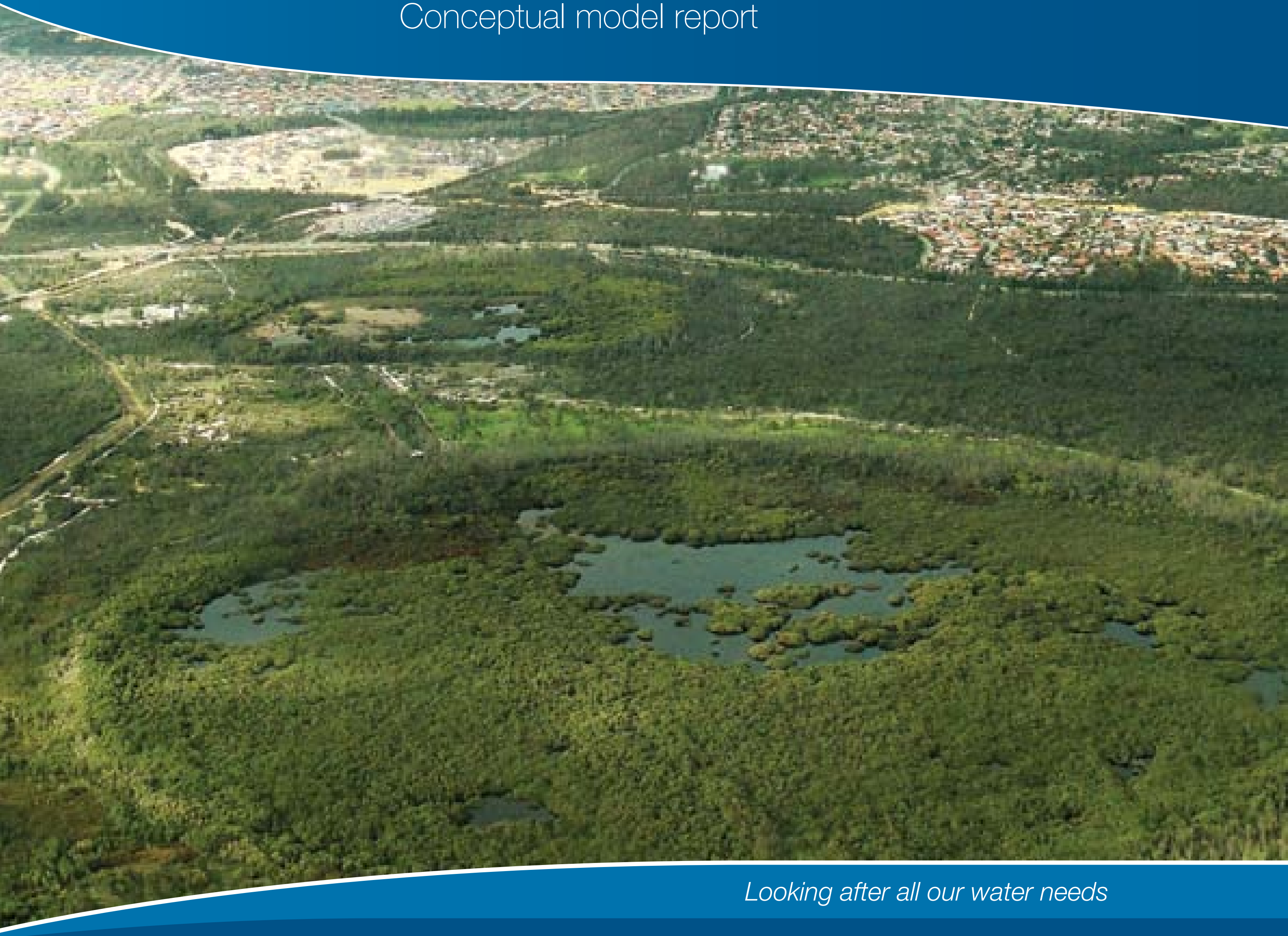
Government of **Western Australia**
Department of **Water**

Lower Serpentine hydrological studies

Conceptual model report



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March 2012

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Department of Water

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Cover photograph: Spectacles Wetland aerial view looking south by Ben Marillier, winter 2011.

Disclaimer

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Summary

This conceptual model report provides a conceptualisation of the surface water and groundwater systems in the Lower Serpentine study area. The conceptual model reflects data collation and analysis based on an extensive literature review, stakeholder consultation and data interpretation. This report is the first of three attached to the *Lower Serpentine hydrological studies*, a project initiated to support future drainage and water management plans (DWMPs) for the region.

A DWMP is a key step in the planning process: it is vital to the development of structure plans that support urban growth, future development and environmental management.

Study area

The Lower Serpentine hydrological study area is a section of the Swan Coastal Plain between the Jandakot Mound in the north and Dirk Brook in the south, and from the Darling Scarp in the east to the ocean in the west. The area receives average annual rainfall of 813 mm along coastal areas and 919 mm at the Darling Scarp, with evaporation averaging around 1675 mm. Elevation varies from 0 to 80 mAHD, with many of the low-lying areas becoming inundated in winter as a result of the Superficial Aquifer's shallow watertable. The area's extensive network of agricultural drains alleviates waterlogging in some parts; its major waterways include the Serpentine River, Peel Main Drain and Birriga Main Drain.

Geology and hydrogeology

An extensive literature review and interpretation exercise was undertaken to develop a three-dimensional conceptual model of the regional geology from the Jurassic to Quaternary period. The descriptions and mapped extents of all formations and members are provided.

Three aquifers are considered in the hydrogeological analysis: the Superficial, Rockingham and upper Leederville (Wanneroo and Pinjar members). Descriptions of the aquifers and aquifer hydraulics are discussed in the context of numerical conceptualisation and modelling, including important aquifer parameters. Horizontal hydraulic conductivities vary between less than 1 m/day in clayey formations and 10 to 20 m/day in sandy formations, to greater than 100 m/day in the Tamala Limestone. Potentiometric and phreatic surfaces were developed for the Superficial, Rockingham, Leederville and Cattamarra aquifers.

Rivers

Hydrographs for the major rivers and drains within the catchment were analysed to identify the groundwater baseflow contribution. A mass balance was also developed for the surface water system to determine relative inflows and outflows to the study area.

Numerical conceptualisation

The conceptual model is based on the collation of hydrological, hydrogeological, geological, climatic and topographical information gathered as part of the literature review and data interpretation process. A numerical steady-state water balance conceptual model was developed that includes surface water, groundwater and their interaction. Gross recharge to the Superficial Aquifer as a percentage of rainfall was estimated as 42.5%. Annual losses as

a percentage of total losses from the Superficial Aquifer were estimated as follows: evapotranspiration 61.4%, drainage to surface water 18.5%, abstraction 12.1%, vertical discharge to deeper aquifers 6.2%, net horizontal flow 1.8%. As vertical leakage comprised a significant component of losses from the Superficial Aquifer, the model domain included the Leederville and Rockingham aquifers. Water balance calculations for these aquifers are described in this report.

1 Introduction

The Western Australian Planning Commission (WAPC) and local government authorities have prioritised the implementation of structure plans for areas experiencing urban growth pressure. Structure plans guide the development of these areas and help manage key environmental issues (WAPC 2007). A key step in the process is the creation of a drainage and water management plan (DWMP). A DWMP sets the standard for an area's total water cycle management and provides a framework for more site-specific water management plans. It addresses the following aspects of the total water cycle:

- significant environmental assets – including meeting their water requirements and managing the potential impacts of development
- water demand – including supply options, opportunities for conservation and demand management measures, as well as wastewater management
- surface runoff – including both peak event (flood) management and water sensitive urban design principles to be applied to frequent events
- groundwater – including the impact of urbanisation, variation in climate, installation of drainage to manage groundwater levels, possible effects on the environment and the potential to use groundwater as a resource
- water quality management – including source control of pollution, acid sulfate soil management, control of contaminated discharges from industrial areas and management of nutrient exports from surface runoff and groundwater through structural measures.

To support the DWMPs planned for the Lower Serpentine region, the Department of Water's Urban Water Management Branch has instigated the following projects:

- a floodplain strategy for Birriga and Oaklands drains including inundation and local catchment stormwater modelling
- hydrological studies to determine pre-development groundwater levels, water balance modelling, climate impacts, extent of current waterlogged areas and impact of development
- preparation of the Birriga and Oaklands drains DWMP
- planning for future DWMPs for the Lower Serpentine area.

The Department of Water's Water Science Branch was commissioned to deliver the 'hydrological studies' project. The area specified for the hydrological studies, referred to as the 'modelling boundary', comprises the Serpentine regional model domain shown in Figure 1-1.

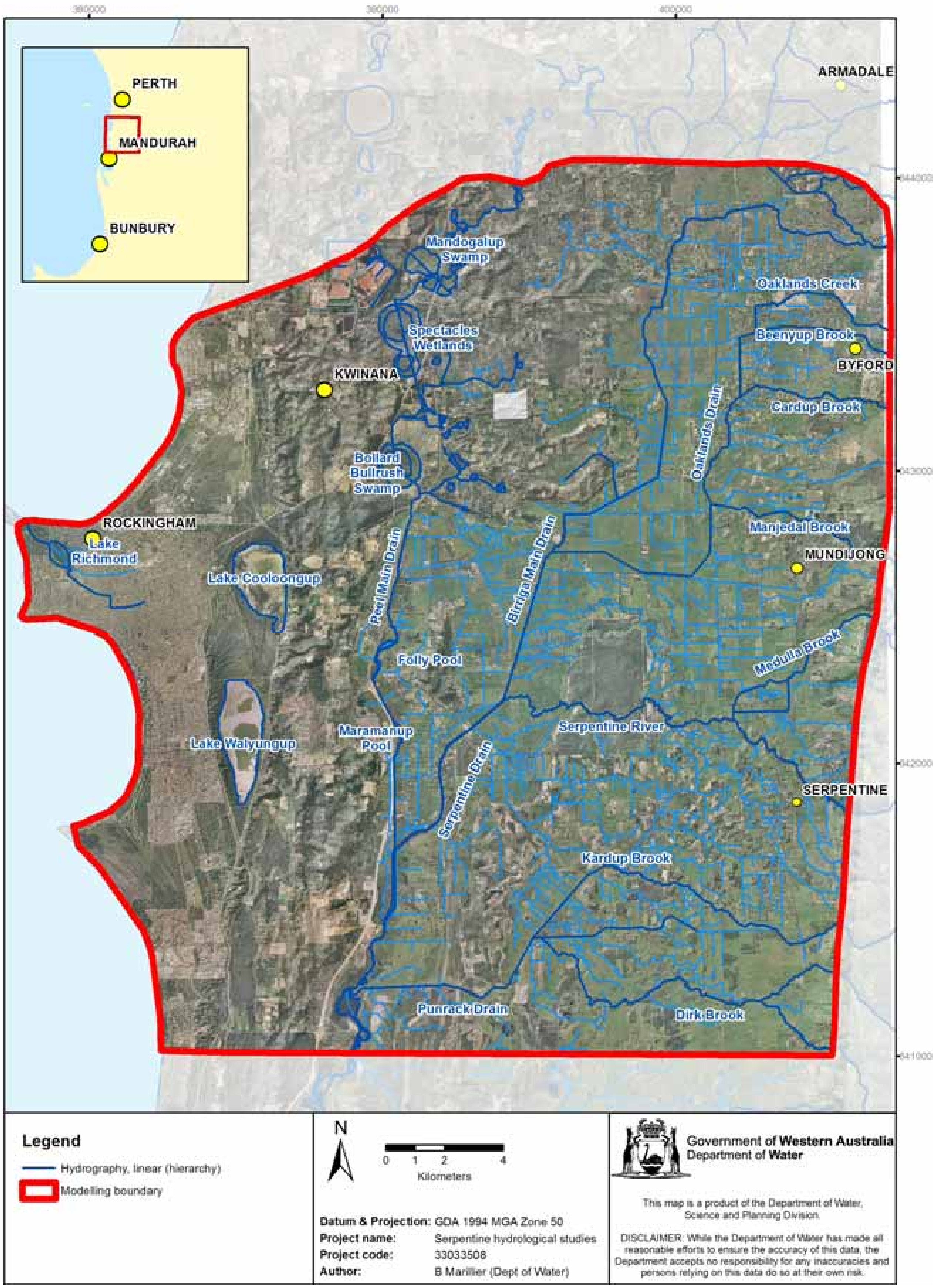

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Figure 1-1 Modelling boundary for the Serpentine region

1.1 Project objective

The purpose of the *Lower Serpentine hydrological studies* is to develop and calibrate a regional-scale integrated surface water and groundwater model capable of simulating climate, drainage and land use scenarios.

The project's primary objectives are to deliver the following products:

- a calibrated regional-scale surface and groundwater model
- climate, drainage and land use scenario modelling results
- maps and ESRI shapefiles associated with the model and scenario results.

The project requires the modelling results to determine the following:

- maximum, minimum, average annual maximum and average annual minimum groundwater levels (MaxGL, MinGL, AAMaxGL and AAMinGL)
- the water balance, including changes in groundwater discharges and interaction with waterways and wetlands
- re-use opportunities such as community bores and surface detention
- likely areas of waterlogging
- flows in rivers, drains and tributaries
- flood, wet, dry, average year and climate change impacts.

1.2 Scope of work

The scope of the *Lower Serpentine hydrological studies* is divided into three phases: this report addresses the first. Each phase is associated with significant project milestones and will be accompanied by a scientific report. The three phases are as follows:

1. Develop a conceptual model of groundwater and surface water within the Serpentine study area, which:
    a) reviews the literature covering previous work in the area
    b) outlines the study area
    c) describes the local hydrology and climate
    d) develops a geological model of the study area
    e) defines the aquifer systems and major hydrogeological processes, including relevant aquifer parameters
    f) provides a numerical steady-state water balance that includes all major groundwater and surface water processes and the interaction between them.
2. Construct and calibrate a transient regional groundwater model covering the Lower Serpentine area. This involves the simulation of surface water in relevant waterways and

groundwater flow in each aquifer, the calculation of flows and water budgets for each of the aquifers, and the determination of groundwater-level contours.

Model construction will be based on the conceptual model described in phase 1. The model will have an appropriate level of detail for capturing major surface water and groundwater processes at the regional scale. The model will be calibrated according to the criteria set by the *Murray Darling Basin Commission guidelines for groundwater flow modelling* (Middlemis 2000). Results of the calibration, validation and sensitivity analysis will be reported as a component of this phase.

A detailed description of model construction and calibration will be provided in a scientific report at the end of phase 2.

3. Create a suite of scenarios to determine the change to water balance and groundwater levels under various land use and climate scenarios. The Department of Water's Urban Water Management Branch will select scenarios for the Water Science Branch to model. These will fit into the following broad categories:
    a) **Land development scenarios:** these will be based on likely areas of urban development within the study area (to be provided by WAPC).
    b) **Drainage scenarios:** these will examine the influence of subsurface drainage on groundwater levels, surface water flows and the water balance within areas of future development.
    c) **Climate scenarios:** a range of future climate scenarios will be simulated to account for various possibilities in changing rainfall and evapotranspiration. These will be based on Intergovernmental Panel on Climate Change (IPCC) predictions, including predicted changes in rainfall and evapotranspiration. Results from appropriate global circulation models will be used to determine scenario inputs.

The results of climate scenario modelling will be reported spatially (groundwater contours) and quantitatively (through water balance results) in the scenario modelling report. The influence of scenario modelling on areas of inundation, volumes of drainage water and depth to groundwater will be presented and discussed.

2 Literature review

The study area has been the subject of a number of surface water, groundwater and geological studies during the past 50 years. Earlier studies are generally associated with the Geological Survey of Western Australia. Later studies reflected an increase in the availability of hydrogeological information generated by drilling programs in the 1970s and 1980s. The Water Science Branch has reviewed the literature to guide the development of a conceptual model of the study area's hydrology and hydrogeology. This literature review is summarised below:

Report on exploratory drilling for underground water in the Perth Basin west of Byford, WA (Berliat 1963)

This report describes an exploratory drilling program undertaken in the Byford area to investigate potential groundwater sources. Jurassic to Quaternary sediments were intercepted, and several aquifers were identified as Lower Jurassic, Lower Cretaceous and Quaternary in age (these aquifers are now known as the Cattamarra, Leederville and Superficial aquifers respectively).

Several important features of the local hydrogeology were identified, including the presence of the Serpentine Fault approximately three and a half miles (5.6 km) to the west of the Darling Scarp. The Serpentine Fault was identified as a hydrogeological barrier for flow between the Lower Jurassic aquifer and aquifers to the west. Recharge to the Lower Jurassic aquifer was described as occurring via seepage from the Darling Scarp. Within the Lower Cretaceous aquifer, recharge was shown to occur along the Serpentine Fault through increasing salinity with depth.

Hydrogeology of the Swan Coastal Plain, Kwinana – Pinjarra area (Morgan 1969)

This early report describes the geology of the Kwinana to Pinjarra area, and focuses on water quality and potential sources of water. It discusses block faulting in the Palaeozoic to Upper Jurassic, stating that block faulting is more pronounced in the older than younger sections. Much of this interpretation is consistent with our modern understanding of the local geology, with some changes in nomenclature.

The report broadly describes the area's stratigraphy in decreasing age as follows:

- Archaean Granitic Rocks – the Darling Scarp
- Proterozoic Cardup Shale – at the base of the Darling Scarp
- Mesozoic sediments:
    - Lower Jurassic – carbonaceous claystone and siltstone, with sandy sections between Pinjarra and Mandurah (referring to the Cattamarra)
    - South Perth Formation – grey-green brown silty sandstone, siltstone and claystone (Cretaceous – referring to the Leederville Formation)
    - Osborne Formation – grey to green silty mudstone; high glauconite content (Cretaceous)

- Quaternary sediments:
    - lateritic alluvium on the Ridge Hill Shelf – laterised beach sands
    - unnamed limestone and sandstone – in hydraulic continuity with the sea (Tamala Limestone)
    - coastal limestone lower unit (Tamala Limestone)
    - alluvium of the Pinjarra Plain (Pinjarra duplex soils/Guildford Clay)
    - Rockingham Sand and other sandy beds – highly permeable
    - coastal limestone upper unit – east of the Spearwood Dunes (Tamala Limestone)
    - estuarine beds
    - Cooloongup Sand, lagoonal deposits, shelly beach deposits
    - Safety Bay Sand.

Shallow coastal aquifers in the Rockingham District, Western Australia (Passmore 1970)

Passmore investigated the sustainable yield of the Safety Bay Sand in the Rockingham area, as well as the potential for saltwater intrusion from the ocean. The work involved drilling of a number of new bores, hydrogeological interpretation, and pump tests being conducted in several locations.

The report shows the Safety Bay Sand is separated from the Rockingham Aquifer by a clay layer, with pump testing indicating negligible leakage. The presence of fresh water in the Safety Bay Sand is further evidence of this, along with the absence of tidal oscillations in its potentiometric head. The saltwater wedge is described as extending no further than 1000 feet (305 m) inland, with the exception of the Cape Peron Peninsula.

Pump testing of the Safety Bay Sand Aquifer indicated a horizontal hydraulic conductivity of 130 feet/day (40 m/day) and a storage coefficient of between 0.1 and 0.3, depending on the local sediment characteristics.

Groundwater management strategy: Kwinana, Western Australia (report for Alcoa) (Dames & Moore 1984)

This report discusses leakage of an alkali contamination plume from the Alcoa Kwinana refinery (which began its operations in 1963). The contaminated water exceeded both drinking and irrigation water criteria. The leakage from ponds may have been due to erosion, omission of clay lines, cracking of clay, weakness in the substrate or a chemical breakdown of the liner. Contaminated water was identified as being confined to the base of the aquifer.

Recovery bores were installed downstream of the plume to abstract contaminated water. Considerable volumes of water had been abstracted in the past.

Results of test-pumping bore CG2 Serpentine (WAWA 1987)

This report concerns testing of bore CG2 near Serpentine to assess the suitability of the Cockleshell Gully (Cattamarra Coal Measures) for production water. The bore was tested in January 1987 for nine days at 7926 kL/day; however, pump testing was shut off due to drawdown in local production bores. Recovery after pumping took 70 days. Pumping resulted in significant drawdown at AM61Y, screened in the Cattamarra Aquifer. The effects of the drawdown decreased with the shallower aquifers, but were still measured at between 0 and 3 m in bores screened in the Guildford Formation within the Superficial Aquifer.

Results indicated the aquiclude between the Cattamarra and Leederville aquifers was more permeable in the south-east compared with the north-west. The vertical permeability of the overlying aquiclude (silt/shale layers of Jurassic period) was calculated at 0.01 m/day.

Warnbro Bay bore completion report (Rockwater 1987)

This report describes the geology and hydrogeology of the Warnbro area, near Rockingham, including the Safety Bay, Rockingham and Leederville aquifers.

The Safety Bay Sand Aquifer is described as separated from the Rockingham Aquifer by a clay bed. The Safety Bay Sand contains fresh water from the land surface to the clay bed, to within 100 m of the coast at the saltwater interface.

Pump testing indicated high transmissivity in the Safety Bay Sand averaging 1360 m^2/day. However, a more conservative value of 300 m^2/day was used to calculate sustainable pumping rates.

Stratigraphy and groundwater contour mapping south-east corridor – Armadale, Byford, Mundijong and Serpentine (Rockwater 1995)

Rockwater installed a number of bores along a 5 to 8 km strip at the foot of the Darling Scarp between Kelmscott and Keysbrook. These bores are referred to as the SES (south-east shallow) and SED (south-east deep) series of bores, and represent the bulk of the limited groundwater data available in this area. The SES bores are generally screened within the top 5 m of the bore, with the SED series screened between 14 and 20 m depth.

The local lithology of the area consists of clayey colluvial deposits and the Guildford Clay with interbedded sand and clay layers. The hydrogeology is defined by steep hydraulic gradients associated with the slope of the foothills, with localised clay lenses and ferruginised layers resulting in perching in some areas. Superficial heads were found to be artesian at up to 0.2 m above the surface in some locations.

At the time the report was written, abstraction was reported to be at low rates and thus unlikely to influence groundwater levels. However, significant development has occurred in the area in recent years, so this statement may no longer apply.

Hydrogeology and groundwater resources of the Perth region, Western Australia (Davidson 1995)

Davidson provides a detailed geological and hydrogeological description of the Perth Basin, including all of the major aquifers. The spatial data and geological sections in this report formed the hydrogeological foundation of the Department of Water’s Perth Regional Aquifer

Modelling System (PRAMS). The water balance of each aquifer was calculated using simple flux equations within each groundwater subarea, including those co-incident with the Serpentine study area.

Hydrogeological report to support licence application for increased groundwater abstraction (BP 1997)

This report accompanied a request from BP to increase its abstraction from the Superficial Aquifer from 706 to 2326 ML/yr. The report describes the geology and geomorphology of the Safety Bay Sand, Spearwood Dunes and Tamala Limestone around the Kwinana area. Over much of the area a 'basal clay' is present, which functions as an aquitard between the Safety Bay Sand and the underlying Tamala Limestone, although this clay layer is described as thinning or not present in some areas near the coast.

Several aquifer parameters were estimated as follows:

- **Dune sand (Safety Bay):** horizontal conductivity 10 to 30 m/day, specific yield 0.1 to 0.3
- **Tamala Limestone:** horizontal conductivity 250 to 550 m/day, specific yield 0.15 to 0.45
- **Leederville:** horizontal conductivity 10 m/day, storage coefficient 10^{-3} to 10^{-4}.

Report for the investigation of groundwater-wetland water level relationships study: Gnangara & Jandakot mounds (Rockwater 2003)

Ten wetland sites on the Jandakot Mound were investigated for groundwater and wetland water level relationships. The report found water levels are maintained by local flow systems associated with the groundwater mounds. They represent permanent or seasonal surface expressions of groundwater.

There was evidence of perching/recharging in some wetlands, although this may have been influenced by criteria bore location. It was noted that:

> …all wetlands on the Swan Coastal Plain are permanently or seasonally in some degree of connection with the regional watertable. Perching of groundwater probably only occurs for a short period after the onset of heavy rain.

Review of groundwater levels in the Leederville Aquifer in Serpentine groundwater area (Lindsay 2004)

Monitoring at 11 artesian monitoring bores in the Leederville Aquifer showed a steady decline in groundwater levels in most cases.

Lindsay reported that hydraulic connectivity between the Leederville and Superficial aquifers in the eastern part of the study area had resulted in harmonious groundwater heads, which were declining at similar rates in the two formations. In the western part of the study area the Leederville was confined with declining heads. In the south-eastern corner, both the Superficial and Leederville aquifers had stable water levels.

In 1992, the Leederville discharged to the Superficial across half of the study area. In 2004, however, Lindsay found the Superficial recharged the Leederville across most of the study area.

Lindsay attributed the high rates of groundwater decline in the Leederville Aquifer to abstraction from borefields and domestic bores.

Jandakot structure plan: groundwater modelling to assess effects of climatic variations and planned urban development (Rockwater 2006)

Rockwater was commissioned by the Water Corporation to develop a groundwater model of the Jandakot structure plan area. The model was used to simulate the effect of urban development and climate change on the Jandakot Mound's western edge. The model area included the Peel Main Drain's northern section, and the Spectacles and Bollard Bulrush wetlands. The conceptual model was based largely on PRAMS.

The report describes the local hydrogeology and wetlands and drains throughout the study area. The wetland systems are described as flow-through, being fed by groundwater flowing west from the Jandakot Mound, with minimal losses to evaporation or drainage. Flows in Peel Main Drain receive a baseflow contribution but are predominantly fed by surface water runoff. High hydraulic gradients immediately west of the Spectacles Wetlands were attributed to locally low hydraulic conductivity in the Tamala Limestone, with higher conductivity closer to the coast. These local variations were accounted for within the model.

Aquifer parameters for the superficial formations were as follows:

- **Tamala Limestone:** horizontal conductivity 83 to 500 m/day, vertical conductivity 5 m/day, specific yield 0.3, storage coefficient 0.2
- **Wetland sediments:** horizontal conductivity 4.1 m/day, vertical conductivity 0.1 m/day, specific yield 0.05
- **Gnangara Sand/Ascot Formation:** horizontal conductivity 10 to 25 m/day, vertical conductivity 1 m/day, specific yield 0.25, storage coefficient 0.002
- **Tamala (localised):** horizontal conductivity 3.3 to 18 m/day.

Rockingham groundwater area water management plan (DoW 2007)

The Rockingham groundwater area covers the Serpentine study area's western portion, and includes Rockingham and the Stakehill Mound. The plan is concerned with setting sustainable allocation limits in the Superficial, Rockingham and Leederville aquifers.

Within the area, the Leederville Aquifer is over-allocated, so no further allocation is likely. For the Rockingham and Superficial aquifers: of the nine groundwater subareas within the region, one is over-allocated, six are fully allocated, and only two have water available. Industry and mining, horticulture, and public open space irrigation are the main water uses within the Rockingham area.

Perth Regional Aquifer Modelling System (PRAMS) model development: Calibration of the coupled Perth regional aquifer model PRAMS 3.0 (CyMod Systems 2009a)

This report deals with the calibration of PRAMS. PRAMS version 3.0 is a coupled MODFLOW groundwater model and unsaturated zone vertical flux model. The model covers the Swan Coastal Plain between Mandurah and Cervantes.

The model achieved a root mean square (RMS) error of 2.2 m and an average absolute error of 1.6 m over the calibration period of 1985 to 2000 for the Superficial Aquifer. Areas of significant error were attributed to scale and localised aquifer characteristics, incorrect or insufficient abstraction data, and changing land uses. The Serpentine Fault was also listed as a source of error, and may influence model results for the Serpentine hydrological studies.

Local scale groundwater modelling of the Mundijong area (Cymod Systems 2009b)

A local area model was developed based on PRAMS 3.0 for the Byford/Mundijong area. An analysis of the lithology using the Water Information Network (WIN) database shows there is more clay in the south and east of the study area, and that a coffee-rock layer occurs in the sandy north-west of the study area (near the Jandakot Mound).

The model was constructed as follows:

- defining the Superficial Aquifer as two computational layers
- setting the Serpentine Fault as impermeable
- applying a 100 m x 100 m grid resolution (160 rows 150 columns)
- defining the base of Layer 1 as the watertable minus 10 m
- considering the Superficial to be connected with the Leederville and Cattamarra aquifers in parts of the study area
- applying time-varying fixed head boundaries on the model's north, west and southern edges using PRAMS regional model results, with the Darling Scarp used as a no-flow boundary.

Estimated parameter ranges for conductivity and specific yield are provided in the report. The model calibration achieved a mean absolute error of 0.99 m and an RMS of 1.37 m.

Jandakot drainage and water management plan, Peel Main Drain (DoW 2009)

This plan, which focuses on the Peel Main Drain, outlines key aspects of water management in an environment subject to urban development. The area includes the Spectacles Wetlands, Bollard Bullrush Swamp and Mandogalup Swamp (which are located in the Serpentine study area). The protection of wetland hydrological regimes under the various development scenarios was emphasised, with groundwater studies completed by Rockwater (2006) being cited. The Spectacles Wetlands were identified as the most important Bush Forever and Environmental Protection Policy lakes in the area.

The Peel Main Drain, which runs through the wetlands, is capable of conveying the 1 in 100 year average recurrence interval (ARI) event. The flow record from 1976 to 2001 is reported to show a peak flow of 2.5 m^3/s, with smaller events of around 0.2 m^3/s more common, and most flow resulting from surface water runoff. However, Rockwater (2006) noted that the wetlands on the western edge of Jandakot Mound intercept groundwater flowing in a westerly direction.

Murray hydrological studies (Hall et al. 2010 a, b & c)

The Murray hydrological studies were undertaken in 2010 to support the *Murray drainage and water management plan* (DoW 2010). The studies focused on developing an integrated surface water and groundwater model to provide groundwater information at a regional scale. The study followed the procedure for model development recommended in the *Murray Darling Basin Commission guidelines for groundwater flow modelling* (Middlemis 2000).

Outcomes of the project included provision of groundwater levels and water balances related to current conditions, and several climate, drainage and land development scenarios. The model was also down-scaled to a finer grid to model eight wetlands and support environmental water requirement (EWR) studies. The model achieved an RMS error of 0.80 m and a mean absolute error of 0.55 m for the calibration period.

A number of estimated and calibrated aquifer and unsaturated zone parameters were given in the final report (Hall et al. 2010c). These are relevant to the Serpentine study area, which is located immediately to the north.

Feasibility of managed aquifer recharge using drainage water (Kretschmer et al. 2011)

This study examines the Cattamarra Aquifer's suitability for managed aquifer recharge in the Peel-Harvey region. As part of the study the Cretaceous sediments within the region were re-interpreted. As such it proposes that the Rockingham Sands were not deposited in a Tertiary paleochannel as was the previous geological understanding. Rather, the Rockingham Sands are an equivalent unit to the Wanneroo Member of the Leederville Formation west of the Mandurah Fault.

Groundwater resource review report: Serpentine groundwater area (Ryan 2011)

The superficial geology over most of the Serpentine study area is described in detail in this report, which formally interprets the hydrogeological information that has been collected during the past 40 years.

Detailed lithological descriptions for all superficial formations were included, with cross-sections showing the lateral and vertical extent of sediments throughout the study area. The interpretation is largely based on the Department of Water's 'T' and 'AM' series bores.

3 Description of study area

3.1 Climate

The Serpentine study area has a temperate climate typical of Western Australia's south-west. It has hot dry summers, and cool wet winters, with most rainfall delivered as winter cold fronts pushed up from the south-west. Intermittent summer rainfall can occur, generally as a result of ex-tropical cyclones tracking south.

Rainfall data was analysed from two stations: Serpentine (9039) at the foot of the Darling Scarp and Medina (9194), closer to the coast. Observations began at Medina in 1983 and Serpentine in 1905. These datasets were sourced from the SILO patch point database, which provides in-filled data from 1889 to the present. Statistics reported in this section relate to the period from 1905 to 2010 unless otherwise stated.

Figure 3-1 shows the monthly distribution of rainfall for the two stations, and Figure 3-2 the long-term annual record for Serpentine. On average Serpentine receives higher rainfall compared with Medina, because the Darling Scarp receives more rainfall than the Swan Coastal Plain, see Figure 3-3. On average 84% of rainfall occurs in the May to October period inclusive.

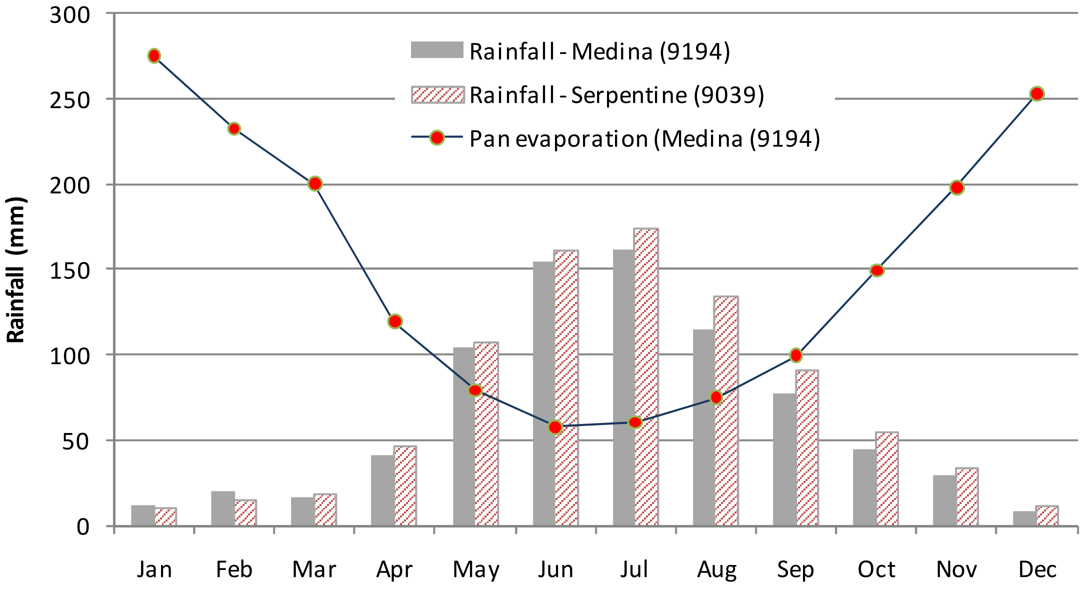

Figure 3-1 Monthly average rainfall and pan evaporation data for Serpentine and Medina (1970 to 2010)

At the Serpentine station, average annual rainfall is 919 mm, with a minimum of 442 mm recorded in 1995 and a maximum of 1389 mm recorded in 1926. The maximum temperature recorded is 45°C in January 1991, with the minimum temperature -2°C in June 1955. Pan evaporation exceeds rainfall in all years, averaging 1675 mm. The average annual rainfall for the period 1905 to 1975 is 964 mm; for the period 1975 to the present it is 13% less – 838 mm. This reduction in rainfall is commonly referred to as a ‘step change’; however, it is actually part of a declining rainfall trend, which is illustrated with a moving average in Figure 3-2 – this demonstrates the steep decline from 2000 onwards.

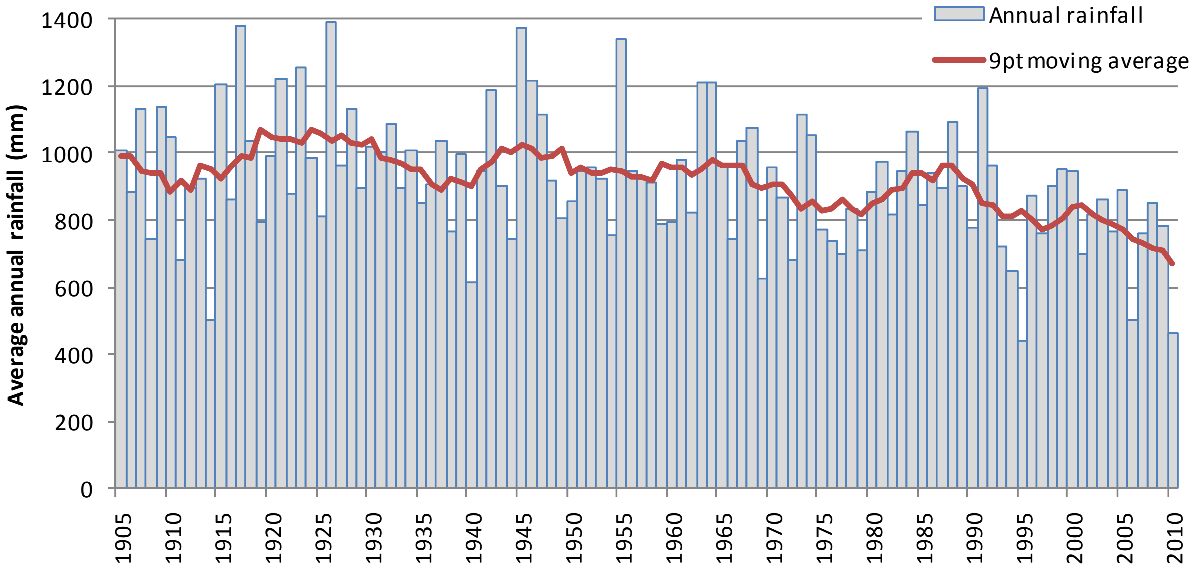

Figure 3-2 Rainfall decline at Serpentine (1905–2010)

At Medina, average annual rainfall is 813 mm, with a minimum of 476 mm recorded in 1914 and a maximum of 1170 mm recorded in 1926.

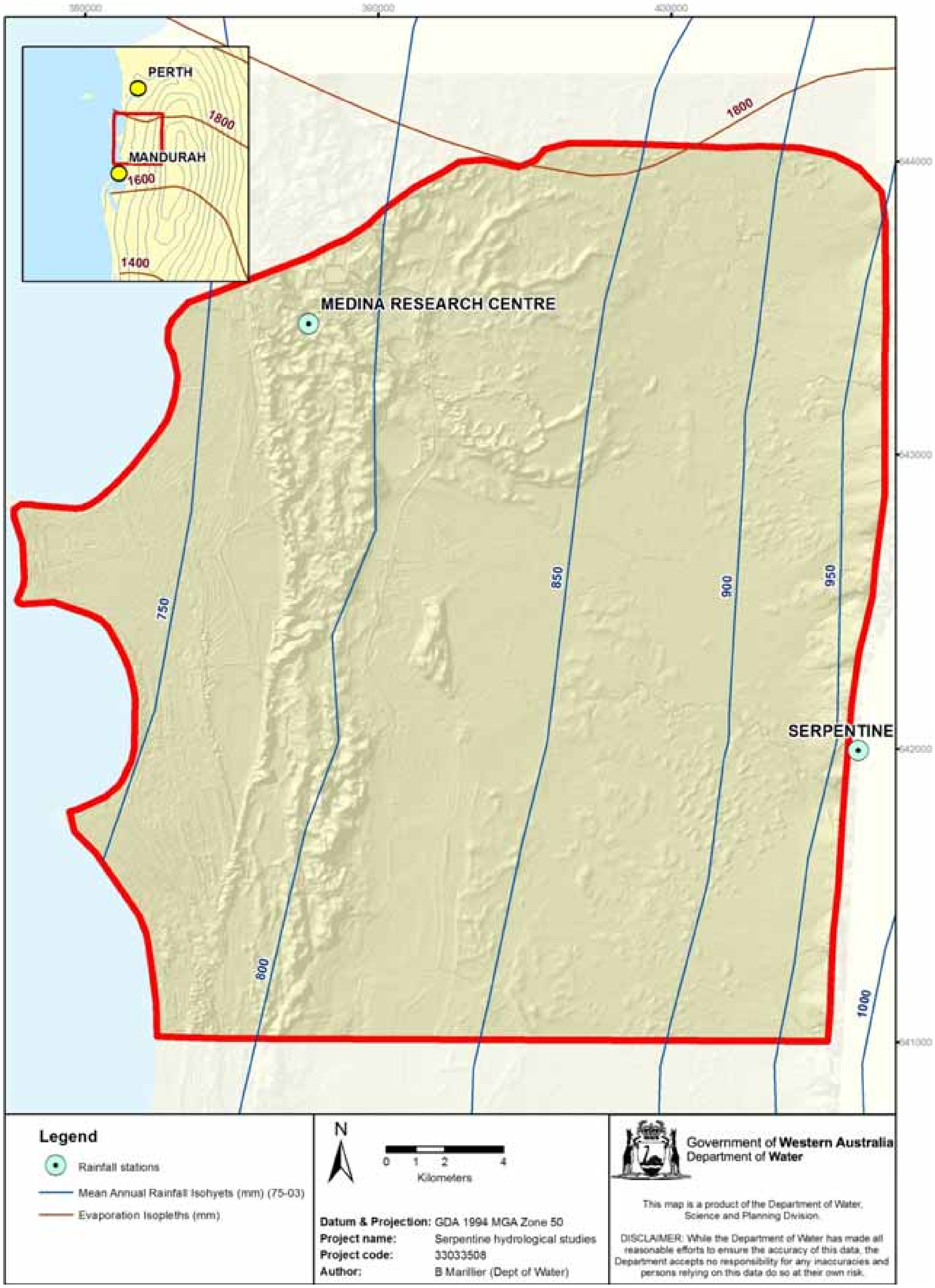

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Figure 3-3 Rainfall isohyets and evaporation isopleths 1975 to 2003 (Department of Environment)

3.2 Topography and hydrology

The study area’s major hydrological features are shown in Figure 3-4. Most of the study area is located on the Swan Coastal Plain, between the Darling Scarp in the east and the Indian Ocean to the west. The topography is characterised by gently undulating dune systems with varying depositional history, with younger geological units located closer to the coast. The association between the geomorphic units, soil types and surface geology (discussed in subsequent sections) are listed in Table 3-1.

Table 3-1 Equivalent geomorphic units, surface geology, and soil types

Geomorphic units	Surface geology	Soil
Quindalup Dunes	Safety Bay Sand	Quindalup
Spearwood Dunes	Tamala Limestone	Spearwood
Bassendean Dunes	Bassendean Sand	Bassendean
Pinjarra Plain	Guildford Clay & recent alluvial deposits	Pinjarra
Colluvium	Colluvium	Forrestfield
Swamp & estuarine deposits	Swamp & lucastrine deposits	Vasse

The southern portion of the Jandakot Mound is associated with a gentle rise in dune formations of Bassendean Sand, with an increase in elevation of up to 15 m from the surrounding Pinjarra Plain. The Spearwood Dune System runs roughly parallel to the coast in the west, and rises as much as 30 m above the Pinjarra Plain. The Stake Hill Mound is associated with the Spearwood Dune System in the study area’s south. Further to the west, the youngest Quaternary dune system – the Safety Bay Sand – holds a fresh groundwater mound.

A number of wetland systems are associated with inter-dunal depressions within the undulating sandplain. Two large saline lakes are present between the Spearwood Dunes and the Safety Bay Sand. These are Lake Cooloongup and Walyungup, which act as evaporation basins for groundwater that flows to the lakes from the Spearwood Dunes in the east, and the Safety Bay Mound in the west. Several wetland systems in the area are located on Jandakot Mound’s western edge and include Mandogalup Swamp, the Spectacles Wetlands, and Bollard Bullrush Swamp. Of these, the Spectacles Wetlands are the most pristine. Water levels in these wetlands are controlled by groundwater levels in the Jandakot Mound, and can be considered groundwater flow-through wetlands. However, the Peel Main Drain also intersects all of these wetlands, so surface water inflows and outflows influence water levels. The Kwinana wastewater treatment plant helps to maintain water levels in the Spectacles Wetlands through infiltration galleries to the west of the wetlands (Shams 2000). Further downstream on the Peel Main Drain, Folly Pool and Maramanup Pool act as flow-through wetlands between reaches characterised by a trapezoidal drain shape.

Another wetland of significance is the linear wetland of the Serpentine River at Lowlands. This wetland is surrounded by privately owned, uncleared native forest. Other smaller wetlands are located throughout the study area.

The low-lying area east of the Spearwood Dunes is commonly referred to as the Pinjarra Plain. The sediments here are characterised by fine- to medium-grained sands overlying sandy clay lenses, termed the Pinjarra duplex soil. The underlying beds have increasing clay content further to the east, as the Guildford Clay becomes the prevalent formation in the Quaternary sediments. In some areas, the high clay content of the underlying sediments is likely to result in temporary perching of surface water and large amounts of infiltration excess runoff after heavy rainfall events. Sediments along the lower reaches of the Peel Main Drain are characterised by clays, see Figure 3-5.

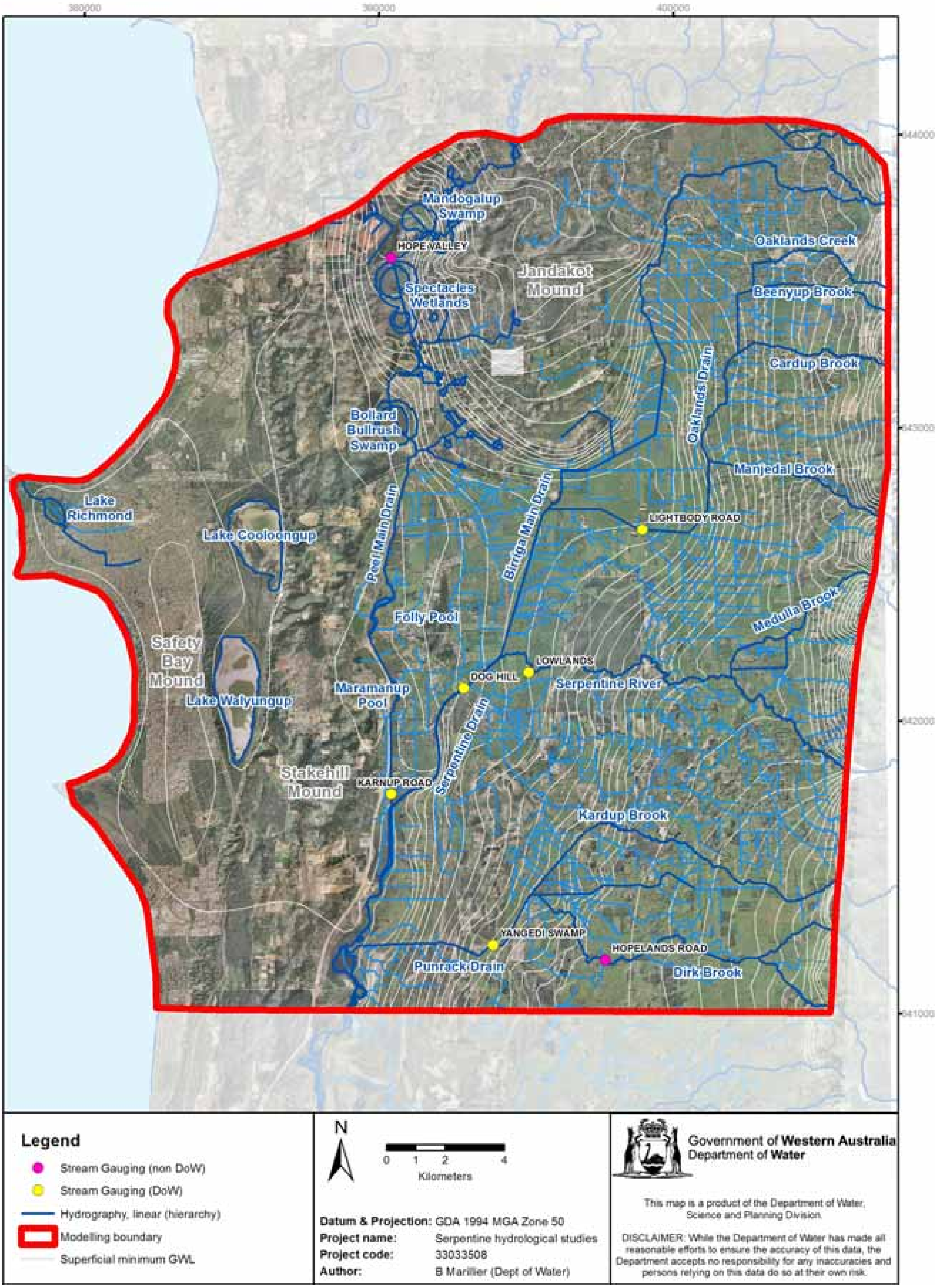


Figure 3-4 Surface water hydrology, flow gauging and superficial groundwater level

Before the area was cleared for agriculture much of it was covered by jarrah and marri forest, which would have lowered watertables through evapotranspiration. With increased clearing from the late 1800s, groundwater tables began to rise. This led to construction of a network of agricultural drains, the draining of wetlands and a program of river straightening and de-snagging to increase conveyance – the largest examples are the Birriga Main Drain, Serpentine Drain and Peel Main Drain (Figure 3-4).

Figure 3-5 Clays near Peel Main Drain, and surface water perching after heavy rainfall (June 2011)

The Serpentine River (Figure 3-6) is the largest natural river within the study area, although flows have been substantially reduced since the Serpentine Pipehead Dam was built in 1957, and the Serpentine Main Dam in 1961. These dams were developed to supply the Perth metropolitan area with additional scheme water. This study is concerned only with the section of the river downstream of the dams, referred to as the lower Serpentine River. During summer, the Water Corporation releases water from the pipehead dam to maintain low flows. The Department of Water collects data at two flow gauges on the Serpentine River: Lowlands (614114) and Dog Hill (614030) further downstream, which includes the catchment area of Birriga Main Drain. The Water Corporation has a gauge located at Serpentine Falls (614072) just outside the study area. The Serpentine River receives a very small volume of baseflow throughout summer; some of this is related to dam releases. The groundwater contribution is minimal upstream of the Lowlands gauge, as the river is only around 2 m deep except in the Darling Scarp where it is more deeply incised. The Dog Hill gauge also records very low flows during summer, indicating that the Birriga Main Drain does not intercept the groundwater table during the dry season.

The catchment of Birriga Main Drain (Figure 3-6) covers most of the study area’s north-west corner. The drain is fed by several tributaries running from the Darling Scarp, including the Manjedal, Cardup and Beenyup brooks and Oaklands Creek. Although the drain is around 3 m deep, it does not intercept groundwater during the summer. However, the drain is important for conveying water during winter, because the low-lying area between the Jandakot Mound and Darling Scarp is prone both to flooding and inundation from groundwater. These winter flows discharge to the Serpentine River just upstream of the Dog Hill gauging station.

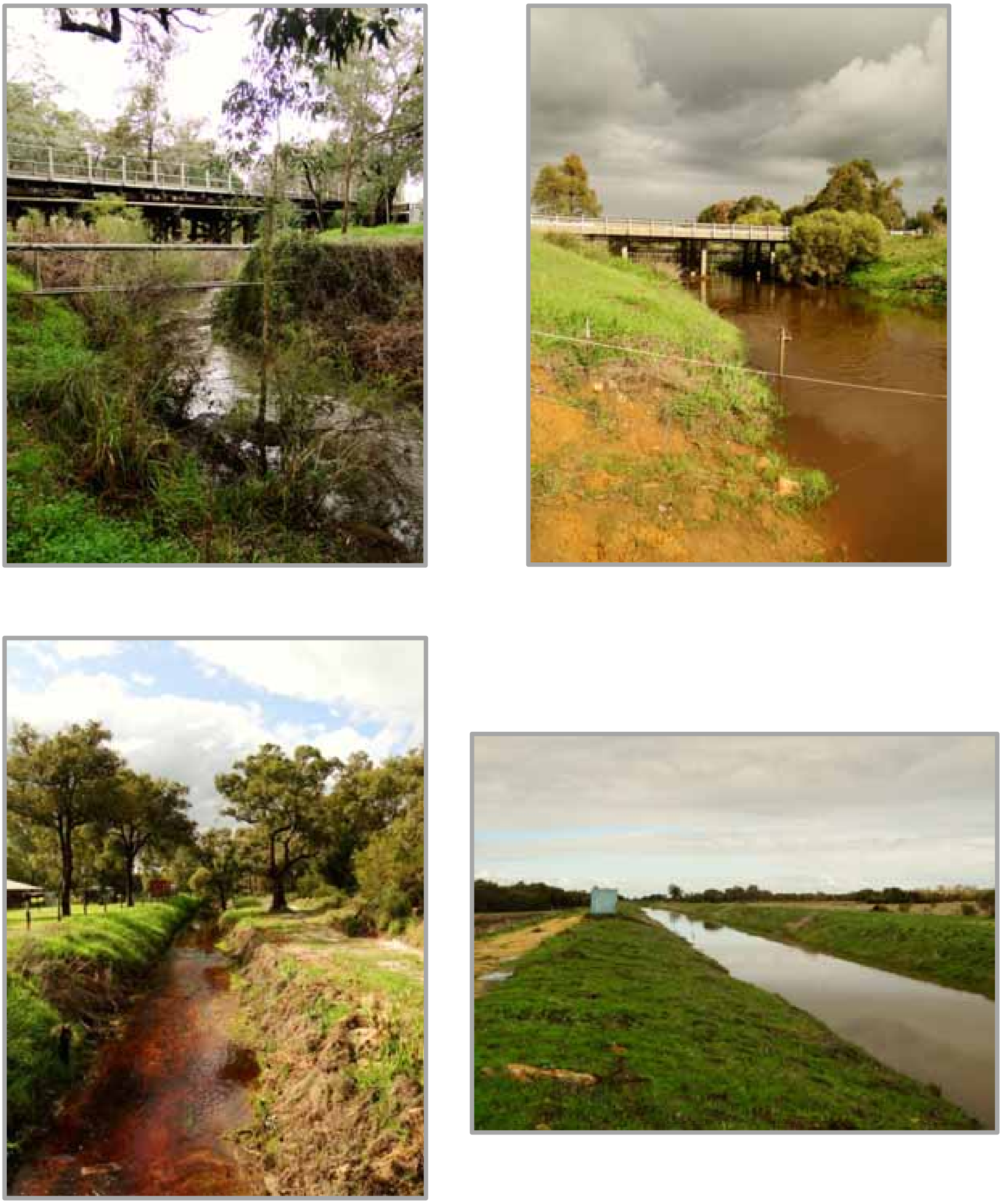


Figure 3-6 Clockwise from top left: Serpentine River at South Western Highway; Birriga Main Drain at Mundijong Road; Punrack Drain looking east; Peel Main Drain at Karnup Road looking south. All photos June 2011 – Ben Marillier.

In the study area's south the Dirk and Karnup brooks feed water into the Punrack Drain (Figure 3-6), which discharges to the lower end of the Serpentine River. The drain and its tributaries are around 2 m deep in most places and do not intercept groundwater during summer, as indicated by the low or no flow recorded at the Yangedi Swamp gauge (614094) in dry periods.

The Peel Main Drain (Figure 3-6) is the only major catchment in the area located completely on the Swan Coastal Plain. The drain runs from north to south, with its headwaters in the wetland systems of the Jandakot Mound, just outside the study area. At Mandogalup Swamp, the drain elevation is at 25 mAHD, and over a distance of 15 km, it drops to an elevation of 4 mAHD, which is a steeper gradient than most drains on the Swan Coastal Plain. The drain's upper section intercepts groundwater during the winter months, which flows east to west from the Jandakot Mound. The Hope Valley gauging station (614013) records flow entering the top end of the Spectacles Wetlands. The drain's low-lying sections probably receive less baseflow than other drains in the catchment due to the clay present in the area; however, several small feeder drains discharge to this section of the drain and convey both baseflow and event-related flow to the main drain. Seasonal minimum water levels in both Folly and Maramanup pools follow the trend observed in Superficial monitoring bore T400 (O), which indicates connection to groundwater. A gauging station with a short-term record, located at Karnup Road (614121), has reliable data from 2007 onwards when Doppler velocity meters were installed. Gauging at Karnup Road shows that the Peel Main Drain dries out completely during average summers, but conveys flows of up to 350 ML/day during winter events.

Only the reliable and appropriate flow gauges have been included in this study. Appendix A shows the selection criteria for the gauges, time-series graphs and baseflow separation for each gauge selected. Table 3-2 summarises information related to the gauging stations selected, including the coefficient of runoff (the proportion of rainfall that results in discharge) and the baseflow component (an estimate of the groundwater contribution to flow: in this case both the deep and shallow baseflow have been included in calculations). Although all waterways receive little or no baseflow in the summer months, it is an important component of winter flows.

Table 3-2 Surface water gauges – summary data

AWRC Ref	Name	Start date	End date	Average annual flow (GL)	Drainage area (km2)	Coefficient of runoff (%)	Baseflow (%)
614114	Lowlands	16/06/1998	ongoing	19.0	185.7	12%	-
614030	Dog Hill	22/02/1979	ongoing	68.3	479.2	18%	29%
614028	Hopelands Road	5/04/1979	29/05/2001	12.2	63.9	21%	-
614094	Yangedi Swamp	9/06/1995	ongoing	19.0	119.8	20%	34%
614013	Hope Valley	16/06/1976	21/05/2001	1.6	20.0	10%	-
614121	Karnup Road	19/03/2005	ongoing	6.8	113.8	6%	64%

3.3 Land use and population

A variety of land uses are present in the study area, including residential areas concentrated around Rockingham and Safety Bay; industrial land uses at Kwinana and Hope Valley; large areas of agriculture; and pockets of native vegetation, plantation and conservation areas.

Seventy-eight per cent of the study area is cleared. The dominant land use is grazing of beef cattle, although urban areas are expanding around Rockingham and the towns of Mundijong, Serpentine and Byford. Figure 3-7 illustrates the area's population growth, with the Rockingham region experiencing the most rapid growth during the past 20 years (ABS 2011).

Table 3-3 shows the area of each land use within the catchment for the year 2006. This was compiled using the detailed land use dataset developed by the Water Science Branch (see Figure 3-8).

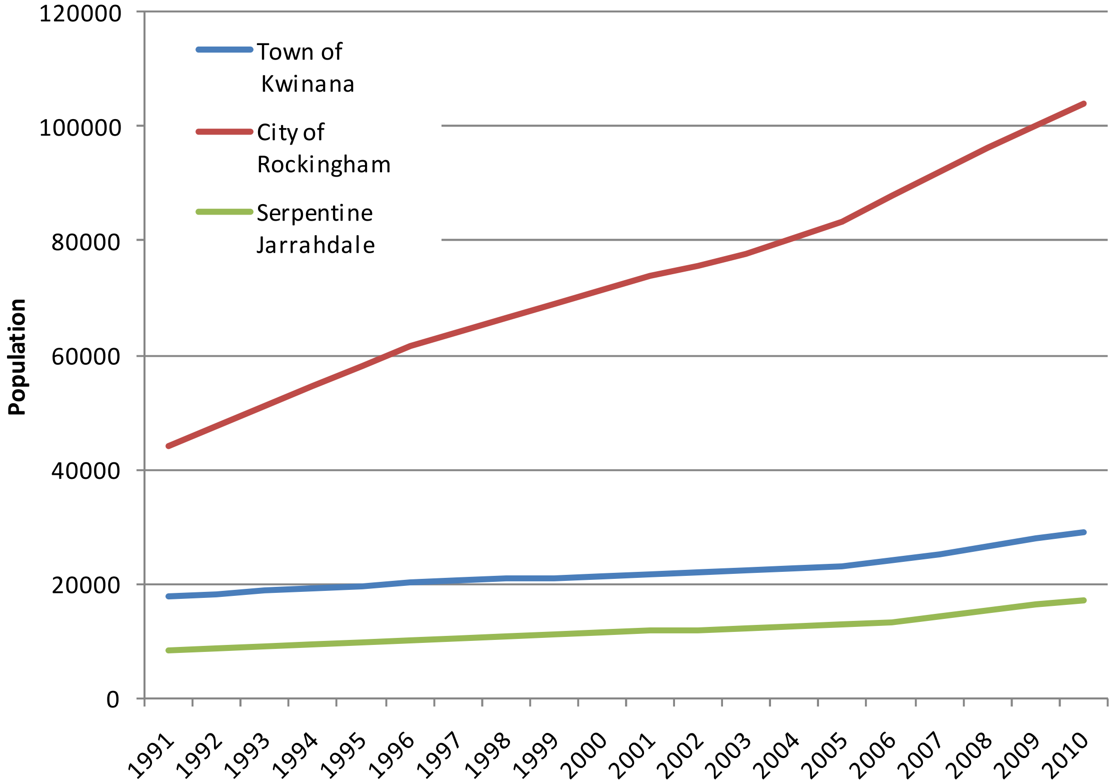


Figure 3-7 Australian Bureau of Statistics population estimates for the Town of Kwinana, City of Rockingham and Shire of Serpentine Jarrahdale (1991–2010)

Table 3-3 Areas for land use categories mapped in the Serpentine study area (2006)

Land use	Area (ha)	# of parcels	% of total area
Cattle for beef	16237	1092	22.34%
Recreation/conservation – trees/shrubs	15964	110842	21.97%
Animal keeping – non-farming	7052	1293	9.70%
Lifestyle block	5746	3452	7.91%
Unused – cleared – grass	4396	3750	6.05%
Road reserve	4108	7181	5.65%
Urban residential	2855	38492	3.93%
Mixed grazing	1975	91	2.72%
Unused – uncleared – trees/shrubs	1803	1454	2.48%
Annual horticulture	1713	306	2.36%
Cattle for dairy	1526	80	2.10%
Waterbody	1164	84	1.60%
Tree plantation	1120	38	1.54%
Recreation – grass	988	468	1.36%
Unused – cleared – bare soil	919	5321	1.26%
Manufacturing/processing	764	252	1.05%
Quarry/extraction	627	34	0.86%
Sheep	593	28	0.82%
Rural residential/bush block	501	278	0.69%
Intensive animal farming	351	7	0.48%
Recreation – turf	304	29	0.42%
Poultry	289	50	0.40%
Hay and silage	284	74	0.39%
Storage/distribution	250	295	0.34%
Community facility – education	169	62	0.23%
Turf farm	167	5	0.23%
Piggery	150	9	0.21%
Perennial horticulture	144	104	0.20%
Community facility – non-education	141	82	0.19%
Aquaculture	96	8	0.13%
Commercial/service centre	72	208	0.10%
Transport access – airport	59	2	0.08%
Viticulture	39	4	0.05%
Office – without parkland	27	62	0.04%
Sewerage – treatment plant	24	3	0.03%
Garden centre/nursery	19	9	0.03%
Utility	18	87	0.03%
Caravan park	17	7	0.02%
Commercial/service – residential	7	38	0.01%
Total	72677	175681	100%

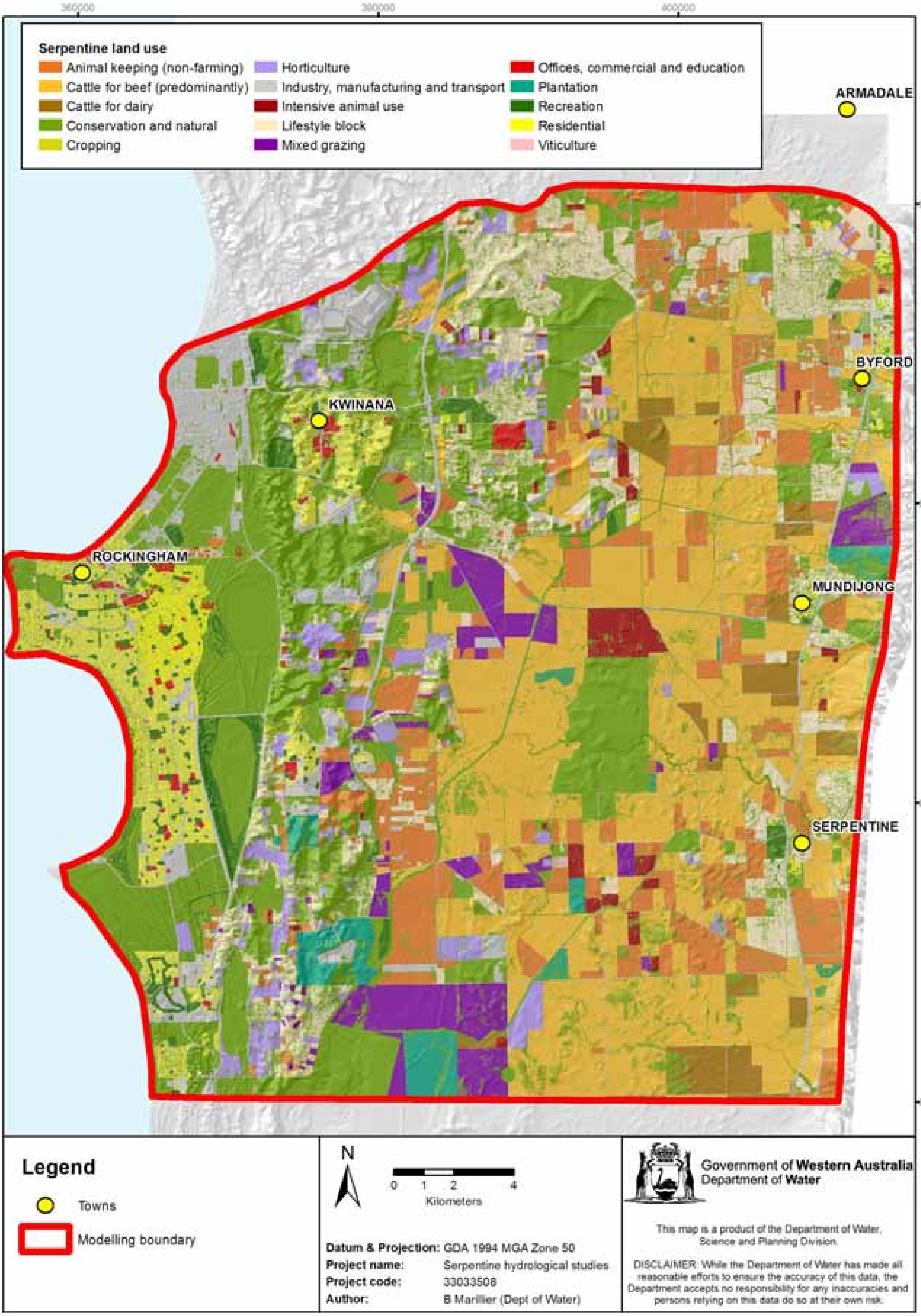


Figure 3-8 Land uses in the study area

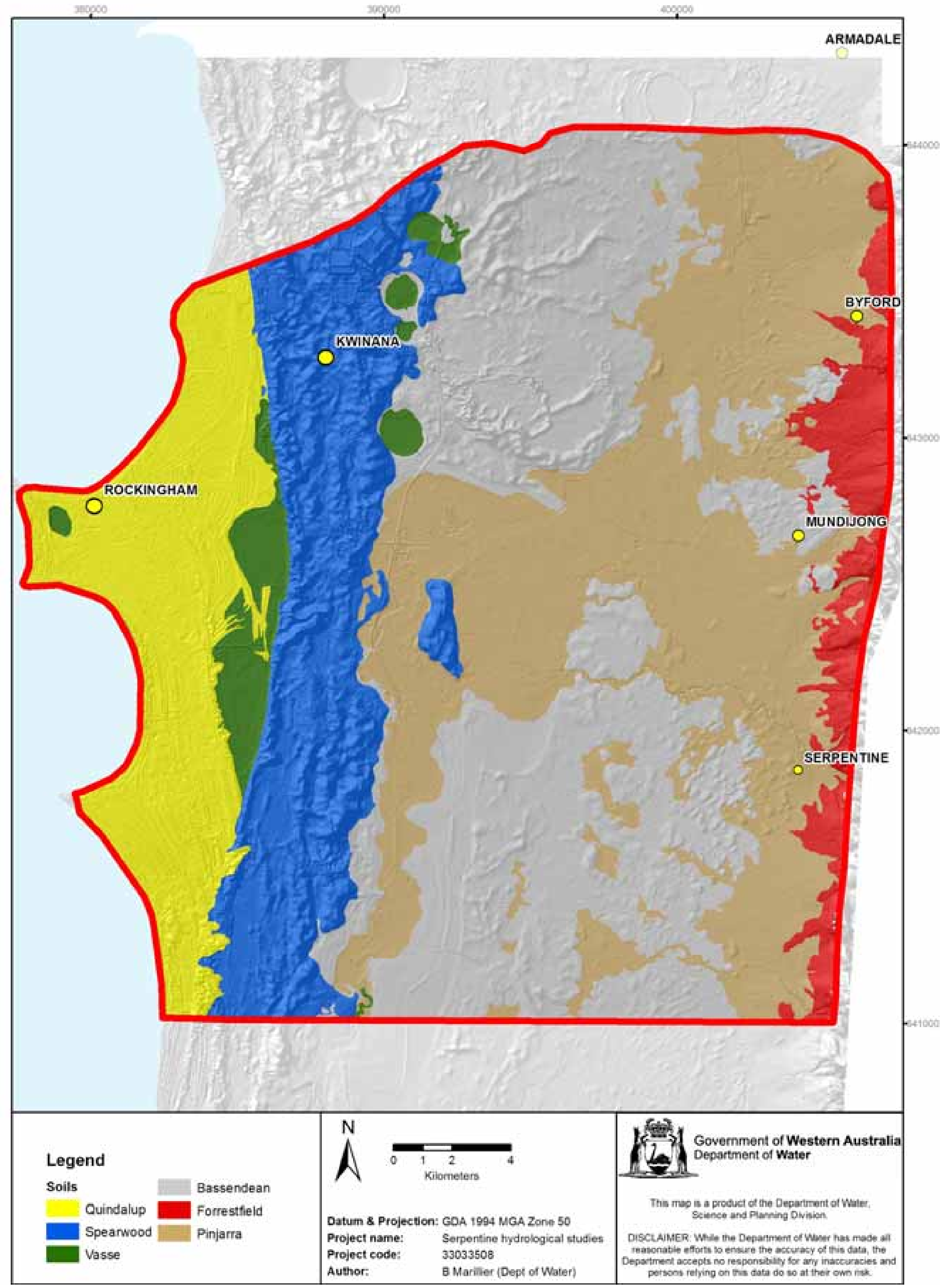
3.4 Soils

Within the study area, the soils of the Swan Coastal Plain have been extensively mapped by the Department of Agriculture and Food, resulting in a spatial dataset of soil landscape units. The study area contains six broad soil classifications: Quindalup, Vasse, Spearwood, Pinjarra, Bassendean and Forrestfield (see Figure 3-9). Each soil type is described in Table 3-4. The equivalent soil classification used in the vertical flux model for PRAMS (Xu et al. 2009) is also listed in the table.

Table 3-4 Soil types within the study area

Soil type	Equivalent soil in PRAMS	Description	Texture
Quindalup	Quindalup	Relict foredunes and gently undulating beach ridge plain with deep uniform calcareous sands. Sands consist of rounded quartz and shell debris.	Coarse sand
Vasse	Lacustrine	Former swamp and wetland areas which consist of uniform loamy and/or peaty sands.	Loamy sands
Spearwood	Spearwood	Deep siliceous yellow brown sands or pale sands with yellow-brown subsoil. Limestone outcrops.	Medium sand
Pinjarra	Guildford	Flat to very gently undulating plain with deep mottled yellow and grey duplex soils. Shallow pale sand to sandy loam over gravelly clay; moderately well drained. In the east the Pinjarra soils overlay the Guildford Formation.	Duplex sandy clay
Bassendean	Bassendean	Undulating sandplain and low relief dunes with deep bleached grey siliceous sands. Weak iron-organic hard pan may be present in places.	Medium sand
Forrestfield	Mesozoic	Low foot slopes along the Darling Scarp. Moderately deep gravelly yellow duplex soils with laterite.	Duplex sandy clay

The Bassendean and Pinjarra soil types cover most of the study area: sands predominating but clay content increasing with proximity to the scarp. See Figure 3-10 for an illustration of the Bassendean soil type collected on the Jandakot Mound and the Pinjarra soil type collected near Mundijong. The relative clay content of different soils in the unsaturated zone is an important consideration in determining recharge and will be included in the numerical model.



Datum & Projection: GDA 1994 MGA Zone 50
Project name: Serpentine hydrological studies
Project code: 33033508
Author: B Marillier (Dept of Water)

This map is a product of the Department of Water, Science and Planning Division.

DISCLAIMER: While the Department of Water has made all reasonable efforts to ensure the accuracy of this data, the Department accepts no responsibility for any inaccuracies and persons relying on this data do so at their own risk.

Figure 3-9 Department of Agriculture and Food soil landscape mapping units

Figure 3-10 Examples of Bassendean soil type (left) and Pinjarra soil type (right)

4 Geology

4.1 Regional setting

The study area is located within the Perth Basin, a north-trending sediment-filled trough extending approximately 1000 km along the south-western margin of the Australian continent. Rifting of the continental plates and deposition of sediments began in the early Permian along the Darling Fault, culminating in the separation of Greater India from Gondwana by the Early Cretaceous. Post break-up tectonic activity abated and the Perth Basin subsided. Sediment deposition has continued episodically though to the present day in progradational shallow water and fluvial environments (Davidson 1995; Pennington Scott 2009).

The high-angle Darling Fault is visible as the Darling Scarp, the most significant structural feature on the Swan Coastal Plain. It separates the Achaean Yilgarn Craton to the east from the Mesozoic to Cenozoic deposits of the coastal plain to the west. The Serpentine Fault passes along a north-south trending line on the study area’s eastern side. The Serpentine Fault is a hydraulic barrier fault that separates the Upper Jurassic Yarragadee Formation from the Lower Jurassic Cattamarra Coal Measures. The Mandurah Fault passes through the south-western corner of the model. The Yarragadee Formation is deposited in a syncline that is bounded to the east and west by the Serpentine and Mandurah faults respectively. It is currently interpreted that the syncline has influenced the depositional extent of the Cretaceous units, potentially through differential compaction of underling sediments and penecontemporaneous subsidence (Davidson 1995). It is thought the underlying formations had settled and ceased movement before the superficial formations were deposited.

The Quaternary and late Tertiary superficial formations are of most interest to this study; although the geological units that directly underlie the superficial formations are also discussed.

The study area’s surface is covered by the collective superficial formations, ranging in thickness from about 12 to 40 m and deposited on a gentle westerly down-sloping surface. The upper surface can be divided into four geomorphic units: the Quindalup Dune System, Spearwood Dune System, Bassendean Dune System and Pinjarra Plain. They are associated with the geological formations of the Safety Bay Sand, Tamala Limestone, Bassendean Sand and Guildford Clay respectively.

Below these units in the study area’s northern and eastern parts are the Yoganup Formation, Quaternary sand or the Ascot Formation. Note that the Yoganup Formation has not been explicitly mapped in this report. This is due to its patchy deposition and similarity to the other formations in the lithology logs, making it difficult to consistently identify its extent and thickness.

These units unconformably overlie the Cretaceous Osborne Formation and Leederville Formation, as well as a minor region of Lower Jurassic Cattamarra Coal Measures in the east, and ramp up against the Achaean rocks of the Darling Scarp.

4.2 Stratigraphic units

Table 4-1 Stratigraphic units

Era	Period	Epoch	Date (Ma)	Stratigraphy		
Cenozoic	Quaternary	Holocene	0 - 0.01	Superficial formations (TQ)	Alluvium, estuarine and swamp deposits	
					Safety Bay Sand (Qs)	
					Becher Sand (Qc)	
		Middle to upper Pleistocene	0.01 - 1.0		Tamala Limestone (Qt)	Bassendean Sand (Qd)
		Lower to upper Pleistocene	1.0 - 1.8		Guildford Formation (Qg)	
	Tertiary	Late Pliocene to early Pleistocene	1.0 - 3.0		Ascot Formation (Ta)	Yoganup Formation (Ty)
Mesozoic	Cretaceous	Upper	91 - 113	Osborne Formation (Kco)	Kardinya Shale (Kcok)	Henley Sandstone (Kcoh)
		Lower	112 - 130	Leederville Formation (Kwl)	Pinjar Member (Kwlp)	
					Rockingham Member (Kwlr) (*proposed*)	
					Wanneroo Member (Kwlw)	
					Mariginiup Member (Kwlm)	
			125 - 136	South Perth Shale (Kws)		
			136 - 140	Gage Sandstone (Kwg)		
	Jurassic	Upper	144 - 181	Yarragadee Formation (Jy)		
		Lower	181 - 200	Cattamarra Coal Measures (Jc)		

Cattamarra Coal Measures

The Lower Jurassic Cattamarra Coal Measures underlies the Cretaceous units east of the Serpentine Fault and west of the Mandurah Fault. In the study area it unconformably underlies either the Mariginiup Member for much of the area between the Serpentine Fault and the scarp. In the study area's very-far-eastern margins it directly underlies the superficial formations, such as around bore AM64. It underlies the Yarragadee Formation between the Serpentine and Mandurah faults, and unconformably underlies the Gage Sandstone west of the Mandurah Fault.

It consists of non-marine interbedded fluvial sands, silts and clay beds, with dark carbonaceous fine-grained clastic rocks and coal seams (Crostella & Backhouse 2000; Davidson 1995). The geophysical logs indicate the sandy beds can be as much as 50 m thick, being predominantly composed of medium- to very-coarse-grained subangular to subrounded quartz with occasional silt and minor clay. Separating the sand beds are silt and clay layers usually less than 30 m thick, although these are not thought to be extensive enough to behave as aquitards at a regional scale.

Yarragadee Formation

The Upper Jurassic Yarragadee Formation lies below the Gage Sandstone and South Perth Shale, and on top of the Cattamarra Coal Measures in the area bounded by the Serpentine Fault to the east and the Mandurah Fault to the west.

The Yarragadee Formation consists of laterally discontinuous interbedded sandstone, siltstone and shale (Davidson 1995). The geophysical logs indicate the sandstone beds are in many instances greater than 30 m thick, while the siltstone and shale layers tend to be less than 20 m thick. The lithology consists of sand that is pale grey, medium- to coarse-grained, poorly sorted, slightly feldspathic and weakly cemented – probably laid down in a shallow marine environment (Davidson 1995).

Gage Formation

The Gage Sandstone is the oldest Cretaceous unit in the study area. It lies above the Jurassic formations and below the South Perth Shale, and extends west of the Serpentine Fault. Its thickness is difficult to accurately assess because its signature in the geophysical logs is quite similar to the Yarragadee Formation and Cattamarra Coal Measures. Nevertheless it is generally thought to be quite thin in the region. It is best defined using palaeontology; even so, interpreting it with palaeontology reports from old investigation holes is difficult because the mud-rotary drilling method used is known to cause contamination. To highlight the subjectiveness of picking the Gage Sandstone, in Becher Point bores 1 and 2 (AM57 and AM58) the thickness was originally interpreted to be less than 30 m (Allen 1978), yet more recently it was estimated to be approximately 60 to 70 m thick in the same locations (Davidson 1995).

Its lithology predominantly consists of alternating beds of silt and sand, with sand beds varying between 3 to 30 m in thickness and silt beds generally less than 6 m thick. The sands are mostly coarse-grained and vary in colour from grey to brown and orange. The silts are mainly dark grey to brown with pyrite and carbonaceous material. Palaeontological evidence indicates a mainly terrestrial deposition environment with intervening periods of shallow marine (Davidson 1995).

South Perth Shale

The South Perth Shale is in conformable contact with the overlying Mariginiup Member and underlying Gage Sandstone. Where the Gage Sandstone is not present it unconformably overlies the Jurassic formations. It ranges in thickness from east to west, being between 30 to 100 m thick, while also thickening towards the north-west. It was deposited in a predominantly marine environment, and consists of a thick sequence of interbedded silt and clay with minor sand content. It is dark grey to black and commonly pyritic and glauconitic. It forms a major confining bed that separates the overlying Leederville Aquifer from the underlying Yarragadee and Cattamarra aquifers (Davidson 1995).

Leederville Formation

The Leederville Formation underlies the superficial formations, with the exception of a narrow margin directly adjacent to the Darling Fault where the Cattamarra Coal Measures is present. It increases in thickness to the north and west, being over 250 m thick in the Swan Syncline bounded by the Serpentine and Mandurah faults. The Leederville Formation conformably overlies the South Perth Shale in most of the study area and unconformably overlies the Cattamarra Coal Measures in some areas east of the Serpentine Fault. It is unconformably overlain by the Osborne Formation in the central-north area and the superficial formations everywhere else. Depth to the Leederville Formation varies between 12 m in the east to greater than 60 m in the north-west beneath the Jandakot Mound.

The Leederville Formation predominantly consists of interbedded sandstones, siltstones and shales, and is subdivided into the Mariginiup, Wanneroo, Rockingham (proposed – see below) and Pinjar members. The Mariginiup Member directly underlies the superficial formations over a narrow extent east of the Serpentine Fault. Immediately to the west of this area the uppermost Cretaceous layer is the Wanneroo Member.

The Mariginiup Member mainly consists of siltstones and shales that are generally dark grey, black, mottled olive green or brown, with interbedded sandy layers. It also contains thin beds of limestone that create large resistivity spikes in resistivity logs. The proportion of siltstone to sand increases towards the north.

The extent and elevation of the Wanneroo Member shows it was deposited in a syncline that is down-faulted between the Mandurah and Serpentine faults. The base of the Wanneroo Member sits higher on the Mandurah Fault's western side than its eastern side.

The sands of the Wanneroo Member are beige to dark grey and occasionally green with glauconite, mostly uncemented, poorly sorted fine- to medium-grained quartz with feldspar and occasionally trace heavy minerals. The siltstones and shales are generally dark grey, black, mottled olive green or brown. They are usually micaceous, with minor carbonaceous material, and commonly associated with pyrite and glauconitic grains (Davidson & Yu 2008). The separation of the Wanneroo and Mariginiup members is defined by a green-clay marker bed that is thought to be a thin confining layer (Commander 1975).

The Rockingham Sand was thought to occupy a paleochannel cut into the Leederville Formation – previously charted between the northern side of the Peel Inlet and Cape Peron Peninsula (see Passmore 1970; Davidson 1995; Hall et al. 2010a). Recently Kretschmer et al. (2011) proposed the Rockingham Sand had an equivalent age to the Wanneroo Member of the Leederville Formation on the western side of an anticline aligned parallel to the Mandurah Fault. This later interpretation has been adopted for the conceptual model, and thus the Rockingham Sand is considered a Cretaceous-aged member of the Leederville Formation in this report. While further investigation is ongoing to assess the unit's future official status, in this report it will be referred to as the Rockingham Member *proposed* (p) and has been given the abbreviation Kwlr (p).

The Rockingham Member (p) consists of medium- to coarse-grained feldspathic quartz sand that is yellow, brown and pale grey. The feldspar grains are fresh, indicating rapid erosion with little chemical weathering of the source rock (Passmore 1970). The base of the Rockingham Member (p) is identifiable as the green-clay marker bed described in Commander (1975). The maximum thickness of the Rockingham Member (p) in the study area is about 150 m. As the Wanneroo Member and Rockingham Member (p) are considered to be equivalent, in this study they have been combined on the western side of the Mandurah Fault. Note that the Mandurah Fault is not believed to dissect the Leederville Formation.

The Pinjar Member has either been eroded or was never deposited in much of the study area; however it is still found in the central area of the syncline between the Mandurah and Serpentine faults, and also over a small extent east of the Serpentine Fault in the study area's north-east corner. The Pinjar Member consists of alternating layers of sand and clays visible as the spiky response in gamma logs. It obtains its maximum thickness of about 100 m at the study area's northern edge.

Osborne Formation

The Osborne Formation is found in the centre of the Swan Syncline at the study area’s northern end. Mainly consisting of the Kardinya Shale Member, it is composed of siltstone, shale and clay. It overlies the Leederville Formation and is overlain by the Tamala Limestone in the west, and the Ascot Formation and Quaternary sands in the central areas. Due to the thick shale beds it is assumed to act as a strongly confining aquiclude between the Leederville and superficial formations.

Superficial formations

The ‘superficial formations’ is the title used in this report for the collective Quaternary and Tertiary deposits. It is not an official title for a defined group of deposits. The base Quaternary and Tertiary contours presented in Figure 4-1 represent the unconformity base that the superficial formations lie above, and represents the upper surface of the previously described Jurassic and Cretaceous units. Figure 4-2 shows the Jurassic and Cretaceous units that lie below the Quaternary and Tertiary deposits.

Ascot Formation

The Ascot Formation rests unconformably on the Osborne Formation and is mainly overlain by the Quaternary sand. The Ascot Formation is described as consisting of grey, poorly sorted, subrounded, medium-grained sand to very fine gravel, fine sand, silt, clay and calcarenite, as well as limestone (Deeney 1989). It generally has a rich assemblage of bivalves, gastropods, echinoid spines and brachiopod shells – and south of Perth thick beds of shelly, silty clay – with thinly bedded glauconitic clay occurring in places (Davidson & Yu 2008).

The Ascot Formation is up to 20 m thick under the Jandakot Mound in the study area’s central-north. Its extent in the study area is illustrated with isopach contours in Figure 4-3.

Yoganup Formation

The Yoganup Formation directly overlies the Leederville Formation and Cattamarra Coal Measures, and may occasionally extend close to the surface along the study area’s eastern margin. In general it is unconformably overlain by colluvium, Bassendean Sand and, more extensively, the Guildford Clay. Due to a lack of detailed lithological information for the study area’s eastern margin and the Yoganup Formation’s patchy nature, it has not been separated out in the superficial formations, but rather combined with the Quaternary sand, Guildford Clay or colluvium depending on lithology and location.

The Yoganup Formation is described as consisting of white, yellowish-brown and orange-brown, poorly sorted, subrounded to subangular fine to very coarse sands and clayey sands. The sands are ferruginised and leached with minor weathered feldspar, and are associated with silts and clays. A gravel containing pebbles of granite and laterite up to 2 cm may be present at the base, and traces of carbonaceous material are sometimes found near the top (Deeney 1989). It is notable that a quartz pebble layer is common at the base of the Quaternary sand. The formation’s thickness is thought to be highly variable (0–15 m).

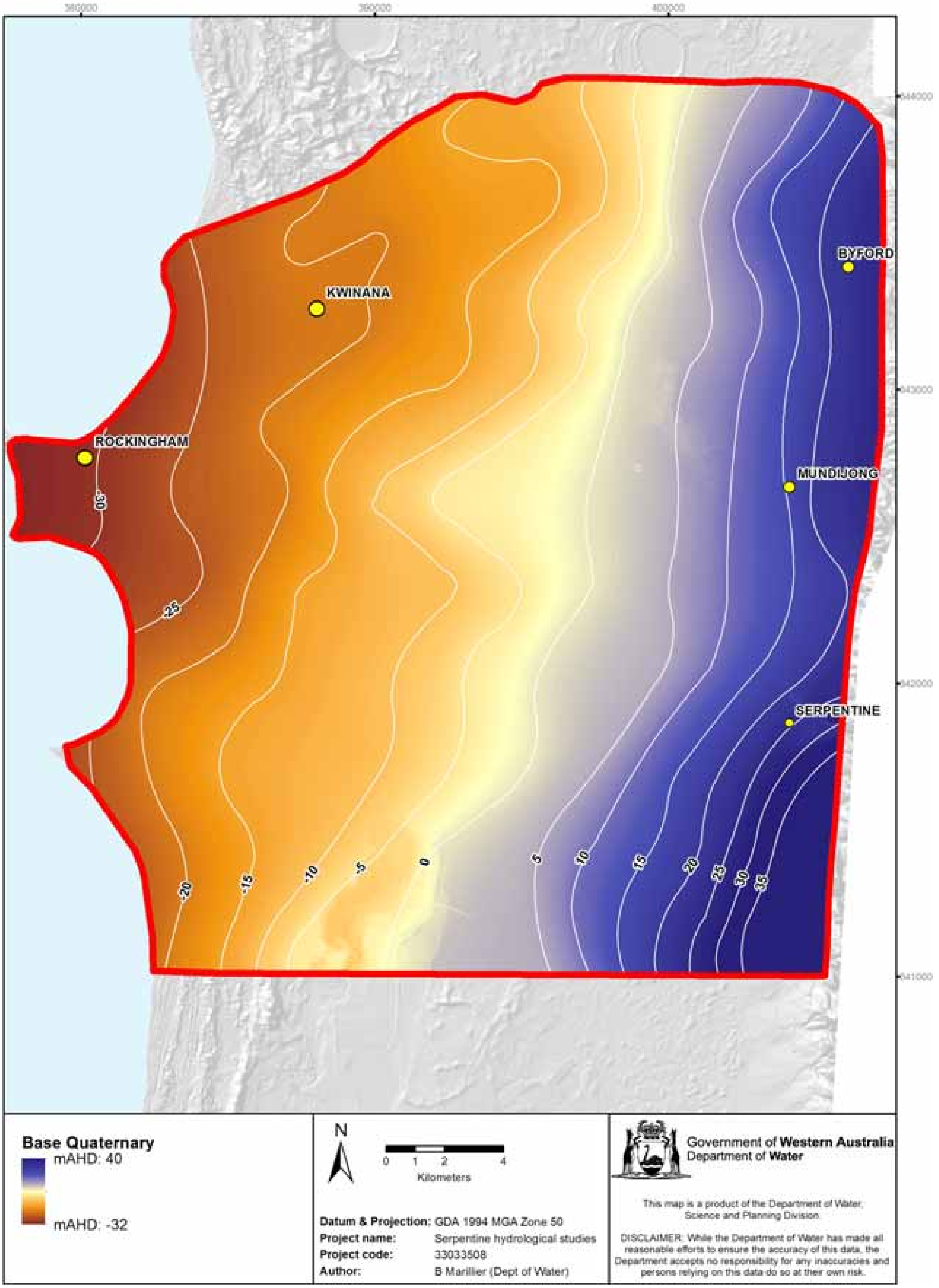


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Figure 4-1 Base Quaternary and Tertiary unconformity, representing the lower extent of the superficial formations

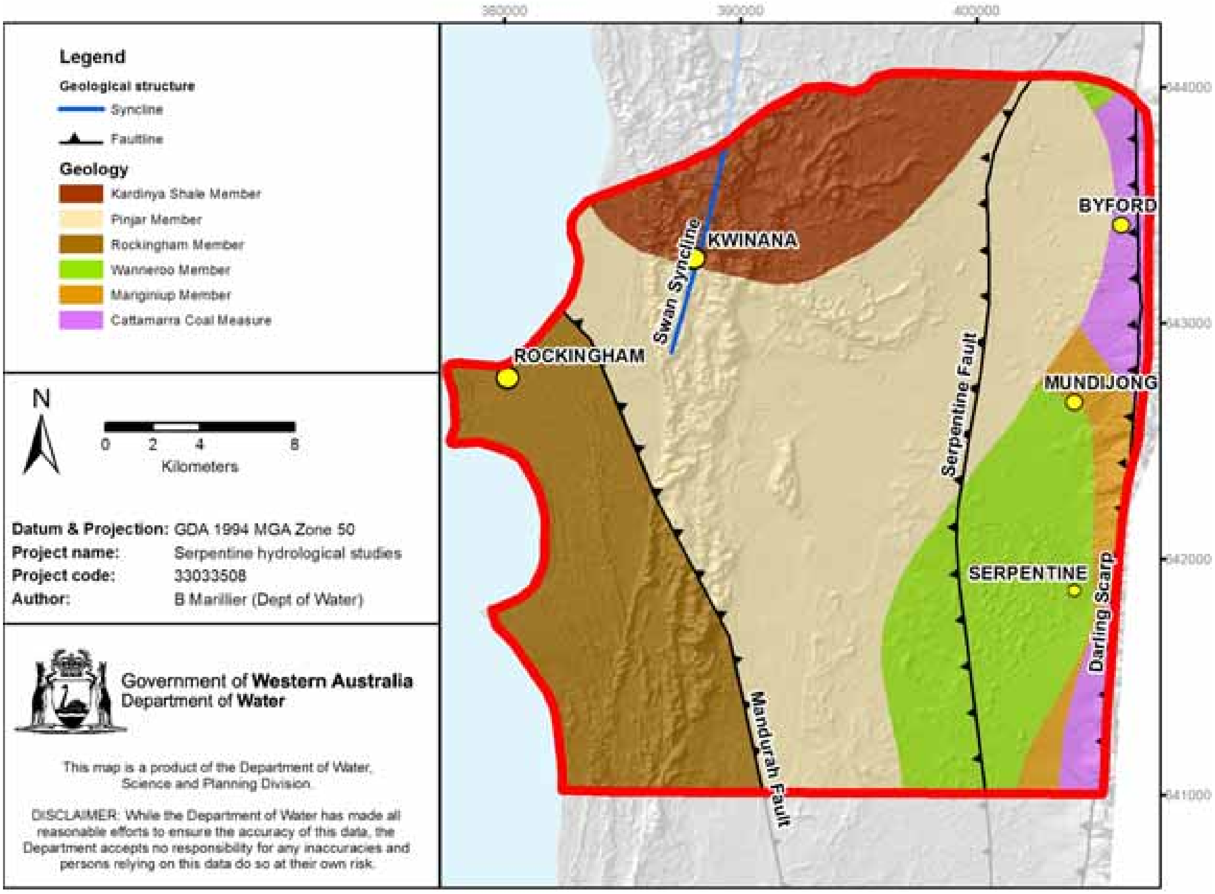

Figure 4-2 Formations underlying the superficial formations

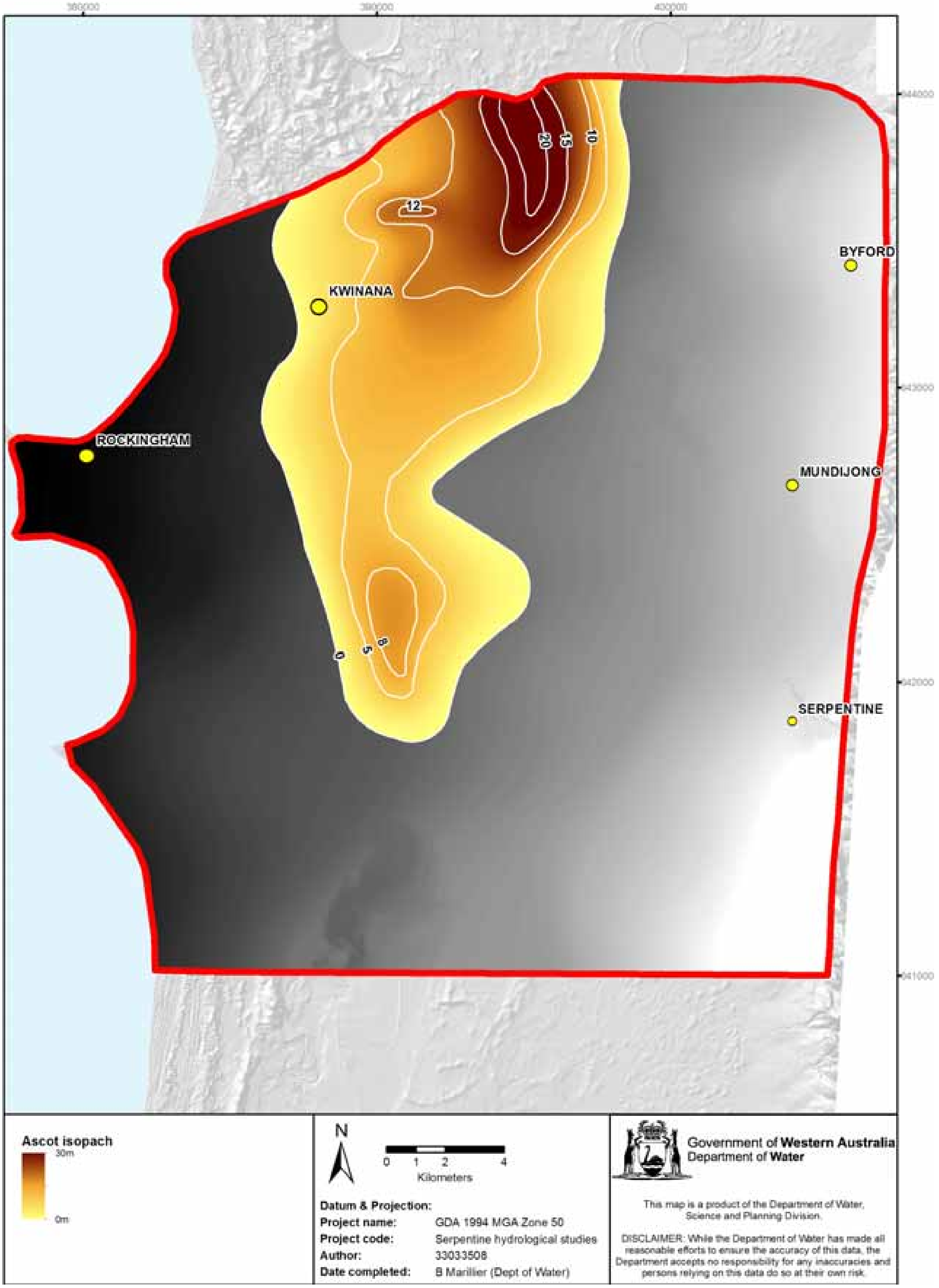

Figure 4-3 Ascot Formation: extent and thickness with underlying formations in grey

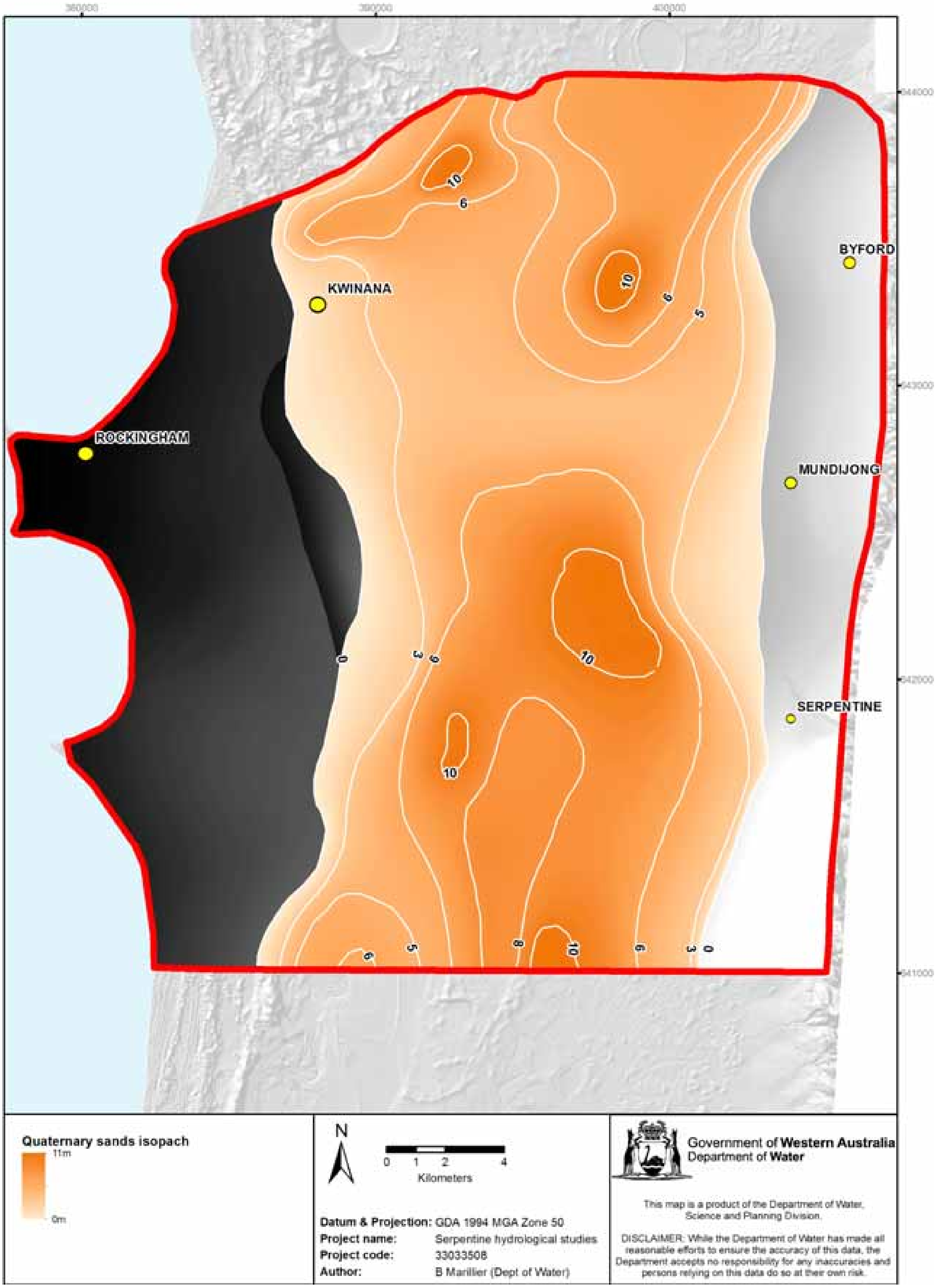

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Figure 4-4 Quaternary sands: extent and thickness with underlying formations in grey

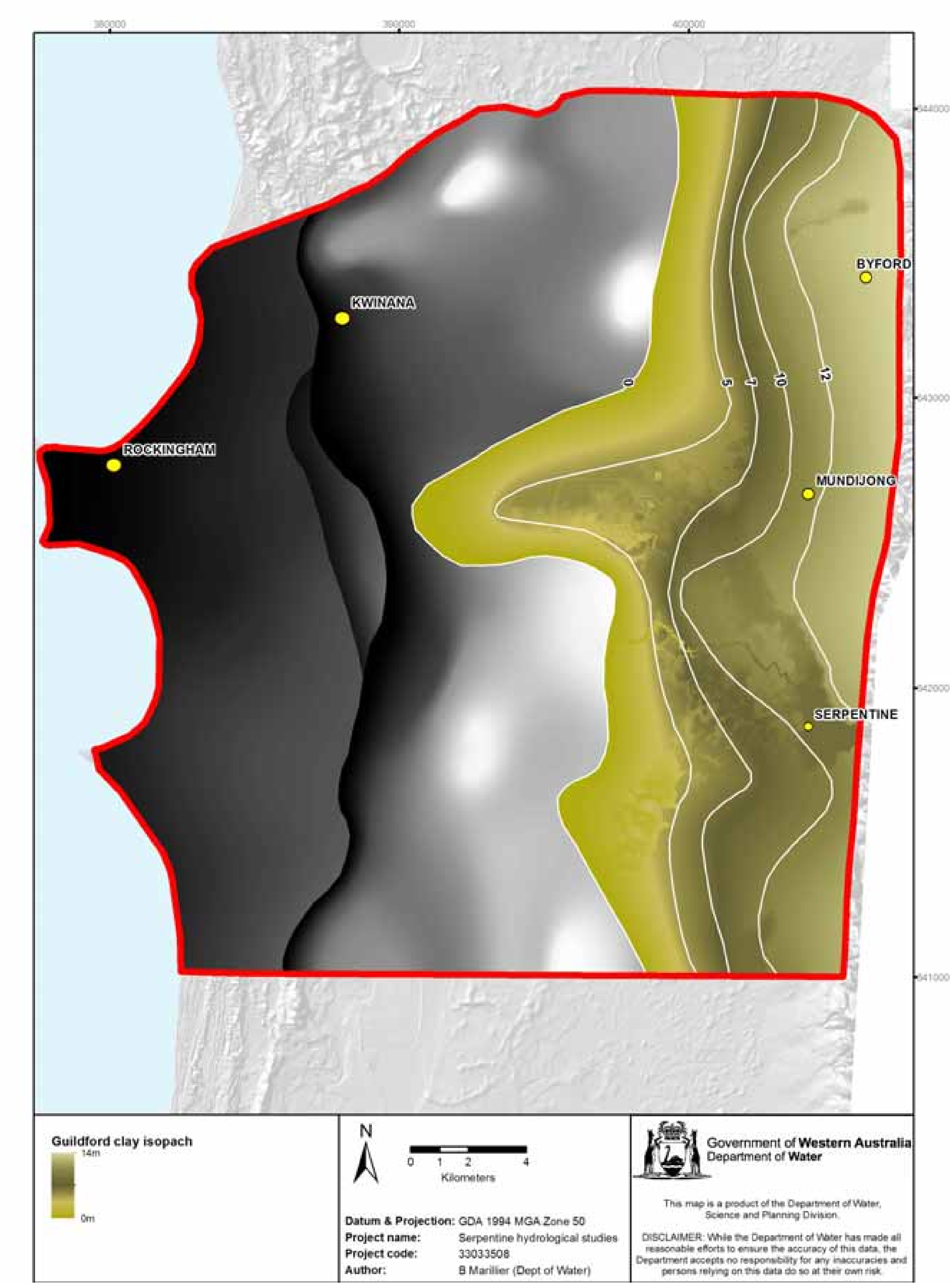

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Figure 4-5 Guildford Clay: extent and thickness with underlying formations in grey

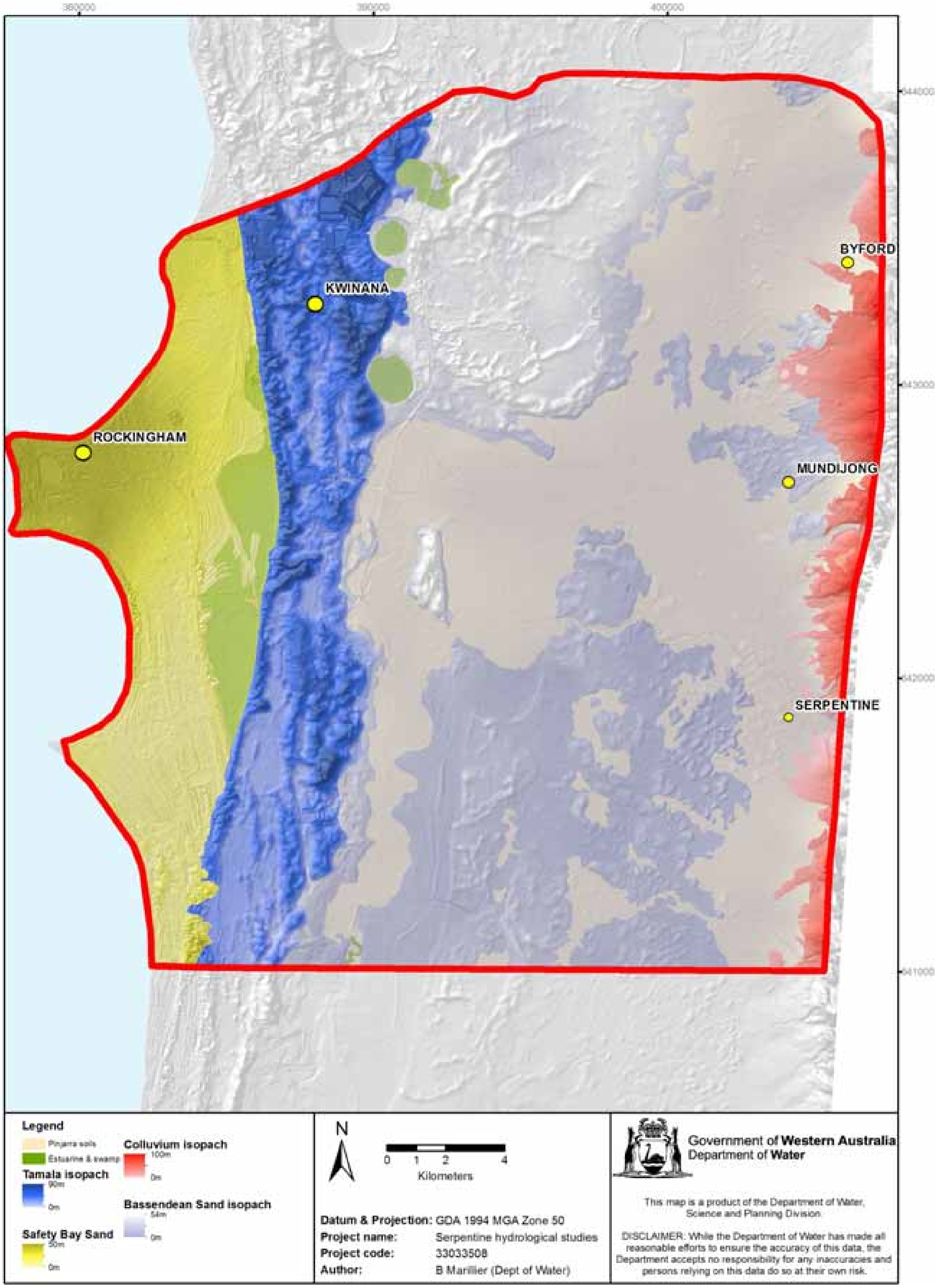

Figure 4-6 Surface geology extent and thickness of formations

Quaternary sand

The term Quaternary sand (Figure 4-4) is not considered to be an official term, with the origin of the sand being somewhat unclear. It may be related to the Gnangara Sand (Ryan 2011), but also may be related to the Yoganup Formation given the common reference to pebbles at its base – similar to the Yoganup Formation mapped by Deeney (1989) – and the way it sits with the Ascot Formation. The Quaternary sand is described as consisting of pale grey to grey-brown, fine- to very-coarse-grained, very poorly sorted, subrounded to rounded quartz and abundant feldspar. In some locations it can be of bimodal sorting, composed of both fine and very coarse grains. It is predominantly of fluvial origin, although it is more likely to be estuarine in areas containing bimodal deposits.

Guildford Clay

The Guildford Clay is predominantly of alluvial origin and is generally constrained to within 5 to 10 km of the Darling Scarp. It unconformably overlies the Yoganup and Ascot formations. It interfingers to the study area's west with the Bassendean Sand. In much of the study area it is overlain by a thin veneer of sand of likely aeolian Bassendean Sand origin.

The Guildford Clay is described as pale grey, blue, but mostly brown silty and slightly sandy clay. It commonly contains lenses of fine- to coarse-grained very poorly sorted conglomeratic sand at its base. These bases may represent remnant deposits of the Yoganup and Ascot formations (Davidson & Yu 2008).

Its thickness is about 12 m in the east, thinning rapidly to the west. See Figure 4-5 for a spatial interpretation of the Guildford Clay's surface and extent in the study area, with upper surface contours in mAHD.

Bassendean Sand

The Bassendean Sand is a pale grey to white and occasionally brown, moderately sorted, fine- to medium-grained quartz sand with traces of heavy minerals (Deeney 1989; Hall et al. 2010a). The grains tend to be subrounded to rounded quartz that commonly has an upward fining progression in grain size (Davidson & Yu 2008). A layer of friable, mostly weakly limonite-cemented sand known as 'coffee rock' is commonly present at or near the watertable.

In the central plain it is deposited as stranded dunes and over the Jandakot Mound is up to 30 m thick. It interfingers with and in many places overlies the Guildford Clay in a thin veneer, indicating it has been deposited during an alternating fluvial, estuarine and shallow marine environment (Davidson & Yu 2008).

Tamala Limestone

The Tamala Limestone is composed of limestone, calcarenite and sand, with minor clay and shell beds (Deeney 1989). It is generally creamy white to creamy yellow, and locally light grey. It is predominantly medium grained, moderately sorted, subangular to rounded, frosted and limonite stained (Davidson & Yu 2008). The limestone contains numerous solution channels that form a karst aquifer. Below approximately +3 mAHD the formation mostly contains marine and lacustrine sediments, while above this it is mainly aeolian sediments (Commander 1988).

The Tamala Limestone is visible as the prominent Spearwood Dune System west of the Peel Main Drain. Depending on its location in the study region it may overlie either the Osborne Formation or Leederville Formation. On its western side it is unconformably overlain by the Safety Bay Sand. Depending on the height of the dunes its thickness is up to 50 m in the study area.

Becher Sand

The Becher Sand is a near-shore marine deposit typically 10 to 15 m thick, with a maximum known thickness of 20 m near Rockingham (Davidson 1995). The Becher Sand unconformably overlies the Tamala Limestone and underlies the Safety Bay Sand. It extends from Woodman Point southwards towards Mandurah. It has been mapped as part of the Safety Bay Sand in this report because its limited coastal extent lies outside this report’s main area of interest.

Safety Bay Sand

The Safety Bay Sand was a name proposed by Passmore (1970) for an extensive band of Holocene-age dunes along the coastline. In places it can be up to 50 m thick and it overlies and extends westwards from the Tamala Limestone (Pennington Scott 2009). It is present as an extensive band of low dunes west of the Tamala Limestone between Mandurah to Rockingham.

The Safety Bay Sand is an aeolian fine- to medium-grained calcareous quartz sand with a large portion of shell debris.

Recent alluvial, estuarine and swamp deposits

The alluvial, estuarine and swamp deposits are associated with the many rivers, lakes and wetlands in the study area. These deposits consist of clays, silts and sand that is angular to rounded, poorly sorted and often containing gravel and pebbles (Pennington Scott 2009). Peaty and sandy swamp deposits are associated with the numerous wetlands, often having a dark brown, grey to black colour and being organic rich.

Colluvium

Along the edge of the Darling Scarp colluvium is identifiable as fragments of granite rocks and laterite unconformably overlying the Guildford Clay, Yoganup Formation and Precambrian rocks (Deeney 1989). The grain size can range from coarse pebbly sand to poorly sorted silty sand and clay. The colluvium’s thickness is highly variable.

4.3 Three-dimensional geological interpretation

Excluding surface mapping, the first regional interpretation of the superficial formations in the study area was only recently completed (Ryan 2011). This interpretation described the superficial units in detail, and illustrated two-dimensional cross-sections of the superficial formations that passed through the Thompson Lake bore series (T-bores) T130 to T570 in the study area. This initial interpretation was used as the basis of the three-dimensional model required for the *Lower Serpentine hydrological studies*. The formations underlying the superficial formations have been mapped and published by Davidson (1995), and again with minor revisions by Davidson and Yu (2008). Much of the data used to construct the three-dimensional model came from these two main sources. Figure 4-7 illustrates the final three-dimensional model, while figures 4-8 to 4-13 show six cross-sections of it.

When the geology interpretation of the Jurassic and Cretaceous units was constructed in 3-D from the published contour layers, some adjustments were made to ensure each layer fitted correctly to underlying and overlying units without gaps. This dictated modifications to the thickness of some units, and the Rockingham Member (p) was realigned with the Mandurah Fault to sit in continuity with the Wanneroo Member to the east. Where units made contact with the base of the superficial formations, their upper surface was adjusted to match the revised base Quaternary and Tertiary interpretation.

As there were no existing contour or extent maps of the superficial formations to construct the 3-D geological model, the stratigraphic picks from Ryan (2011) had to be converted into such a format. To ensure there were enough bores to extend the interpretation across the entire study area, additional T-series, private and Jandakot Mound bores were included. At each bore location the thickness of each unit was mapped and isopach contours drawn for the Ascot Formation, Quaternary sand, Guildford Clay, and Tamala Limestone (where it underlies the Safety Bay Sand). The isopach maps also delineated the extent of these formations with a zero-thickness contour.

Using ArcGIS the isopach map for each unit was stacked on top of the base Quaternary surface in order of their deposition. Steps were taken to ensure the stacked surfaces did not sit above the modern landscape elevation – an issue that is particularly relevant where rivers cut into the thickness of the superficial formations.

The process of assessing data topographically and in cross-section led to a continuous, chronologically correct three-dimensional layering profile being developed. The completed stratigraphical surfaces have been converted to a three-dimensional block model that can be used to create a computational groundwater model.

Sources of error

The block model and surfaces generated within the modelling area are a conceptual representation of the regional lithology. Heterogeneity within the sediments will not be completely represented within the model. The purpose is to capture the superficial formations’ coarse variability with enough accuracy to enable realistic calibration of the numerical model and the scale implemented. The accuracy of the model depends on the interpretation and classification of each lithological log, as well as the original stratigraphic description of the log. As additional information is collected over time, the interpretation should be reviewed. However, the interpretation is consistent with our geological understanding of the region.

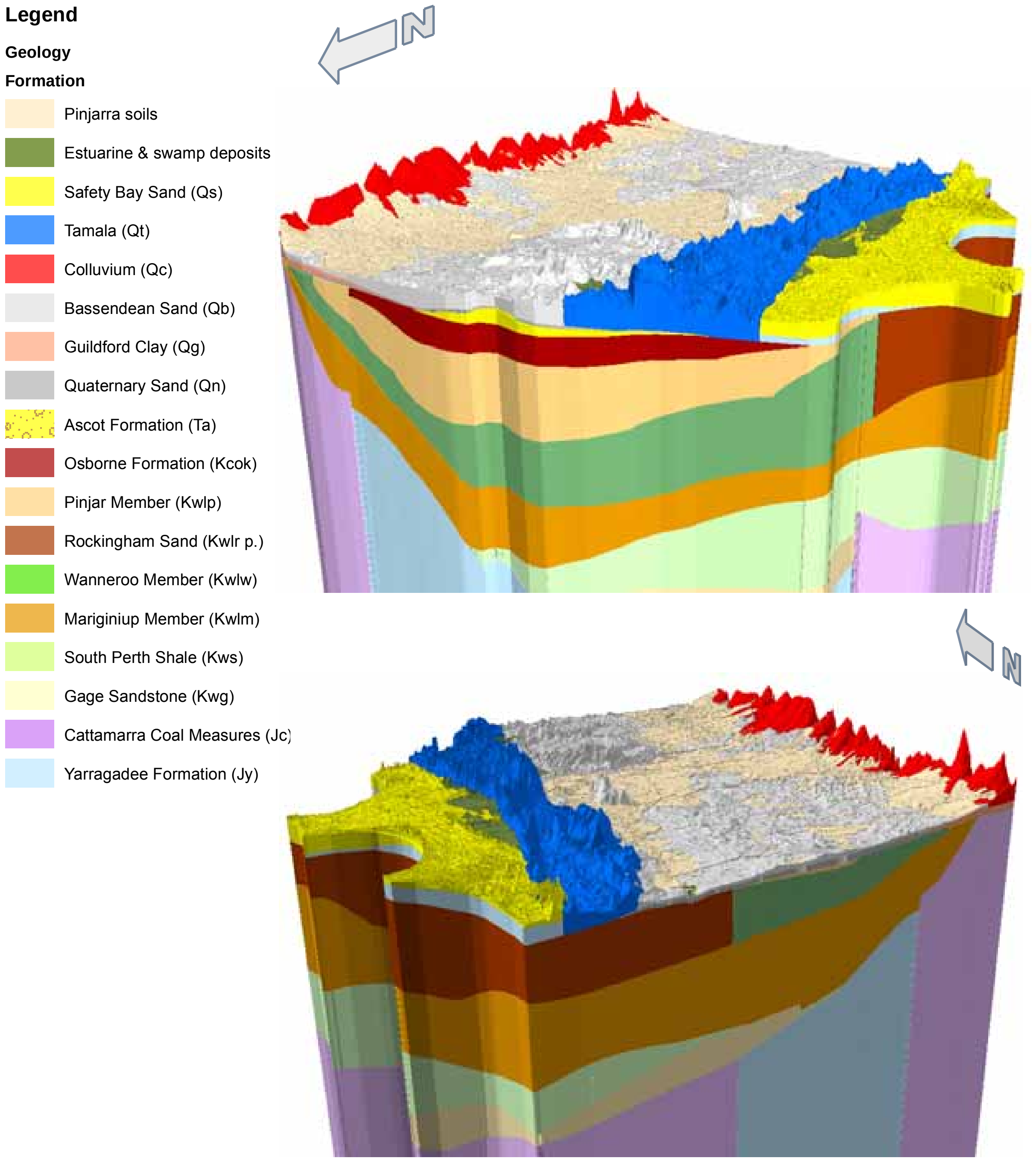

Figure 4-7 *Three-dimensional block model showing the geological interpretation used in the Serpentine conceptual model*

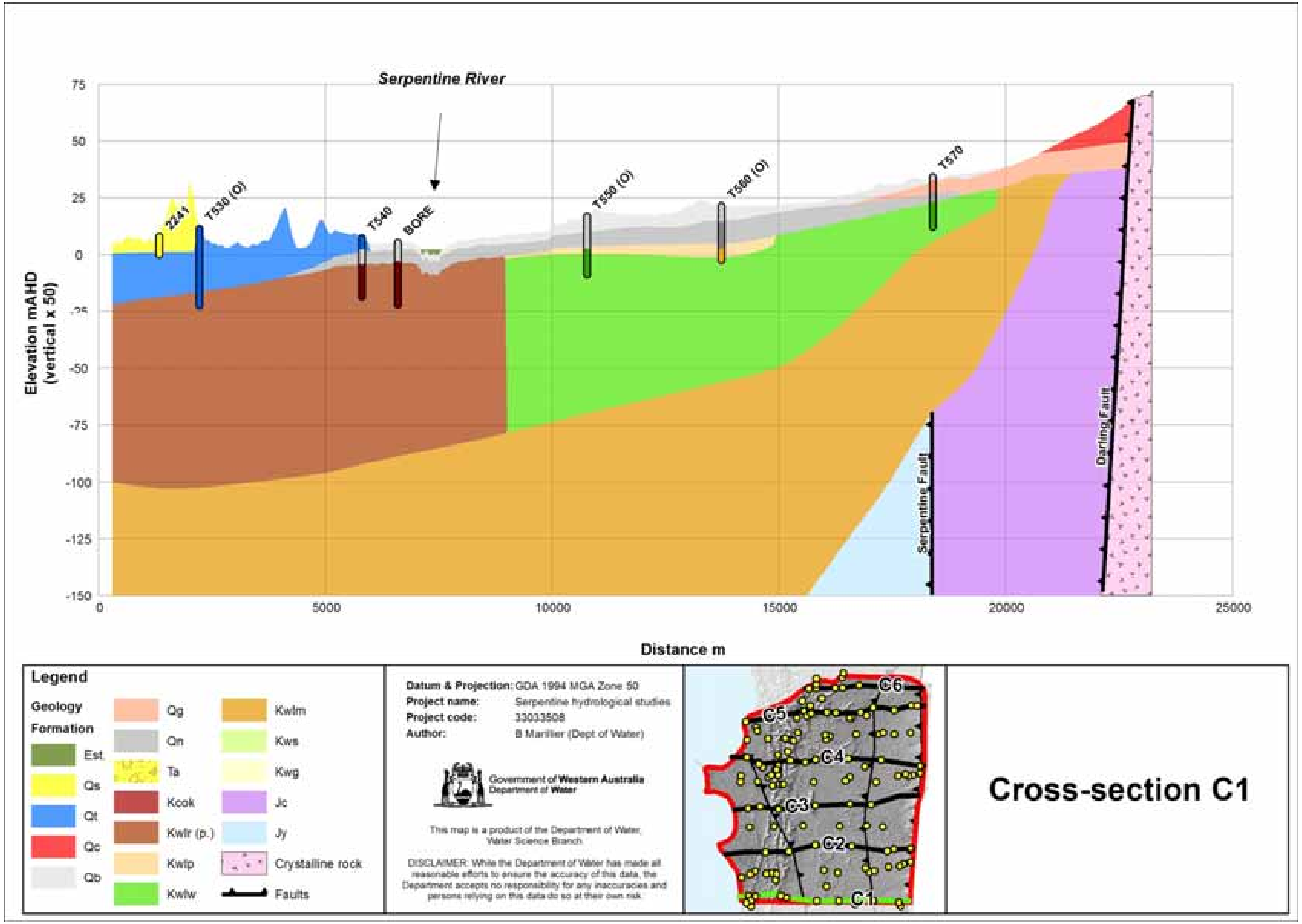

Figure 4-8 Cross-section C1

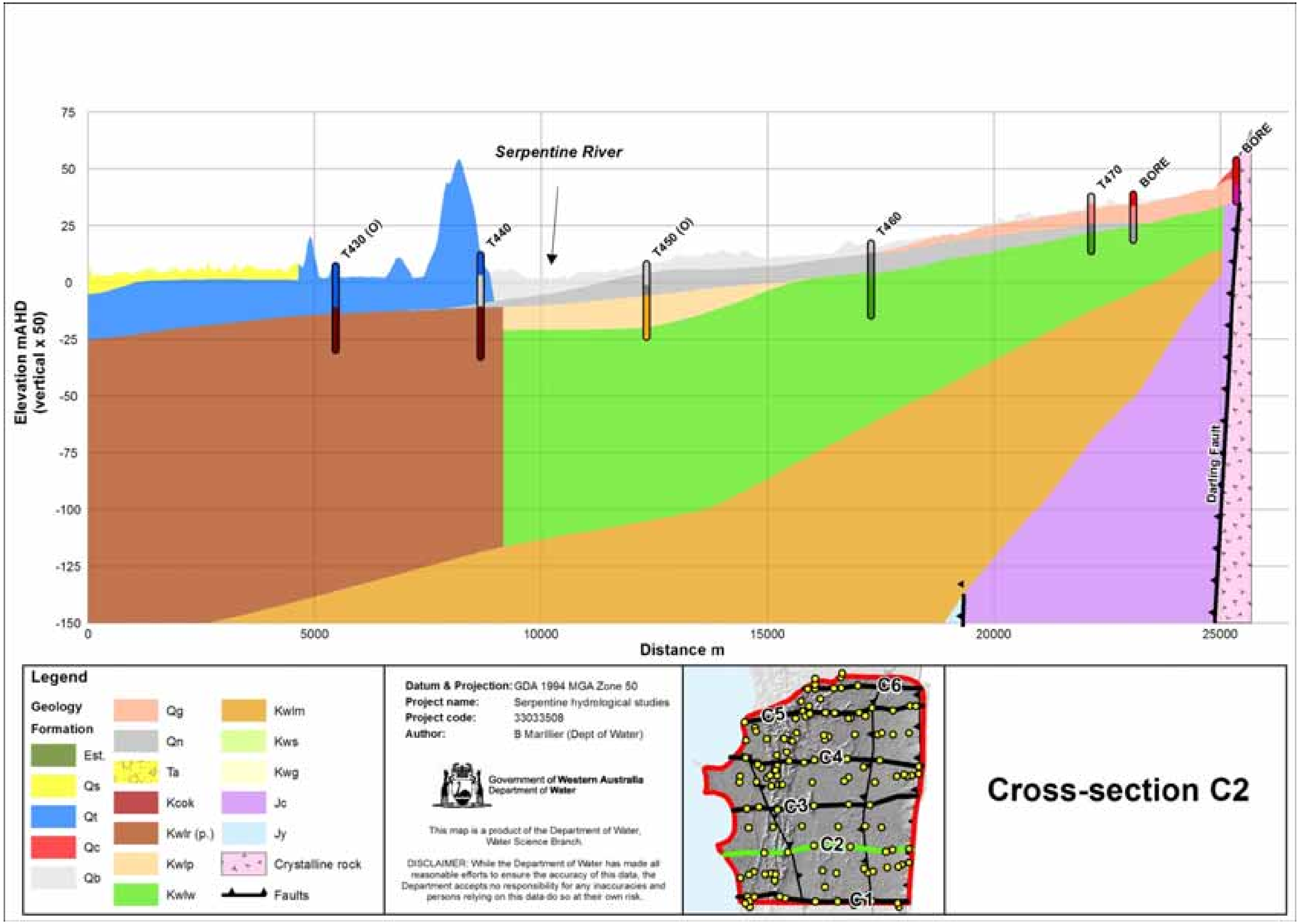

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Figure 4-9 Cross-section C2

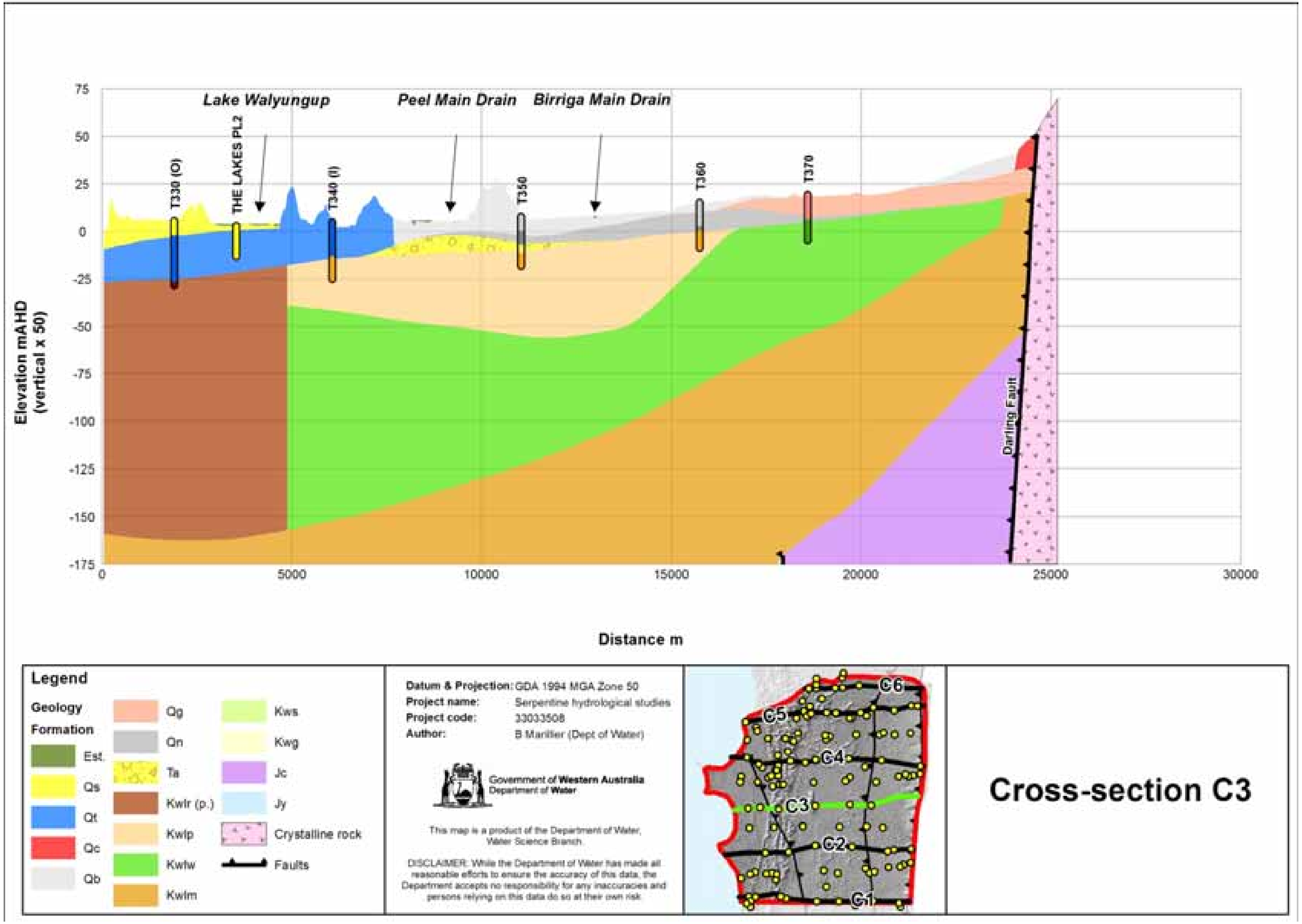

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Figure 4-10 Cross-section C3

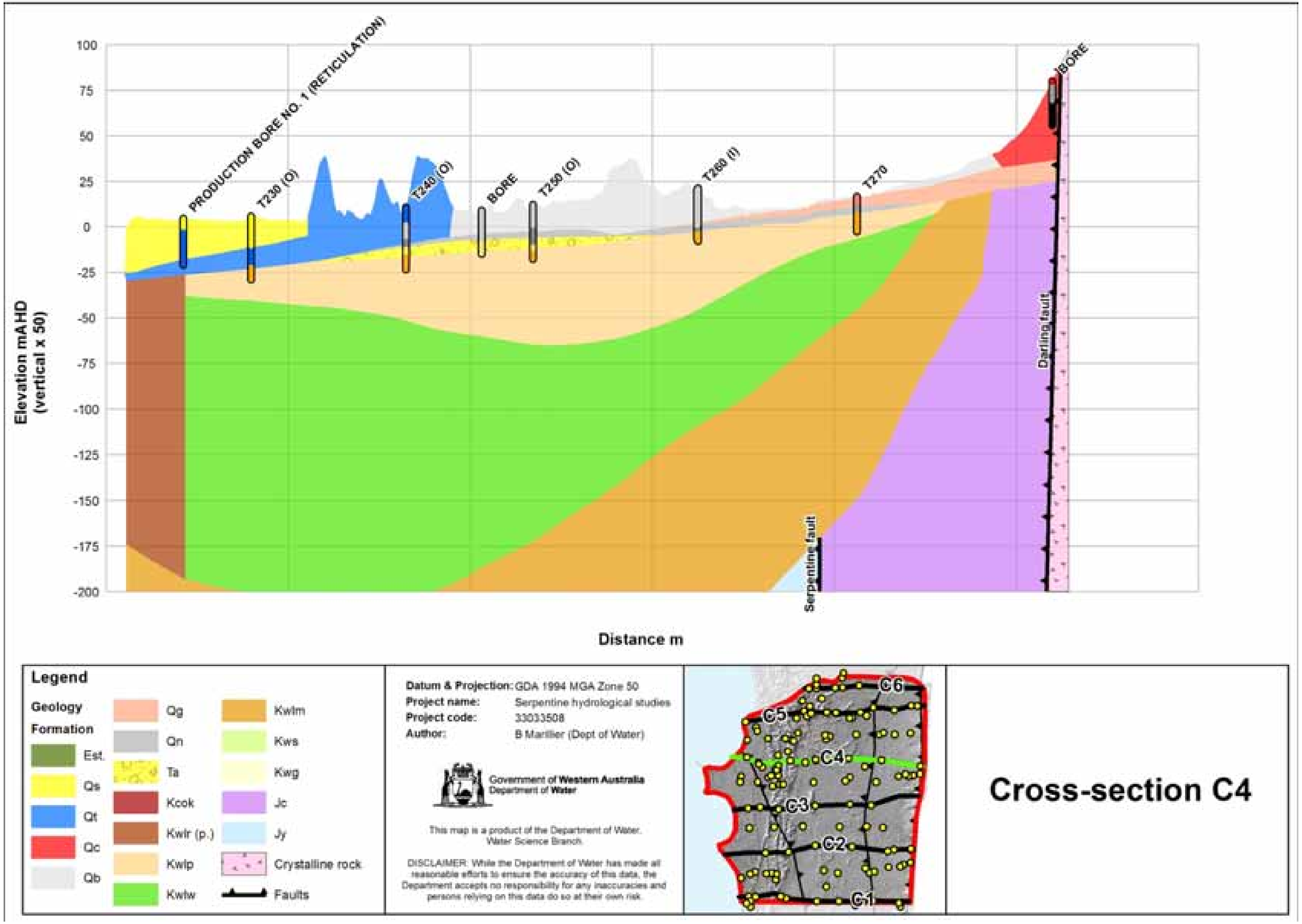

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Figure 4-11 Cross-section C4

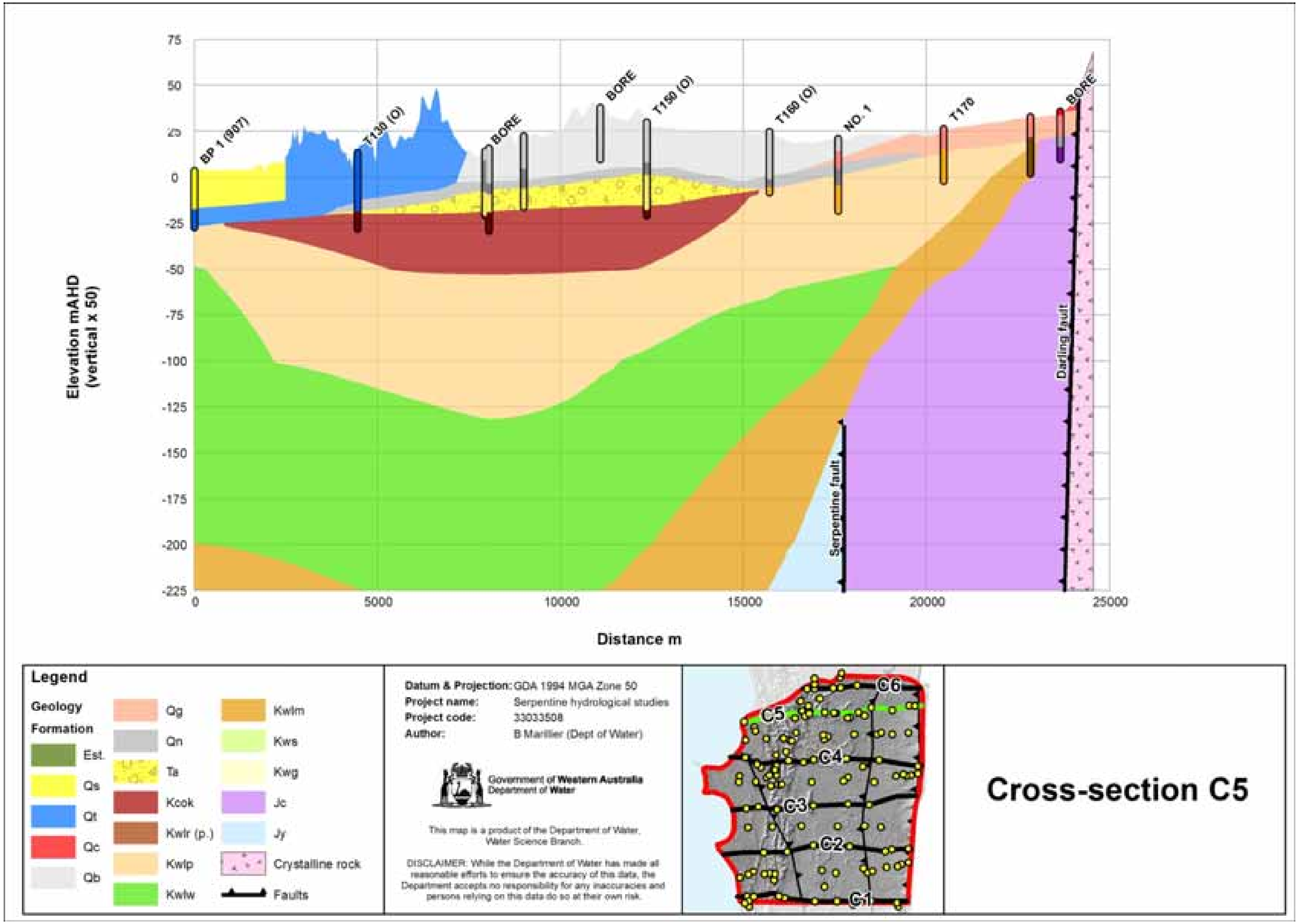


Figure 4-12 Cross-section C5

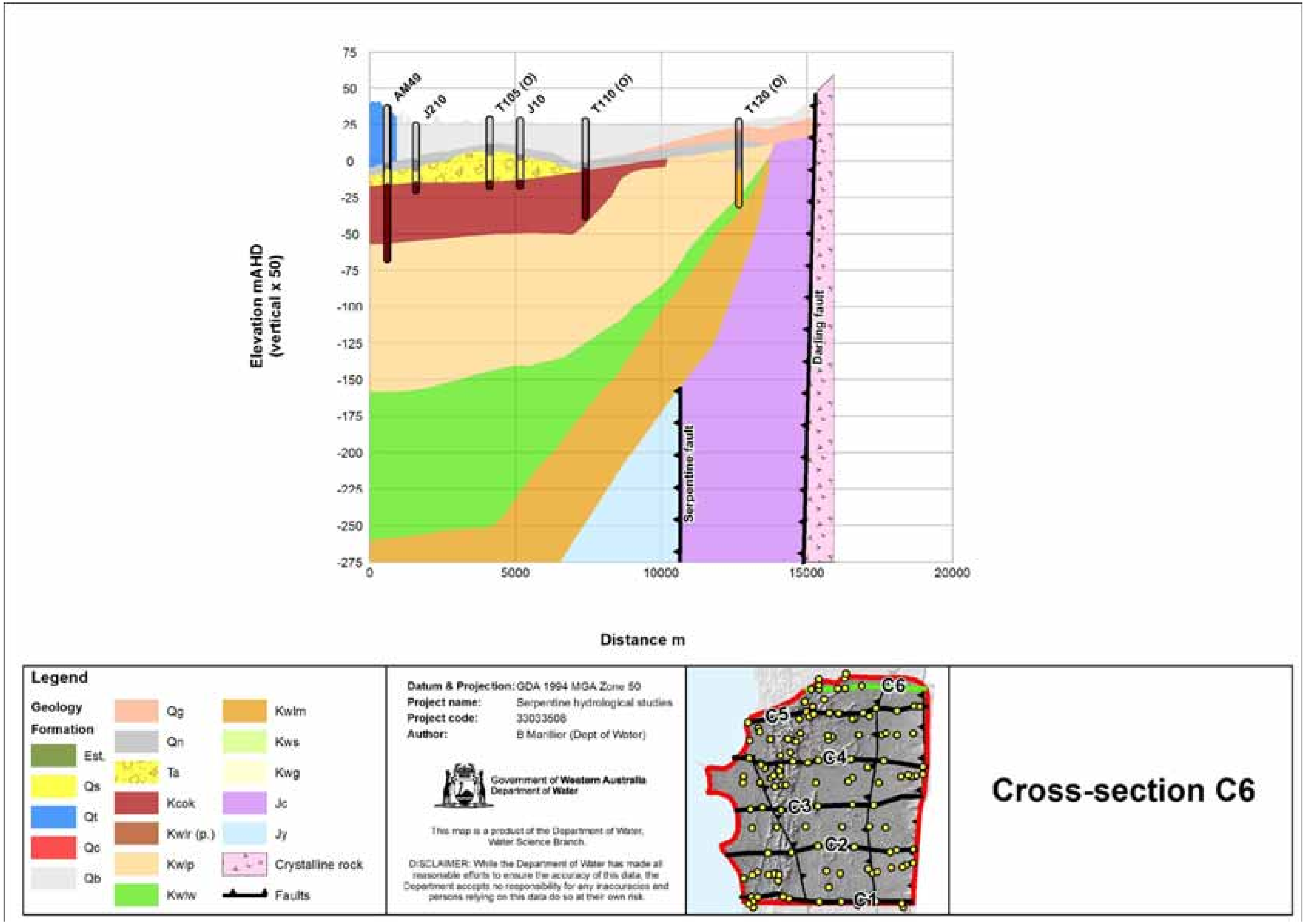
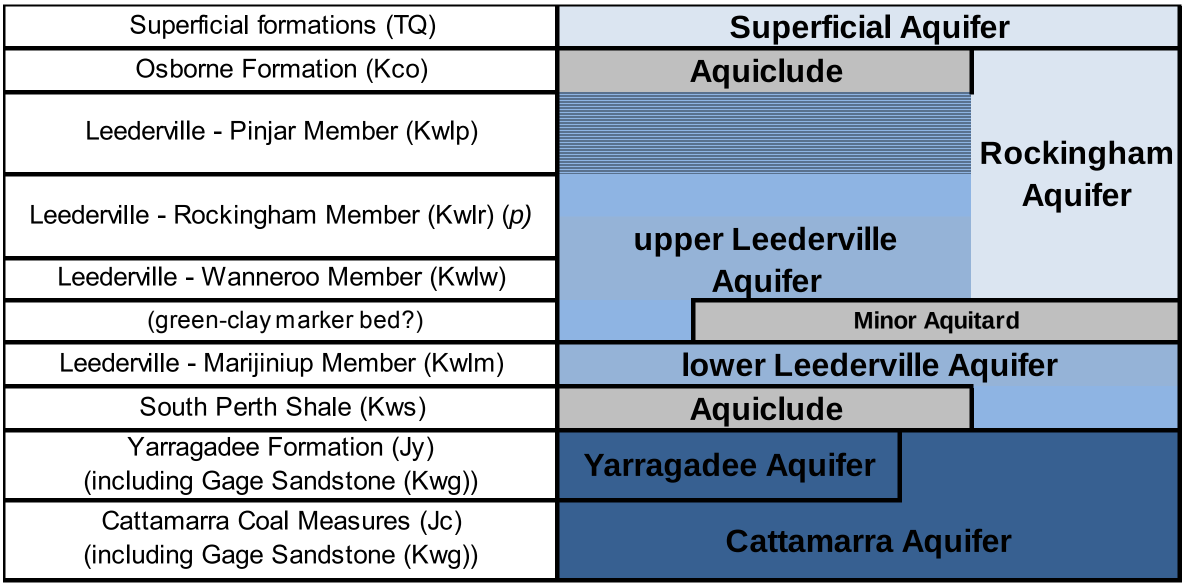


Figure 4-13 Cross-section C6

5 Hydrogeology

Within the study area the sedimentary deposits of the Swan Coastal Plain can be divided into six aquifers: the Superficial, Rockingham, upper and lower Leederville, Yarragadee and Cattamarra. Where the Gage Sandstone overlies the Yarragadee Formation and Cattamarra Coal Measures, it has been merged with the respective underlying aquifer.

Table 5-1 Hydrogeology



Superficial formations (TQ)	**Superficial Aquifer**	
Osborne Formation (Kco)	**Aquiclude**	**Rockingham Aquifer**
Leederville - Pinjar Member (Kwlp)		
Leederville - Rockingham Member (Kwlr) *(p)*	**upper Leederville Aquifer**	
Leederville - Wanneroo Member (Kwlw)		
(green-clay marker bed?)		**Minor Aquitard**
Leederville - Marijiniup Member (Kwlm)	**lower Leederville Aquifer**	
South Perth Shale (Kws)	**Aquiclude**	
Yarragadee Formation (Jy) (including Gage Sandstone (Kwg))	**Yarragadee Aquifer**	
Cattamarra Coal Measures (Jc) (including Gage Sandstone (Kwg))	**Cattamarra Aquifer**	

Phreatic and potentiometric surface analysis

The Department of Water measures the phreatic surface in the study area at the Thompson Lake (T-series) bores, Jandakot Mound monitoring bores and, historically, some additional locations (e.g. the south-east corridor bores). A subset of the large number of monitoring bores in the area was selected for calibration. The subset was chosen on the basis of data reliability and achieving good spatial distribution within the study area without duplication. In general, paired bores within the Superficial Aquifer were not included, because the intent was to use a single computational layer to model the aquifer. Where paired bores were present, the shallower bore was chosen for the calibration dataset. In most cases this resulted in the T-series observation (O) bores being selected over the investigation bores (I). In addition, generally the (O) bores are screened through the entire Superficial Aquifer and therefore better represent the average hydraulic head. Note that bore T320 was removed from the Superficial Aquifer dataset, as it is screened between 5 and 30 m depth, which is well into the Leederville Aquifer – in this area – where the base Quaternary unconformity is at around 10 m depth.

Figure 5-1 shows the locations of the selected bores, and Appendix C their hydrographs. A phreatic surface map of the study area was developed using head measurements recorded in May 2010. The interpretation was aided by the use of topography, previous groundwater studies and regional groundwater contours. Figure 5-1 shows the contour map of the May 2010 phreatic surface.

The Leederville Aquifer’s potentiometric surface is measured in the artesian monitoring (AM) series of bores screened in the Leederville Aquifer. Figure 5-2 shows the locations of these bores, and Appendix C the hydrographs for each bore used in the calibration. A contour map of isopotentials has been constructed for the Leederville Aquifer from hydraulic head measurements recorded in May 2010, see Figure 5-2. Note that only six bores are screened within the upper Leederville Aquifer, so additional bores screened in the lower Leederville were used to delineate the isopotentials.

The potentiometric surface for both the Yarragadee and Cattamarra aquifers is measured in the deep artesian monitoring bores screened in the each respective aquifer. Figure 5-3 shows the locations of these bores. A contour map of isopotentials has also been constructed for the two aquifers from hydraulic head measurements recorded in May 2010, see Figure 5-3.

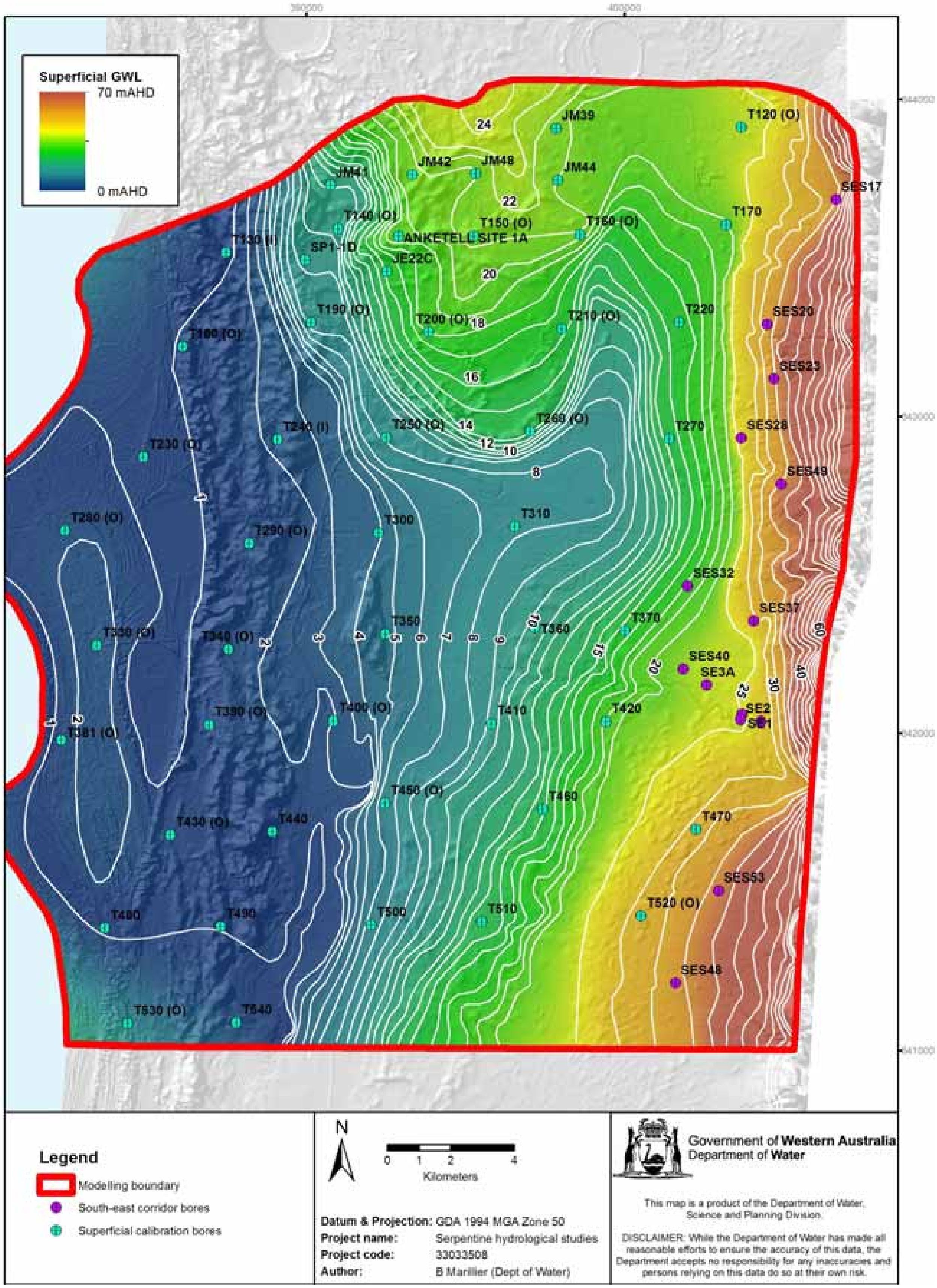


Figure 5-1 Superficial minimum groundwater contours and monitoring bores, derived from May 2010 water levels in Superficial bores

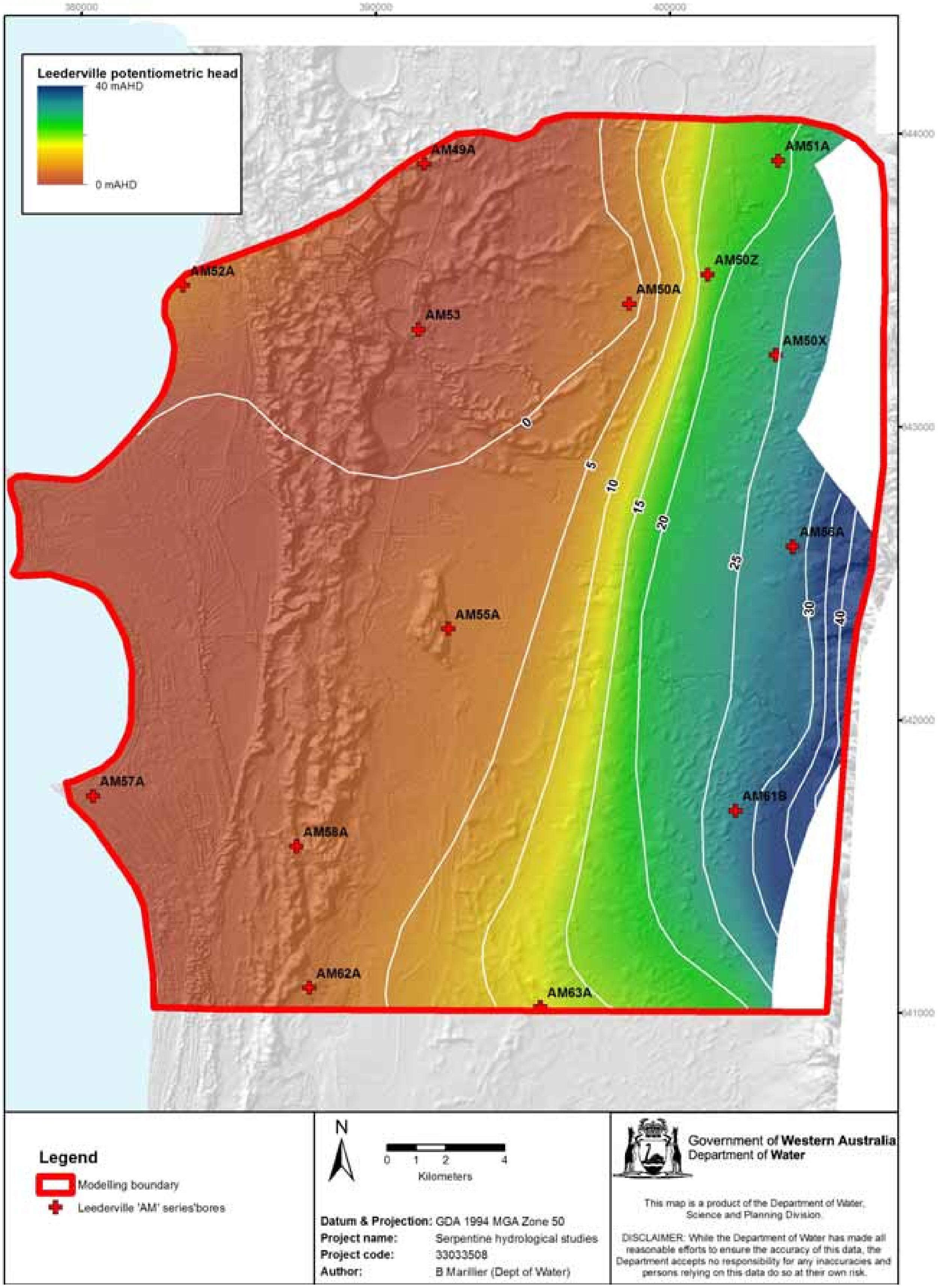


Figure 5-2 Leederville minimum groundwater contours and monitoring bores, derived from May 2010 water levels in the Leederville 'AM' series bores

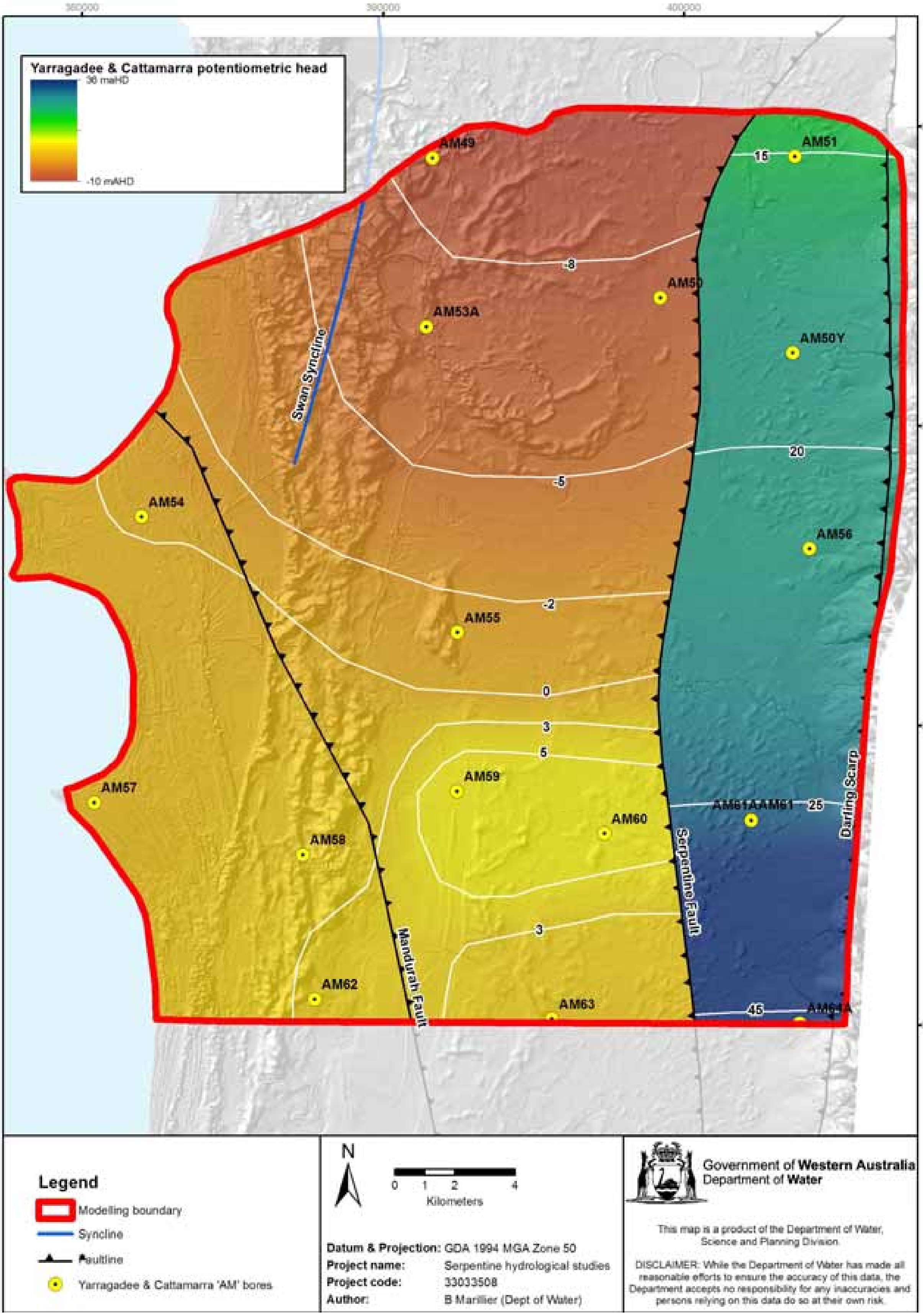


Figure 5-3 Yarragadee and Cattamarra minimum groundwater contours and monitoring bores, derived from May 2010 water levels in the relevant 'AM' series bores

5.1 Superficial Aquifer

Characteristics

The Superficial Aquifer in the study area is synonymous with the Quaternary and Tertiary superficial formations, and thus is characterised by clayey deposits in the east and sandy deposits in the west. The Superficial overlies a small section of the Cattamarra Aquifer along the Darling Fault; the Leederville Aquifer and Osborne aquiclude in the central and northern areas; and the Rockingham Aquifer west of the Mandurah Fault.

In most of the study area except for the foothills, the watertable tends to be located within 5 m of the surface, rising in winter by 1 to 2 m in the eastern plain and a more subdued 0.5 to 1 m in the western areas of the plain. In the eastern plain the annual fluctuation in water level can be 2 to 3 m because of the combined effects of lower hydraulic conductivity, clayey lithology, pumping and increased leakage to underlying aquifers. This variation in the watertable is the driver of the wetting and drying cycles of the study area's wetlands. To reduce maximum watertable heights and surface saturation, a network of drains was developed during the 20th century to channel water to the rivers and estuaries. These drains are an important control on the Superficial Aquifer's maximum groundwater level in many locations.

Recharge

Superficial Aquifer recharge predominantly occurs via direct rainfall on the Swan Coastal Plain, particularly in areas with a sandy profile. The Guildford Clay acts as a minor aquitard reducing recharge on the eastern side, however surface exposures of the sandier Yoganup Formation near the Darling Scarp may act as preferential recharge areas.

Some recharge to the Superficial Aquifer may occur via upward leakage from the Leederville Aquifer in areas with upward head gradients. The potential for upward leakage from the Leederville to the Superficial Aquifer occurs in the centre of the study area close to the Darling Scarp. Localised upward head gradients may also occur along streamlines where they have cut into the superficial formations.

Across most of the study area, recharge to the superficial groundwater is through free-draining sandy soils. In areas where the watertable reaches the surface there will be a component of rejected recharge; that is, water that would have recharged the aquifer but instead runs off as surface flow. Most of the water flux in the Superficial Aquifer is expected to be vertical via recharge and evaporative losses, with lateral movement consisting of a much smaller portion (Hall et al. 2010c). A major recharge area is the Jandakot Mound, see Figure 5-1. Groundwater flows in a radial direction out from the mound, and recharge is high due to the sandy sediments and large unsaturated thickness.

The watertable's elevation has been decreasing in much of the study area. In the north-east a cluster of T-series bores shows decreasing winter maximum water levels of between 1and 3 m since 1980 (see T120 (O) and T170 in Appendix C). In many other areas the decreasing trend is around 0.5 m, with the magnitude of the reduction tending to lessen towards the south and west.

The decreasing water levels have several potential causes including declining hydraulic heads in underlying aquifers increasing losses via vertical leakage, decreasing rainfall and recharge in areas with deep watertables, and increased unlicensed abstraction from the Superficial Aquifer.

Hydrodynamics

Groundwater flow in the Superficial Aquifer is predominantly east to west across the study area, although the rivers dissecting the plain and Jandakot Mound cause a deviation of flow in some areas (Figure 5-1). The phreatic surface reduces from more than 70 mAHD along the Darling Scarp to around 1 mAHD near the coast and lower Serpentine River. The Serpentine River has eroded through some areas of the Guildford Clay on the plain's eastern side, and would now likely has a connection to the Quaternary sand. Further west the Serpentine River intercepts the east to west flow in the study area's southern part, creating a groundwater divide. The Jandakot Mound is a major regional flow system. Water flowing to the south and east is intercepted by the Birriga Main Drain, while water flowing to the west contributes to the Spectacles Wetlands and Bollard Bullrush Swamp before being either intercepted by the Peel Main Drain or continuing west towards the coast. The numerous smaller paddock drains in the region do not appear to illicit a significant response in the regional flow directions, however this is unlikely to be seen in contours based on annual minimum water levels because the drainage channels are higher than the watertable.

The groundwater hydraulic gradient rapidly decreases from east to west. In the central plain the gradient is low, shown by the increased distance between lines of equipotential. The equipotential contours illustrate that the streams are gaining groundwater from the Superficial Aquifer in most areas. This may not be true of the uppermost reaches of the rivers and brooks flowing off the Darling Scarp, but the lack of watertable and river stage measurements in the far-eastern margin precludes us from knowing what is actually occurring. The low hydraulic gradient and shallow watertable indicate that the water balance will have high vertical fluxes (e.g. recharge from rainfall and evapotranspiration) and small lateral fluxes (e.g. horizontal groundwater flow).

See Section 6.2 for a discussion of horizontal and vertical hydraulic conductivity, and specific yield for each member in the superficial geology.

Discharge

Groundwater discharge from the Superficial Aquifer occurs via several mechanisms: the aforementioned surface drains and rivers, downward leakage, evapotranspiration, wetland-related pond evaporation, abstraction and marine discharge.

Evaporative losses are by far the largest discharges from the Superficial Aquifer, as demonstrated by Hall et al. (2010c). In the case of the Murray area, evaporative losses can exceed greater than 60% of the gross recharge. Water evaporates both directly from inundated areas and waterways and indirectly through vegetation. Deep-rooted vegetation can have a major influence on watertable elevations.

Discharge to underlying aquifers occurs where a negative (downward) head gradient exists and no confining layer is present. In the entire study area hydraulic heads in aquifers below the Superficial have significantly decreased over time. Figure 5-4 shows the potentiometric head difference between the Leederville and Superficial aquifers. The area beneath the Jandakot Mound has a head differential of up to 30 m, however in a large section of this area the Osborne Formation behaves as an aquiclude that greatly reduces leakage to the Leederville Aquifer. Where the Pinjar Member underlies the Superficial Aquifer, slightly more discharge will occur; where the Wanneroo Member's thick sandy beds directly underlie the Superficial Aquifer, preferential recharge zones are likely. Around the township of Serpentine, the Superficial and Cattamarra aquifers have been shown to be strongly connected (WAWA 1987). This was demonstrated during a pump test on a bore screened within the Cattamarra Coal Measures at 170 to 248 m bgl. After just nine days of pumping, observed drawdown was as high as 0.75 m in the Superficial Aquifer (WAWA 1987).

Coastal discharge from the Superficial Aquifer occurs directly along the coastline and via the Rockingham Aquifer. It is likely that more discharge occurs in the study area's north-west corner where the gradients from the Jandakot Mound to the coastline are steepest.

Groundwater abstraction can be a significant component of the aquifer water balance. Total licensed abstraction from the Superficial Aquifer within the study area is 25.6 GL/yr, with a further 8.7 GL/yr allocated from the Rockingham Aquifer and an estimated 15.1 GL/yr abstracted from unlicensed garden bores. Most groundwater drawpoints in the area are found around Rockingham and Kwinana. The Water Corporation extracts water from borefields in the Superficial Aquifer in the Jandakot Mound, and several of these drawpoints exist in the study area's far north. Alcoa also has a substantial allocation from the Superficial Aquifer around the Hope Valley refinery site. Historically abstraction has occurred near the site to intercept contaminated groundwater sourced from its tailings dams.

5.2 Rockingham Aquifer

Characteristics

The Rockingham Aquifer extends northwards from the Peel Inlet to the Rockingham district, and consists of the Rockingham Member (p) of the Leederville Formation. As previously discussed, its eastern boundary has been interpreted to align with the Mandurah Fault. It is a locally important aquifer. It dips towards the north-west, the same as the Leederville Aquifer, and increases in thickness from around 70 m in the south to around 150 m in the north. It is in hydraulic connection with the overlying Superficial Aquifer, as well as the Wanneroo Member of the Leederville Aquifer to the east and the ocean interface to the west. The green-clay marker bed at its base is thought to behave as an aquitard that reduces interaction with the underlying Mariginiup Member of the Leederville Aquifer.

Recharge

Recharge to the Rockingham Aquifer occurs from the Superficial and Leederville aquifers. In places the superficial formations are less than 5 m thick and quite sandy, so percolation is likely to be an important part of its water balance. Recharge occurs laterally from the Wanneroo Member to the east.

Recharge to the Rockingham Aquifer occurs above the saltwater/freshwater interface at -64 mAHD several kilometres inland. Quantitative estimates of recharge using flow-net analysis conducted by Davidson (1995) found recharge rates of 14 300 kL/d, or about 2% of rainfall over its mapped area. The westerly flow from the Wanneroo Member contributed about 3300 kL/d to that figure, however it is expected that decreasing heads in the Leederville since 1995 will have reduced this value.

Hydrodynamics

Hydraulic heads in the top of the Rockingham Aquifer are similar to those recorded in the Superficial. Observation bores T480 (Superficial Aquifer) and T481 (Rockingham Aquifer) illustrate that hydraulic head fluctuations in the Rockingham mimic those of the Superficial. A matching trend, though the head difference is small, is similarly observed between T280 (Superficial Aquifer) and T281 (Rockingham Aquifer).

Early investigations of the Rockingham Aquifer recognised seawater intrusion as a threat to water quality (Passmore 1970). A saltwater interface was identified between 65 to 75 m BGL several kilometres inland (Davidson 1995), although since then the interface may have moved because of reduced recharge relating to a changing climate, the reduced head gradient from the Wanneroo Member into the Rockingham Member and increased abstraction. The saltwater interface is also prone to upconing in areas of high extraction rates. This process may have already affected some users: a transition from fresh to brackish water has been noted in some bores.

5.3 Leederville Aquifer

Characteristics

Within the study area the Leederville Aquifer is synonymous with the Mariginiup, Wanneroo and Pinjar members of the Leederville Formation. It is a major aquifer below the Swan Coastal Plain, becoming confined over short distances due to the nature of its interbedded shale, clay and sandstone layers. The ratio of sandstone to siltstone and shale within the Leederville Aquifer is approximately 0.5, being highest in the Wanneroo Member and lowest in the Mariginiup Member (Davidson 1995). Its eastern boundary is either the Achaean basement rocks of the Yilgarn Block, or the Cattamarra Aquifer where it subcrops under the Superficial Aquifer. The aquifer extends north and south of the study area and westwards under the ocean (Pennington Scott 2008). It increases in thickness from its tapered eastern boundary towards the coast, but achieves maximum thickness and depth in the centre on the Swan Syncline at the study area’s northern end. Within the study area the Leederville Aquifer is overlain by the Superficial Aquifer (recharge source) and Osborne Formation (confining aquiclude). Underlying the Leederville Aquifer is the South Perth Shale, which acts as an aquiclude between the Leederville and Cattamarra aquifers.

The Leederville Aquifer can be further subdivided into the upper and lower Leederville aquifers owing to their different lithology and partial hydraulic separation by the green-clay marker bed. The influence of the green-clay marker bed is discussed in more detail in early studies such as Commander (1975). The upper Leederville Aquifer consists of the Wanneroo and Pinjar members. The Wanneroo Member is the most relevant unit given the Pinjar

Member has a higher shale content. The lower Leederville Aquifer consists of the Mariginiup Member. The highly interbedded sand and thick beds of shale reduce both the vertical hydraulic conductivity and average horizontal hydraulic conductivity in the lower Leederville Aquifer.

Recharge

Within the study region recharge occurs predominantly via downward vertical leakage from the Superficial Aquifer along the eastern margin, in areas where negative head differences prevail. In the eastern areas of the plain recharge is likely to be limited by the Guildford Clay, although sandy components of the Quaternary sand and Yoganup Formation may act as preferential recharge flow paths. Figure 5-4 illustrates the potential for recharge across the study area. Due to the decreasing heads in the Leederville Aquifer the recharge area is extending further west over time.

Recharge is likely to be most rapid in the areas of the Superficial Aquifer underlain by the Wanneroo Member, while recharge rates to the Mariginiup and Pinjar members will be affected by the interbedded layers of clay, which limit vertical hydraulic conductivity.

Hydrodynamics

The flow system underlying the study area is generally east to west, with isopotentials running parallel to the Darling Scarp. The potentiometric head reduces from around 40 mAHD close to the Darling Scarp to more than 5 m below sea level in the north-west. Abstraction of groundwater from areas north of the study area is the main cause of negative hydraulic heads. During the past 25 years hydraulic heads have decreased by up to 6 m at AM49A and AM51A in the north, to less than 0.5 m at AM60E and AM63A in the south (see Appendix C).

Seasonal head fluctuations are about 2 to 4 m. The lower hydraulic gradients in the west reflect the increasing thickness and transmissivity of the Wanneroo Member. The higher rates of abstraction are also increasing the size of the seasonal fluctuation of the potentiometric head. For example, the potentiometric head in bore AM50X varied around 2 m seasonally in the early 1980s, but in recent years the fluctuation has been 4 m. The aquifer's horizontal hydraulic conductivity varies for each stratigraphic member, given their very different lithology. The horizontal conductivity of the Pinjar Member is around 1 m/day, of the Wanneroo Member 1 to 10 m/day, and of the Mariginiup Member 0.1 to 1 m/day (Davidson & Yu 2008). The vertical conductivity is constrained due to the interbedded shale and siltstone, particularly in the Pinjar and Mariginiup members.

Discharge

At present the head differences shown in Figure 5-4 illustrate that the upper Leederville Aquifer is discharging to the Rockingham Aquifer; however, with heads decreasing in the Leederville while mostly remaining stable in the Rockingham, this situation may eventually reverse.

Below the green-clay marker bed the lower Leederville Aquifer continues westward where the groundwater discharges offshore via a saltwater interface (Davidson 1995). Some flow may discharge vertically to the Superficial Aquifer where upward vertical gradients are present, although this is constrained by the Rockingham Aquifer and green-clay marker bed confining layer. There is also likely to be groundwater movement to the north-west, where Leederville heads have declined to below sea level, see Figure 5-2.

The other major discharge flux is groundwater abstraction. In some locations abstraction may exceed aquifer recharge, therefore removing water from storage (mostly the confined storage component initially). Total licensed abstraction from the Leederville Aquifer within the study area is currently 5.7 GL/yr, which is an increase from 1.8 GL/yr in 1997. Within the area a total licensable allocation of 7.4 GL/yr is available.

5.4 Vertical leakage between aquifers

The differences in hydraulic head between the aquifers located in the study area have been calculated using gridded surfaces, see figures 5-4 to 5-6. These surfaces are used in the water balance calculations discussed in Section 6, and show likely areas of vertical recharge and discharge within the Superficial and Leederville aquifers. Note that no head difference was calculated between the Superficial and Rockingham aquifers, which are observed to be in hydraulic continuity in the study area.

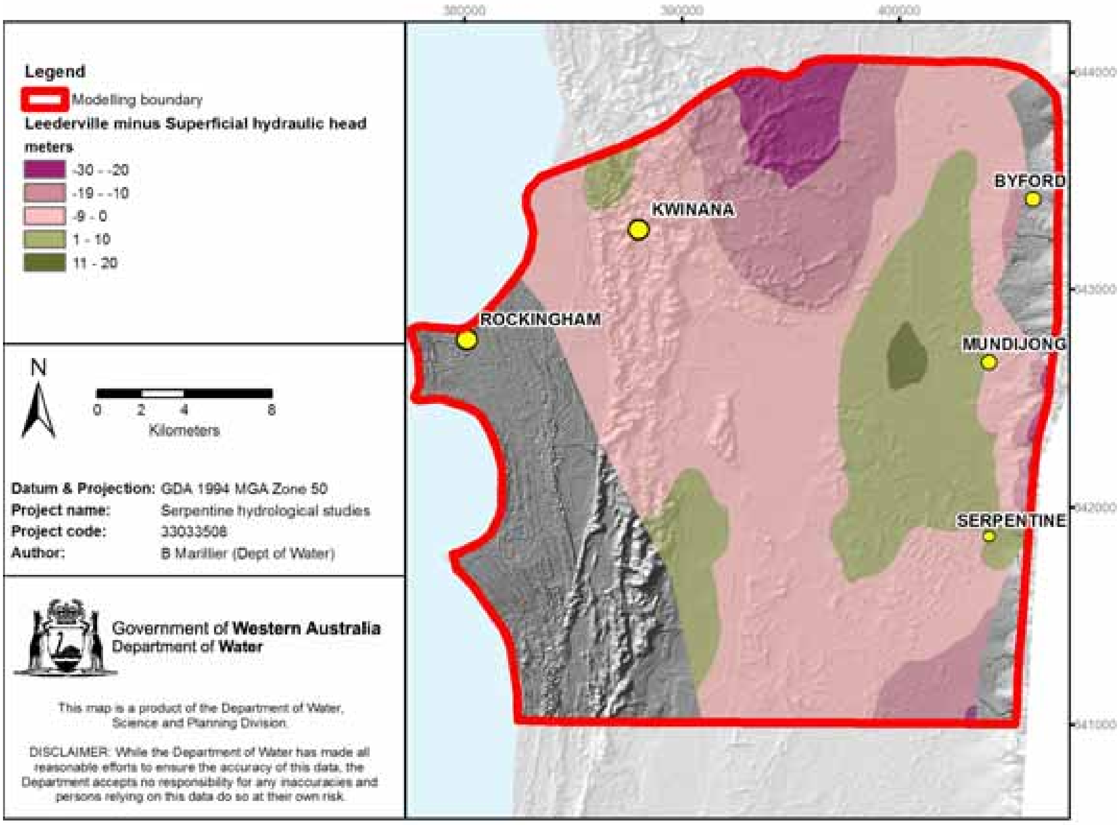


Figure 5-4 *Difference in hydraulic head between the Superficial and Leederville aquifers*

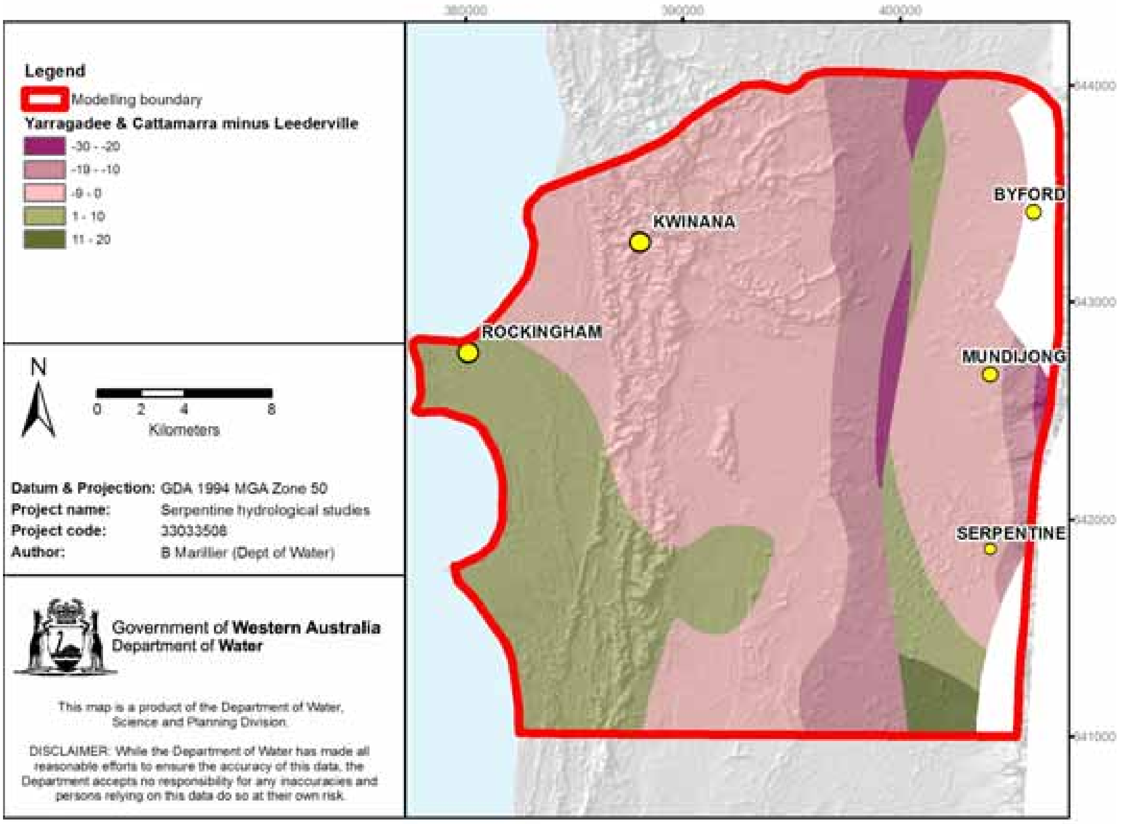


Figure 5-5 *Difference in hydraulic head between the Leederville and Yarragadee aquifers*

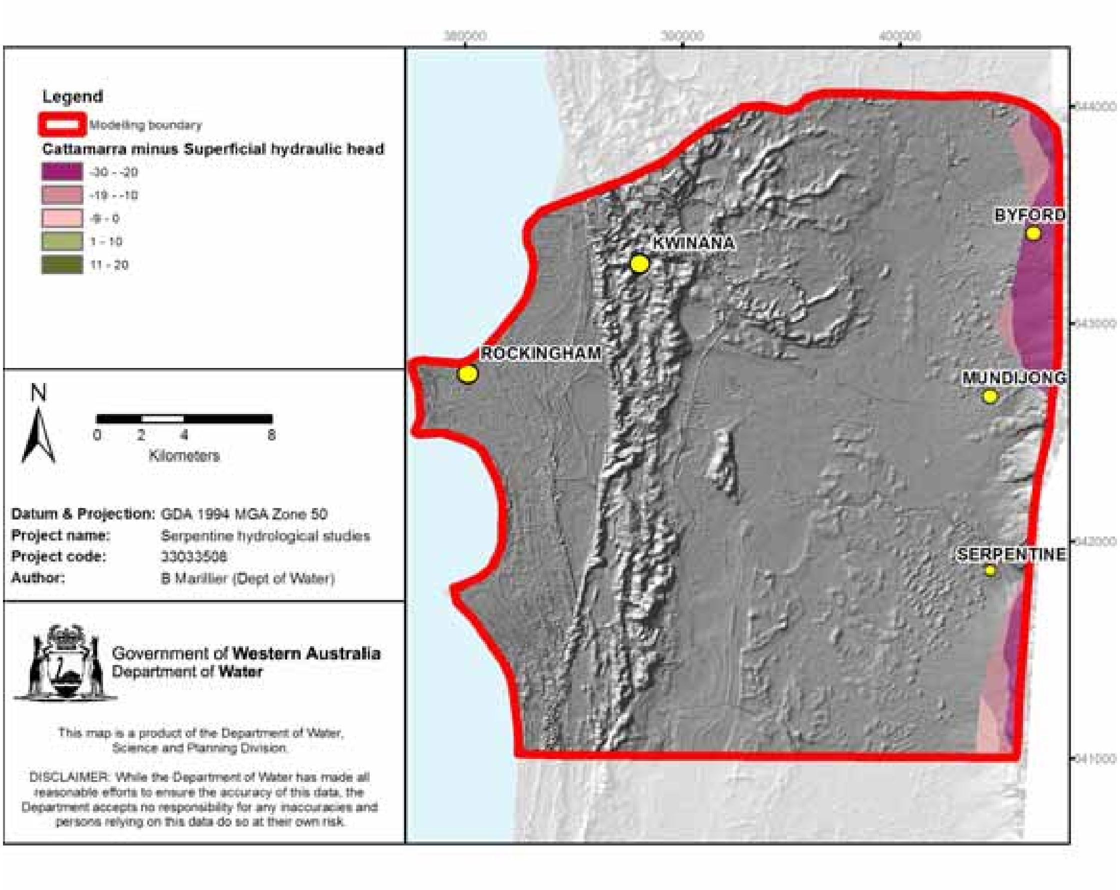


Figure 5-6 Difference in hydraulic head between the Superficial and Cattamarra aquifers

5.5 Cattamarra Aquifer

Because of the Cattamarra Aquifer's limited extent and interaction in the study area, only a brief summary is given.

Within the study area the Cattamarra Aquifer is analogous to the Cattamarra Coal Measures. It is present immediately below the Superficial Aquifer along a narrow section adjacent to the Darling Scarp (Figure 4-2), and below the Leederville Aquifer between those areas and the Serpentine Fault further to the west. The South Perth Shale prevents interaction between the Cattamarra and Leederville aquifers west of the Mandurah Fault. East of the Serpentine Fault, hydraulic connection between the Cattamarra Aquifer and the overlying Superficial and Leederville aquifers has been well established near the township of Serpentine (WAWA 1987).

Generally the hydraulic conductivities observed in the upper Cattamarra Aquifer are slightly higher than those in the Leederville, ranging up to 10 m/day. However, the clayey sediments in the eastern areas of the superficial formations act to reduce recharge to the aquifer. Low recharge rates are indicated by the rapidly increasing salinity with depth (Davidson 1995).

The flow system in the study area is generally south to north, radiating out from the recharge area near Myarup Brook close to the study area's south-east boundary. The isopotentials are perpendicular to the Darling and Serpentine faults, reflecting their status as hydraulic barriers (Berliat 1963). The potentiometric heads in the recharge area of the Cattamarra Aquifer range from 45 mAHD in the south to 15 mAHD in the north.

In the recharge area near AM64A, maximum seasonal water levels have reduced from around 53 to 51 mAHD during the past 20 years, but the hydrograph also shows a strong relationship to dry years in 2001, 2006 and 2010. During these years the maximum head was 3 to 5 m lower than average. At AM51 in the study area's north the decline in hydraulic head has been very significant, decreasing from 27 to 16.5 mAHD since 1980. Since 2000 the rate of decline has increased at this location.

Abstraction is the main form of discharge from the Cattamarra Aquifer, which in the study area is quite limited, with a total licensed allocation of 0.3 GL/yr. However, significant abstraction occurs regionally, and has increased since the 1980s. As such, declining heads in the Cattamarra Aquifer are likely to be a combination of reduced recharge and increased abstraction at the regional scale.

5.6 Yarragadee Aquifer

Given the Yarragadee Aquifer is separated from the rest of the study area by the hydraulic barriers of the Serpentine Fault and South Perth Shale, it is not discussed further in this report.

6 Numerical conceptualisation

This section outlines the numerical description of the Serpentine conceptual model. The conceptual model is based on the collation of hydrological, hydrogeological, geological, climatic and topographical information gathered as part of the literature review and data interpretation process described in the previous chapters. The conceptual model reflects our general understanding of the system. This conceptualisation deals with the Superficial Aquifer, upper Leederville Aquifer, Rockingham Aquifer and surface water processes. Numerical steady-state water balances are presented for these systems in the following section.

The model area covers 728 km2 and is located on the Swan Coastal Plain, approximately between Dirk Brook in the south and Rowley Road in the north (see Figure 1-1). The aim of the numerical conceptualisation is to quantify the water balance of the entire system being modelled. The conceptual model is based on our understanding of the hydrological system, and it outlines the key processes to be implemented in the numerical model. Quantifying the main fluxes in the water balance enables any issues with system conceptualisation to be identified early in the modelling lifecycle. The numerical conceptualisation aims to capture a number of hydrogeological processes, including rainfall, recharge, evapotranspiration, runoff, wetland and drainage interaction with groundwater, leakage between aquifers, abstraction and horizontal movement of groundwater. See 6-2 for a diagram of the conceptual model, which identifies the main fluxes considered in the numerical conceptualisation.

6.1 Model boundaries

To quantify fluxes within an aquifer system, it is necessary to define a discrete area using hydrogeological boundaries. There are two forms of model boundary: physical (real) and hydraulic (artificial). Physical boundaries are well-defined geologic and hydrologic features that permanently influence the pattern of groundwater flow. Examples include impermeable contact between two geologic units or contact between the porous medium and a large body of surface water. It is preferable to have physical model boundaries as external model boundaries. If that is not possible because of model scale limitations (i.e. the real boundaries are too far and it is not feasible to include them), then hydraulic boundaries need to be defined. Hydraulic boundaries are derived from the groundwater flow-net and are therefore ‘artificial’ boundaries. The Serpentine model area has a combination of real and artificial boundaries.

For the Superficial Aquifer, the model’s eastern boundary is the Darling Fault, where crystalline bedrock forms a physical barrier to groundwater flow. However, surface water may still enter this boundary via overland flow and rivers, and this flux must be accounted for in water balance calculations. The model’s northern and southern boundaries are defined as perpendicular to the superficial groundwater contours. These are hydraulic boundaries and assume no lateral movement of groundwater parallel to the defined contours. The western boundary is defined by the Indian Ocean, which forms fixed head boundary, and is set to mean sea level. See Figure 6-3 for model boundary conditions for the Superficial Aquifer.

The Leederville Aquifer's boundary conditions differ to those of the Superficial because the direction of groundwater flow varies. Boundary conditions in the east, south and west are identical to those of the Superficial. However, flow-net analysis (Appendix B) shows the northern boundary acts as a discharge boundary from the Leederville. As such, it must be set as a time-varying head boundary. The boundary conditions can be approximated by the observed heads in bores AM52A, AM49A and AM51A. Using a sinusoidal curve-fitting procedure, it is possible to generate a time-series of hydraulic head from these bores that can be implanted as a time-varying head boundary, see Figure 6-1. See Figure 6-4 for the spatial extent of the model boundary conditions for the Leederville Aquifer.

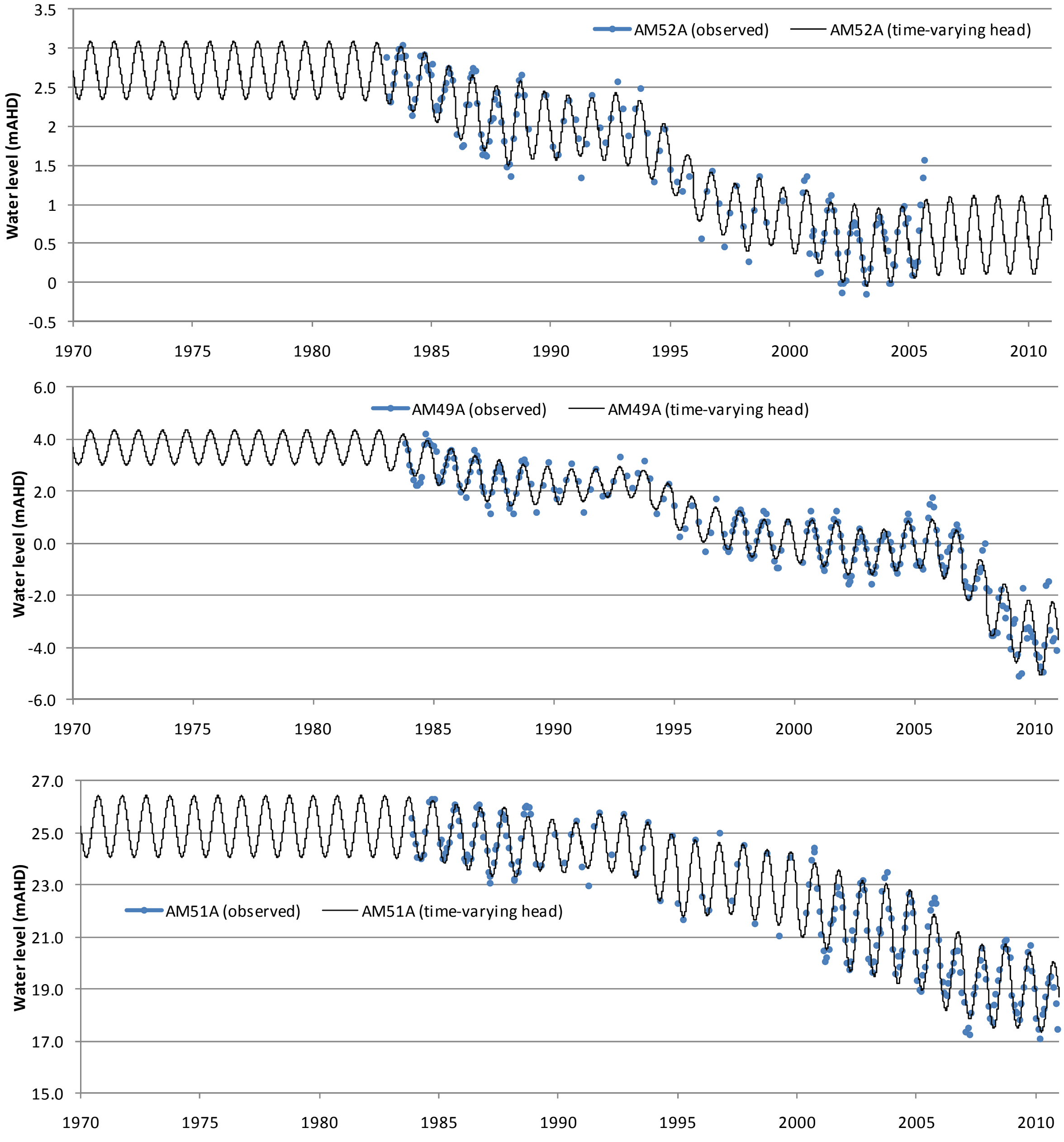


Figure 6-1 Time-varying head boundary conditions for the Leederville Aquifer

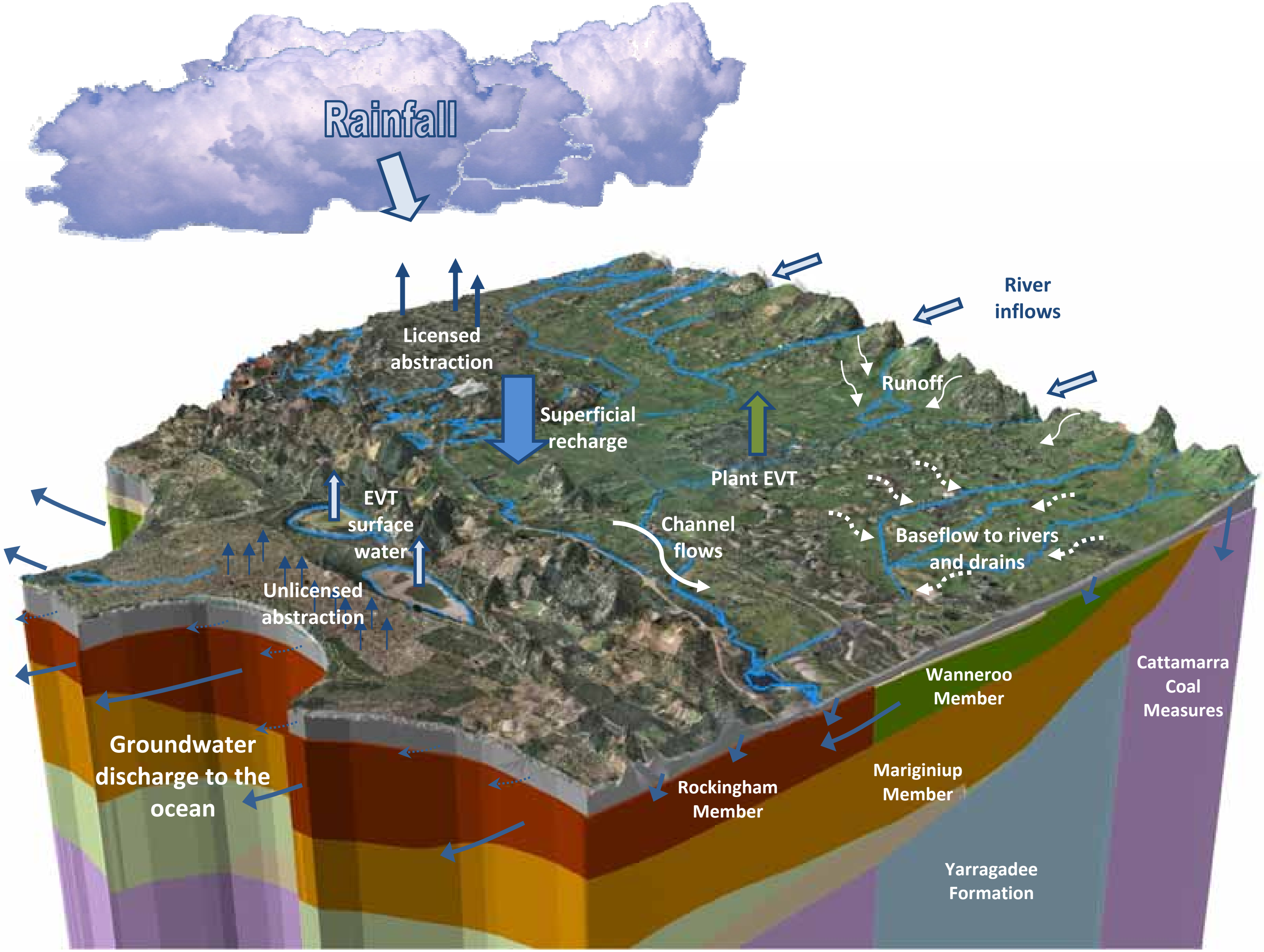


Figure 6-2 Conceptual model diagram

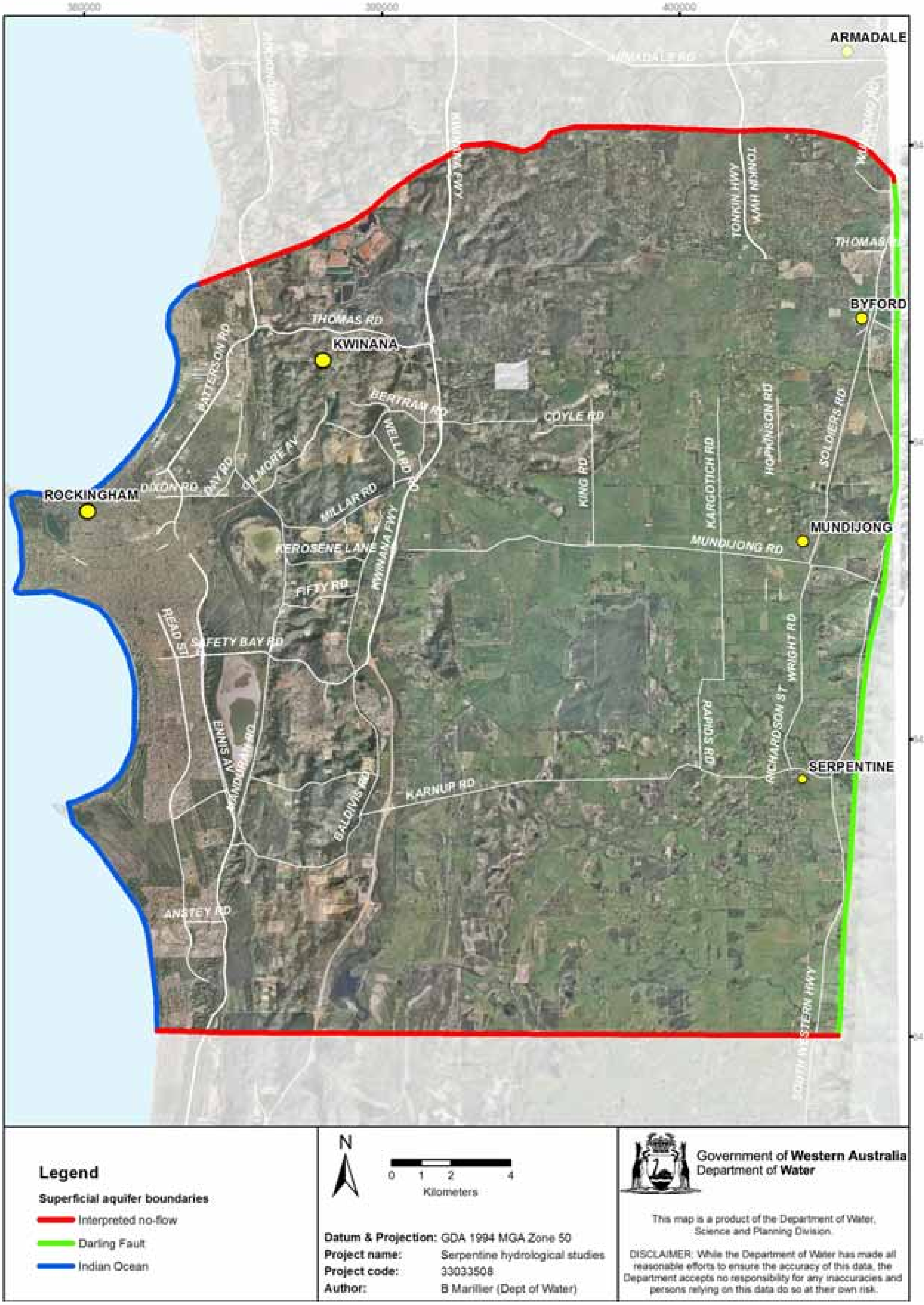


Figure 6-3 Model boundary conditions – Superficial Aquifer

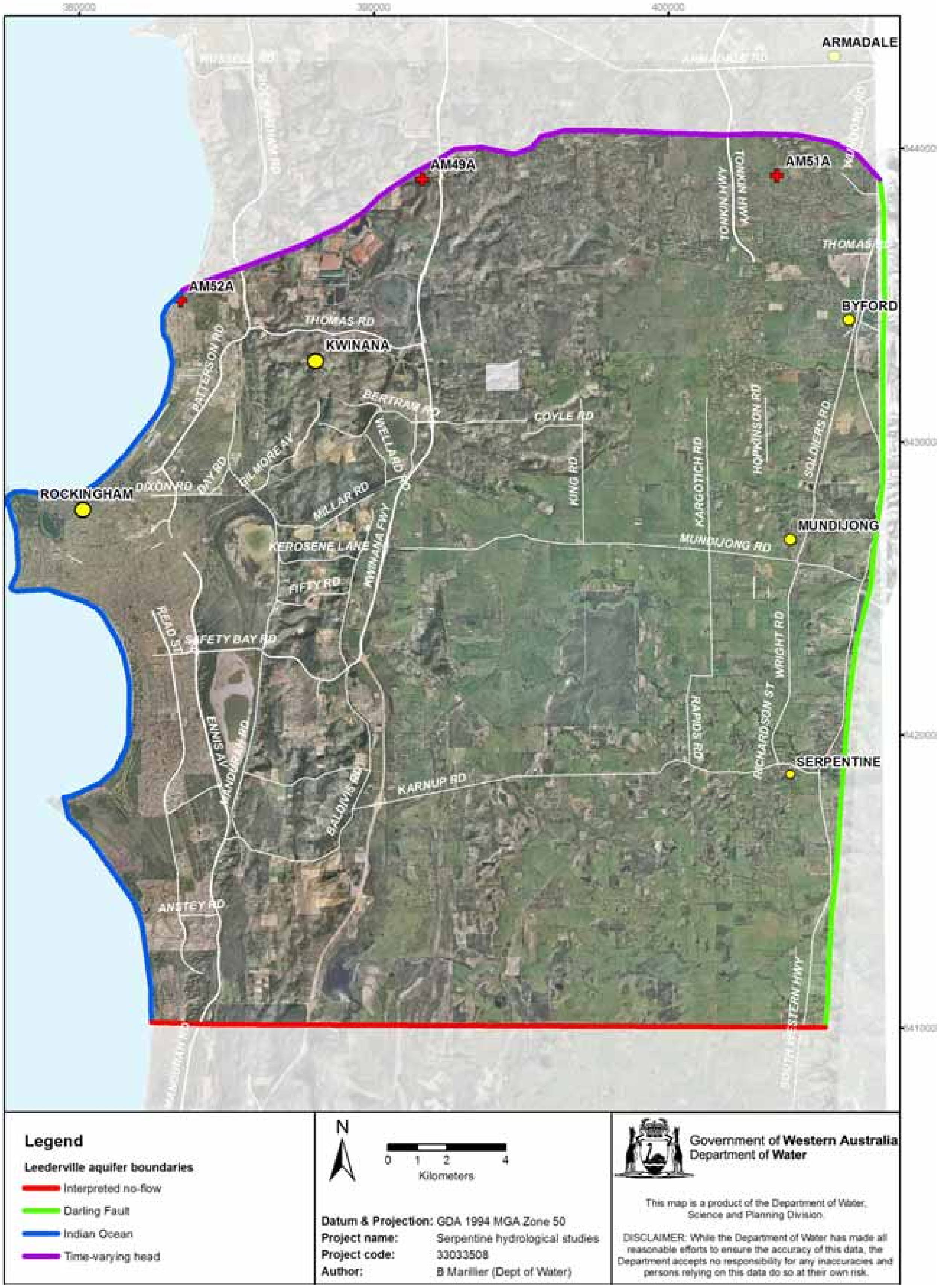


Figure 6-4 Model boundary conditions – Leederville Aquifer

6.2 Parameters

Hydrogeological parameters

The conceptual model consists of 15 geological units. Each of these units represents an area of distinct hydrogeological properties. Table 6-1 shows the range of possible values for hydraulic parameters associated with each formation. These values are estimates based on previous modelling studies and hydrogeological investigations (Xu et al. 2009; Pennington Scott 2008; Davidson 1995; Deeney 1989; Hall et al. 2011b). During calibration of the numerical model, groundwater parameters will be constrained to the suggested ranges. For the superficial formations, vertical conductivity was estimated to be one-tenth of horizontal conductivity (as per Xu et al. 2009). For the Leederville, Kardinya Shale and Cattamarra formations, the lower end of the range of acceptable vertical conductivity was based on Davidson (1995). These units consist of interbedded shale, siltstone and sandstone and thus have lower vertical conductivities compared with the other units.

Table 6-1 Hydraulic conductivity (K_h), vertical conductivity (K_z),specific yield (S_y) and specific storage (S_S) for the respective geological units

Stratigraphy	K_H (range) m/day	K_z (range) m/day	S_Y (range)	S_S
Estuarine/swamp	0.1 to 10	0.01 to 1.0	0.05 to 0.15	$5x10^{-5}$
Bassendean	5 to 50	0.5 to 5.0	0.10 to 0.28	$1x10^{-6}$
Tamala	100 to 1000	10 to 100	0.1 to 0.3	$1x10^{-6}$
Safety Bay	10 to 15	1.0 to 1.5	0.10 to 0.28	$1x10^{-6}$
Guildford	0.1 to 10	0.01 to 1.0	0.05 to 0.15	$5x10^{-5}$
Colluvium	1 to 10	0.1 to 1.0	0.05 to 0.15	$5x10^{-5}$
Quaternary sands	5 to 20	0.5 to 2.0	0.15 to 0.32	$1x10^{-6}$
Yoganup	0.1 to 10	0.01 to 1.0	0.15 to 0.32	$1x10^{-6}$
Ascot	1 to 28	0.1 to 2.8	0.15 to 0.32	$1x10^{-6}$
Kardinya Shale	$1x10^{-4}$ to $1x10^{-6}$	$1x10^{-6}$ to $1x10^{-7}$	0.05 to 0.15	$5x10^{-5}$
Leederville: Pinjar Member	1 to 2	$5x10^{-4}$ to 0.2	0.01 to 0.2	$1x10^{-6}$
Leederville: Rockingham Member	5 to 50	0.5 to 5.0	0.2 to 0.35	$1x10^{-6}$
Leederville: Wannaroo Member	1 to 21	$5x10^{-4}$ to 2.1	0.01 to 0.2	$1x10^{-6}$
Leederville: Mariginiup Member	0.1 to 1	$5x10^{-4}$ to 0.1	0.01 to 0.2	$1x10^{-6}$
Cattamarra	1 to 3	$5x10^{-4}$ to 0.3	0.05 to 0.2	$5x10^{-5}$

Hydraulic parameters

The Manning Equation is the most commonly used equation to analyse open channel flows. It is a semi-empirical equation for simulating water flows in channels and culverts where the water is open to the atmosphere; that is, not flowing under pressure. The Manning Equation was developed for uniform steady-state flow and uses the coefficient *n* to describe the channel roughness.

Work by the US Bureau of Reclamation and other government agencies indicates the Manning roughness factor should be increased (by approximately 10 to 15%) for hydraulic radii greater than 3 m. The loss in capacity of large channels is due to the roughening of surfaces with age, plant growth, deposits, and the addition of bridge piers as highway systems expand. Values of the coefficient *n* are given in Table 6-2.

Table 6-2 Average values of the Manning roughness factor for various boundary materials

Boundary material	Manning *n*
Natural waterways	
Clean and straight	0.030
Major rivers	0.035
Sluggish rivers with deep pools	0.040
Excavated earth channels	
Clean and straight	0.022
Weedy	0.025
Gravelly	0.030
Stony	0.035

The study area contains a range of channel forms and Manning's *n* is likely to vary significantly. For example, the Serpentine River has some thickly vegetated sections, such as at Lowlands, while further downstream the Serpentine Drain has a large, cleared, trapezoidal channel for flood conveyance. The Peel Main Drain has similarly varying reaches that include both traditional drain forms and thickly vegetated wetland sections. Therefore, some distribution of Manning's *n* may be necessary in main channels for realistic simulation of channel flows.

Unsaturated zone parameters

Vegetation parameters

Parameters that control unsaturated zone processes relate to vegetation and soil properties. The vegetation parameters affecting the unsaturated zone are leaf area index (LAI) and rooting depth (RD). LAI is important in flux calculations as it is correlated with evapotranspiration; RD is important because it controls the depth beyond which evapotranspiration in the soil profile can no longer occur.

Hall et al. (2009b) noted that both LAI and RD were sensitive model parameters for the Superficial Aquifer; however, very little observational data is available for south-west Western Australia to guide model calibration. Hall et al. (2009b) highlighted the fact that in waterlogged areas, root depth is likely to be controlled by depth to groundwater. The Serpentine study area contains a range of native woodland, dominated by *Acacia*, *Eucalyptus* and *Melaleuca* species. Given that much of the study area has shallow groundwater, maximum RD is not likely to exceed 3 m for areas of native vegetation and plantation. Based on previous modelling studies, LAI for native woodland is likely to vary between 0.7 and 1.5.

Table 6-3 estimates LAI and RD for some plant species and land uses based on previous studies. The numerical model will be calibrated using these parameter values as a guide.

Table 6-3 Leaf area index and rooting depth estimates from various studies

Land use	**LAI (m^2/m^2)**	**RD (m)**	**Sources**
Banksia – high density	> 1.2	5 to 25	Xu et al. (2009)
Banksia – medium density	0.7 to 1.2	5 to 25	Xu et al. (2009)
Banksia – low density	< 0.7	5 to 25	Xu et al. (2009)
Pasture	Seasonal 0 to 3	0.5 to 1	Xu et al. (2009)
Pine – high density	2.5 to 3.5	5 to 15	Xu et al. (2009)
Pine – medium to high density	2.0 to 2.5	5 to 15	Xu et al. (2009)
Pine – medium density	1.5 to 2.0	5 to 15	Xu et al. (2009)
Pine – low to medium density	1.0 to 1.5	5 to 15	Xu et al. (2009)
Pine – low density	0.5 to 1.0	5 to 15	Xu et al. (2009)
Eucalyptus		1.5 to 2.0	Stone and Kalisz (1991)
Malaleuca		2.5	Stone and Kalisz (1991)
Acacia		1.2 to 35	Stone and Kalisz (1991)
Eucalyptus marginata (jarrah)	1.2 to 2.5	up to 40m	Crombie, DS (1992)
Plantation	1.8	2	Hall et al. (2010b)[1]
Native vegetation	1.3	2	Hall et al. (2010b)[1]
Grazing (irrigated)	3	1.2	Hall et al. (2010b)[1]
Grazing (non-irrigated)	0 to 3	0 to 1.2	Hall et al. (2010b)[1]

[1] *Values derived from model calibration*

Soil parameters

Soil parameters are an important factor in determining recharge to the Superficial Aquifer and evapotranspiration from the unsaturated zone because they influence infiltration rates and plant-available water. Depending on the recharge model used, different soil parameters are required. The soil parameters described in this section are based on the requirements of the Danish Hydrological Institute's MIKE SHE two-layer unsaturated zone model. They include the water content at saturation (θ_s), water content at field capacity (θ_{fc}), water content at wilting point (θ_{wp}) and saturated hydraulic conductivity (K_s).

The Serpentine study area consists of six main soil types, which are listed in Table 6-4 along with suggested parameter values from previous studies. These are based on the estimates used in the vertical flux model (Xu et al. 2009), calibrated parameters from the Murray hydrological studies (Hall et al. 2009b) and standard values based on soil texture (Fetter 2001).

Table 6-4 Unsaturated zone soil parameters

Soil types	**K_s (m/day)**	**θ_s**	**θ_{wp}**	**θ_{fc}**	**Reference**
Quindalup	5.5 to 15	0.33	-	0.03 to 0.04	Xu et al. (2009)
Spearwood	3.4 to 5	0.33 to 0.37	-	0.035 to 0.06	Xu et al. (2009)
Bassendean	1.6 to 10	0.33 to 0.38	-	0.03 to 0.035	Xu et al. (2009)
Pinjarra	0.01	0.32	-	0.125	Xu et al. (2009)
Vasse	0.01 to 5	0.3 to 0.32	-	0.06 to 0.17	Xu et al. (2009)
Forrestfield	1 to 5	0.3 to 0.35	-	0.125	Xu et al. (2009)
Bassendean	1	0.3	0.03	0.09	Hall et al. (2010b)
Spearwood	1	0.33	0.03	0.05	Hall et al. (2010b)
Pinjarra	0.05	0.37	0.13	0.20	Hall et al. (2010b)
Sands	0.9 to 90[1]	-	< 0.06[3]	0.05 to 0.12[3]	Fetter (2001)
Sandy loams	0.009 to 0.9[2]	-	0.05 to 0.10[4]	0.15 to 0.22[4]	Fetter (2001)

[1] *Values for well-sorted sands*

[2] *Values for silty sands*

[3] *Values for sands*

[4] *Values for sandy loam*

6.3 Hydrogeological processes

The numerical model must simulate the main hydrological processes and calculate the water balance within the aquifer system. The hydrological processes included in the model are recharge from rainfall, recharge to and discharge from deeper aquifers, evapotranspiration, surface water runoff and drainage, abstraction from groundwater, groundwater recharge from irrigation and lateral groundwater flow. For the Serpentine area, where the Superficial, Rockingham and Leederville aquifers have all experienced a long-term decline in groundwater head, the model should satisfy the groundwater flux equation (Equation 6-1). For the deeper aquifers, the unsaturated zone and drainage components are not considered in flux calculations.

Equation 6-1 Groundwater flux equation

$$RE_g - \Delta L_y - \Delta D - EVT - \Delta L_z + I_{re} - A = \Delta V$$

where RE_g is gross recharge from rainfall, ΔL_y is horizontal flow of groundwater across model or aquifer boundaries, ΔD is net drainage from groundwater to surface water, EVT is evapotranspiration, ΔL_z is net leakage between aquifers, I_{re} is recharge from irrigation, A is groundwater abstraction, and ΔV is the change in storage of the aquifer

The sum of the fluxes on an annual time-step should be proportional to the change in storage observed in the aquifer over one year. All fluxes vary in space and time. Some values can be measured directly, such as the abstraction from production bores, whereas other values have to be indirectly evaluated by appropriate methods or models. The results can be inserted into the conceptual model in the form of tables or functions. Methods of measurement of each of the fluxes are outlined below, and average annual and average monthly estimation of the fluxes is presented. The absolute value of the fluxes is likely to contain error due to spatial lumping, parameter estimation and various assumptions used in the calculations. However, the order of magnitude of each of the fluxes is important when considering the hydrological system and the process of numerical evaluation of the fluxes will help to determine the relative importance of specific drivers of groundwater levels in the Serpentine study area.

Gross recharge from rainfall to the Superficial Aquifer

The recharge to the Superficial Aquifer is the proportion of net rainfall over the land surface that reaches the watertable. The amount of recharge depends on the rainfall (intensity, frequency and duration), land use, depth to watertable, and soil and geological conditions. Two terms will be discussed in the context of water balance calculations:

- **Gross recharge** is the proportion of net rainfall that reaches the watertable after losses from plant evapotranspiration as water infiltrates through the unsaturated zone.
- **Net recharge** is gross recharge, minus evapotranspiration from the groundwater table – either as evaporation directly from shallow groundwater within the soil profile or wetland areas where the watertable is at the surface, or from evapotranspiration from vegetation that has roots extending to the watertable.

Recharge occurs from three main sources – direct recharge from rainfall, recharge from irrigation, and recharge from losing stream reaches, which enter the study area in the east and drain the Darling Scarp. Recharge to the Superficial Aquifer is mostly through sandy soils with high vertical conductivity. As such, lateral flow in the unsaturated zone is negligible.

Xu et al. (2009) estimates recharge rates under a variety of land uses on the Swan Coastal Plain. These estimates were applied to the land use mapping available for the Serpentine study area to give an average annual estimate of recharge, see Table 6-5. The annual recharge was distributed on a monthly basis according to recharge fractions simulated using the Water Atmosphere Vegetation Energy Solutes (WAVES) recharge model as shown by URS (2009) in the Peel Harvey coastal groundwater model. The fractions were altered by 2 to 3% for the months of June, July and August to more closely represent the changes in groundwater levels observed in the Serpentine area. Using an average annual rainfall of 821 mm – based on Medina (9194) and Serpentine (9039) stations – maximum average annual recharge is estimated to be 348 mm (254 GL). Annual recharge was distributed monthly, see Table 6-6.

Table 6-5 Annual recharge estimates under different land uses in the Serpentine study area

PRAMS land use	Area (km^2)	Recharge as % of rainfall	Recharge (mm)	Recharge (GL)
Banksia low density	110.1	38%	312	34.3
Lakes and wetlands	12.9	-85%	-698	-9.0
Market garden	111.1	40%	328	36.5
Pasture	364.6	45%	369	134.7
Pine low density	14.8	28%	230	3.4
Urban commercial	65.9	63%	517	34.1
Urban residential	48.4	50%	411	19.9
Totals	727.9	42%	349	253.9

Table 6-6 Monthly distribution of recharge

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Recharge proportion (WAVES)	3%	2%	1%	1%	1%	5%	17%	26%	20%	13%	7%	4%
Recharge (mm)	10	7	3	3	3	17	59	91	70	45	24	14
Recharge (GL)	7.6	5.1	2.5	2.5	2.5	12.7	43.2	66.0	50.8	33.0	17.8	10.2

Percentages in red were alterered by 2-3% from the original numbers reported in URS (2009)

The estimated annual recharge of 348 mm is 42% of rainfall, which represents the upper limit of recharge in free-draining soils. In the Serpentine area, evapotranspiration from the shallow groundwater table means that net recharge is considerably less than gross recharge. Also, rejected recharge due to inundation is not considered. As such, the actual gross recharge is likely to be lower than the estimate given here.

Horizontal groundwater flow

Horizontal or lateral throughflow is the horizontal movement of groundwater in the saturated zone. It is the means by which groundwater can move from recharge areas to discharge areas such as rivers, wetlands and the ocean interface. To develop a first-order estimate of lateral throughflow, flow-net analysis of the study area was undertaken. A flow-net is a graphical representation of two-dimensional steady-state flow through an aquifer. It is created by a combination of hydraulic head contours and flow-lines, where a flow-line is an estimate of the path a groundwater molecule would take as it moved through the aquifer, being perpendicular to the hydraulic head contours. The combination of the lines creates 'quasi-square' shapes known as flow-cells. Two adjacent flow-lines mark out a flow-channel, also referred to as a flow-tube. The flow-channel geometry and physical aquifer parameters allow lateral throughflow to be calculated using Darcy's law.

The flow-net technique was used to estimate lateral throughflow within the Superficial and upper Leederville aquifers. In the Superficial Aquifer, lateral throughflow discharges to the Serpentine River, Peel and Birriga main drains or the ocean. In the upper Leederville Aquifer, lateral throughflow discharges to the ocean, Rockingham Aquifer or to the north-west through the model boundary. The upper Leederville Aquifer discharges to the Rockingham Aquifer along the vertical contact zone of the Rockingham Member (Z_1), see Figure 6-5. Lateral flow through the lower Leederville Aquifer (Z_2), comprised of the Mariginiup Member, was not included in flow-net calculations.

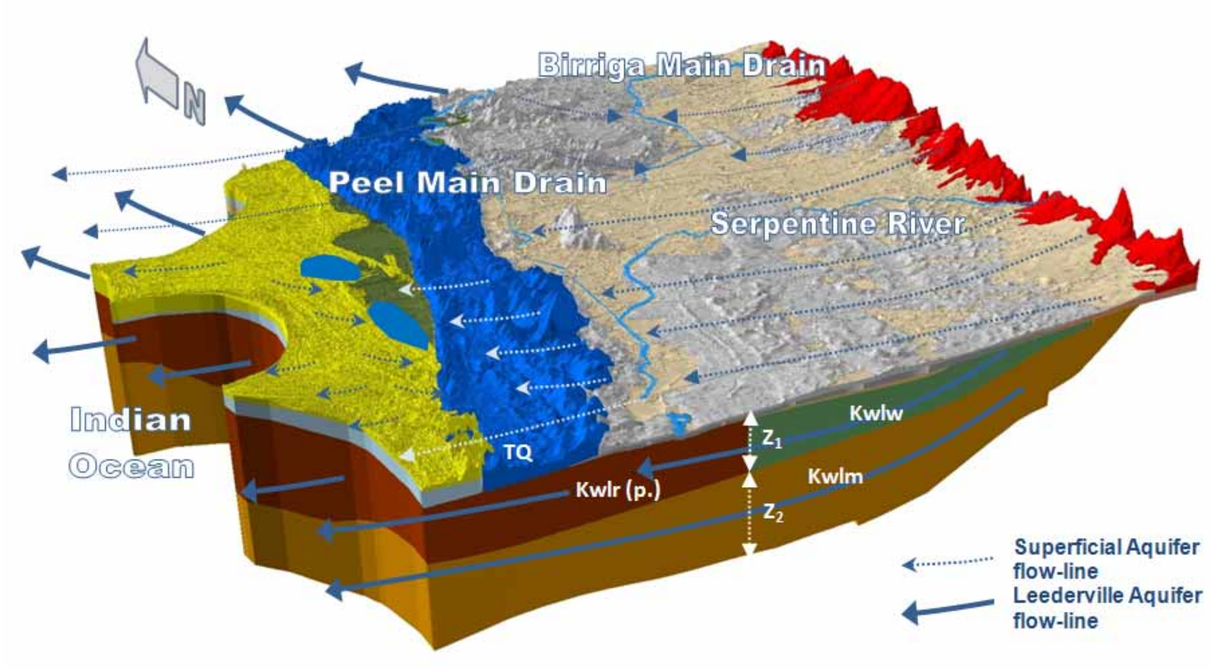


Figure 6-5 Horizontal flow in the Serpentine study area

Table 6-7 shows the summary results of the flow-net analysis. Calculations of lateral throughflow for each of the flow channels are shown in Appendix B.

Table 6-7 Results of flow-net analysis

Aquifer	Horizontal flow in (GL)	Horizontal flow out (GL)
Superficial	0.0	4.9
Leederville	0.0	5.7
Rockingham	4.2	4.6

In the study area's southern portion, horizontal flow in the Superficial Aquifer is intercepted by the Peel Main Drain and Serpentine River. In the study area's north-east, horizontal flow west from the Darling Scarp and east from the Jandakot Mound is intercepted by the Birriga Main Drain in winter, but moves laterally below the channel to the south in summer. As such, this component of the water balance is accounted for (in the following section) as baseflow to these waterways. In the study area's north-west around the Jandakot Mound, horizontal flow passes through the wetland systems rather than discharging via the drainage system – except in the winter months. As such, there is a component of horizontal flow that discharges from the Superficial to the ocean through the study area's north-western boundary. Part of the study area's south-eastern section is internally draining, towards Lake Cooloongup and Lake Walyungup (see Figure 6-5), and therefore no horizontal flow was calculated in this area. Superficial groundwater flows laterally to the ocean west of the Safety Bay Mound. It was assumed the Superficial Aquifer does not receive lateral inflows from east of the Darling Fault. A volume of 4.9 GL/yr is estimated to discharge from the Superficial Aquifer to the ocean.

A total of 5.7 GL/yr is estimated to discharge from the Leederville Aquifer, of which 4.2 GL/yr laterally discharges to the Rockingham Aquifer and 1.5 GL/yr discharges across the north-western model boundary. The Leederville may receive some lateral inflow from the Cattamarra Coal Measures in the east, although the volume is likely to be negligible due to the relatively narrow contact zone at the Leederville Aquifer's eastern edge.

Flow-net analysis for the Rockingham Aquifer was based on observed Superficial groundwater levels. The Rockingham Aquifer receives lateral inflows of 4.2 GL/yr from the Leederville and discharges 4.6 GL/yr to the ocean.

Drainage from groundwater to surface water

A number of artificial drains and natural or modified river channels drain the Superficial Aquifer and receive overland flow from surface water catchments. The four major waterways in the area include the Serpentine River, Peel and Birriga main drains and Dirk Brook. The waterways receive inflows from the network of shallow surface drains that cover much of the study area.

The lower Serpentine River runs from the Serpentine Pipehead Dam in the east to a point where it is joined by the Peel Main Drain in the west, before discharging to the Peel-Harvey estuary outside the study area to the south. The Serpentine River is between 2 and 5 m deep, and its influence as a gaining reach is evident in the Superficial Aquifer minimum groundwater contours (Figure 5-1).

The Peel Main Drain starts just north of the study area and runs through the Mandogalup Swamp, Spectacles Wetlands and Bollard Bulrush Swamp to discharge into the Serpentine Drain upstream of Punrack Drain. Minimum groundwater contours around these wetlands indicate they are flow-through systems, and that the Peel Main Drain only intersects the watertable in this area under winter maximum conditions. At the drain's southern end before it joins the Serpentine River, it intercepts lateral flow from the Superficial Aquifer in some sections during summer, such as at Folly and Maramanup pools; however, this does not result in flow due to the drain invert level downstream of the pools.

The Birriga Main Drain flows from the study area's north-east to the south-west. It is around 2 m deep across the study area. It receives lateral inflows from the east, north and Jandakot Mound in the west.

Dirk Brook is located in the study area's south and runs from the Darling Scarp to the Serpentine River via Punrack Drain. It is between 1 and 3 m deep and intersects the watertable in winter and early spring.

Baseflow separation from modelled surface water flows

Hydrographs at a daily time-step were produced for all major waterways in the Serpentine study area using the Streamflow Quality for Rivers and Estuaries (SQUARE) model developed by Kelsey et al. (2010). The SQUARE model can provide discharge information for each of the subcatchments shown in Appendix E. Calibration of the model's hydrological component was undertaken against the flow-gauging stations listed in Table 6-8 using the Nash-Sutcliffe efficiency (NSE) as the objective function.

Table 6-8 Calibration statistics for SQUARE modelling within the Serpentine study area

Gauging station reference (AWRC)	SQUARE model	Daily NSE	Monthly NSE	Annual NSE
614013*	Peel Main Drain	0.76	0.87	0.83
614030	Upper Serpentine	0.73	0.90	0.82
614094	Dirk Brook	0.68	0.84	0.74

**note Peel Main Drain was calibrated to the Hope Valley gauge (614013)*

Table 6-9 shows average annual modelled flows (1975–2007) for waterways in the area. Drainage quantities into and out of the area are displayed in Table 6-10, which accounts for surface water flows into and out of conceptual model.

As the SQUARE calibration over-estimated flow for the Peel Main Drain at Karnup Road, which has an observed coefficient of runoff of only 6%, baseflow has been reduced by 80% for water balance calculations to account for the discrepancy.

Table 6-9 Average annual flows in GL (1975–2007) for the Serpentine study area, sourced from SQUARE modelling

Year	Serpentine River (GL)	Peel Main Drain (GL)	Birriga Main Drain (GL)	Manjedal Brook (GL)	Dirk Brook (GL)
1975	58.5	12.2	29.8	16.2	14.3
1976	36.4	8.8	19.9	10.6	13.7
1977	32.8	6.4	16.3	9.0	13.7
1978	80.3	17.9	41.8	22.3	20.6
1979	34.0	7.6	16.6	9.0	12.5
1980	79.7	17.1	40.7	22.3	19.2
1981	105.0	20.5	48.0	26.6	21.6
1982	57.8	14.1	29.3	15.1	20.1
1983	90.8	15.1	41.7	23.5	25.7
1984	94.5	19.4	45.0	23.9	17.5
1985	61.8	14.3	30.9	15.8	16.8
1986	77.3	19.2	41.8	20.6	13.4
1987	61.6	12.2	31.7	16.8	10.8
1988	123.0	21.9	59.4	31.8	31.2
1989	58.7	13.3	29.0	15.1	20.1
1990	61.8	11.7	30.6	16.8	20.2
1991	137.8	26.1	63.9	34.5	25.8
1992	112.6	20.2	58.6	31.9	21.1
1993	46.8	9.1	22.6	12.3	14.4
1994	48.6	10.1	26.4	14.0	14.2
1995	50.2	10.4	26.5	14.2	22.5
1996	83.9	15.4	44.3	24.1	25.8
1997	55.7	10.8	28.3	15.4	17.6
1998	51.8	10.4	26.3	14.2	19.6
1999	70.8	15.9	36.8	18.8	31.1
2000	94.6	17.6	50.6	27.2	21.0
2001	23.0	5.7	14.4	7.1	10.8
2002	45.1	8.3	24.0	12.8	17.9
2003	75.9	15.6	41.5	21.6	16.7
2004	42.4	8.1	22.1	11.8	17.2
2005	72.1	16.9	39.7	19.8	25.0
2006	16.3	3.8	8.9	4.7	7.0
2007	57.7	10.5	29.6	16.1	16.4
Average	66.6	13.5	33.8	18.1	18.7

Table 6-10 Average annual inflows, outflows and net total flows (inflow – outflow) for major waterways in the Serpentine study area (GL)

Average annual:	Serpentine River (GL)	Peel Main Drain[1] (GL)	Birriga Main Drain (GL)	Mandjadel Brook (GL)	Dirk Brook (GL)
Inflow	29.0	0.0	18.5	4.8	1.7
Inflow (baseflow)	15.6	0.0	9.7	2.4	1.0
Outflow	66.6	7.9	33.8	18.1	18.7
Outflow (baseflow)	37.1	1.4	18.1	9.4	12.6
Net outflow	37.7	7.9	15.3	13.3	16.9
Net outflow (baseflow)	21.4	1.4	8.5	7.0	11.6

[1] *Baseflow component reduced by 80%*

The groundwater component of the surface flows was estimated using baseflow separation (Eckhart 2005) for hydrographs of the waterways entering and discharging the area. Table 6-11 shows the monthly baseflow contributions of each of the major waterways. Note that it is not possible to calculate negative baseflow using this method, and some recharge from the rivers to the groundwater may occur at certain times of year when the groundwater level in the Superficial Aquifer is below the riverbed level. However, this flux is small as river flows correspond to periods of high groundwater table during winter.

Table 6-11 Monthly net baseflow contribution (GL) for major waterways in the Serpentine study area

	Serpentine River (GL)	Peel Main Drain[1] (GL)	Birriga Main Drain (GL)	Manjedal Brook (GL)	Dirk Brook (GL)
January	0.2	0.0	0.1	0.1	0.1
February	0.2	0.0	0.1	0.1	0.1
March	0.2	0.0	0.1	0.1	0.1
April	0.2	0.0	0.1	0.1	0.1
May	0.4	0.0	0.2	0.1	0.3
June	1.4	0.1	0.6	0.5	1.1
July	4.3	0.3	1.7	1.4	2.4
August	6.4	0.4	2.5	2.0	2.9
September	4.8	0.3	1.8	1.5	2.4
October	2.3	0.1	0.9	0.7	1.4
November	0.7	0.0	0.3	0.2	0.6
December	0.3	0.0	0.1	0.1	0.2
Total	21.4	1.4	8.5	7.0	11.6

[1] *Baseflow component reduced by 80%*

Baseflow separation estimates that on average, 49.9 GL/yr is drained from the Superficial Aquifer. Around half of this drainage is via the Serpentine River. The Birriga Main Drain and Manjedal Brook drain 8.5 and 7.0 GL/yr respectively from the study area's north-west. The

Dirk Brook drains 11.6 GL/yr from the south. Peak monthly baseflow occurs in August, and declines to very low levels in the summer and autumn months.

Evapotranspiration from groundwater

Evapotranspiration from groundwater can occur via three mechanisms:

- directly from the groundwater in all areas where inundation occurs, including wetlands, lakes and waterlogged sections of the palusplain
- from within the soil profile, down to a defined depth below which no evaporation will occur (the extinction depth)
- deep-rooted vegetation, which may evapotranspire water from the saturated zone.

To estimate monthly evapotranspiration, the area of each of these classes was determined for each month of the year.

Areas of deep-rooted vegetation were determined using non-ground returns from the Department of Water's Swan Coastal Plain LiDAR dataset. All vegetated areas 2 m or more in height were deemed deep rooted.

Areas of inundation were determined by generating a monthly gridded time-series of depth to watertable. These grids were created from spatially distributed estimates of the superficial maximum and minimum groundwater levels calculated for October 2009 and May 2010. The intra-annual fluctuation of the groundwater surface was estimated using Superficial monitoring bores and distributed on a monthly basis, see Table 6-12.

Table 6-12 Scaling of monthly fluctuation in groundwater heads

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Scaling factor (S)	35%	17%	5%	2%	0%	33%	74%	88%	100%	94%	74%	50%

**Monthly superficial groundwater head is calculated by (Max GWL - Min GWL) x S + Min GWL for each grid cell*

The evapotranspiration flux was calculated for each of these subareas at a monthly time-step. Evapotranspiration was calculated using climatic data sourced from Medina (9194) and Serpentine (9039) stations, see Table 6-13.

Table 6-13 Monthly average evaporation and rainfall data provided by SILO, average of Medina (9194) and Serpentine (9039) stations (1970–2010)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Rainfall (mm)	12	17	17	44	106	158	168	125	84	50	31	9
Evaporation (mm)[1]	273	230	197	118	78	58	60	74	97	145	194	250
FAO56 (mm)[2]	201	170	150	98	67	48	50	65	85	123	154	188

[1] Pan evaporation, [2] Potential evapotranspiration calculated using the FAO56 method

In inundated areas, evaporation from the water surface was calculated directly from the pan evaporation rate, with a pan correction factor of 0.70 applied (Ladson 2008). Evaporation from the soil profile was calculated using an exponential decay function (Shah et al. 2007), with decreasing evaporation occurring as the extinction depth is approached.

Equation 6-2 describes the relationship between evapotranspiration and depth to watertable.

Equation 6-2 The relationship between depth to watertable, potential evapotranspiration and evapotranspiration, after Shah et al. (2007)

$$\frac{ET}{PET} = \begin{Bmatrix} 1 \\ e^{-b(d-d')} \end{Bmatrix} \begin{matrix} for\ d \leq d' \\ for\ d > d' \end{matrix}$$

where ET is actual evapotranspiration, PET is potential evapotranspiration, b is the decay exponent, d is the depth to watertable, and d' is the extinction depth

Shah et al. (2007) recommend the following parameters for bare soil and grasses:

- bare soil: extinction depth 50cm, *d'* 18cm, *b* 0.17
- grass: extinction depth 145cm, *d'* 30cm, *b* 0.043.

An average of the grass and bare soil parameters were used in calculations. Using the monthly time-series of depth to watertable and FAO56 evaporation data, evapotranspiration from the soil profile was determined.

For the deep-rooted vegetation, the evapotranspiration can be approximated to be equal to the potential evaporation multiplied by a vegetation factor. The vegetation factor is equal to 1 for the months June to November. During summer, plants are likely to transpire less due to energy constraints and the closure of their stomata. For the summer months, a vegetation factor of 0.1 is applied to the potential evaporation.

A total of 169.5 GL/yr was estimated to be lost from the superficial groundwater as a result of evapotranspiration. Of this, 67.4 GL/yr was used by deep-rooted vegetation, 63.7 GL/yr was lost through evaporation from surface water, and 34.5 GL/yr was lost through evaporation from the soil profile. Determining inundated areas using hand-drawn groundwater contours and an elevation surface does not take into account subtle changes in elevation, and as such, the estimate of evaporation from surface water is probably excessive. The monthly evapotranspiration calculations are summarised in Appendix D.

Groundwater vertical leakage and discharge

To calculate the flux between aquifers, the parameters for Darcy's law (Equation 6-3) were determined for the Superficial, Rockingham, Leederville, Cattamarra and Yarragadee aquifers. These include the pressure difference between the two aquifers (the difference in hydraulic head), the length over which the pressure gradient occurs (all or a portion of the saturated thickness of the aquifer), the cross-sectional area (the lateral contact area of the aquifers), and the resistance of the medium (the vertical hydraulic conductivity).

Equation 6-3 Darcy's law

$$Q = -k_z A \frac{(P_b - P_a)}{L}$$

where k_z is vertical hydraulic conductivity, A is cross-sectional area, P is pressure, and L is length

To determine the head difference between aquifers, gridded potentiometric surfaces for May 2010 were generated from hand-drawn contours and water level readings in the 'AM' series bores for the Leederville, Cattamarra and Yarragadee aquifers (Figure 5-2 and Figure 5-3). A gridded phreatic surface for the Superficial Aquifer was generated in a similar fashion based on May 2010 water levels in the 'T' series bores (Figure 5-1). Only two monitoring bores located in the study area were screened in the Rockingham Aquifer (T481 and T281): the water level readings indicate the aquifer is in hydraulic continuity with the Superficial Aquifer, see Figure 6-7.

The difference in head between the relevant gridded potentiometric or phreatic surface was calculated. This indicated the leakage and recharge zones within the study area, see figures 5-4 to 5-6. It was assumed there was no head difference between the Rockingham and Superficial aquifers given they are in hydraulic continuity.

Saturated thickness was determined for the Superficial Aquifer by calculating the difference between the May 2010 phreatic surface and the base of the aquifer. For the Leederville and Rockingham aquifers, saturated thickness was half the thickness of the formation, as defined by the conceptual geological model. Saturated thickness was set to 100 m for the Cattamarra and Yarragadee aquifers.

The vertical hydraulic conductivity of the subcrop geology was used to determine the resistance to vertical flow for each aquifer.

Leakage between the Superficial and Leederville aquifers

The Superficial Aquifer overlays the Leederville across the centre of the study area, between the Mandurah and Serpentine faults. In the study area's north, the Kardinya Shale forms an effective hydraulic barrier to vertical flow between the Superficial and Leederville aquifers.

The Superficial Aquifer overlays the Pinjar, Wanneroo and Mariginiup members of the Leederville Formation. Kz was set to 1 x 10^{-3} m/day for the Leederville Formation, and 1 x 10^{-6} m/day for the Kardinya Shale (Davidson 1995). Although a single value of Kz was used for conceptual flux calculations, it is likely that conductivity will be lower for the Pinjar Member relative to the Wanneroo. The saturated thickness used in flux calculations was estimated as half the thickness of the Leederville Aquifer, plus the full saturated thickness of the Superficial Aquifer.

Over most of the study area, the Superficial Aquifer discharges to the Leederville. The average annual loss is estimated at 9.0 GL. In a small area immediately to the west of the Darling Scarp, the Leederville discharges to the Superficial at a rate of 2.3 GL/yr. The net annual flux is therefore a loss of 6.7 GL. Superficial groundwater heads are up to 25 m higher than Leederville heads over the Jandakot Mound.

See Figure 6-6 for the recharge and discharge areas of the Superficial Aquifer. The area of recharge from the Leederville has substantially decreased since Davidson's interpretation in 1995.

Leakage between the Superficial and Rockingham aquifers

The Superficial Aquifer is in hydraulic continuity with the Rockingham in the area west of the Mandurah Fault, as indicated by the paired bores T480 and T481 (Figure 6-7). As such, the vertical flux could not be calculated between the two aquifers using groundwater surfaces. For water balance calculations, it was assumed that recharge from the Superficial Aquifer to the Rockingham was roughly proportional to abstraction from the Rockingham, which totals 6.9 GL/yr.

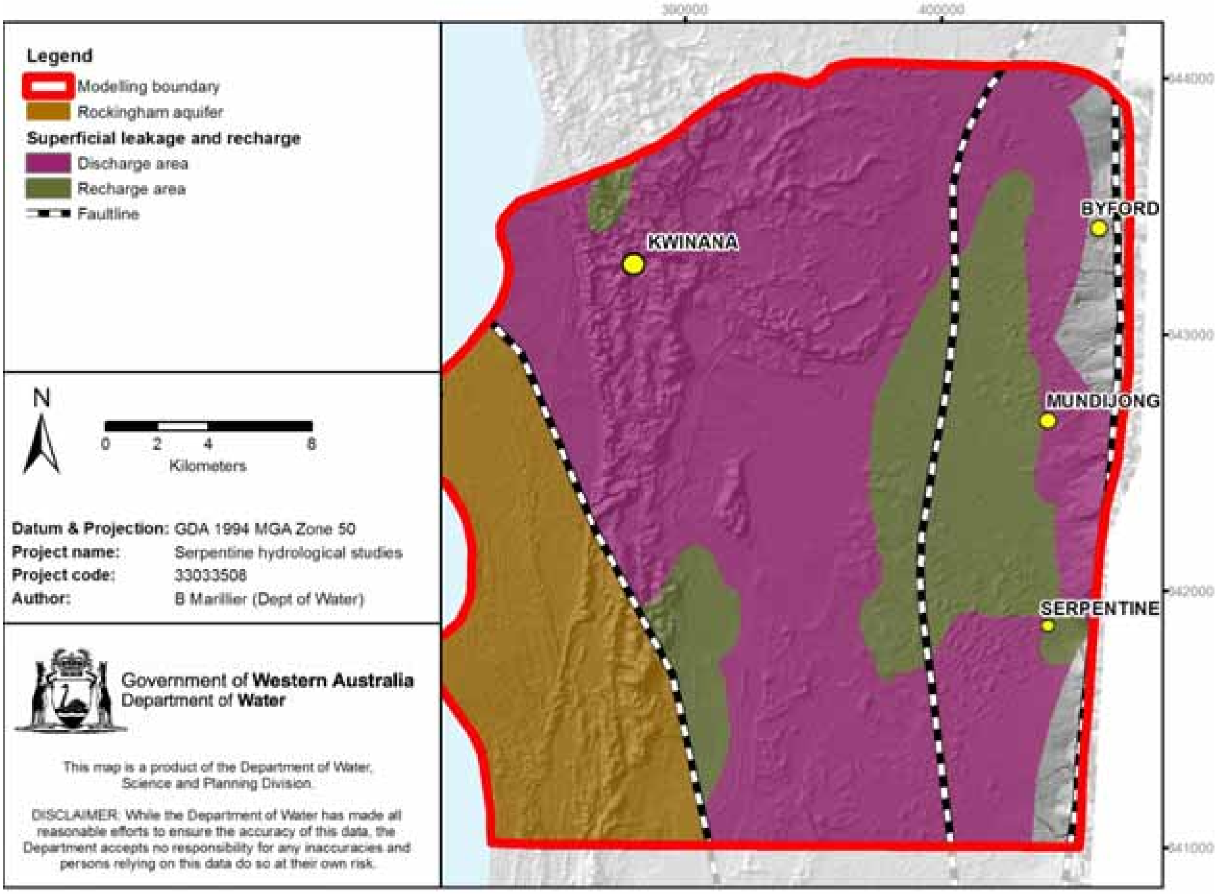


Figure 6-6 *Recharge and discharge areas of the Superficial Aquifer (note that the Superficial is in hydraulic continuity with the Rockingham Aquifer so no discharge or recharge areas can be defined)*

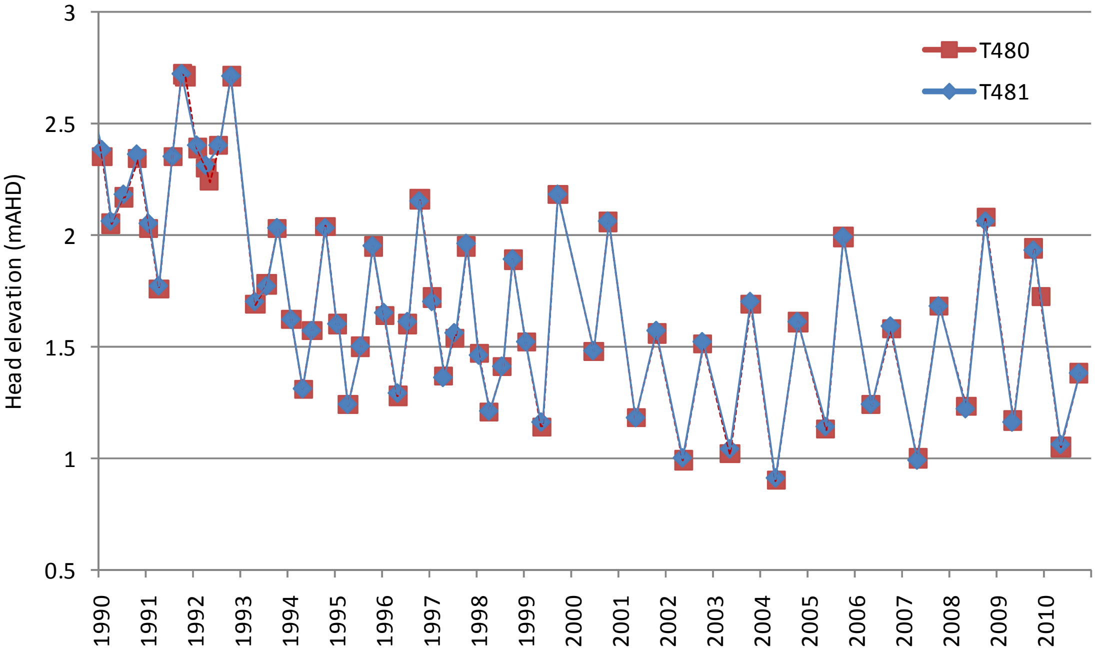


Figure 6-7 *Water levels for T481 (Rockingham Aquifer) and T480 (Superficial Aquifer)*

Leakage between the Superficial and Cattamarra aquifers

In two small areas in the study's north-east and north-west corners, the Superficial Aquifer overlays the Cattamarra Coal Measures, which form the Cattamarra Aquifer. The Kz of the Cattamarra Coal Measures was estimated to be 1 x 10^{-4} m/day by Davidson (1995). However, pump testing in the area indicates a high degree of connectivity between the Superficial and Cattamarra (LBG 1971; WAWA 1987); as such, the Kz for the Cattamarra was set to 5 x 10^{-4} m/day. This value may still underestimate vertical conductivity, given this area is considered a major recharge point for the Cattamarra. For flux calculations the saturated thickness was estimated as 100 m of the Cattamarra Aquifer (approximate bore screen depth), plus the full saturated thickness of the Superficial Aquifer.

Heads in the Cattamarra Aquifer are between 0 and 25 m lower than those of the Superficial within the study area, indicating a recharge area for the Cattamarra. The total downward flux of water from the Superficial Aquifer to the Cattamarra is estimated to be 0.7 GL/yr.

Leakage between the Rockingham and lower Leederville aquifers

The Rockingham Aquifer overlays the lower Leederville west of the Mandurah Fault. The sediments underlying the Rockingham Aquifer are those of the Mariginiup Member of the Leederville Formation. These are assumed to have a Kz of 1 x 10^{-4} m/day (Davidson 1995).

Downward leakage from the Rockingham Aquifer to the lower Leederville was estimated to be less than 0.1 GL/yr. Given the presence of the green-clay marker bed at the top of the Mariginiup Member, downward leakage is likely to be close to zero.

Leakage between the Leederville, Cattamarra and Yarragadee aquifers

Over much of the study area, the Yarragadee is overlain by the South Perth Shale, which acts as a confining layer between the Yarragadee and the Leederville aquifers. Towards the east of the study area the Cattamarra Aquifer is overlain by the Mariginiup Member of the Leederville Formation, and by the superficial formations closer to the scarp.

The vertical hydraulic conductivity of the Yarragadee and Cattamarra formations was estimated to be 5 x 10^{-4} m/day, and 1 x 10^{-7} m/day for the South Perth Shale. Across the study area, heads in the Leederville Aquifer are between 0 and 25 m higher than for the Yarragadee. East of the Serpentine Fault, heads in the Leederville Aquifer are 5 to 10 m higher than those in the Cattamarra. The Serpentine Fault is assumed to act as a hydraulic barrier between the Cattamarra Coal Measures and the Yarragadee Formation, and as such, a marked drop in head of around 15 to 20 m occurs in the Yarragadee Aquifer moving from east to west across the fault. For flux calculations the saturated thickness was estimated as 100 m of the Yarragadee or Cattamarra, plus half the thickness of the Leederville.

The net annual downward flux from the Leederville to the Yarragadee and Cattamarra aquifers is estimated to be 1.0 GL.

Groundwater abstraction – licensed abstraction

Licensed groundwater abstraction in Western Australia falls into two categories:

- abstraction that requires reporting of metered data (including large water users such as the Water Corporation and mine sites)
- other private abstraction that is not required to report actual consumption.

Where metered data is provided, the actual rate of abstraction is known at the drawpoint. However, for private unmetered abstraction, there is a difference between the licensed entitlement and the actual usage of groundwater. Davidson (1995) estimated a usage to entitlement ratio of approximately 0.8 between 1985 and 1995. This ratio has been used in subsequent groundwater models including the South-West Aquifer Modelling System (SWAMS) (Sun 2005) and the Murray Regional Model (Hall et al. 2010b)

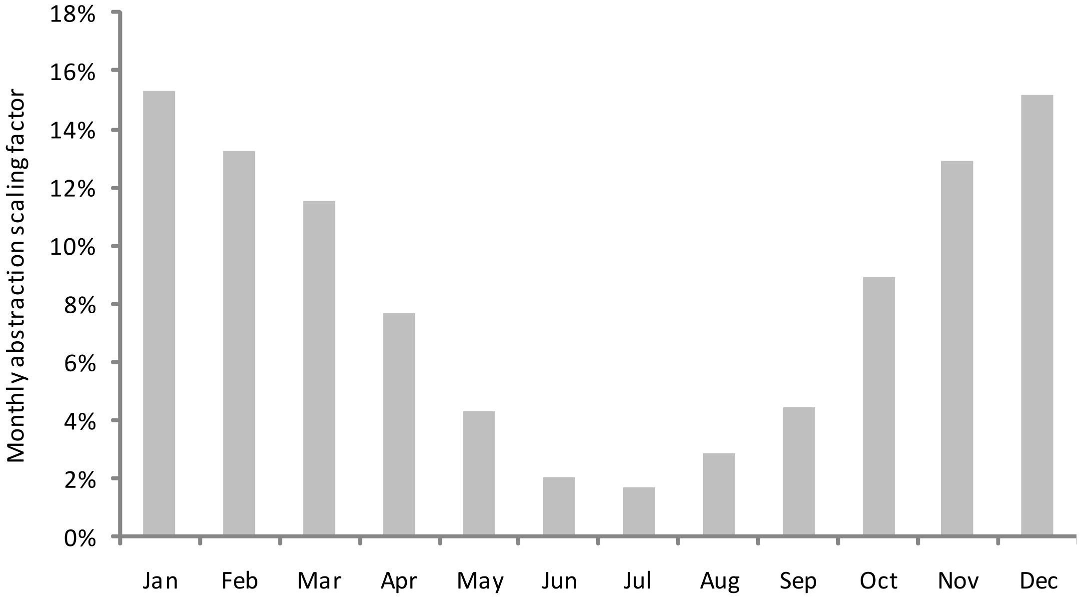
Within the Serpentine study area, abstraction occurs from the Superficial, Rockingham, Leederville and Cattamarra aquifers. Several users in the study area are required to report metered water usage annually, including the Water Corporation and Alcoa. Table 6-14 shows the estimated groundwater abstraction allocations from the four aquifers, as well as unlicensed superficial abstraction (discussed in the following section).

Table 6-14 Abstraction in the Serpentine study area

Aquifer	Number of drawpoints	Total allocation volume (GL/yr)	Maximum allocation from a single drawpoint (ML/yr)	Average allocation per drawpoint (ML/yr)
Cattamarra Coal Measures	18	0.3	90	14
Leederville	658	5.7	450	9
Superficial	1409	25.6	400	18
Rockingham	439	8.7	375	20
Unlicensed Superficial	18932	15.1	0	1
Total	**21456**	**55.3**	**-**	**-**

Sun (2005) estimated the monthly distribution of abstraction for different industries in the south-west. The average monthly factor across all industries described by Sun (2005) was used as the scaling factor. To convert annual allocation to a monthly abstraction rate, the total annual allocation was multiplied by the monthly scaling factor shown in Figure 6-8.

For water balance calculations it was assumed that 80% of the total licensed allocation was used each year, for all licences.



Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Scaling factor	15%	13%	12%	8%	4%	2%	2%	3%	4%	9%	13%	15%

Figure 6-8 Monthly scaling factors for abstraction

Groundwater abstraction - unlicensed abstraction

Western Australian residential properties do not require licences for bores used for domestic garden watering. The average garden bore pumps about 800 kL/yr in the Perth metropolitan area (Davidson & Yu 2008). In 2003, 30% of the total households in Perth had garden bores and abstracted a total of 112 GL/yr, with almost all garden bores pumping from the Superficial Aquifer. Based on the latest land use dataset (Figure 6-9), there are 63 107 residential premises in the area, most of which are located west of the Serpentine River and in the study area's north. Using figures derived for the Perth metropolitan region (30% of houses with bores, extracting an average of 800 kL/yr), a total of 15.1 GL/yr of water is estimated to be extracted by unlicensed residential premises in the Serpentine study area. Most of the garden bores are located around Kwinana and Rockingham.

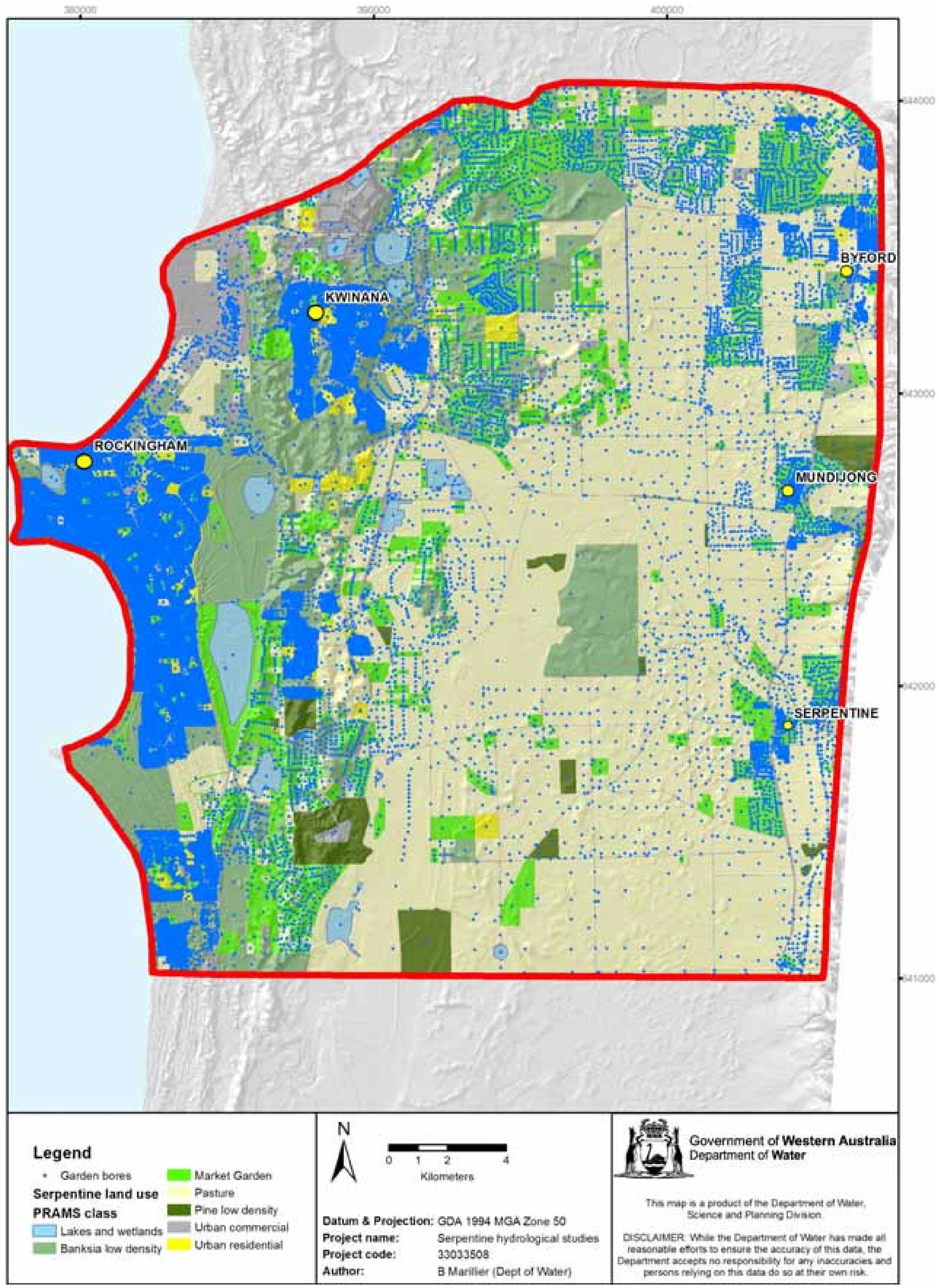


Figure 6-9 Land use within the Serpentine study area with unlicensed abstraction points

Groundwater recharge from irrigation

Most of the licensed abstraction is for irrigation purposes, although some large allocations are for industrial purposes. It is assumed that 20% of the water abstracted by licensed users for irrigation purposes return to the watertable. This was the figure used in PRAMS modelling (Davidson & Yu 2008). The recharge return from irrigation is estimated to be 9.5 GL/yr, which comprises 3.6% of the total recharge. Irrigation recharge was scaled to a monthly time-step using the same factors applied to the abstraction data, as shown in Table 6-15.

Table 6-15 Recharge from irrigation

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Scaling factor	15%	13%	12%	8%	4%	2%	2%	3%	4%	9%	13%	15%
Irrigation recharge (GL)	1.4	1.3	1.1	0.7	0.4	0.2	0.2	0.3	0.4	0.8	1.2	1.4

6.4 Water balance

Annual water balance

An annual water balance describes the flow of water in and out of the aquifer system. The summary of annual flux in and out of the Superficial, Rockingham and Leederville aquifers is shown in Table 6-16.

In the Superficial Aquifer, the water balance deficit (change in storage) is estimated to be 3.9 GL/yr, which is consistent with the slow decline in head observable in many of the T-series bores in the study area. The change in head of an aquifer can be related to the change in volume using Equation 7-4. The Superficial Aquifer has experienced on average a drop in head of 5 cm/yr during the past 30 years. Using Equation 7-4 and assuming a specific yield of 0.25 for sandy sedimentary deposits, a change in head of 0.05 cm/yr relates to a reduction in water stored in the aquifer of 8.5 GL/yr. Therefore, the water balance deficit is consistent with the observed head decline in the Superficial, given the uncertainty associated with the value of the storage coefficient parameter.

Equation 6-4 Change in aquifer storage

$$\Delta V = A.\Delta h.b.S$$

where ΔV is the change in volume, A is area, Δh is change in head, b is aquifer thickness (when considering confined aquifers) and S is the storage coefficient of the aquifer (for confined aquifers) or the specific yield for unconfined aquifers

Table 6-16 Annual conceptual flux summaries for the Superficial, Rockingham and Leederville aquifers in the Serpentine study area

	Input / output	Flux	Quantity (GL)	Quantity (mm)	(%)
Superficial Aquifer	Inputs	Gross recharge from rainfall	253.9	349	95.6%
		Recharge from irrigation	9.5	13	3.6%
		Vertical recharge from other aquifers	2.3	3	0.9%
	Outputs	Evapotranspiration from groundwater	-165.6	-227	61.4%
		Net drainage from groundwater to surface water	-49.9	-69	18.5%
		Abstraction from superficial groundwater	-32.6	-45	12.1%
		Vertical discharge to other aquifers	-16.7	-23	6.2%
		Net horizontal flow	-4.9	-7	1.8%
		Water balance deficit or surplus	**-3.9**	**-5.3**	**-1%**
Rockingham Aquifer	Inputs	Vertical recharge from other aquifers	6.9	10	100.0%
	Outputs	Abstraction from Rockingham groundwater	-6.9	-10	93.1%
		Net horizontal flow	-0.4	-1	6.0%
		Vertical discharge to other aquifers	-0.1	0	0.9%
		Water balance deficit or surplus	**-0.5**	**-0.7**	**-7%**
Leederville Aquifer	Inputs	Vertical recharge from other aquifers	9.3	13	100.0%
	Outputs	Abstraction from Leederville groundwater	-4.6	-6	36.8%
		Net horizontal flow	-4.2	-6	33.6%
		Vertical discharge to other aquifers	-3.7	-5	29.0%
		Water balance deficit or surplus	**-3.1**	**-4.2**	**-33%**
Surface water	Inputs	Baseflow to rivers	49.9	69	50.5%
		Rainfall/runoff (overland flow)	20.8	29	21.1%
		River inflows	28.1	39	28.4%
	Outputs	River discharges	98.8	-349	100.0%
		Water balance deficit or surplus	**0.0**	**0.0**	**0%**

The main loss from the Superficial is evapotranspiration from groundwater, which totals 61% (165.6 GL/yr). Drainage is the second-largest loss from the system, totalling 19% of losses (49.9 GL/yr). Abstraction makes up 12% (32.6 GL/yr) of losses from the Superficial, and it is likely that abstraction is the main influence on declining groundwater heads in some parts of the study area. Downward leakage to deeper aquifers is estimated at 6% (17 GL/yr) of losses from the Superficial Aquifer. Leakage rates are expected to be higher where the Quaternary sediments are sub-cropped by the Wanneroo Member of the Leederville Formation, relative to the Pinjar and Mariginiup members. Horizontal flow from the Superficial out of the study area boundary makes up 2% of outputs.

The Rockingham Aquifer experiences abstraction of 6.9 GL/yr: it is assumed this is balanced by recharge from the Superficial Aquifer of the same volume. Net horizontal inflow of water from the Leederville (4.2 GL/yr) is balanced by net horizontal outflow (4.6 GL/yr) beyond the study area boundary. Vertical leakage to the Mariginiup Member of the Leederville Aquifer is estimated to be less than 1% of the water balance, at 0.1 GL/yr. The Rockingham Aquifer is experiencing declining heads at a similar rate as those of the Superficial. As such, the water balance deficit of 0.5 GL/yr is probably an underestimate.

The Leederville Aquifer receives vertical recharge from the Superficial totalling 9.3 GL/yr. The main loss from the Leederville is through abstraction, which accounts for 37% (4.6 GL/yr) of outputs from the aquifer. Vertical leakage to the Yarragadee Aquifer accounts for 30% (3.7 GL/yr) of outputs, and net horizontal flow across the model boundary accounts for 33% (4.2 GL/yr). This equates to a 3.1 GL/yr deficit in the Leederville Aquifer water balance. Using Equation 6-4, with a storage coefficient of 0.001 – based on pump testing near the Beenyup wastewater treatment plant (Martin et al. 2009), an average aquifer thickness of 90 m and an average drop in head of 15 cm/yr, the annual decline in volume stored is 8.9 GL/yr. Therefore the estimated deficit in the water balance is fairly consistent with the estimated change in storage based on declining heads, given the inherent uncertainty of the flux calculations.

Monthly water balance

The monthly water balance describes the flow of water into and out of an aquifer on a monthly time-step. Of the fluxes in the conceptual water balance, rainfall recharge, irrigation recharge, evapotranspiration, abstraction and drainage were calculated on a monthly time-step. Vertical recharge and discharge and horizontal flow were calculated on an annual time-step, and distributed evenly between months. As such, only the Superficial Aquifer's water balance is reported in this section because most fluxes in the Rockingham and Leederville aquifers were not calculated on a monthly basis (horizontal flow and vertical leakage). The monthly flux calculations are reported in Table 6-17.

Figure 6-10 shows the change in storage in the Superficial Aquifer over one year. This is calculated based on the cumulative total of fluxes at one-month intervals. As heads in some parts of the Superficial Aquifer are in slow decline, an overall downward trend in the aquifer storage is occurring, equivalent to 3.9 GL/yr. The shape and period of the change in storage approximates observed water levels in Superficial bores.

Table 6-17 Monthly water balance of the Superficial Aquifer

SUPERFICIAL	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (GL)	8.4	12.6	12.7	31.9	77.0	115.1	122.3	90.9	61.3	36.1	22.6	6.9	597.8
Rainfall recharge (GL)	7.6	5.1	2.5	2.5	2.5	12.7	43.2	66.0	50.8	33.0	17.8	10.2	253.9
Irrigation recharge (GL)	1.4	1.3	1.1	0.7	0.4	0.2	0.2	0.3	0.4	0.8	1.2	1.4	9.5
EVT (GL)	-14.0	-9.2	-6.8	-4.1	-2.7	-7.8	-10.4	-14.3	-19.8	-28.4	-32.3	-15.7	-165.6
Recharge - Rockingham (GL)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recharge - Leederville (GL)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	2.3
Recharge - Yarragadee (GL)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Discharge - Rockingham (GL)	-1.1	-0.9	-0.8	-0.5	-0.3	-0.1	-0.1	-0.2	-0.3	-0.6	-0.9	-1.1	-6.9
Discharge - Leederville (GL)	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-9.0
Discharge - Yarragadee (GL)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.7
Licensed abstraction (GL)	-3.1	-2.7	-2.4	-1.6	-0.9	-0.4	-0.3	-0.6	-0.9	-1.8	-2.6	-3.1	-20.5
Unlicensed abstraction (GL)	-1.8	-1.6	-1.4	-0.9	-0.5	-0.2	-0.2	-0.3	-0.5	-1.1	-1.6	-1.8	-12.1
Horizontal flow (GL)	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-4.9
Drainage: baseflow (GL)	-0.5	-0.5	-0.4	-0.5	-0.9	-3.7	-10.2	-14.3	-10.8	-5.4	-1.9	-0.8	-49.9
Totals	-12.5	-9.6	-9.2	-5.4	-3.4	-0.4	21.0	35.6	17.7	-4.5	-21.3	-12.0	-3.9
Cumulative total	-12.5	-22.1	-31.3	-36.6	-40.0	-40.4	-19.3	16.2	33.9	29.4	8.1	-3.9	

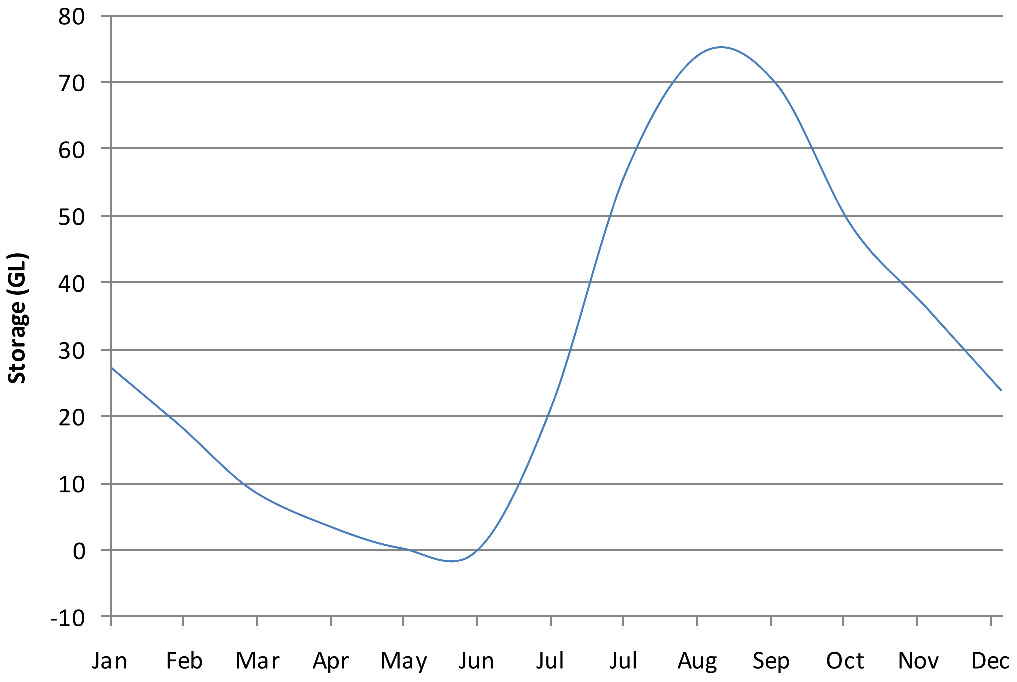


Figure 6-10 Monthly time-series of change in storage for the Superficial Aquifer

6.5 Numerical model selection

The modelling tool Mike SHE will be used to develop the numerical groundwater model. Mike SHE can simulate the entire land phase of the hydrologic cycle. It is particularly useful for evaluating wetland management, surface water impact from groundwater withdrawal, land use and climate change effects, environmental flows and water quality.

Mike SHE (Refsgaard & Knudsen 1996) is a deterministic physically-based distributed model. The hydrological processes are modelled by finite difference representations of the partial differential equations for the conservation of mass, momentum and energy, in addition to some empirical equations. The major flow components (processes) considered in the model are flow in the saturated zone, flow in the unsaturated zone, evapotranspiration and overland channel flow. The components in the model describing the different parts of the hydrological cycle can be used individually or in combination, depending on the scope of the study (DHI 2011). To account for the spatial variations in catchment properties, Mike SHE represents the basin horizontally by an orthogonal grid network, and uses a vertical column at each horizontal grid square to describe the variation in the vertical direction. This is achieved by discretising the catchment into a large number of elements or grid squares and solving the equations for the stated variables for every grid into which the study area is divided.

Numerous independent reviews rank Mike SHE as the world’s most comprehensive and scientifically-sound model for surface water/groundwater interaction (Middlemis 2004, Camp Dresser & McKee Inc 2001, West Consultants et al 2001, Kaiser Hill 2001). Mike SHE uses a MODFLOW-equivalent (the same equations) to model subsurface flows. It is an ideal model for the high-groundwater-table environment of the Swan Coastal Plain where there are strong groundwater and surface water interactions. Mike SHE is a product of the Danish Hydrological Institute, an independent, international consulting and research organisation.

In the study area the maximum groundwater level reaches or is above the ground in many locations in most years. Flows in drains are derived from discharge from the superficial groundwater and from surface runoff. The groundwater balance is highly dependent on the surface water hydraulics (drain invert and capacity). As such an integrated surface water/groundwater model is critical if an accurate water balance is to be achieved.

Model calibration

The model will be calibrated for the period 1980 to 2005, and validated from 2005 to 2010. The calibration period was selected to capture the increasing trend in rainfall in the 1980s and the decline in the early 2000s. The results of the calibration/validation will be assessed by a suitable quantitative comparison of measured and simulated water levels at selected bores and flows at selected gauging stations, over the calibration and verification periods based on the *Murray Darling Basin Commission groundwater flow modelling guidelines* (Middlemis 2000).

The following calibration targets are expected to be achieved for the Superficial Aquifer:

- RMS error between measured hydraulic head and simulated hydraulic head of less than 5% of the measured drop in hydraulic head drop across the model area. Final calibration results will report the RMS error, mean absolute error and mean error.
- The RMS error for the spatial distribution of the water levels/flows for current conditions (as defined in the conceptual model) will be reported, as well as the RMS error for fitting the hydrographs and matching the magnitude of water level variations.
- The difference between the total simulated inflow and the total simulated outflow (water balance error) of less than 0.1% and ideally less than 0.05%.

The following calibration targets will be achieved for surface water flows in the study area:

- daily Nash-Sutcliffe coefficient of efficiency of better than 0.7 at flow-gauging stations
- total water balance error of less than 10% at flow-gauging stations.

6.6 Knowledge gaps

Knowledge gaps in the conceptual model include a lack of understanding of the spatial distribution of geological units (particularly at depth), limited field tests to determine aquifer hydraulic properties, a lack of detailed vegetation mapping and local-scale information on vegetation LAI and RD, poor quality historical data related to abstraction, and an absence of paired bores that could indicate areas of connectivity between the Superficial and Leederville aquifers.

The geological interpretation included in the conceptual model for the Cretaceous and Jurassic sediments is largely based on the PRAMS model, which was developed using Davidson’s work from 1995. As such, the extent of the deeper formations is based on only the limited number of AM bores in the area, and the geological model was not developed using the latest analytical software. The Department of Water’s Water Resource Assessment Branch is currently re-interpreting the deep geology of this area for the next version of PRAMS, and it is suggested this be used in future modelling work for the area. The installation of paired bores and pump testing is required in the area around the Serpentine Fault, and further east, to determine connectivity between the Superficial, Leederville and Cattamarra aquifers. This area is understood to be an important recharge point for the Cattamarra Aquifer; however, it is also data poor, making it difficult to accurately determine vertical leakage between aquifers.

The lack of reliable information about historical abstraction makes it difficult to simulate historical groundwater trends resulting from pumping. While some large water users such as the Water Corporation are required to report actual consumption, most licensed users are not required to report, and actual water drawn by the user may vary significantly from the allocation. This problem is compounded by the fact that the relevant production bore’s location – and information about its construction – is not always known.

As indicated by Hall et al. (2010b) and Xu et al. (2009), plant RD and LAI are important factors controlling recharge. However, in groundwater and integrated modelling, vegetation and land use categories are usually lumped into broad functional units. RD is likely to vary significantly with vegetation type and landscape location, and these are not well accounted for by the land use mapping available at present. Local data on seasonal variation and response in LAI and RD is not available, which may make transitions between very wet and very dry years difficult to model.

6.7 Conclusions

The Serpentine area has considerable hydrogeological and hydrological complexity. To accurately simulate the system with a numerical model such as MIKE SHE, all fluxes between aquifers, exchange between surface water and groundwater, and interactions across model boundaries must be accounted for.

The conceptual model developed in this phase of the project is an important foundation on which the numerical model is to be built.

The conceptual model's structural component defines the spatial extents of important geological formations within the model domain, maps soil and land use functional units that will act to control recharge rates, and identifies key drainage lines, lakes and wetlands that will interact with the Superficial Aquifer. It also identifies appropriate boundary conditions that will constrain the model's horizontal and vertical dimensions. The identification of aquifer, unsaturated zone and hydraulic parameters provides guidelines for model calibration, such that the calibrated numerical model remains within realistic physical bounds consistent with our understanding of the aquifer system. The numerical flux calculations are important for two reasons. Firstly, they enable a first-pass check that the conceptual model is a realistic representation of the system and identify any potential mass-balance errors before construction of the numerical model. Secondly, they identify the largest and most important fluxes within the system, therefore providing a focal point for model calibration.

In the Superficial Aquifer's case, it is clear that three fluxes are of the most importance: gross recharge and evapotranspiration, drainage to rivers and drains, and abstraction of groundwater. Of less importance are the vertical and horizontal discharge components of the water balance. Within the Leederville and Rockingham aquifers, abstraction, recharge from the Superficial and horizontal discharge are all important fluxes. It is also clear that the winter baseflow component of discharge from the main rivers and drains is substantial, and will therefore be an important factor in achieving calibration at surface water gauges.

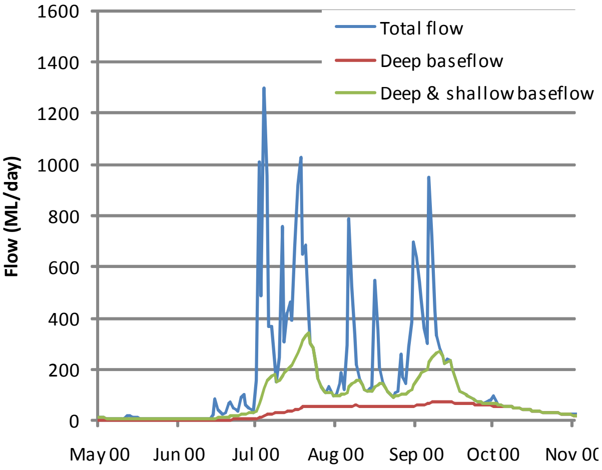
Appendices

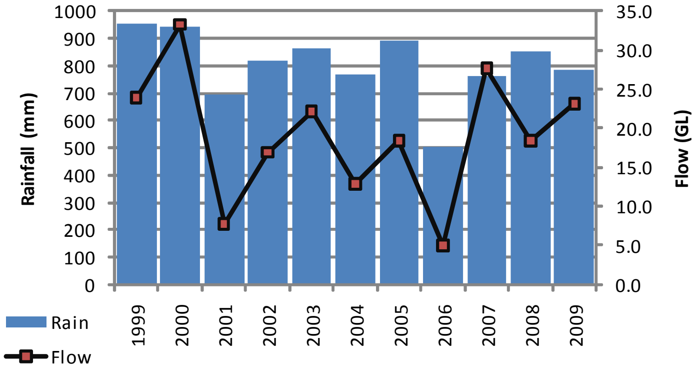
Appendix A — Flow-gauging data

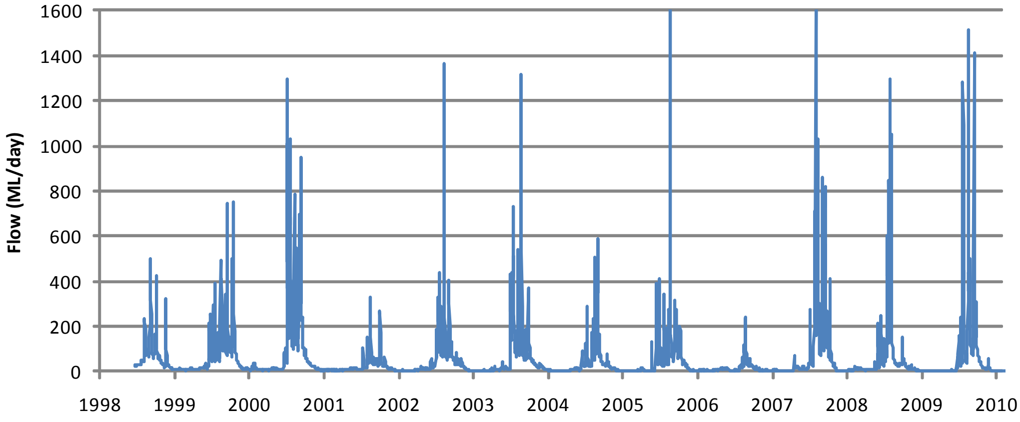
AWRC Ref	Name	Context	Start date	End date	Average annual flow (GL)	Drainage area (km^2)	Coefficient of runoff (%)	Used in calibration	Hydrographer's comments
614114	Lowlands	Serpentine River	16/06/1998	7/10/2010	19.0	185.7	12.8	Yes	Good quality since the broad crest weir was installed in April 2008. Prior to that it is probably only fair – reasonable. Low flows may be a bit dodgy due to the unstable low flow control.
614030	Dog Hill	Serpentine River	22/02/1979	7/10/2010	68.3	479.2	17.8	Yes	Good record, decent flows
614028	Hopelands Road	Dirk Brook	5/04/1979	29/05/2001	12.2	63.9	24.0	Yes	Data quality is a bit of an unknown – get the rating curve comments from the Water Corp. Probably OK as it had a gauging weir but at some stage it ended up with flow beneath it.
614094	Yangedi Swamp	Punrack Drain	9/06/1995	6/05/2010	19.0	119.8	19.9	Yes	Reasonably good flow record but low flows (particularly this year & possibly in late 2009) will be a bit doubtful due to vegetation growth in the channel.
614013	Hope Valley	Peel Main Drain	16/06/1976	21/05/2001	1.6	20.0	10.2	Yes	Check the rating curve comments because there may be significant tailwater problems at this site.
614095	Spectacles SSP	Peel Main Drain	1/06/1995	6/01/1998	0.9	26.0	4.3	No	Poor quality data, trace missing spikes, doesn't correlate
614078	SPSS4 Thomas Road	Peel Main Drain	22/07/1992	6/01/1998	1.1	27.0	4.9	No	Poor quality data, trace missing spikes, doesn't correlate
614119	Zig Zag Road	Peel Main Drain	9/08/2000	7/03/2005	6.6	80.9	10.2	Maybe	Data may be OK (fair quality), need to check the rating curve comments. It is quite likely to be intermittently affected by downstream water levels in Folly Pool.
614096	Folly Road	Peel Main Drain	28/05/1994	21/02/1998	12.5	93.6	16.8	No	Data of dubious quality, CR seems to high
614121	Karnup Road	Peel Main Drain	19/03/2005	14/12/2009	6.8	113.8	7.5	Yes	Doppler has produced more relaible flows recently
614129	Lightbody Road	Oaklands Drain	12/05/2010	2/11/2010	1.2	133.2	1.1	No	1 year data (2010), so only used in validation
614099	Maramanup Pool (inflow)	Peel Main Drain	22/06/1994	26/03/1995	-	-	-	No	Very little data of poor quality, not useable
614100	Maramanyup Pool (outflow)	Peel Main Drain	28/05/1994	27/03/1995	-	-	-	No	1 year of data, poor slope so poor quality

614114 Serpentine River - Lowlands

	614114	Area (km2) =	185.71	
Year	Flow (GL)	Flow (mm)	Rain (mm)	CR
1999	23.9	129	951	14%
2000	33.3	179	945	19%
2001	7.7	41	697	6%
2002	16.9	91	817	11%
2003	22.2	120	865	14%
2004	12.8	69	768	9%
2005	18.4	99	892	11%
2006	5.0	27	500	5%
2007	27.7	149	763	20%
2008	18.5	99	853	12%
2009	23.1	124	783	16%
Average	**19.0**	**102.5**	**803**	**12%**

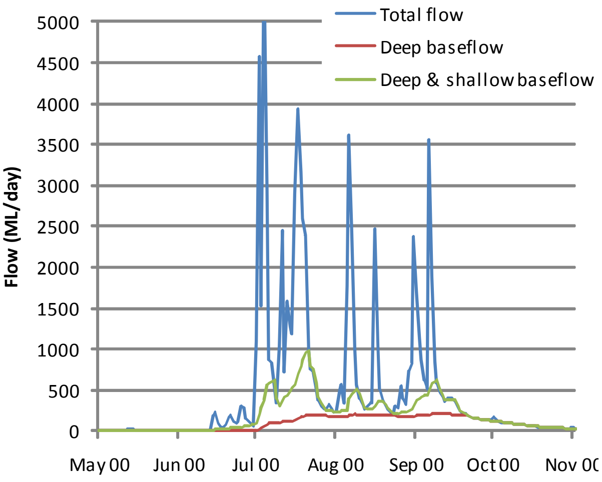


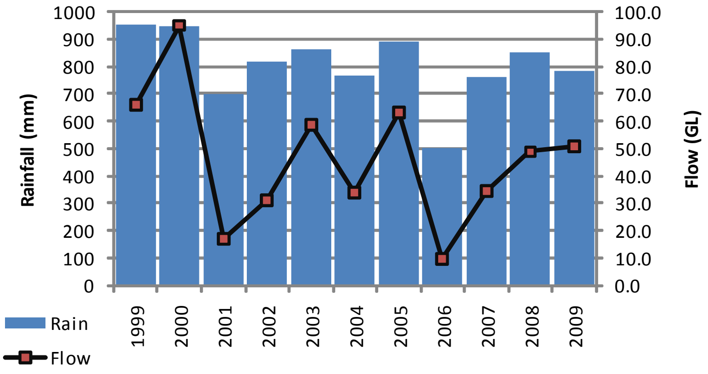


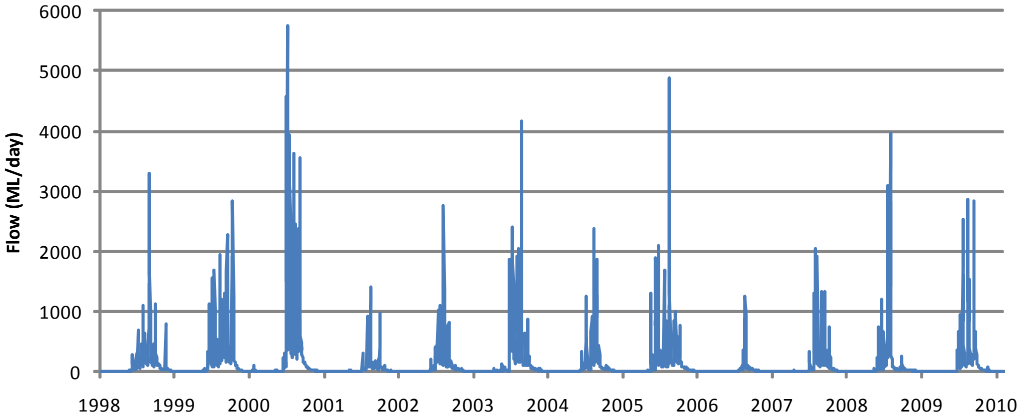


614030 Serpentine River - Dog Hill

Year	614030	Area (km2) =	479.19	
	Flow (GL)	Flow (mm)	Rain (mm)	CR
1980	76.7	160	884	18%
1981	108.9	227	973	23%
1982	66.5	139	819	17%
1983	93.2	195	945	21%
1984	102.7	214	1065	20%
1985	65.4	136	847	16%
1986	83.2	174	942	18%
1987	61.1	127	896	14%
1988	98.5	206	1092	19%
1989	58.2	121	902	13%
1990	48.2	101	780	13%
1991	132.2	276	1196	23%
1992	121.3	253	961	26%
1993	57.2	119	724	16%
1994	71.7	150	649	23%
1995	86.5	180	442	41%
1996	120.4	251	872	29%
1997	47.5	99	759	13%
1998	42.3	88	902	10%
1999	66.1	138	951	14%
2000	95.0	198	945	21%
2001	17.1	36	697	5%
2002	31.2	65	817	8%
2003	58.8	123	865	14%
2004	33.9	71	768	9%
2005	63.1	132	892	15%
2006	9.7	20	500	4%
2007	34.6	72	763	9%
2008	48.8	102	853	12%
2009	50.7	106	783	13%
Average		**163.6**	**922**	**18%**

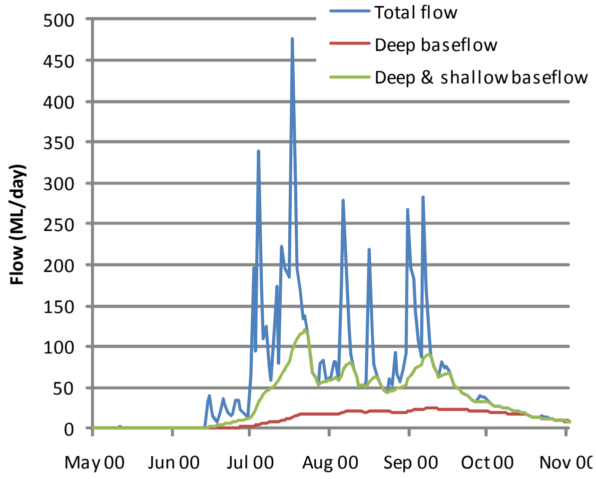


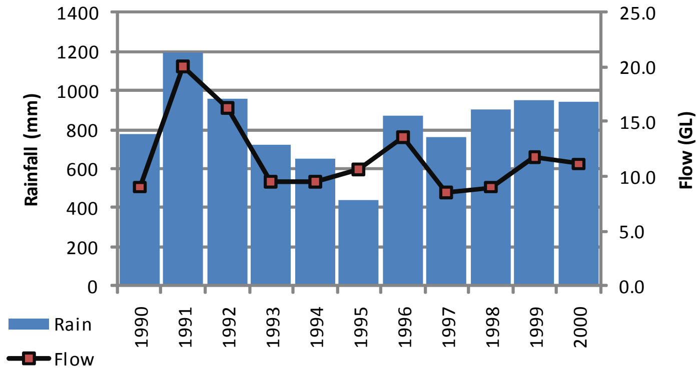


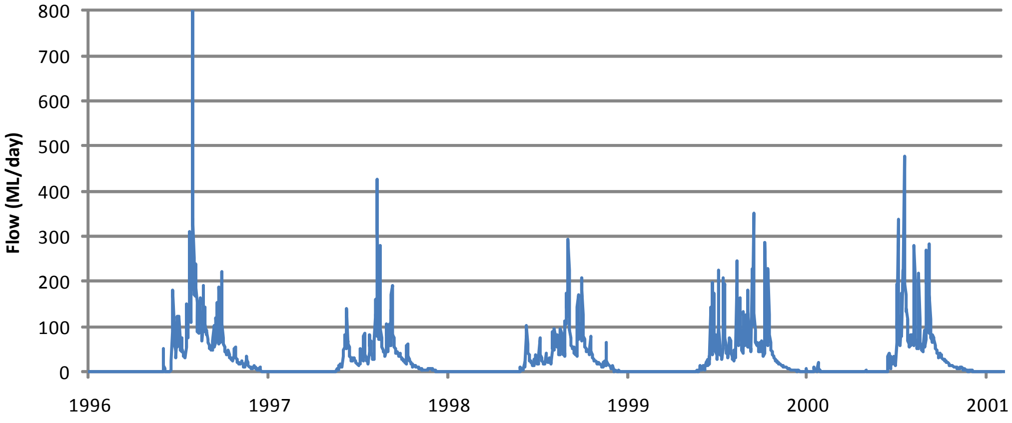


614028 Hopelands - Dirk Brook

Year	614028	Area (km2) =	63.88	
	Flow (GL)	Flow (mm)	Rain (mm)	CR
1980	11.5	180	884	20%
1981	17.2	270	973	28%
1982	11.4	179	819	22%
1983	14.6	228	945	24%
1984	16.4	257	1065	24%
1985	10.1	158	847	19%
1986	10.4	163	942	17%
1987	7.8	123	896	14%
1988	17.9	280	1092	26%
1989	10.8	169	902	19%
1990	9.0	141	780	18%
1991	20.0	313	1196	26%
1992	16.2	254	961	26%
1993	9.5	149	724	21%
1994	9.5	149	649	23%
1995	10.6	167	442	38%
1996	13.5	212	872	24%
1997	8.5	133	759	18%
1998	9.0	141	902	16%
1999	11.7	184	951	19%
2000	11.2	175	945	18%
Average		**195.3**	**922**	**21%**

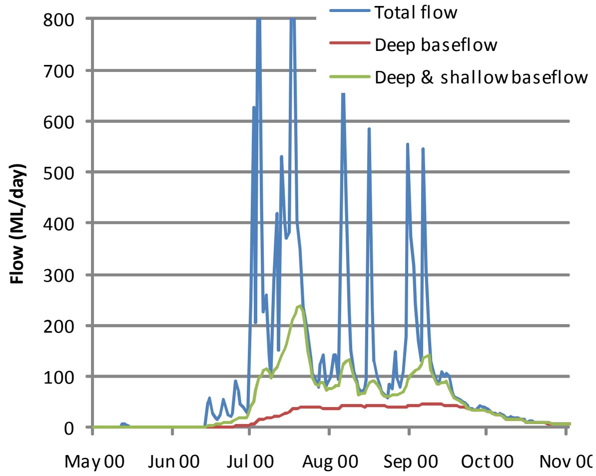


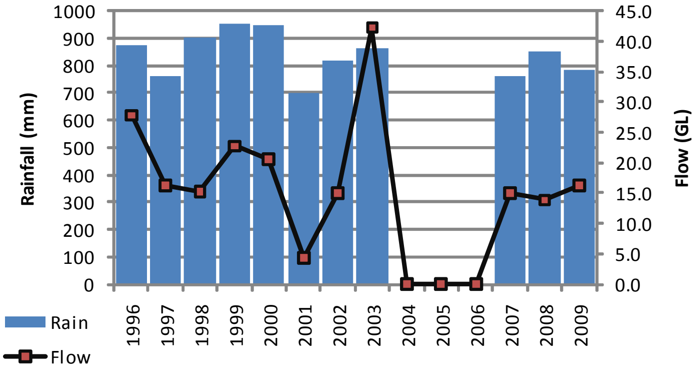


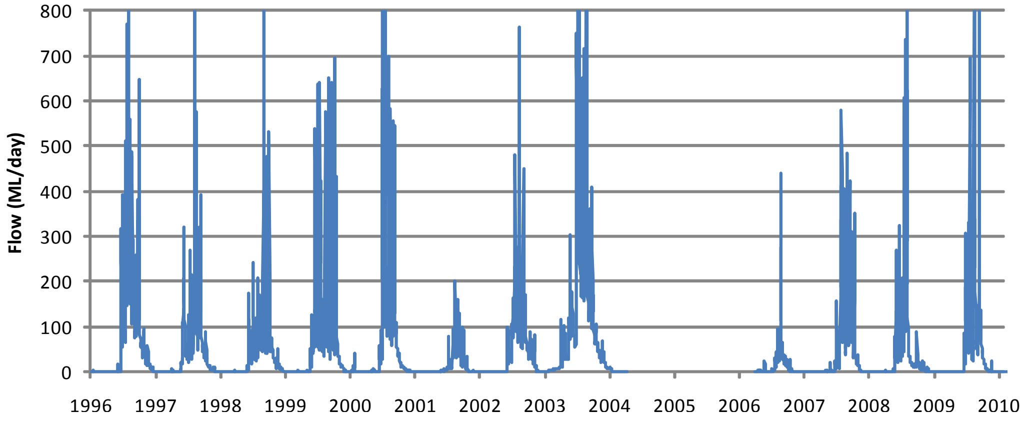


614094 Yangedi - Punrack Drain

	614094	Area (km2) =	119.77	
Year				
	Flow (GL)	Flow (mm)	Rain (mm)	CR
1996	27.8	232	872	27%
1997	16.3	136	759	18%
1998	15.3	128	902	14%
1999	22.7	190	951	20%
2000	20.6	172	945	18%
2001	4.3	36	697	5%
2002	15.0	125	817	15%
2003	42.2	352	865	41%
2004				
2005				
2006				
2007	14.9	125	763	16%
2008	13.9	116	853	14%
2009	16.3	136	783	17%
Average		**171.4**	**851**	**20%**

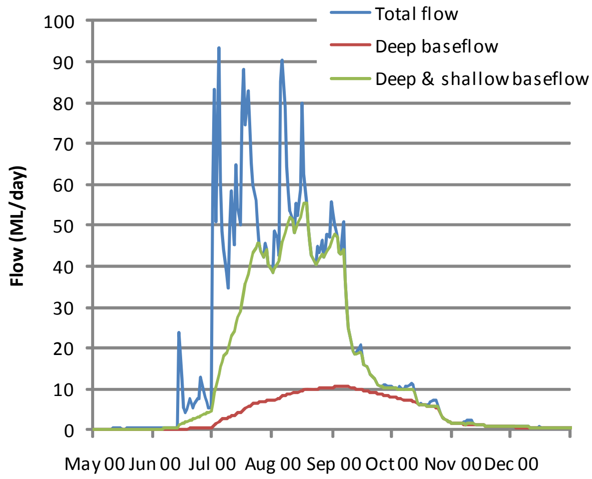


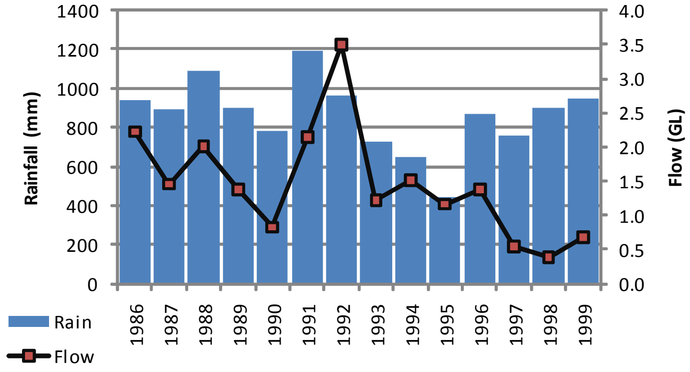


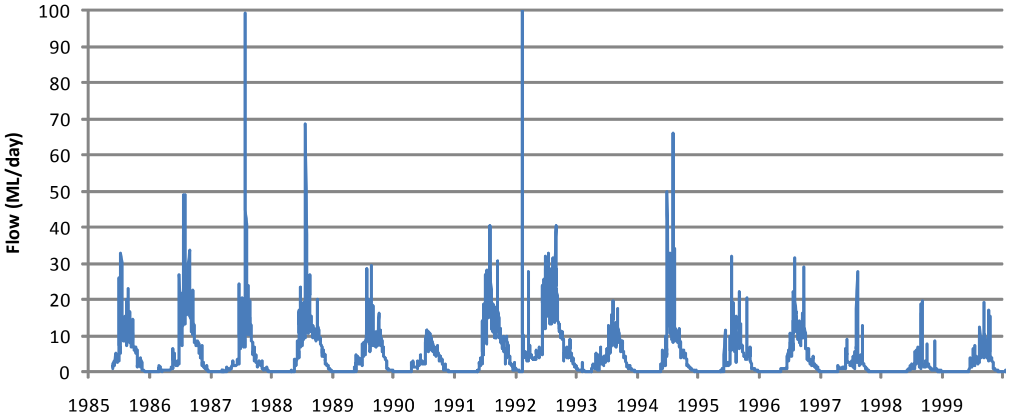


614013 Hope Valley - Peel Main Drain

	614013	Area (km2) =	20.0	
Year	Flow (GL)	Flow (mm)	Rain (mm)	CR
1986	2.2	111	942	12%
1987	1.5	73	896	8%
1988	2.0	101	1092	9%
1989	1.4	69	902	8%
1990	0.8	41	780	5%
1991	2.1	107	1196	9%
1992	3.5	175	961	18%
1993	1.2	61	724	8%
1994	1.5	75	649	12%
1995	1.2	58	442	13%
1996	1.4	69	872	8%
1997	0.5	27	759	4%
1998	0.4	19	902	2%
1999	0.7	34	951	4%
Average	**1.5**	**85.5**	**860**	**10%**

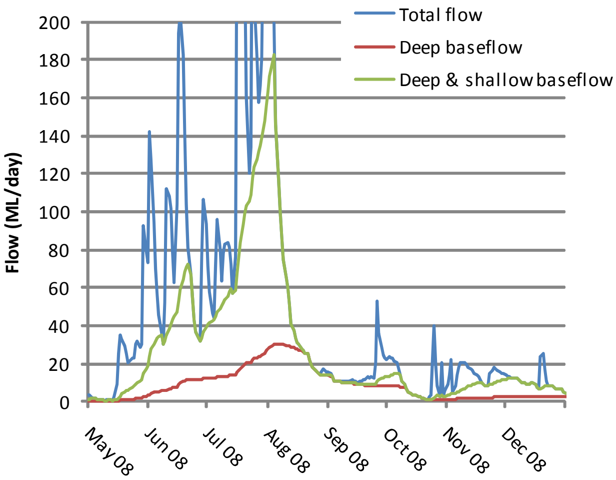


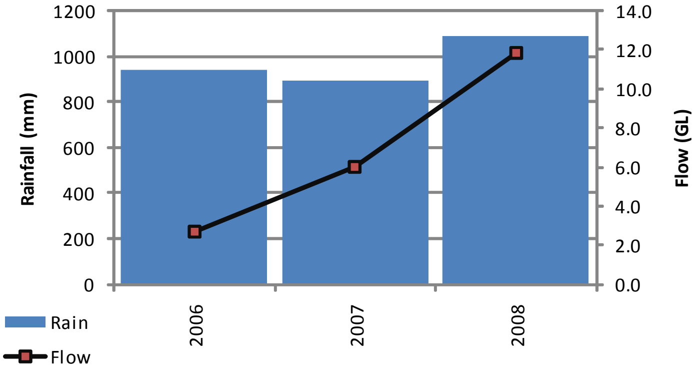


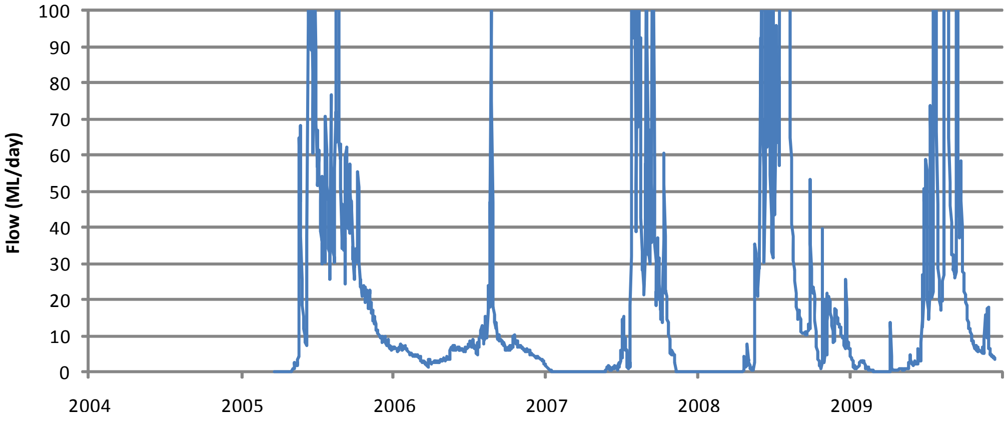


614121 Karnup Road - Peel Main Drain

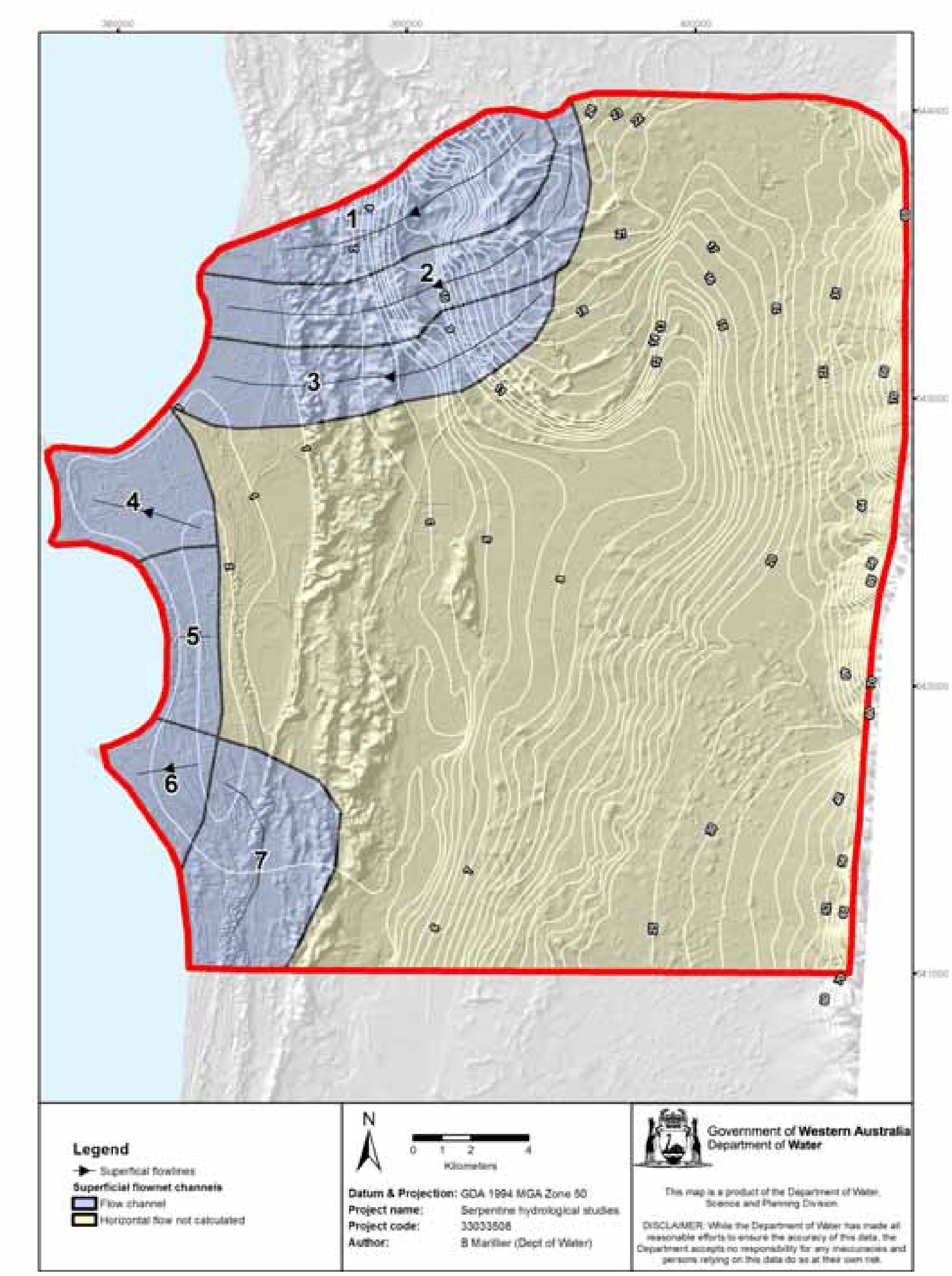
	614121	Area (km2) =	113.8	
Year	Flow (GL)	Flow (mm)	Rain (mm)	CR
2006	2.7	24	942	3%
2007	6.0	53	896	6%
2008	11.8	104	1092	10%
Average	**6.8**	**60.1**	**977**	**6%**





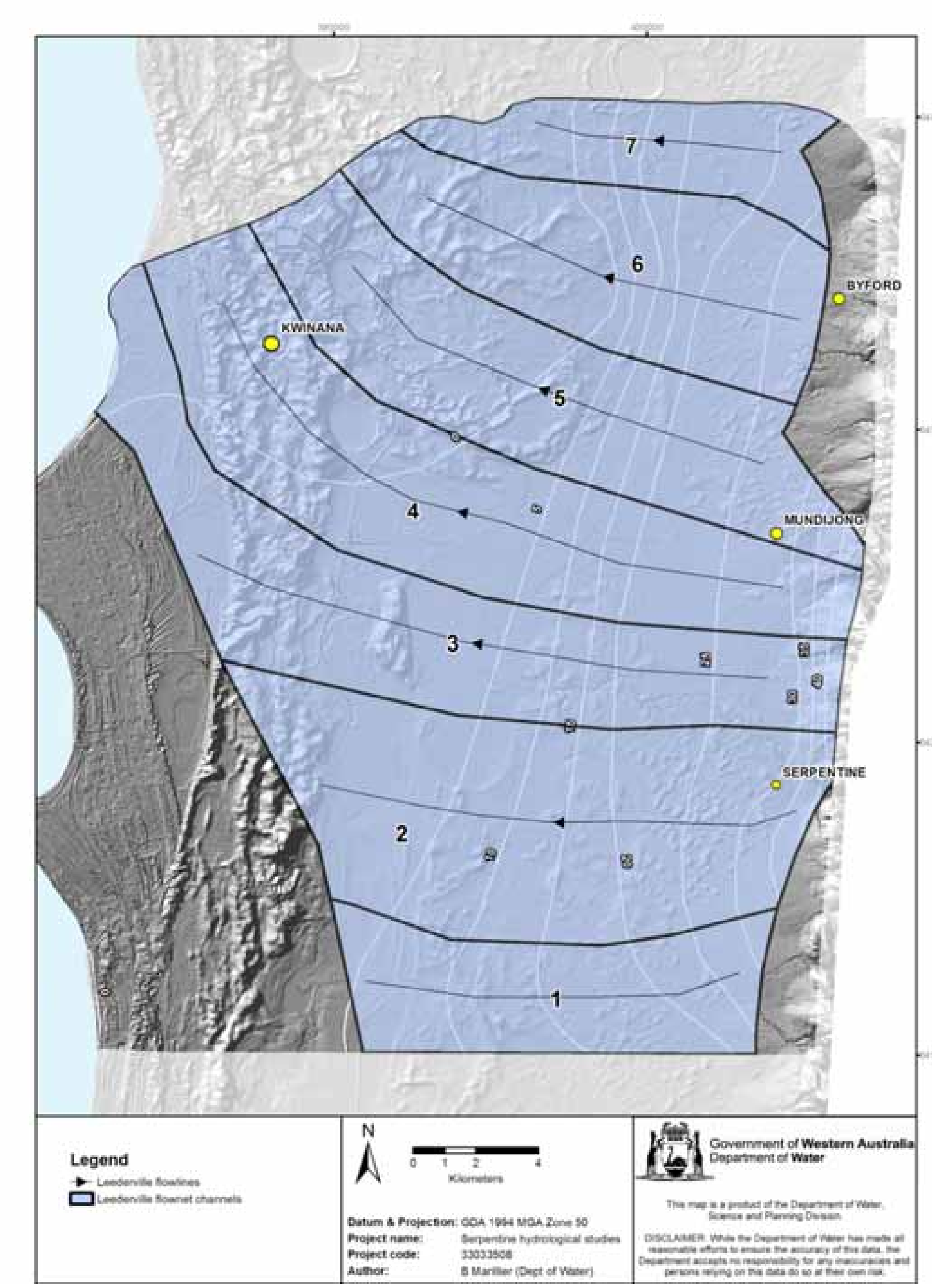


Appendix B — Flow-net calculations



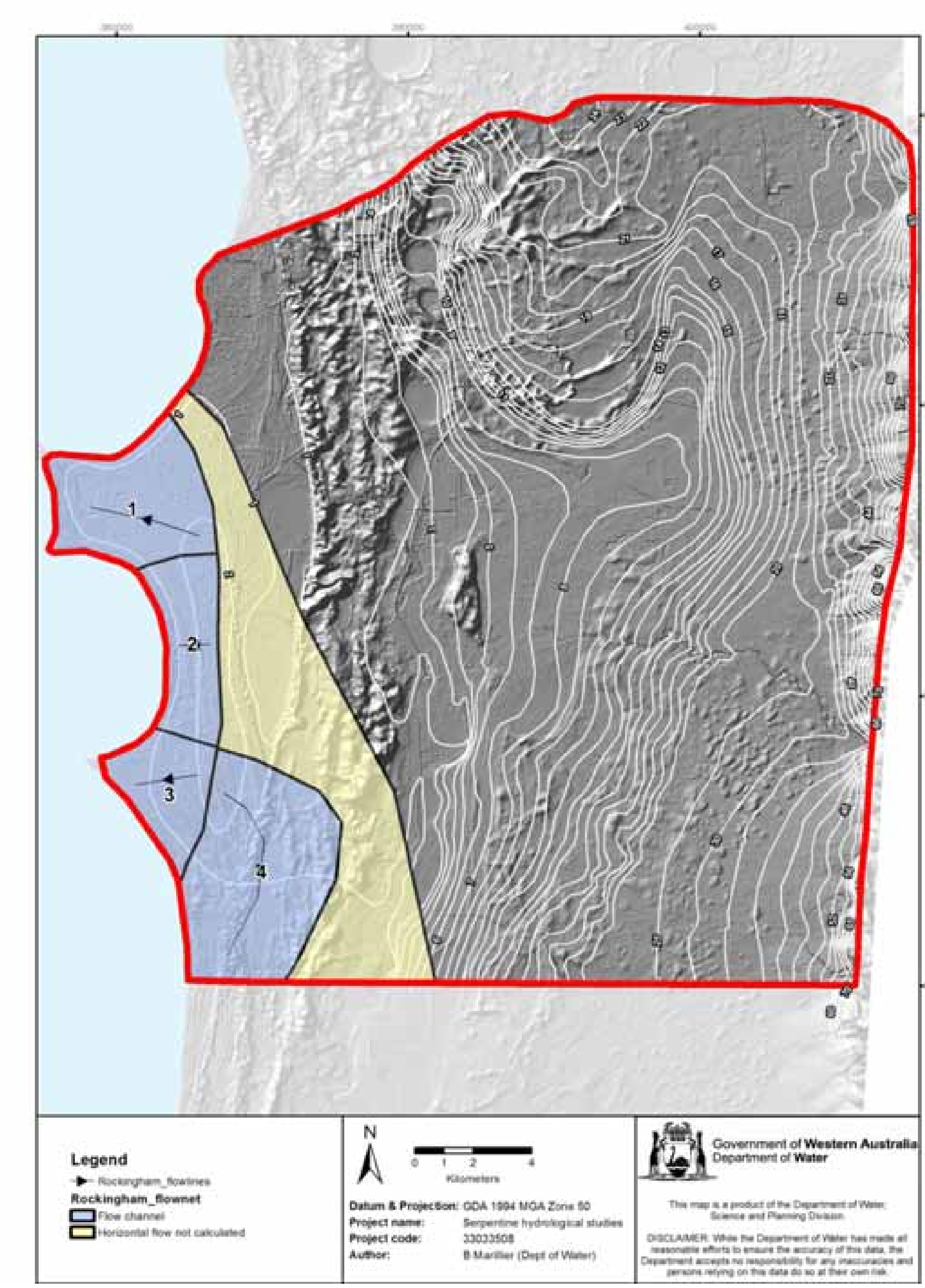
Superficial aquifer flow-net calculations

Flow-Net Channel	Flow-Cell	Flow channel width (m)	Avg length (m)	Upper h	Lower h	Change h	Hydraulic Gradient	Aquifer thickness (m)	Hydraulic Cond (K) (m/d)	Transmissivity (T) (m^2/day)	Q_{Do} (m^3/day)	GL/Year
1	All	3969	13140	24	0	24	0.0018	30	15	450.0	3262	1.2
2	All	6747	15055	24	0	24	0.0016	30	15	450.0	4840	1.8
3	All	4650	14218	20	0	20	0.0014	25	15	375.0	2453	0.9
4	All	6160	6729	2	0	2	0.0003	20	15	300.0	549	0.2
5	All	6704	4204	2	0	2	0.0005	20	15	300.0	957	0.3
6	All	5558	4002	2	0	2	0.0005	20	15	300.0	833	0.3
7	All	6551	8389	2	0	2	0.0002	17	15	255.0	398	0.1
										Totals	13292	4.9



Leederville aquifer flow-net calculations

Flow-Net Channel	Flow-Cell	Flow channel width (m)	Avg length (m)	Upper h	Lower h	Change h	Hydraulic Gradient	Aquifer thickness (m)	Hydraulic Cond (K) (m/d)	Transmissivity (T) (m^2/day)	Q_{Do} (m^3/day)	GL/Year
1	All	4000	13000	30	5	25	0.0019	73	1.5	109.5	842	0.3
2	All	7000	16600	40	2	38	0.0023	88	1.5	132.0	2115	0.8
3	All	4200	22000	40	2	38	0.0017	115	1.5	172.5	1251	0.5
4	All	4700	25500	40	-2	42	0.0016	127	2.5	317.5	2458	0.9
5	All	4400	19500	30	-3	33	0.0017	122	2.5	305.0	2271	0.8
6	All	5000	15000	30	-5	35	0.0023	115	2.5	287.5	3354	1.2
7	All	3700	10000	25	-5	30	0.0030	120	2.5	300.0	3330	1.2
										To boundary	4209	1.5
										To Kwlr	11413	4.2
										Totals	15622	5.7

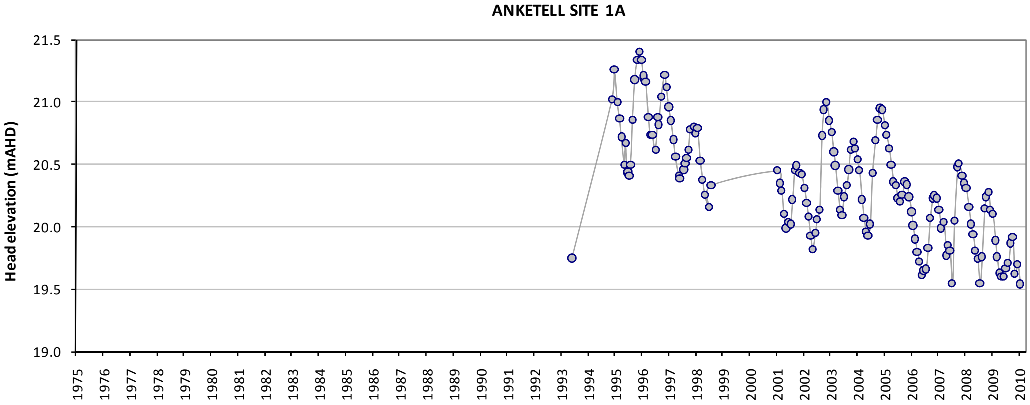


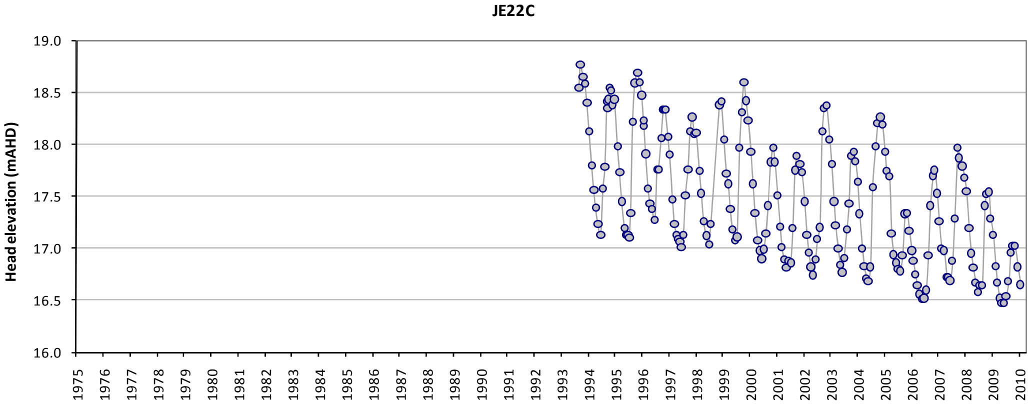
Rockingham aquifer flow-net calculations

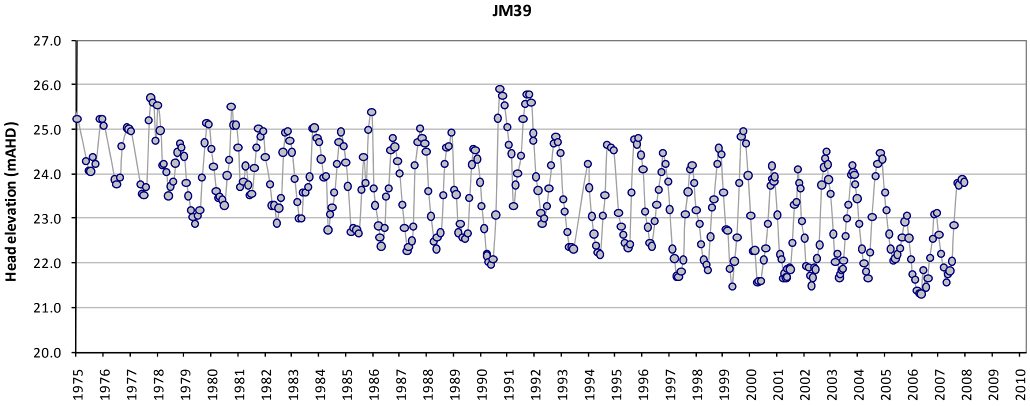
Flow-Net Channel	Flow-Cell	Flow channel width (m)	Avg length (m)	Upper h	Lower h	Change h	Hydraulic Gradient	Aquifer thickness (m)	Hydraulic Cond (K) (m/d)	Transmissivity (T) (m^2/day)	Q_{Do} (m^3/day)	GL/Year
1	All	6160	6729	2	0	2	0.0003	90	15	1350.0	2472	0.9
2	All	6704	4204	2	0	2	0.0005	90	15	1350.0	4305	1.6
3	All	5558	4002	2	0	2	0.0005	90	15	1350.0	3750	1.4
4	All	6551	8389	2	0	2	0.0002	90	15	1350.0	2109	0.8
										Totals	12635	4.6

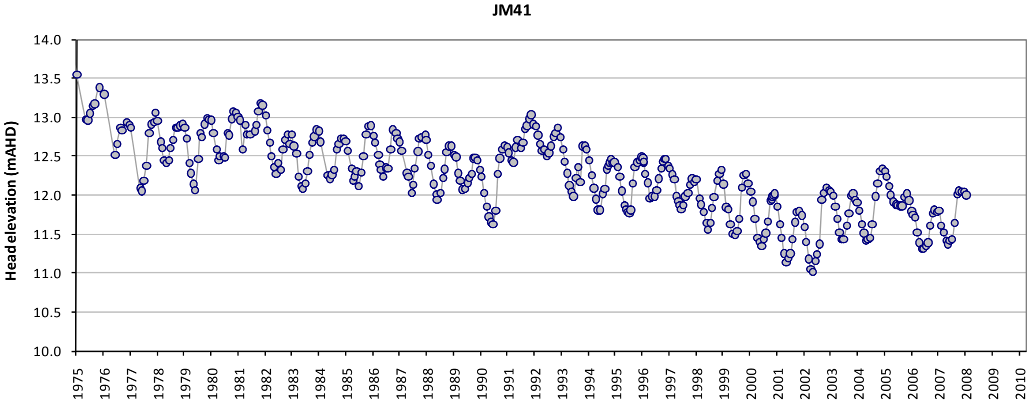
Appendix C — Water levels in monitoring bores

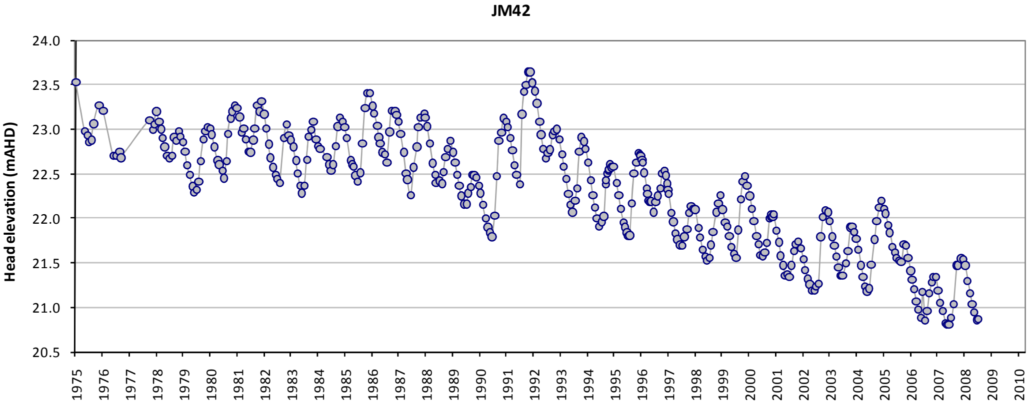
Jandakot Mound bores










JM42
Head elevation (mAHD)
24.0
23.5
23.0
22.5
22.0
21.5
21.0
20.5
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
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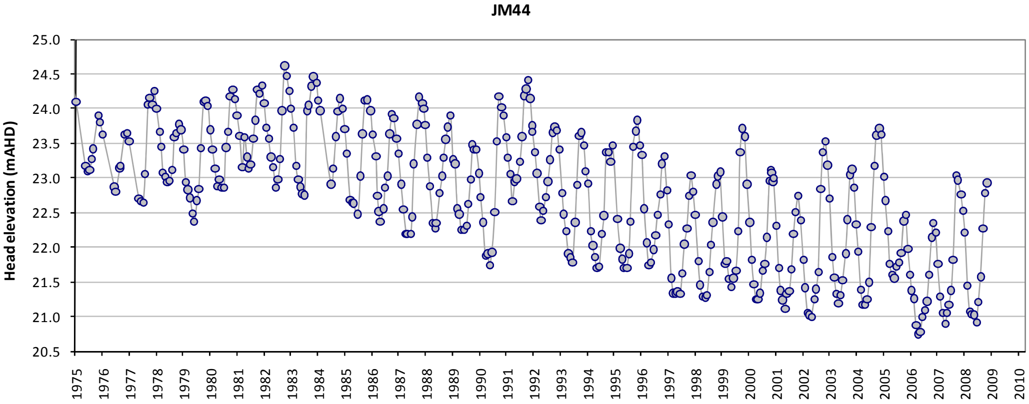
JM44
Head elevation (mAHD)
25.0
24.5
24.0
23.5
23.0
22.5
22.0
21.5
21.0
20.5
1975
1976
1977
1978
1979
1980
1981
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1983
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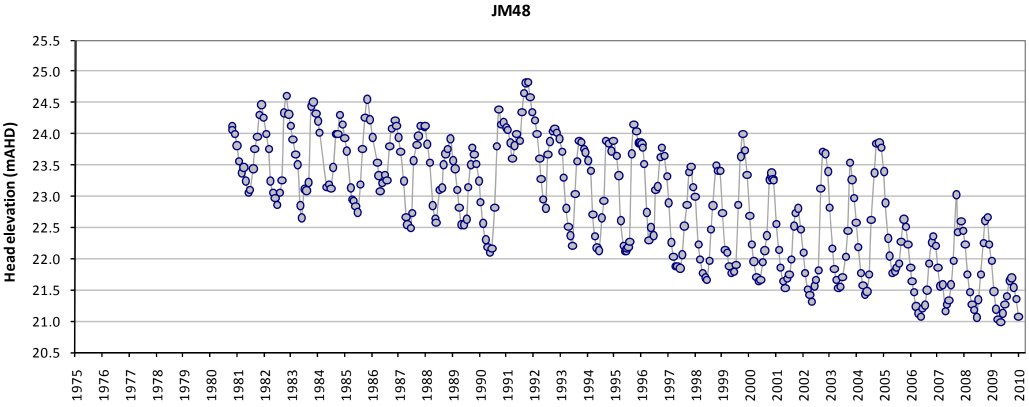
JM48
Head elevation (mAHD)
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24.5
24.0
23.5
23.0
22.5
22.0
21.5
21.0
20.5
1975
1976
1977
1978
1979
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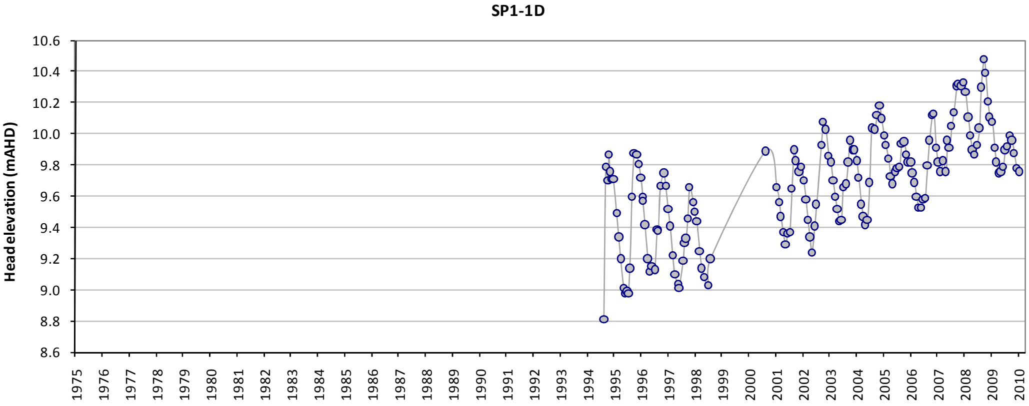
SP1-1D
Head elevation (mAHD)
10.6
10.4
10.2
10.0
9.8
9.6
9.4
9.2
9.0
8.8
8.6
1975
1976
1977
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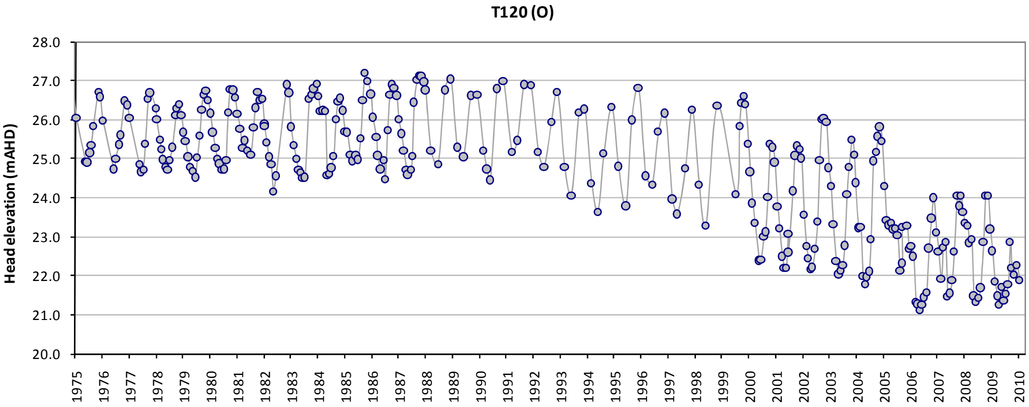
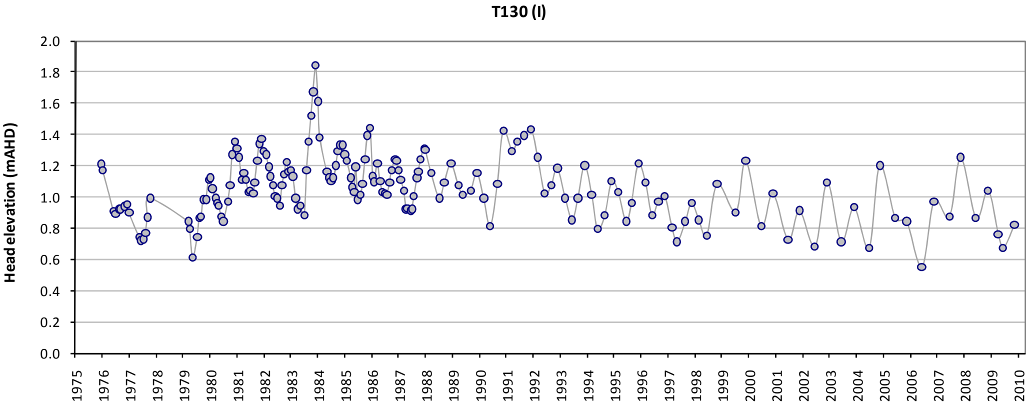
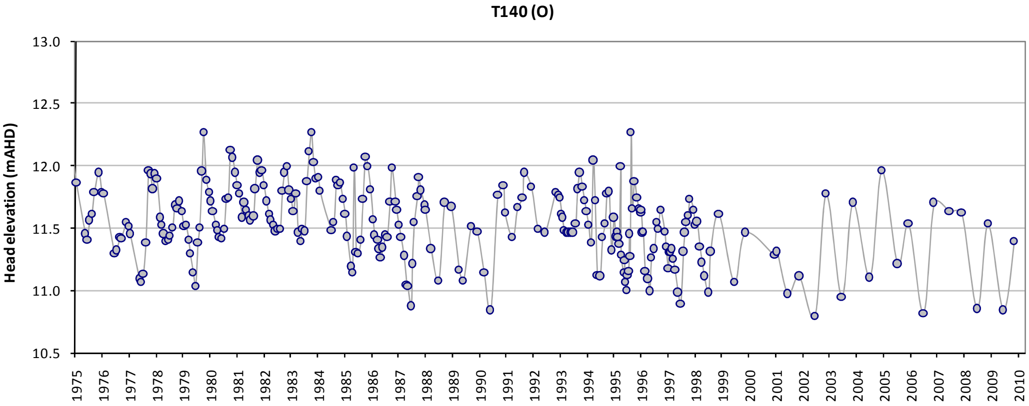
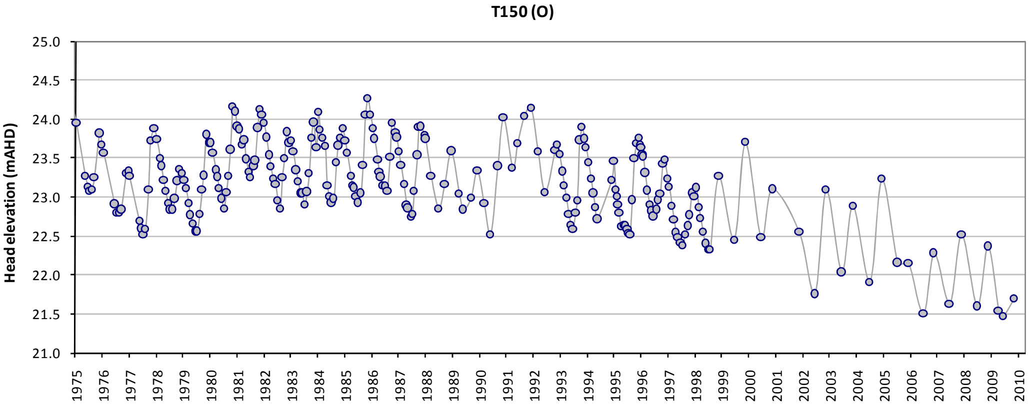
'T' series bores








T150 (O)
Head elevation (mAHD)
25.0
24.5
24.0
23.5
23.0
22.5
22.0
21.5
21.0
1975
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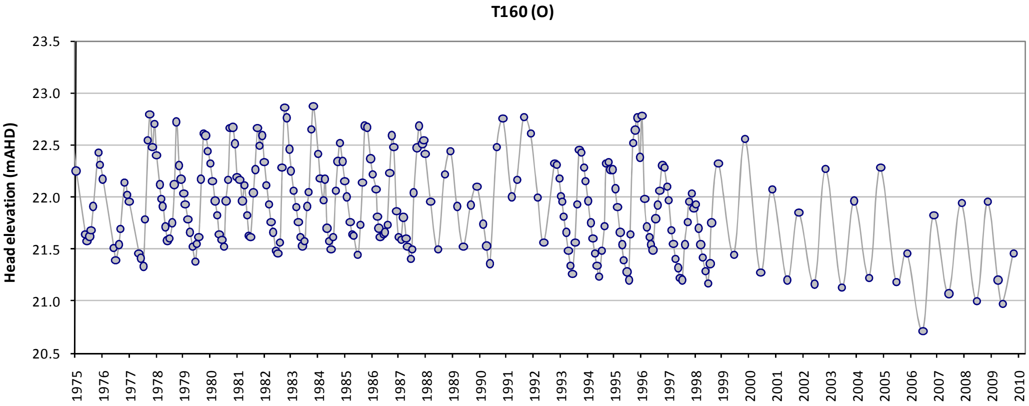
T160 (O)
Head elevation (mAHD)
23.5
23.0
22.5
22.0
21.5
21.0
20.5
1975
1976
1977
1978
1979
1980
1981
1982
1983
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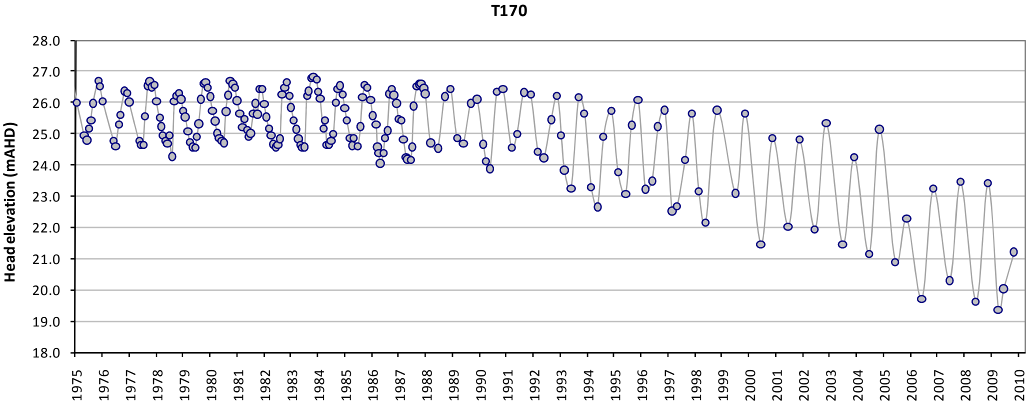
T170
Head elevation (mAHD)
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
19.0
18.0
1975
1976
1977
1978
1979
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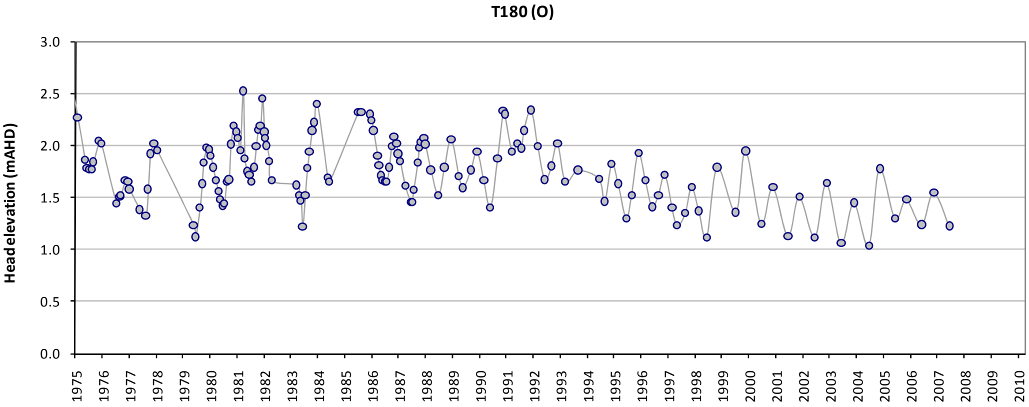
T180 (O)
Head elevation (mAHD)
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2.5
2.0
1.5
1.0
0.5
0.0
1975
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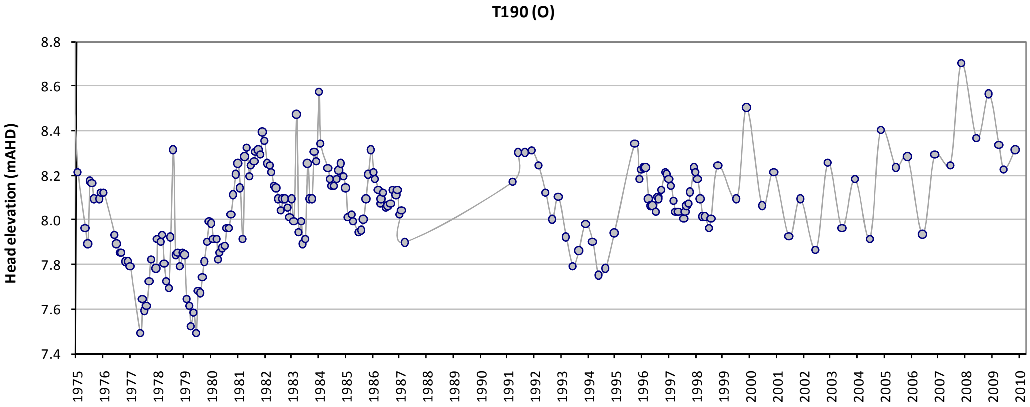
T190 (O)
Head elevation (mAHD)
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
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1976
1977
1978
1979
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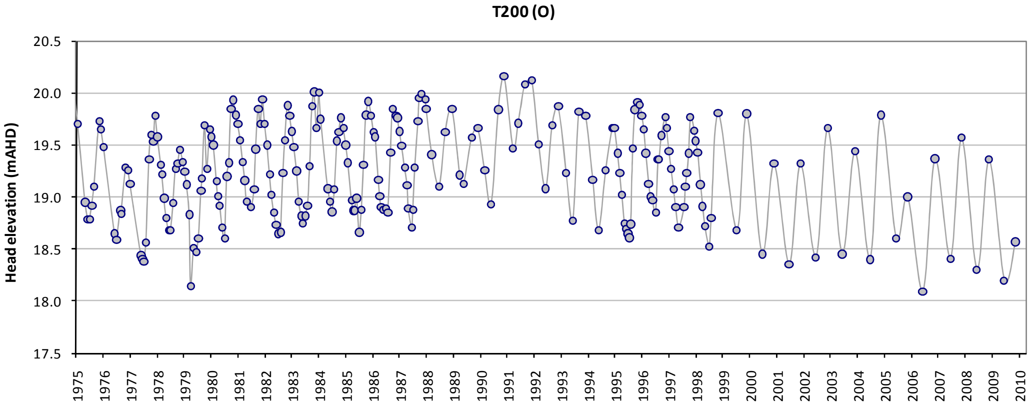
T200 (O)
Head elevation (mAHD)
20.5
20.0
19.5
19.0
18.5
18.0
17.5
1975
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1978
1979
1980
1981
1982
1983
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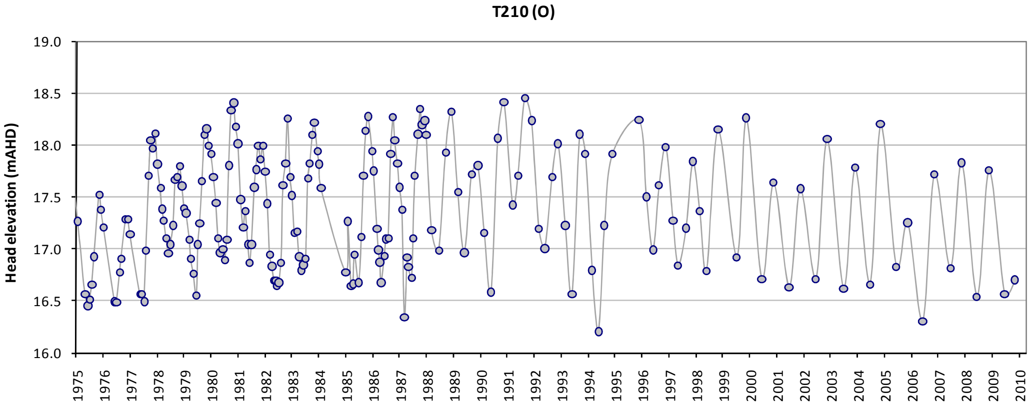
T210 (O)
Head elevation (mAHD)
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18.5
18.0
17.5
17.0
16.5
16.0
1975
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1979
1980
1981
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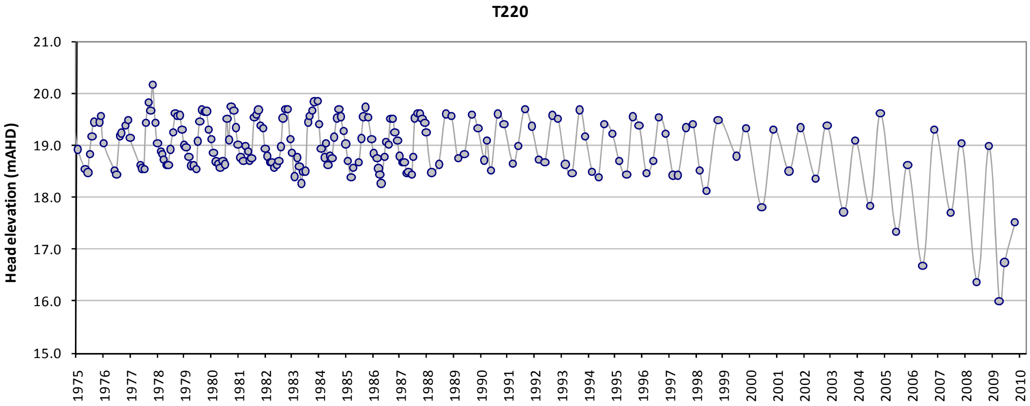
T220
Head elevation (mAHD)
21.0
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19.0
18.0
17.0
16.0
15.0
1975
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1980
1981
1982
1983
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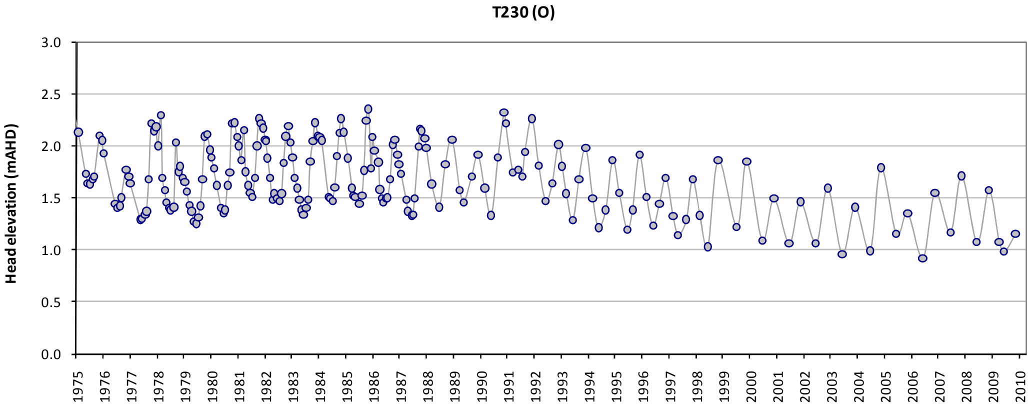
T230 (O)
Head elevation (mAHD)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
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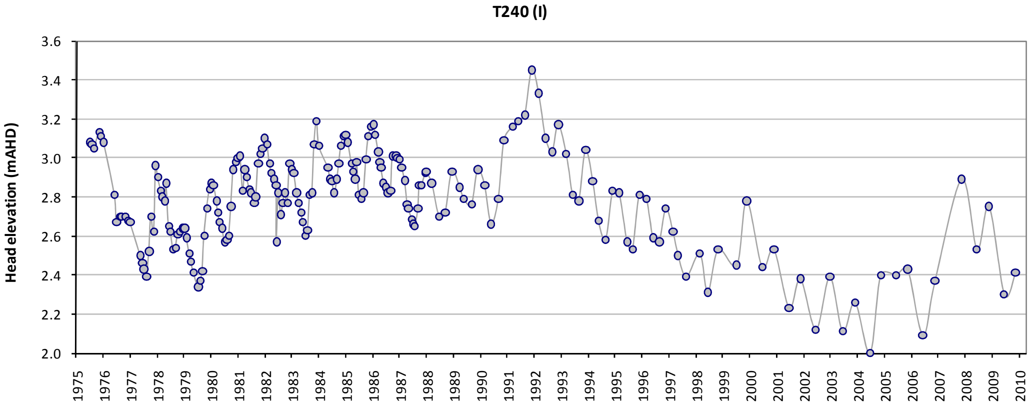
T240 (I)
Head elevation (mAHD)
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1975
1976
1977
1978
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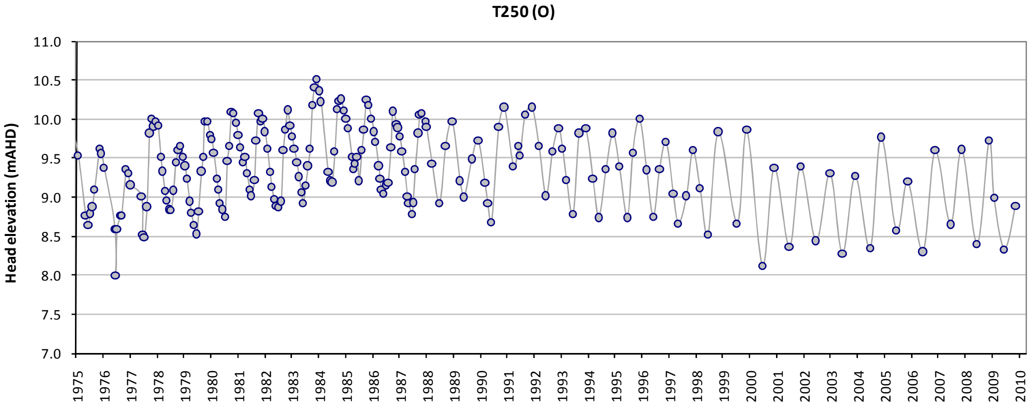
T250 (O)
Head elevation (mAHD)
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
1975
1976
1977
1978
1979
1980
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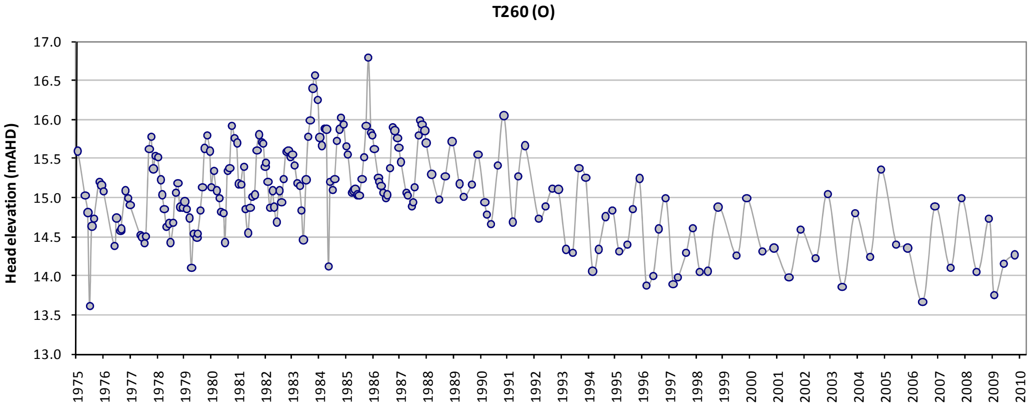
T260 (O)
Head elevation (mAHD)
17.0
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
1975
1976
1977
1978
1979
1980
1981
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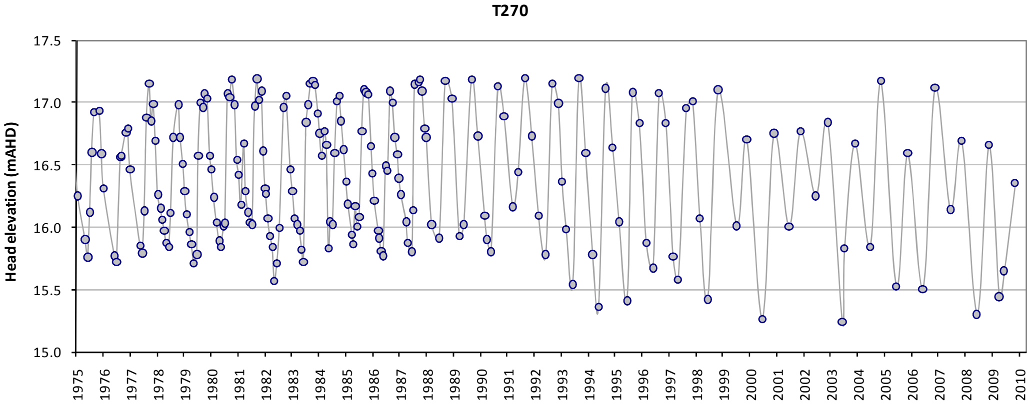
T270
Head elevation (mAHD)
17.5
17.0
16.5
16.0
15.5
15.0
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1981
1982
1983
1984
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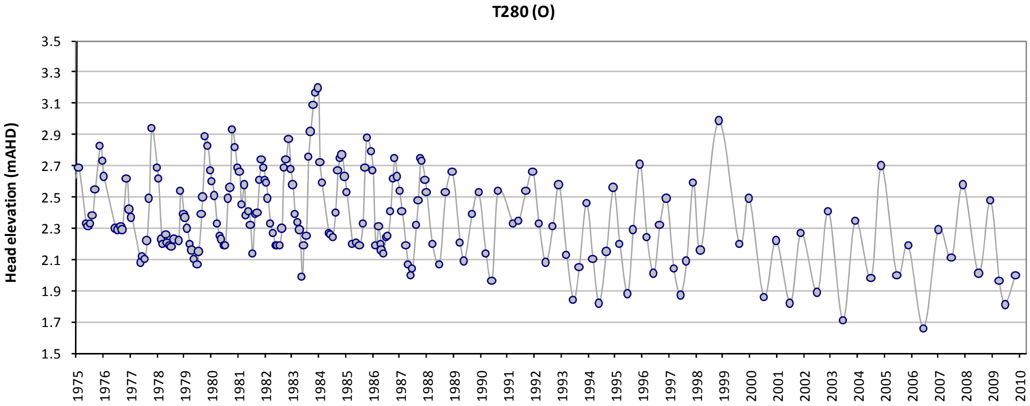
T280 (O)
Head elevation (mAHD)
3.5
3.3
3.1
2.9
2.7
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2.3
2.1
1.9
1.7
1.5
1975
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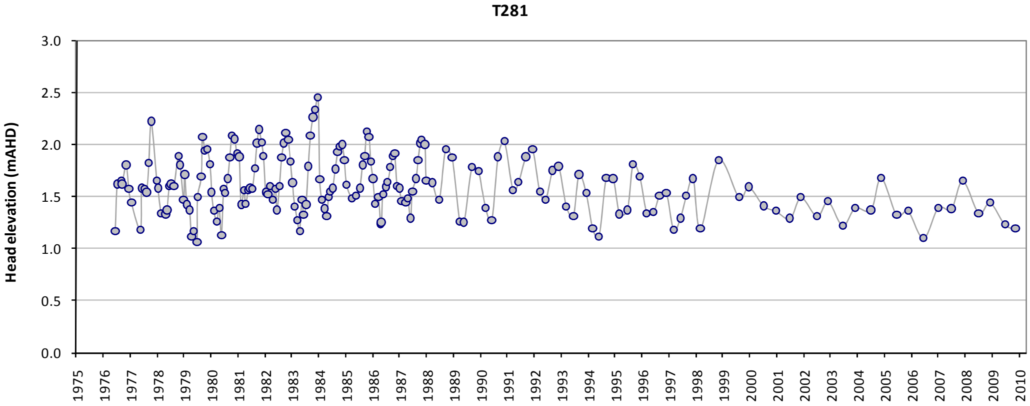
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Head elevation (mAHD)
3.0
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0.5
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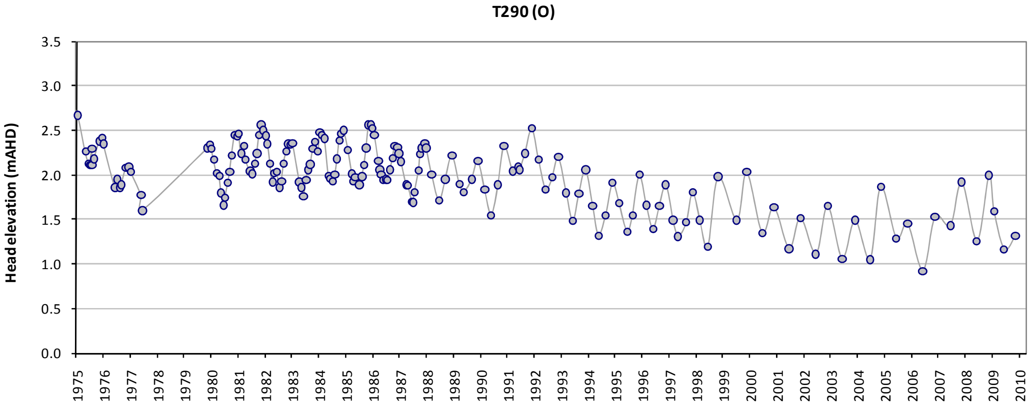
T290 (O)
Head elevation (mAHD)
3.5
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1.5
1.0
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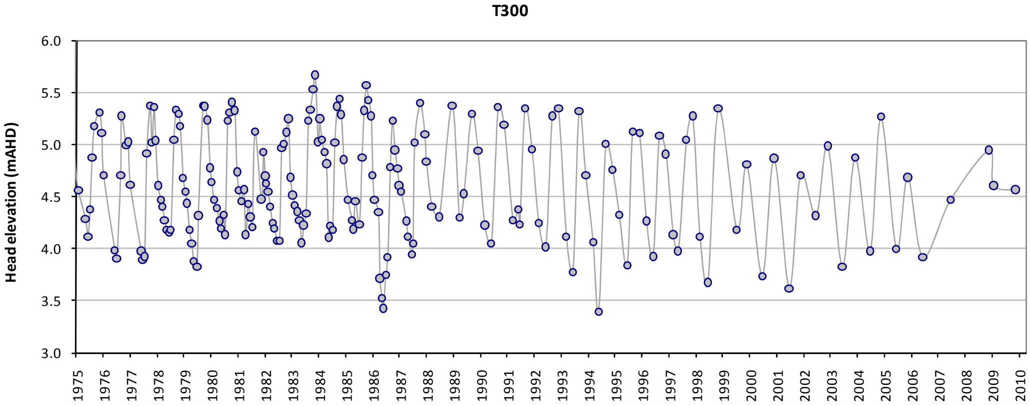
T300
Head elevation (mAHD)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
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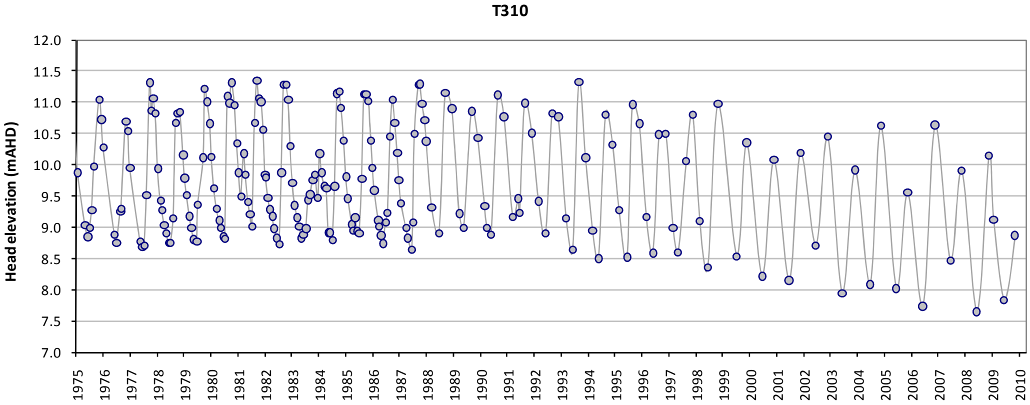
T310
Head elevation (mAHD)
12.0
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11.0
10.5
10.0
9.5
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8.5
8.0
7.5
7.0
1975
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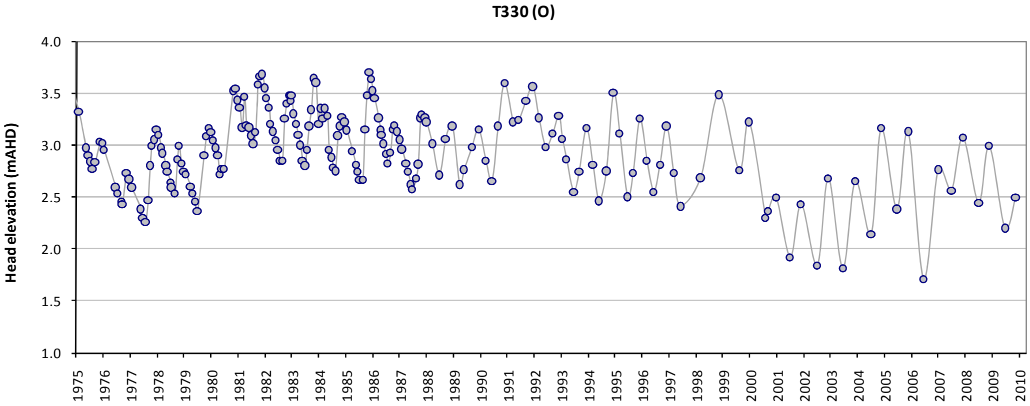
T330 (O)
Head elevation (mAHD)
4.0
3.5
3.0
2.5
2.0
1.5
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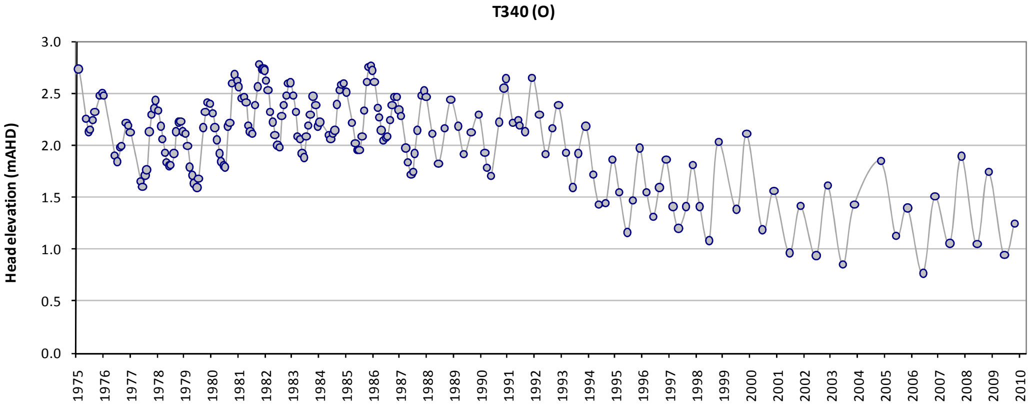
T340 (O)
Head elevation (mAHD)
3.0
2.5
2.0
1.5
1.0
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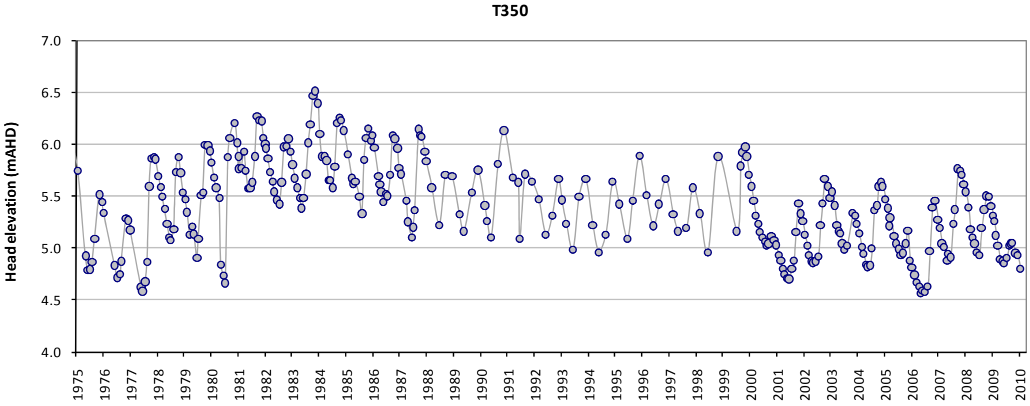
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Head elevation (mAHD)
7.0
6.5
6.0
5.5
5.0
4.5
4.0
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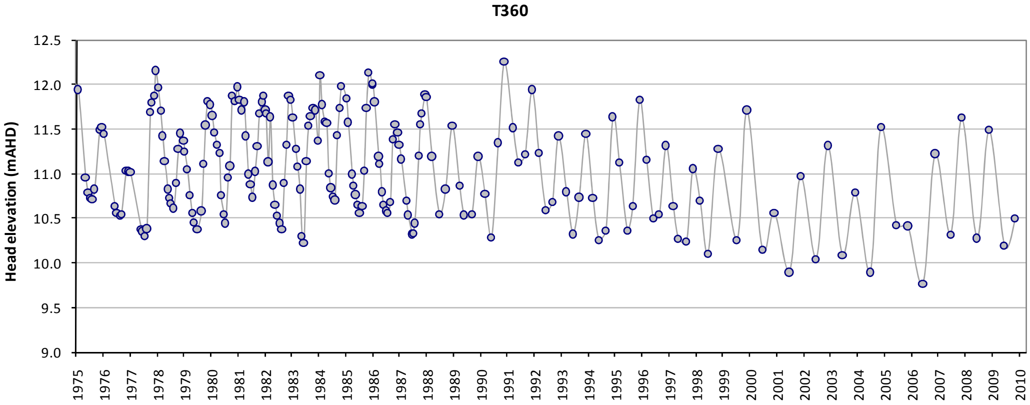
T360
Head elevation (mAHD)
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
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1976
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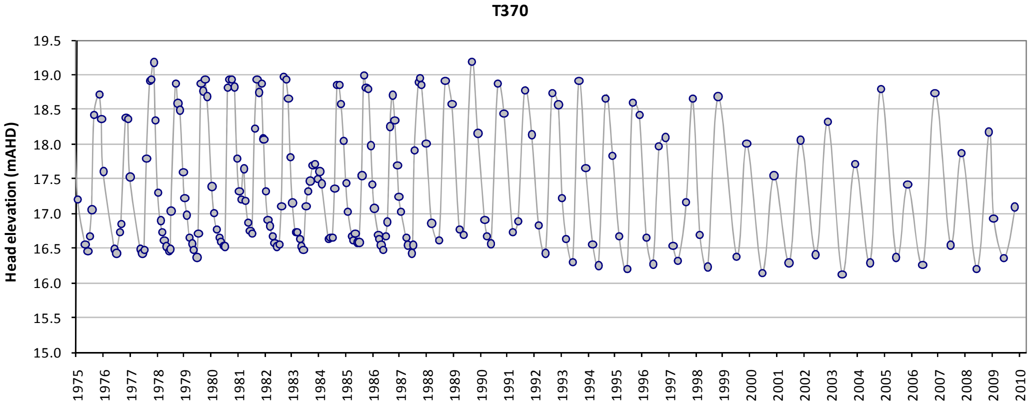
T370
Head elevation (mAHD)
19.5
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18.5
18.0
17.5
17.0
16.5
16.0
15.5
15.0
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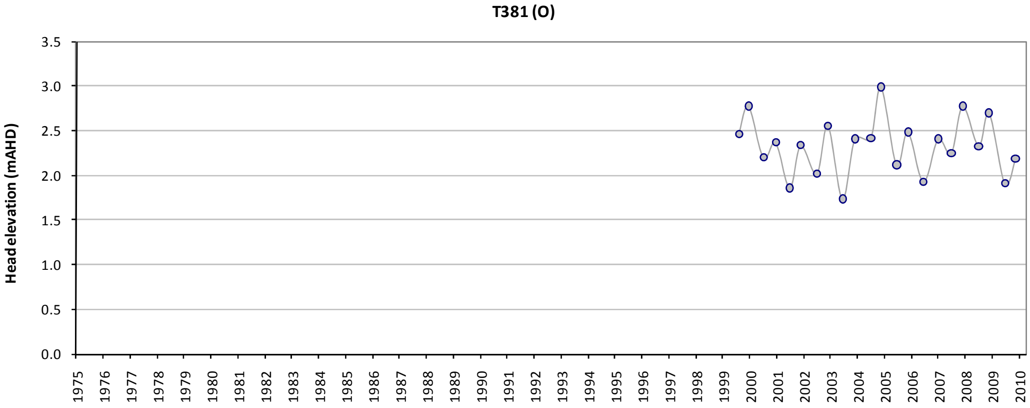
T381 (O)
Head elevation (mAHD)
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2.0
1.5
1.0
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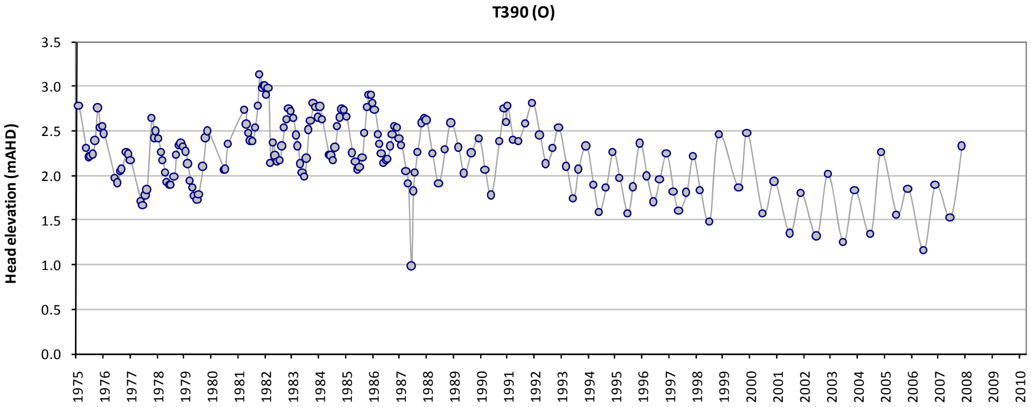
T390 (O)
Head elevation (mAHD)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
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1975
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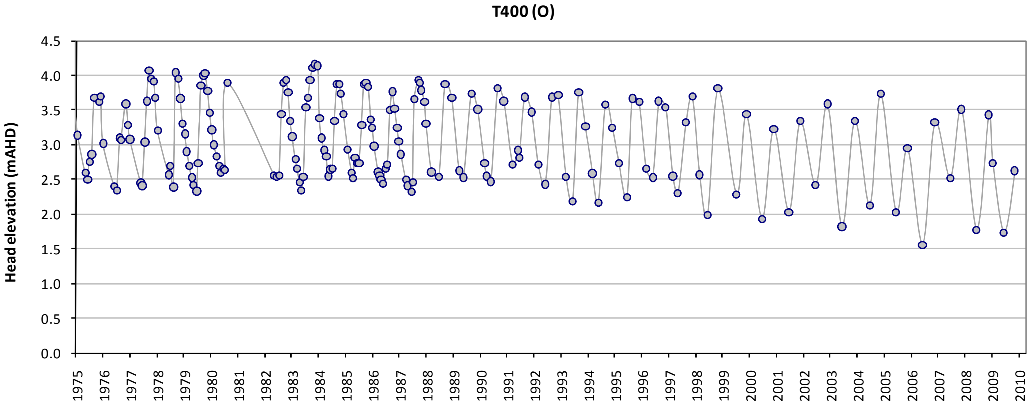
T400 (O)
Head elevation (mAHD)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
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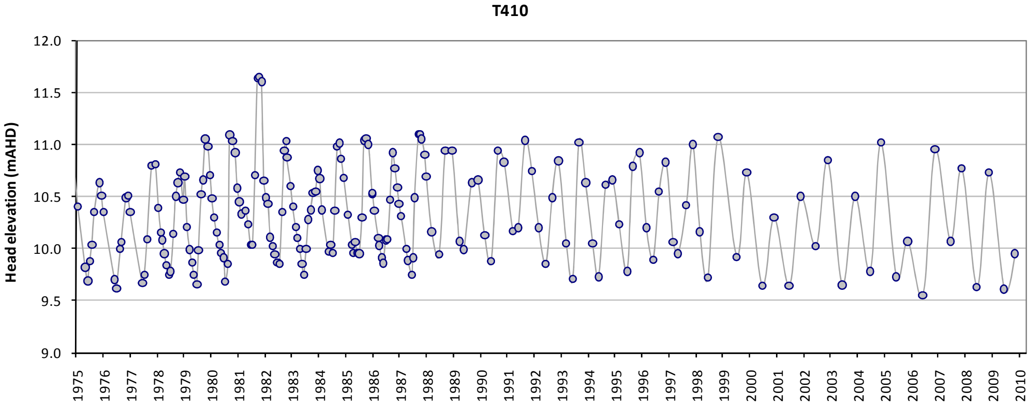
T410
Head elevation (mAHD)
9.0
9.5
10.0
10.5
11.0
11.5
12.0
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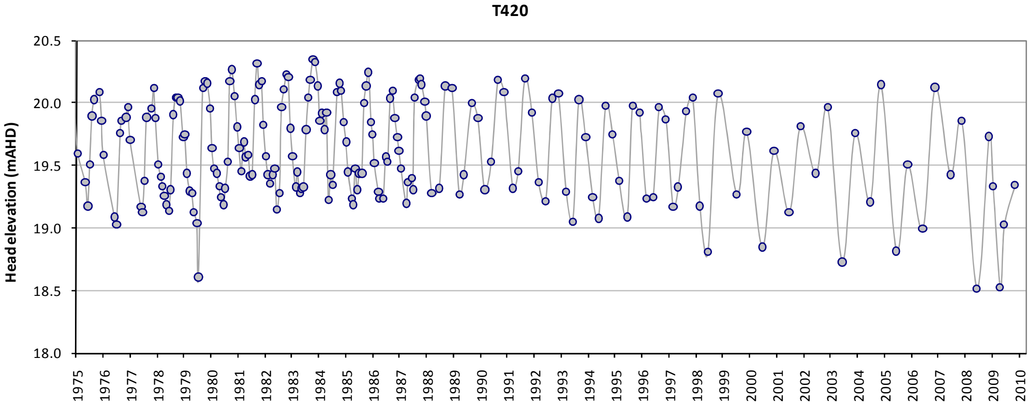
T420
Head elevation (mAHD)
18.0
18.5
19.0
19.5
20.0
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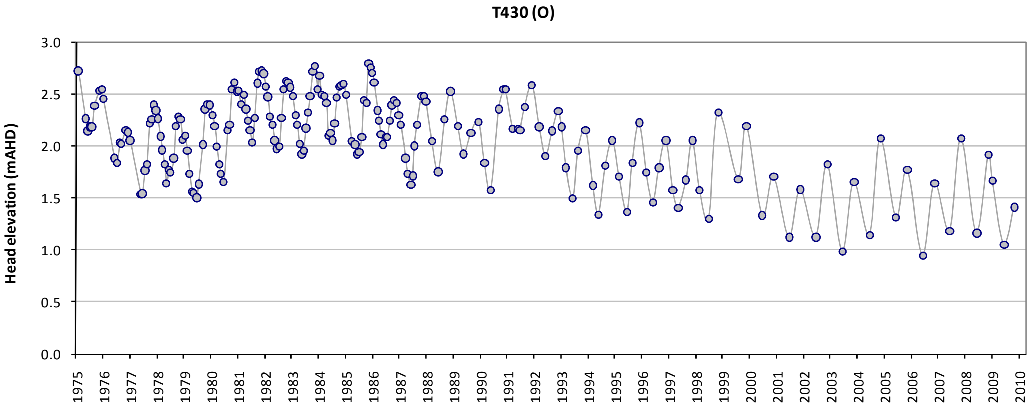
T430 (O)
Head elevation (mAHD)
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2.5
2.0
1.5
1.0
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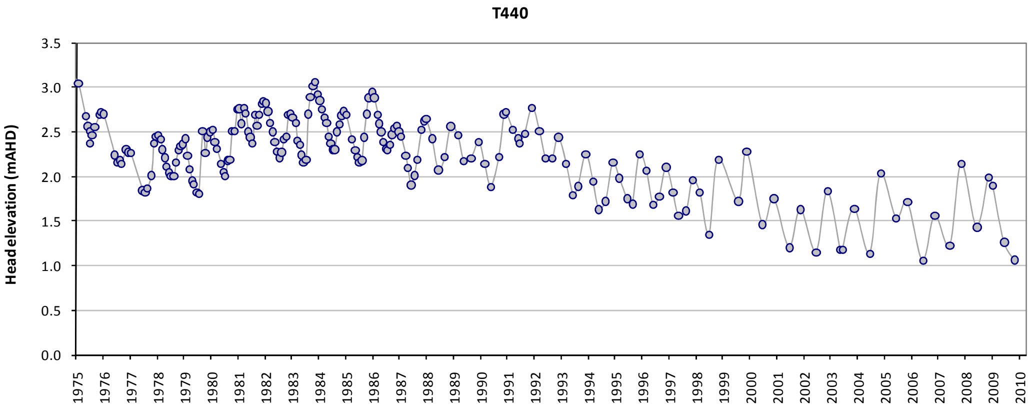
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Head elevation (mAHD)
3.5
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2.5
2.0
1.5
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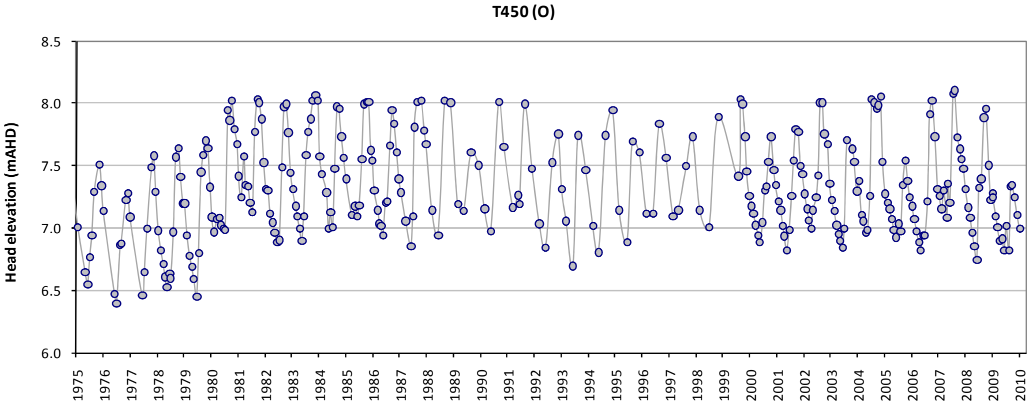
T450 (O)
Head elevation (mAHD)
8.5
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7.5
7.0
6.5
6.0
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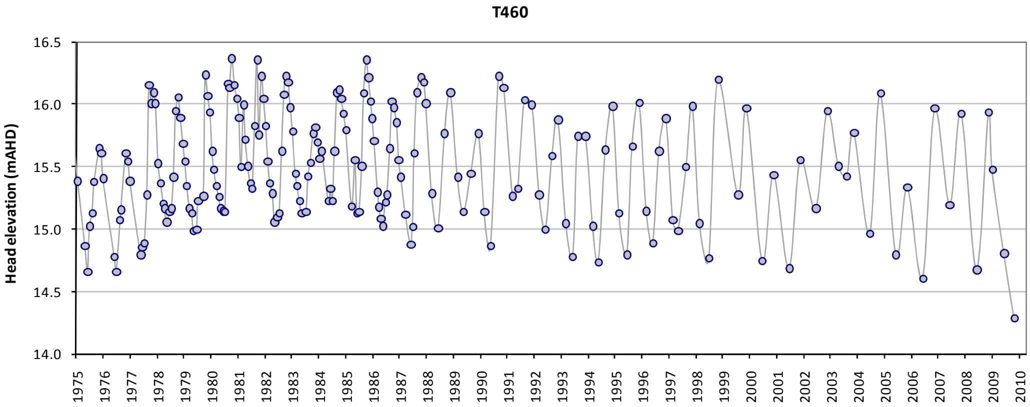
T460
Head elevation (mAHD)
16.5
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15.5
15.0
14.5
14.0
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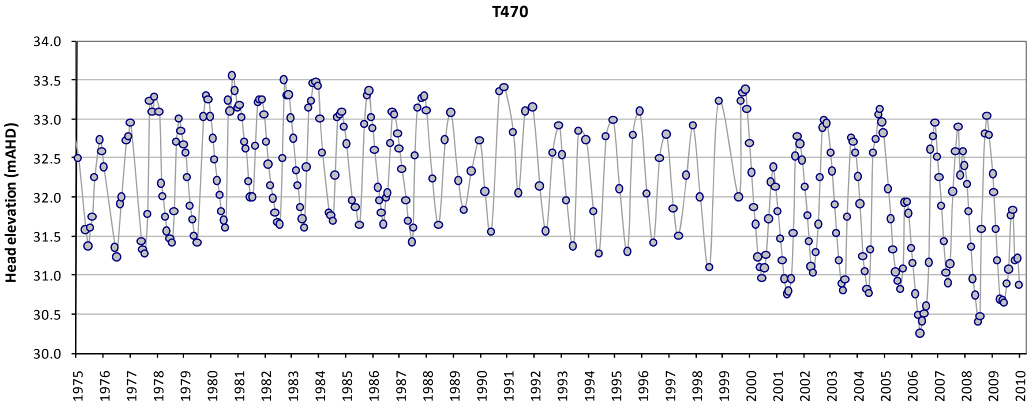
T470
Head elevation (mAHD)
34.0
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32.5
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31.5
31.0
30.5
30.0
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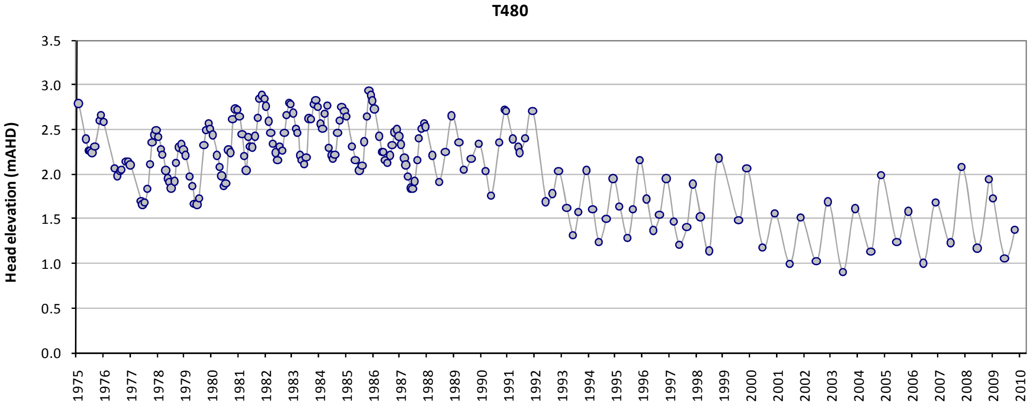
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Head elevation (mAHD)
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1.5
1.0
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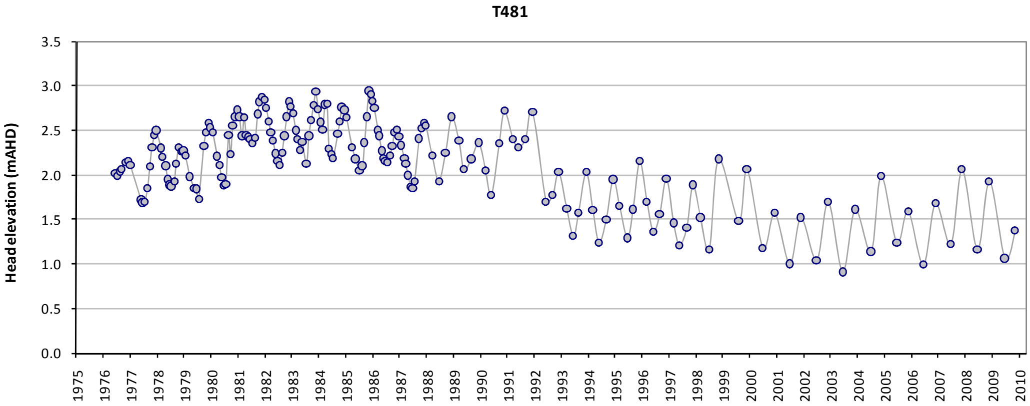
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Head elevation (mAHD)
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2.0
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1.0
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0.0
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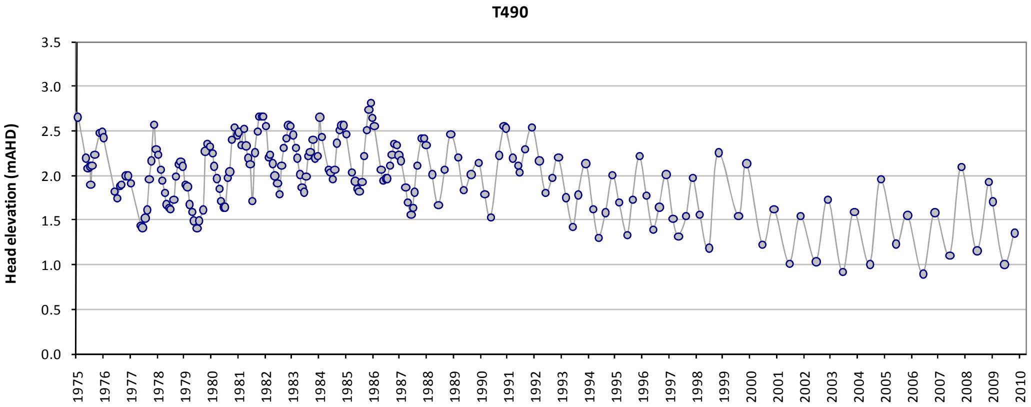
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Head elevation (mAHD)
3.5
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2.5
2.0
1.5
1.0
0.5
0.0
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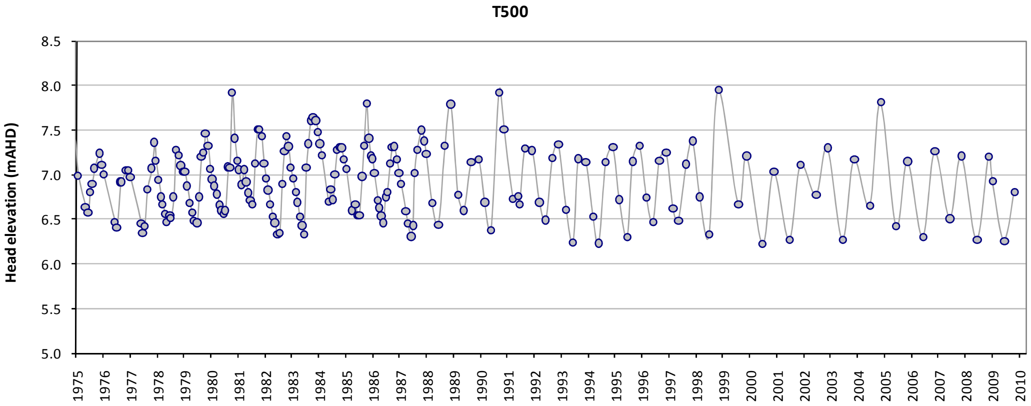
T500
Head elevation (mAHD)
8.5
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7.0
6.5
6.0
5.5
5.0
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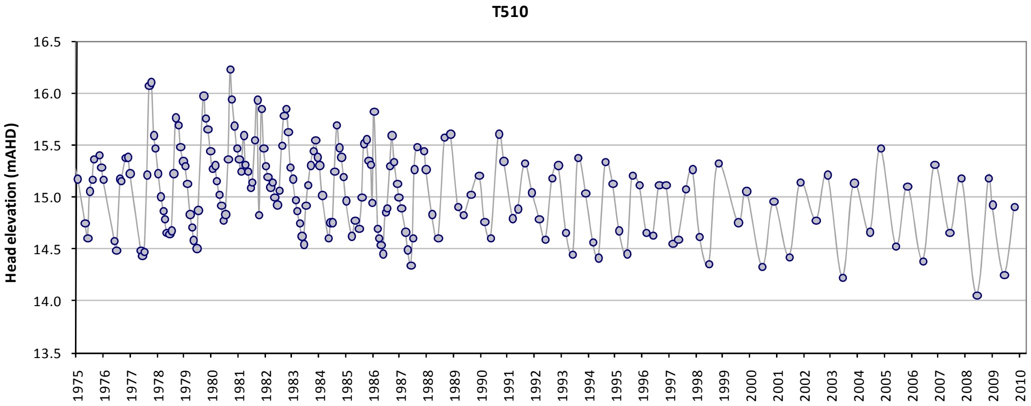
T510
Head elevation (mAHD)
16.5
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15.0
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14.0
13.5
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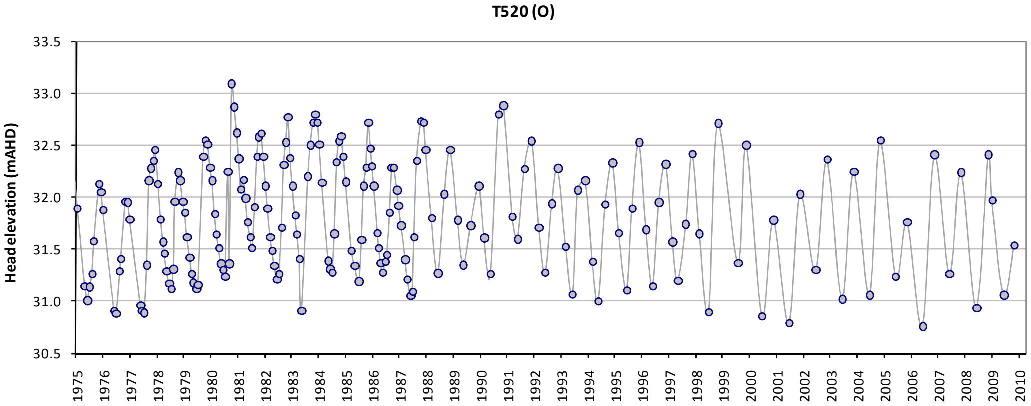
T520 (O)
Head elevation (mAHD)
33.5
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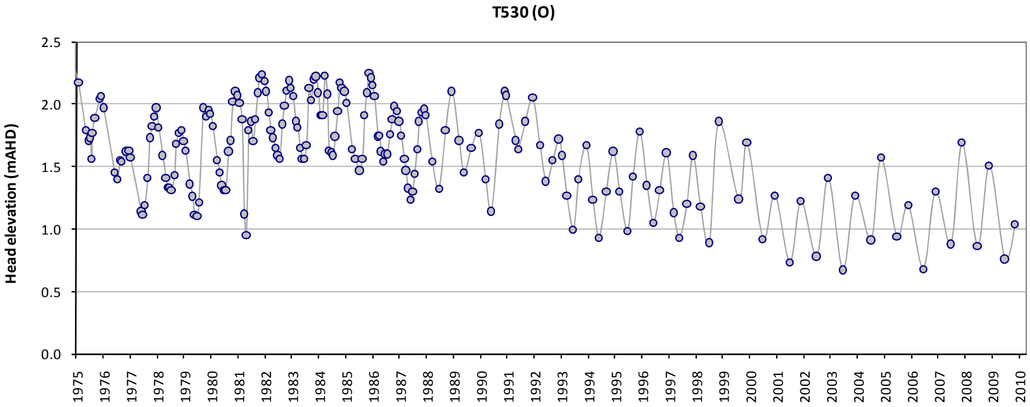
T530 (O)
Head elevation (mAHD)
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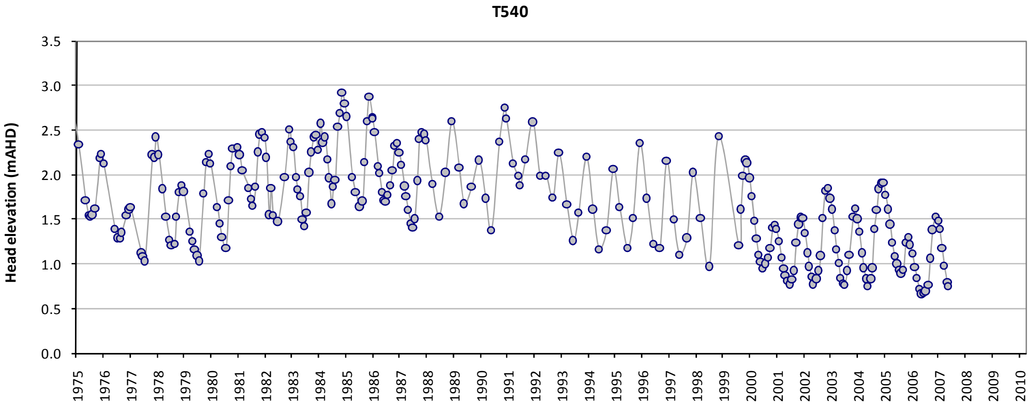
T540
Head elevation (mAHD)
0.0
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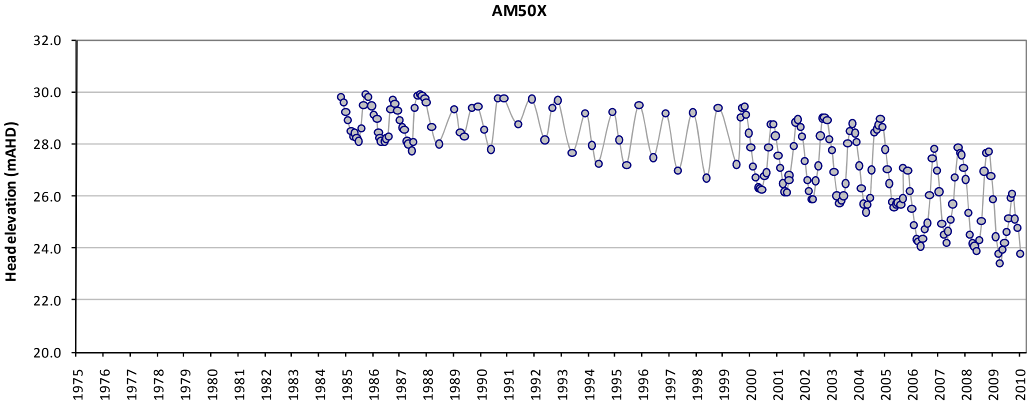

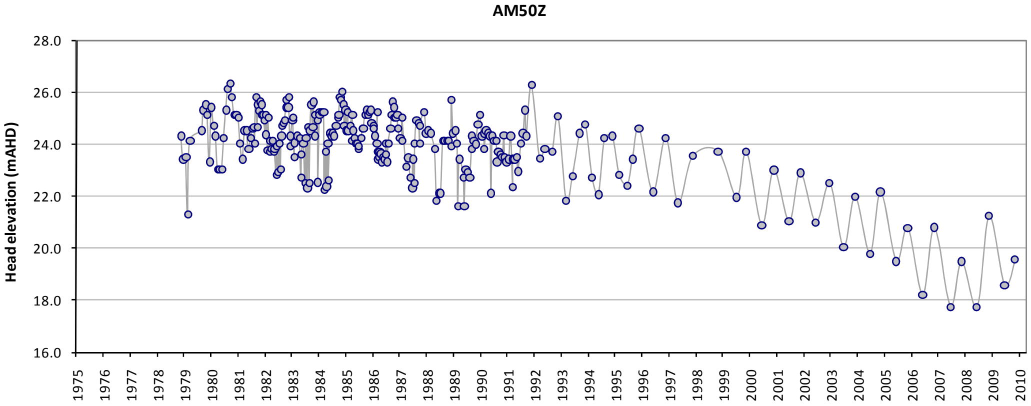

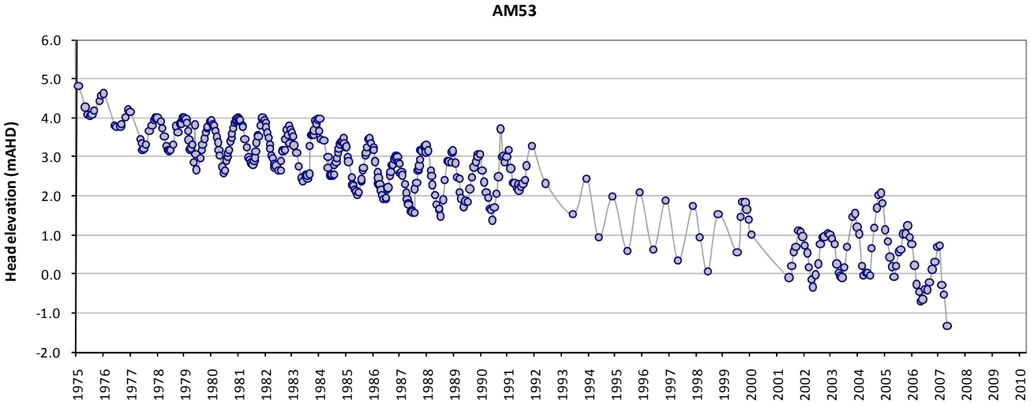

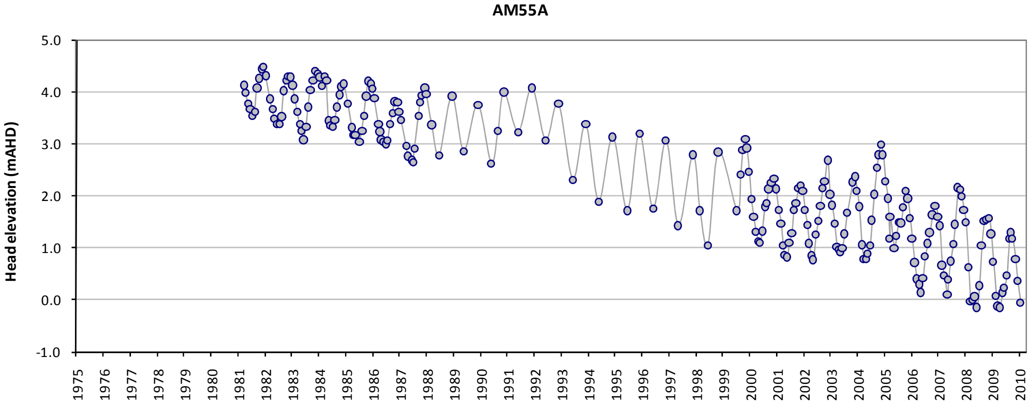
AM55A
Head elevation (mAHD)
5.0
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3.0
2.0
1.0
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-1.0
1975
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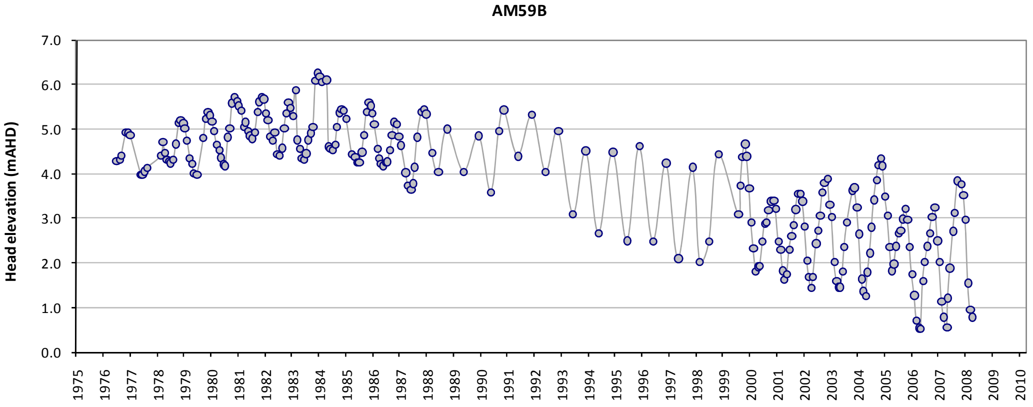
AM59B
Head elevation (mAHD)
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6.0
5.0
4.0
3.0
2.0
1.0
0.0
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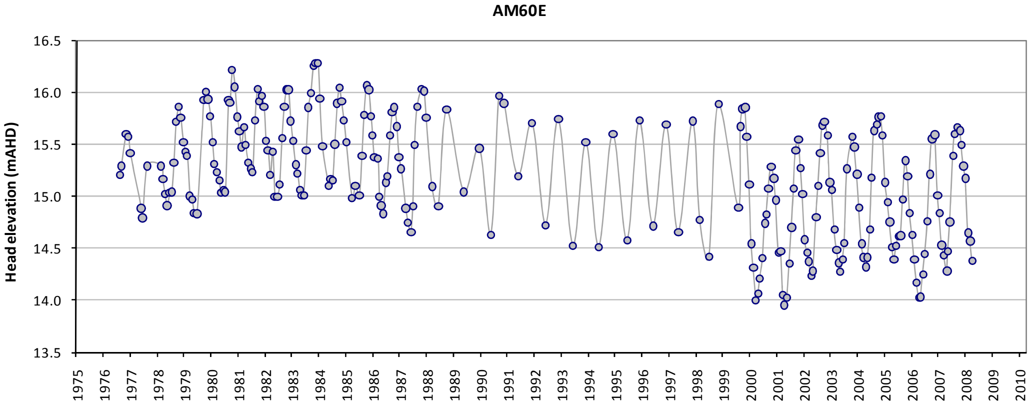
AM60E
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13.5
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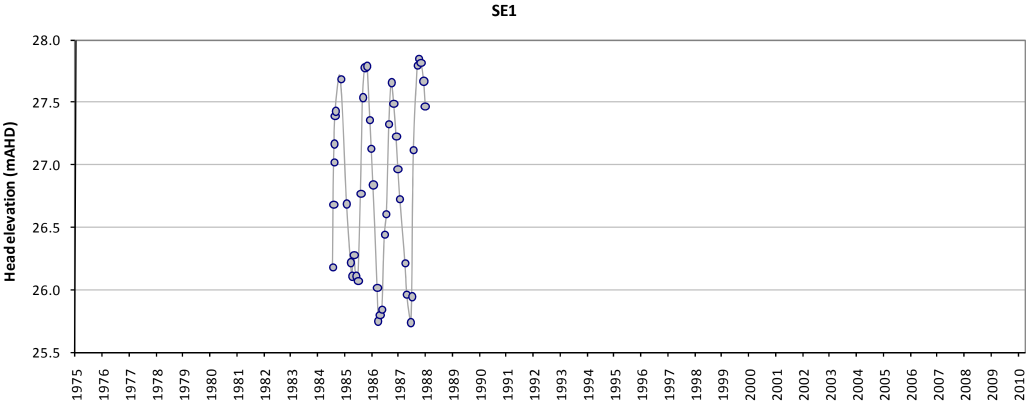
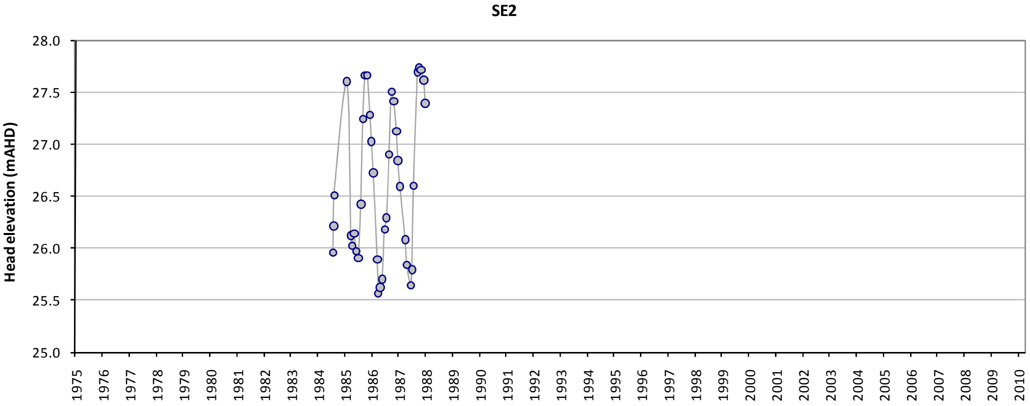
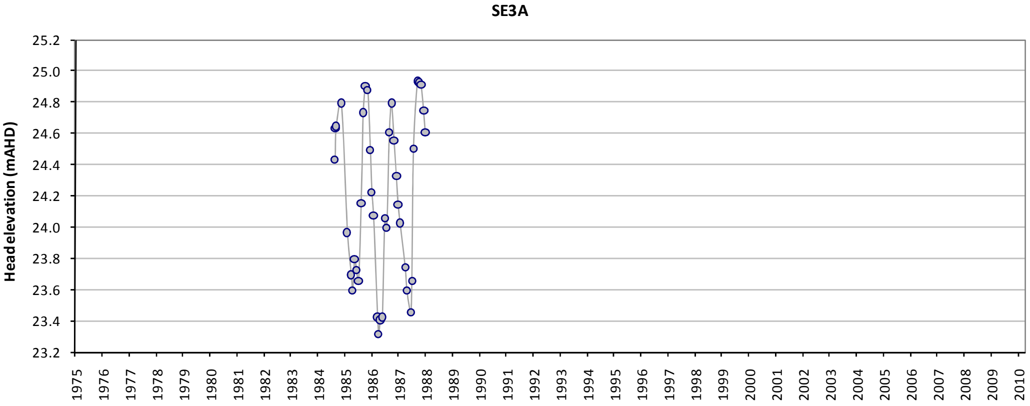
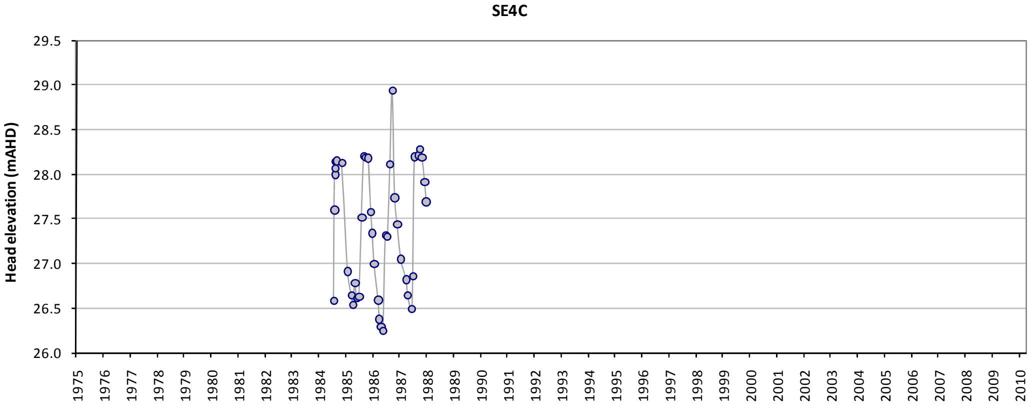
'SE' series bores





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27.5
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26.5
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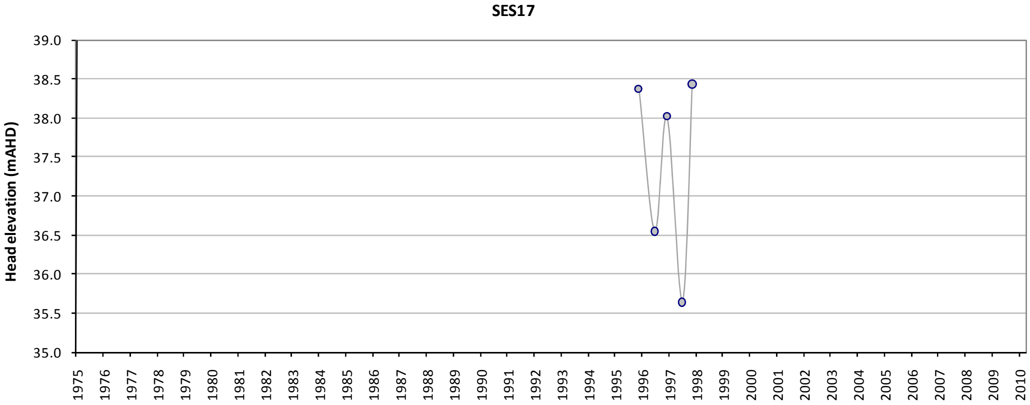
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Head elevation (mAHD)
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38.0
37.5
37.0
36.5
36.0
35.5
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1975
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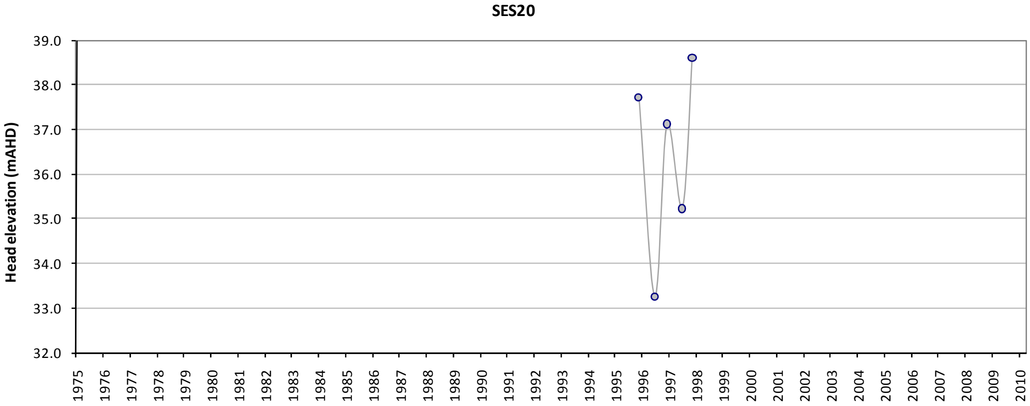
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Head elevation (mAHD)
39.0
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37.0
36.0
35.0
34.0
33.0
32.0
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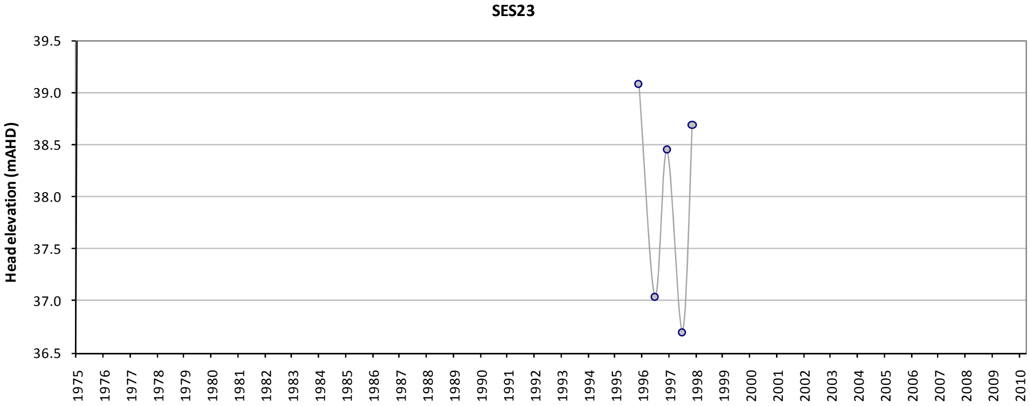
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Head elevation (mAHD)
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37.5
37.0
36.5
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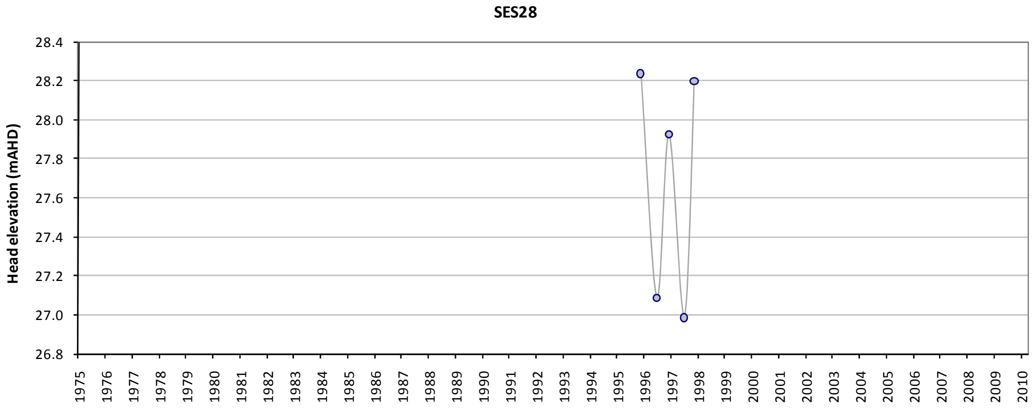
SES28
Head elevation (mAHD)
28.4
28.2
28.0
27.8
27.6
27.4
27.2
27.0
26.8
1975
1976
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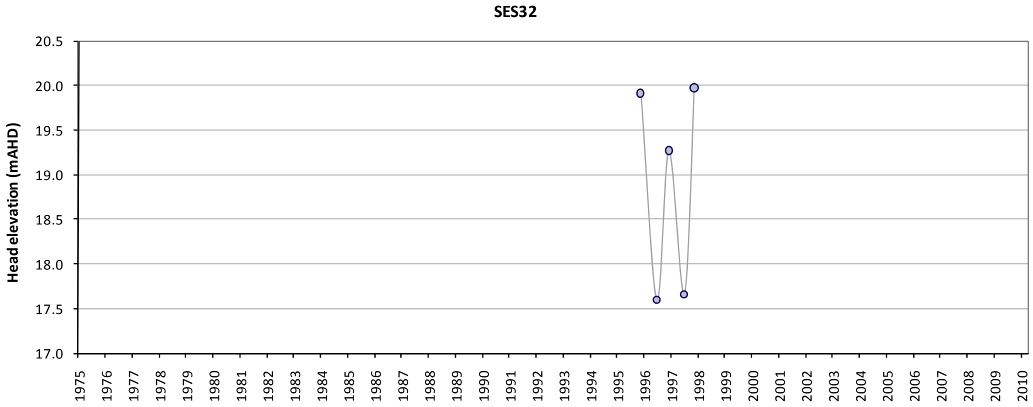
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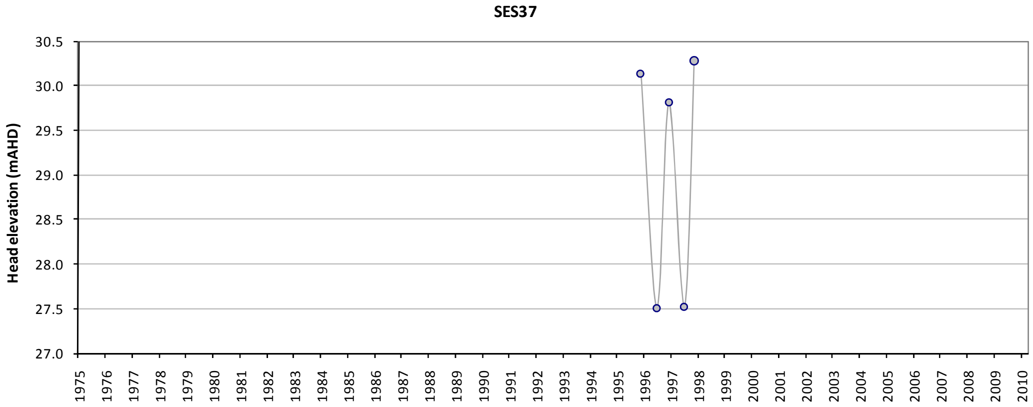
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Head elevation (mAHD)
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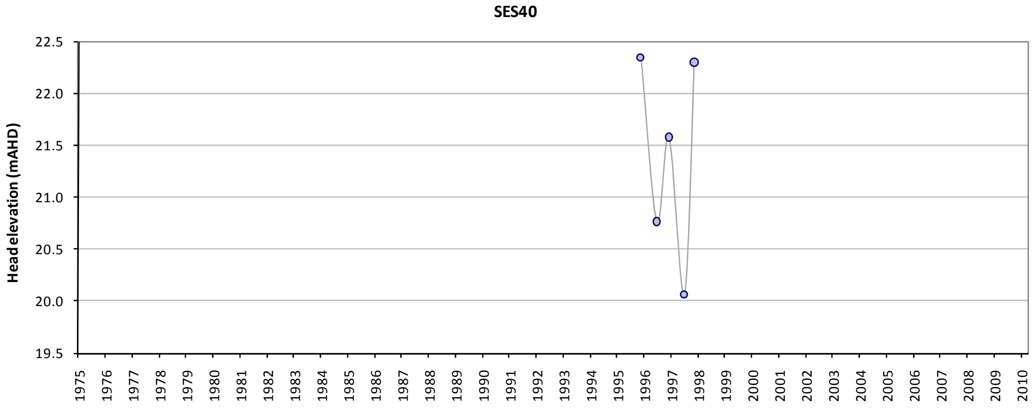
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21.5
21.0
20.5
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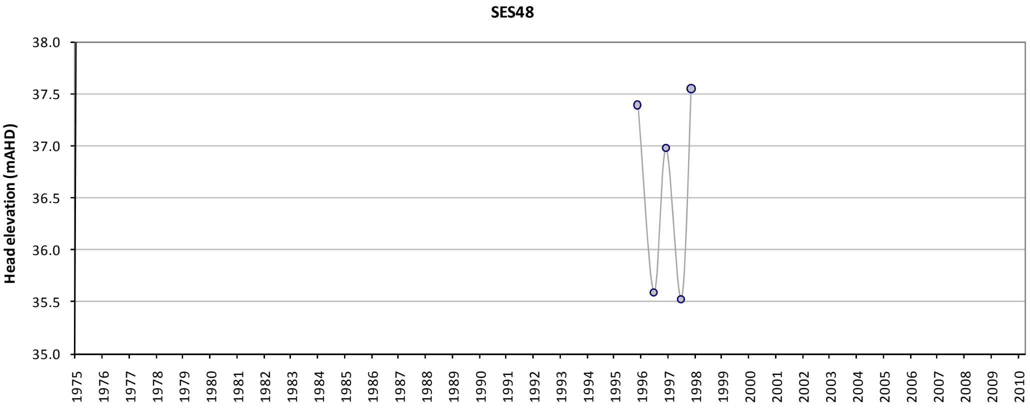
SES48
Head elevation (mAHD)
38.0
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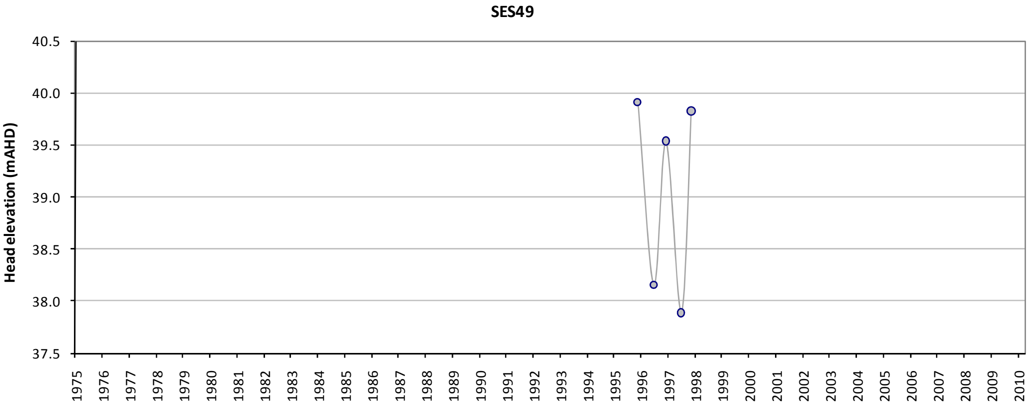
35.5
35.0
1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010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Head elevation (mAHD)
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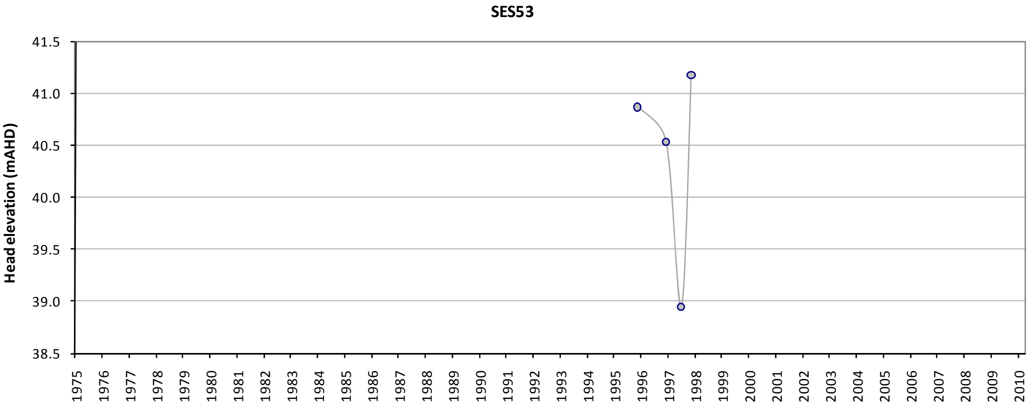
37.5
1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010


SES53
Head elevation (mAHD)
41.5
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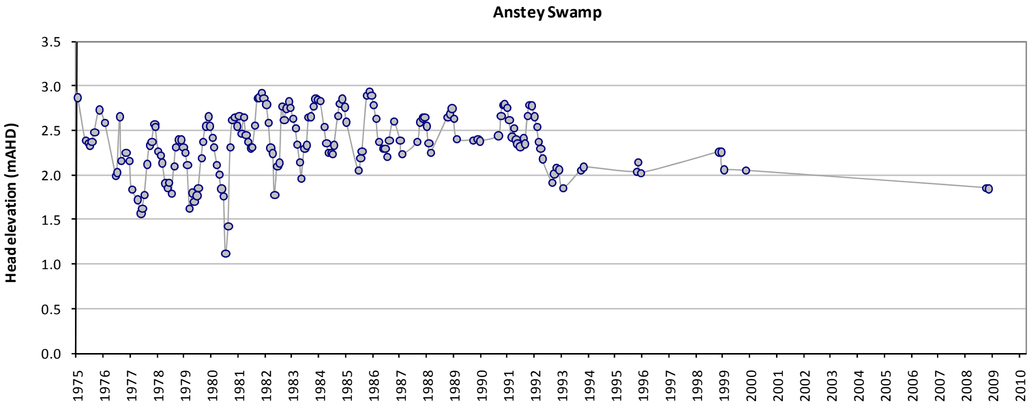
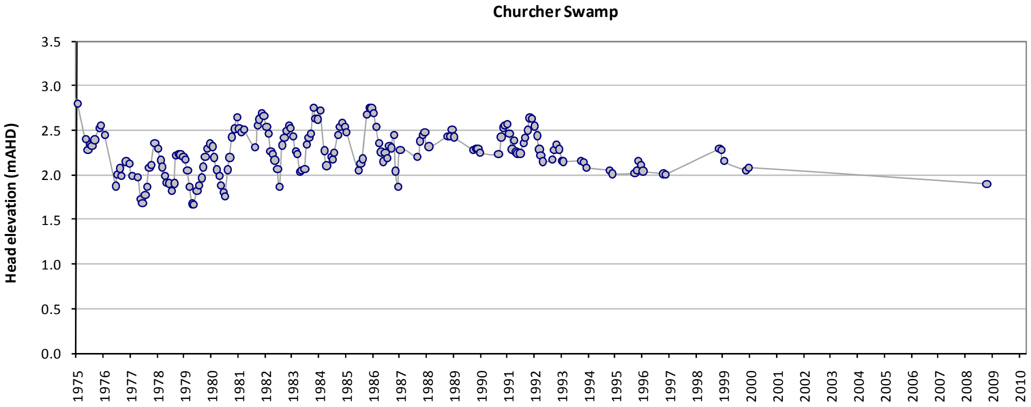
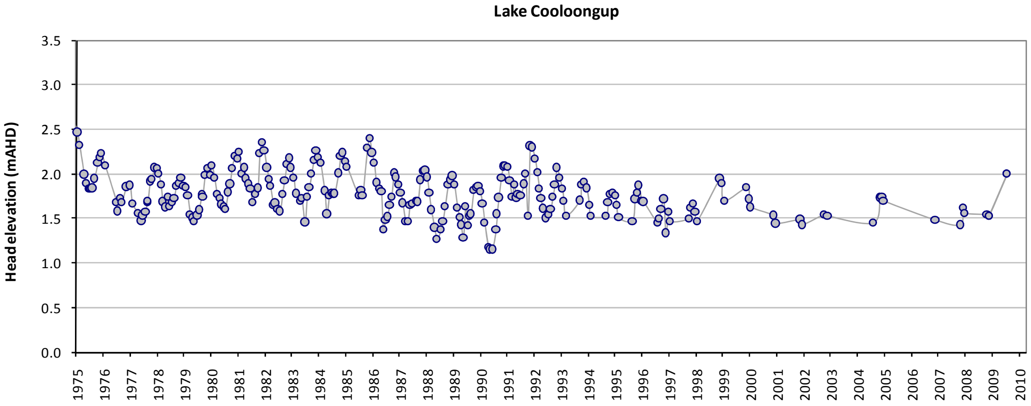
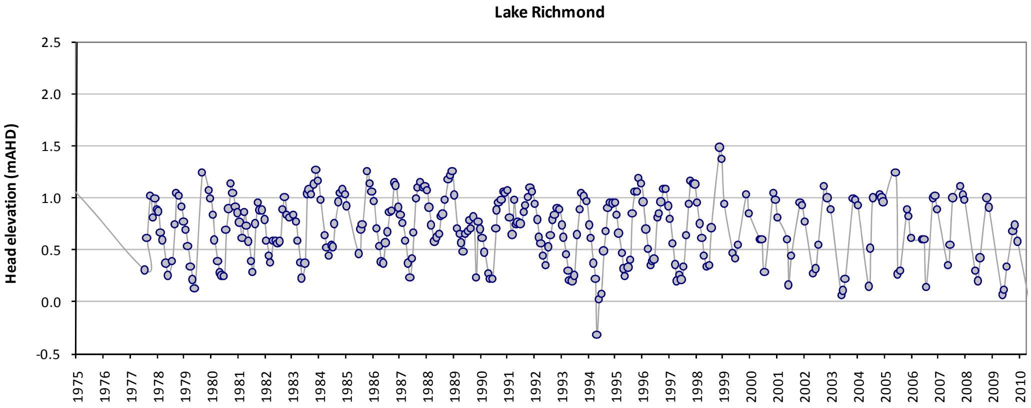
40.5
40.0
39.5
39.0
38.5
1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

Lake and wetland water levels








Lake Richmond
Head elevation (mAHD)
2.5
2.0
1.5
1.0
0.5
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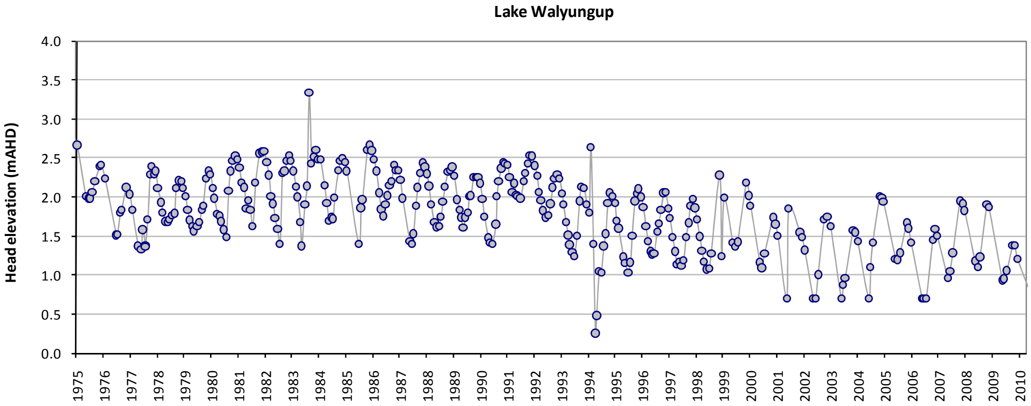
Lake Walyungup
Head elevation (mAHD)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
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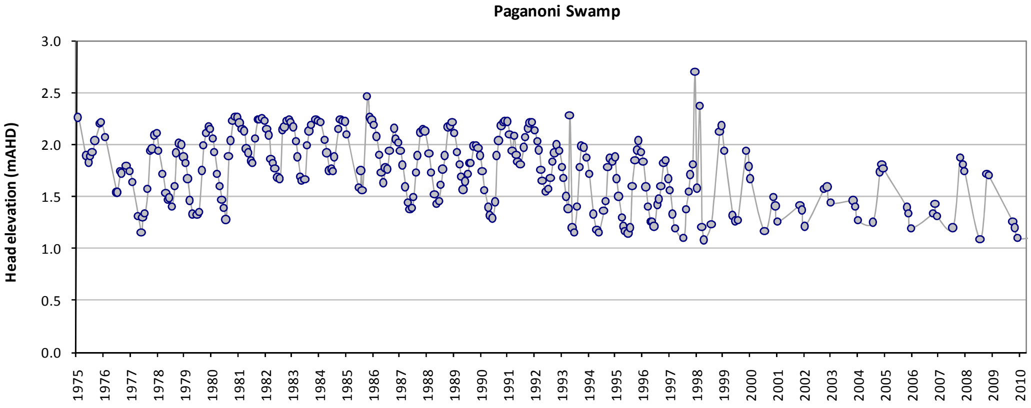
Paganoni Swamp
Head elevation (mAHD)
3.0
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2.0
1.5
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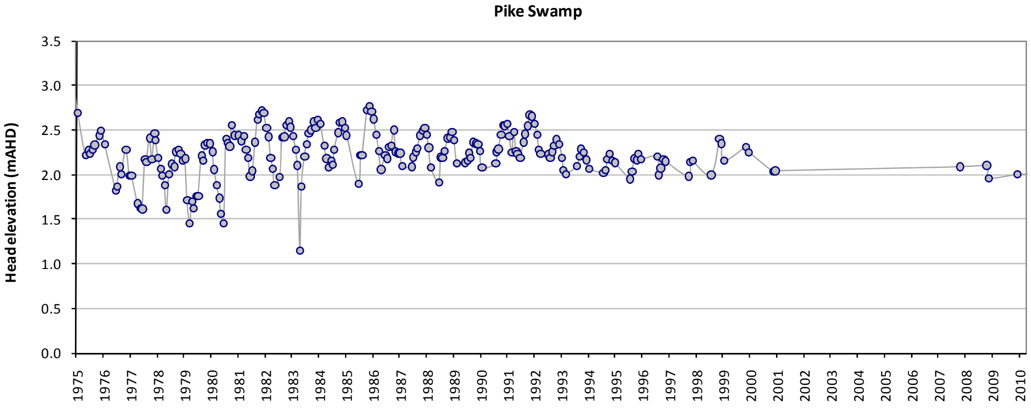
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Head elevation (mAHD)
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2.5
2.0
1.5
1.0
0.5
0.0
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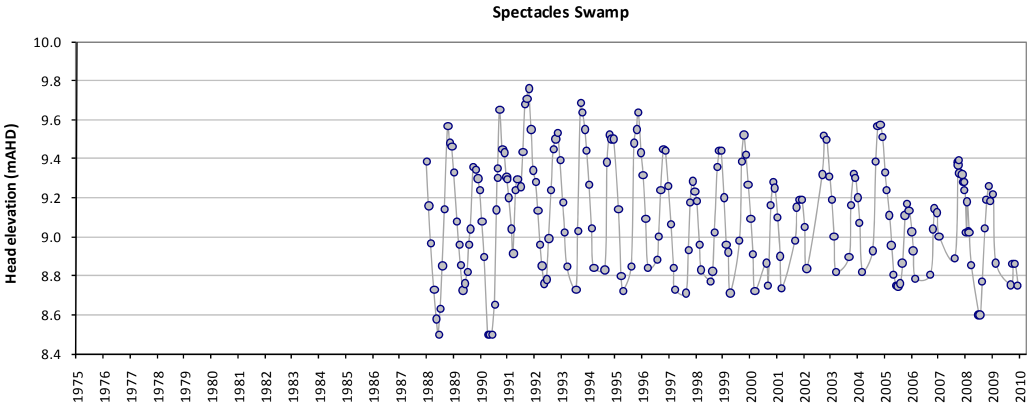
Spectacles Swamp
Head elevation (mAHD)
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9.8
9.6
9.4
9.2
9.0
8.8
8.6
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1975
1976
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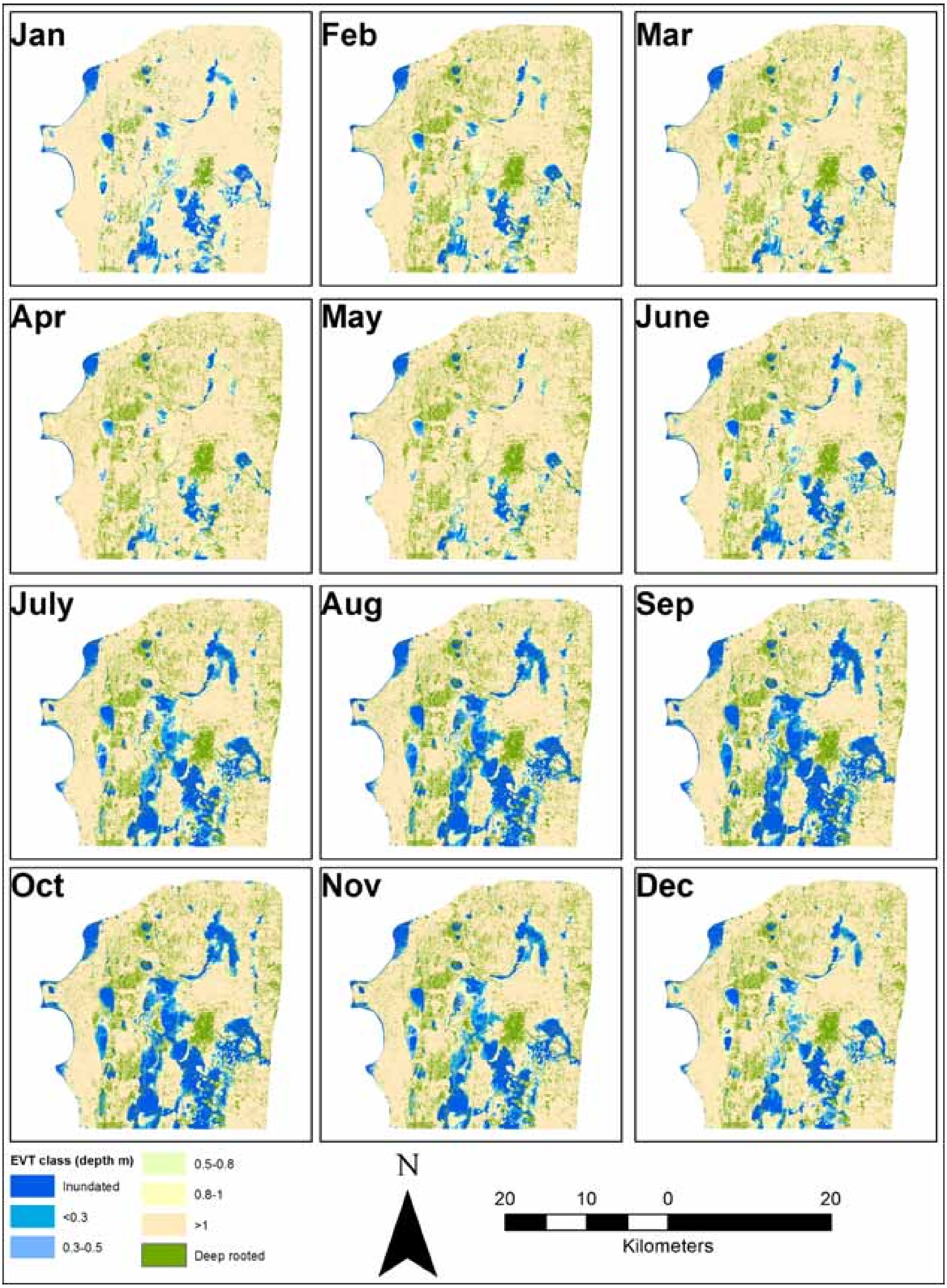
Appendix D — Monthly evapotranspiration calculations



Areas of evapotranspiration classes

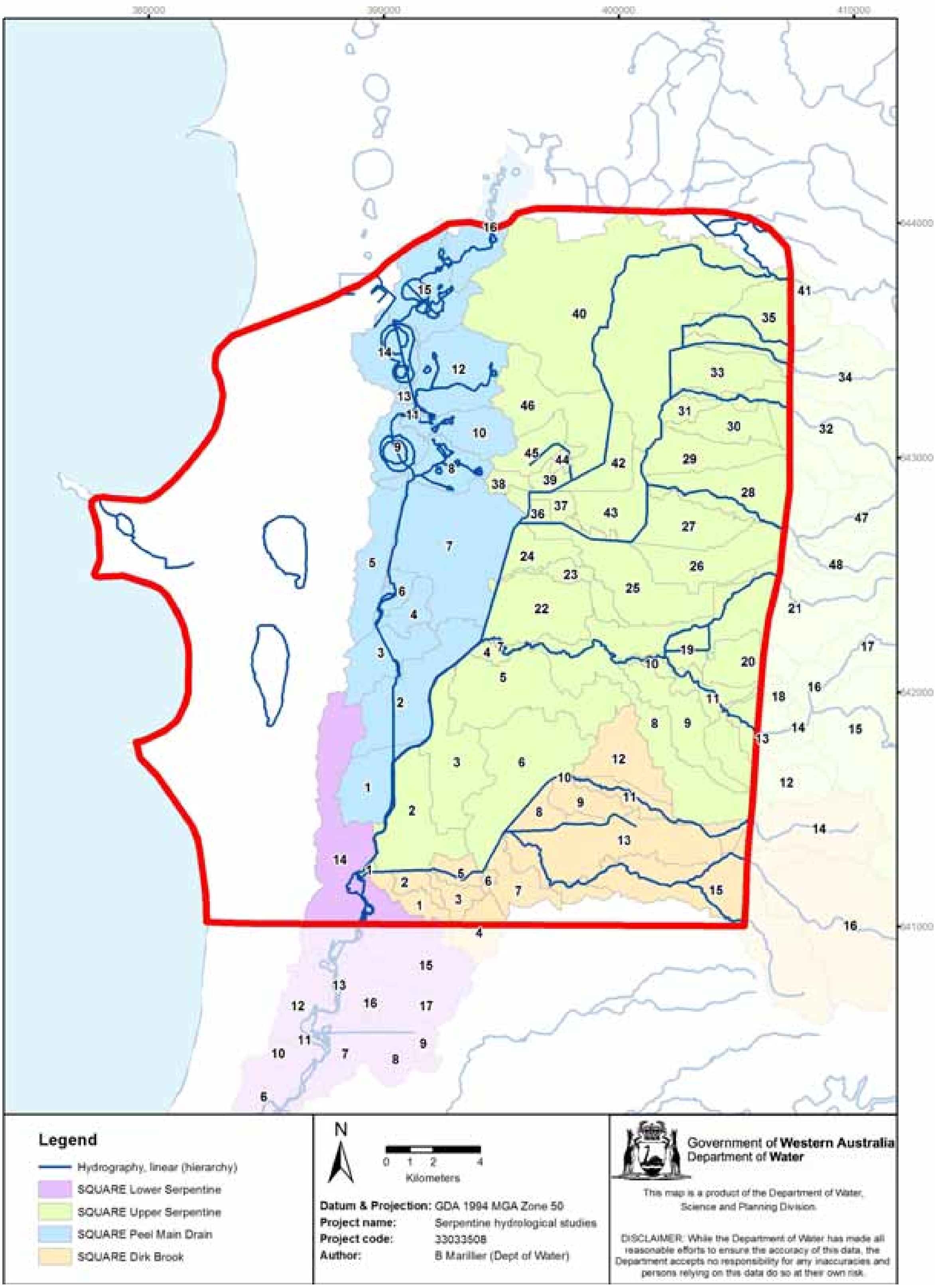
				Area (sqkm)							
Month	**Rainfall (mm)**	**Pan Evaporation (mm)**	**Penman Monteith (mm)**	**Deep Rooted Veg**	**Water logged**	**<0.3m**	**0.3 - 0.5**	**0.5 - 0.8**	**0.8 - 1**	**> 1**	**Total area**
Jan	11.5	273.2	200.9	109.9	38.6	18.8	15.9	30.2	22.3	491.8	727.6
Feb	17.3	230.2	170.0	109.9	27.5	14.6	12.6	24.3	20.4	518.3	727.6
March	17.5	197.0	149.9	109.9	22.3	11.5	11.2	20.8	18.0	533.8	727.6
April	43.8	117.8	97.8	109.9	21.1	10.9	10.6	20.1	17.2	537.7	727.6
May	105.7	78.5	66.5	109.9	20.2	10.5	10.2	19.6	16.6	540.6	727.6
June	158.1	57.6	48.0	109.9	37.5	18.5	15.6	29.8	22.2	494.0	727.6
July	168.0	60.4	50.4	109.9	74.3	30.4	22.3	30.6	18.6	441.4	727.6
August	124.9	73.8	64.9	109.9	92.0	32.8	20.9	28.7	17.9	425.3	727.6
September	84.2	96.7	85.2	109.9	108.9	32.7	19.8	27.3	17.0	411.8	727.5
October	49.6	145.2	123.4	109.9	101.4	33.0	20.2	27.8	17.6	417.6	727.5
November	31.1	193.9	154.0	109.9	74.3	30.4	22.3	30.6	18.6	441.4	727.6
December	9.5	249.9	187.7	109.9	50.2	22.4	19.5	32.8	20.9	471.9	727.6
Total Annual	**821.3**	**1774.1**	**1398.7**								

Monthly evapotranspiration flux calculations

				Evapotranspiration flux (GL) using exp decay function							
Month	**Rainfall**	**Pan Evap**	**Penman Monteith**	**Deep Rooted Veg**	**Water logged**	**<0.3m**	**0.3 - 0.5**	**0.5 - 0.8**	**0.8 - 1**	**> 1**	**TOTAL EVT**
Jan	11.5	273.2	200.9	2.2	7.4	3.8	0.6	0.1	0.0	0	14.0
Feb	17.3	230.2	170.0	1.9	4.4	2.5	0.4	0.0	0.0	0	9.2
March	17.5	197.0	149.9	1.6	3.1	1.7	0.3	0.0	0.0	0	6.8
April	43.8	117.8	97.8	1.1	1.7	1.1	0.2	0.0	0.0	0	4.1
May	105.7	78.5	66.5	0.7	1.1	0.7	0.1	0.0	0.0	0	2.7
June	158.1	57.6	48.0	5.3	1.5	0.9	0.1	0.0	0.0	0	7.8
July	168.0	60.4	50.4	5.5	3.1	1.5	0.2	0.0	0.0	0	10.4
August	124.9	73.8	64.9	7.1	4.8	2.1	0.2	0.0	0.0	0	14.3
September	84.2	96.7	85.2	9.4	7.4	2.8	0.3	0.0	0.0	0	19.8
October	49.6	145.2	123.4	13.6	10.3	4.1	0.4	0.0	0.0	0	28.4
November	31.1	193.9	154.0	16.9	10.1	4.7	0.6	0.1	0.0	0	32.3
December	9.5	249.9	187.7	2.1	8.8	4.2	0.6	0.1	0.0	0	15.7
Total Annual	**821.3**	**1774.1**	**1398.7**	**67.4**	**63.7**	**30.0**	**4.0**	**0.42**	**0.0**	**0.0**	**165.6**

Extinction depth: 1.00
Pan correction: 0.70
Vegetation factor: 1
Vegetation factor (summer): 0.1
Transition Depth (cm) 24
Decay coefficient 0.11

Appendix E — SQUARE subcatchments



Datum & Projection: GDA 1994 MGA Zone 50
Project name: Serpentine hydrological studies
Project code: 33033508
Author: B Marillier (Dept of Water)

This map is a product of the Department of Water, Science and Planning Division.

DISCLAIMER: While the Department of Water has made all reasonable efforts to ensure the accuracy of this data, the Department accepts no responsibility for any inaccuracies and persons relying on this data do so at their own risk.

Appendix F — Wetlands of interest

Introduction

Wetlands are areas where water covers the soil surface for all or part of the year. On the Swan Coastal Plain, wetlands are permanent or seasonal outbreaks of groundwater at the surface, which commonly occur in depressions between the Bassendean and Spearwood dunes. Water levels in these wetlands are maintained by regional groundwater flow systems (Rockwater 2003). However, some surface water discharge may occur via drainage to the wetlands and, in many cases, wetland water levels are artificially lowered by drains.

Inside the Serpentine study area, nine wetlands have been selected for further investigation. Environmental water requirements (EWRs) will not be determined as a component of this study; however, the model will be developed with consideration for providing data to support further investigations of wetland hydrology at a later stage. Several bores and at least one gauge board were installed at each wetland in autumn 2011, such that the data collected can be used for calibration of local-scale groundwater models should they be required for future projects in the area.

Of the wetlands selected, four are linear wetlands located on drainage lines, and five are circular wetlands located in depressions.

Wetland hydrology and hydrogeology

Most of the wetlands do not intercept the groundwater table during summer and can be considered ephemeral. However, two linear wetlands (Serpentine linear wetland and Maramanup Pool) are supplemented by surface water, and are thus likely to persist later in the season, and may receive inflows during summer rainfall events. Maramanup Pool intercepts groundwater year-round as is indicated by harmonious summer water levels in the pool compared with nearby groundwater levels.

Towney et al. (1993) adopted the classification of wetlands into three broad categories based on interaction with groundwater:

- **recharge** in which lakewater recharges the groundwater over the entire area of the lake/wetlands
- **discharge**, where the aquifer discharges water over the lakebed area
- **throughflow**, where water moves in and out of the lake in different areas.

In the case of the wetlands considered here, seven can be considered throughflow wetlands. Maramanup Pool and Serpentine linear wetland are also throughflow; however, they receive significant volumes of surface water flow in winter and are therefore surface water-dominated.

Within each circular wetland the water surface is horizontal; thus the piezometric head at the lakebed is equal to the elevation of the lake surface. This creates a region beneath each wetland where there is effectively no horizontal gradient, and where the groundwater flow tends to stagnate. At the same time, a waterbody itself provides less resistance to flow than an aquifer, so groundwater tends to rise towards a wetland on the up-gradient side, travel through the wetland and then discharge to the aquifer at the down-gradient side. The waterbody acts as a conduit or a short circuit in the wetland-aquifer system. It causes flow to deviate from being essentially horizontal; that is, it induces significant upward and downward components of flow. It is this fact that makes wetlands particularly important in the context of a regional flow system. Wetlands interrupt the essentially horizontal movement of groundwater by diverting flow through the waterbodies themselves (Hill et al. 1996a).

Inflows to a wetland include direct rainfall onto the wetland surface, surface inflow from a nearby surface catchment or surface capture zone, and groundwater inflow from a groundwater capture zone. Outflows include evaporation from the surface, surface outflows to rivers, streams or drains and groundwater outflow to a groundwater release zone. Bottom sediments affect both the physical interaction between the wetland and the underlying groundwater flow system and the chemistry of the lake waters. The physical effect of bottom sediments is to add resistance along a flow path between the regional groundwater flow system and the body of the lake, thus tending to reduce the degree of inter-connection. Due to evaporation and other processes in a body of surface water, chemical characteristics of surface water and groundwater are usually quite different. This can lead to observable differences in sediment characteristics depending on the direction of flow through the sediments.

All of the wetlands considered here are located in predominantly sandy sediments associated with the Bassendean Sand, except for Maramanup Pool which is in an area of clay sediments along Peel Main Drain. In some areas, the sands overlay a friable coffee-rock layer, or clay sediments associated with the Guildford Clay further to the east. Four of the wetlands are located on the Pinjarra Plain, which consists of duplex soils that may inhibit upward or downward flux between the aquifer and the wetland. The drilling program conducted in 2010 identified the presence of clay layers and coffee rock in some locations, as discussed for each wetland in the following section.

Wetland monitoring

A small-scale drilling operation was conducted in May 2011 to provide local-scale information and water level data for the winters of 2011 and 2012. This involved the installation and development of 23 new bores which have been registered in the Department of Water's WIN database under the context name *Serpentine Surface Bores* with the prefix SSB. Each bore was drilled to a depth shallower than 5 m bgl or 0.5 m below the watertable using a truck-mounted auger. See Appendix G for construction details and a lithological description of each bore.

Where possible, bores were located in a triangular pattern around the wetlands to capture the up- and down-gradient groundwater levels. If not already present, a gauge board was installed at each wetland to capture surface water levels. Water level data will be collected at these locations monthly. As more data become available, our conceptual understanding of the wetlands may change.

Key wetlands

Orton Road (UFI 12987)

The Orton Road wetland is located on the southern edge of the Jandakot Mound, just south of Thomas Road, and is located in a shallow depression within dunes of Bassendean Sand. Superficial groundwater heads drop from around 20 to 18 mAHD from the north-west to the south-east. The groundwater is several metres below the surface in this area and is unlikely to intercept the surface even in winter under the current climate regime. Historically, when groundwater levels were higher in the 1970s and 80s, this wetland may have been seasonally inundated – acting as a throughflow wetland for groundwater flowing north to south off the Jandakot Mound. Of the aerial photography available (as early as 1953), no images show water at the surface in this wetland. At present, it is likely the wetland does not hold water for significant periods of time in winter, and any ponded water quickly recharges to the superficial groundwater.

Drilling in the area indicated the presence of sandy beds overlaying a hard iron cemented layer at around 3.6 to 3.7 m depth at SSB21, and at 1.6 to 2.2 m depth at SSB2. The presence of the cemented layer may result in lower vertical conductivity around the wetland, and a slightly higher water level in the immediate area after rainfall.

Figure F-1 Orton Road wetland and associated bores and gauge boards

Banksia Road (UFI 6805)

The Banksia Road wetland is located on the southern edge of the Jandakot Mound and is bisected by the railway line. The wetland sits in a depression between two sand dunes, as shown below. The wetland is seasonally inundated with groundwater flowing laterally into the wetland from the north and discharging to the south.

At bore SSB17, the groundwater level was recorded at 1.9 m bgl in May 2011 – after one of the driest years on record. Given the amplitude of the groundwater fluctuation is around 1.5 m in this area, it is likely the wetland intersects the groundwater in most winters. None of the three bores drilled intercepted clay or coffee-rock layers, with the top 5 m of sediment consisting of fine- to medium-grained sands with some organic matter close to the surface.

A Water Corporation drain takes discharge from the wetland south-east towards Birriga Main Drain.

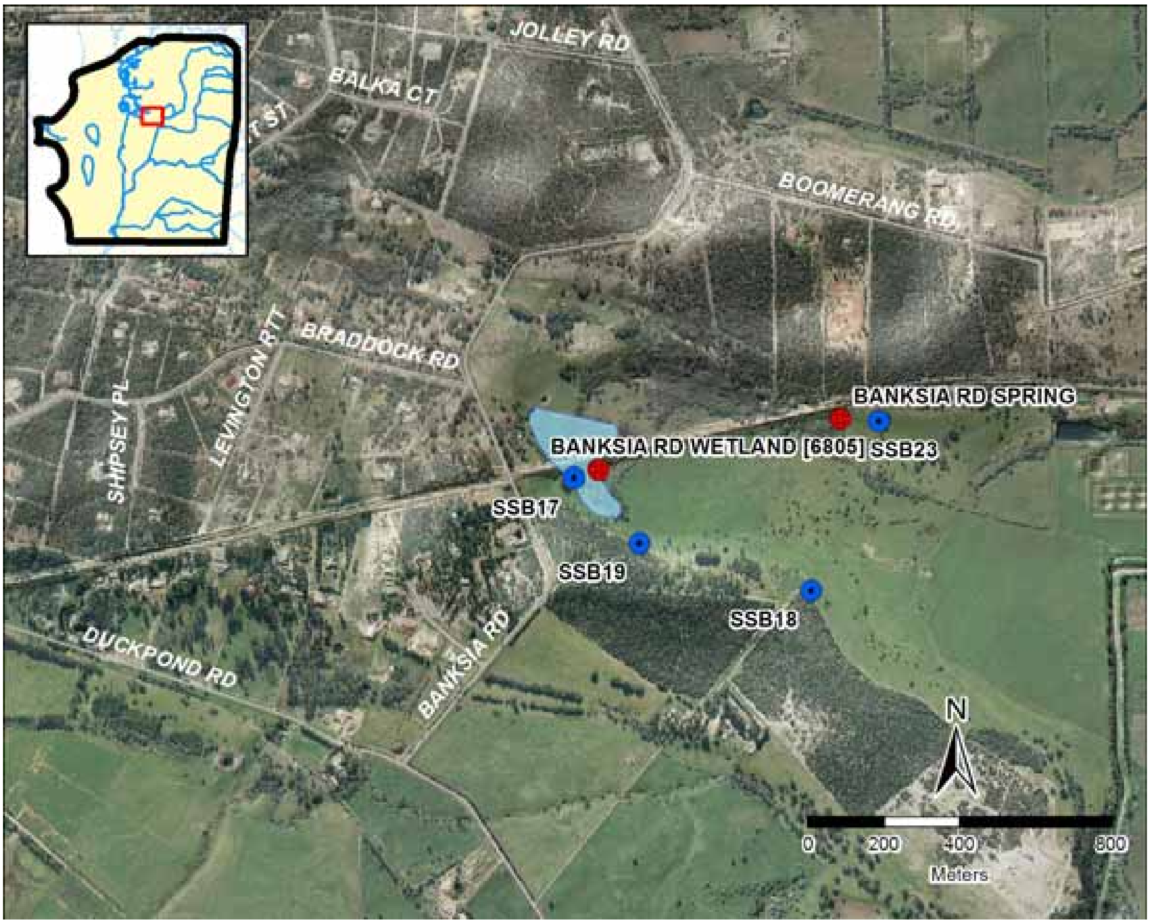


Figure F-2 Banksia Road wetland and associated bores and gauge boards

Lightbody West (UFI 6959)

The Lightbody West wetland is in the bed of an orphaned river channel, just south of Mundijong Road. Groundwater gradients are quite flat in this area, with a gentle south-east to north-west slope apparent in both the land surface and the phreatic surface. The channel is around 1.5 m below the surrounding plain, and is therefore likely to intercept groundwater which is close to or at the surface in winter. In flood years, the channel may activate as a conveyance mechanism, discharging water to the Birriga Main Drain further to the west.

All three bores in this area intercepted clay beds close to the surface at around 1.5 m, below sandy topsoil. This is consistent with the Pinjarra Plain's duplex soils, and is likely to lower infiltration in rainfall events, possibly producing temporary perching of water at the surface.

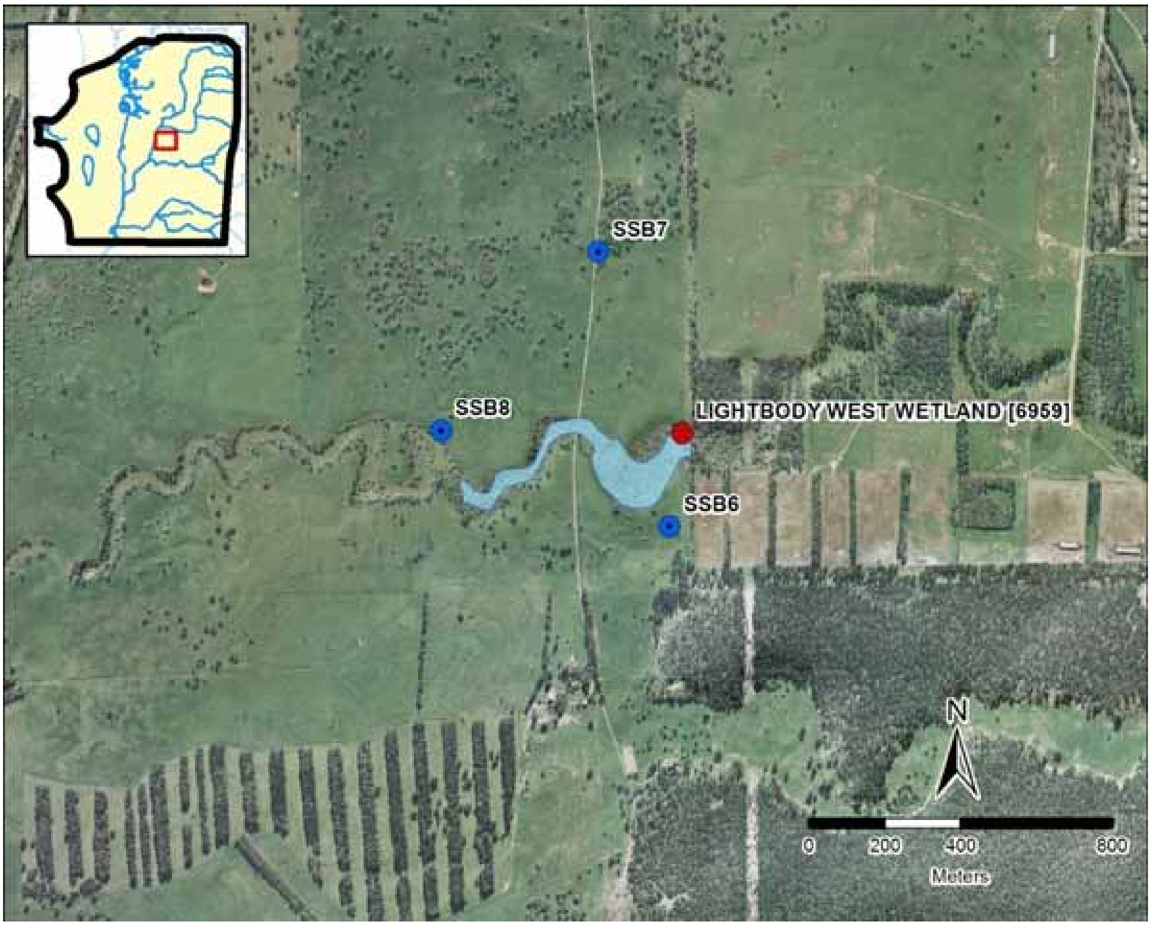


Figure F-3 Lightbody West wetland and associated bores and gauge boards

Lowlands bush and linear wetlands (UFIs 6963 and 6960)

The Lowlands bush and linear wetlands are located to the east of the pristine Lowlands bushland, located close to the Serpentine River. Lowlands bush wetland is a shallow depression on the edge of a sand dune, which drops from 15 to 10.5 m. As such, the wetland's water levels probably depend on recharge to the neighbouring dunes, which then flow into the wetlands following the low-gradient east-west groundwater flow. The linear wetland is located slightly further to the west in a small channel incised in the Pinjarra Plain. The wetland is in a low point of the channel, which probably only connects with the Serpentine River to the south in flood years.

Drilling at bore SSB9 indicated the presence of sandy clays in the top 3 m. Groundwater was intercepted at around 3 m depth, which would be very close to the surface in the lower-lying linear wetland. Both wetlands are likely to be inundated each winter and act as throughflow wetlands.

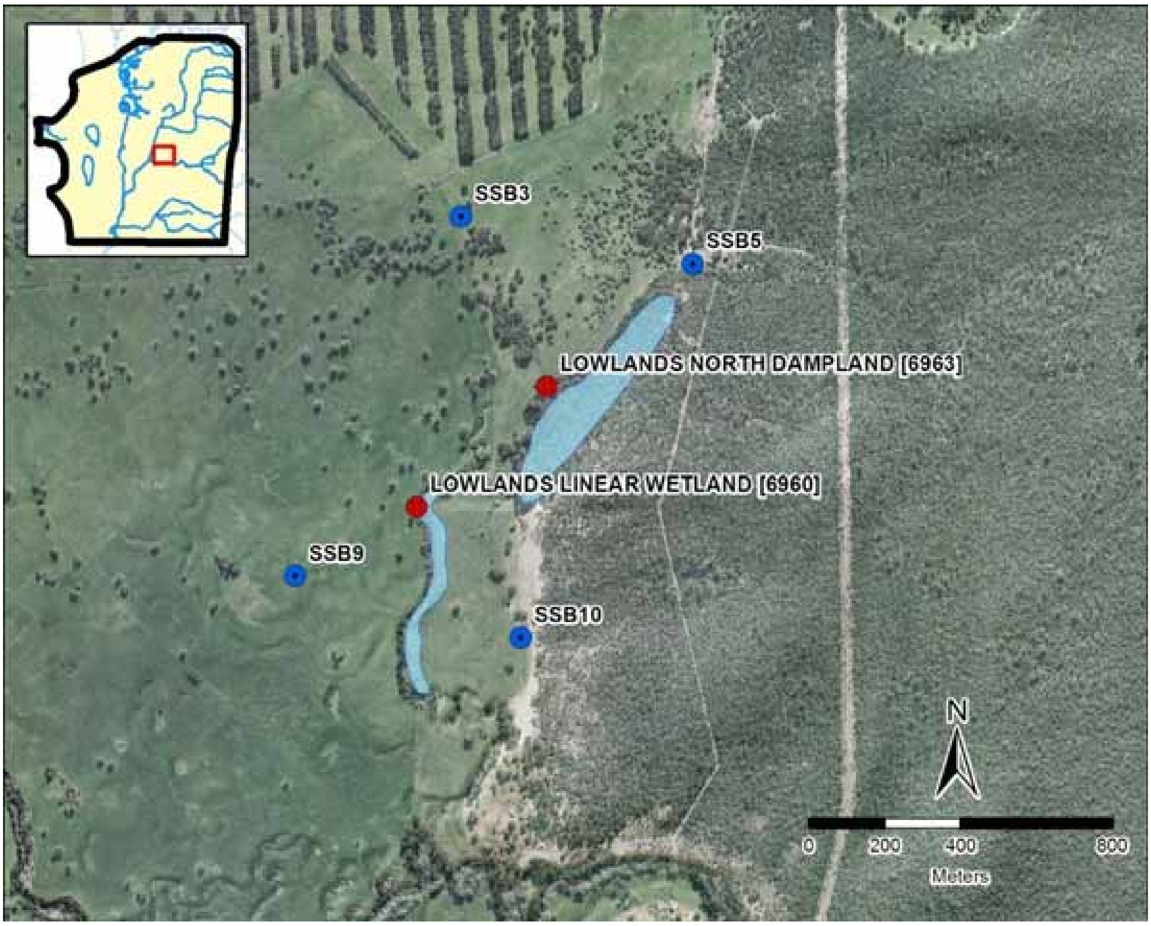


Figure F-4 Lowlands bush and linear wetlands and associated bores and gauge boards

Serpentine River linear wetland

This wetland is located on the Serpentine River in the centre of the Lowlands bushland. The wetland is the main channel of the river. There is likely to be some lateral inflow of groundwater from the surrounding sand dunes that supplement the river flow; however, the linear wetland is primarily dependent on surface water flows from the upstream catchment. In many years the Serpentine River has some flow year-round, and summer baseflows may be supplemented by releases from the Serpentine Pipehead Dam and other discharge points.

The Lowlands gauging station is located immediately downstream of the wetland and has recorded summer flows in most years, although these have declined since 2000, with peak flows of up to 1000 ML/day during winter. As the Serpentine River receives runoff from tributaries in the Darling Scarp, the linear wetland is likely to receive water earlier in the season compared with the groundwater-dependent wetlands, as a result of autumn runoff events that precede rising groundwater levels.

Figure F-5 Serpentine River linear wetland and associated bores and gauge boards

Maramanup Pool (UFI 6732)

Maramanup Pool is located in the main channel of Peel Main Drain, between two reaches of trapezoidal drains. It is perennially inundated even in dry years, but does not discharge via Peel Main Drain until the water level is above the downstream drain invert level. Peak water levels in the pool are controlled by discharge received from the Peel Main Drain in the north end of the wetland. However, the long-term water level monitoring at Maramanup Pool (AWRC 6142513) and nearby monitoring bore (T400 (O)) indicate the low water level is controlled by the groundwater level in the Superficial Aquifer. In the summer of 2010–11, both monitoring points recorded a record low of 1.2 mAHD. Drilling at bore SSB4 showed the presence of heavy black clays, which occur near the surface in many places along Peel Main Drain. However, a comparison of water and groundwater levels shows the pool is still in connection with the regional groundwater table.

Peel Main Drain has a gauging station located at Karnup Road, 3 km downstream of Maramanup Pool. This station shows that no flow occurs during much of the summer period, despite water being observed in the pool, demonstrating that it is disconnected during this time. Peak flows of up to 300 ML/day are recorded at Karnup Road during winter.

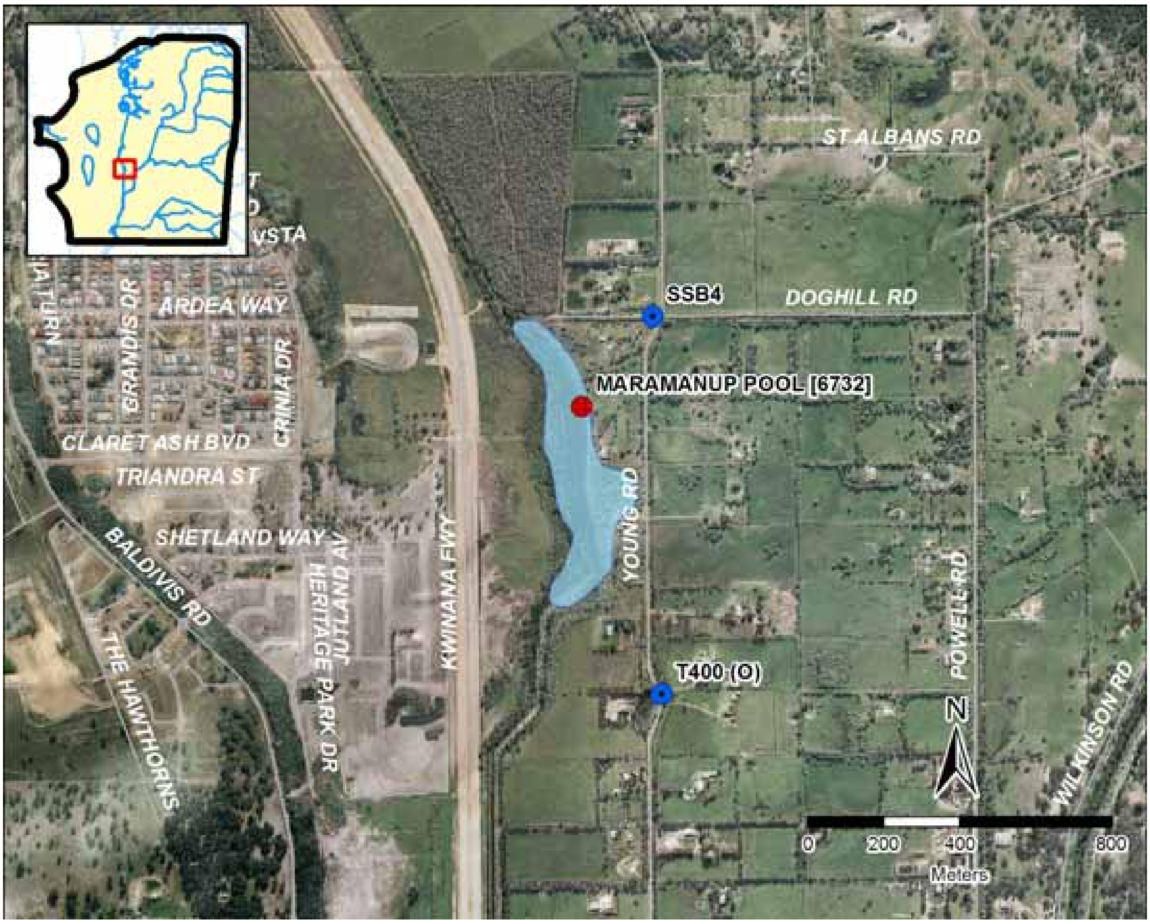


Figure F-6 Maramanup Pool and associated bores

Yangedi North wetland (6906)

The Yangedi North wetland is situated in a depression surrounded by Bassendean dunes. There are several other small depressions nearby; however, the Yangedi North wetland has substantially more vegetative cover and is at a local low point. A small agricultural drain runs through the wetland and is likely to control maximum water levels in winter. The drain runs from the wetland to an artificial sump that is lower than the wetland. On the northern side of the sump the drain continues under Jarrah Road to the north. Water levels are likely to be controlled by the invert level of the drain, which is at around 13.5 mAHD. Based on aerial photography and site visits in autumn 2011, the sump appears to intersect the groundwater even in very dry years, indicating that groundwater is quite close to the surface, however, the wetland at a slightly higher elevation appears to be ephemeral.

The wetland is a throughflow wetland, which receives groundwater inflows on the eastern side and discharges to the west. Drilling of SSB16 and SSB15 showed fine- to medium-grained sands for the 4 m depth of the holes.

Figure F-7 Yangedi North wetland and associated bores

Hymus Swamp (13133)

The Hymus Swamp is in the model area's centre near the Serpentine Drain. The wetland is surrounded by remnant vegetation and located down slope of several sand dunes to the immediate north-west, which may provide localised recharge. The swamp is in a localised depression and a small sump has been dug towards the edge. The sump intersects the groundwater even in summer at an elevation of around 6.4 mAHD; however, most of the wetland bed is at around 7.5 mAHD elevation and so is only inundated during winter. Bore logs of SSB12, SSB13 and SSB14 showed sandy sediments up to 4.5 m depth in the area, consistent with its position in locally elevated sand dunes.

Regional groundwater contours indicate a gradual east-west slope through the wetland, although during winter rainfall events, localised mounding from the surrounding dunes may result in groundwater flow to the wetland from the western side as well as the east.

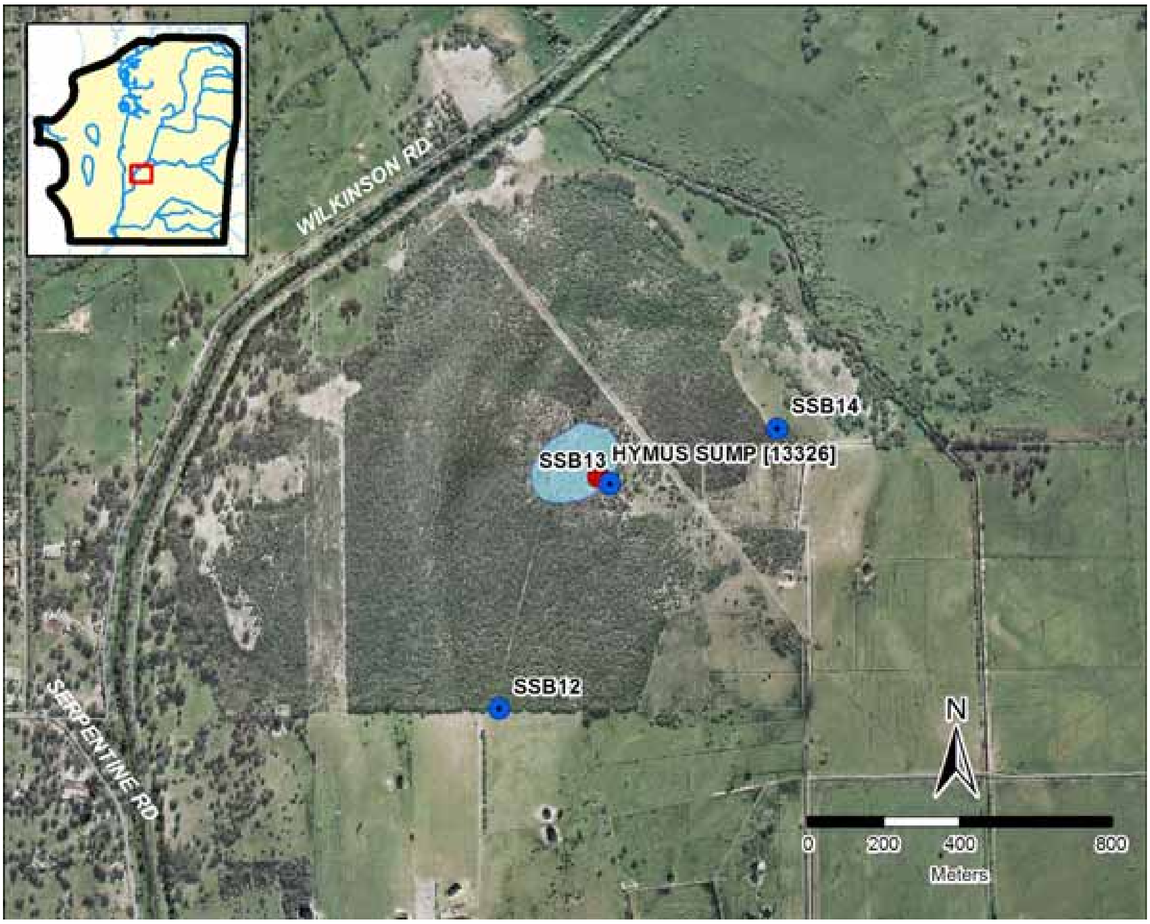


Figure F-8 Hymus Swamp and associated bores

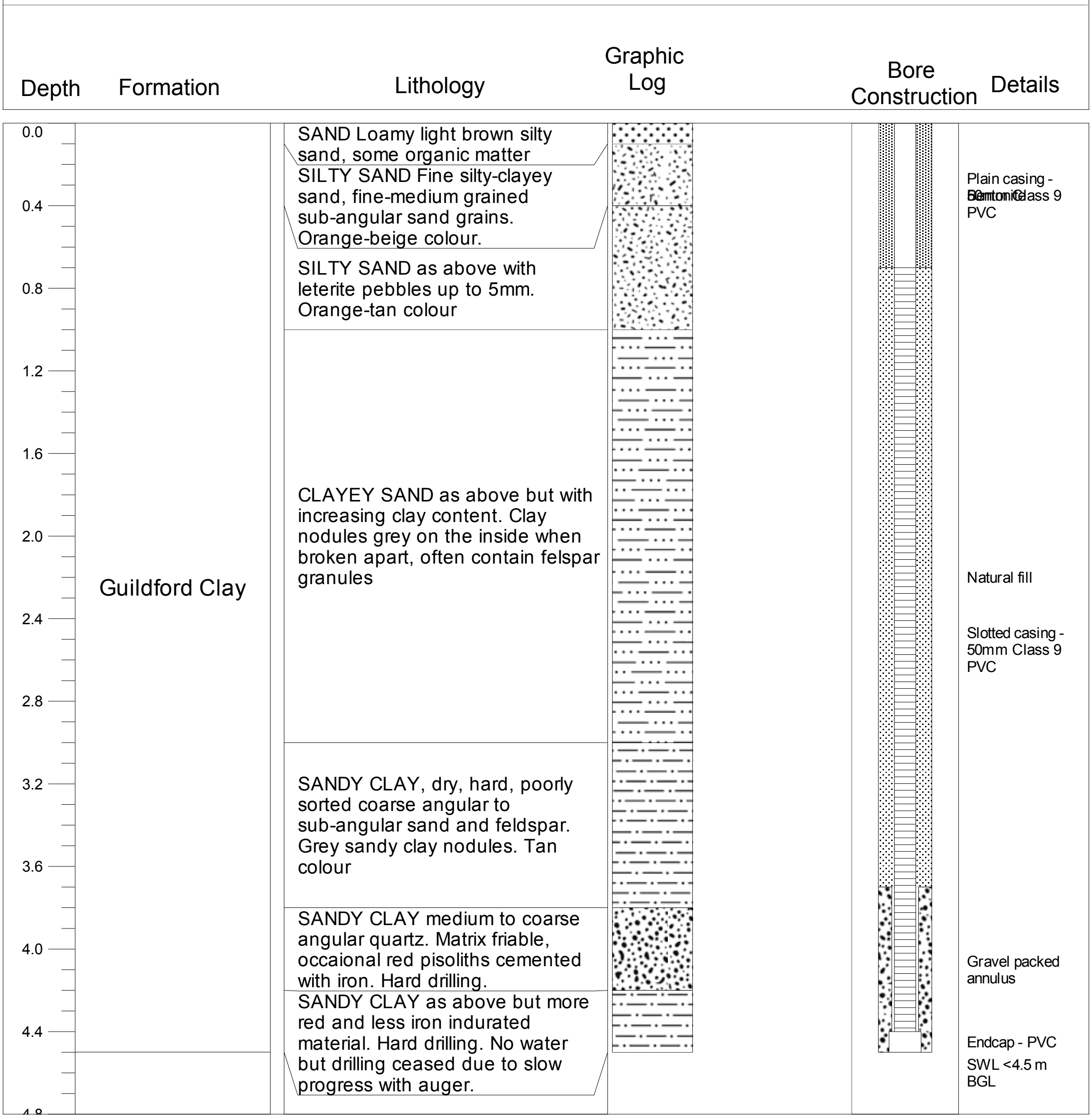
Appendix G — Bore construction diagrams

BORE COMPLETION DETAILS

AWRC Name: **SSB2**

AWRC Number: **61410476**

Serpentine DWMP Shallow Observation Bores



SAND Loamy light brown silty sand, some organic matter

SILTY SAND Fine silty-clayey sand, fine-medium grained sub-angular sand grains. Orange-beige colour.

SILTY SAND as above with leterite pebbles up to 5mm. Orange-tan colour

CLAYEY SAND as above but with increasing clay content. Clay nodules grey on the inside when broken apart, often contain felspar granules

SANDY CLAY, dry, hard, poorly sorted coarse angular to sub-angular sand and feldspar. Grey sandy clay nodules. Tan colour

SANDY CLAY medium to coarse angular quartz. Matrix friable, occaional red pisoliths cemented with iron. Hard drilling.

SANDY CLAY as above but more red and less iron indurated material. Hard drilling. No water but drilling ceased due to slow progress with auger.

Plain casing - 50mm Class 9 PVC

Bentonite

Natural fill

Slotted casing - 50mm Class 9 PVC

Gravel packed annulus

Endcap - PVC

SWL <4.5 m BGL

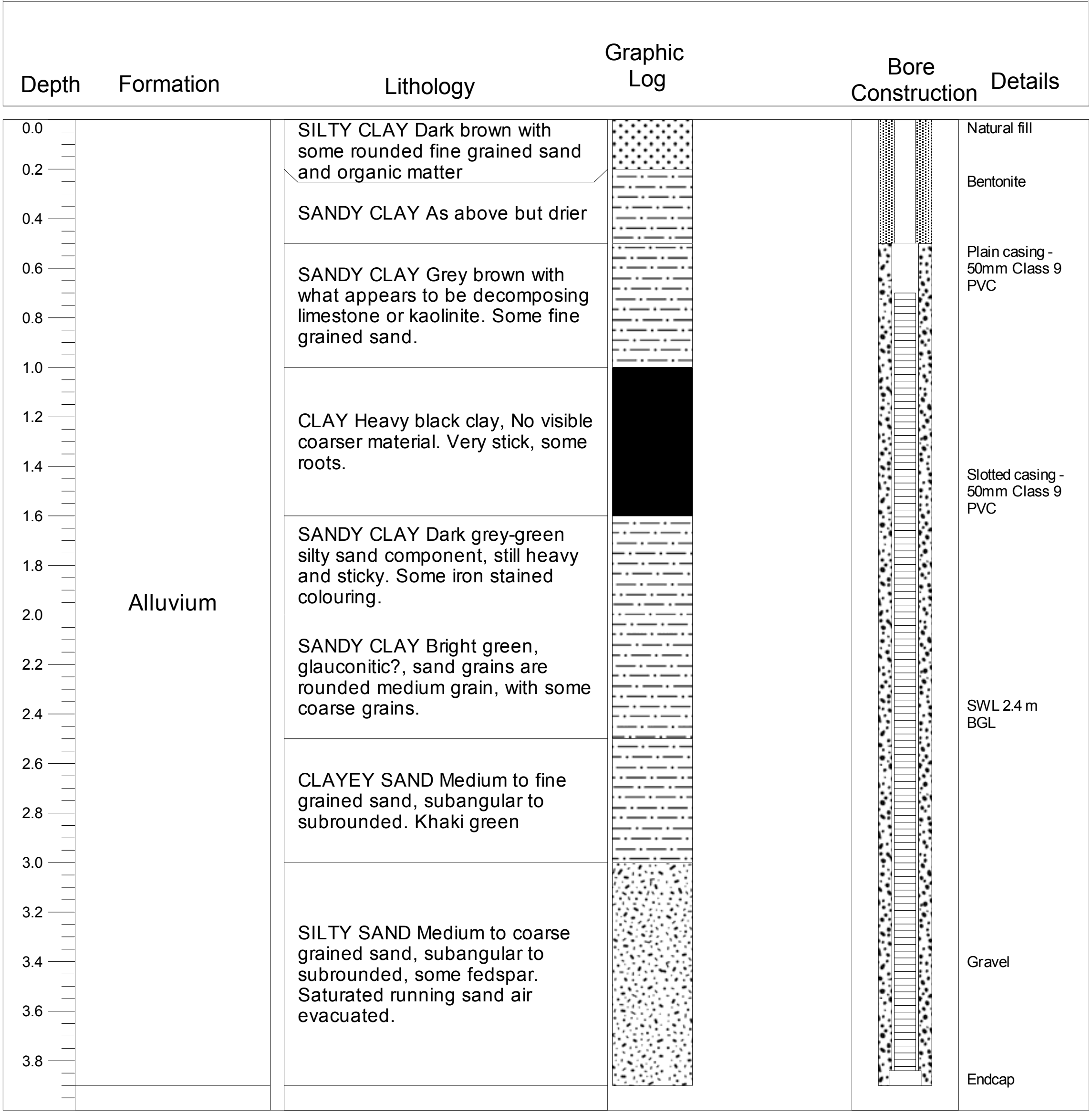
Drilled by:	Contractor	Northing (Z50):	6425908.682	Screens (m BNS):	0.7 - 4.4
Date drilled:	5/24/11	Easting (Z50):	404127.75	SWL (m BNS):	
Logged by:	Peter Kretschmer	Surface (m AHD):	34.16		
Aquifer:	Superficial	Drill depth (m BNS):	4.5		

BORE COMPLETION DETAILS

AWRC Name: **SSB4**

AWRC Number: **61410478**

Serpentine DWMP Shallow Observation Bores



SILTY CLAY Dark brown with some rounded fine grained sand and organic matter

SANDY CLAY As above but drier

SANDY CLAY Grey brown with what appears to be decomposing limestone or kaolinite. Some fine grained sand.

CLAY Heavy black clay, No visible coarser material. Very stick, some roots.

SANDY CLAY Dark grey-green silty sand component, still heavy and sticky. Some iron stained colouring.

SANDY CLAY Bright green, glauconitic?, sand grains are rounded medium grain, with some coarse grains.

CLAYEY SAND Medium to fine grained sand, subangular to subrounded. Khaki green

SILTY SAND Medium to coarse grained sand, subangular to subrounded, some fedspar. Saturated running sand air evacuated.

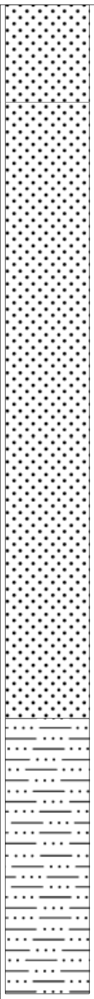
Drilled by:	Contractor	Northing (Z50):	6421388.131	Screens (m BNS):	0.7 - 3.9
Date drilled:	5/4/11	Easting (Z50):	390790.952	SWL (m BNS):	2.4
Logged by:	Peter Kretschmer	Surface (m AHD):	3.98		
Aquifer:	Superficial	Drill depth (m BNS):	3.9		

BORE COMPLETION DETAILS

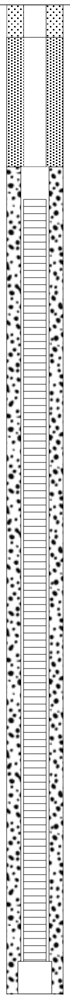
AWRC Name: **SSB5**
AWRC Number: **61410479**

Serpentine DWMP Shallow Observation Bores

Graphic Log



Bore Construction



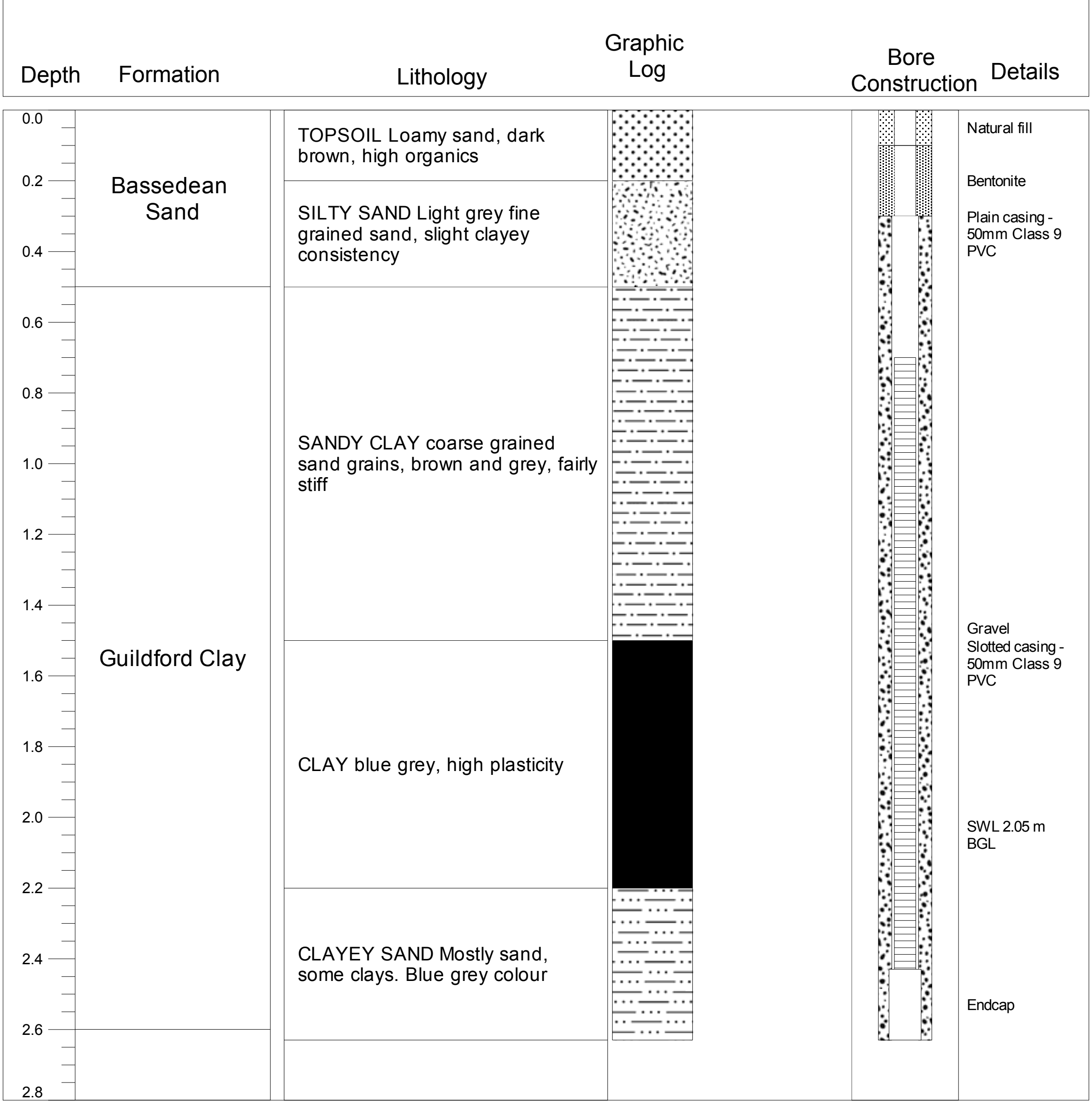
Depth	Formation	Lithology	Details
0.0		TOPSOIL Sandy, brown with organics, medium grained.	Plain casing - 50mm Class 9 PVC
0.2			Bentonite
0.4			
0.6			
0.8			
1.0			
1.2		SAND Grey brown medium grained, traces or organics. No iron or clay	
1.4			
1.6	Bassedean Sand		Natural fill
1.8			Slotted casing - 50mm Class 9 PVC
2.0			Gravel
2.2			
2.4			SWL 2.35 m BGL
2.6		CLAYEY SAND Mostly medium grained sand, trace of clay, brown, wet, (at watertable)	
2.8			
3.0			Endcap

Drilled by:	Contractor	Northing (Z50):	6423635.398	Screens (m BNS):	0.6 - 3.05
Date drilled:	4/28/11	Easting (Z50):	396763.22	SWL (m BNS):	2.35
Logged by:	Joel Hall	Surface (m AHD):	11.729		
Aquifer:	Superficial	Drill depth (m BNS):	3.05		

BORE COMPLETION DETAILS

AWRC Name:	**SSB6**
AWRC Number:	**61410480**

Serpentine DWMP Shallow Observation Bores



Bassedean Sand

Guildford Clay

TOPSOIL Loamy sand, dark brown, high organics

SILTY SAND Light grey fine grained sand, slight clayey consistency

SANDY CLAY coarse grained sand grains, brown and grey, fairly stiff

CLAY blue grey, high plasticity

CLAYEY SAND Mostly sand, some clays. Blue grey colour

Natural fill

Bentonite

Plain casing - 50mm Class 9 PVC

Gravel

Slotted casing - 50mm Class 9 PVC

SWL 2.05 m BGL

Endcap

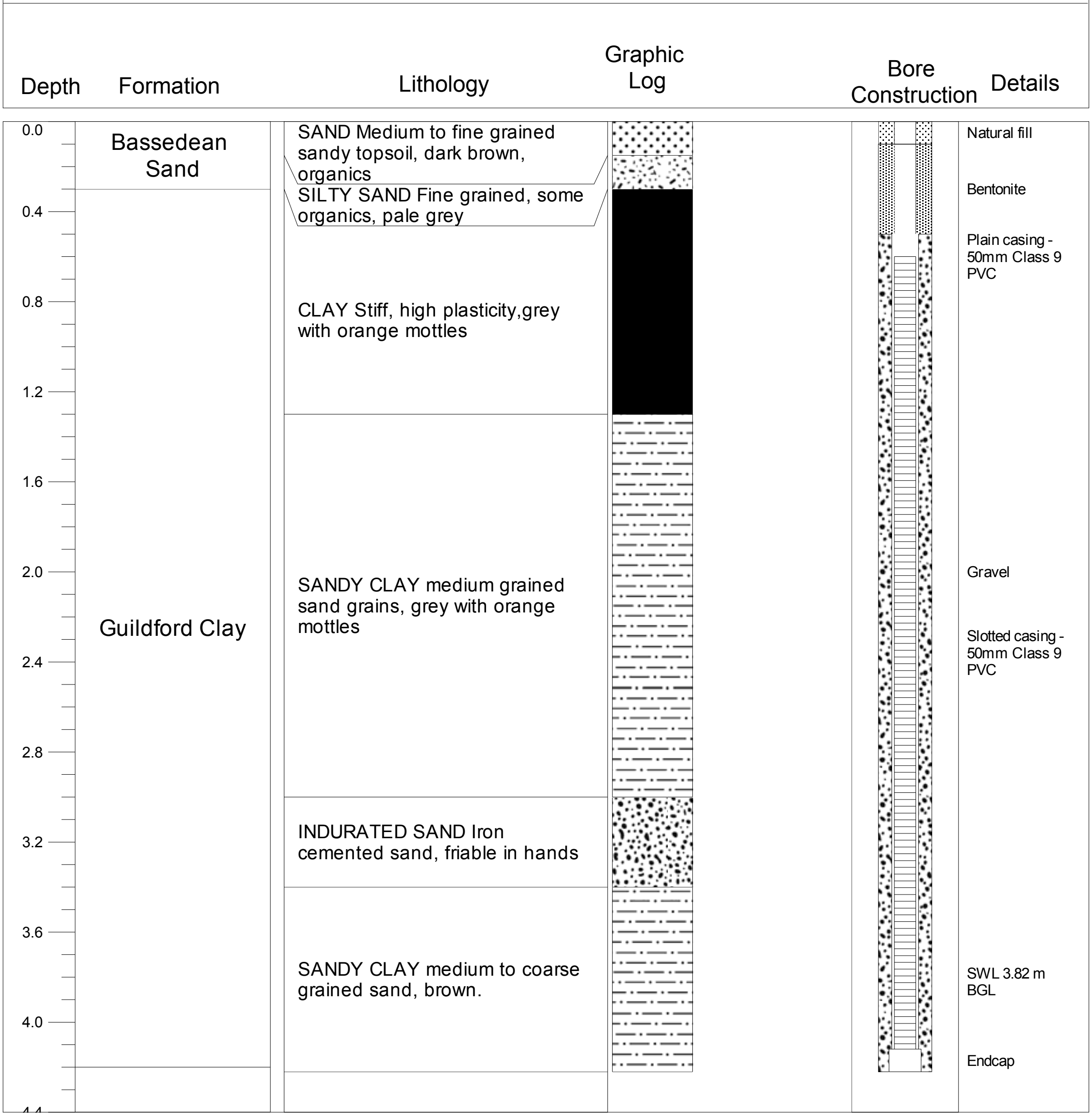
Drilled by:	Contractor	Northing (Z50):	6425001.552	Screens (m BNS):	0.7 - 2.43
Date drilled:	4/28/11	Easting (Z50):	396936.122	SWL (m BNS):	
Logged by:	Joel Hall	Surface (m AHD):	12.001		
Aquifer:	Superficial	Drill depth (m BNS):	2.63		

BORE COMPLETION DETAILS

AWRC Name: **SSB7**

AWRC Number: **61410481**

Serpentine DWMP Shallow Observation Bores



SAND Medium to fine grained sandy topsoil, dark brown, organics

SILTY SAND Fine grained, some organics, pale grey

CLAY Stiff, high plasticity,grey with orange mottles

SANDY CLAY medium grained sand grains, grey with orange mottles

INDURATED SAND Iron cemented sand, friable in hands

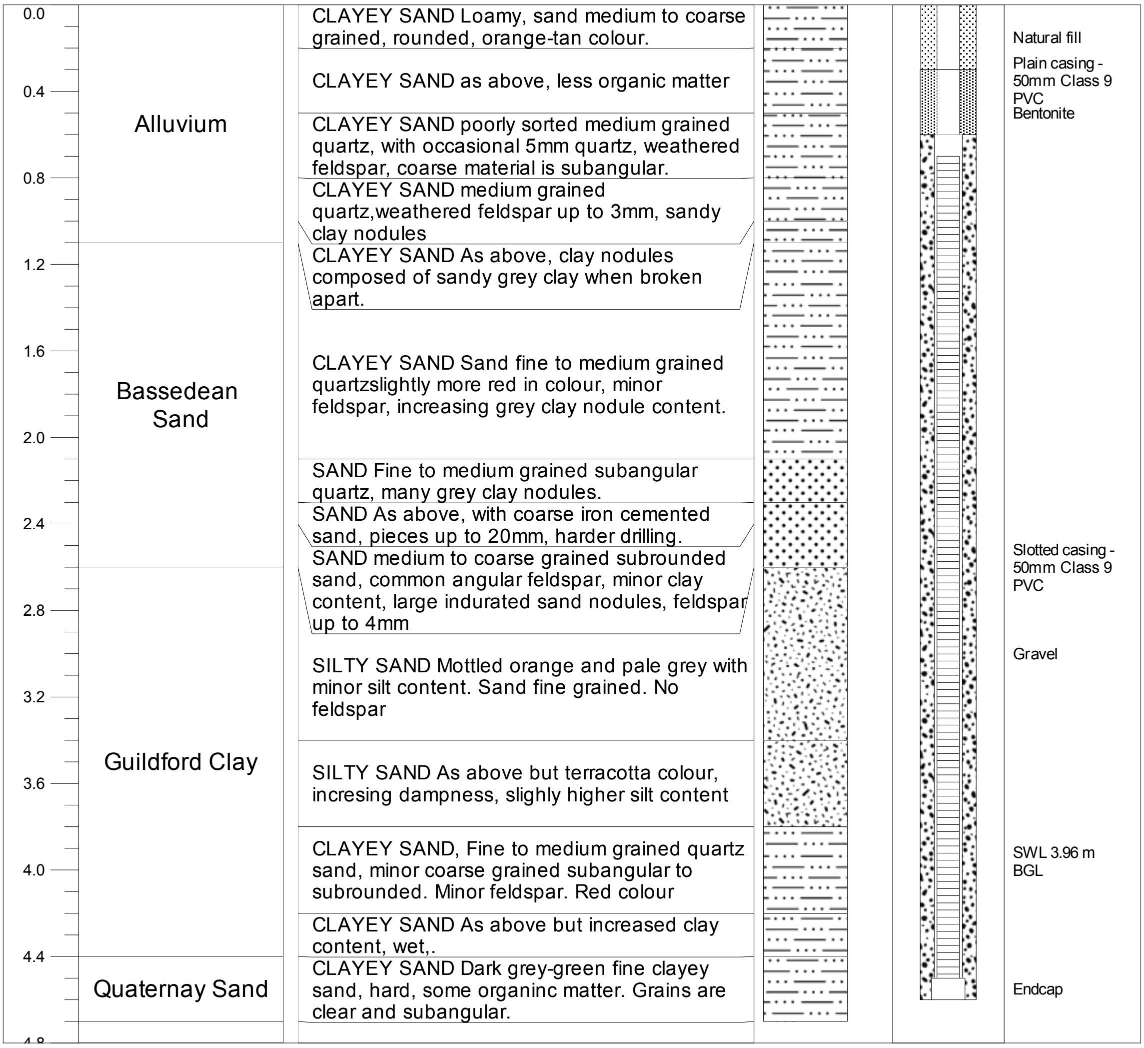
SANDY CLAY medium to coarse grained sand, brown.

Drilled by:	Contractor	Northing (Z50):	6425731.808	Screens (m BNS):	0.6 - 4.12
Date drilled:	4/28/11	Easting (Z50):	396750.476	SWL (m BNS):	3.82
Logged by:	Joel Hall	Surface (m AHD):	11.711		
Aquifer:	Superficial	Drill depth (m BNS):	4		

BORE COMPLETION DETAILS

AWRC Name: **SSB8**
AWRC Number: **61410482**

Serpentine DWMP Shallow Observation Bores



Formation	Lithology
Alluvium	CLAYEY SAND Loamy, sand medium to coarse grained, rounded, orange-tan colour.
	CLAYEY SAND as above, less organic matter
	CLAYEY SAND poorly sorted medium grained quartz, with occasional 5mm quartz, weathered feldspar, coarse material is subangular.
	CLAYEY SAND medium grained quartz,weathered feldspar up to 3mm, sandy clay nodules
Bassedean Sand	CLAYEY SAND As above, clay nodules composed of sandy grey clay when broken apart.
	CLAYEY SAND Sand fine to medium grained quartzslightly more red in colour, minor feldspar, increasing grey clay nodule content.
	SAND Fine to medium grained subangular quartz, many grey clay nodules.
	SAND As above, with coarse iron cemented sand, pieces up to 20mm, harder drilling.
Guildford Clay	SAND medium to coarse grained subrounded sand, common angular feldspar, minor clay content, large indurated sand nodules, feldspar up to 4mm
	SILTY SAND Mottled orange and pale grey with minor silt content. Sand fine grained. No feldspar
	SILTY SAND As above but terracotta colour, incresing dampness, slighly higher silt content
	CLAYEY SAND, Fine to medium grained quartz sand, minor coarse grained subangular to subrounded. Minor feldspar. Red colour
	CLAYEY SAND As above but increased clay content, wet,.
Quaternay Sand	CLAYEY SAND Dark grey-green fine clayey sand, hard, some organinc matter. Grains are clear and subangular.

Details
- Natural fill
- Plain casing - 50mm Class 9 PVC
- Bentonite
- Slotted casing - 50mm Class 9 PVC
- Gravel
- SWL 3.96 m BGL
- Endcap

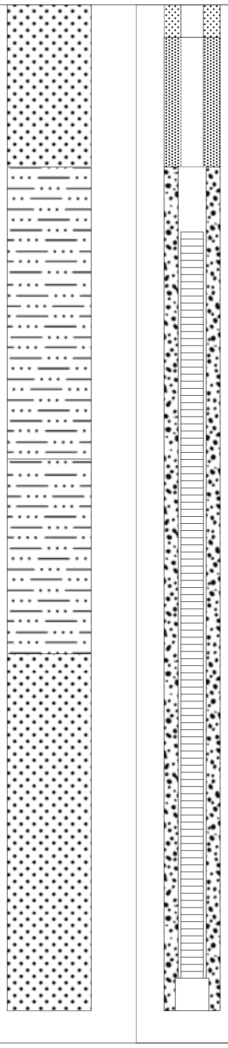
Drilled by:	Contractor	Northing (Z50):	6425257.481	Screens (m BNS):	0.7 - 4.5
Date drilled:	4/29/11	Easting (Z50):	396332.883	SWL (m BNS):	3.96
Logged by:	Peter Kretschmer	Surface (m AHD):	11.234		
Aquifer:	Superficial	Drill depth (m BNS):	4.6		

BORE COMPLETION DETAILS

AWRC Name: **SSB9**
AWRC Number: **61410483**

Serpentine DWMP Shallow Observation Bores

Depth	Formation	Lithology
0.0–0.5	Alluvium	SANDY LOAM Slight clay content, dark brown. Pasture surface
0.5–1.4		CLAYEY SAND Orange, medium to coarse grained quartz
1.4–2.0		CLAYEY SAND As above but with higher clay content
2.0–3.1	Quaternay Sand	SAND, coarse grained, orange



Details:
- Natural fill
- Bentonite
- Plain casing - 50mm Class 9 PVC
- Gravel
- Slotted casing - 50mm Class 9 PVC
- SWL 2.24 m BGL
- Endcap

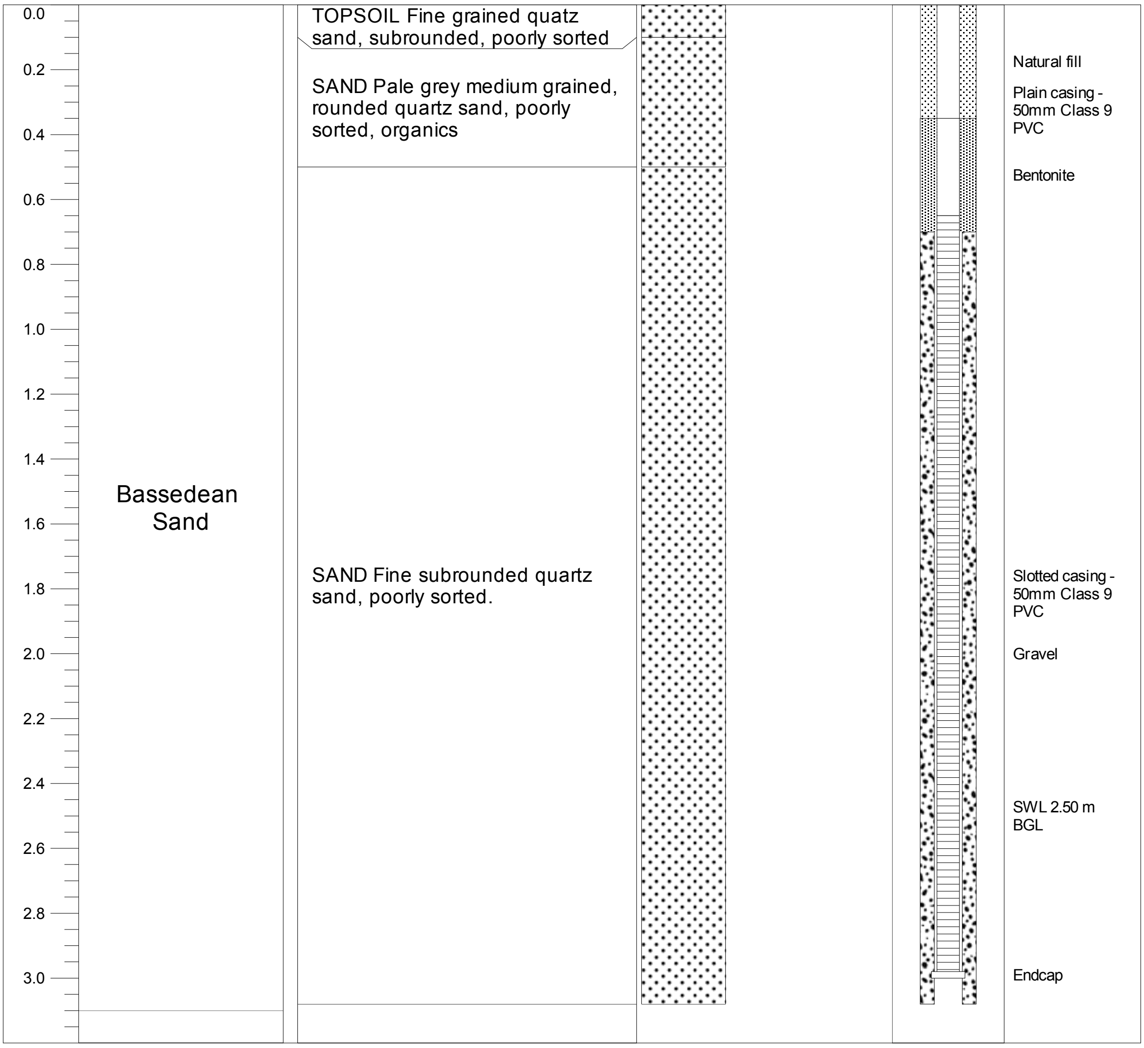
Drilled by:	Contractor	Northing (Z50):	6422811.708	Screens (m BNS):	0.7 - 3.0
Date drilled:	4/28/11	Easting (Z50):	395718.995	SWL (m BNS):	2.24
Logged by:	Joel Hall	Surface (m AHD):	10.95		
Aquifer:	Superficial	Drill depth (m BNS):	3.1		

BORE COMPLETION DETAILS

AWRC Name: **SSB10**
AWRC Number: **61410484**

Serpentine DWMP Shallow Observation Bores

Depth | Formation | Lithology | Graphic Log | Bore Construction | Details



TOPSOIL Fine grained quatz sand, subrounded, poorly sorted

SAND Pale grey medium grained, rounded quartz sand, poorly sorted, organics

SAND Fine subrounded quartz sand, poorly sorted.

Drilled by:	Contractor	Northing (Z50):	6422649.603	Screens (m BNS):	0.65 - 3.0
Date drilled:	4/27/11	Easting (Z50):	396311.334	SWL (m BNS):	2.5
Logged by:	Ben Marillier	Surface (m AHD):	12.103		
Aquifer:	Superficial	Drill depth (m BNS):	3.1		

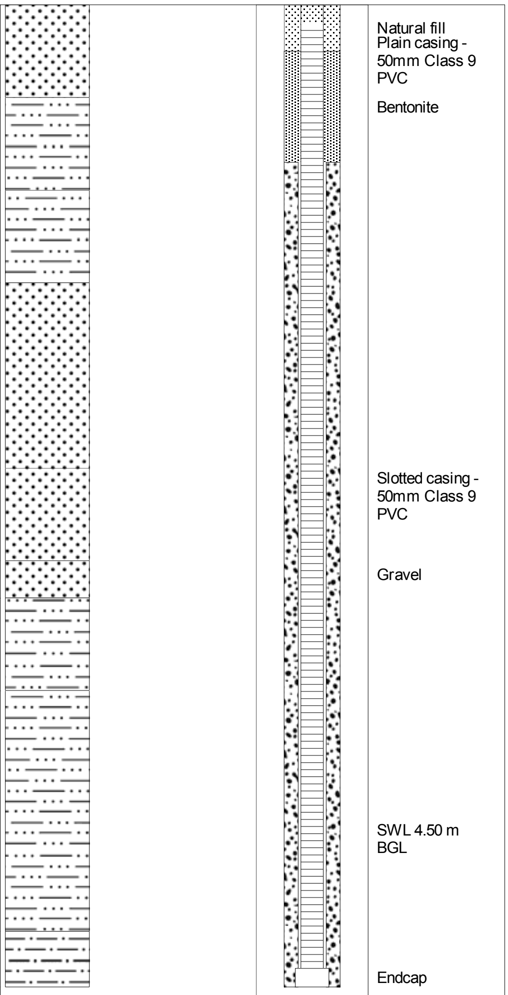
BORE COMPLETION DETAILS

AWRC Name: **SSB11**
AWRC Number: **61410485**

Serpentine DWMP Shallow Observation Bores

Depth	Formation	Lithology
0.0 0.4	Bassedean Sand	SAND Medium grained quatz sand, some organics
0.8	Alluvium	CLAYEY SAND with some lateritic gravel, very sticky clay with medium sized quartz grains. Red-brown colour
1.2		CLAYEY SAND becoming more clayey with depth. Medium to coarse subrounded quartz grains. Brown-grey colour.
1.6 2.0 2.4		COARSE SAND Subrounded coarse quartz sand, varying up to very coarse (4mm), some clay. Yellow brown colour.
2.8		COARSE SAND Moderately sorted coarse to very coarse sand with some fine content, subrounded. Pinkish brown colour.
3.2	Guildford Clay	SAND subrounded medium grained quartz sand, silty, cream coloured
3.6		CLAYEY SAND Coarse subangular to subrounded clear quartz grains, polished, in light grey-brown clayey matrix
4.0 4.4 4.8		CLAYEY SAND Coarse subangular to subrounded clear quartz grains, polished, in light grey-brown clayey matrix
5.2 5.6		SANDY CLAY Grey-black clay with fine sand and dark minerals

Graphic Log | Bore Construction | Details



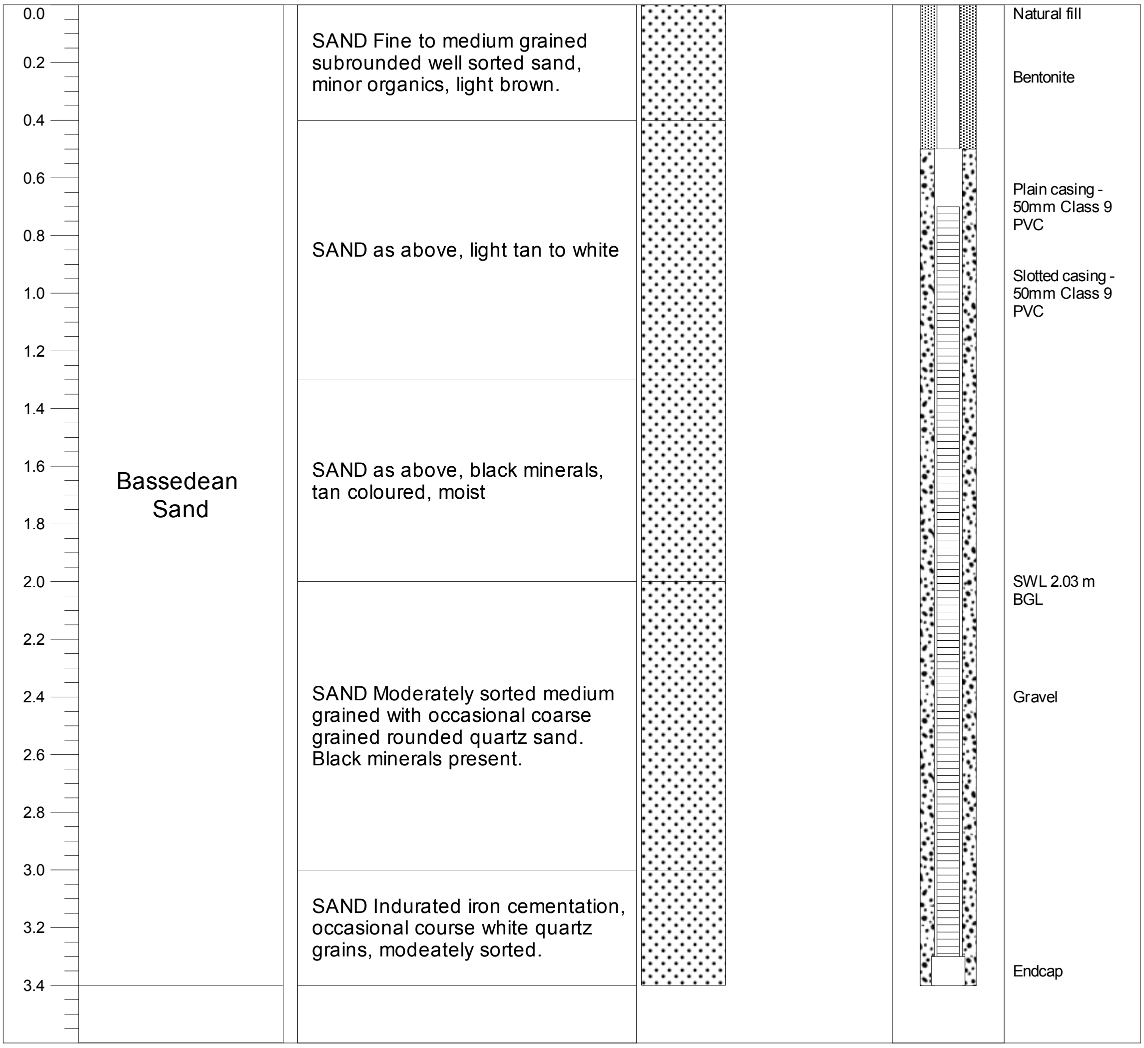
Drilled by:	Contractor	Northing (Z50):	6422304.526	Screens (m BNS):	0.1 - 5.3
Date drilled:	4/27/11	Easting (Z50):	398827.101	SWL (m BNS):	4.5
Logged by:	Ben Marillier	Surface (m AHD):	17.473		
Aquifer:	Superficial	Drill depth (m BNS):	5.3		

BORE COMPLETION DETAILS

AWRC Name: **SSB12**
AWRC Number: **61410486**

Serpentine DWMP Shallow Observation Bores

Depth | Formation | Lithology | Graphic Log | Bore Construction | Details



SAND Fine to medium grained subrounded well sorted sand, minor organics, light brown.

SAND as above, light tan to white

SAND as above, black minerals, tan coloured, moist

SAND Moderately sorted medium grained with occasional coarse grained rounded quartz sand. Black minerals present.

SAND Indurated iron cementation, occasional course white quartz grains, modeately sorted.

Drilled by:	Contractor	Northing (Z50):	6419588.266	Screens (m BNS):	0.7 - 3.3
Date drilled:	5/4/11	Easting (Z50):	392917.198	SWL (m BNS):	2.03
Logged by:	Peter Kretschmer	Surface (m AHD):	9.016		
Aquifer:	Superficial	Drill depth (m BNS):	3.4		

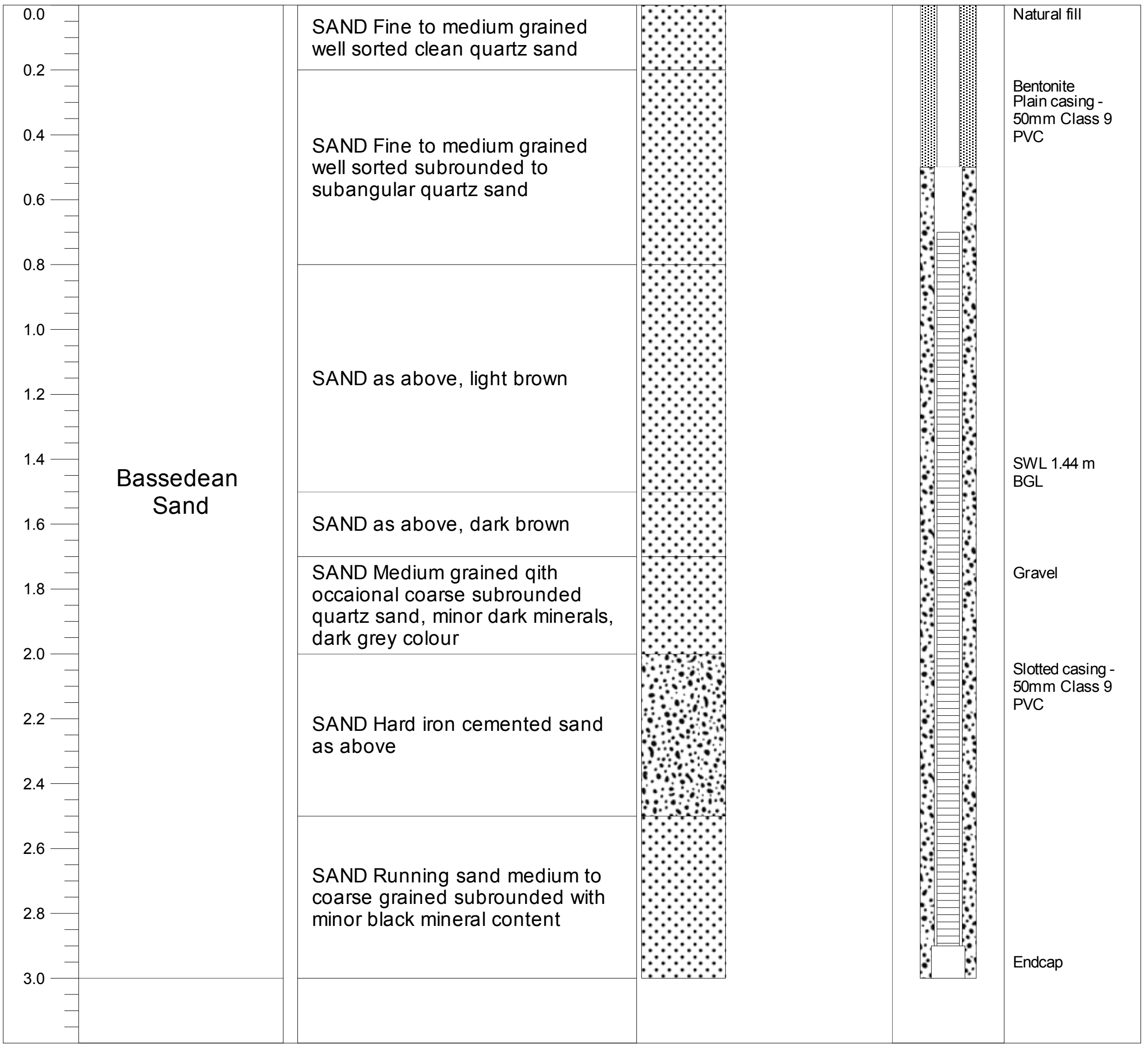
BORE COMPLETION DETAILS

AWRC Name: **SSB13**

AWRC Number: **61410487**

Serpentine DWMP Shallow Observation Bores

Depth	Formation	Lithology	Graphic Log	Bore Construction	Details



Bassedean Sand

SAND Fine to medium grained well sorted clean quartz sand

SAND Fine to medium grained well sorted subrounded to subangular quartz sand

SAND as above, light brown

SAND as above, dark brown

SAND Medium grained qith occaional coarse subrounded quartz sand, minor dark minerals, dark grey colour

SAND Hard iron cemented sand as above

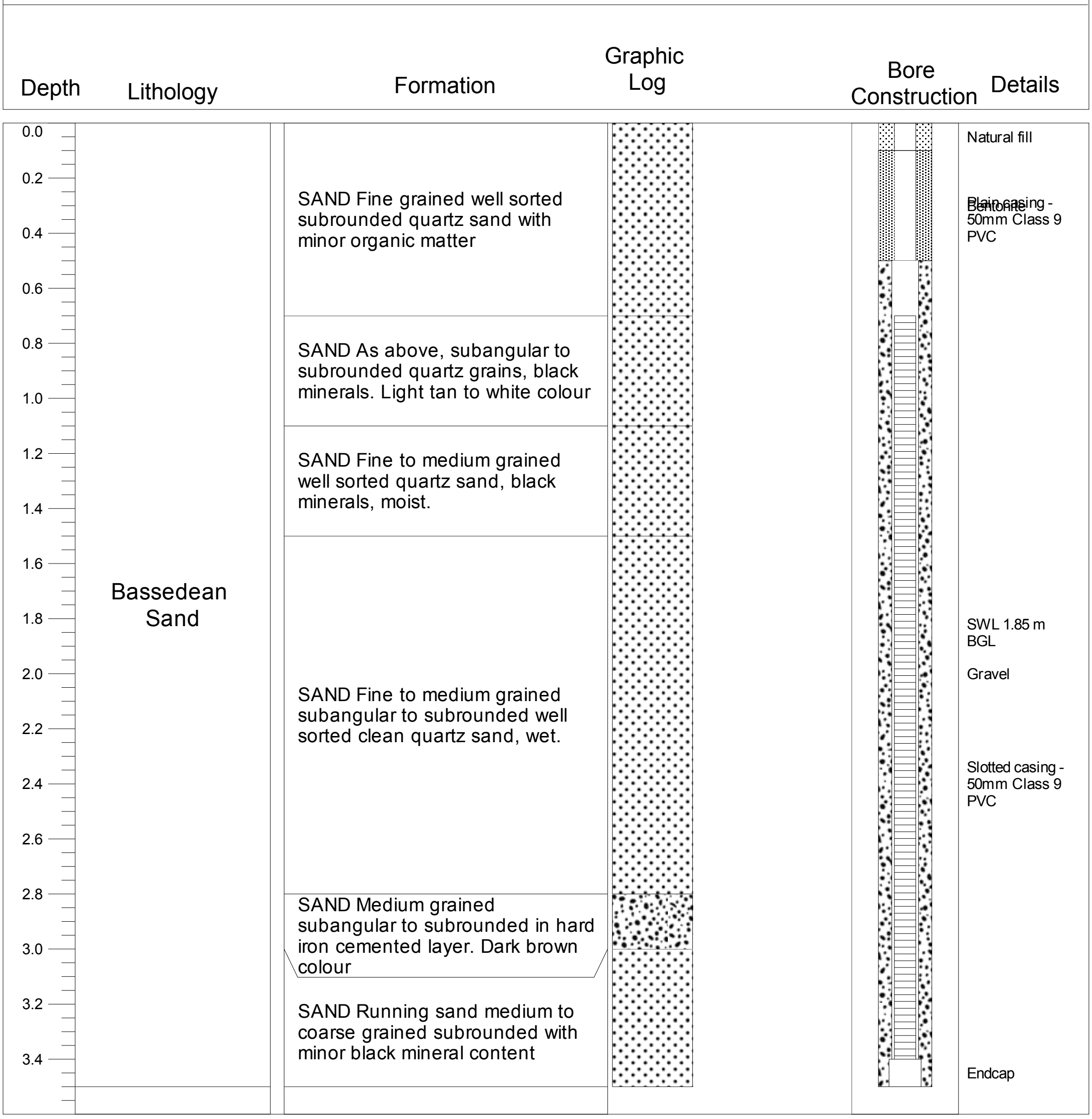
SAND Running sand medium to coarse grained subrounded with minor black mineral content

Drilled by:	Contractor	Northing (Z50):	6420193.307	Screens (m BNS):	0.7 - 2.9
Date drilled:	5/4/11	Easting (Z50):	393215.339	SWL (m BNS):	1.44
Logged by:	Peter Kretschmer	Surface (m AHD):	7.848		
Aquifer:	Superficial	Drill depth (m BNS):	3		

BORE COMPLETION DETAILS

AWRC Name: **SSB14**
AWRC Number: **61410488**

Serpentine DWMP Shallow Observation Bores



SAND Fine grained well sorted subrounded quartz sand with minor organic matter

SAND As above, subangular to subrounded quartz grains, black minerals. Light tan to white colour

SAND Fine to medium grained well sorted quartz sand, black minerals, moist.

SAND Fine to medium grained subangular to subrounded well sorted clean quartz sand, wet.

SAND Medium grained subangular to subrounded in hard iron cemented layer. Dark brown colour

SAND Running sand medium to coarse grained subrounded with minor black mineral content

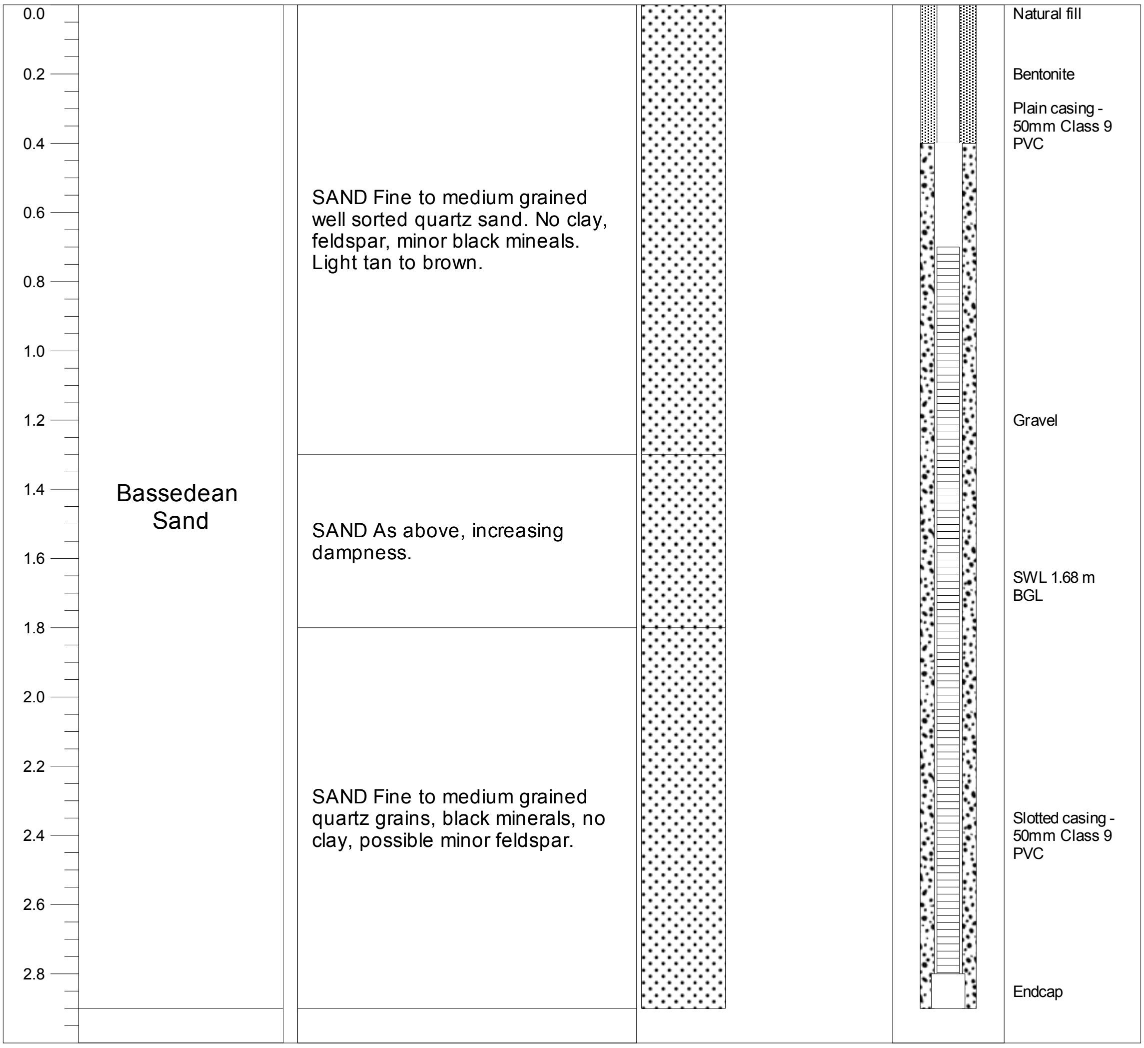
Drilled by:	Contractor	Northing (Z50):	6420330.742	Screens (m BNS):	0.7 - 3.4
Date drilled:	5/4/11	Easting (Z50):	393654.331	SWL (m BNS):	1.85
Logged by:	Peter Kretschmer	Surface (m AHD):	8.179		
Aquifer:	Superficial	Drill depth (m BNS):	3.5		

BORE COMPLETION DETAILS

AWRC Name:	**SSB15**
AWRC Number:	**61410489**

Serpentine DWMP Shallow Observation Bores

Depth	Formation	Lithology	Graphic Log	Bore Construction	Details



SAND Fine to medium grained well sorted quartz sand. No clay, feldspar, minor black mineals. Light tan to brown.

SAND As above, increasing dampness.

SAND Fine to medium grained quartz grains, black minerals, no clay, possible minor feldspar.

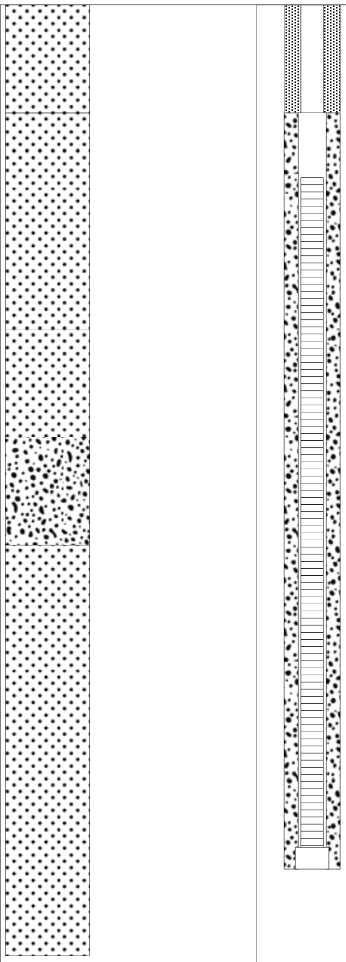
Drilled by:	Contractor	Northing (Z50):	6416153.287	Screens (m BNS):	0.7 - 2.8
Date drilled:	5/3/11	Easting (Z50):	394225.831	SWL (m BNS):	1.68
Logged by:	Peter Kretschmer	Surface (m AHD):	14.03		
Aquifer:	Superficial	Drill depth (m BNS):	2.9		

BORE COMPLETION DETAILS

AWRC Name: **SSB16**
AWRC Number: **61410490**

Serpentine DWMP Shallow Observation Bores

Depth	Formation	Lithology
0.0	Bassedean Sand	SAND Fine grained quartz sand, well sorted, no feldspar, black minerals or clay. Minor organics. Grey colour.
0.4		SAND Fine to medium grained well sorted quartz sand, black minerals, no clay or feldspar.
0.8		
1.2		
1.6		SAND As above, occaional white quartz grains (not feldspar). Becomes saturated
2.0		SAND Indurated iron cementation, occasional course white quartz grains, modeately sorted, harder drilling. Dark brown.
2.4		SAND Running fine to medium grained well sorted quartz sand. (blown out with air)
2.8		
3.2		
3.6		
4.0		
4.4		

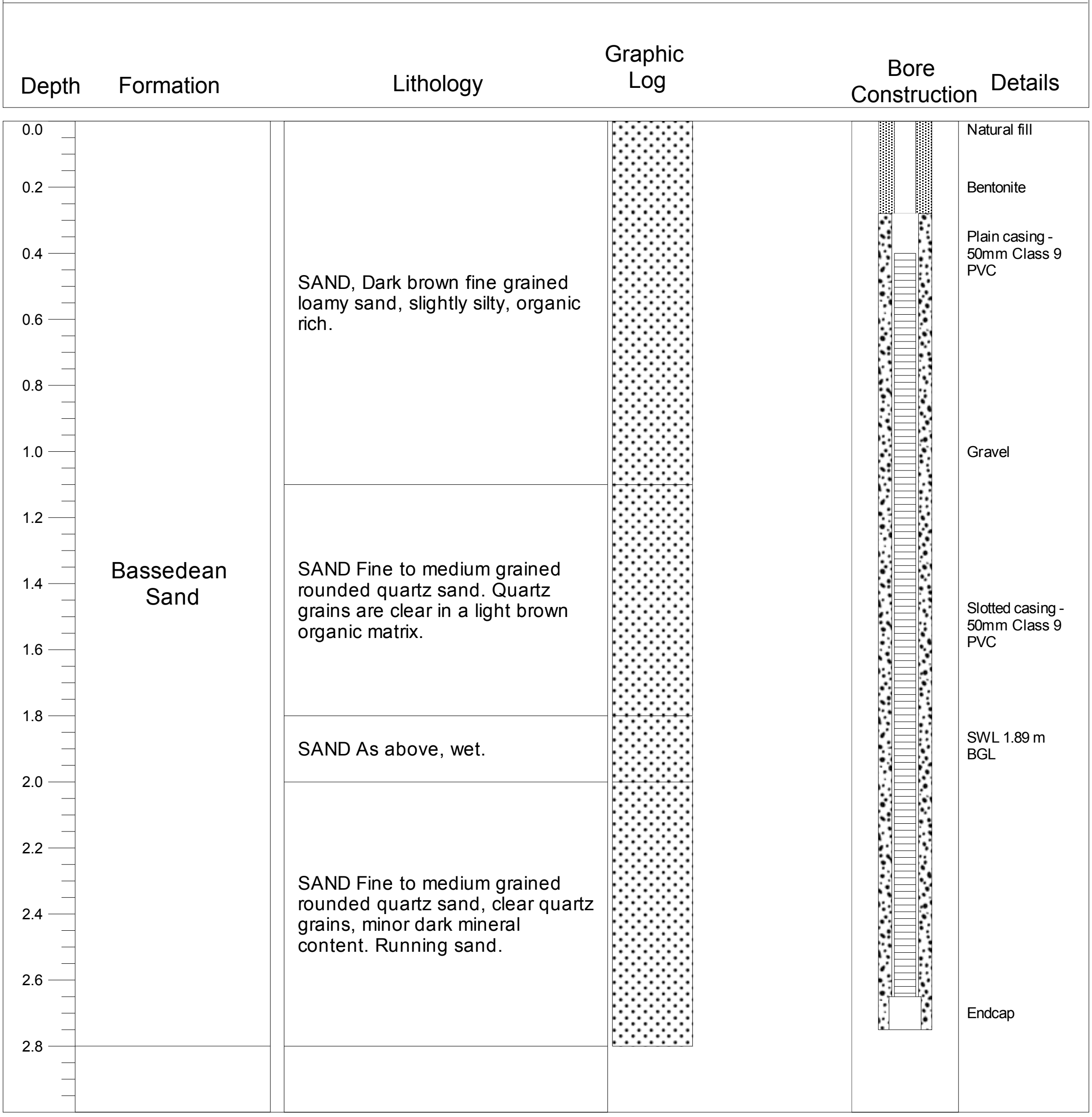


Drilled by:	Contractor	Northing (Z50):	6416536.31	Screens (m BNS):	0.8 - 3.9
Date drilled:	5/3/11	Easting (Z50):	394071.999	SWL (m BNS):	2.19
Logged by:	Peter Kretschmer	Surface (m AHD):	14.024		
Aquifer:	Superficial	Drill depth (m BNS):	4		

BORE COMPLETION DETAILS

AWRC Name: **SSB17**
AWRC Number: **61410491**

Serpentine DWMP Shallow Observation Bores



Bassedean Sand

SAND, Dark brown fine grained loamy sand, slightly silty, organic rich.

SAND Fine to medium grained rounded quartz sand. Quartz grains are clear in a light brown organic matrix.

SAND As above, wet.

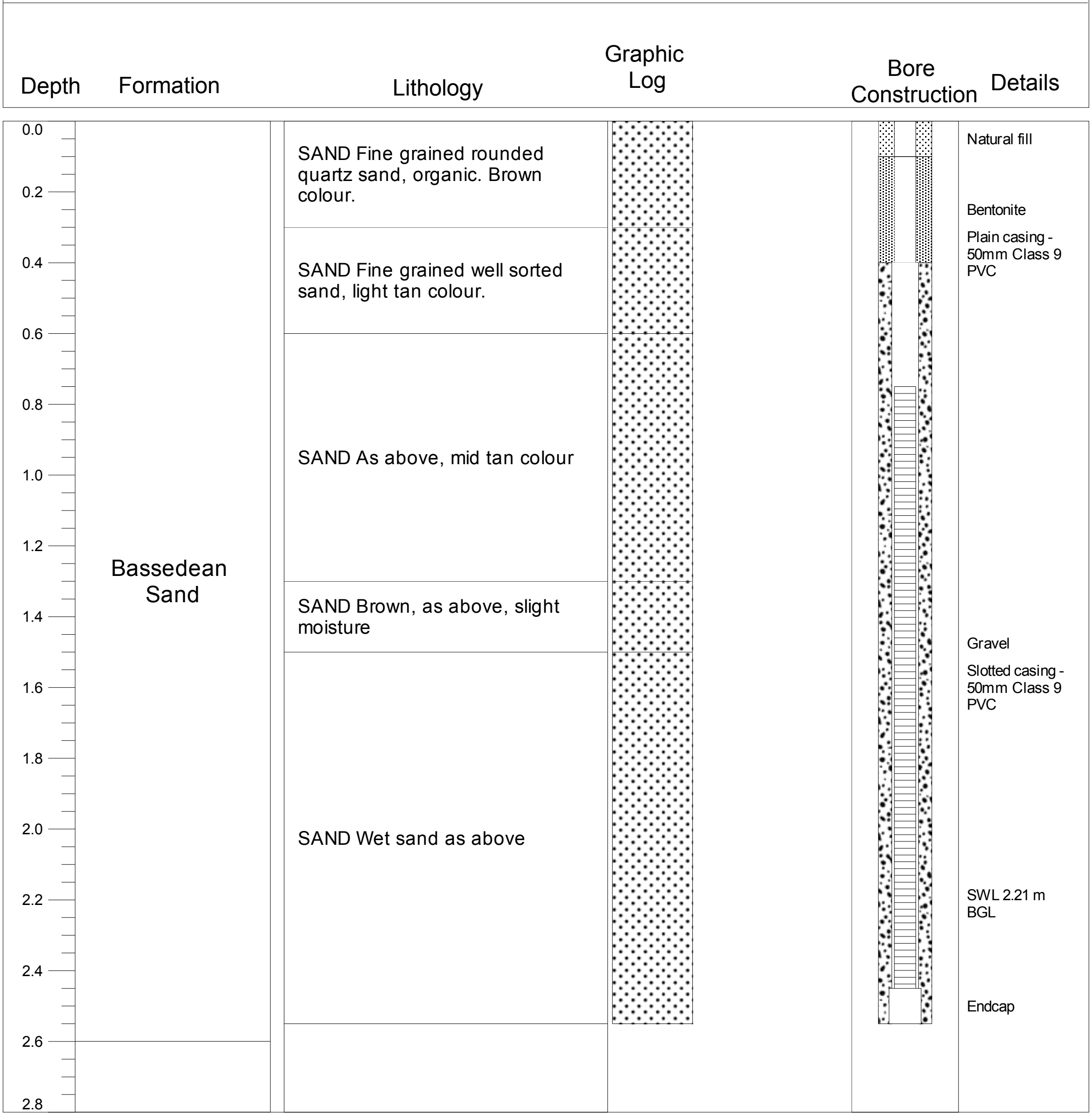
SAND Fine to medium grained rounded quartz sand, clear quartz grains, minor dark mineral content. Running sand.

Drilled by:	Contractor	Northing (Z50):	6428760.872	Screens (m BNS):	0.4 - 2.65
Date drilled:	4/29/11	Easting (Z50):	394757.087	SWL (m BNS):	1.89
Logged by:	Peter Kretschmer	Surface (m AHD):	10.327		
Aquifer:	Superficial	Drill depth (m BNS):	2.75		

BORE COMPLETION DETAILS

AWRC Name: **SSB18**
AWRC Number: **61410492**

Serpentine DWMP Shallow Observation Bores



SAND Fine grained rounded quartz sand, organic. Brown colour.

SAND Fine grained well sorted sand, light tan colour.

SAND As above, mid tan colour

SAND Brown, as above, slight moisture

SAND Wet sand as above

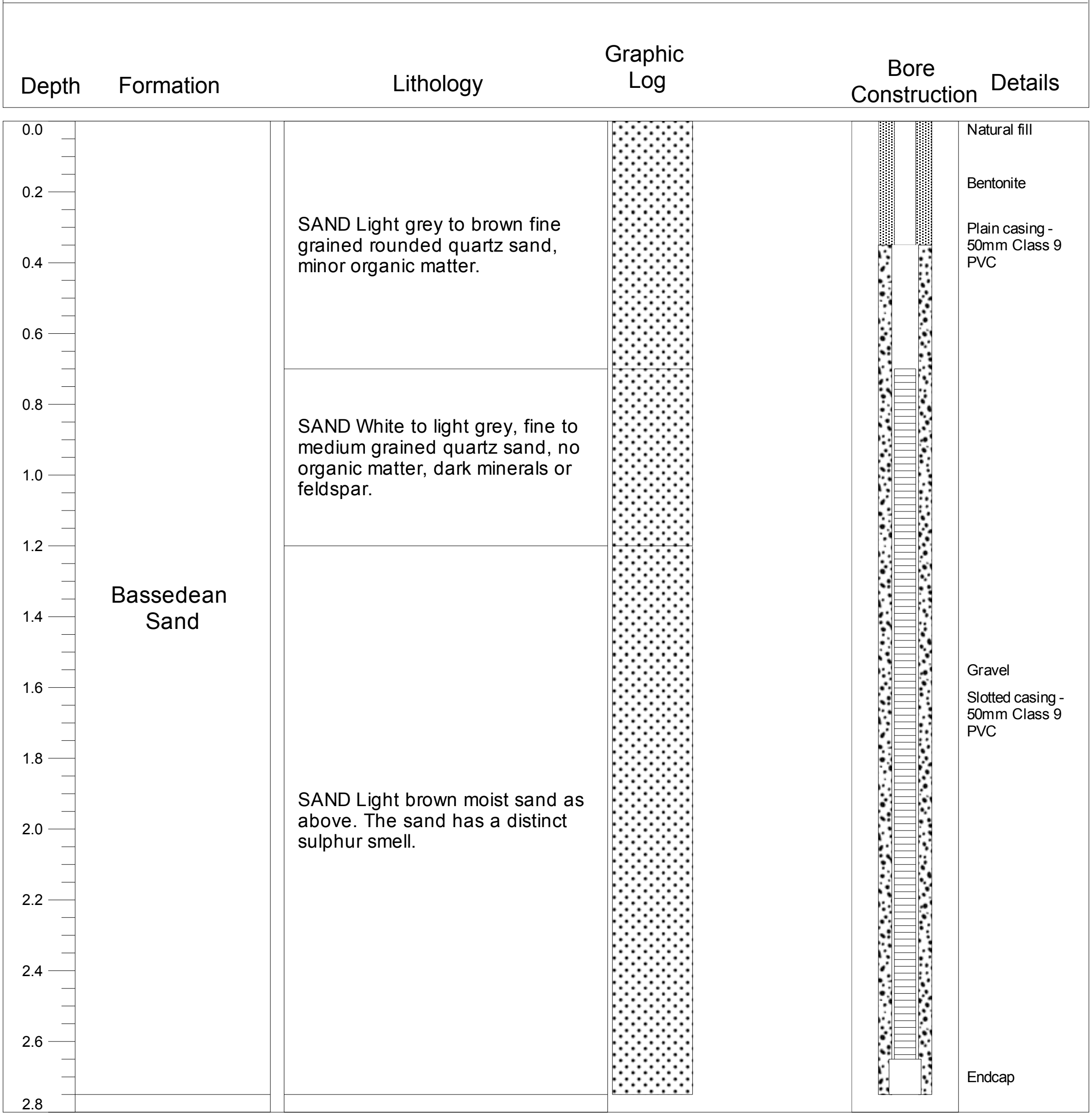
Drilled by:	Contractor	Northing (Z50):	6428464.125	Screens (m BNS):	0.75 - 2.45
Date drilled:	4/29/11	Easting (Z50):	395381.233	SWL (m BNS):	2.21
Logged by:	Peter Kretschmer	Surface (m AHD):	11.173		
Aquifer:	Superficial	Drill depth (m BNS):	2.55		

BORE COMPLETION DETAILS

AWRC Name: **SSB19**

AWRC Number: **61410493**

Serpentine DWMP Shallow Observation Bores



SAND Light grey to brown fine grained rounded quartz sand, minor organic matter.

SAND White to light grey, fine to medium grained quartz sand, no organic matter, dark minerals or feldspar.

SAND Light brown moist sand as above. The sand has a distinct sulphur smell.

Drilled by:	Contractor	Northing (Z50):	6428588.344	Screens (m BNS):	0.7 - 2.75
Date drilled:	5/2/11	Easting (Z50):	394929.58	SWL (m BNS):	
Logged by:	Peter Kretschmer	Surface (m AHD):	11.642		
Aquifer:	Superficial	Drill depth (m BNS):	2.75		

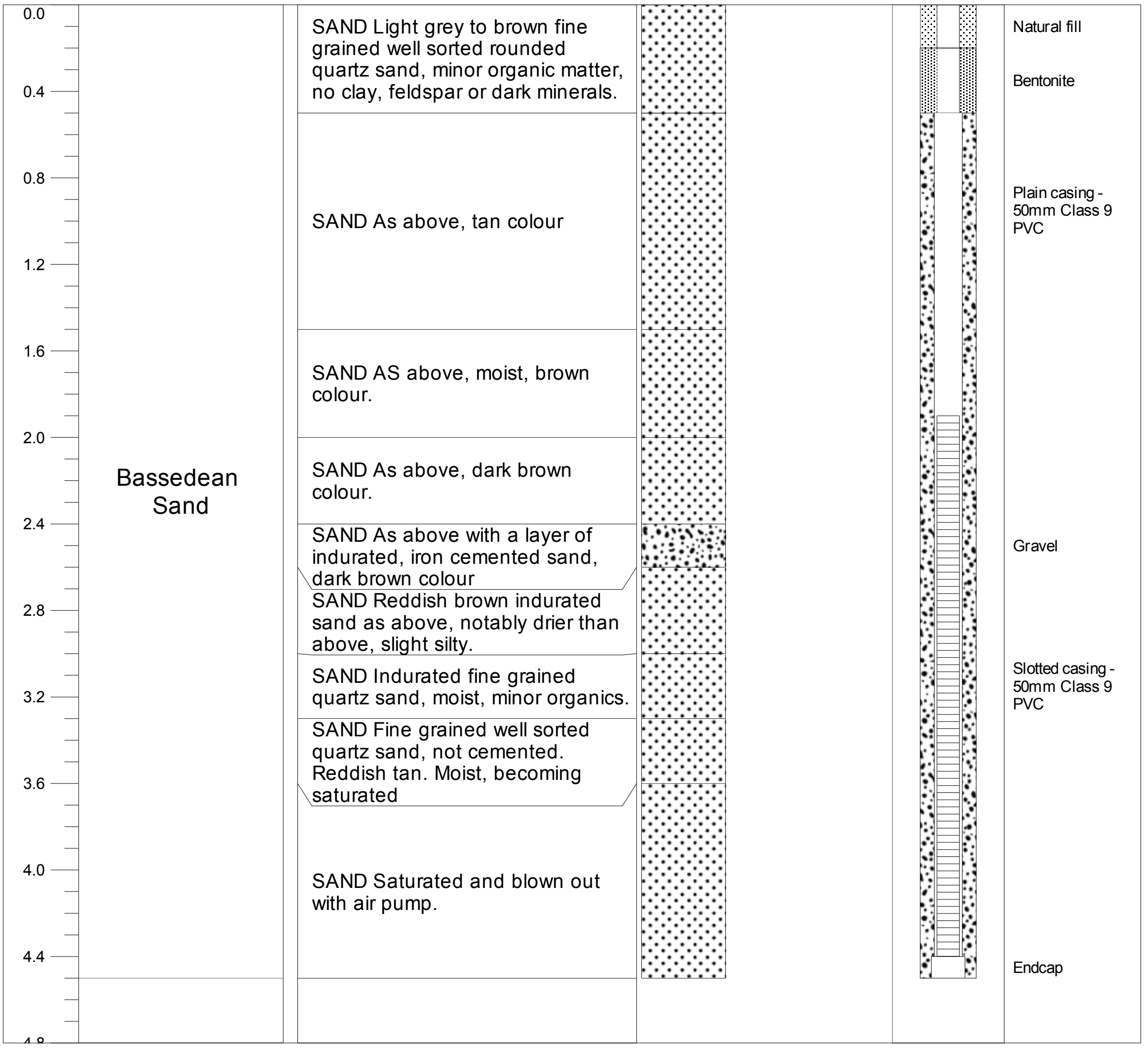
BORE COMPLETION DETAILS

AWRC Name: **SSB20**

AWRC Number: **61410494**

Serpentine DWMP Shallow Observation Bores

Depth	Formation	Lithology	Graphic Log	Bore Construction	Details



SAND Light grey to brown fine grained well sorted rounded quartz sand, minor organic matter, no clay, feldspar or dark minerals.

SAND As above, tan colour

SAND AS above, moist, brown colour.

SAND As above, dark brown colour.

SAND As above with a layer of indurated, iron cemented sand, dark brown colour

SAND Reddish brown indurated sand as above, notably drier than above, slight silty.

SAND Indurated fine grained quartz sand, moist, minor organics.

SAND Fine grained well sorted quartz sand, not cemented. Reddish tan. Moist, becoming saturated

SAND Saturated and blown out with air pump.

Drilled by:	Contractor	Northing (Z50):	6434278.928	Screens (m BNS):	1.9 - 4.4
Date drilled:	5/2/11	Easting (Z50):	397595.878	SWL (m BNS):	
Logged by:	Peter Kretschmer	Surface (m AHD):	21.18		
Aquifer:	Superficial	Drill depth (m BNS):	4.5		

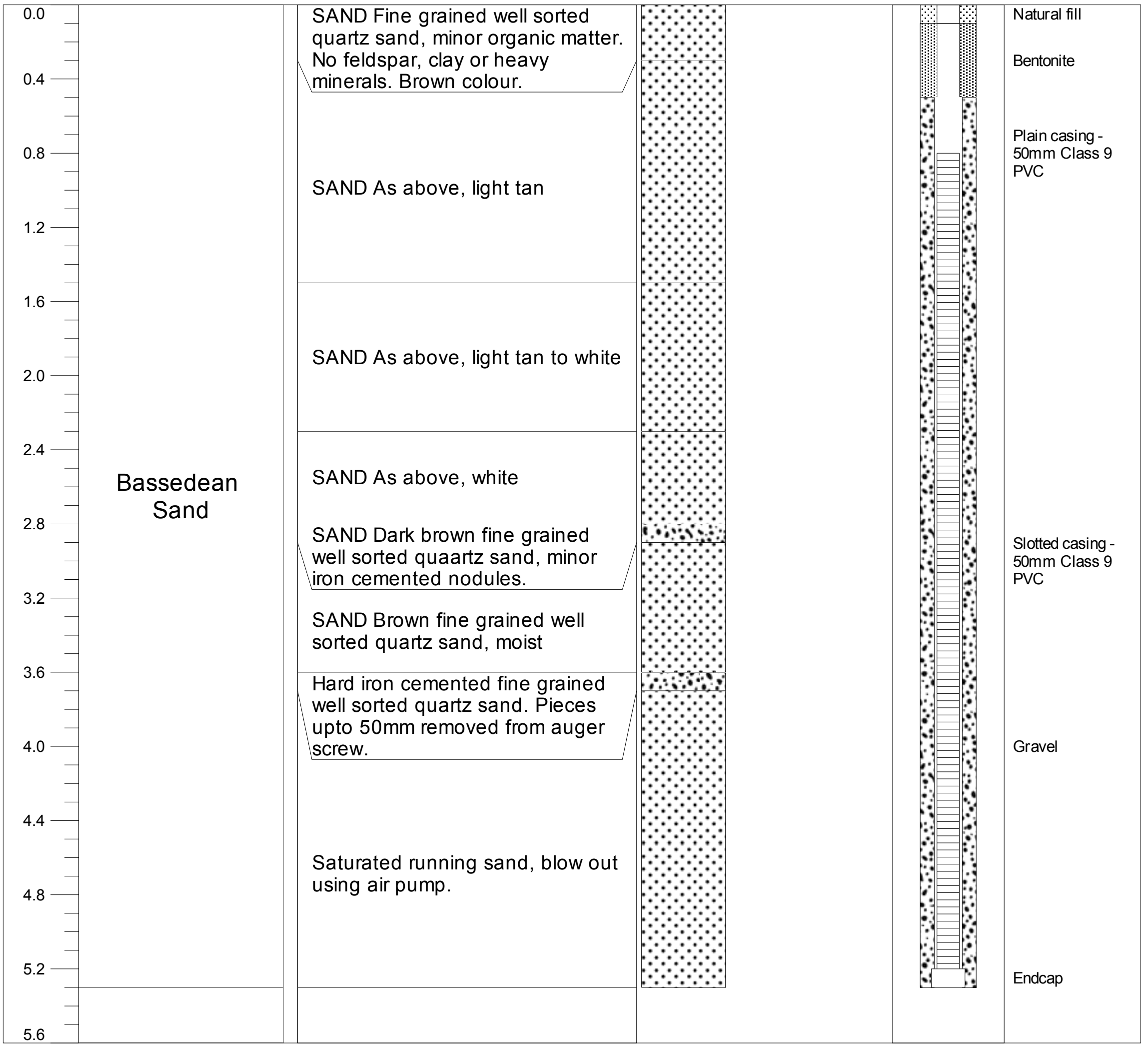
BORE COMPLETION DETAILS

AWRC Name: **SSB21**

AWRC Number: **61410495**

Serpentine DWMP Shallow Observation Bores

Formation	Lithology
Bassedean Sand	SAND Fine grained well sorted quartz sand, minor organic matter. No feldspar, clay or heavy minerals. Brown colour.
	SAND As above, light tan
	SAND As above, light tan to white
	SAND As above, white
	SAND Dark brown fine grained well sorted quaartz sand, minor iron cemented nodules.
	SAND Brown fine grained well sorted quartz sand, moist
	Hard iron cemented fine grained well sorted quartz sand. Pieces upto 50mm removed from auger screw.
	Saturated running sand, blow out using air pump.



Drilled by:	Contractor	Northing (Z50):	6433898.497	Screens (m BNS):	0.8 - 5.2
Date drilled:	5/2/11	Easting (Z50):	395309.424	SWL (m BNS):	
Logged by:	Peter Kretschmer	Surface (m AHD):	24.556		
Aquifer:	Superficial	Drill depth (m BNS):	5.3		

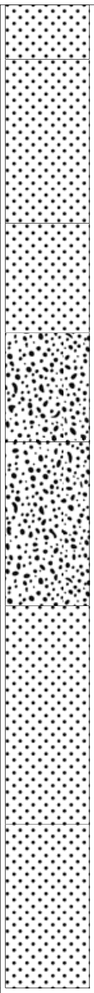
BORE COMPLETION DETAILS

AWRC Name: **SSB22**
AWRC Number: **61410496**

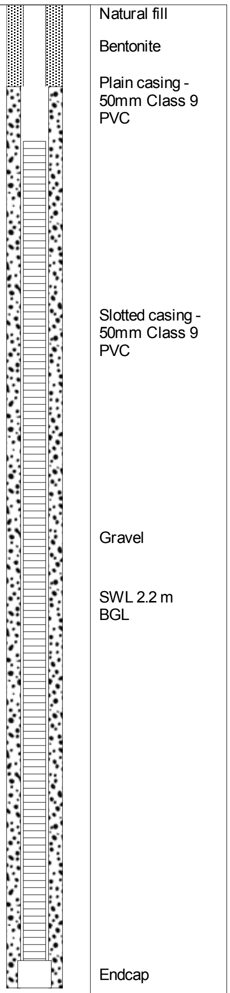
Serpentine DWMP Shallow Observation Bores

Depth	Formation	Lithology
0.0	Bassedean Sand	SAND Fine grained well sorted slightly organic sand.
0.2		SAND Light brown sand as above. No feldspar, black minerals or clay.
0.8		SILTY SAND Reddish brown iron cemented fine grained silty sand. Hard layer with gravelly pieces of cemeted sand coming up the auger.
1.2		SAND Dark brown and grey fine grained sand, organic odour, some iron cemented gravel.
1.6		SILTY SAND Hard iron-cemented layer. Changed to small auger bit to break though layer. Silty and clayey indurated sand.
2.2		SAND Fine to medium grained well sorted quartz sand, moistm, tan coloured.
3.0		SAND As above but saturated and running.
3.6		

Graphic Log



Bore Construction / Details



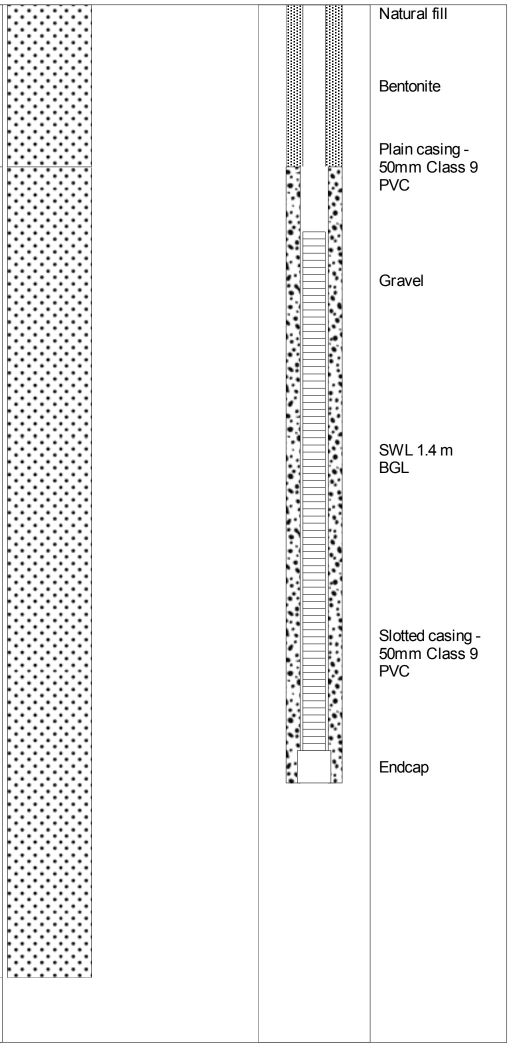
Drilled by:	Contractor	Northing (Z50):	6432462.494	Screens (m BNS):	0.5 - 3.5
Date drilled:	5/3/11	Easting (Z50):	395944.765	SWL (m BNS):	
Logged by:	Peter Kretschmer	Surface (m AHD):	20.862		
Aquifer:	Superficial	Drill depth (m BNS):	3.6		

BORE COMPLETION DETAILS

AWRC Name: **SSB23**
AWRC Number: **61410497**

Serpentine DWMP Shallow Observation Bores

Depth	Formation	Lithology
0.0 – 0.5	Bassedean Sand	SAND Fine to medium grained, well sorted sand. No dark minerals
0.5 – 3.0		SAND White medium grained wel sorted roudned to subrounded clean quartz sand. No dark minerlas or feldspar.



Drilled by:	Contractor	Northing (Z50):	6428910.171	Screens (m BNS):	1.7 - 2.3
Date drilled:	5/24/11	Easting (Z50):	395565.293	SWL (m BNS):	1.4
Logged by:	Peter Kretschmer	Surface (m AHD):	13.26		
Aquifer:	Superficial	Drill depth (m BNS):	2.4		

Shortened forms

ABS	Australian Bureau of Statistics
ARI	average recurrence interval
BP	British Petroleum
DHI	Danish Hydrological Institute
DoW	Department of Water
DWMP	drainage and water management plan
EWR	environmental water requirement
IPCC	Intergovernmental Panel on Climate Change
LBG	Leggette, Brashears & Graham
LAI	leaf area index
LiDAR	Light Detection and Ranging
NSE	Nash-Sutcliffe efficiency
PRAMS	Perth Regional Aquifer Modelling System
RD	rooting depth
RMS	root mean square
SWAMS	South-West Aquifer Modelling System
SQUARE	Streamflow Quality for Rivers and Estuaries model
TDS	total dissolved solids
WAPC	Western Australian Planning Commission
WAVES	Water Atmosphere Vegetation Energy Solutes model
WAWA	Water Authority of Western Australia (former)
WIN	Water Information Network

Glossary

Abstraction	pumping groundwater from an aquifer
Australian height datum (AHD)	height datum used within the study
Alluvium	detrital material transported by streams and rivers and deposited
anticline	sediments folded in an arch
aquifer	a geological formation or group of formations able to receive, store and transmit significant quantities of water
unconfined aquifer	a permeable bed only partly filled with water and overlying a relatively impermeable layer – its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure
confined aquifer	a permeable bed saturated with water and lying between an upper and a lower impermeable layer
semi-confined	a permeable bed saturated with water and lying between an upper and a lower impermeable layer
artesian aquifer (bore)	a confined aquifer with sufficient hydraulic head that the water in a bore would rise above the ground surface
perched aquifer	an unconfined aquifer separated from an underlying body of groundwater by an unsaturated zone (contains a perched watertable)
baseflow	that portion of a river and streamflow coming from groundwater discharge
basin (geological)	a depression of large size, which may be of structural or erosional origin (contains sediments)
beds (geological)	a subdivision of a formation: smaller than a member
bore	small-diameter well, usually drilled with machinery
coffee rock	colloquial term for iron oxide (limonite)-cemented sand grains
colluvium (colluvial)	material transported by gravity down hill slopes
confining bed	sedimentary bed of very low hydraulic conductivity

conformably	sediments deposited in a continuous sequence without a break
unconformably	time break in sequence of deposition
Cretaceous	final period of the Mesozoic era spanning 65 to 135 million years ago
discharge (groundwater)	all water leaving the saturated part of an aquifer
effective porosity	drainable pore space, considered synonymous with specific yield of unconfined aquifer
Aeolian	wind-blown; deposit formed by wind action
ephemeral stream	stream or river that flows briefly in direct response to rainfall and whose channel is above the watertable
estuary (estuarine)	the seaward or tidal mouth of a river where fresh water comes into contact with seawater
evapotranspiration	a collective term for evaporation and transpiration
facies	a mappable lithostratigraphic unit, differing in lithology from adjacent units deposited at the same time and in lithological continuity
fault	a fracture in rocks or sediments along which there has been an observable displacement
field capacity	soil moisture retained by capillarity, not removable by gravity drainage
fluvial	pertaining to streams and rivers
flux	outflow or inflow
formation (geological)	a group of rocks or sediments which have certain characteristics in common and which were deposited in about the same geological period and constitute a convenient unit for description
geographical information systems (GIS)	an arrangement of computer hardware, software and geographic data that people interact with to integrate, analyse and visualise the data; identify relationships, patterns and trends; and find solutions to problems (A GIS is designed to capture, store, update, manipulate, analyse and display the geographic information. It is typically used to represent maps as data layers that can be studied and used to perform analyses.)
group (geological)	includes two or more contiguous or associated formations with significant lithological features in

	common
hydraulic	pertaining to water motion
conductivity (permeability)	ease with which water is conducted through an aquifer
gradient	the rate of change of total head per unit of distance of flow at a given point and in a given direction
head	the height of the free surface of a body of water above a given subsurface point
infiltration	movement of water from the land surface to below ground level
interfinger	lithological facies being conformably and alternatingly deposited
isopach	a contour line joining points of equal geological-unit thickness
isopotential	equipotential; having uniform hydraulic head
Jurassic	the second period of the Mesozoic era spanning 135 to 190 million years ago
juxtaposition	side by side
karst	a type of topography that is formed on limestone by dissolution, and that is characterised by sink holes, caves, dolines, solution channels and underground drainage
lacustrine	pertaining to, produced by, or formed in a lake
LiDAR (Light Detection and Ranging)	an optical remote sensing technology that has been used in the study to define the topography at a horizontal scale of 1 m x 1 m and a vertical accuracy 0.15 m
lateritised (lateritic)	a surficially formed deposit consisting mostly or entirely of iron and/or aluminium oxides and hydroxides
leach (leaching)	removal of soluble matter by percolation of water
leakage (groundwater)	movement of groundwater from one aquifer to another
levee	bank of a watercourse
member (geological)	a lithostratigraphic unit of subordinate rank, comprising some specially developed part of a formation
Mesozoic	an era of geological time spanning 65 to 225 million years ago

model (modelling system)	a simplified version of the hydrological system that approximately simulates the excitation-response relations of the real system
Neocomian	lowermost stage of the Cretaceous period
oxidising	combine with oxygen
percolation	movement of water from the land surface to the watertable after infiltration
permeable	ability to permit water movement
plain	tract of flat or level terrain
pore space	the open spaces in sediments, considered collectively
potentiometric surface	an imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a bore (The watertable is a particular potentiometric surface.)
Quaternary	the latest period in the Canozoic era
recharge (groundwater)	all water reaching the saturated part of an aquifer (artificial or natural)
salinity	a measure of the concentration of total dissolved solids (TDS) in water: 0 to 500 mg/L, fresh 500 to 1500 mg/L, fresh to marginal 1500 to 3000 mg/L, brackish 3000 mg/L and greater, saline
scarp	a line of cliffs (steep slopes) produced by faulting or by erosion
shelf	shallow, marginal part of a sedimentary basin
solution channel	tubular or planar channel formed by solution of calcium carbonate in limestone
specific yield	the volume of water that an unconfined aquifer releases from storage per unit surface area of the aquifer per unit decline in the watertable
storage coefficient	the volume of water that a confined aquifer releases from storage per unit surface area of aquifer per unite decline in the component of hydraulic head normal to the surface
stratigraphy	the science of rock strata: concerned with original succession and age relations of rock strata and their form, distribution, lithology, fossil content, geophysical and geochemical properties

syncline	a basin shaped fold in sedimentary strata
tectonic	pertaining to the forces involved in major earth movements in, or the resulting structures or features of, rocks
Tertiary	the first period of the Canozoic era spanning two to 65 million years ago
throughflow (groundwater)	groundwater flow within an aquifer
transmissivity	the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient
transpiration	the loss of water vapour from a plant, mainly through the leaves
trough (geological)	a linear depression or basin that subsides as it receives clastic material, located not far from the source supplying the sediment
watertable	the surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere
well	large-diameter bore, usually dug or drilled for abstracting groundwater; also petroleum bore
yield	sustainable rate at which a bore or well can be pumped

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