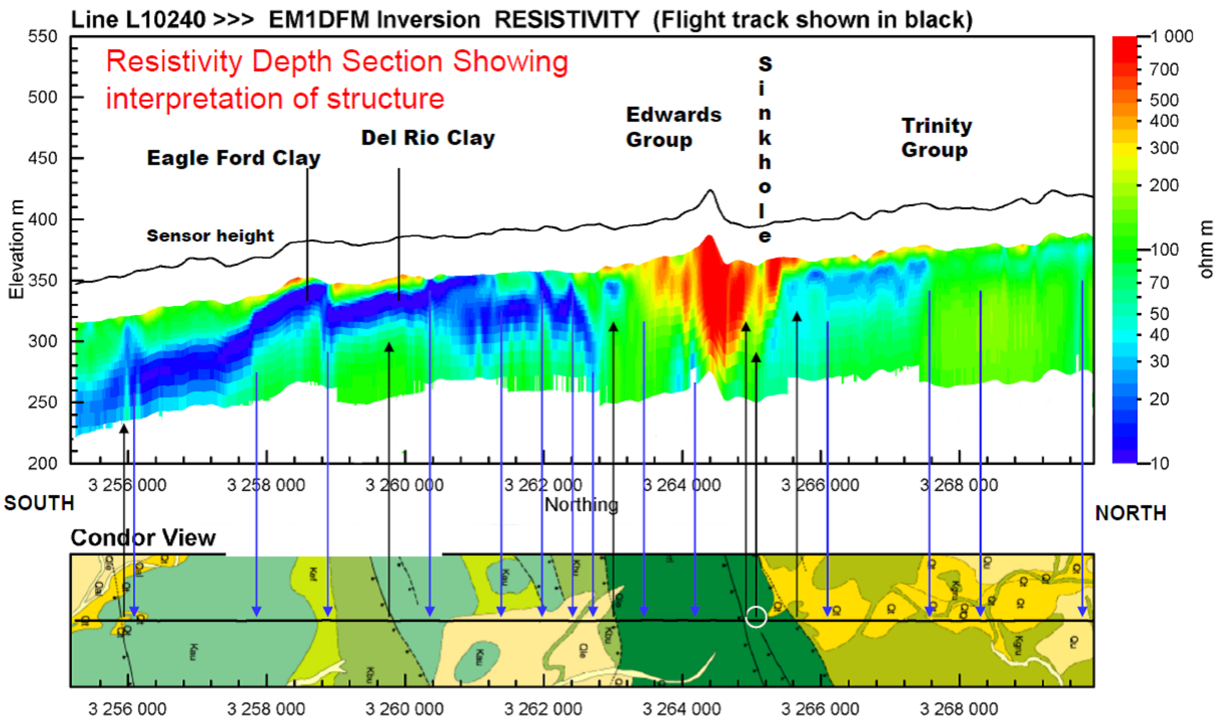


Figure 4.4. Resistivity depth section from Helicopter EM survey of the Seco Creek area showing structural; interpretation. From Smith et al., (2003).

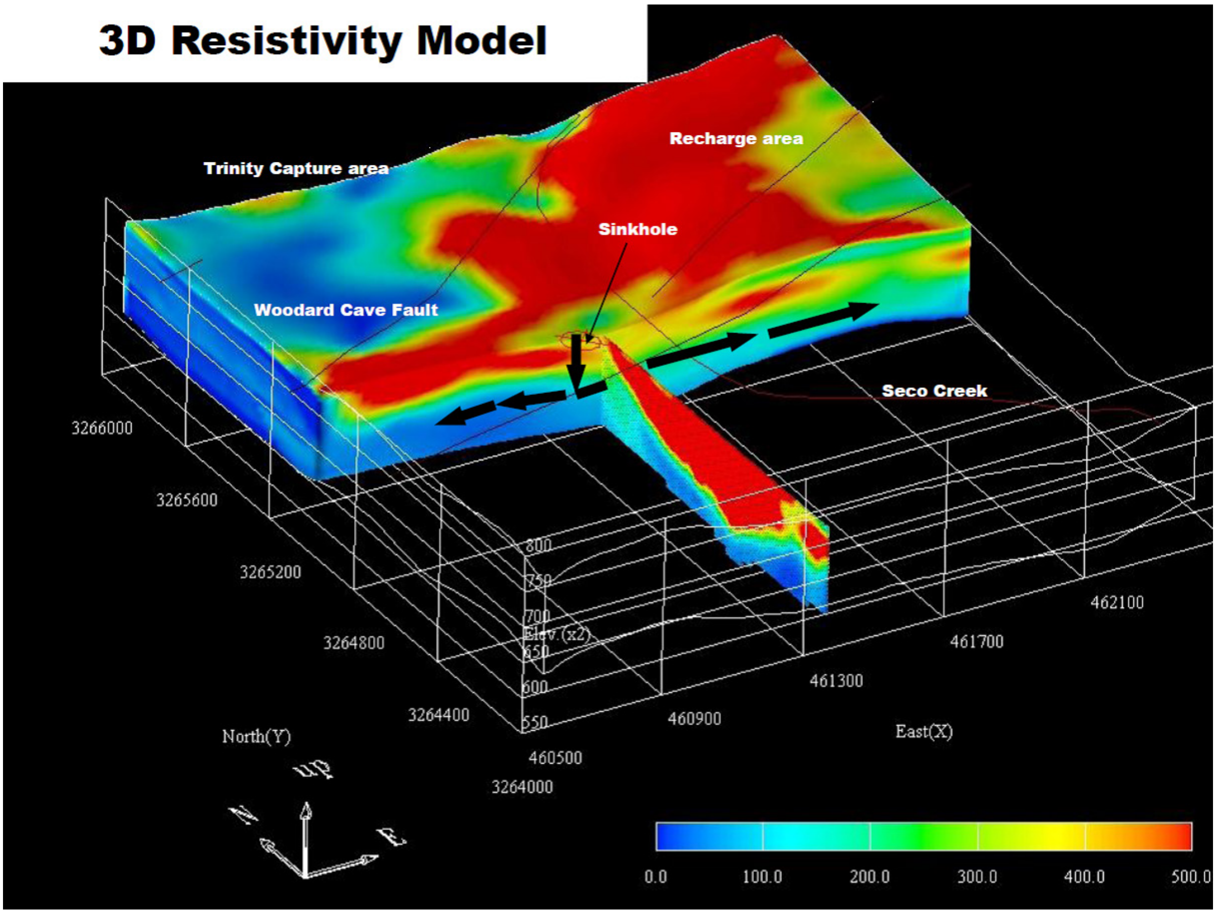


Figure 4.5. 3D resistivity model of the Seco Creek area (after Smith et al., 2003) interpreted from HEM.

4.3 Camp Crowder, Missouri, USA

This area is part of the Pools Prairie National Priority List (NPL). DNAPL contamination found within the soil and groundwater is suspected of migrating off-post through conduit and fracture systems within the underlying karst bedrock. A weathered cherty residuum overlies the more competent bedrock. Most of the groundwater is confined to the bedrock layers. The thickness of the residuum is highly variable and the transition to competent bedrock is commonly poorly defined. There is a slight regional trend in bedrock dip and ground water flow to the northeast. This is independent of the bedrock topography, which is caused by in situ weathering.

The DIGHEM$_{VRES}$ HEM system was used to acquire data to map potential groundwater flow paths (Gamey et al., 2002; Smith et al., 2008). The frequencies in this system are set to 0.4, 1.5, 6.3, 25, and 102 kHz with a transmitter-receiver coil separation of 7.9 m in a coplanar coil configuration. Apparent resistivity maps were derived for each of the five frequencies. The higher frequencies were the most useful, in that they represented a shallower response and showed less impact from power-line interference. The moderately conductive zones were partially coincident with the valley topography.

In summary, the airborne multi-frequency electromagnetic mapping provided a regional view of the site (Figure 4.6, Figure 4.7). Conductivity inversion of the data correlated well with the surface geophysical data and indicated that the mantle of friable material extended farther than originally anticipated. This extension brought potential contaminant pathways into contact with several additional lineaments. Derived bedrock topography indicated that the contaminant source area is situated on a transition zone between deep and shallow residuum, with paths and pools leading in several directions.

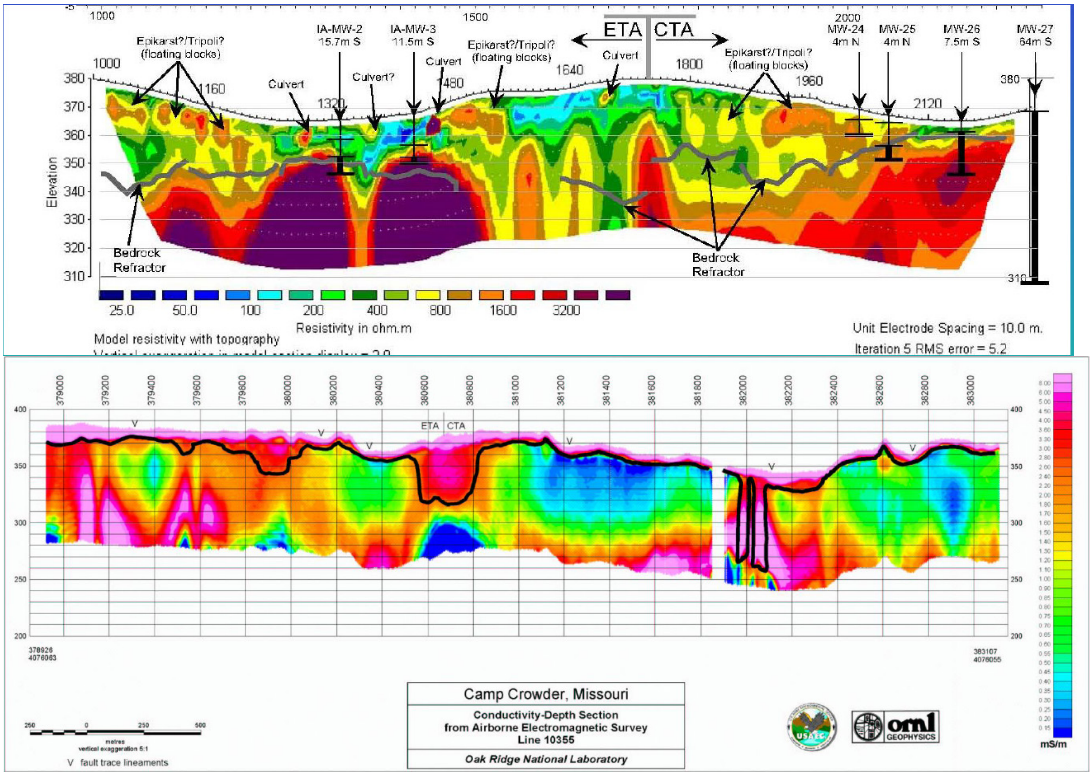


Figure 4.6. Ground resistivity (above) and HEM survey line (below). From Smith et al. (2008).

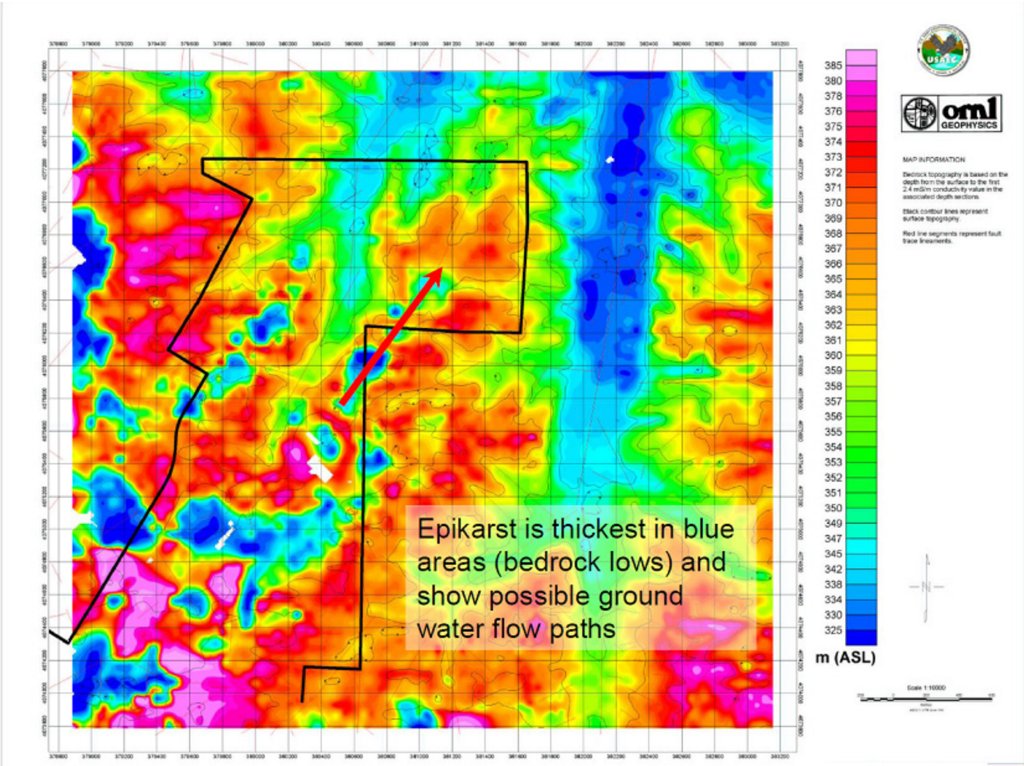


Figure 4.7. Relationship between mapped resistivity features and topography from Smith et al., 2008 showing interpreted karstic features.

4.4 Oak Ridge National Laboratory, Tennessee, USA.

A HEM survey successfully mapped the stratigraphy of interbedded carbonate and shale units, as well as karst sinkhole and collapse features within the limestones, as shown in Figure 4.8 (Doll et al., 2000).

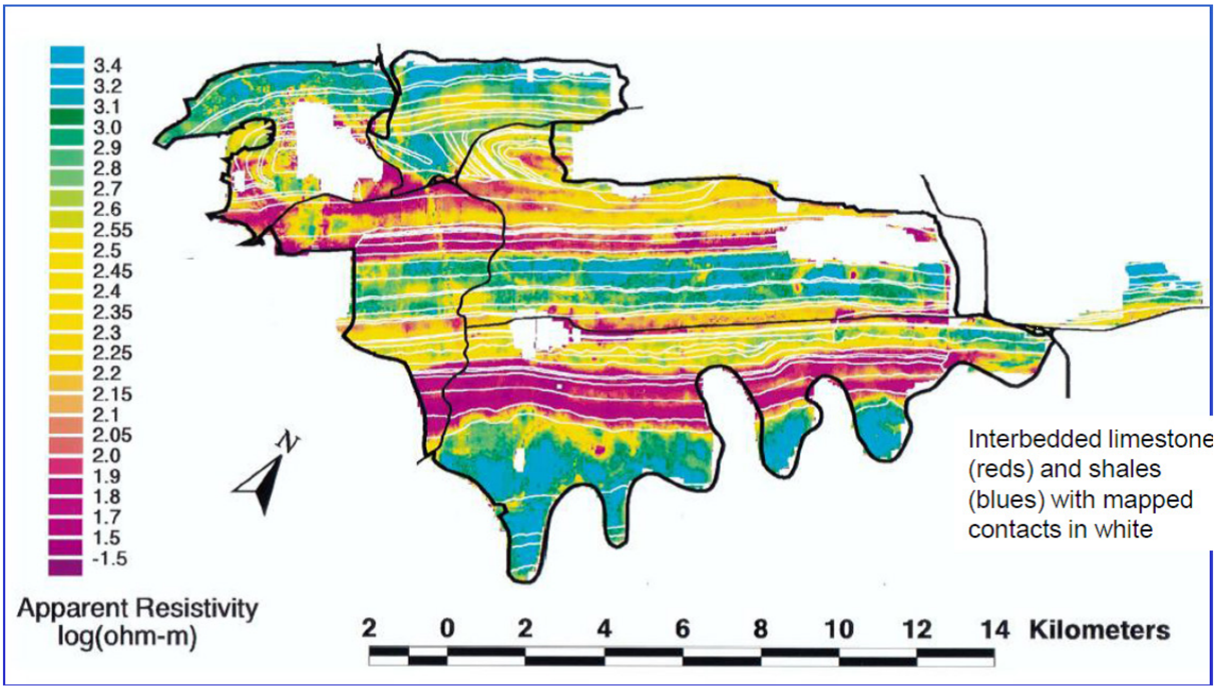


Figure 4.8. HEM resistivity mapping of carbonate and karst terrain, Oak Ridge National Laboratory, Tennessee. From Doll et al., (2000).

4.5 Northern Territory Coastal Plain, Northern Territory, Australia

SWI is an incipient hazard in many areas of the Northern Territory and a localised seawater intrusion hazard has previously been reported within the coastal plains region of the Darwin Rural Water Control District, DRWCD (CSIRO, 2009a, b). However, the threat posed by SWI is considered to be much greater than presently known, hidden at depth in a hydrogeologically complex area with very limited appropriate data to fully assess the potential effects. There are ten aquifers in the DRWCD; however, this project focussed on assessing the threat to the main producing aquifer, the Howard East Aquifer (HEA). The HEA consists of a complex sequence of Proterozoic rocks in which dolostone (the Koolpinyah-Coomalie Dolostone, or KCD) provides the main source of extracted groundwater.

Seawater intrusion is most likely driven by over-production from the aquifer. Through the NWC-funded Koolpinyah Dolomite Aquifer Characteristics Project, appraisal of groundwater monitoring data indicated that the system is already under significant stress (Fell-Smith and Sumner, 2011). Accelerated groundwater development in the region since the 1990's has resulted in significant impacts on regional groundwater levels, reduced seasonal flows in the Howard River and the earlier cessation of flows from the iconic Howard Springs. Continued production at current rates is likely to increase the rate of seawater intrusion, and future population increases will further exacerbate the situation.

The 'Northern Territory Coastal Plain: Seawater Intrusion' project used AEM data acquired and processed by Geoscience Australia during 2008-2010 for the Pine Creek AEM survey as part of Geoscience Australia's Onshore Energy and Security Program (OESP). This project was based on the Woolner AEM survey that extended east from Darwin across the Koolpinyah and Marrakai uplands, the floodplain of the lower Adelaide River and the western margin of the Mary River floodplain (Figure 4.9). The project used the AEM survey data in combination with additional geophysical, geologic and hydrogeologic datasets to assess the occurrence and potential risk of seawater intrusion into coastal aquifers in the Darwin peri-urban area. A total of 3,875 line kilometres of AEM data were acquired in 2008-2009 within the 3,775 km^2 of the project area, using the TEMPEST^{TM} time domain AEM system. The survey was flown at a range of flight line spacings, with infill acquisition acquired at 555 m over the existing and proposed borefield sites, and more broadly (1.66 m and 5 km spacings) outside these areas. The AEM survey was designed to map regional-scale variations in ground conductivity that may be associated with broad scale changes in the character of the SWI wedge, regional aquifer characteristics, groundwater conductivity and salinity. It was not designed for more detailed “within-borefield” investigations.

Data obtained from an advanced drilling technology (sonic coring) in conjunction with existing hydrogeological information provided the basis for the validation and interpretation of the TEMPEST AEM dataset, and the production of a suite of derived products.

Tan et al. (2012) reported that an integrated AEM-based assessment method successfully mapped the key elements of the NT coastal plains groundwater system with a high-level of confidence, and indicated that there is a potential hazard for seawater intrusion to impact on the main producing aquifer in the region, the Howard East Aquifer. However, it was difficult to quantify this risk to the producing borefield without incorporating the data in a predictive groundwater model. Drilling confirmed the presence of saline groundwater in a ‘wedge’ within the Proterozoic Dolostone Aquifer (the Koolpinyah/Coomalie Aquifer) in at least one part of the project area. Figure 4.10 shows the project area and an interpreted map of groundwater salinity obtained from an AEM elevation slice.

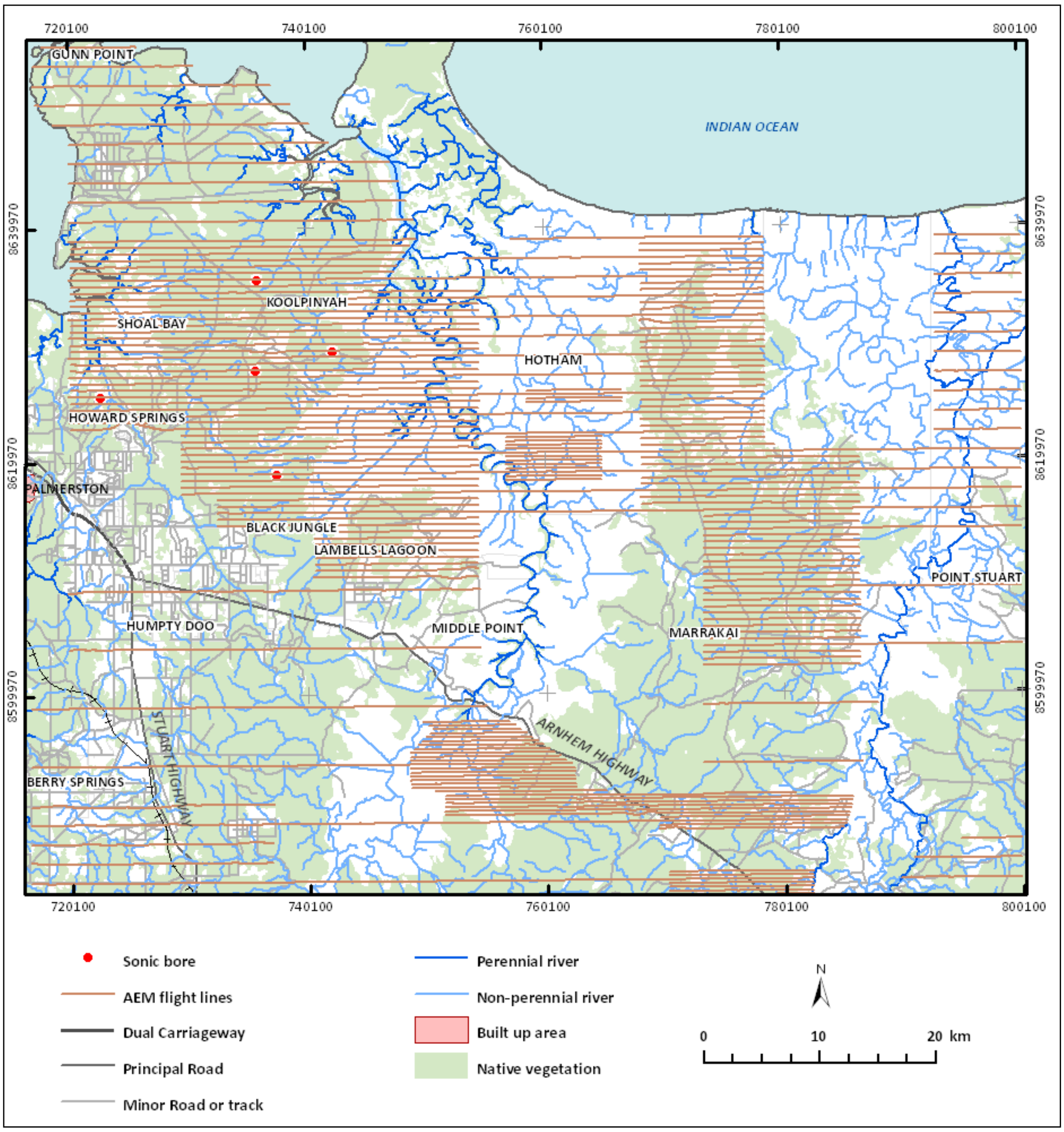


Figure 4.9. AEM survey flight lines in the Northern Territory Coastal Plain (NTCP) project area.

Tan et al. (2012) concluded that there is sufficient confidence in the inverted electrical conductivity data and AEM-derived interpretation products to recommend that groundwater modelling, utilising these products, be undertaken to assess the SWI risk to the area. However, model predictions would be improved with further refinements in model conceptualisation and parameterisation. Modelling should incorporate the latest sea-level rise modelling scenarios, as well as projected population growth, expected changes to land use and variations in other environmental or socio-economic factors that may be impacted by SWI. Importantly, there is a need for further work using better tailored AEM systems to map SWI area, rather than using a survey of opportunity.

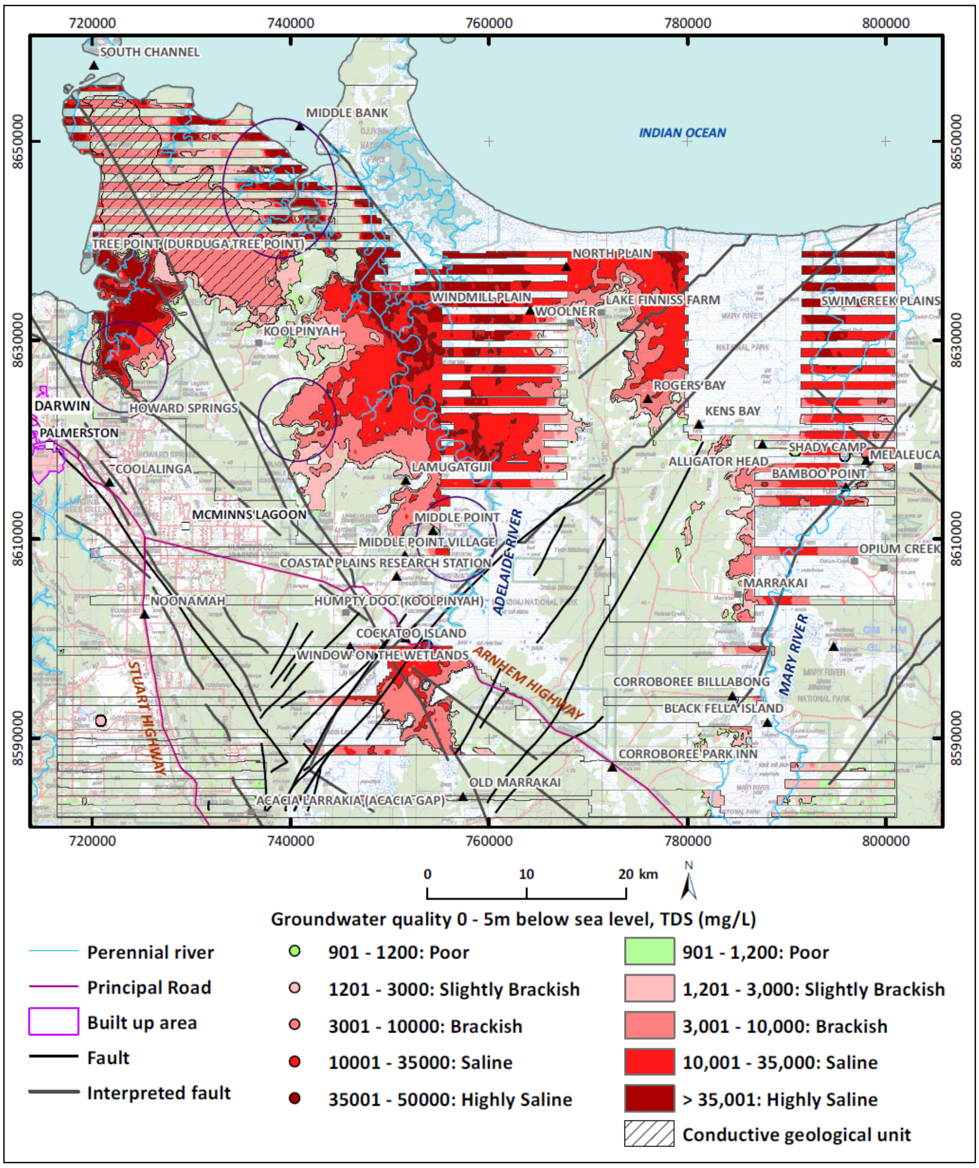


Figure 4.10. Groundwater salinity interpreted from AEM elevation slices in the Northern NTCP project area. The coastal saline wedge is clearly visible.

4.6 Daly Basin, Northern Territory, Australia

Dolostones and karsts are important components of the aquifer systems that play important role in underpinning horticulture and other agricultural developments in the Daly Basin. Significant springs derived from underlying dolomitic aquifers provide dry season baseflow to the Daly River which is considered the Northern Territory's most significant groundwater dependent ecosystem (GDE). The Daly River Basin shows strong connectivity between the Daly River and underlying Proterozoic dolostones which have karstic porosity (Smeedon, 2010). With a strongly season “spill and fill” character, the Daly River Basin supports a number of important groundwater dependent ecosystems that provide habits for endangered species, such as the pig-nosed turtle (NRETAS, 2010). The main aquifer is the Ordovician Oolloo Dolostone (Smeedon, 2010) which is highly productive and locally karstified.

Regional AEM data (5 km line-spacing) was collected in 2008 as part of Geoscience Australia’s Onshore Energy Security Program using the TEMPEST time domain system. A small infill survey (200 m line spacing) was also acquired over a reach of the Daly River where major springs had previously been identified. Unfortunately, no funding was available for drilling to calibrate and validate the survey, with only very sparse pre-existing drilling data available. This restricted the ability to produce the constrained inversions of the AEM data required to produce accurate conductivity depth slice images and interpretation products.

However, despite these limitations, AEM test lines along a key reach of known spring baseflow in the Daly River appear to have successfully identified a karstic aquifer palaeo-topography (Lawrie et al., 2010c). The AEM data also reveal ‘holes’ in overlying Cretaceous rock sequences where underlying dolostone aquifers may discharge directly to the river. These data should assist with targeting groundwater resources and sites for monitoring and evaluation.

At a regional scale, the AEM survey has successfully defined the extent of the Oolloo Dolostone as well as the extent of overlying confining beds (Tickell, 2009). In addition, a new Daly Basin formation has been identified (Tickell, 2009). This formation overlies the Oolloo Dolostone aquifer and locally hosts significant aquifers. Both aquifer systems appear to be hydraulically connected.

Overall, the AEM surveys in the Daly Basin and Darwin Coastal Zone have demonstrated the potential for AEM technologies to map aquifer carbonate/dolostone hydrostratigraphy and karst aquifers in areas where traditional methods struggle to map and predict aquifer properties due to significant aquifer heterogeneity.

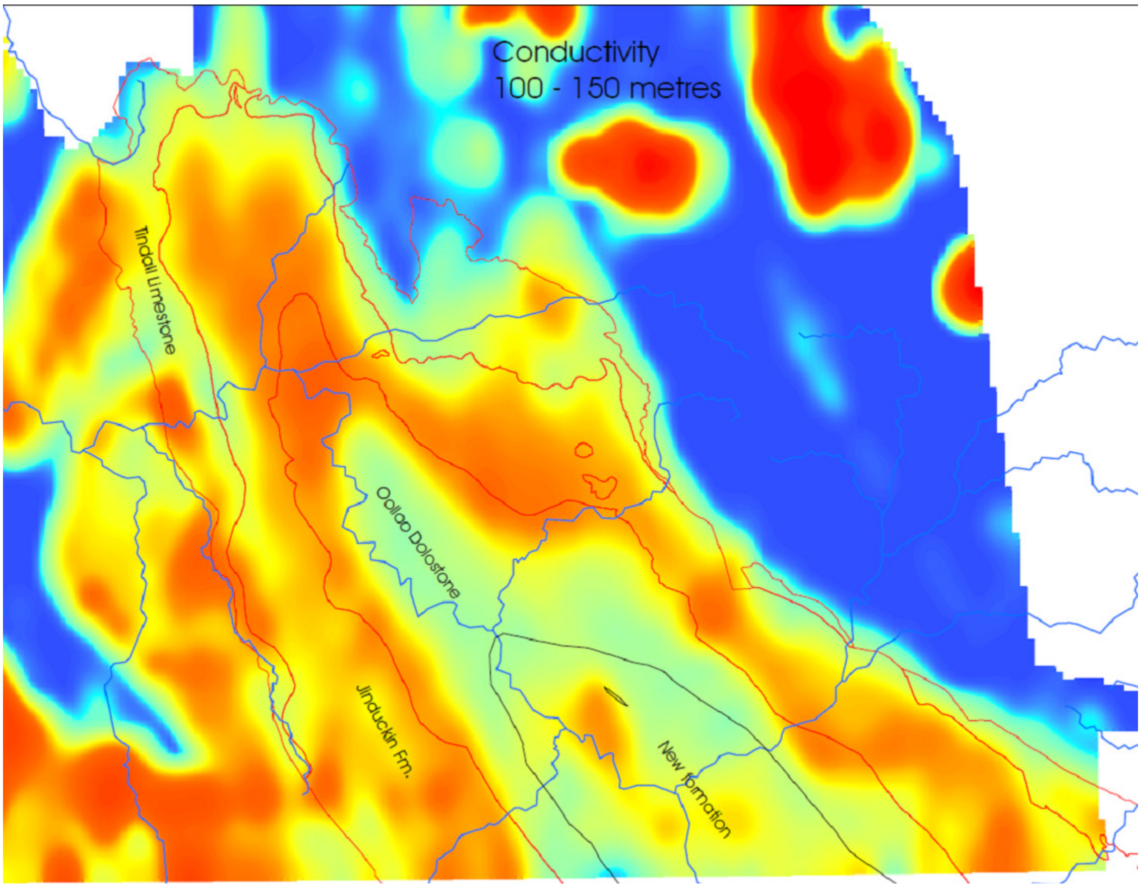


Figure 4.11. AEM conductivity depth slice from regional data shows outline of a new formation in the Daly Basin that has since been validated by drilling (Lawrie et al., 2010a; S. Tickell, pers. comm., 2012).

5 Preliminary Assessment of AEM Suitability for Assessing Seawater Intrusion Hazard in Australian Coastal Aquifers

Australian sites of current sea water intrusion and those areas thought to be at high risk are shown in Figure 1.1 (Dixon-Jain et al., 2010). Brief descriptions of the hydrogeology, SWI hazard, and key groundwater management issues in some of the priority sites are documented below. Any further detailed assessment of AEM suitability must be considered within the context of broader hydrogeological investigations, as well as a full technical risk evaluation of the suitability of individual AEM technologies to map the key elements of the hydrogeological system.

5.1 Queensland

5.1.1 Burdekin River

The Burdekin River Delta and Haughton – Barratta system are together one of the largest deltaic/alluvial aquifer systems in Australia (NRMW, 2006). To the east of the delta is the Coral Sea, to the north are tidal flats, to the south are outcrops of basement rock known as the Stokes Ranges and to the west, the Stokes Ranges continue and Mt Kelly outcrops (NRMW, 2006). The Burdekin Delta is an area with known seawater intrusion and where groundwater management involving both extensive extraction and artificial recharge has resulted in a dynamic groundwater situation.

The aquifer is shallow and unconfined, consisting of heterogeneous, unconsolidated alluvial and deltaic sediments in excess of 100 m thick (Figure 5.1). The Quaternary sediments include a mixture of discontinuous lenses of inter-bedded gravel, channel sands, silt, mud and clay. The lenses are vertically connected and inter-fingered. Clean permeable channel sands form areas of high transmissivity compared to the low permeability clay layers. The complexity of sedimentation and the inconsistent distribution of extensive layers justifies the inclusion of all layers into one hydrostratigraphic unit rather than multiple units (NRMW, 2006).

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

Recharge to the alluvial aquifer occurs through a range of mechanisms; including infiltration of rainfall, channel seepage, percolation through sites of artificial recharge; flood flows and infiltration into overbank deposits and irrigation returns (McMahon, 2000).

Preliminary studies (Fitzpatrick et al., 2004) suggested that the conductivity structure in the Burdekin area was amenable to geophysical mapping the distribution of aquifers and saline groundwater related to salt water intrusion in the coastal zone. The scale of the major landscape such as channels is a key role in determining the resolution of any survey. This study suggested an airborne survey using TEMPEST, in the event only ground, in-water, and down-hole surveys were performed (Lawrie et al., 2006). The latter study concluded that it is likely that conductivity contrasts between saline clays and fresh-water filled distributary sands will be discriminated in the Holocene succession of the Burdekin Delta, and possibly in older sediments as well. However, discrimination of salt-water filled sands may be more problematic, although it is possible that AEM may be able to show, through loss of conductivity contrast, the point at which fresh water is replaced by saline water in a channel sand aquifer (Lawrie et al., 2006). AEM techniques should also detect the contact between cover and Palaeozoic bedrock, and between weathered and fresh bedrock. Should a survey be carried out, it is important that it include areas outside the immediate study area (such as the coastal fringe of the delta) to allow the context to be seen.

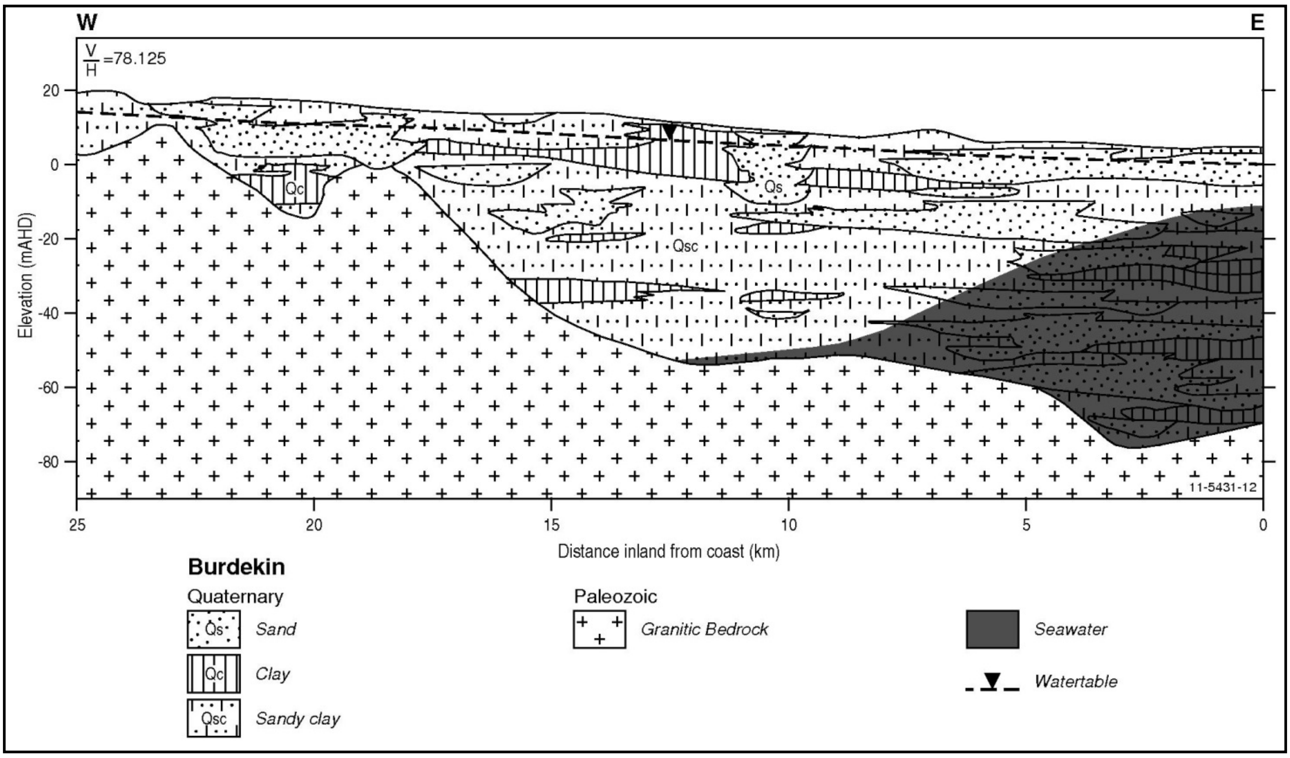


Figure 5.1: Burdekin River geological cross-section with interpreted seawater wedge (NRMW 2006).

Lawrie et al., (2006) also concluded that existing 3-D models of the Burdekin Delta succession have significantly underestimated the proportion of sand and gravel in the delta and therefore the potential 3-D connectivity of hydrogeological units. New AEM data, added to existing drill-hole databases will allow improved 3-D facies mapping of channel sands and gravels, their associated flood plain sediments, and disconformities in the succession. Integrating this with detailed geomorphic analysis of the DEM would provide improved understanding of the facies architecture of the Burdekin Delta and its implications for groundwater flow systems.

5.1.2 Burnett Heads

The coastal Burnett region is located within subtropical Queensland approximately 10 km from the town of Bundaberg. To the east is the Coral Sea, to the north is the Kolan River and the Gregory River partly bounds the south. Seawater intrusion was first reported in the 1960's due to intense extraction of groundwater for irrigation. Since the 1960's it is estimated that 12,500 hectares of land in the Gooburrum area have been lost to seawater intrusion and the interface is estimated to be moving at 100 m per year, mainly within the highly permeable aquifer channels that are hydraulically connected to the sea (Bajracharya et al., 1998). During the period of 1977-1979, rainfall was well below average and groundwater levels were drawn to be in excess of 3 m below mean sea level for over 15 months. At this time considerable seawater intrusion occurred and salinity increased to 50, 000 μS/cm in some areas.

Groundwater occurs in three aquifers, the upper Elliot Formation and the underlying Gooburum Formation and the Fairymead Beds (Figure 5.2). In addition, Quaternary coastal dune sands and alluvium have a minor to moderate groundwater potential in locally perched aquifers. The major Elliot and Fairymead aquifers consist of Tertiary unconsolidated to semi-consolidated alluvial sediments unconformably overlying the Lower Cretaceous Burrum Coal Measures (Bajracharya et al., 2006). Both aquifers have been described as having 'moderate to high groundwater potential' (Moser 2004), although this may be regionally variable. A leaky, aquitard clay layer of variable thickness and distribution lies between the two aquifers and creates a spatially variable hydraulic connection.

Rainfall is the primary source of recharge to the unconfined to semi-confined aquifer systems and the groundwater is generally of high quality; commonly less than 500 μS/cm in the inland areas. About 50% of the Elliot Formation aquifer is located below mean sea level, and the Fairymead Beds are entirely below. The deepest section is ~ 80 m below mean sea level near the coast (Zhang et al., 2004).

Limited ground geophysical investigations suggested that it is worth assessing whether AEM could delineate seawater intrusion in the Burnett Heads region, particularly for mapping the unconfined Elliott Formation and for mapping the basement topography of the underlying Burrum Coal Measures inland of the coast. Mapping of the lower Fairymead Beds is dependent on the clay content in the semi-confining Gooburrum Formation which may be conductive. This may attenuate the response of the lower Fairymead Beds and limit the depth of AEM investigation. Ground-based or borehole EM geophysics should be investigated to ascertain the response of the layered aquifer system near the coast.

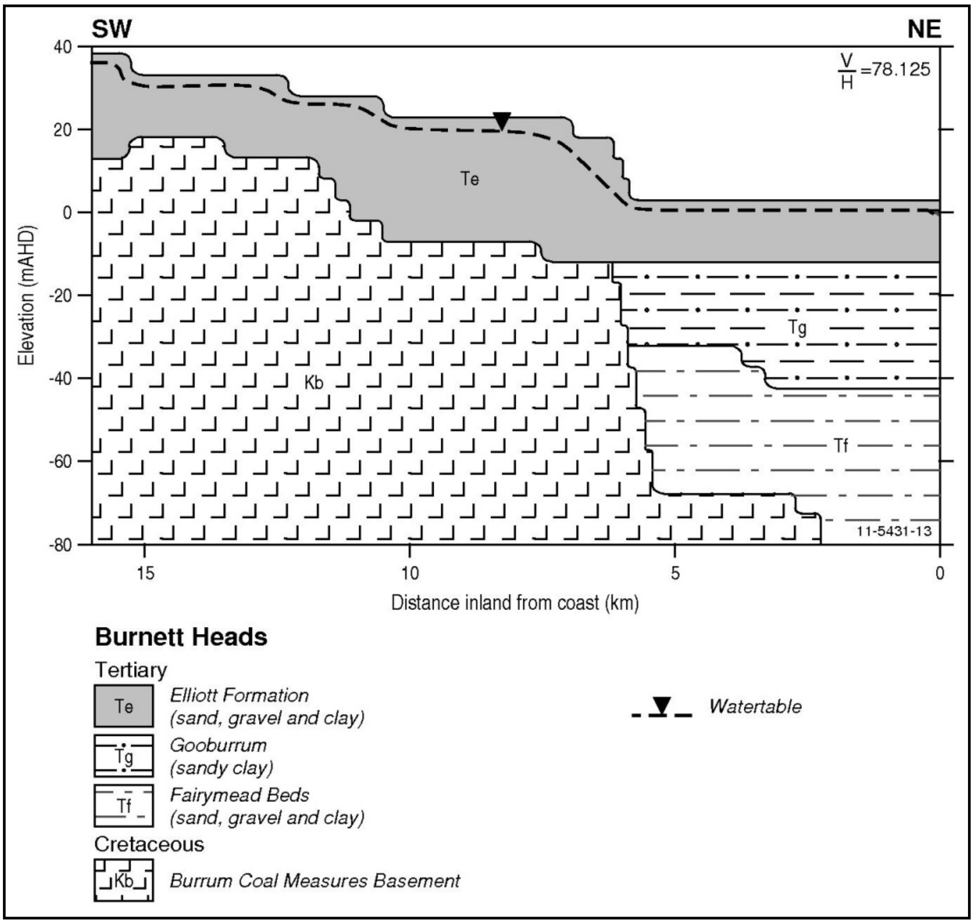


Figure 5.2. Burnett Heads geological cross-section after Bajracharya et al., (2006).

5.1.3 North Stradbroke Island

North Stradbroke Island is in Moreton Bay, 40 km east of Brisbane. It belongs to a group of massive sand islands in the south-east of Queensland. These include South Stradbroke Island, North Stradbroke Island, Moreton Island, Bribie Island and Fraser Island. North Stradbroke Island is approximately 267 km^2 (Chen, 2001). Stradbroke Island land use is characterised by settlements, sand mining, reserves as well as significant wetlands, lakes and lagoons. Groundwater is used to provide town water supplies, including additional off-island water supply, and also supports sand mining.

Stradbroke Island is subject to the threat of seawater intrusion. Modelling has determined that: 1.) centralised groundwater extractions from the central groundwater mound will have the least impact on SWI, 2.) some production bores have shown a downward trend in water-levels due to below-average rainfall (Chen, 2001); 3). swampy areas may act as a hydraulic barrier to SWI (Kaegi, 2006), 4). the island has an insufficient number of suitably constructed monitoring bores to delineate the seawater interface (EHA, 2005).

The hydrogeology of Stradbroke Island was described by Laycock (1975), Chen (2001) and EHA (2005). These studies indicated that good quality groundwater is stored within the porous Quaternary dune sands, which can be quite thick and elevated in places reaching a height of 76 m above sea level. The average depth to groundwater on the island is 16 m, and the maximum elevation of the groundwater is 50 to 60 mAHD in the central north of the island, forming a groundwater mound (Figure 5.3). Seawater has formed a wedge around the perimeter of the island and its position changes with the amount of fresh groundwater discharged to the coast, which is mostly influenced by the balance between recharge to the groundwater system and extractions.

The hydrogeology suggests that AEM systems are worth further consideration for mapping seawater intrusion along the coastal fringe of North Stradbroke Island and possibly for mapping depth to watertable across the island if there is a conductivity contrast at the interface. The method may elucidate the extents of the perched freshwater lakes on the island along with the extents of the underlying indurated confining layers for these lakes. Ground-based measurements would aid in calibrating and ground-truthing of the AEM surveys.

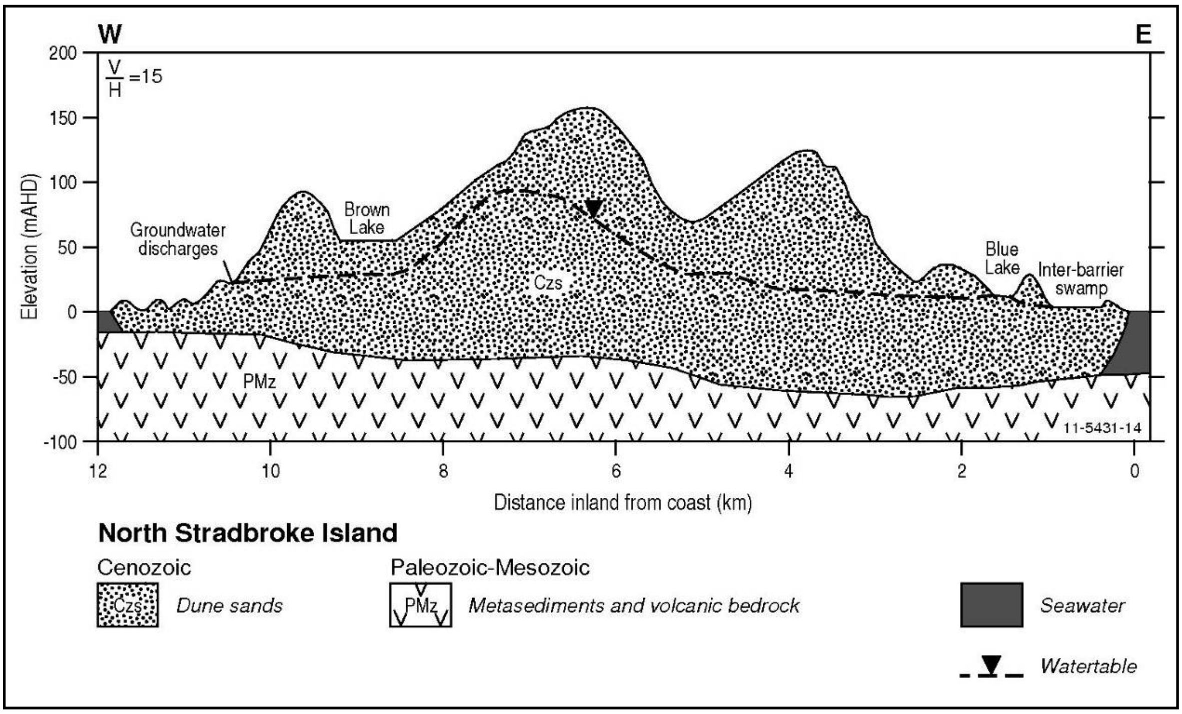


Figure 5.3. Cross-section through North Stradbroke Island, adapted from Text Fig 2 in Laycock (1978).

5.1.4 Pioneer Valley Aquifer

The Pioneer Valley Aquifer (PVA) is situated in North Queensland approximately 1200 km north of Brisbane. The region contains extensive sugarcane cultivation and related industries with significant water demands that are heavily dependent on groundwater, especially during periods of drought. The region has a subtropical climate with distinct warm wet summers and cool dry winters. The tidal regime along the coastal boundary of the PVA is macro-tidal. Land use since the 1980's has been primarily for sugarcane growing, with most groundwater irrigation used to supplement rainfall. The groundwater resources are also used by the domestic sugar-milling industry and for urban water supply, stock water, and farm and rural domestic water supplies.

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

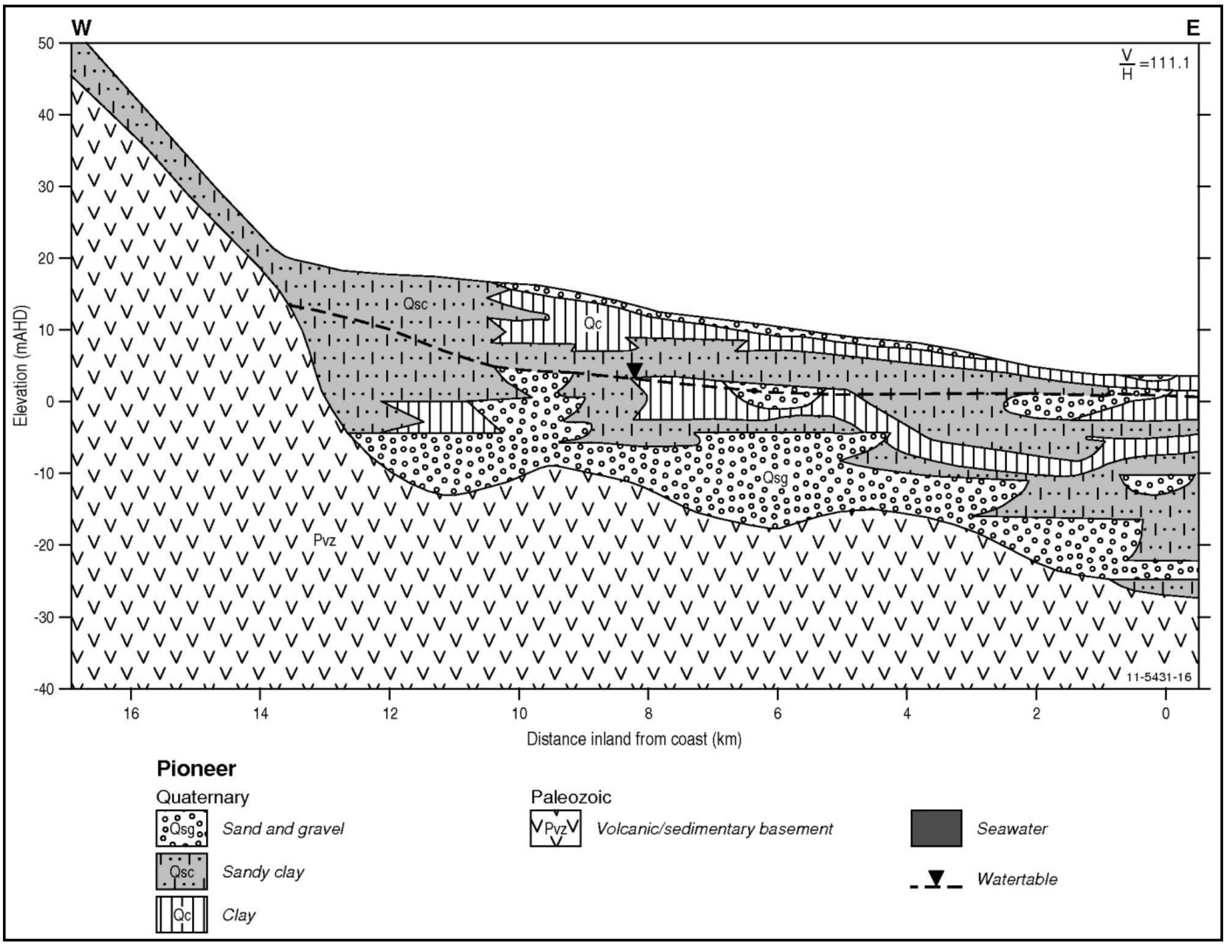


Figure 5.4. Pioneer Valley geological cross-section (after Murphy et al., 2005).

Murphy et al., (2005) defined the Pioneer Valley groundwater system as a regionally unconfined aquifer, although confined aquifer conditions are expected to occur locally in some areas. Groundwater recharge is mainly from rainfall and irrigation returns. The flow of groundwater is generally towards streams and the ocean (Murphy et al., 2005). However, groundwater hydrographs indicate that abstraction for irrigation during dry periods causes these flow directions to be reversed near the coast, and seawater intrusion is impacting on the groundwater quality in coastal plain production bores (Werner & Gallagher, 2006). Carey et al., (2009) indicated an increase in coastal groundwater head levels as a result of the non-linear interaction of macro-tidal oscillations at the oceanic/groundwater interface. This causes a time averaged watertable over-height, which reduces the seaward gradient of near coastal groundwater.

Pioneer Valley groundwater resources are contained within alluvial deposits and fractured rock units, which behave as a singular aquifer system (Bedford, 1978). A schematic cross-section through this aquifer is shown in Figure 5.4. Most groundwater is extracted from the alluvial aquifer system. The unconsolidated alluvial aquifers are unconfined and less than 40 m thick (Bedford, 1978). In the lower alluvial domain above the weathered basement rocks, there are higher-yielding deposits of coarse sands and gravels. Rainfall is the primary source of recharge to the aquifers, with watertables rapidly responding to rainfall events.

Palaeochannels that have been incised into the basement rock may form preferential flow pathways (Bedford 1978; Murphy & Sorensen, 2000). These channels reflect the current and previous alignments of the Pioneer River, Bakers Creek and Sandy Creek. Fractures within the basement rock may also transmit groundwater, forming a continuous aquifer with the weathered zone and the upper alluvium.

Ground and borehole geophysical measurements suggest that AEM may be worth considering further for mapping seawater intrusion in the Pioneer Valley Aquifer. The area of investigation worth considering may extend beyond the coast to aid in mapping estuarine/groundwater interaction. The tidal limits for the macro-tidal affected estuaries can be up to 12 km inland. This can lead to the influx of saline water into groundwater adjacent to estuaries. Of concern for the AEM method, Murphy & Sorensen (2000) noted the lenticular nature of marine clays and mangrove deposits in the system, and Carey et al., (2009) showed that these are highly conductive (using a pole-dipole surface resistivity survey). These lenticular clays may reduce the effectiveness of an AEM survey to map the spatial distribution and extent of these conductive clay lenses and pods.

5.2 South Australia

5.2.1 Adelaide Coastal Plains

Adelaide is located north of the Fleurieu Peninsula between the Gulf St. Vincent and the Mount Lofty Ranges. Adelaide is the capital city of South Australia and is highly urbanised. Land use is mainly urban and residential, industrial, recreational and parkland. The city is flanked on its western coast by sandy beaches and a port, and by hills on its eastern side. The second-most upper Tertiary aquifer is used by industry and for irrigating recreational areas such as parks and golf courses. The uppermost Tertiary aquifer is sometimes used to supplement the Adelaide metropolitan water supply.

The hydrological setting of the Adelaide Coastal Plains is complex. A cross-section through the Adelaide Metro area is shown in Figure 5.5. The Quaternary and Tertiary sediments within the Adelaide Geosyncline are up to 600 m thick, containing up to 10 semi-confined to confined aquifer systems. These sediments overlie a Precambrian fractured rock aquifer. Prior to development on the Adelaide coastal plain, the Quaternary and Tertiary aquifers were artesian.

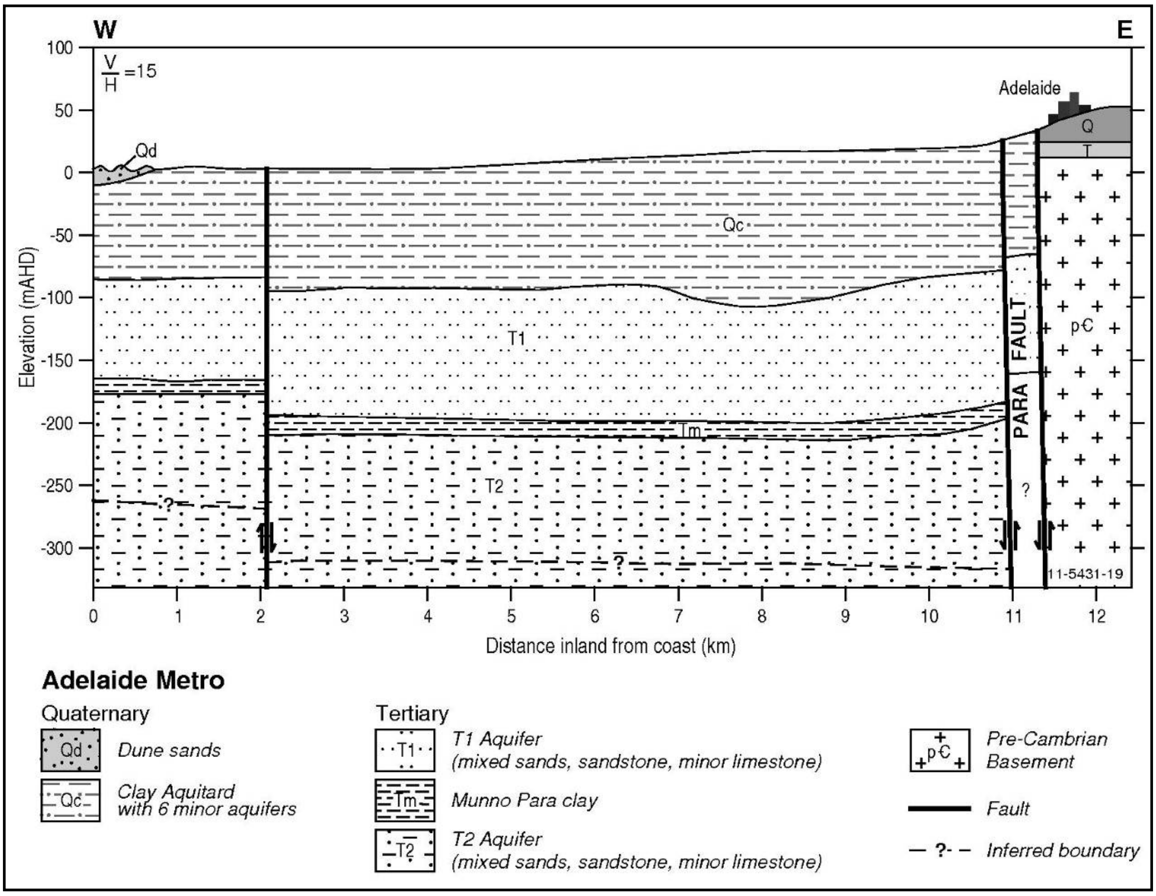


Figure 5.5. Cross-section through the Adelaide area, adapted from Fig.1 in Gerges (1996).

Most Quaternary aquifers (Q1 – Q6) are insignificant due to their low yields and high salinity. These units vary in thickness (from 1-18 m), lithology and hydraulic conductivity (Lamontagne et al., 2005). Localised areas provide good quality water. The main groundwater resources in the Adelaide Plains are contained in four confined Tertiary aquifers (T1 – T4). The Tertiary sands, sandstones and limestone form the aquifer units, and clay, chert and marl form leaky confining beds. The uppermost two Tertiary aquifers are the most productive and hold good quality groundwater.

Recharge to the Tertiary aquifers primarily occurs through outcrops on the western slopes of the Mount Lofty Ranges and along the Eden Burnside Fault (Gerges, 1996).

Lamontagne et al, (2005) assessed the volumes of water being discharged to coastal waters between Port Gawler to Sellicks Beach in the Gulf St Vincent. They suggested that intrusions of seawater may be more widespread than previously thought along the length of the Adelaide coastline. Unfortunately, a poor monitoring network makes the potentiometric surface uncertain. The T1 and T2 aquifers have cones of depression due to heavy use, with groundwater elevations at the centre of the depression below sea level. These aquifers are also used for managed aquifer recharge using storm water (Gerges, 2000).

5.2.1.1 Le Fevre Peninsula

A sub-region of the Adelaide Coastal Plains is the Le Fevre Peninsula near Port Adelaide. In the Le Fevre Peninsula the uppermost Q1 aquifer is overlain by dune sands, known as the St Kilda Formation (including the Semaphore Sands unit). These store good quality water due to local, direct recharge from rainfall. Q1 sediments are underlain by the hydraulically connected Q2 aquifer, which has a salinity of up to 21,000 mg/L. A thick sequence of Tertiary sediments underlies the Quaternary sediments. The Tertiary aquifers include the Carisbrooke and Dry Creek Sands and the Port Willunga Limestone Formation. These are all laterally extensive and contain water of relatively good quality. The Hindmarsh Clay underlies the unconsolidated Quaternary sediments and is highly impermeable. It forms an aquitard, inter-bedded with minor aquifers. These aquifers are not exploited due to high groundwater salinity.

Le Fevre Peninsula is heavily urbanised with residential and industrial developments. Reclamation of land has occurred along the Port Adelaide River and mangroves occur along the estuary. Groundwater in the Le Fevre Peninsula is being increasing used by industry, mainly the Tertiary aquifers. The Q1 aquifer is used extensively for watering domestic gardens and for recreational parks.

The Le Fevre Peninsula groundwater has been found to be at risk of saline water intrusion because of serious losses to annual recharge into the aquifer due to increased abstractions from wells (Russell, 1996). Over-pumping of the Q1 aquifer has the potential to cause up-coning from the underlying salty aquifer. Heavy pumping from the underlying Tertiary aquifers in the area has led to an expanding cone of depression that has induced downward leakage and the lowering of the watertable in the Q1 aquifer.

The saline waters in the upper Quaternary aquifers of the greater Adelaide plains may not allow for the ready mapping of the more productive, deep, and confined Tertiary aquifers. The saline groundwater may attenuate the AEM response and limit the depth of investigation. The deeper Tertiary aquifers (T2 – T4) may be a depth beyond the resolution capabilities of AEM systems. Mapping of seawater intrusion in the Quaternary aquifers in the Le Fevre Peninsula may be feasible although a full technical evaluation is required. The urbanised environment of the Adelaide metropolitan may preclude the use of AEM for seawater intrusion mapping in the Adelaide Coastal Plains region.

5.3 Northern Territory

In the Northern Territory, dolostones and karsts are important components of the aquifer systems that play an important role in underpinning Darwin’s water supply and in supporting horticulture and other agricultural developments more broadly in the Darwin Coastal Zone and the Daly Basin. Significant springs derived from underlying dolomitic aquifers provide dry season baseflow to the Daly River which is considered the Northern Territory’s most significant groundwater dependent ecosystem (GDE). Following the success of AEM investigations at a regional scale in mapping the SWI interface (Tan et al., 2012) further investigations using higher resolution and/or time series AEM data to assess and monitor the SWI interface may be warranted in the NT Coastal Plain. The method would also be suitable for application in other more remote areas where ground access is limited.

5.4 Western Australia

5.4.1 Bunbury

Bunbury is located on the western coast of Australia approximately 120 km south of Perth within the Swan Coastal Plain. Most of the land has been cleared for agriculture, which uses predominantly groundwater for irrigation. Other than agriculture the area contains native vegetation, State Forest pine plantations and urban districts (Deeney, 1988).

Bunbury contains aquifers within the Superficial Formation, Leederville Formation Aquifer, Bunbury Basalt Aquifer, Yaragadee Formation and Cockleshell Formations (Figure 5.6). The Superficial Formation, consisting predominantly of clay and sand in the east and of sand and limestone in the west, forms an unconfined aquifer. In the east and the upper part of the aquifer, the Guildford Formation clay member is an aquitard. Within this formation, the watertable ranges from 1-30 m deep. The aquifer is anisotropic and heterogeneous due to lithological variability and stratification of the sediments. The aquifer is recharged directly by rainfall but the amount varies with lithology, depth to the water table and topographic gradient. Groundwater discharge is through major and minor watercourses, inlets, coastal swamps, evapotranspiration as well as downward leakage to Mesozoic sediments (Deeney, 1988).

The Yaragadee and Cockleshell Formations are hydraulically connected. They consist of coarse- to very coarse-grained quartz sand with minor inter-beds of commonly weathered shale. The proportion of shale increases with depth. Recharge occurs predominantly where these formations outcrop on the Blackwood Plateau, with a minor portion coming from downward leakage from overlying formations. Groundwater flow in the upper aquifer is toward the northwest. Some discharge occurs along the coast to the Superficial Formation but most is out to sea. Groundwater levels fluctuate and are lowest during the summer due to increased abstractions (Commander, 1981).There is some connectivity between the Superficial Formation aquifer and lower Mesozoic aquifers as both upward and downward leakage occur (Deeney, 1988).

In the Bunbury area a saltwater interface intrudes up to 3 km inland within the Yarragadee Formation where the aquifer sub-crops the Superficial Formation offshore and is in hydraulic connection with the ocean (Wharton, 1981). Recent observations of increased salinity in the Yarragadee aquifer have been documented in the Bunbury area.

AEM may be worth further consideration for mapping SWI in western coastal margins of the superficial sedimentary aquifer. Further assessment of the potential for AEM systems to map the upper bounds, and possibly the lower bounds, of the seawater intrusion interface identified in the Yarragadee Formation may be warranted. However, AEM systems may not be able to readily differentiate all key elements of the hydrogeology due to the similarities in composition of many aquifer units within five kilometres of the coast. Initial ground based surveys would be required to assess the suitability of the system for AEM mapping.

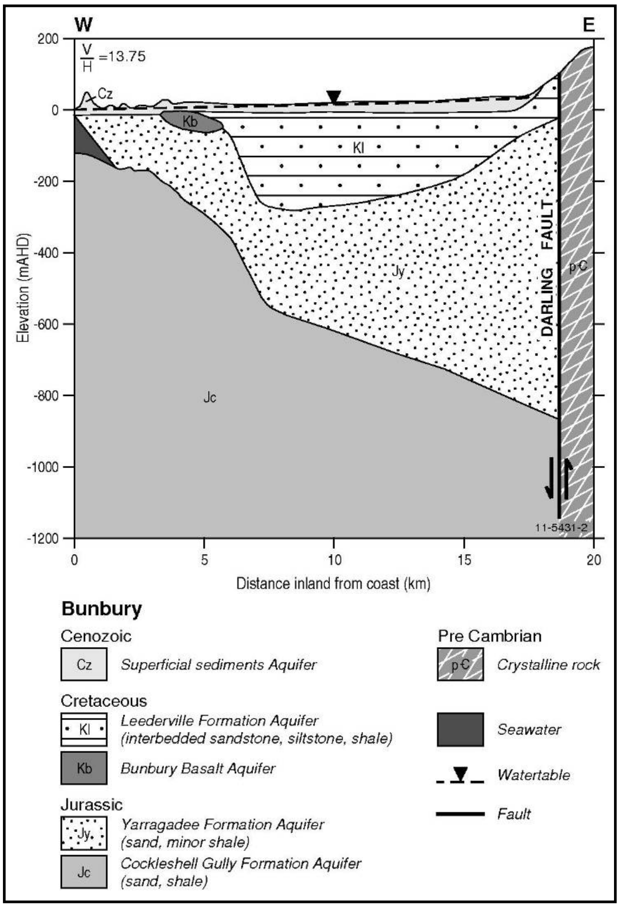


Figure 5.6. Cross-section through the Bunbury area, adapted from Plate 1, Section D, Commander (1982).

5.4.2 Busselton

Busselton is approximately 200 km south of Perth situated on the south-western coast of Australia on what is known as the Swan Coastal Plain. The region has a Mediterranean climate with cool wet winters and hot dry summers. The mean annual rainfall is ~810 mm. The land in the Busselton area is mostly used for mixed farming of horticulture, pasture production, viticulture, olives, plantation forestry, dairying and grazing. Along the coast there is urban and light industrial development.

In the Busselton area there are two regional aquifers known as the superficial aquifer and the Leederville aquifer (Figure 5.7). The Superficial aquifer is thin and unconfined. It comprises the Tamala Limestone, Bassendean Sand, Guildford Formation and Yoganup Formation. Due to the variability in the aquifer substrate, there is a large variation in its permeability. Recharge into the superficial aquifer occurs mostly by direct infiltration of rainfall and is greater over areas of cleared land. Groundwater flow is generally northward (Schafer et al., 2008).

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

The Permian Sue Coal Measures (Sue Aquifer) do not have well documented groundwater occurrence, though it has been estimated to contain fresh groundwater via leakage from the overlying Leederville Formation (Schafer et al., 2008).

The rate of flow and interconnection between the Leederville and Superficial aquifers is not significant (Panasiewicz, 1996b). Groundwater flow between the Leederville aquifer and the underlying Sue aquifer is also considered small. There is no significant interconnection with basement rocks of the Leeuwin Complex (Schafer & Johnson, 2009).

Near Busselton, unpublished data indicates strong hydraulic heads result in the seawater interface occurring offshore. The interface extends for 4-5 km, forming a wedge that increases in depth to the south. The interface cuts across the older succession of Jurassic (Leederville Formation) and Permian (Sue Coal Measures) sedimentary rocks. Groundwater levels in the area are monitored (Panasiewicz, 1996a).

AEM surveys have the potential to establish a baseline for monitoring of the SWI interface, as continuing and increasing groundwater use is likely to cause a decline in seaward groundwater flow gradients. By establishing a baseline seawater intrusion map of the Sue Coal Measures, future studies may compare the propagation of a seawater wedge in the Leederville Formation as a result of inland groundwater drawdown or changes in sea level. The AEM method can readily distinguish between the Leederville Formation and the underlying Sue Coal Measures. However a full technical risk assessment is required to establish whether AEM can map the key elements of the hydrogeological system.

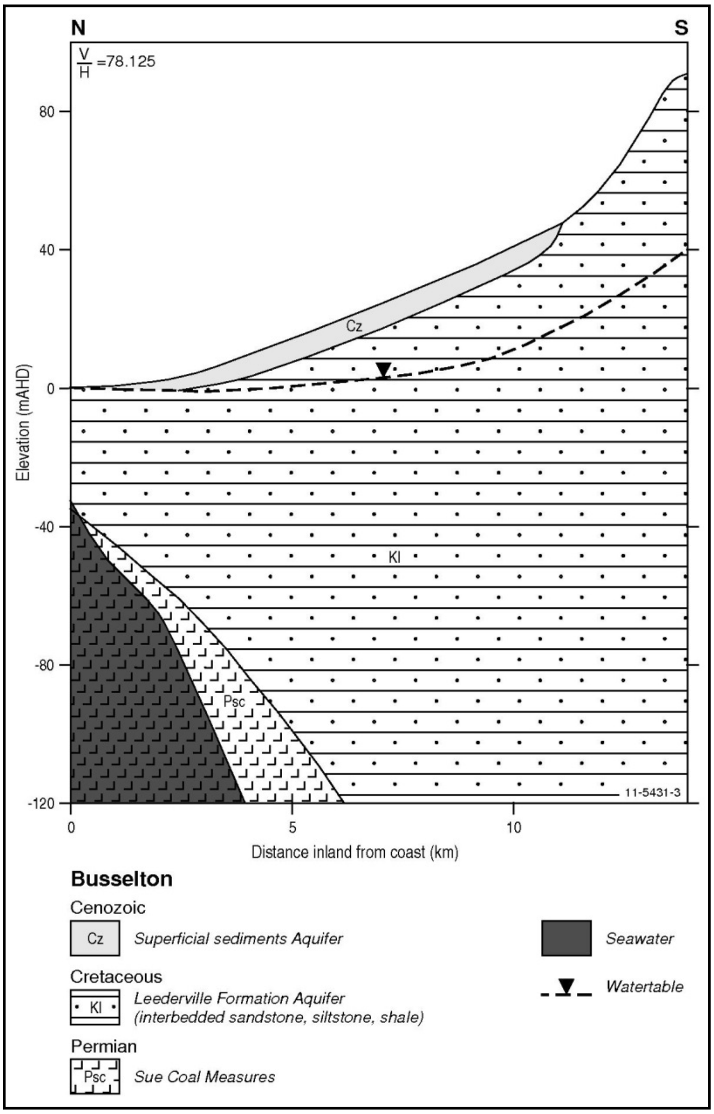


Figure 5.7. Busselton geological cross-section and interpreted seawater interface (Hirschberg, 1989).

5.4.3 Broome

Broome is in the southwest Kimberly region of Western Australia, on the 4 km wide Broome Peninsula, which lies at the southwest extremity of the Dampier Peninsula. Cable Beach and the Indian Ocean, and Roebuck Bay lie to the immediate west and east of Broome, respectively. Broome is approximately 1700 km north-northeast of Perth, and relies on groundwater for its potable water supply. Groundwater is also used for horticulture, watering of parks and gardens, domestic and industrial purposes. Most groundwater development is near the coast.

The Broome Sandstone forms a major unconfined aquifer in the area. A schematic cross-section through the Broome area is shown in Figure 5.8. The Broome Sandstone mainly consists of sandstone, with minor beds of grey siltstone and claystone. The grainsizes range from very fine to very coarse and there are minor thin pebble conglomerate bands. It thins eastwards from potentially 280 m thick near the coast to a zero thickness east of Mt Jowlaenga (Laws, 1984). There has been little hydraulic testing carried out on the Broome Sandstone to determine its hydraulic parameters. Groundwater flow is generally from the northeast to the south, southwest and west. The watertable is highest in the east.

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

Quaternary and Tertiary superficial deposits form an unconfined aquifer in the area. These sediments include sands, silts, clays and minor gravel. In the north of Broome, Quaternary Aeolian sands contain significant perched groundwater and to the southwest, the coastal dunes contain groundwater in hydraulic continuity with the Broome Sandstone.

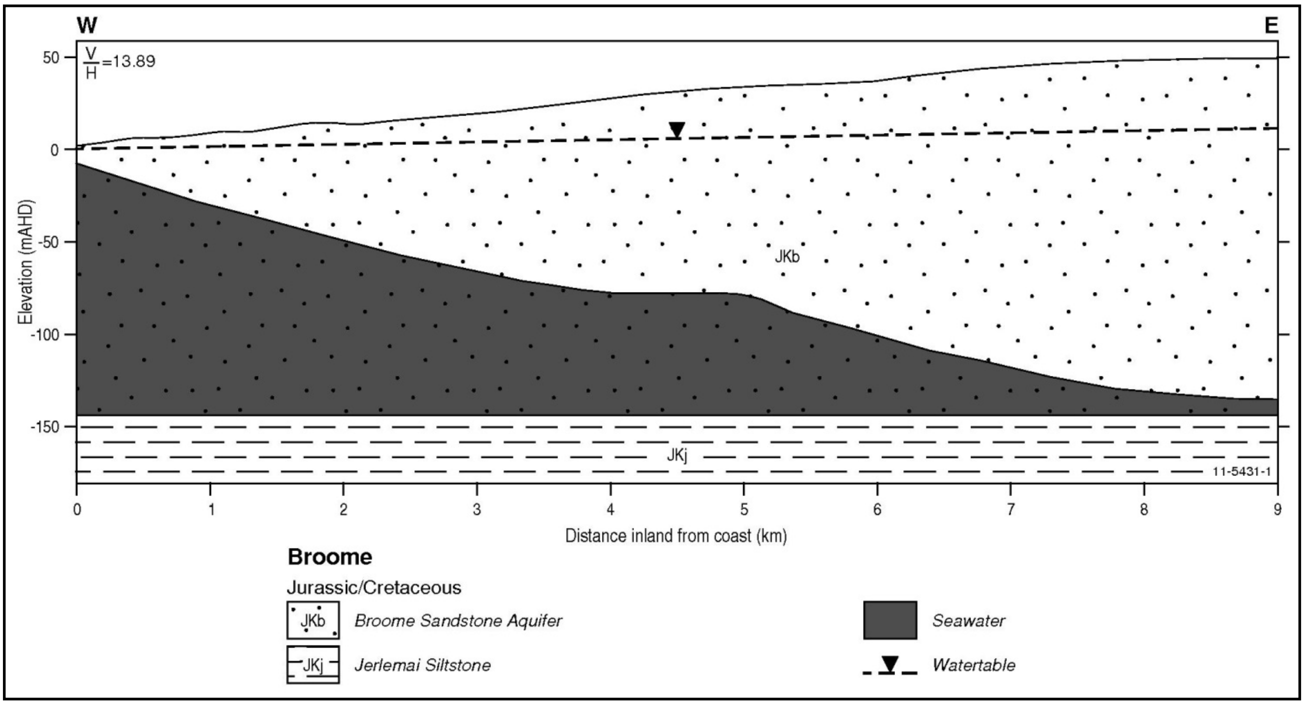


Figure 5.8. Broome geological cross-section and interpreted seawater interface (Laws, 1991).

SWI has been documented in the unconfined Jurassic-Cretaceous Broome sandstone aquifer as well as in the confined Jurassic Alexander Formation and Wallal Sandstone aquifer that lie below the Jerlemai Siltstone. Limited groundwater elevation and salinity data are available and no published reports were noted for this region that specifically addressed SWI.

AEM investigations may be worth pursuing further in coastal aquifers such as those at Broome, where there is a high conductivity contrast between the seawater wedge and fresh groundwater systems in coastal aquifers. AEM systems may be able to map the top SWI interface where it has considerable landward extent. Hydrogeological investigations suggest that there is potential for AEM systems to map the spatial extent of a ‘classic’ seawater intrusion wedge in the Broome sandstone aquifer (Figure 5.8). However, to date the EM response of the Broome sandstone aquifer is unknown, and will require further investigation via ground-based geophysics.

5.4.4 Carnarvon

Carnarvon is approximately 900 km north of Perth at the mouth of the Gascoyne River on the Indian Ocean. Carnarvon has an arid climate in which annual evaporation exceeds annual precipitation. Rainfall is unreliable, summers are hot and winters are mild. Average annual rainfall is ~230 mm with approximately 38 mm/month during winter and approximately 11 mm/month during summer. There is significant groundwater use both by public and private water supplies and the local horticulture industry in these areas (CyMod Systems Pty Ltd 2009). Within the Lower Gascoyne River the main agricultural activity is commercial horticulture. Within the wider Carnarvon catchment, the main land and water use is pastoral and mining. Groundwater is also used by for the town water supply and is supplemented by surface water when the river is flowing.

The hydrogeology in the Carnarvon region consists of two hydraulically connected, unconfined to semi-confined aquifer systems that are bounded to the west by a saltwater interface and to the east by a geological anticline (Figure 5.9). The principal aquifers for the region are the aggraded sand deposits within and below the Gascoyne River channel, known informally as the River Bed Sands (RBS). The thickness of these deposits varies from ~1-2 m to 18 m (CyMod Systems Pty Ltd, 2009). Older, deeper alluvial terraces provide a secondary aquifer with substantially greater storage, but less efficient recharge, known as the Older Alluvium Aquifer (OAA). A conceptualisation of the RBS aquifer overlying the OAA can be seen in Figure 5.9. Salinity levels and water quality are highly variable in the older alluvium aquifers. The flows in the Gascoyne River are intermittent, and during periods of river flow the aquifer systems are usually fully replenished.

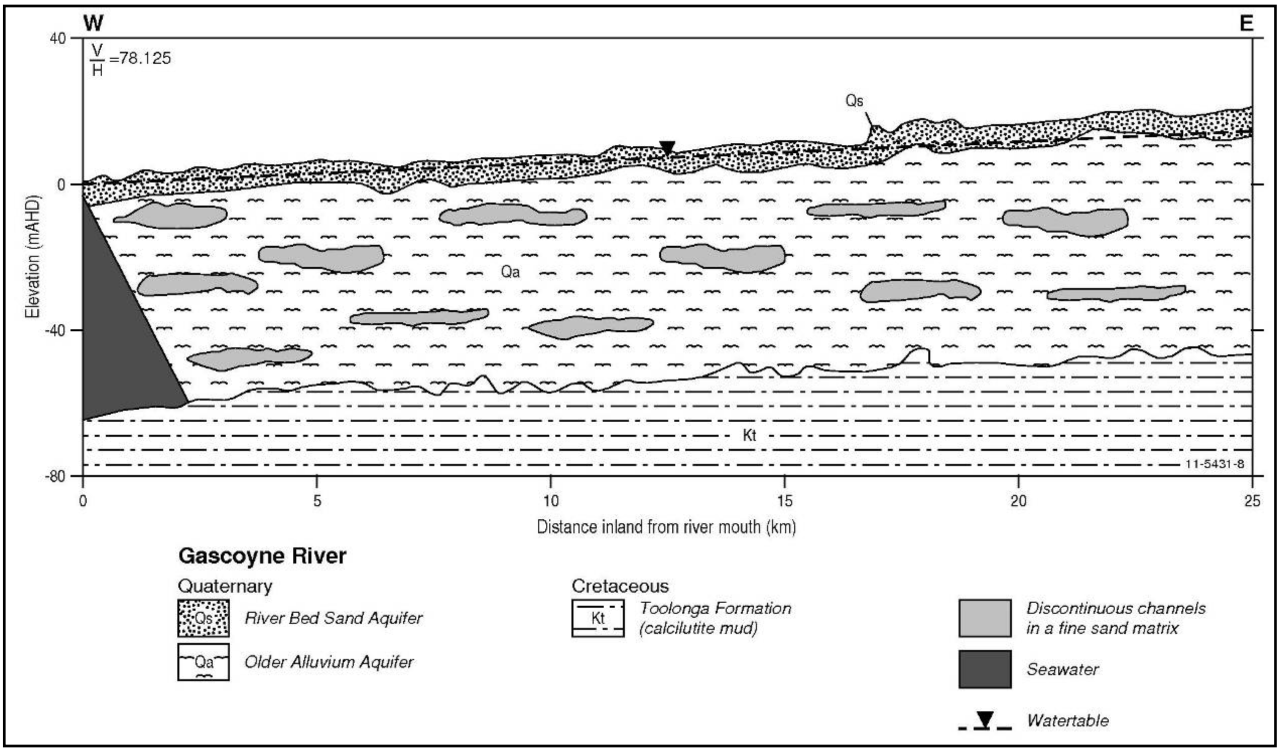


Figure 5.9. Cross-section of the Carnarvon area, after CyMod Systems Pty Ltd (2010).

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

The use and dependence on groundwater for the arid Gascoyne River region suggests the system is susceptible to a reversal of coastal groundwater gradients resulting in an influx of seawater into the groundwater system. Currently the region has groundwater resource management in place that mitigates salinisation by enforcing "cease to pump" measures. Should there be an increase in groundwater demand or prolonged dry climatic conditions, these measures may be ineffective. An AEM survey may be able to establish the current condition baseline for the region with regards to existing distance of seawater intrusion. This could aid resource management initiatives by identifying regions of the coast and river that are most likely to be affected as result of reduced inland head levels due to abstraction. A full technical risk evaluation would be required to assess the potential for AEM systems to map key elements of the hydrogeological system.

5.4.5 Derby

Derby is on the eastern side of King Sound, on a peninsula in the southwest Kimberly region of Western Australia, approximately 220 km northeast of Broome. The dominant land use is for beef cattle production on large pastoral leases. There is horticultural and other varied agriculture near Derby, which is an urban centre of approximately 3000 people. Derby is reliant on groundwater as a water supply (Groundwater Consulting Services Pty Ltd, 2008). 75 % of groundwater extracted from within the Wallal aquifer is used for domestic private use and the remainder is used for gardens and stock. Water extracted from the Lower Erskine aquifer is used for town water supply only.

In Derby, there are two major aquifer systems that are used for groundwater, the Wallal aquifer and the underlying Lower Erskine aquifer (Figure 5.10). The Wallal aquifer is unconfined and is hydraulically linked to the Upper Erskine aquifer, which contains relatively poor quality groundwater. The Wallal aquifer consists of the Meda Formation and the Wallal Sandstone. It is lithologically variable and therefore has varied aquifer transmissivity values (ranging from 90 – 630 m^2/day). It contains water that is low in salinity (< 200 mg/L), although it may have elevated levels of magnesium or iron. Recharge into the aquifer is through direct rainfall infiltration, and water from the aquifer is thought to discharge beneath mudflats near Derby (Groundwater Consulting Services Pty Ltd 2008).

Between the Wallal aquifer and the Erskine Sandstone, the Munkayarra Shale acts as an aquitard, except for where it has been eroded from an anticline beneath the Derby peninsula. The two aquifers are in hydraulic connection beneath Derby and the contact between the Wallal aquifer and Upper Erskine can be difficult to determine.

The Erskine sandstone comprises fine-grained sandstone and shale in roughly equal proportions. It is separated into two aquifers, the Upper and Lower Erskine aquifers, by a shale layer. This shale acts as an aquitard, and controls the distribution of SWI within the aquifer. The shale layer confines the Lower Erskine aquifer and this aquifer contains better quality groundwater than its upper counterpart. The Lower Erskine aquifer has transmissivity of ~16 m^2/day. Recharge occurs mostly from downward leakage from overlying aquifers and discharge occurs into the May River or directly into King Sound (Groundwater Consulting Services Pty Ltd, 2008).

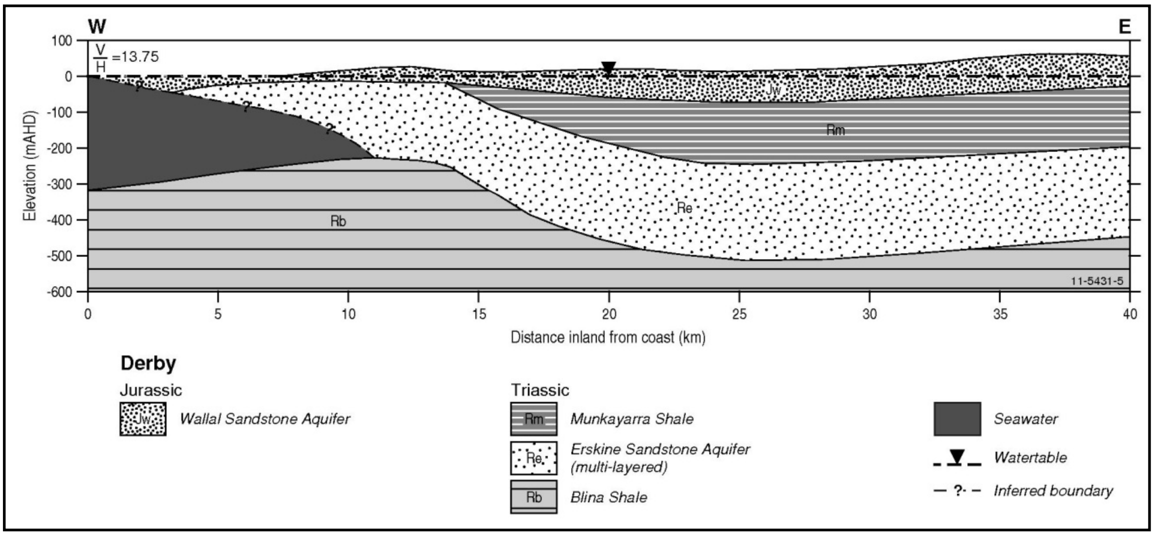


Figure 5.10. Cross-section through the Derby area, after Laws and Smith (1988).

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

The presence of shale layers in the Wallal and Erskine aquifers is likely to complicate the interpretation of AEM data and the delineation of seawater intrusion for the region. The total depth of the aquifer systems may allow AEM surveys to identify the upper bounds of a saline wedge. Further ground-based geophysical studies would be required to provide conductivity data to assist with assessment of the applicability of AEM in this scenario.

5.4.6 Esperance

Esperance is in the south eastern corner of Western Australia approximately 600 km east-southeast of Perth. Esperance is a growing tourist and retirement town that traditionally has been used for fishing and agriculture. Groundwater is used for the town water supply, domestic, agricultural and industrial supply, irrigating recreational areas, parks and gardens. Continued growth is expected for the area (Crisalis International Pty Ltd. 2010). An extensive area of saline alluvium occurs on the coastal plain behind the coastal sand dunes where saline lakes and wetlands are found. Ephemeral creek systems, draining from the north, flow into the wetland systems. An escarpment, which was probably an erosional shoreline, marks the inland extent of the coastal plain.

Quaternary and minor Tertiary sediments along the coastline form the regionally significant superficial aquifers (Department of Water, 2007) (Figure 5.11). The Quaternary coastal sediments, dune sands and limestone, are approximately 10-30 m thick and highly permeable, storing good quality water derived from rainfall. The underlying sediments contain brackish to saline groundwater, and are hypersaline near Pink Lake. The groundwater system has been represented by a schematic cross-section in Figure 5.11.

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

Conductivity mapping in the Esperance region may have the potential to assist in quantifying the extent of freshwater in the unconfined Quaternary aquifers. This information would help understand the volume of resources available and appropriate management strategies. A full technical risk assessment is required to assess whether AEM systems could possibly map the connection of saline groundwater between the oceanic waters and the inland Pink Lake. Depth maps of the underlying saline groundwater would assist in identifying areas of abstraction “up-coning”. However, a more comprehensive assessment of AEM suitability depends on more detailed evaluation of logistical and scientific issues.

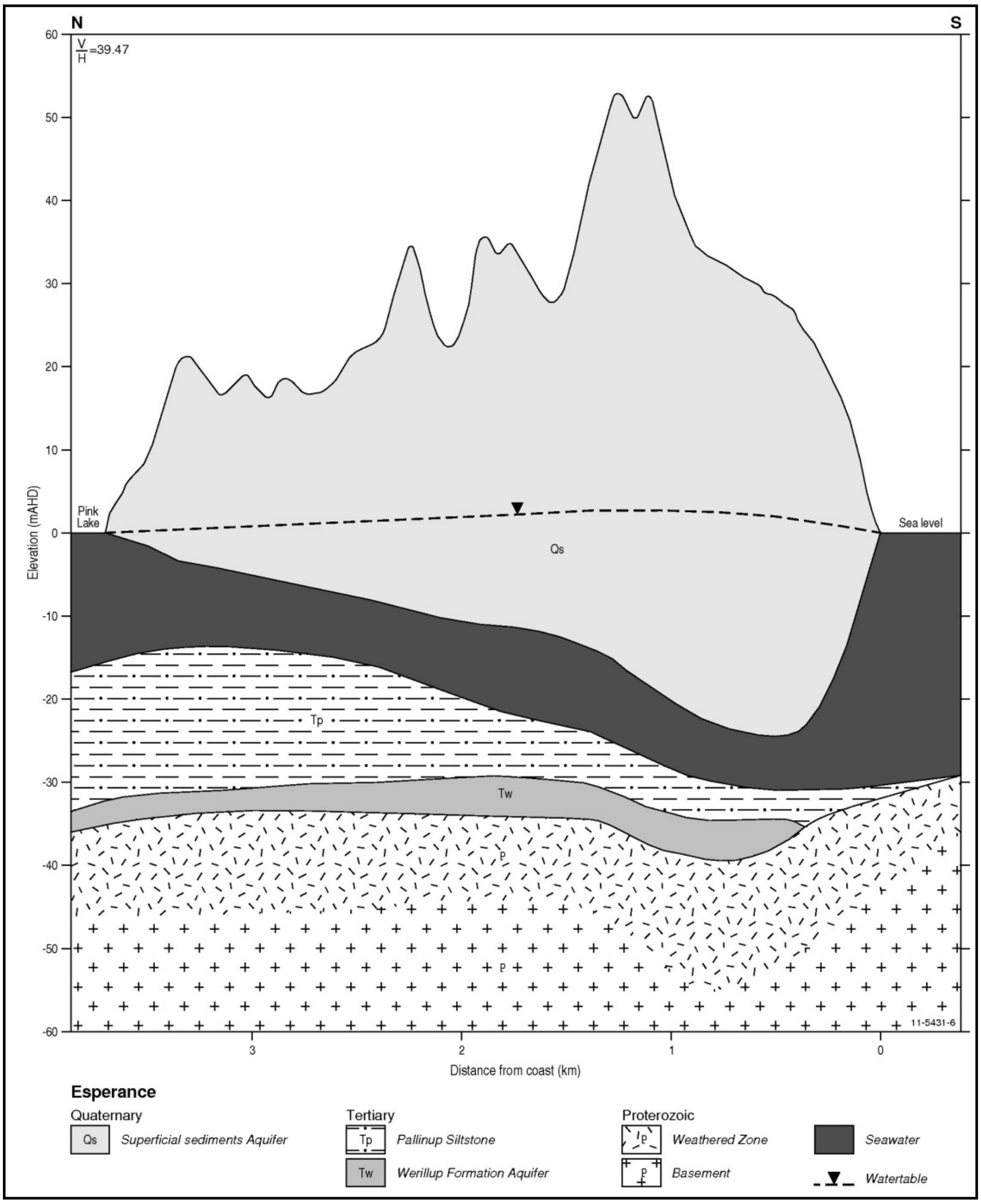


Figure 5.11. Esperance geological cross-section and interpreted sea water intrusion (after DoWWA, 2007)

5.4.7 Perth

Perth is the capital city of Western Australia, at the mouth of the Swan River and adjacent to the Indian Ocean. Groundwater in the Perth region is used mostly for the city's residential or industrial use as well as agriculture in the rural fringe. As the population continues to grow in Perth, groundwater use has also been increasing and is often added to surface water supplies for Water Authority reticulation.

In Perth, groundwater exists within Quaternary Superficial Formation sediments as an unconfined aquifer and in the deeper stratigraphic successions as confined to semi-confined aquifers. These can be visualised in Figure 5.12, which is a schematic cross-section through the area.

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

The deeper, confined aquifer systems are bound to the east by the Darling Fault and it is unknown how far they extend west. They comprise sandstones, greensands and chalk limestones and are inter-bedded with mudstones, shales and siltstones forming aquitards. The water within these aquifers ranges from approximately 600-37,700 years (Davidson, 1995).

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

A full technical risk assessment is required to assess whether AEM systems could map the Quaternary Superficial Formations and associated groundwater mounds and to assess whether it is possible to delineate the seawater intrusion fringe along the coast of the Superficial aquifer. The deeper Perth region aquifers present a greater challenge for the AEM method with depths of investigations towards the limits of contemporary AEM systems. The seawater interface for the deeper aquifer systems is thought to be off-shore and is unlikely to be detected by AEM due to the depth of overlying oceanic water and the depth of the aquifer systems. The urban footprint of Perth and aviation regulations may not allow AEM surveys to be conducted in the vicinity of the city. However, a more comprehensive assessment of AEM suitability is dependent upon a more detailed evaluation of logistical and scientific issues.

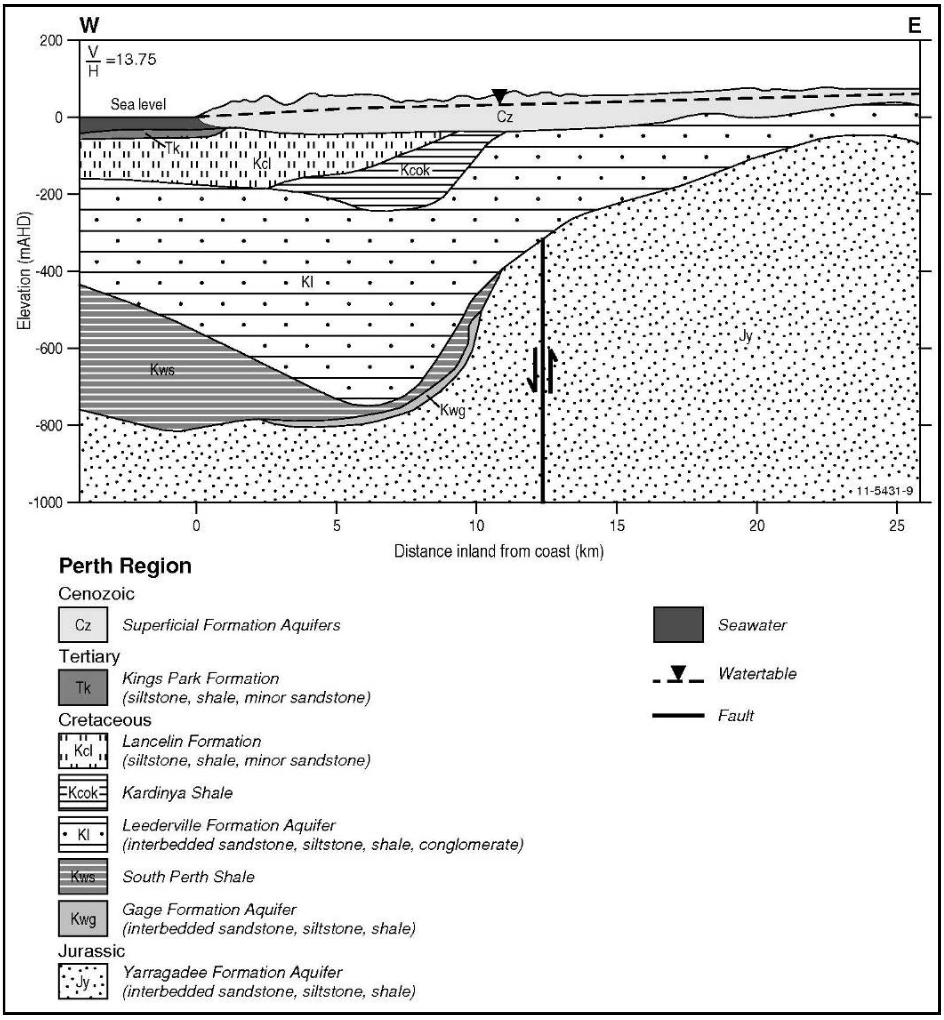


Figure 5.12. Cross-section through the Perth area, adapted from Fig. 10, Section B, Davidson and Yu (2008).

5.4.8 Fortescue Swamp

The problems associated with seawater intrusion and the technologies used to map SWI extent can also be applied to similar problems. For example, in the Fortescue Swamp in the Pilbara region of Western Australia, ingress of non-marine hypersaline waters as a result of mine operations, especially dewatering, are a potential risk to environmentally and culturally significant brackish water marshes. SkyTEM has been successfully used to map the subsurface distribution of saline water. This AEM data has assisted in mapping the 3D position of the salt interface and highlighted its heterogeneity. It has also delineated surface drainages and brackish groundwater processes, identified saline zones disconnected from principle flow mechanisms, and been used to assess transient saline-interface changes (De Roos et al*.,* 2010; Figure 5.13).

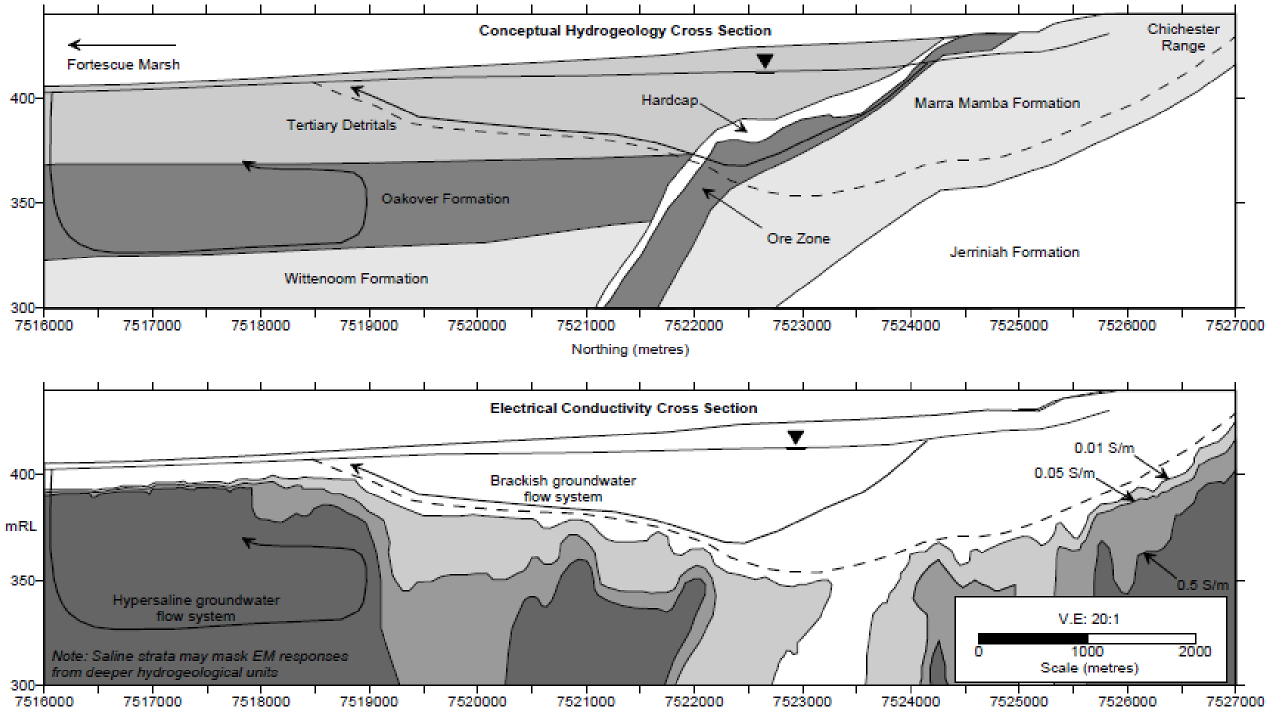


Figure 5.13. SkyTEM section through Fortescue Swamp and interpretation showing hydrogeological relationships between hypersaline waters at lower elevations and shallow and higher brackish water zone. From de Roos et al., (2010).

5.5 Victoria

5.5.1 Point Nepean

Point Nepean is approximately 60 km south-southwest of Melbourne at the end of the Nepean Peninsula, which separates Port Phillip Bay from Bass Strait. Point Nepean is highly urbanised, especially along the northern coastline. It contains some land dedicated to recreation or national park. Groundwater is allocated for both stock and domestic use. In the south-western Melbourne area, groundwater has been relied upon more heavily following years of decreased rainfall. 36 % of all of Southwest Melbourne groundwater licenses are in the Nepean zone, yet this area accounts for 72 % of all of the licensed volume in the area.

Point Nepean is the site of unconfined Quaternary and Tertiary aquifers. The heterogeneity of the aquifer sediments means that localised confined or perched aquifers can exist due to the presence of clay, sandy clay or palaeosol. Quaternary sedimentary aquifers dominate along the Nepean Peninsula. These sediments are generally highly permeable and groundwater flow is towards the west from the Mornington highland area, to Nepean Peninsula. Along Nepean Peninsula, parallel to the shoreline, there is a groundwater divide and groundwater either flows north into Port Phillip Bay or southward toward Bass Strait. This has resulted in a freshwater lens with the Quaternary aquifer, and a saltwater interface within the Tertiary aquifer. This lens is represented in Figure 5.14, which shows the narrow aquifer sediments whose distribution has been influenced by the orientation of the Nepean Peninsula.

A saltwater interface is present at depth at Point Nepean. Steady declines in water levels have been documented along the Nepean Peninsula since 1997 and these conditions are expected to continue, leaving Point Nepean at considerable risk to SWI.

AEM surveys may have the potential to map the SWI interface at Point Nepean, although a full technical risk assessment is required. Additional targets would include mapping of freshwater lenses and the extents of the fresh groundwater resource. This will allow for improved quantification of freshwater resources which will contribute to informed management practices. However, a more comprehensive assessment of AEM suitability is dependent upon a more detailed evaluation of logistical and scientific issues.

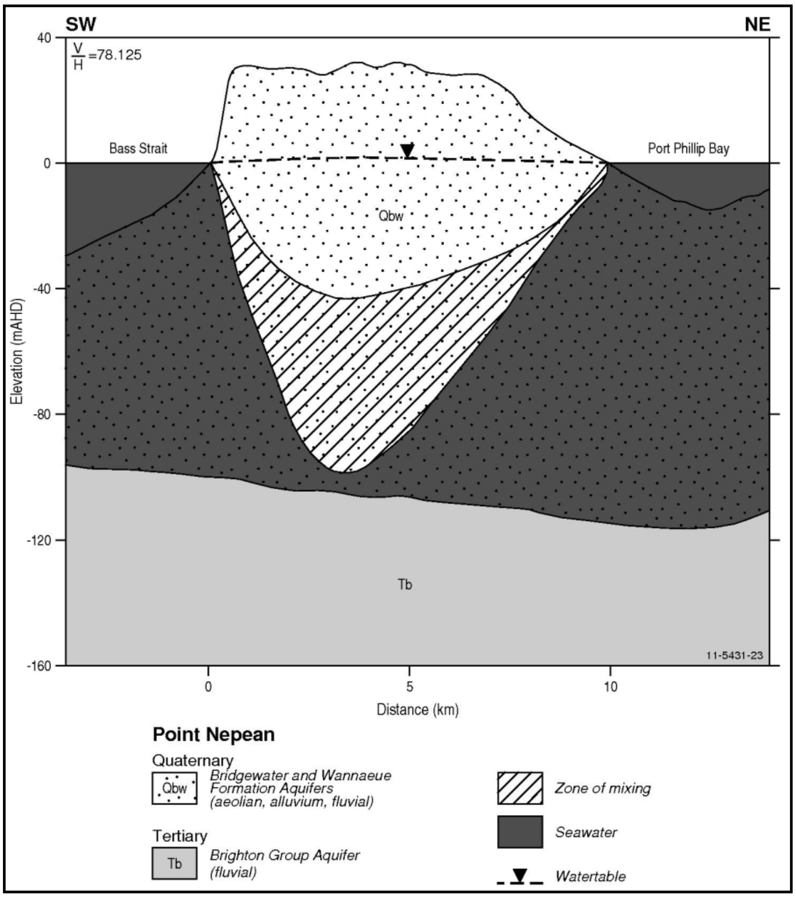


Figure 5.14. Cross-section through the Port Nepean area, adapted from Fig. 6 in Parsons Brinckerhoff (2010).

5.6 New South Wales

5.6.1 Stockton

Stockton is located immediately northeast of the city of Newcastle on the Newcastle Bight on the NSW coast. Groundwater is used for stock and domestic activities, sand mine and mineral processing, small scale irrigation as well as for industry.

The area contains two aquifers derived from the North Stockton Sandbeds and the Tomago Sandbeds. These two aquifers are usually hydraulically connected but are separated by estuarine mud forming a confining layer in some parts. This is shown as the Tilligerry Mud Member in Figure 5.15, which provides a schematic cross-section of the area. At the base of these aquifers the Medowie Clay member forms a continuous aquitard and the base is sloping away from the coast where it has a height of -20 mAHD to the Tilligerry Creek, at -40 mAHD.

Groundwater flow is both northwest, towards the estuary and southeast, towards the ocean, as a groundwater divide runs parallel to the coast along the centre of the aquifer. Recharge occurs primarily as infiltration into the dunes directly from rainfall and discharges occur to the ocean and Tilligerry Creek, as well as through evapotranspiration and via groundwater abstractions or engineered drains. Basement Carboniferous and Permian rocks are relatively impermeable and are not effective aquifers.

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

Of concern is the increased future use of groundwater in the Stockton region. Coastal sands by nature have low groundwater head levels and shallow seaward flow gradients. A reversal of head gradients can quickly occur as a result of unsustainable abstraction. An AEM survey could potentially provide a baseline to map the extent of the intrusion of saline water from Tilligerry Creek. As indicated there has been no increase of salinity at the coast. The mapping of the seawater interface along the coast of the Quaternary Stockton Sandbed aquifer would aid in understanding the current day status of the seawater wedge position and allow for comparative analysis against future surveys. However, a more comprehensive assessment of AEM suitability depends on more detailed evaluation of logistical and scientific issues.

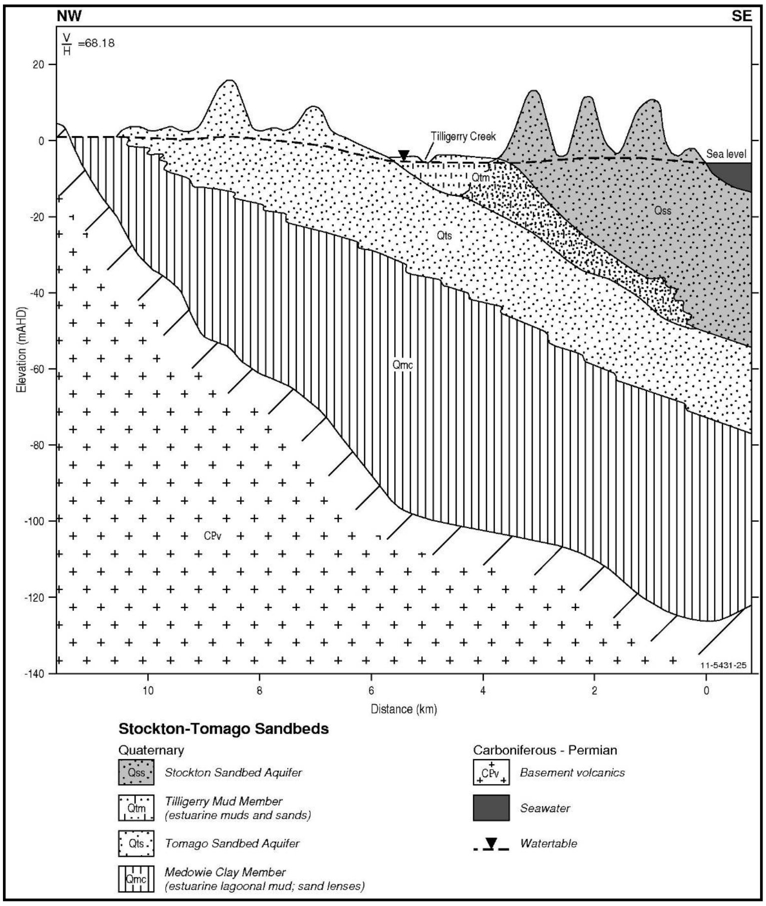


Figure 5.15. Cross-section through Stockton-Tomago Sand beds, adapted from Wooley et al., (1995).

5.6.2 Stuart's Point

Stuart's Point is located on the Mid North Coast in NSW, approximately 45 km northeast of Kempsey near Fisherman's Reach and Grassy Head. In the Stuart's Point area, groundwater is extracted for domestic use, town supply and horticulture. The dominant type of horticulture includes avocadoes, potatoes, flowers and stone fruit. There is a Nature Reserve immediately south of Stuart's Point.

A status report by DNR (2006) found there was clear evidence of seawater intrusion at Stuart's Point based on observed salinity increases. However, the reason for salinity increase was unclear (low rainfall, over extraction, or a combination). The impact of seawater intrusion to the entire aquifer was considered minor.

The aquifers at Stuart's Point are dominantly sands which can contain muds and clays when associated with the McLeay River or estuarine deposits (SKM, 2011). Groundwater within the aquifer exists either as a perched aquifer system or within a shallow, unconfined aquifer. The perched aquifers are extensive but not entirely laterally extensive. In parts, they are supported by an almost impermeable coffee rock layer, which is only locally extensive. This rock layer suppresses, though doesn't entirely inhibit, infiltration of groundwater as it creates a perched aquifer. The coffee rock is located approximately 2 – 5 m below ground. Below this, a shallow, sandy aquifer exists, which overlies a laterally extensive clay package. The two layers are hydraulically connected and have been included as one unit in this investigation. Beneath the clay layer, there is a deeper aquifer that contains groundwater with elevated arsenic concentrations (NSW 2004).

The aquifers receive the majority of their recharge from direct infiltration of rainfall into the sediments. Discharge occurs via subsurface flow to surface water bodies, groundwater abstraction and evapo-transpiration.

The Stuart's Point groundwater source is a coastal sands fresh groundwater resource that is susceptible to unsustainable extraction. The low inland head levels can result in readily reversed groundwater flow gradients and induced seawater intrusion. The locations of perched aquifers on top of indurated sands are at a lower risk of salinisation if they are above sea level, but are still susceptible to depletion from over abstraction. AEM surveying of the region has the potential to assist in mapping the extents and possible thickness of perched aquifers, and the quantification of those resources. However, a full technical risk assessment is required to assess whether AEM surveying can map groundwater/seawater interfaces within the unconfined coastal sands aquifer from both the coastal margin and the estuary of the Macleay River. A more comprehensive assessment of AEM suitability is dependent upon a more detailed evaluation of logistical and scientific issues.

6 Preliminary Assessment of AEM Suitability for Mapping Australian Carbonate-Karstic Aquifer Systems

Karstic aquifers are comparatively minor in Australia compared to other continents (Figure 1.3). Many of those are either limited in extent or occur in areas of saline groundwater. Those of importance all lie in coastal or near-coastal areas and are therefore potential candidates for SWI. Grimes (2006) identified syngenetic karst aquifers in Australia as limited to the western and southern coastal belts from Barrow Island around to Bass Strait. The following section briefly describes some representative karstic aquifers but is not a comprehensive review.

6.1 Lower Limestone Coast, South Australia

The Gambier Limestone is an Oligo-Miocene succession that occurs throughout much of the Otway Basin between eastern South Australia and western Victoria and is the major karstic aquifer for the Limestone Coast. It is a near flat-lying, highly porous bryozoan limestone (James et al., 1989) deposited on a cool-water shelf. The Gambier limestone is a major unconfined regional aquifer (Mustafa and Lawson 2002, Holmes and Waterhouse 1983) and extensively used for agriculture and industry. Karst is well developed (White, 1998) throughout the Gambier limestone. Karst distribution is strongly controlled by bedding and structure. Seawater intrusion is present in the south-western part of the Otway Basin, near Port MacDonald (Dixon-Jain et al., 2010). Minor karstic aquifers are also present in the overlying Bridgewater Formation which is a discontinuous but extensive unit of calcareous sands deposited as coastal dunes during the Pleistocene (Grimes, 2006). These are highly porous and have been partly indurated. Locally, well developed karst is present, despite their young geologic age. The formation has good examples of syngenetic karst (Grimes, 2006). The Bridgewater Formation is hydrologically connected with the unconfined aquifers of the Gambier Limestone (Holmes & Waterhouse, 1983).

Port MacDonnell is located in the southwest corner of South Australia, approximately 30 km south of Mount Gambier. The region surrounding Port MacDonnell hosts many industries and groundwater is the main source of water. Groundwater in Port MacDonnell is a part of the Gambier Basin, which is a sub-basin of the larger Otway Basin. The Gambier Basin is composed of a sedimentary sequence that was deposited intermittently from Jurassic through to recent times.

Information about the hydrogeology of Port MacDonnell was derived from King and Dodds (2002). Within the area there are two main regional aquifer systems that are separated by aquitards (refer to Figure 6.1). The main hydrogeological units are the Tertiary Gambier Limestone unconfined aquifer and the Tertiary Dilwyn Formation confined aquifer. These are separated by the Dilwyn Formation aquitard, which comprises poorly consolidated marls and clays. The Tertiary Gambier Limestone ranges in thickness from 100 to 300 m. The Gambier Limestone is a major unconfined regional aquifer (It has an intrinsic primary permeability and in some areas numerous karstic features have formed a well-developed secondary permeability. The Dilwin Formation is up to 800 m in thickness and is composed of interbedded quartz sand, finer grained sediment and clay horizons.

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

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

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

The relative simplicity of the stratigraphy of this area, the strong contrasts in the electrical conductivity signatures between the clay-rich Dilwyn aquitard and the limestone Gambier Formation and siliceous Dilwyn Formation aquifers, and the relatively low salinity groundwater in the producing aquifers suggests that AEM may be a useful tool in mapping the extent of seawater intrusion. However, any investment in such a study should be preceded by a thorough assessment of the suitability of candidate AEM systems, consisting of both theoretical and practical considerations as outlined previously.

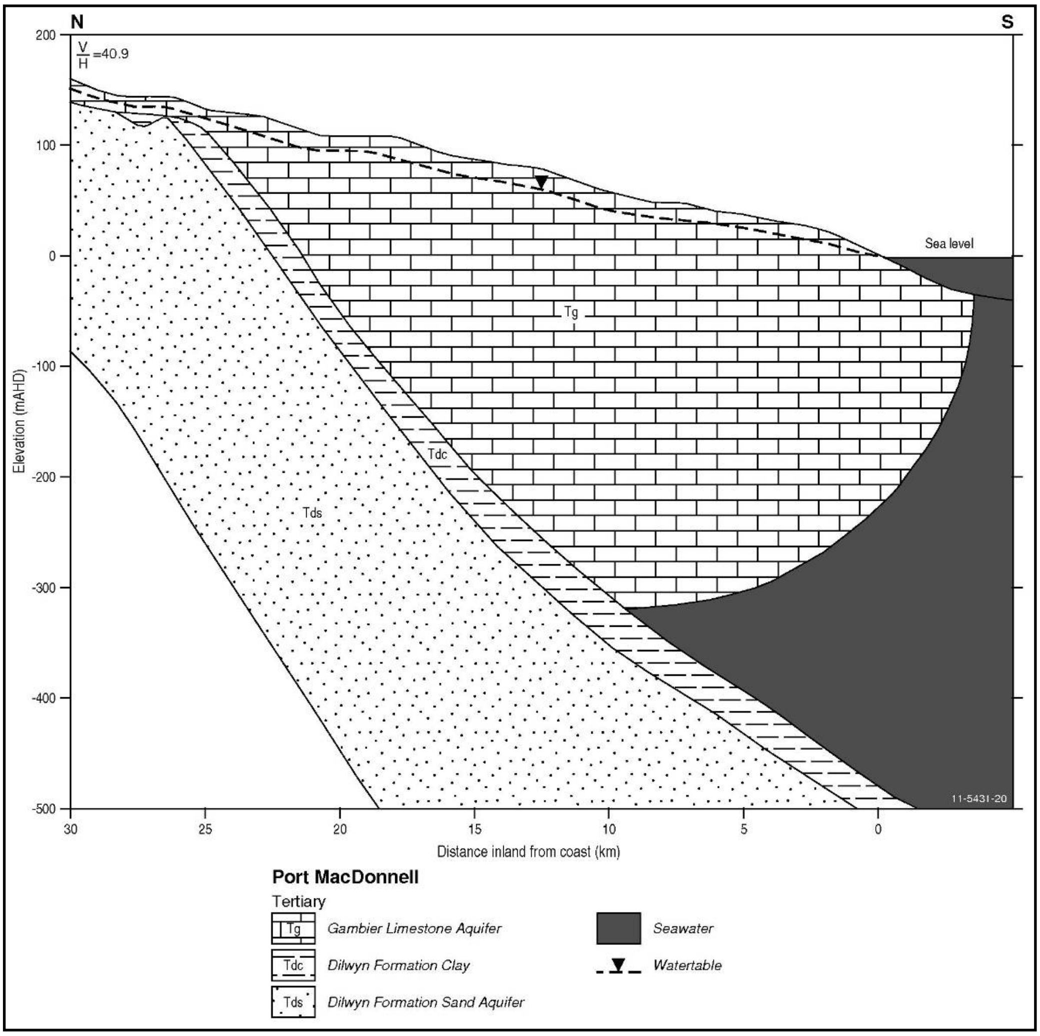


Figure 6.1. Cross-section through the Port MacDonnell area, adapted from Fig. 2 in King & Dodds (2002).

6.2 Exmouth (Cape Range), Western Australia

Exmouth is located ~1260 km to the north of Perth on the Cape Range peninsula, bounded to the west by the Indian Ocean and to the east by the Exmouth Gulf. Exmouth draws tourism and recreational activities and supports fishing, mining and pastoral industries. Potable water is limited to groundwater, which is carefully harvested from within the sensitive karst system (EPA, 1999).

Karstic aquifers are the most productive in the Cape Range area of Western Australia where they provide urban water supplies. Karst is developed in shallow marine to coastal carbonate sediments of the Miocene Cape Range Group (Allen, 1993; Wyrwoll et al., 1993). Although individual caves are poorly developed, in aggregate more than 300 are known; the dominant control on aquifer properties is along karstic enlarged fractures and pores.

The main freshwater groundwater resources are located in the hinterland within the Tertiary Cape Range Group. A cross-section through the aquifer system is shown in Figure 6.2. The Cape Range Group Tertiary limestone has been calcified to a depth of 50 m. This aquifer is unconfined to semi-confined. The Mandu Formation forms the base and each unit slopes towards the east. The deeper aquifers and Mezosoic to Palaeozoic basement rocks both contain saline water (Martin, 1990).

Recharge into the unconfined aquifers occurs predominately by direct rainfall infiltration or through the ephemeral streams while discharge occurs through abstraction, evapo-transpiration, flow into the ocean or via springs (Water and Rivers Commission, 1999). The watertable lies a couple of m above sea level near the coast and rises to 15 m in elevation towards inland (EPA, 1999).

In this area, there is likely to be less of an electrical conductivity contrast between limestone aquifers and marl aquitards. This may hinder distinguishing between saline groundwaters and fresher extractable waters in any AEM survey. The degree of karst development in aquifers and aquitards may also influence the ability of AEM to discriminate between ambient saline waters and intruding seawater. For this reason, any investment in an AEM study should be preceded by a thorough evaluation of existing hydrostratigraphic and hydrochemical information, before assessing the suitability of candidate AEM systems, consisting of both theoretical and practical considerations as outlined previously

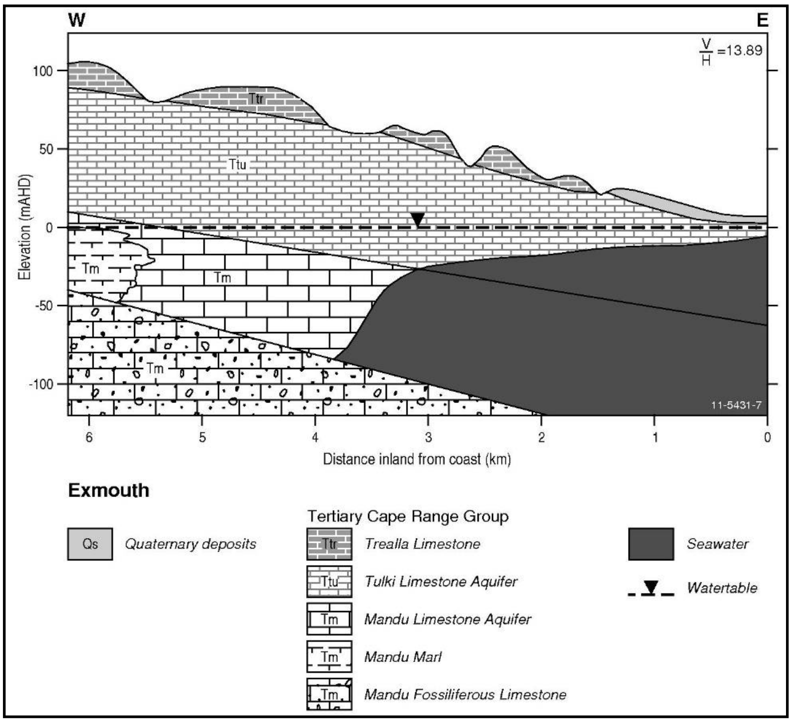


Figure 6.2. Cross-section through the Exmouth area modified from Fig 6 of Water and Rivers Commission (1999).

6.3 Rottnest Island, Western Australia

Rottnest Island is the largest of a chain of limestone islands and reefs on the WA continental slope, approximately 18 km offshore from Perth. It is approximately 10.5 km long and 4.5 km wide, oriented east to west. Surface runoff water is used for domestic consumption and groundwater is used for washing, showering and sanitary purposes within the Thompson Bay settlement. An increase in numbers of summer visitors to Rottnest Island has increased groundwater demand.

Groundwater exists within a sedimentary unconfined aquifer in the form of a freshwater lens that overlies brackish and salty water, as shown in Figure 6.3. The lens reaches 0.5 m above sea level and extends to 8.5 m below sea level (Leech, 1976). Below the freshwater lens, there is a gradation with depth to saltwater known as the zone of mixing.

Rottnest Island is an offshore extension of similar sediments to those found in the Swan Coastal Plain that were deposited during periods of low sea level. The island is composed largely of indurated calcareous sands (aeolinite), and like other sand islands has the potential for shallow freshwater lenses and SWI. The predominant aquifer is the Tamala Limestone, which is also the most widespread unit and occurs on the mainland. The Tamala Limestone is a correlate of the Bridgewater Formation in southern and eastern Australia and has similar characteristics (Searle et al., 1988; Grimes, 2006). Low salinity aquifers in the Formation are unconfined and, in the Swan Coastal Plain, commonly continuous with older aquifer units. Karst is well developed in Formation the south-western corner of Western Australia (Grimes, 2006).

The Herschell Limestone is a poor aquifer, because of its proximity to salt lakes and its low elevation. Dune sands are porous but do not form aquifers because they are above the watertable.

Recharge to Rottnest Island aquifers occurs through rainfall infiltration into sediments. During summer, the watertable falls due to lack of recharge. Confined Mesozoic aquifers have been assessed for suitability as a freshwater source for the island (Playford & Leech, 1977). These were found to be too saline for domestic use.

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

The lens of freshwater in the unconfined Tamala Limestone aquifer can be viewed as a vulnerable resource. The over-extraction of water is likely to result in the contraction of the freshwater lens and seawater encroaching into the aquifer. An AEM survey has the potential to map the extents of the freshwater lens, which could aid in water resource quantification and sustainable management practices. However, a full AEM technical risk assessment is required.

The applicability of AEM to map seawater intrusion in this aquifer system is not clear, as there is stratification of the groundwater and a significant mixing zone overlying the seawater interface. Given the relatively small scale of the area, monitoring of seawater intrusion using a well designed network of nested bores may well be more appropriate.

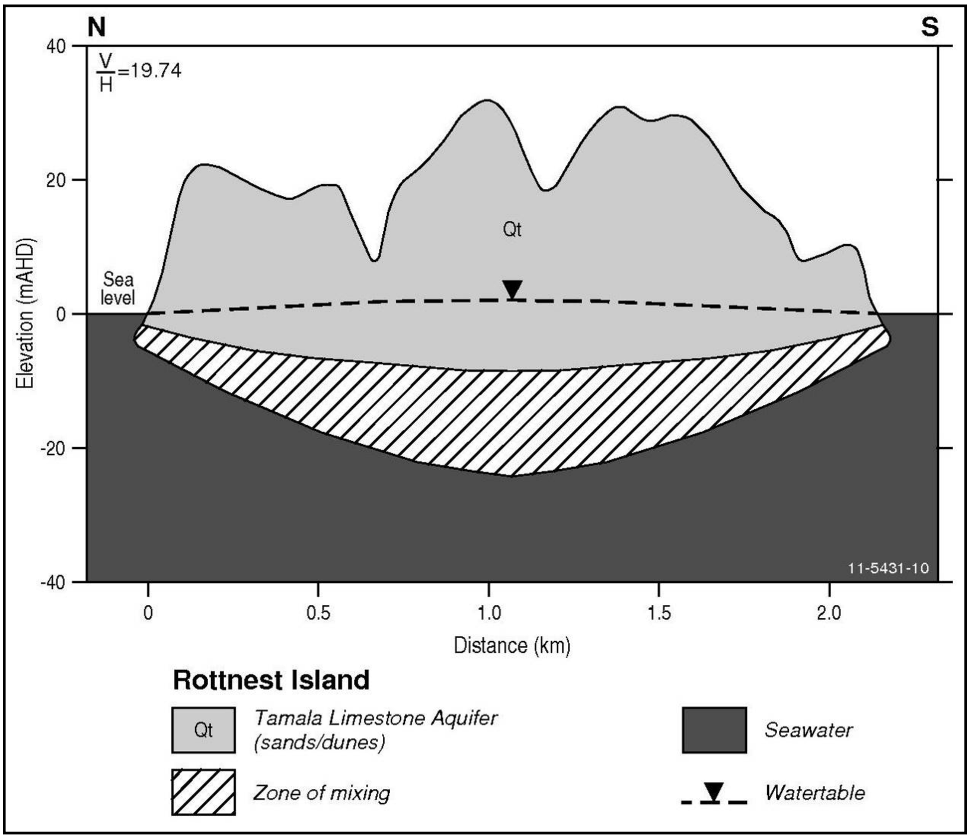


Figure 6.3. Cross-section through Rottnest Island, adapted from Fig 30, Playford. and Leech (1977).

6.4 Daly Basin, Northern Territory

Dolostones and karsts are important components of the aquifer systems that underpin horticulture and other agricultural developments in the Daly Basin. Significant springs derived from underlying dolomitic aquifers provide dry season baseflow to the Daly River which is considered the Northern Territory's most significant groundwater dependent ecosystem (GDE). The Daly River Basin shows strong connectivity between the Daly River and underlying Proterozoic dolostones with karstic porosity (Smeedon, 2010). With a strongly seasonal “spill and fill” character, the Daly River Basin supports a number of important groundwater dependent ecosystems that provide habits for endangered species, such as the pig-nosed turtle (NRETAS, 2010). The main aquifer is the Ordovician Oolloo Dolostone (Smeedon, 2010) which is highly productive and locally karstified.

Regional AEM data (5 km line-spacing) was collected in 2008 as part of Geoscience Australia's Onshore Energy Security Program using the TEMPEST time domain system (Figure 4.11). A small infill survey (200 m line spacing) was also acquired over a reach of the Daly River where major springs had previously been identified. Further investigations are required to map the potential surface-groundwater interactions along the Daly River using this infill AEM data. Potential also exists to further refine the hydrostratigraphy and karstic porosity of the Daly Basin using the existing regional AEM dataset.

6.5 Georgina Basin, Northern Territory/Queensland

The Georgina Basin (Randall, 1978) is a large basin with shallow-dipping to sub-horizontal sediments extending from the Northern Territory into Queensland. Cambrian limestone, with its complex diagenetic history (e.g. Radke, 1990; 1982), has extensive karstic porosity along fracture systems. Groundwater resources are primarily for stock and domestic use (ANRA, 2002). Major karstic aquifers include the Thorntonia Limestone and Camooweal Dolomite Formation. Insufficient data exists for preliminary assessment of the suitability of AEM methods to map the key elements of the hydrogeology in this Basin.

6.6 Smithton Dolomite, Tasmania

Replies to the Stakeholder Questionnaire for the National SWI Phase 2 report (Dixon-Jain et al., 2010) highlighted a number of heavily utilised groundwater basins in the far northwest coast of Tasmania, near Smithton. These are the Duck, Montague, and Welcome River catchment areas. Data on these appears limited with no published results. Groundwater recharge is from alluvial aquifers into fractured and karstic Proterozoic dolostones (the Smithton Dolomite). At the extreme northwest tip of Tasmania SWI is reported from the Woolnorth area to have occurred within the Tertiary limestone aquifer as a consequence of groundwater extractions (Cradle Coast NRM Committee, 2005). It is not known however whether this aquifer is karstic, intergranular or fractured rock in character. Comparison is roughly equivalent limestones near Mount Gambier would suggest that both intergranular and karstic porosity is likely to be present.

There was insufficient data to make any preliminary assessment of the suitability of AEM methods to map the key elements of the hydrogeology in this area.

7 Conclusions

There have been significant advances both in AEM technologies and data processing and modelling over the past decade. Almost as importantly, there is increasing sophistication in the use of this technology within multi-disciplinary systems approaches that use products derived from AEM surveys. Of equal importance, there is a broad realisation that AEM is only one technology, and despite the range of systems now commercially available, AEM may not be able to map the desired features for a range of hydrogeological, technical and logistic reasons. Other methods may also be more appropriate or cost-effective, depending on the scale of investigation and other logistic issues. For this reason, full technical risk assessments in the context of broader hydrogeological investigations are essential before committing to acquisition of an AEM survey.

These caveats notwithstanding, AEM surveys have been used very successfully in a wide range of landscape and hydrogeological settings in mapping SWI in complex geological environments. These include coastal alluvial sediments, fractured rock aquifers, and coastal carbonate-karstic systems. International examples include the Everglades (USA), Denmark, Galapagos Islands (Ecuador), Malaysia, Venice (Italy) and Aceh (Indonesia). Australian examples include Coffin Bay-Uley South, and the Coorong, and Lake Albert and Alexandrina (South Australia); the Roper and Ord Rivers (Western Australia), Northern Territory Coastal Plain (Northern Territory).

Internationally and nationally, AEM methods have also been used to map the hydrogeology of carbonate and dolomitic sediments of varying age and character, as well as to characterise karstic groundwater systems. International examples include Edwards Aquifer, Cooper Ridge, Camp Crowder and at the Oak Ridge National laboratory (USA), Denmark and Yucatan (Mexico). Australian examples are the Northern Territory Coastal Plain and Daly Basin (Northern Territory), and Renmark Group Limestones (South Australia).

In summary, AEM technology has the potential to be applied to the mapping and characterisation of SWI and carbonate-karstic groundwater systems in a wide range of additional landscape and hydrogeological settings in Australia. AEM may be of use in mapping SWI hazard in a number of priority sites identified as part of a national-scale vulnerability assessment (Ivkovic et al., 2012). More detailed hydrogeological and geophysical technical risk evaluation is required at each of these sites.

AEM may be of use in mapping and characterising the groundwater system in karstic systems. However, unlike many successful applications internationally, where AEM may only have to map variations in aquifer (karstic) porosity, many Australian examples are complicated by having to discriminate variations in porosity and groundwater salinity. This makes mapping of karstic systems more problematic in many settings. In general, higher resolution surveys may be required to map karstic porosity, which is typically smaller scale than SWI interfaces.

8 Recommendations

1. As with several earlier AEM-based studies (Lawrie et al., 2009, 2010a, 2011), a phased or staged approach should be employed for future AEM-based SWI and/or carbonate-karstic groundwater systems. Integrated assessments should be phased, and include:
   - Collation and review of existing information for the purpose of identifying critical knowledge gaps.
   - Scoping and technical risk evaluation to assess the methods and technologies best suited to addressing identified knowledge gaps.
   - A comparative system resolution analysis should be carried out to determine the optimal AEM system for particular survey aims (Christensen & Lawrie, 2012). The resolution of an AEM system depends critically on the achievable signal-to-noise ratio, and this must be factored in to any technical assessment.
   - An assessment of the scale of the groundwater systems and key elements to be mapped to ascertain the area to be flown and the appropriate flight-line spacing.
   - Integrated geoscientific studies to enable key elements of the hydrogeological system to be mapped, and groundwater flow and hydrogeochemical processes to be understood.
   - Data synthesis and interpretation using contemporary ‘systems’ approaches (Lawrie et al., 2000; Lane et al., 2004a, b; Spies & Woodgate, 2005; Lawrie, 2008; Lawrie et al., 2008, 2009, 2010, 2011, 2012), with an emphasis on delivering products that address specific issues and assist with the improved parameterisation of hydrogeological models.
   - Groundwater, surface-groundwater modelling and land use modelling to ascertain the sustainability of proposed developments. Modelling should utilise the best available climate data and modelling scenarios.
2. In considering AEM technology suitability for a particular mapping task, a range of parameters and their influence on the modelled ground response should be considered in comprehensive modelling studies. Such approaches include inversion analysis to compare systems. A pragmatic way forward may include:
   - Theoretical analysis based on noise figures that have been deemed reasonable by the analyst.
   - Test lines of field data for all systems in a range of hydrogeological settings.
   - Comparison of the contractors' own inversion of their test line data.
   - Inversion with a GOOD inversion program of all data sets for comparison.
3. The acquisition of AEM data for SWI and carbonate-karstic groundwater system mapping should only be considered within the context of the broader and integrated hydrogeological assessment of an area (Lawrie et al., 2010; 2012). Technical risk evaluation is required to gauge the merits of employing different geophysical approaches and technologies.
   - Acquisition of AEM data should only proceed after completion of scoping studies to assess the likelihood of success arising from their acquisition.
   - Scoping studies are required to identify target aquifers and groundwater systems, and the scale, depth and orientation of target objectives (where possible). This should then be

followed by completion of a technology suitability assessment exercise in each area. Technology selection should include forward modelling of system responses, and should follow the best practice procedures developed by the Commonwealth, taking particular note of the ability of AEM system to map key elements of relevant elements of the hydrogeological system.

– AEM data analysis and interpretation should follow a ‘hydrogeological systems’ approach based on the methodology recommended by the Joint Academies of Science Review of Salinity Mapping Methods in the Australian Landscape Context (Spies & Woodgate, 2005). Based on these recommendations, AEM-based projects need to incorporate a drilling program, complementary ground investigations and hydrogeochemical studies to ensure appropriate survey calibration, validation and interpretation.

Future AEM surveys should carefully consider the merits of using calibrated AEM systems and inversion software that can significantly shorten data acquisition and delivery timeframes. These technologies and methods can significantly shorten overall project timeframes and potential costs.

Acknowledgements

Matt Kendall, Alistair Usher, Adam Sincock and Shane Hogan from the National Water Commission are thanked for their support for the project. Des Yin Foo, Jon Sumner and Steve Tickell from NRETAS are thanked for many discussions about the dolomitic-karstic groundwater systems in the Northern Territory.

Ross S. Brodie and Phil Commander provided useful background information on Australia's carbonate-karstic aquifer systems. Baskaran Sundaram provided invaluable information, and time from his team members at Geoscience Australia, to provide input on the assessment of SWI hazard in Australia.

Laura Gow and Steve Lewis are thanked for the otherwise thankless task of editing and formatting this report. Steve and Jane Coram are thanked for reviewing the report.

References

Allen A. D., 1993. Outline of the geology and hydrogeology of Cape Range, Carnarvon Basin, Western Australia. Records of the Western Australian Museum Supplement No.45, pp. 25-38.

Allen, D., 2005. A Review of Geophysical Equipment applied to Groundwater and Soil Investigation. ANCID/Sustainable Irrigation Travel Fellowship Report. 77p.

ANRA, 2002. Groundwater Management Unit: Unincorporated Area – Georgina. Australian National resource Atlas, address when accessed 15/6/12 http://www.anra.gov.au/topics/water/availability/qld/gmu-unincorporated-area-georgina.html#char

Auken, E., Christiansen, A.V., Jacobsen, L. and Sørensen, K.I., 2005. Laterally Constrained 1D-Inversion of 3D TEM Data. SAGEEP 2005, Atlanta, USA, EEGS. Best of EEGS-NS 2004 papers. Proceedings of SAGEEP 2005, Atlanta, EEGS.

Auken, E., Pellerin, L., Christensen, N.B., & Sørensen, K., 2006. A survey of current trends in near-surface electrical and electromagnetic methods. Geophysics,Vol. 71, No. 5, September-October 2006; p. G249–G260.

Auken, E., Christiansen, A. V., Viezzoli, A., Fizpatrick, A., Cahill, K. & Berens, V., 2009a. Investigation on the groundwater resources of the South Eyre Peninsula, South Australia, determined from laterally constrained inversion of TEMPEST data. 20th International Geophysical Conference and Exhibition. Adelaide, South Australia.

Auken, E., Violette, S., d'Ozouville, N., Deffontaines, B., Sørensen, K. I., Viezzoli, A. & de Marsily, G., 2009b. An integrated study of the hydrogeology of volcanic islands using helicopter borne transient electromagnetic: Application in the Galápagos Archipelago. Comptes rendus - Géoscience 341(10): 899-907.

Bajracharya, K., Arunakumaren, J. & Huxley, W. J., 1998. Numerical modeling of seawater intrusion in Gooburrum, Bundaberg, Queensland. International Groundwater Conference, Groundwater: Sustainable Solutions. T. R. Weaver and C. R. Lawrence. Melbourne, Australia: 613–618.

Bajracharya, K., Moser, A., Heidke, K. & Werner, A. D., 2006. Regional scale instructional seawater intrusion model for the coastal Burnett region in Queensland. 30th Hydrology and Water Resources Symposium, 4 - 7 December 2006, Launceston, Tasmania.

Barlow, P. M., 2003. Ground water in freshwater-saltwater environments of the Atlantic Coast. Reston, Virginia, U.S. Geological Survey.

Barnett, S. R., 1976. Carpenter Rocks town water supply, Bores 1, 1A and 2 completion report, Report No. 76/41, Geological Survey, Engineering Division, Department of Mines, South Australia.

Barron, O. V., Crosbie, R. S., Charles, S. P., Dawes, W. R., Ali, A., Evans, W. R., Cresswell, R., Pollock, D., Hodgson, G., Currie, D., Mpelasoka, F., Pickett, T., Aryal, S., Donn, M. & Wurcker, B., 2011. Climate change impact on groundwater resources in Australia. In: Waterlines Report. Canberra: National Water Commission.

Bauer-Gottwein, P., Gondwe, B. R. N., Charvet, G., Marín, L. E., Rebolledo-Vieyra, M. & Merediz-Alonso, G., 2011. Review: The Yucatán Peninsula karst aquifer, Mexico. Hydrogeology Journal 19(3): 507-524.

Bedford, K., 1978. Report on groundwater resources: Pioneer Valley. Brisbane, Australia, Queensland Irrigation and Water Supply Commission, Queensland Government.

Brodie, R. & Sambridge, M., 2006. A holistic approach to inversion of frequency-domain airborne EM data. Geophysics 71(6): G301-G312.

Butters, S., Reid, M., Hone, I., Pain, C. F., Lawrie K. & McCauley, S., 2006. Australian government airborne electromagnetics project. Victoria. Techinical assessment of sites: 50.

Carey, H., Lenkopane, M. K., Werner, A. D., Li, L. & Lockington, D. A., 2009. "Tidal controls on coastal groundwater conditions: field investigation of a macrotidal system." Australian Journal of Earth Sciences 56(8): 1165-1179.

Chamberlain, T. & Wilkinson, K., 2004 (eds.). Salinity investigations using airborne geophysics in the Lower Balonne area, Southern Queensland. Queensland Department of Natural Resources and Mines, 257p.

Chen, D., 2001. North Stradbroke whole-of-island groundwater management model phase 3: Development of a computer model and user interface. Queensland, Groundwater Assessment Section, Department of Natural Resources and Mines.

Christensen, N.B., 2008. Approximate 1D inversion of the Bookpurnong SkyTEM Data Set. CSIRO Flagship Water for a Healthy Country Report CEM: P2008/1320, 24p.

Christensen, N.B. & Lawrie, K.C., 2012. Model Resolution Analyses for Selecting an Appropriate Airborne Electromagnetic (AEM) System. J. Applied Geophysics.

Commander, D. P., 1981. The geology and hydrogeology of Bunbury: Western Australia Geological Survey, Hydrogeology Report 2327 (unpublished).

Commander, D. P., 1982. An outline of the groundwater resources of the Mandurah-Bunbury region: Western Australia Geological Survey, Hydrogeology Report 2412 (unpublished).

Cresswell R. G., Mullen, I. C., Kingham, R. Kellett, J., Dent, D. L. & Jones, G. L., 2007. Airborne electromagnetics supporting salinity and natural resource management decisions at the field scale in Australia. International Journal of Applied Earth Observation and Geoinformation 9(2), p. 91-102.

Crisalis International Pty Ltd., 2010. Groundwater Modelling to assess the suitability of existing protection boundaries in Esperance Groundwater Area, unpublished report commissioned by the Western Australia Department of Water.

Cradle Coast NRM Committee, 2005. Cradle Coast Natural Resource Management Strategy, August 2005, Cradle Coast Natural Resource Management Committee, Burnie.

CyMod Systems Pty Ltd., 2009. The development of the Gascoyne River Floodplain Aquifers Modelling System GASFAMS V1, Volumes 1 and 2, September 2009, Prepared for Department of Water Western Australia.

CyMod Systems Pty Ltd., 2010. The development of the Gascoyne River Floodplain Aquifers Modelling System GASFAMS V1.1, Volumes 1 and 2, September 2010, Prepared for Department of Water Western Australia.

d'Ozouville, N., Auken, E., Sorensen, K., Violette, S. Marsily, G. de, Deffontaines, B. & Merlen, G., 2008. "Extensive perched aquifer and structural implications revealed by 3D resistivity mapping in a Galapagos volcano." Earth and Planetary Science Letters 269(3): 518-522.

Davidson, W. A., 1995. Hydrogeology and Groundwater Resources of the Perth Region, Western Australia. D. o. M. a. Energy, Geological Survey of Western Australia. Bulletin 142: 270.

Davidson, W. A. & Yu, X., 2008. Perth regional aquifer modelling system (PRAMS) model development: Hydrogeology and groundwater modelling, Western Australia Department of Water, Hydrogeological record series HG 20.

Deeney, A. C., 1988. Geology and groundwater resources of the Superficial Formations of the coastal plain between Pinjarra and Bunbury: Western Australia Geological Survey, Hydrogeology Report 1988/5 (unpublished).

De Roos, I. B., Jenke, G. & Brown, D., 2010 The use of SkyTEM geophysics in a salt water intrusion setting. SWIM21 - 21st Salt Water Intrusion Meeting, Azores, Portugal, 61-64

Department of Water, 2007. Esperance Groundwater Area, Water Management Plan, Department of Water, Government of Western Australia, Water Resource Allocation Planning Series Report No. WRAP 16.

Dixon-Jain, P., Ivkovic, K.M., Clarke, J.D.A, Wallace, L., Werner, A.D. & Sundaram, B., 2010. National-scale Vulnerability Assessment of Seawater Intrusion Project, Milestone 2 Report. Geoscience Australia non-circulated report.

DNR, 2006. Stuarts Point groundwater investigations 2005/2006 - Status report, August 2006, New South Wales Department of Natural Resources, Grafton.

Doble, R., Walker, G. & Simmons, C., 2005. Understanding spatial patterns of discharge in semi-arid regions using a recharge-discharge balance to determine vegetation health. CSIRO Land and Water Technical Report No 13/05. Adelaide: CSIRO. http://www.clw.csiro.au/publications/technical2005/tr13-05.pdf

Doble, R. C., Connor, J., Stenson, M., Elmahdi, A., Jolly, I. D., Miles, M. & Walker, G. R., 2008. Future landscape scenarios in the lower River Murray, south-eastern Australia and their implications for river salinity and floodplain health. Final papers of the 2nd International Salinity Forum, Adelaide, March 30-April 3rd, 2008. http://www.internationalsalinityforum.org/Final%20Papers/doble_E3.pdf

Doll, W. E., Nyquist, J. E., Beard, L. P. & Gamey, T. J., 2000. "Airborne geophysical surveying for hazardous waste site characterization on the Oak Ridge Reservation, Tennessee." Geophysics 65(5): 1372-1387.

EHA, 2005. Groundwater review of Southeast Queensland on-shore sandmass systems & sand islands, Draft North Stradbroke Island Report, GW-05-18-REP-002 Rev A, Report Prepared by Environmental Hydrology Associates (EHA Pty Ltd) for Queensland Department of Natural Resources & Mines.

EPA, 1999. Environmental protection of Cape Range Province, Position Paper No. 1, Environmental Protection Authority, Western Australia.

Evans, S. L., 2002. Southern Basins Prescribed Wells Area groundwater monitoring status report, South Australia. Department of Water, Land and Biodiversity Conservation. Report, DWLBC 2002/13.

Fish, J. E. & Stewart, M. T., 1991. Hydrogeology of the surficial aquifer system, Dade County, Florida. Water-Resources Investigations Report, U.S. Geological Survey ; Books and Open-File Reports [distributor]: v, 50 p. :ill. (some col.), maps ;28 cm.

Fitterman, D. V. & Deszcz-Pan, M., 1998. "Helicopter EM mapping of saltwater intrusion in Everglades National Park, Florida." Exploration Geophysics 29(2): 240-243.

Fitzpatrick, A., Apps, H., Clarke, J., and Lawrie, K., 2004. Mapping salt water intrusion and understanding water-rock interactions in saline aquifers in the lower Burdekin Delta - phase 1 report. Perth, Cooperative Research Centre for Landscape Environments and Minerals Exploration.

Fitzpatrick, A., Cahill, K., Munday, T. J. & Berens, V., 2009. Informing the Hydrogeology of Coffin Bay, South Australia, through the Constrained Inversion of TEMPEST AEM Data. Water for a Healthy Country Flagship Report series, CSIRO: 167.

Fountain, D., 1998. "Airborne electromagnetic systems - 50 years of development." Exploration Geophysics 29(2): 1-11.

Gamey T.J., Thompson M., Mandell W., Frano G. & Miller S., 2002. Karst pathway delineation using combined spatial and geophysical analysis at Camp Crowder, Missouri. Proceedings of the SAGEEP 2002, Expanded Abstracts.

Gerges, N., 1996. Overview of the hydrogeology of the Adelaide metropolitan area, South Australia. Department of Water, Land and Biodiversity Conservation. DWLBC Report 2006/10.

George, R., Lawrie, K.C. & Woodgate, P., 2003. “Convince me all your bloody data and maps are going to help me manage salinity any better ?” A review of remote sensing methodologies for salinity mapping. In Proceedings 9th PURSL (Productive Use of Saline Land) Conference, Yepoon, Qld. 14p.

Ghyben, B. W., 1888. Nota in verband met de voorgenomen putboring nabij Amsterdam (Notes on the probable results of the proposed well drilling near Amsterdam), Tijdschrift van het Koninklijk Institut van Ingeniers, The Hague: 8-22.

Green, A. and Munday, T.J., 2003. Forward modelling airborne electromagnetic data for the Riverland, South Australia. CRCLEME Open File Report 171.

Grimes, K. G., 2006. "Syngenetic Karst in Australia: a review." Helictite 39(2): 27-38.

Groundwater Consulting Services Pty Ltd., 2008. Study for Derby Groundwater Management Plan Review, unpublished report prepared for Western Australia Department of Water, Project DOW001.

Herzberg, A., 1901. "Die Wasserversorgung einiger Nordseebader (The water supply on parts of the North Sea coast in Germany)." Journal Gabeleucht ung und Wasserversorg ung 44: 815-819, 824-844.

Hirschberg, K.-J. B., 1989. Busselton shallow-drilling groundwater investigation, Perth Basin: Western Australia Geological Survey, Professional Papers, Report 25: 17-38.

Homes, J.. W. & Waterhouse, J. D., 1983. Hydrology. In Tyler, M. J., Twidale, C. R., Ling, J. K., and Holmes, J. W. (eds.) Natural History of the South East. Occasional Publications of the Royal Society of South Australia 3, Royal Society of South Australia Inc., 49-60.

Ivkovic, K.M., Dixon-Jain, P., Marshall, S.K., Sundaram, B., Clarke, J.D.A., Wallace, L. & Werner, A.D., 2012. Seawater intrusion in Australian coastal aquifers - literature review and project methodology, National-scale Vulnerability Assessment of Seawater Intrusion Project, Technical Report. Geoscience Australia and National Centre for Groundwater Research and Training, Unpublished report.

Jacobson, G., 1987. Hydrogeology of Australia. 1:5,000,000 scale map. Bureau of Mineral resource, Canberra.

James, N.P. & Bone, Y., 1989. Petrogenesis of Cenozoic, temperate water calcarenites, South Australia: a model for meteoric/shallow burial diagenesis of shallow water calcite sediments. Journal of Sedimentary Petrology 59,191-203.

Johnson, C. & Mifflin, M., 2006. "The AEM and regional carbonate aquifer modeling." Ground water 44(1): 24-34.

Kaegi, T., 2006. Seawater intrusion in a sand island aquifer dominated by a near-coastal freshwater wetland, The University of Queensland, Bachelor of Engineering Thesis, School of Engineering, Faculty of Engineering, Physical Sciences and Architecture.

King, H. J. & Dodds, A. R., 2002. Geophysical investigation of salt water invasion of freshwater aquifers in the Port MacDonnell area of South Australia. South Australia Department of Water, Land and Biodiversity Conservation. Report, DWLBC 2002/21.

Kirsch, R., 2006. Groundwater geophysics: a tool for hydrogeology. New York, Springer Berlin Heidelberg.

Lamontagne, S., Le Gal La Salle, C., Simmons, C., James-Smith, J., Harrington, N., Love, A., Smith, A., Hancock, G. & Fallowfield, H., 2005. Estimation of groundwater and groundwater N discharge to the Adelaide Coastal Waters Study area. ACWS Technical Report No. 4 prepared for the Adelaide Coastal Waters Study Steering Committee by the Flinders Centre for Coastal and Catchment Environments.

Lane, R., 2002. Ground and airborne electromagnetic methods. Open File Report 144. CRC LEME Perth.

Lane, R., Green, A., Golding, C., Owers, M., Pik, P., Plunkett, C., Sattel D., & Thorn, B., 2000. "An example of 3D conductivity mapping using the TEMPEST airborne electromagnetic system." Exploration Geophysics 31(2): 162-172.

Lane, R., Heislers, D. & McDonald, P., 2001. "Filling in the gaps ? Validation and integration of airborne EM data with surface and subsurface observations for catchment management ? An example from Bendigo, Victoria, Australia." Exploration Geophysics 32(4): 225.

Lane, R., Brodie, R.C. &Fitzpatrick, A., 2004a. Constrained inversion of AEM data from the Lower Balonne area, Southern Queensland, Australia. CRC LEME Open File Report 163.

Lane, R., Brodie, R.C, & Fitzpatrick A., 2004b. A revised inversion model parameter formulation for fixed wing transmitter loop – towed bird receiver coil time-domain airborne electromagnetic data. ASEG 17th Geophysical Conference and Exhibition, Sydney 2004.

Lawrie, K. C., Munday, T. J., Dent, D. L., Gibson, D. L., Brodie, R. C., Wilford, J., Reilly, N. S., Chan, R. A. & Baker, P., 2000. A ‘Geological Systems’ approach to understanding the processes involved in land and water salinisation in areas of complex regolith- the Gilmore Project, central-west NSW. AGSO Research Newsletter, v. 32, p. 13-32, May 2000.

Lawrie K. C., Pain, C. F., Gibson, D., Munday T. J., Wilford J. & Jones G., 2002. Regolith – a missing link in mapping salinity processes and predicting dryland salinity hazards. In Phillips, G.N. & Ely, K.S., (eds.), Victoria Undercover: Benalla 2002 Conference proceedings and field guide: collaborative geoscience in northern Victoria. p. 167-173. CSIRO Exploration and Mining.

Lawrie, K.C., Gray, M. Fitzpatrick, A., Wilkes, P., Lane, R., Pain C. & Lambert, I., 2003a. Assessing cost-effective salinity mapping strategies using a landscape- based approach for methodology and technology selection. In Submission to National Review of Salinity Mapping Methods and Technologies in the Australian Context. CRC LEME Open File Report.

Lawrie, K.C., Gray, M., Fitzpatrick, A., Wilkes P., & Lane, R., 2003b. Reducing the Acquisition Costs of Airborne Electromagnetics Surveys for Salinity and Groundwater Mapping. Preview, October 2003.

Lawrie, K.C., 2006. Land use questions and models of AEM targets report by technical working group chair on proposed River Murray Corridor (South Australian border to Gunbower) Victorian AEM mapping project. CRC LEME Restricted Report 265r. 27p.

Lawrie, K., Fitzpatrick, A., Clarke, J., Hatch, M., Kepic A., and Apps, H., 2006. Mapping salt water intrusion and understanding rock-water interactions in saline aquifers in the lower Burdekin Delta: Phase 2 Report, CRC LEME Restricted Report.

Lawrie, K., 2008a. To what extent can recent advances in salinity mapping and assessment create new salinity management and policy opportunities? 2nd International Salinity Forum (Plenary Address) Ext. Abs. http://www.internationalsalinityforum.org/Final%20Papers/lawrie_plenary.pdf

Lawrie, K.C., 2008b. Recent advances in the application of hydrogeophysics and regolith geoscience for groundwater and salinity mapping and management. AESC 2008. (Abs. Keynote Address).

Lawrie, K. C., Tan, K. P., Halas, L., Cullen, K., Pain, C. F., Brodie, R. C., Apps, H., Wong, V., Reid, M., Clarke J. & Gibson D., 2009. River Murray Corridor (RMC) Salinity Mapping and Interpretation Project: Report on the Barr Creek - Gunbower Island Region, Murray Basin, SE Australia.: 207.

Lawrie, K.C., Tan, K.P., Clarke, J.C., Munday, T.J., Fitzpatrick, A., Brodie, R.S., Apps, H., Halas, L., Cullen, K., Pain, C.F., Kuske, T.J. ,Cahill, K. & Davis, A., 2010a. Using the SkyTEM Time Domain Airborne Electromagnetics (AEM) System to Map Aquifer Systems and Salinity Hazard in the Ord Valley, Western Australia. Geoscience Australia Professional Opinion 2010/01, 500p.

Lawrie, K.C., Christensen, N.B., Munday, T.J., Brodie, R.C., Fitzpatrick, A., & Richardson, M., 2010b. Selecting an Appropriate Airborne Electromagnetic (AEM) System for Hydrogeological Investigation- a Discussion. Australian Society of Exploration Geophysicists (ASEG) Conference, Sydney. (Abs.)

Lawrie, K.C., Tickell, S., Sumner, J., Ley-Cooper, Y., Davis, A., Costelloe, M., Tan, K.P., Halas, L. & Cullen, K., 2010c. Utilising Airborne Electromagnetics (AEM) to Map Regional Hydrostratigraphy, and Karstic Aquifers in the Daly Basin, Northern Territory, Australia. Australian Society of Exploration Geophysicists (ASEG) Conference, Sydney. (Abs.)

Lawrie, K.C., Blackmore, D. & Kendall, M., 2011a. Australia's Groundwater Future. Paper to the Federal Government. www.groundwater2010.com. Geological Society of Australia. 12p.

Lawrie, K.C., Brodie R.S., Dillon, P., Tan, K.P., Halas, L., Christensen, N.B., Ley-Cooper, A.Y., Davis, A., Somerville, P., Smith, M.S., Apps, H.E., Magee, J., Gibson, D., Clarke, J.D.A., Page, D., Vanderzalm, J., Miotlinski, K., Barry, K., Levett, K., & Gow, L., 2011b. Securing Broken Hill's water supply: Assessment of groundwater extraction and conjunctive water supply options at Menindee Lakes. Geoscience Australia Professional Opinion 2011/02.

Lawrie, K.C. Brodie, R.S., Dillon, P., Tan, K.P., Gibson, D., Magee, J., Clarke, J.D.A., Somerville, P., Gow, L., Halas, L., Apps, H.E., Page, D., Vanderzalm, J., Abraham, J., Hostetler, S., Christensen, N.B., Miotlinksi, K., Brodie, R.C., Smith, M. & Schoning, G., 2012. BHMAR Project: Assessment of conjunctive water supply options to enhance the drought security of Broken Hill, regional communities and industries – Summary report. Geoscience Australia Record, 2012/15, 213p.

Laws A. T., 1991. Explanatory notes on the Broome 1:250 000 hydrogeological sheet. Geological Survey of Western Australia Hydrogeological series - explanatory notes, Department of Mines, Western Australia.

Laws, A. T., 1984. Broome hydrogeological map preliminary report, unpublished hydrogeology report 2575. Perth, Western Australia Geological Survey.

Laws, A. T. & Smith R. A., 1988. Derby Regional Groundwater Investigation. G. S. o. W. Australia.

Laycock, J. W., 1975. North Stradbroke Island - Hydrogeological Report. Geological Survey of Queensland. Report No. 88.

Laycock, J. W., 1978. "North Stradbroke Island, Papers, Department of Geology, University of Queensland." Papers of the Department of Geology, University of Queensland 8: 89-96.

Leech, R. E. J., 1976. Hydrology of Rottnest Island, Hydro Rept No. 1459, Water and Rivers Commission.

Ley-Cooper, A. Y., Macnae, J. and Viezzoli, A., 2010. "Breaks in lithology: Interpretation problems when handling 2D structures with a 1D approximation." Geophysics 75(4): WA179-WA188.

Maclay, R. W., 1995. Geology and hydrology of the Edwards Aquifer in the San Antonio area, Texas. Water-Resources Investigations Report, U.S. Geological Survey ; Earth Science Information Center, Open-File Reports Section [distributor]: v, 64 p. :ill., maps (some col.) ;28 cm. [PGS - 69 p.].

Macnae, J.C., 2007. Develooments in broadband airborne electromagnetics in the past decade. In Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration. 9-12 September, Toronto, Canada. (Ed. B. Milkereit). pp. 387-398. Prospectors and Developers Association of Canada, Toronto, Canada.

Martin, M. W., 1990. Exmouth town water supply investigation report and recommendations for future work, unpublished report, Western Australia Geological Survey, Perth.

McMahon, G., 2000. "Hydrogeological Conceptualisation of the Burdekin River Delta." Interactive Hydrogeology Hydro 2000 Proceedings(3rd International Hydrology Symposium of the Institution of Engineers, Australia, Perth 20 - 23 November 2000): 6.

Moser, A. B., Woodgate, M, McMahon, G, Heidke, K, & Evans, M., 2004. Coastal Burnett Groundwater Project Conceptualisation Report N. R. M. a. Energy. 1 of 3: 93.

Mullen, I.C., Wilkinson, K.E., Cresswell, R.G. & Kellett, J., 2007. Three-dimensional mapping of salt store in the Murray-Darling Basin, Australia 2. Calculating landscape salt loads from airborne electromagnetic and laboratory data. International Journal of Applied Earth Observation and Geoinformation, 9, 103-115.

Munday, T., Overton, I., Fitzpatrick, A., Tan, K.P. & Marsden, Z., 2009. Spatial modelling incorporating AEM data to show the effects of manipulating flow regimes and groundwater lowering options over the Chowilla floodplain, SA. ASEG 2009 Conference Extended Abstracts (1) 1 - 7

Munday, T.J., 2008. Regolith Geophysics. In Scott, K.M & Pain, C.F., (Eds.) Regolith Geology. pp. 219-250. CSIRO, 2008.

Munday, T.J., 2010. Regional Lines, Select Traverses, Calibrated Data - The Future for Airborne EM in Aquifer and Groundwater Characterisation? Groundwater 2010. Address when accessed 15/6/12 http://www.groundwater2010.com/documents/1DTimMunday.pdf

Munday, T.J. Overton, I. Fitzpatrick, A. Cahill, K. Berens, V. Hatch, M. & Brodie, R. C., 2007. Spatio-temporal monitoring of floodplain environments using electromagnetic methods: a scaled approach to understanding surface water- groundwater interactions on the Chowilla floodplain, S. Australia. In 20th SAGEEP, Denver.

Munday, T., Fitzpatrick, A. & White, J., 2008. Spatial Patterns of Groundwater Induced Salt Accumulation in a Salinising Floodplain and links with the Murray River, South Australia. AGU.

Murphy, S., Kuhanesan, S., Foster L. & Durick, A., 2005. Groundwater Investigation for the Amendment to the Pioneer Valley Water Resource Plan, Report 1: Conceptualisation of Groundwater Resources for the Pioneer Valley Flow Model, Water Assessment Group, Natural Resource Sciences, Queensland Department of Natural Resources and Mines.

Murphy, S. F. & Sorensen, R. C., 2000. Develop a water resource management strategy for the Mackay coastal aquifer system, Department of Natural Resources, Resource Management, Water Management and Use, Mackay.

Mustafa, S. & Lawson, J.S., 2002. Review of Tertiary aquifer properties, Gambier Limestone, Lower South-East, South Australia. South Australia. Department of Water, Land and Biodiversity Conservation. Report, DWLBC 2002/24.

Narayan, K. A., Schleeberger, C. & Bristow, K. L., 2007. "Modelling seawater intrusion in the Burdekin Delta Irrigation Area, North Queensland, Australia." Agricultural Water Management 89(3): 217-228.

Newman, G.A., Anderson, W.L. and Hohmann, G.W., 1987. Interpretation of transient electromagnetic soundings over three-dimensional structures for the central-loop configuration: Geophysical Journal of the Royal Astronomical Society, 89, p. 889-914.

NRETAS, 2010. Information Report for the Oolloo Dolostone Aquifer Water Allocation Plan. Address when accessed 19/6/12 http://www.nretas.nt.gov.au/__data/assets/pdf_file/0003/19254/info_report_oolloo.pdf

NRMW, 2006. Burdekin Basin draft water resource plan, environmental assessment report phase 1, current environmental condition volume 1, July 2006, Queensland Department of Natural Resources, Mines and Water.

NSW, 2004. Stuarts Point Groundwater Source. D. o. W. a. Energy. Water Sharing Plans: 2.

Paine, J. G. & B. R. S. Minty (2005). Airborne Hydrogeophysics. Dordrecht, Springer Netherlands. 50: 333-357.

Panasiewicz, R., 1996a. Busselton-Capel groundwater area saltwater interface monitoring bores-drilling proposal. Hydrogeology Report. Perth, Water and Rivers Commission: 12.

Panasiewicz, R., 1996b. Busselton-Capel Groundwater Area Saltwater Interface Monitoring Bores - Completion Report. Perth, Water and Rivers Commission.

Parsons Brinckerhoff, 2010. Groundwater resource appraisal for Southeast Melbourne, report prepared for Southern Rural Water Authority.

Peters, W.S., 2001. Ground electromagnetics: the basics and recent developments. Recent Developments and Future Directions in Geophysics. AIG Bulletin 33, p. 15-32.

Playford, P. E. & Leech, R. E. J., 1977. Geology and hydrology of Rottnest Island, Geological Survey of Western Australia, Report 6.

Radke, B. M., 1980. Epeiric carbonate sedimentation of the Ninmaroo Formation (Upper Cambrian-Lower Ordovician), Georgina Basin. BMR Journal of Australian Geology and Geophysics 5(3), 183-200

Radke, B. M., 1982. Late diagenetic history of the Ninmaroo Formation (Cambro-Ordovician), Georgina basin, Queensland and Northern Territory. BMR Journal of Australian Geology and Geophysics 7(4), 231-254

Randall, M. A., 1978. Hydrogeology of the southeastern Georgina Basin and environs, Queensland and Northern Territory. Queensland Dept. of Mines, Brisbane.

Reid, M., 2007. Hydrogeological Review of the Victorian side of the Murray River Floodplain AEM survey site (Gunbower Island to Lindsay-Wallpolla). CRC LEME Restricted Report 257R: 71.

Richardson, S. Evans, R., Haworth, D. & Prider, J., 2007. Tri-State Hydrogeological Benchmark Assessment. Resource & Environmental Management Pty Ltd. (Unpublished report).

Richter, B. C. & Kreitler, C. W., 1993. Geochemical techniques for identifying sources of ground-water salinisation, CRC Press, Boca Raton, FL.

Russell, R. R., 1996. Sustainability of supplies from a coastal aquifer and the impact of artificial recharge; LeFevre Peninsula, South Australia, MSc Thesis, School of Earth Sciences, The Flinders University of South Australia.

Sattel, D., 2005. Inverting airborne electromagnetic (AEM) data with Zohdy's method: Geophysics, 70 (4), p. G77-G85.

Schafer, D. B. & Johnson, S. L., 2009. Groundwater resource assessment of the Western Busselton-Capel groundwater area, Department of Water Hydrogeological record series, Report no. HG38, Government of Western Australia.

Schafer, D. B., Johnson, S. L. & Kern A. M., 2008. Hydrogeology of the Leederville aquifer in the western Busselton-Capel Groundwater Area, Department of Water, Hydrogeological Record Series, HG31.

Searle, D.J., Semeniuk, V. & Woods, P.J., 1988. Geomorphology, stratigraphy and Holocene history of the Rockingham-Becher Plain, south-western Australia. Journal of the Royal Society of Western Australia, 70(4), 89-109.

Sengpiel, K.P. and Siemon, B., 2000. Advanced inversion methods for airborne electromagnetic exploration. Geophysics, 65, p. 1983-1992.

Siemon, B. & Steuer, A., 2011. Airborne Geophysical Investigation of Groundwater Resources in Northern Sumatra after the Tsunami of 2004. The Tsunami Threat - Research and Technology. N.-A. Mörner, InTech.

SKM, 2011. NSW coastal GDE and aquifer modelling, Prepared by Sinclair Knight Merz for the NSW Office of Water.

Smeedon, B., 2010. Groundwater 2010. Linking the Oolloo Dolostone Aquifer and the Daly River, NT: using tracers and flow models to investigate connectivity. Address when accessed 19/6/12 http://www.groundwater2010.com/documents/7ABrianSmerdon.pdf

Smith, R., 2001. "On removing the primary field from fixed-wing time-domain airborne electromagnetic data: some consequences for quantitative modelling, estimating bird position and detecting perfect conductors." Geophysical Prospecting 49(4): 405-416.

Smith, B. D., Cain, M. J., Clark, A. K., Moore, D. W., Faith, J. R.. & Hill, P. L., 2005. Helicopter electromagnetic and magnetic survey data and maps, northern Bexar County, Texas. Open-File Report: 122 p. with digital data.

Smith, B. D., Smith, D. V., Hill, P. L. & Labson, V. F., 2003. Helicopter Electromagnetic and Magnetic Survey Data and Maps, Seco Creek Area, Medina and Uvalade Counties, Texas. Open-File Report: 53 p., 51 over-size sheet.

Smith, B.D., Smith, D.V. & Blome, C.D., 2008. Helicopter electromagnetic surveys of carbonate karstic aquifers with emphasis on recent applications by the U.S. Geological Survey: 5th International Conference on Airborne Electromagnetics, Haikko Manor, Finland, 4 p.

Sorensen, K. I. & Auken, E., 2004. "SkyTEM ? a new high-resolution helicopter transient electromagnetic system." Exploration Geophysics 35(3): 194.

Spies, B. & Woodgate, P., 2005. Salinity mapping methods in the Australian context. Land and Water Australia, Department of the Environment and Heritage; and Agriculture Fisheries and Forestry, June 2005. 236p. Website addressed when accessed 14/6/11 at http://www.nrm.gov.au/publications/books/pubs/salinity-mapping.pdf

Stadter, F. & Yan, W., 2000. Assessment of the potential use of the groundwater resources in the area south of Mount Gambier, Report Book 2000/040, Department for Water Resources, South Australia.

Supper, R., Ahl, A., Motschka, K., Ottowitz, D., Bauer, P., Alonso, G. M., Jochum, B. & Gondwe, B., 2009. "Spatial Mapping of Submerged Cave Systems by Means of Airborne Electromagnetics: Results from the 2008 Mapping Campaign in the Area Around Tulum, Yucatan." Symposium on the Application of Geophysics to Engineering and Environmental Problems 22(1): 499-510.

Tan, K.P., Apps, H., Halas, L., Gibson, D. & Lawrie, K., 2005. Utilizing airborne electromagnetic data to model the subsurface salt load. In: Zerger, A. and Argent, R.M. (eds.). A catchment, Bland Basin, NSW. MODSIM 2005, International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, 1478-1484. Website address when accessed 14/6/11 http://www.mssanz.org.au/modsim05/papers/ascough_1.pdf

Tan, K.P., Lawrie, K.C., Halas, L., Pain, C.F., Clarke, J.D.A., Gibson, D., Apps, H., Cullen, K., Brodie, R.C., & Wong, V., 2009. Methodology for the customised products developed as part of the River

Murray Corridor Victorian AEM mapping project. Geoscience Australia, Professional Opinion 2009/12, 75p.

Tan, K.P., Clarke, J.D.A., Halas, L., Lawrie, K.C., Apps, H.E., Brodie, R.C., Costelloe, M., Sumner, J., Fell-Smith, S., Christensen, N.B., Schoning, G.L., Halas, V., and Lewis, S.J., 2012. Northern Territory Coastal Plain: Mapping Seawater Intrusion in Coastal Plain Aquifers Using Airborne Electromagnetic Data. Geoscience Australia Record, 2012/41, Canberra. 210p.

Thomson, S., Fountain, D & Watts, T., 2007. Airborne geophysics- evolution and revolution. In Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration. 9-12 September, Toronto, Canada. (Ed. B. Milkereit). pp. 19-37. Prospectors and Developers Association of Canada, Toronto, Canada.

Tickell, S., 2009. Assessment Of Major Spring Systems In The Oolloo Dolostone, Daly River. NWC Groundwater Forum 24/25 November 2009.

Von der Borch, C.C., 1965. The distribution and preliminary geochemistry of modern carbonate sediments of the Coorong area, South Australia. Geochimica et Cosmochimica Acta 29, 781–799.

Walker, G., Cresswell, R., Munday, T. & Liddicoat, C., 2004. South Australian Salinity Mapping and Management Support Project: Final Report (Overall Project Summary Report), South Australia. Department of Water, Land and Biodiversity Conservation. Report, DLWBC 2004/39.

Wang, E., Miles, M., Schultz, T., Cook, P., Maschmedt, D., Munday, T., Leaney, T., Walker, G. & Barnett, S., 2005. Targeting Dryland Areas in the Mallee for Controlling Groundwater Recharge and Salt Load to the Murray River. Report to Client No. #/2005. CSIRO Canberra, ACT, Australia. Address when accessed http://www.clw.csiro.au/publications/consultancy/2005/WfHC_targeting_dryland_areas.pdf

Ward, J. D., Werner, A. D. & Howe, B., 2009. Saltwater intrusion in Southern Eyre Peninsula: Report developed through the Eyre Peninsula Groundwater Allocation and Planning Project.

Water and Rivers Commission, 1999. Groundwater allocation plan: Exmouth Groundwater Sub-area, Water and Rivers Commission, Water resources allocation and planning series report No. WRAP 9.

Werner, A. D. & Gallagher, M. R., 2006. "Characterisation of sea-water intrusion in the Pioneer Valley, Australia using hydrochemistry and three-dimensional numerical modelling." Hydrogeology Journal 14(8): 1452-1469.

Wharton, P. H., 1981. Geology and Hydrogeology of the Picton Line of Bores, Perth Basin. Record 1981/2.

White, S., 1998. Karst of the Cainozoic limestones of the Otway Basin, southeastern Australia. Suppl. Geogr. Pis. Dinanz. Quat. in, T. 4, 129-132, 3

Wooley, D., Mount, T. & Gill, J., 1995. Tomago Tomaree Stockton Groundwater Technical Review, NSW Department of Water Resources.

WRC, 2004. Managing the groundwater resources of the Lower Gascoyne River (Carnarvon) WA - Groundwater Management Strategy. Water and Rivers Commission.

Wyrwoll, K.H., Kendrick, G.W. & Long, J.A., 1993, The geomorphology and Late Cenozoic geomorphological evolution of the Cape Range – Exmouth Gulf region. Records of the Western Australian Museum Supplement No.45, pp. 1-23.

Yan, W. & Howe, B., 2008. Chowilla Floodplain Groundwater Model. Water Down Under Conference, Adelaide. p 1260-1271.

Zhang, Q., Volker, R. E. & Lockington, D. A., 2004. "Numerical investigation of seawater intrusion at Gooburrum, Bundaberg, Queensland, Australia." Hydrogeology Journal 12(6): 674-687.

Zulfic, D., Harrington, N. & Evans, S., 2006. Uley Basin groundwater modelling project, volume 2: Groundwater flow model, DWLBC Report 2007/04, Department of Water, Land and Biodiversity Conservation, Adelaide.