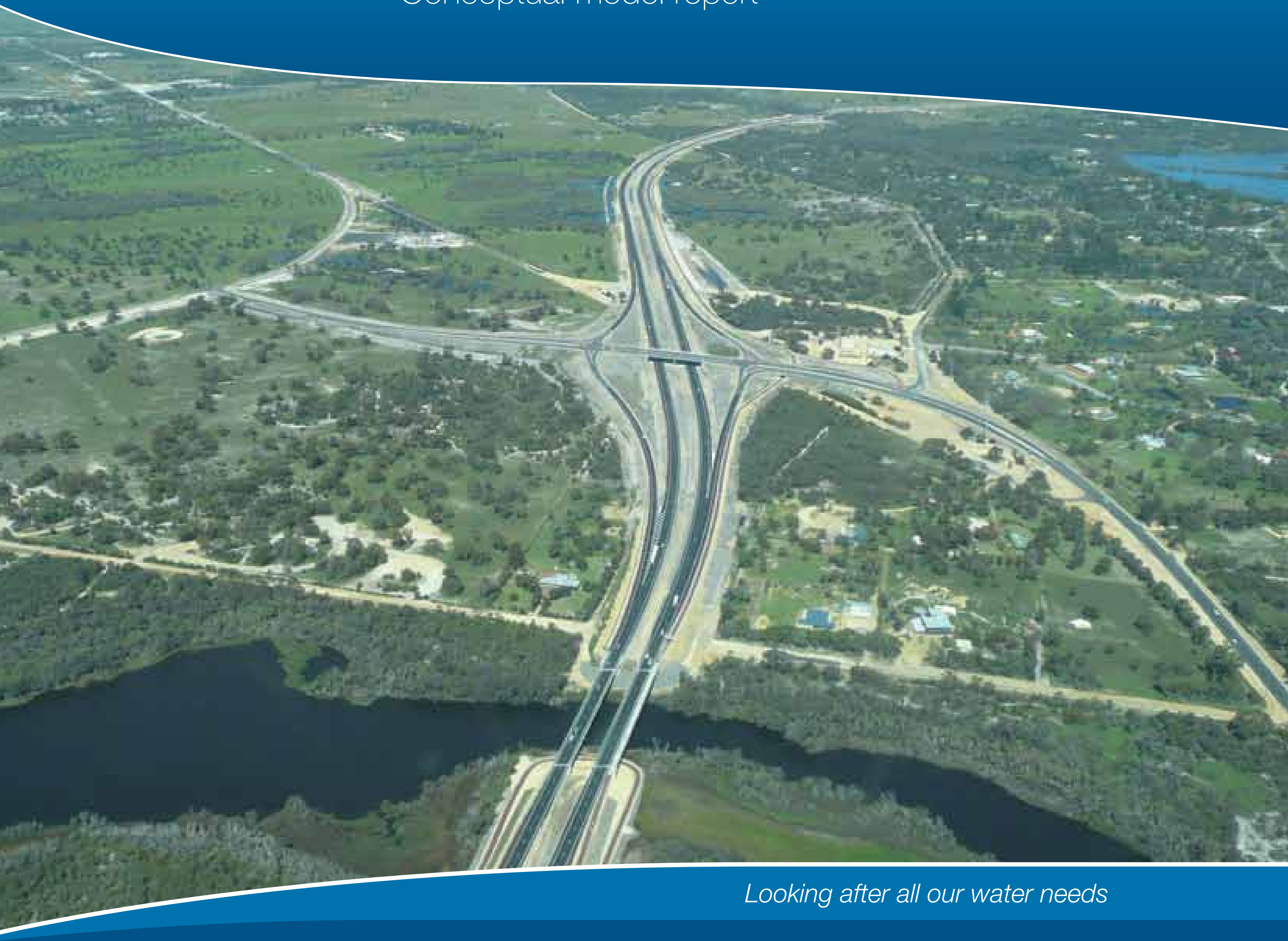
Government of **Western Australia**
Department of **Water**

Murray hydrological studies: surface water, groundwater and environmental water

Conceptual model report



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Water*Science*
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Report no. WST 16
May 2010

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Department of Water

Water Science Branch Technical Series

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Cover photograph: Aerial view of the Murray DWMP region facing south east, J Hall (2010)

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Summary

The purpose of the *conceptual model report* was to develop a conceptual groundwater / surface water model and steady-state water balance model for the Murray study area, and to provide a conceptual design of water movement in the wetland systems. It constitutes one of three project reports which comprise the overall project deliverable specified by Drainage and Waterways Branch of the Department of Water. The conceptual model reflects data collation and analysis, based on an extensive literature review, stakeholder consultation, and data interpretation.

The report is a component of the Murray drainage and water management plan (DWMP). The DWMP is a key step vital for the development of structure plans that are required for urban growth, future development and for management of environmental issues. The *conceptual model report* includes two component studies:

- Groundwater studies: the purpose of the groundwater study is to develop and calibrate a regional scale groundwater model, and to use this model to run various climate, drainage and land use change scenarios.
- The hydrological component of the ecological water requirements study, which includes the estimation of surface and groundwater inflows, outflows and water levels for key wetlands within the study area.

Study area

The study region receives approximately 900 mm of rainfall per year and annual pan evaporation averages approximately 1540 mm. The area lies on the Perth Basin which is bordered by the Darling Scarp to the east and the Indian Ocean and Peel Harvey estuary to the west. Most of the study area lies on the Swan Coastal Plain, where elevations range from approximately 0 – 80 m AHD. The catchment is characterised by a high water table, and an extensive drainage system throughout the catchment is used to relieve water-logging and flooding during winter months. Major waterways include the Murray River and Serpentine River which discharge to the Peel Inlet.

Geology and hydrogeology

Over 500 bore logs were assessed and the lithology classified to construct a three-dimensional model of the geology between the ground surface and the top of the Leederville Formation. The model includes ten sub-classifications in the superficial formation, plus the Rockingham Sand and Leederville Formation. The descriptions and mapped extents of all formations and members are provided, including an extensive revision of the Rockingham Sand Paleochannel.

The three aquifers discussed in the hydrogeology are the Superficial, Rockingham and Leederville. Descriptions of the aquifers and aquifer dynamics are discussed and parameters provided. Horizontal hydraulic conductivities range from around 1 m/d in clayey formations, 10-20 m/d in the sandy formations and up to 140 m/d in the Tamala Limestone. Updated phreatic and potentiometric surface maps were created for the Superficial and Leederville Aquifers, generally illustrating an east-west flow pattern intersected by the Murray River in the south and Serpentine River and Nambeelup River in the north.

Wetlands

Eight key wetlands were selected for analysis of their ecological water requirements, which involved detailed hydrodynamic investigations. Maps are provided for recently drilled monitoring bores located in close proximity to the wetlands. Water level measurements in monitoring bores were used to relate wetland water levels with local and regional groundwater hydrodynamics. Most wetlands are connected to the drainage network, and in some cases it is likely that drain levels will constrain the maximum wetland water levels. All eight wetlands appeared to be flow-through wetlands, and some are likely to be recharging wetlands for small periods following rainfall events.

Numerical conceptualisation

The conceptual model is based on the collation of hydrological, hydrogeological, geological, climate and topological information gathered as part of the literature review and the data interpretation process. A numerical steady-state water balance conceptual model was developed which includes surface water, groundwater and their interaction. The annual average water balance as a percentage of rainfall is: gross recharge 49%, irrigation recharge 0.6%, evapotranspiration 30.3%, net drainage 14.3%, abstraction 2.2%, horizontal groundwater flow leaving the model 1.9% and vertical percolation (to the Leederville Aquifer) 0.8%. Based on the knowledge gained during conceptualisation the decision was made not to incorporate the Leederville Aquifer into the regional model due to its relatively small contribution to water fluxes in the study area. The conceptual model forms a basis for the construction and calibration of a transient numerical groundwater / surface water model.

1 Introduction

The Western Australian Planning Commission in consultation with local government authorities, have identified the need to develop structure plans for areas of urban growth as a high priority. Structure plans provide guidance for future development and management of environmental issues. A key step in the implementation of a structure plan is the creation of a drainage and water management plan (DWMP) that embraces water sensitive urban design (WSUD), best management practices and provides a framework for more site specific water management plans. A DWMP addresses the following aspects of the total water cycle:

- Protection of significant ecological assets within the structure plan area, including meeting their water requirements and managing potential impacts from development.
- Water demands, supply options, opportunities for conservation and demand management measures and wastewater management.
- Surface runoff, including peak event (flood) management and WSUD principles to be applied to frequent events.
- Groundwater, including the impact of urbanisation, variation in climate, installation of drainage to manage maximum annual groundwater levels, potential impacts on the environment and the potential to use groundwater as a resource.
- Water quality management, which includes source control of pollution inputs by catchment management, acid sulphate soil management, control of contaminated discharges from industrial areas and management of nutrient exports from surface runoff and groundwater through structural measures.

As part of the Murray region DWMP, the Drainage and Waterways Branch (DWB) of the Department of Water (DoW) has instigated the following projects:

1. Flood-plain development study including inundation and local catchment stormwater modelling
2. Groundwater studies including regional pre-development groundwater levels, water balance modelling, climate impacts and extent of current waterlogged areas
3. Preparation of a DWMP for the DWMP study area
4. Formulation of detailed stormwater drainage strategies as required for selected areas of proposed development.

GHD Pty Ltd (GHD) has been contracted to write the DWMP for the Murray region, which will integrate the results of the other studies. The Water Science Branch (WSB) of the DoW has been commissioned to deliver the ‘Groundwater studies’ project, and for the provision of the hydrological deliverables of the ‘Ecological water requirements and ecological study’ project component.

The DWMP area includes a portion of the Swan Coastal Plain centred on Ravenswood, where there is relatively flat terrain, significant water logging, wetlands of significance, and risk of riverine flooding. The study extends from the Nambeelup Brook catchment in the north, Lower Serpentine River and Peel Inlet/Harvey Estuary in the west, Fauntleroy Drain catchment in the south and the Murray River / Darling Range foothills in the east.

The area specified for the groundwater studies, designated 'Modelling boundary' in Figure 1-1, is larger than the DWMP area, and is referred to as the 'Murray study area' in this document. The Murray study area extends east to the Darling Fault, west to the Indian Ocean and Peel-Harvey estuary and approximately 5 km north and south of the DWMP study area to the boundary of Dirk Brook and Caris Drain.

1.1 Project objective

Groundwater studies

The purpose of the groundwater study is to develop and calibrate a regional scale groundwater model, and to use this model to run various climate and land use change scenarios. The groundwater study has been re-named 'Murray hydrological studies: surface water, groundwater and environmental water', due to the high degree of surface/groundwater interaction, the requirement to study both parts of the water regime in the Murray region, and the requirement to determine EWRs (environmental water) for wetlands. The model will thus be an integrated surface/groundwater model, and will reflect the nature of the local environment which has wetlands of significant size and value.

The primary objectives of the study are to deliver a calibrated regional scale groundwater model, to develop and run a suite of scenarios, and to deliver associated maps and ESRI shape-files.

The project requirements include the modelling of various climate scenarios, pre- and post-development scenarios, and Water Sensitive Urban Design construction philosophies to determine:

- maximum, minimum, average annual maximum and average annual minimum groundwater levels (MaxGL, MinGL, AAMaxGL, AAMinGL)
- water balance modelling including changes in groundwater discharges, interaction with surface water and environmental water
- likely impacts of acid sulphate soils (ASS)
- reuse opportunities such as community bores and surface detention
- likely areas of water-logging
- water balance modelling including flows in drains and tributaries
- flood, drought, wet, dry and average year impacts
- impacts on water dependent ecosystems (wetlands) and ecology
- guidance for the design of the drainage (surface and groundwater infrastructure).

Ecological water requirements and ecological study

Ecological water requirements (EWR) are defined as the low risk water regime required to maintain the ecological values of water dependent systems. EWR estimates are based on the water requirements of wetland vegetation with limited consideration of other factors.

An EWR is composed of two parts:

- A hydrologic study providing a detailed hydrological assessment of wetlands. This information is used to determine wetland water levels and surrounding groundwater levels, under various climate and land use conditions.
- A vegetation study including a detailed vegetation survey, drilling, monitoring, and analysis for the key wetlands. GHD have been contracted to conduct this component of the EWR.

The hydrological study of the EWR includes the estimated surface and groundwater inflows, outflows and water levels from the modelling for key wetlands within the study area. These key wetlands will be identified by DWB. WSB will conduct this component of the EWR.

Integration of studies

The groundwater and surface water study will estimate groundwater levels, surface flows, groundwater interactions, water-logging, and will provide MinGL, MaxGL, AAMaxGL and AAMinGL. This will allow the development of a controlled groundwater level (CGL) which takes into account the wetland EWR defined in the ecological study.

The specific deliverables from WSB will be a description of the current hydrology and the predicted hydrology for each of the wetlands taking into account land use and climate change. The ecological team from GHD can then assess the potential impacts on the wetlands. The EWR will be specified for each wetland in collaboration with the ecological team.

1.2 Scope of work

The scope of the surface and groundwater hydrological studies and EWR hydrological studies can be broadly divided to three phases. Each phase will have its own detailed scientific report, which will be reviewed before the following phase is undertaken. The three phases involved in surface and groundwater component of the study include:

1. To develop a conceptual groundwater / surface water model and steady-state water balance model for the Murray study area including:
    - a review of relevant literature
    - description of the study area
    - description of the climate and hydrology
    - interpretation and development of a three-dimensional conceptual model of the geology
    - definition of all aquifers and major hydrogeological processes

- a description of the hydrological and hydrogeological processes and parameters
- a numerical steady-state water balance conceptual model which includes surface water, groundwater and their interaction

This project phase is described in the following report.

2. Construct and calibrate a regional transient numerical model for the Murray study area. This will involve the simulation of surface water in relevant waterways, groundwater flow in each aquifer, the determination of a water budget for each of the aquifers and the determination of groundwater level contours. This phase will involve sensitivity analysis for the major parameters in the model. This work will follow on from 1) and will be described in a subsequent report titled the "*Model construction and calibration report"* (Hall *et al* 2010b).
3. A suite of predictive runs will be undertaken to determine the change to water budgets and groundwater levels under various climate and land use scenarios. This phase will follow on from 2) and will be described in a subsequent report titled the *"Land development, drainage and climate scenario report"* (Hall *et al* 2010c).

The three phases of the EWR hydrological studies component of the project have the following scope:

1. Characterisation and conceptualisation of the wetlands included in the EWR. Determination of the appropriate drivers for wetland water levels, based on available literature and data gathered from hydrogeological measurements and stratigraphy interpretation from the recent drilling programme undertaken by GHD. This project phase is described in the following report.
2. Construction and calibration of finer grid scale wetland models using modelling results from Phase 2 of the surface water and groundwater studies. Detailed calibration of fine-scaled models will be completed using data collected during the 2009 winter by Department of Water staff. Boundary conditions for wetland models will be taken from the regional model. This phase will be described in the "*Model construction and calibration report".*
3. A suite of predictive runs will be undertaken to determine the change in water levels and water balances in the wetlands under various climate, land use and drainage scenarios. This phase will be described in the "the *"Land development, drainage and climate scenario report"*.

2 Literature review

Geological, hydrogeological, and wetland investigations have been undertaken in the study area since the late 1960s. Until the late 1980s investigations were mostly undertaken by the Geological Survey of Western Australia (GSWA), however increasing demands for groundwater and minerals have led to an increasing number of commercial investigations. An extensive review of the publications was undertaken by WSB to aid the development of a regional conceptual model. Listed below, in chronological order, is a summary of previous studies.

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

Driller's logs, surface geology mapping and seismic surveys were used to map the regional stratigraphy. A detailed surface geology map is included. Descriptions of the stratigraphic units contained in this report require careful interpretation as it was published prior to much of the Superficial Formation nomenclature being finalised. The main superficial stratigraphic units described are:

- lateritic alluvium and sand on the Ridge Hill Shelf
- coastal Limestone (lower unit)
- alluvium of the Pinjarra Plain
- Rockingham Sand and other sandy beds concealed in deep channels
- coastal limestone (upper unit)
- Safety Bay Sand.

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

The stratigraphic name 'Rockingham Sand' was first proposed in this study. Passmore describes the Rockingham Sand type-section as thin sandy clay beds amongst yellow and brown sands. A brown clayey matrix is common and several metres of yellow-brown sandy claystone is also recorded near the top of the formation at one location. Based on grain size and shape it is inferred that the sand travelled from the Darling Scarp to the erosion channel via a direct route. This inference is supported by the new geological interpretations produced during this study.

Hydrogeology of the Mandurah – Pinjarra area, Perth Basin D.P. Commander (1975)

The stratigraphy of 41 government exploration and private industry bores were analysed during this study. The report provides detailed information on the Mesozoic formations, including cross-sections, hydrochemistry and flow-systems. For the Tertiary and Quaternary deposits the information is relatively brief. The analysis illustrates the existence of the South Perth Shale, separating the Leederville and Cattamarra Aquifers.

An outline of the groundwater resources of the Mandurah–Bunbury region D.P. Commander (1982)

This study produced quantitative estimates of the storativity, recharge, throughflow and abstraction for six of the regional superficial flow systems, plus the underlying pre-Tertiary aquifers. It maps out the regional isopotentials of the superficial formation, and divides it into separate regional flow systems. Later in Davidson (1984) two of the flow systems relevant to this study are titled the Waroona Flow System and the Serpentine Flow System, located south and north of the Murray River respectively.

Hydrogeology of the eastern coastal plain between North Dandalup River and South Dandalup River W.A. Davidson (1982)

This report describes an investigation into the effect on groundwater recharge by the damming of the North Dandalup River. The investigation concludes there will be little difference as most recharge occurs via direct rainfall on the plain rather than infiltration from the river. It notes the upper surface of the Leederville has been eroded and unconformably overlain by flat, westerly sloping sediments of the superficial formations. It also notes that the superficial formations overly the Cockleshell Gully formation under the far eastern margin of the coastal plain. A downward head gradient is also observed from both the North Dandalup River to the superficial formations and from the superficial to the Mesozoic formations, However, due to the high clay content little interaction occurs between the formations.

A flow-net analysis of the unconfined groundwater in the superficial formations of the southern Perth area, Western Australia W.A. Davidson (1984)

Flow-net analysis and the chloride mass balance approach is used to calculate the groundwater through-flow of six discrete hydrological areas. The results inferred that there is significant downward flux from the superficial to the underlying aquifers. The report contains a potentiometric map recorded in April – May 1976 which illustrates the influence of the Jandakot Mound and a second mound at Stake Hill west of the Serpentine River. East of the Serpentine River the dominant flow direction is east to west. The study does not extend south of the Murray River.

In the Serpentine Flow System the flow-net method estimated that 24.5 ML/d discharges to the Serpentine River directly and via drains, 37 ML/d leaks into the underlying aquifers, and 4.5 ML/d drains into the Nambeelup River, North Dandalup River and Murray River. Further, 1 ML/d is lost to evaporation, and an additional 2.5 ML/d is gained from upward leakage. The water balance estimates 6.5% of rainfall becomes net recharge. It is noteworthy that these figures are based on late summer potentiometric heads.

Geology and hydrogeology of the superficial formations and coastal lakes between Harvey and Leschenault Inlets
D.P. Commander (1988)

The superficial formations along the coastal margin south of the Peel Inlet are described in this report. In some locations there is a downward head gradient of around 0.4 m between the water table and the base of the superficial, with this gradient being greatest at the end of winter. Other observations include locations within the Superficial Aquifer where confinement occurs due to clay lenses at the surface; coastal lakes that act as groundwater sinks due to evaporative loss. An estimate of 5.1%–5.8%.of through-flow to the lakes is estimated from the water balance.

The geology and groundwater resources of the superficial formations of the coastal plain between Pinjarra and Bunbury
A.C. Deeney (1989)

151 bores in the study area, bounded by the Murray and South Dandalup Rivers to the north, were used to provide detailed descriptions and maps of the Yoganup Formation, Ascot Formation, Guildford (Gnangara) Sand, Guildford Clay, Bassendean Sand, Tamala Limestone, Safety Bay Sand, Colluvium and Alluvium. The study also investigated the hydrogeology of the area. Relevant observations include:

- the aquifer is heterogeneous and anisotropic
- the Guildford Clay is an important aquitard
- the water table is generally between 1 – 2 m below the surface
- estimates of regional transmissivity, hydraulic conductivity, and coefficient of elastic storage
- pumping tests show K_z is 10 – 1000 times smaller than K_h
- three regional flow systems exist; Waroona, Serpentine, and Myalup
- cross-sections indicate that the Yoganup Formation extends underneath the Guildford Clay and interconnects with the Ascot Formation
- groundwater salinities are generally higher in the Guildford Clay.

Groundwater allocation plan – Murray Groundwater Area
Scatena and King (1998)

This report summaries the knowledge of the regional hydrogeology up to the time of publishing, and discusses the sustainable allocation limits. The main points are:

- total available groundwater allocation for all aquifers is 69000 ML/yr
- the licensed 1998 abstraction by aquifer was: Superficial 2900 ML/year, Leederville 3200 ML/year, Cattamarra 4200 ML/yr
- the main users of groundwater are: Industry (51.4%), crop and pasture (28.4%), public water supply (6.8%), and recreation (7.2%)
- the Alcoa bauxite refinery and mineral sand mines are significant users

- it is likely that much of the recharge to the superficial aquifer is intercepted by drains prior to deep percolation
- the Murray River has eroded the Guildford Clay and it now cuts into the Yoganup Formation, acting as a discharge point for groundwater
- the Rockingham Aquifer is in hydraulic connection with the Superficial Aquifer where the clay lenses are absent
- recharge to the Leederville Aquifer is inferred in parts of the central and eastern portion of the plain where the downward gradient is in excess of 5 m
- recharge to the Cattamarra Coal Formation occurs along the eastern edge of the coastal plain where the superficial formations overly the Cattamarra Coal Formation.

Nambeelup groundwater study
Parsons Brinckerhoff (2002)

The findings of this study are based on 13 shallow bores, drilled to approximately 5 m, of which the bore construction and lithological logs are included in the report. The geology is interpreted to be Bassendean Sand overlying Guildford Clays. Groundwater flows are interpreted to be towards the Serpentine River, although the Nambeelup River exerts some influence on the southern boundary of their study area. Localised swamp depressions which waterlog in winter are also present, as well as localised ‘coffee rock’ layers approximately 1 m below the water table. Seasonal water table fluctuations are around 2 m. An updated water levels memorandum was published in 2008.

Waroona Deposit impacts of mining on shallow groundwater deposits
URS for Iluka Resources Ltd (2002)

This study used a high density of bore sampling over a proposed mineral sands project. Extensive testing was done to estimate hydraulic conductivity values and specific yield. Detailed stratigraphy illustrating the relationship of the Yoganup Formation with the scarp is described. The location of the Guildford Formation and colluvium is also included. A finite-element model was developed using 20 computational layers. The majority of these layers were 8 m thick, and were assigned material type based on varying hydraulic parameters.

Rockingham–Stakehill groundwater management plan
Department of Water (2008)

This report provides details on sustainable abstraction limits for its study area, as well as the current status of the resources. It illustrates that some wetland water levels have a long term decreasing trend while others remain constant. The trends in wetlands are shown to be related to downward trends in the Superficial Aquifer, potentially due to abstraction and decreased rainfall. The Leederville and Yarragadee Aquifers also show clear downward trends in head level as a result of abstraction. The spatial distribution of licensed allocations is detailed as well as by the user categories, for example; industry, mining and pastoral. It is noted that the Rockingham Aquifer hydraulic heads are very similar to the Superficial Aquifer trends.

Perth Regional Aquifer Modelling System (PRAMS) model development: hydrogeology and groundwater modelling
Davidson and Yu (2008)

This project produced a coarse resolution MODFLOW regional model that also details the pre-Tertiary stratigraphy. Descriptions of the various lithological layers and aquifer parameters are also given, although limited detail is provided for the superficial formations. The modelling does not extend south of the Murray River and Dandalup Rivers.

Local scale groundwater modelling of Mundijong
CyMod Systems Pty Ltd (2009)

This report outlines the development of a local-area groundwater model based on PRAMS, focusing on the Superficial Aquifer. It was also based on a MODFLOW approach, however in higher resolution and more detail within the Superficial Aquifer compared to Davidson & Yu (2008). Points of interest include:

- the Superficial Aquifer was divided into 2 layers and the geology was divided by grain size rather than formation type
- clay lenses were marked out using a coarse interpretation between bores for the two layers, however K_h was assumed to be constant in both layers for a given location
- PRAMS was used for time varying north, south, and west model boundaries, the east (Darling Scarp) is considered a no flow boundary.

The southern Perth groundwater bulletin
Pennington Scott (2008) for the Department of Water

This report contains a detailed summary of the geology for south-west Western Australia, south of the Peel Inlet. The summary is based on the DoW monitoring bore network and includes information on depth to the base of the superficial, thickness of the superficial, and its salinity. It also summarises the regional aquifers and aquitards and contains a summary of regional hydrodynamics and abstraction.

Peel-Harvey coastal groundwater model: conceptual model
URS (2009a)

This report outlines the design of the Peel Harvey Regional Modelling System (PHRAMS), a model designed to fill the gap between PRAMS and the South West Aquifer Modelling System (SWAMS). The geology is largely based on the earlier work by Deeney (1989), and Commander (1975, 1988). The model construction is largely based on PRAMS (Davidson & Yu 2008), with an important exception being the division of the Superficial Aquifer into three layers rather than two. The model boundaries are the Darling Scarp (no flow), ocean (0 mAHD), the South Dandalup and Murray Rivers to the north, and the Collie River to the south.

Peel-Harvey coastal groundwater model: model construction and calibration URS (2009b)

Following on from the conceptual model report (URS 2009a), this report summaries the model construction and calibration. Calibrated values for hydraulic conductivity are generally lower than for PRAMS, except for the Ascot Formation which is considerably higher. Investigations into groundwater extraction from the study area found it is split 93% superficial to 7% from the underlying aquifers. Estimates of recharge are shown to be highly variable spatially, and evaporation is between 1100–1400 mm/year. The calculated annual groundwater balance for year 2002 is:

- inputs: Recharge (69%), and storage (29%)
- outputs: Evaporation (51%), storage (29%), drains (11%), and abstraction (8%).

Model error is highest in the eastern margin where it generally over-predicts the hydraulic head of the Superficial Aquifer. The cause of this is thought to be a combination of hydraulic connection in the Guildford Formation (presumably with the underlying Yoganup Formation), initial heads being too high, and drainage not removing enough water from the system.

3 Description of study area

3.1 Climate

The Murray study area has a Mediterranean climate with hot dry summers and cool wet winters, typical of the south-west region of Western Australia. Rainfall data within the modelling area is sparse and only 5 historical and current rainfall stations exist in the DWMP area (Figure 3-1). Rainfall analysis at two long term stations in the study area was undertaken; the Pinjarra rainfall site (9596) and the Mandurah rainfall site which is a collation of data from station 9572 (1893 – 2001) and the currently operating station 9977 (2001–2008).

An average of 86% of the rain falls within the May – October period, and the average monthly distribution of rainfall is similar at both the Mandurah and Pinjarra sites (Figure 3-2). However, individual rainfall events are often localised on the Swan Coastal Plain, and the spatial heterogeneity of the rainfall is important to capture in a distributed numerical model.

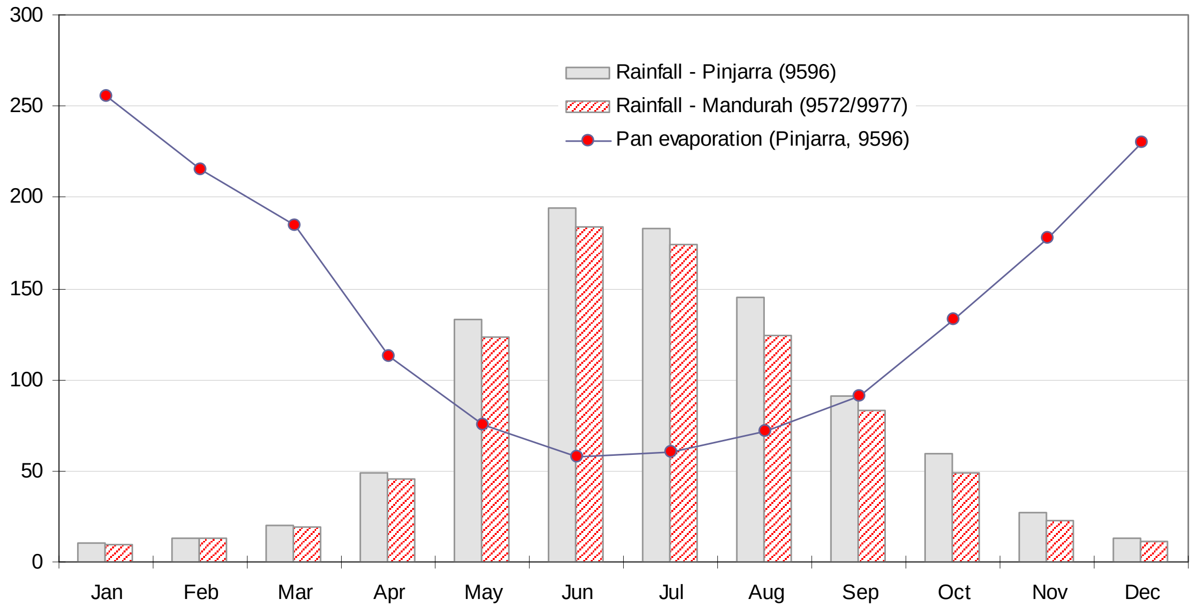

Figure 3-2: *Monthly average rainfall and pan evaporation data for Pinjarra and Mandurah*

The average annual rainfall for Pinjarra is 939 mm, with a maximum rainfall of 1493 mm recorded in 1955; and a minimum rainfall of 531 mm recorded in 1941. The average annual rainfall from 1877 to 1975 was 970 mm, which is 14% greater than the average rainfall between 1975 and 2008 (Figure 3-3), indicating that the commonly referred to 'step-down' in rainfall over the past 30 years is present in the study area. The mechanism for the 'step-down' in rainfall is generally due to the winter weather systems staying further south than previously. In the Murray study area, during the cool winter months, rainfall results from sub-polar, low-pressure cells that cross the region as cold fronts. These weather conditions are usually accompanied by strong winds and cloudy skies. Since 1968, the high pressure anticyclone belt in the Murray study area has moved southward, deflecting the cold fronts further south, resulting in a drier climate for the south west of Western Australia.

Climatic conditions have little spatial variability within the Murray study area. Annual rainfalls range from 900 – 1000 mm within the Murray DWMP area, and range from 850 – 1200 mm in the Murray study area. The larger range in the study area compared to the DWMP area is due largely to the inclusion of the scarp in the south east, which is responsible for more rainfall through orographic lift. Average rainfall in Pinjarra is higher than Mandurah, and generally the rainfall isohyets follow an east–west gradient.

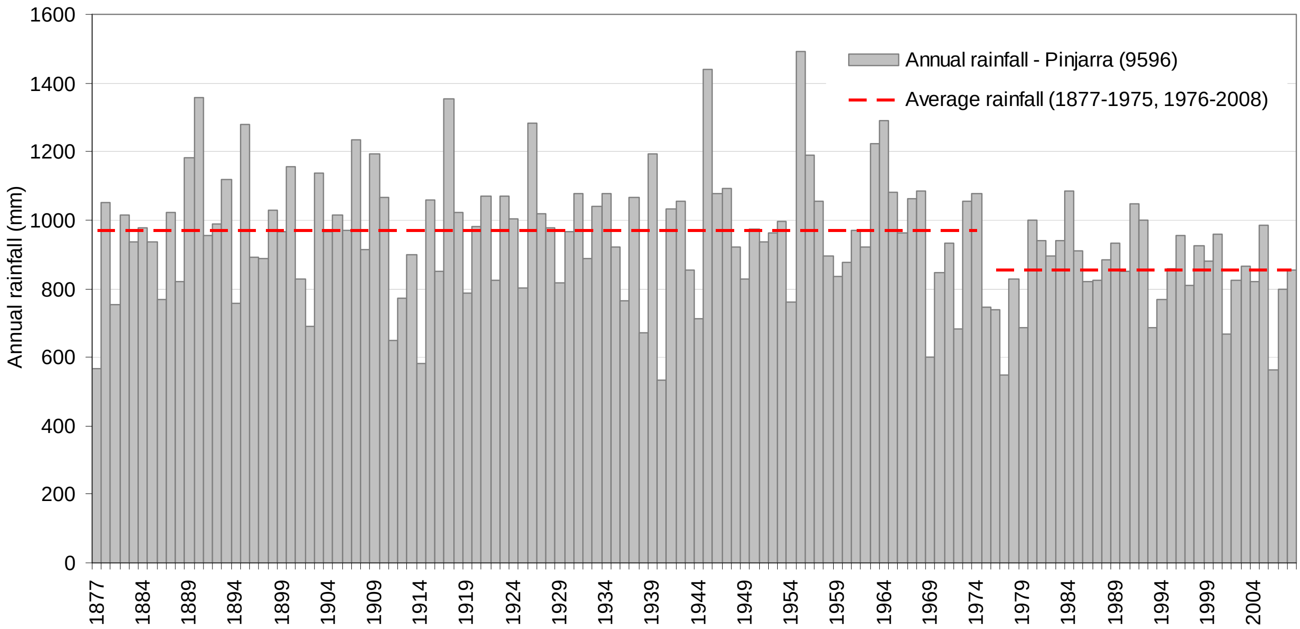

Figure 3-3: *Annual rainfall in Pinjarra displaying 'step-down' in average rainfall post 1975*

The average annual rainfall for Mandurah is 860 mm, with a minimum annual rainfall of 435 mm in 2006 and a maximum of 1305 mm in 1955. Mean annual pan evaporation in Mandurah is 1539 mm, significantly more than the mean annual rainfall. Average annual maximum and minimum daily temperatures are 23.3 ^{o}C and 13.4 ^{o}C respectively for Mandurah. The highest maximum temperature in January and February is 43 ^{o}C and the lowest minimum temperature in August is 0.6 ^{o}C. Pan evaporation is highest in January and lowest in June (Figure 3-2). A pan correction factor between 0.7 – 0.9 is appropriate for the Murray study area, to correct pan to open water evaporation, which can in turn be used to estimate potential and actual evaporation.

The long-term annual rainfall data from the late 1800s – 2008 have been plotted with the 12 year moving average for Pinjarra (Figure 3-4) and Mandurah (Figure 3-5). The moving average indicates a decreasing trend in rainfall at both sites.

The Mandurah rainfall station has recorded hourly rainfall data since 2001, and 5 minute rainfall observations are available on the Serpentine River at Dog Hill (2 km north of the study area boundary) since 1975. A new pluviometer was installed at Ravenswood in April 2009, to capture sub-daily rainfall within the Murray DWMP area.

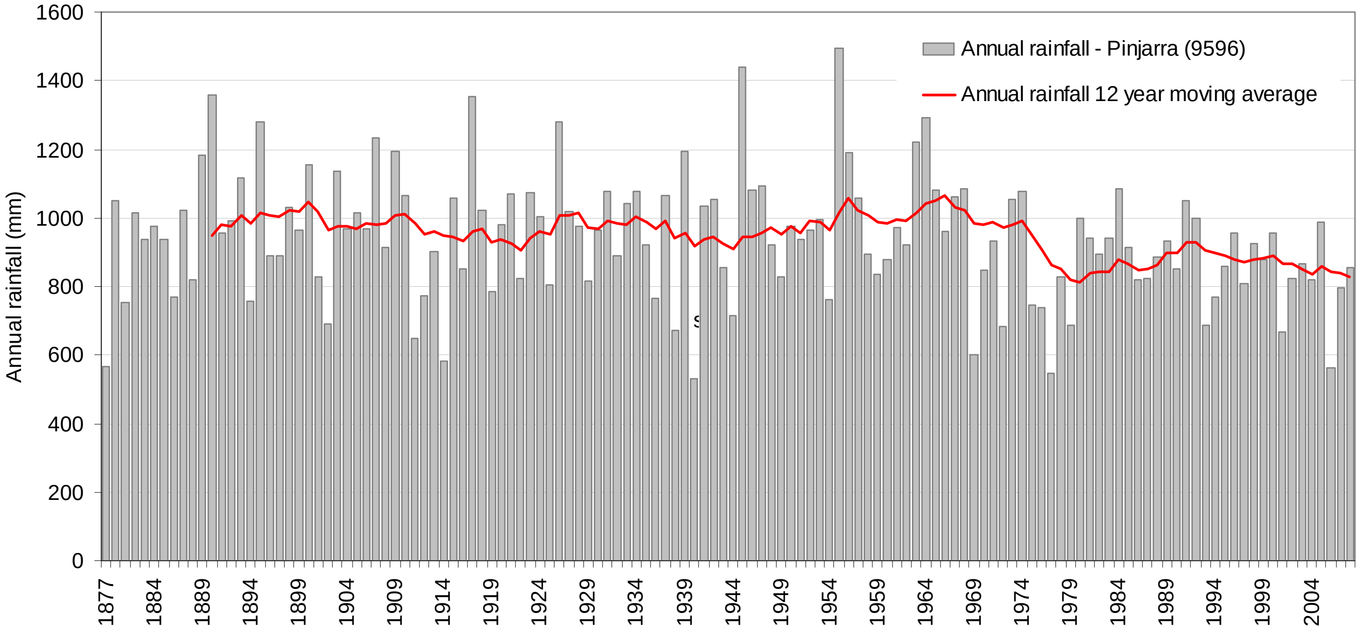

Figure 3-4: *Annual rainfall in Pinjarra with 12 year moving average*

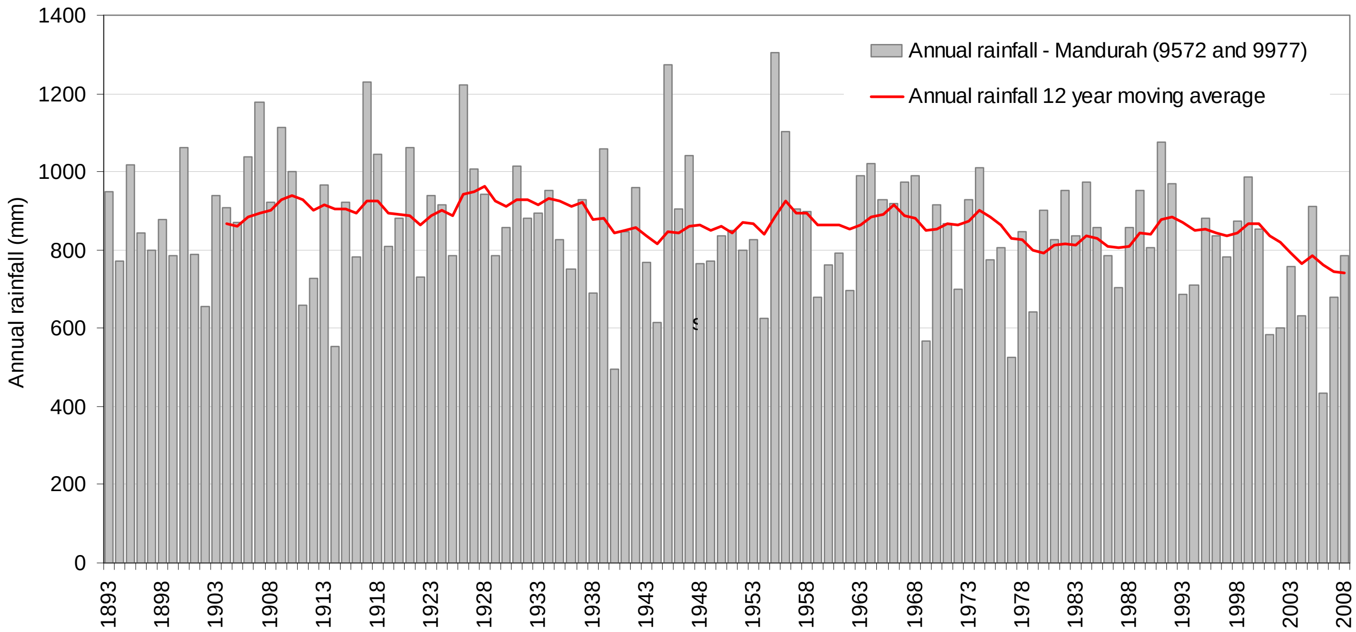

Figure 3-5: *Annual rainfall in Mandurah with 12 year moving average*

3.2 Topography and hydrology

The study area lies on the Perth Basin which is bordered by the Darling Scarp to the east and the Indian Ocean and the Peel Harvey estuary to the west (Figure 3-6). Most of the Murray study area lies on the Swan Coastal Plain, which is divided into sets of dune systems corresponding to different geological units. The dunal systems are generally parallel to the coastline, with lakes and swamps commonly occurring in the low-lying inter-dunal depressions. Elevations range from approximately 0 – 80 m AHD (Figure 3-7). The major waterways in the study area include the Murray River, Serpentine River, Nambeelup Brook, South Dandalup and North Dandalup Rivers and major drains include Buchanan's Drain, Punrack Drain, Caris Drain and Coolup Drain (Figure 1-1). The Murray and Serpentine Rivers are significantly deeper than the other water bodies in the catchment. As such, they are perennial, and drain significant quantities of water year round from the Superficial Aquifer. With the exception of the lower reaches of the North Dandalup River, and estuarine lakes at the lower reaches of the Serpentine River, all other waterways in the study area are seasonal, and generally do not flow between February – April. Due to the low topography on the Swan Coastal Plain, the lower reaches of the Serpentine and Murray River are also influenced by the Peel Estuary, and sea water intrudes the entire length of the study area along the Serpentine River, and in excess of 20 km upstream of the Peel estuary along the Murray River during low flow periods.

Historically, the land was heavily vegetated with paperbark woodland and jarrah-marri forests to the east of the catchment. With increased colonisation in the late 1800's, came increased clearing of the land which resulted in rises in the groundwater table. This exacerbated the extent of seasonal inundation. Eventually the government chose to address the problem of inundation by implementing a network of drains, after landholders in the region lodged numerous complaints relating to lost crops and property damage. In 1900, the first Drainage Bill was passed by State Parliament. Over the following 70 years, trees on the banks of the waterways were removed; lower riverine reaches were de-snagged; the rivers were straightened and deepened; and systems of interconnecting drains were dug across pastoral lands. Swamps were drained and the flow rate of the river courses increased. A detailed hydrological drainage map which includes local and regional drainage is displayed in Figure 3-8.

Most of the study area is overlain by a layer of coarse sands of varying depths on top of layers of low-permeability clay or 'coffee rock' - a friable, mostly weakly limonite cemented sand. Inundation is common during winter because of the flat landscape and the short but relatively wet and intense winter rainfall season. This is typical of palusplain wetlands, as most of the study area is described. Winter rainfall exceeds evaporation and when combined with ground saturation and soil types of the area, large run-off rates can occur. Consequently there are many lakes and some areas of seasonal water-logging. The drainage network constructed since the 1930s greatly reduced the amount of inundation. Despite this, stream flow rises and peaks over several days following rain events as water pools and is stored on the flat landscape. It is likely that the sandy soils become saturated because of relatively impermeable ironstone and clay under-layers, which will be discussed further in the following chapters. The surface water and the superficial groundwater are very closely connected in the Murray study area, and drains and waterways influence groundwater levels.

There are eight surface water gauging stations within the Murray study area (only three of which are within the Murray DWMP area with a continuous record of over 5 years). The three gauging stations within the Murray DWMP region are Nambeelup Brook (614063), Murray River (Pinjarra, 614065), and Oakley Brook (Pinjarra South, 614009). The catchments above the three gauging stations have their headwaters in or upstream of the scarp, outside of the study area. In response to the lack of data within the DWMP area, the Kwinana-Peel Regional Office and the DWB of the DoW has established two flow gauging stations in the major waterways which have head-waters within the Murray DWMP areas: Winter Brook at Pinjarra Road (614127) and Buchanans Drain at Beachams Road (614128). The location of DoW flow gauging stations is displayed in Figure 3-9.

Major flow parameters including coefficient of runoff (annual runoff as a percentage of annual rainfall), average annual flow, baseflow component of flow and the years for which flow measurements were taken are displayed in Table 3-1. Coefficient of runoff (CR) values of greater than 20% are observed for all waterways on the Swan Coastal Plain apart from in the main channel of the Murray (614045). These values are approximately twice as much as would be expected in a forested catchment and reflect the density of catchment drainage throughout the coastal plain region of the Murray study area, which relieves waterlogged areas and locally lowers the regional superficial groundwater water table. This is also reflected in the relatively high baseflow component of the waterways in the Swan Coastal Plain (18–58%). The baseflow component in the Murray River is significantly higher than the other gauged waterways in the Murray study area (Nambeelup Brook, Upper Serpentine River, Dirk Brook, Caris and Coolup Drains), and is related to the channel depth of the Murray River, which commonly exceeds 10 m, whereas most other waterways in the catchment have a maximum channel depth of 5 m. As such, the Murray River drains the Superficial Aquifer year round, which contributes to large baseflow component and regional groundwater contours tending towards the river channel.

Table 3-1: *Hydrological parameters for eight flow gauging stations within the Murray study area*

Station ID (AWRC)	Years operating	Catchment area (sqkm)	Average flow (GL/yr)	Average *CR*	Baseflow component (%)
614063	1990-1998, 2005-2007	115.5	24.7	20.9%	20.4%
614094	1995-2004, 2006-2007	122.9	19.9	22.3%	27.6%
614065	1992-2007	7044.3	364.9	7.1%	58.3%
614028	1979-2001	63.9	12.2	25.6%	38.6%
614009	1974-1984	35.8	6.4	20.6%	10.9%
613032	1991-1999	26.0	5.4	29.5%	20.7%
616030	1991-1995	51.0	7.4	29.3%	18.4%
616029	1991-1995	18.8	4.2	33.7%	-

Further analysis of surface flow data is displayed in Appendix A, and includes daily flow traces, annual flows plotted against annual rainfall to give annual coefficients of runoff, and baseflow separation to give the relative quantities of baseflow and interflow components of the hydrograph.

Water quality issues

Decades of declining water quality have led to subsequent severe algal blooms in the Peel Inlet and Harvey Estuary. In response to this a Peel Inlet and Harvey Estuary Management Strategy (Peel-Harvey Study Group 1985) was announced and approved in January 1989. This consisted of construction of the Dawesville Channel (a large linear channel linking the north western tip of the Harvey Estuary with the Indian Ocean); implementing catchment management measures (including a catchment management plan); continued weed (nuisance macro-algae) harvesting and implementing appropriate monitoring to measure the success of the Strategy.

A report by the EPA (EPA 2007) on the compliance with environmental conditions of the Strategy found the Dawesville Channel (opened in 1994) to have been successful in improving water quality in the main body of the Peel Inlet and Harvey Estuary. However, water quality and environmental problems remained in the rivers, and areas such as the Serpentine Lakes. The second part of the strategy which explicitly addresses phosphorus inputs to waterways in the catchment was found to require significant action.

In response, a series of projects, co-funded by the State Government and the Federal Government's Coastal Catchments Initiative (CCI) commenced, which included the production of a Water Quality Improvement Plan (WQIP) for the rivers and estuary of the Peel-Harvey system (EPA 2007). The WQIP aims to improve water quality by reducing phosphorus discharges from the catchment through changes to agricultural and urban practices and land use planning. The WQIP also documents detailed strategies for water quality improvement in defined areas. These strategies aim to achieve median annual loadings of total phosphorus to estuarine waters of less than 75 tonnes per annum (21 tonnes from the Serpentine, 16 tonnes from the Murray and 38 tonnes from the Harvey River). In addition, water qualities in streams in winter were to meet mean concentrations of 0.1 mg/L total phosphorus at current flow regimes. The WQIP proposes various management measures to reduce phosphorus inputs to the estuary. One key component includes the management of urban land practices, better soil and soil amendment practices, and water sensitive urban design that focuses on the 'whole of water cycle' approach, applied through the environmental and planning referral and approvals processes. Whilst water quality modelling is outside of the scope of the Murray hydrological studies project, the details of the WQIP need to be considered when future urban planning is implemented in the Murray study area.

3.3 Land use

Agriculture is the primary land use in the area, since extensive land clearing began in the early 1800's. Cattle grazing for beef covers more area than any other land use (55% of the study area, and 68% of the DWMP area), with sheep grazing, dairying, horses, lifestyle blocks, and existing urban comprise significant areas of the catchment. A land use map is displayed in Figure 3-10. Land uses and their corresponding areas and percentage area of the total model study area and Murray DWMP area are displayed in Table 3-2.

Ninety five percent of the Murray DWMP area has been cleared, and 88% of the model area has been cleared over the past two centuries. The land east of the Darling Scarp remains largely forested with native *Eucalyptus marginata* (jarrah) and two of the major rivers (the North Dandalup and the South Dandalup) have been dammed in this region. Land further east, in the upper Murray River catchment, is largely cleared for wheat and sheep farming. In recent years, significant new urban development and rural land use intensification has occurred in the Murray catchment in close proximity to waterways and wetlands, in response to peri-urban land pressures and in advance of new rail and highway infrastructure. The areas of remaining deep-rooted vegetation, derived from analysis of non-ground return analysis of LiDAR data in the study area, is displayed in Figure 3-11.

Table 3-2: Relative areas and number of parcels of land use types in the model study area and in the Murray DWMP study area, for the 2006 land use coverage.

Land Use	Model study area			Murray DWMP area		
	No. parcels	Area (km^2)	% Area	No. parcels	Area (km^2)	% Area
Cattle for beef	737	401.75	55.48%	472	255.65	68.63%
Unused - uncleared - trees/shrubs	347	39.58	5.47%	146	6.25	1.68%
Mixed grazing	52	37.09	5.12%	19	9.06	2.43%
Recreation / conservation	312	36.56	5.05%	151	14.95	4.01%
Roads and transport	3242	26.05	3.60%	845	12.38	3.32%
Cattle for dairy	35	22.59	3.12%	31	18.49	4.96%
Horses	310	21.91	3.03%	261	14.35	3.85%
Lifestyle block	727	17.99	2.48%	514	12.87	3.45%
Residential - single/duplex dwelling	18037	17.59	2.43%	3238	4.85	1.30%
Tree plantation	11	14.62	2.02%	3	0.00	0.00%
Water body	123	13.64	1.88%	68	7.30	1.96%
Manufacturing / processing	153	11.91	1.64%	32	0.29	0.08%
Unused - cleared - grass	1155	10.01	1.38%	209	2.60	0.70%
Perennial horticulture	28	9.90	1.37%	18	1.03	0.28%
Rural residential / bush block	479	9.03	1.25%	189	3.26	0.88%
Unused - cleared - bare soil	3992	6.22	0.86%	770	0.89	0.24%
Quarry/extraction	15	5.94	0.82%	70	3.04	0.82%
Recreation - grass	256	4.80	0.66%	0	0.00	0.00%
Sheep	7	2.88	0.40%	1	0.01	0.00%
Annual horticulture	20	2.36	0.33%	6	0.14	0.04%
Airport	3	2.18	0.30%	3	2.18	0.59%
Recreation - turf	12	1.29	0.18%	5	0.41	0.11%
Community facility - education	16	1.13	0.16%	3	0.10	0.03%
Turf Farm	2	0.96	0.13%	0	0.00	0.00%
Community facility - non-education	76	0.93	0.13%	39	0.35	0.09%
Residential - multiple dwelling	262	0.79	0.11%	55	0.14	0.04%
Commercial / service - centre	264	0.68	0.09%	52	0.11	0.03%
Storage / distribution	151	0.47	0.07%	30	0.13	0.03%
Intensive animal farming	2	0.41	0.06%	1	0.28	0.08%
Sewerage - treatment plant	4	0.41	0.06%	0	0.00	0.00%
Caravan park	17	0.38	0.05%	9	0.27	0.07%
Residential - aged person	8	0.31	0.04%	3	0.01	0.00%
Hay and Silage	5	0.31	0.04%	1	0.14	0.04%
Piggery	3	0.27	0.04%	2	0.18	0.05%
Feedlot	2	0.22	0.03%	2	0.22	0.06%
Aquaculture	2	0.18	0.03%	1	0.12	0.03%
Landfill	1	0.15	0.02%	1	0.15	0.04%
Utility	39	0.12	0.02%	15	0.02	0.00%
Poultry	4	0.12	0.02%	4	0.12	0.03%
Residential - temporary accommodation	14	0.08	0.01%	2	0.04	0.01%
Commercial / service - residential	32	0.08	0.01%	9	0.02	0.01%
Office - without parkland	33	0.07	0.01%	7	0.02	0.01%
Garden centre / nursery	4	0.05	0.01%	2	0.04	0.01%
Water storage and treatment	2	0.03	0.00%	0	0.00	0.00%
Viticulture	1	0.03	0.00%	0	0.00	0.00%
Yacht facilities	12	0.02	0.00%	0	0.00	0.00%
Office - with parkland	6	0.01	0.00%	6	0.01	0.00%
Grand Total	31017	724.1		7297	372.5	

4 Geology

4.1 Regional setting

The study region 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 commenced 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 current day in progradational shallow water and fluvial environments (Pennington Scott 2009).

The high angle Darling Fault is visible as the Darling Scarp, and it is the most significant structural feature on the coastal plain. It separates the Archean Yilgarn Craton to the east from the Mesozoic to Canozoic deposits of the Swan Coastal Plain to the west. The Cretaceous period's Leederville Formation, the Neogene (Tertiary) period's Rockingham Sand, and Quaternary period's superficial formations are the main formations of interest for this study. The stratigraphic sequence is given in Table 4-1 and is illustrated in seven cross sections, Figure 4-10 – Figure 4-16.

The surface of the study area is covered by the collective superficial formations, which ranges in thickness from about 12 – 30 m and has been deposited on a gentle westerly sloping surface. The upper surface can be divided into four geomorphic units, the Quindalup Dune System, the Spearwood Dune System, the Bassendean Dune System and the Pinjarra Plain. They correspond to the Safety Bay Sand, Tamala Limestone, Bassendean Sand and Guildford Clay respectively (Deeney 1989). Generally below these the Yoganup Formation, Gnangara Sand, Ascot Formation or Rockingham Sand is present. The Rockingham Sand fills a sharply defined paleochannel cut into the Mesozoic formations and ranges in thickness from 50 – 70 m in the study area. These units unconformably overlie the Cretaceous aged Leederville Formation, a minor region of Jurassic-aged Cattamarra Coal Measures, and ramp up against the Precambrian rocks of the Darling Scarp.

4.2 Data analysis

The literature review revealed that the detail of the superficial formation and the Rockingham Sand are at best mapped coarsely in the study area. Until recently no superficial formation groundwater monitoring bores had been drilled in the central portion of the study area. Consequently the profile of the superficial formations had never been fully mapped in the region. As a result it was decided to invest considerable time and resources into the creation of a new three-dimensional geological map of the superficial stratigraphy. Further, it is hoped that a more accurate representation of the stratigraphy would more adequately provide for the detailed data requirements of a coupled groundwater – surface water interaction model.

To construct the new geological model a collation of data from DoW's Water Information System (WIN), bore licensing files, and newly acquired drill hole data was entered into a

Microsoft Access™ database where it could be interrogated through automated queries as well as manual assessment. The lithology logs from more than 500 bores have been assessed and classified as representative of a particular stratigraphy member (Figure 4-1). Hundreds of additional bores were excluded from the interpretation due to insufficient information for stratigraphy identification. The analysed data was converted into spatial files in ArcGIS, through which further analysis was undertaken to improve the accuracy of the stratigraphy interpretation. Boundaries for each formation were developed by analysing the data topographically and dividing areas where a particular formation existed from those where it did not. These boundaries then marked the location where a particular stratigraphic sequence would pinch out.

The classification of the drill log descriptions was a careful process of relating an often very basic lithological description of one bore to those of surrounding bores that may contain more information, and then interpreting that information against the various descriptions given for each stratigraphy unit in references such as Passmore (1970), Deeney (1989), Davidson (1995), Davidson and Yu (2008) and Pennington Scott (2009). Due to the similar descriptions for the several different sand formations and the similar sandy-clay consistency of the Yoganup Formation and Guildford Clay, the data also had to be interpreted on its position in the landscape. The process of assessing data topographically and in cross-section led to the development of a continuous, chronologically correct three-dimensional layering profile.

The completed database of stratigraphy interpretations was converted to a three-dimensional block model that could be used to create a hydrogeological model at a later stage. The details of this are outlined in Section 4.3 below.

4.3 Stratigraphic units

Leederville Formation

The Leederville Formation underlies the entire region excluding a narrow margin directly adjacent to the Darling Fault where the Cattamarra Coal Measures is present. It increases in thickness to the northwest, being over 117 m thick near Mandurah (Commander 1975). The Leederville formation predominantly consists of discontinuous, inter-bedded sandstones, siltstones and shales, and can be sub-divided into the Mariginiup (lower), Wanneroo (middle) and Pinjar (upper) Members. The Pinjar Member has been eroded from the study region and therefore the Wanneroo Member is the upper most Cretaceous layer in the central and western areas, and the Mariginiup Member in the eastern areas. The sandstones of the Leederville Formation are dark grey to dark green, weakly cemented, poorly sorted fine to medium grained with 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.

The Leederville Formation conformably overlies the South Perth Shale in the study area. It is unconformably overlain by the Rockingham Sand, Osborne Formation and superficial formations west of the Peel Inlet. The spatial interpretation of the upper surface of the Leederville formation with upper surface contours in m AHD is presented in Figure 4-2. Depth to Leederville varies between 12 m in the east to greater than 60 m in the west.

Osborne Formation

The Osborne Formation is found on the western side of the Peel Inlet. 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 and Safety Bay Sand. Due to the shale beds it is assumed to act as an aquitard between the Leederville and the superficial formations where present. Because the formation lies outside the model boundary it is not discussed further in this report.

Rockingham Sand

The Rockingham Sand occupies a paleochannel cut into the Leederville Formation that has previously been charted between the northern side of the Peel Inlet and Cape Peron Peninsula. Detailed investigation undertaken as part of this study has increased the extent of the Rockingham Sand south underneath the Peel Inlet, and discovered a deeply cut extension of the paleochannel running east-west in the Nambeelup region. The Rockingham Sand was defined by Passmore (1970), and consists of medium to coarse grained feldspathic quartz sand of yellow, brown, and pale grey colour. The upper 1 – 3 m contains a marl bed, which is thought to be a lagoonal facies (Morgan 1969). The feldspar grains are fresh, indicating rapid erosion with little chemical weathering of the source rock (Passmore 1970).

Investigation of the paleochannel extension in the Nambeelup region found it to be approximately 60 m deep and extending approximately 18 km inland from the coast (Figure 4-2). It is possible the channel represents the course through which eroded material from the Darling Scarp and surrounding plain filled the Rockingham Sand paleochannel. The recognition of the channel extension as a source of the sediments would support the conclusions of Passmore (1970) that the rivers transporting the Rockingham Sand from the source area most likely had a short and direct path to the shallow sea environment in which the sand was deposited. The maximum thickness of the Rockingham Sand within the study area is around 60 m. A spatial representation of the Rockingham Sand with upper surface contours in mAHD is presented in Figure 4-3.

Superficial Formation

The superficial formation is the title used in this report for the collective Quaternary Period deposits outlined below. It is not an official title for a defined group of deposits. The base Quaternary contours presented in Figure 4-4 represent the unconformity base that the superficial formations lie above, and represents the surface of the Leederville and Rockingham formations.

Ascot Formation

The Ascot Formation rests unconformably on the Leederville Formation and is overlain by the Gnangara Sand, Guildford Clay and possibly Tamala Limestone. Within the study area it appears the northern extension of the Ascot Formation is truncated by sediments possibly related to the Bassendean or Gnangara Sands. Along its eastern margin the Ascot Formation interfingers with the Yoganup Formation.

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, and 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, and thinly bedded glauconitic clay occur in places (Davidson and Yu 2008). A number of bores east of the Peel Inlet towards Pinjarra have recorded marly beds with granite boulders and fossil-rich sands underlying clearly-defined Ascot Formation. However, it is appears these are associated with the a much earlier deposit, possibly the Mariginiup Member of the Leederville Formation.

Where the area of the new geological interpretation overlies that of the area interpreted by Deeney (1989) there is a similarity in the mapped extent of Ascot and Yoganup Formations. The Ascot Formation ranges in thickness from 2.5 – 25 m, depending on the depositional topography and post-depositional erosion (Deeney 1989). The extent of the Ascot Formation in the study area with upper surface contours in mAHD is presented in Figure 4-5.

Yoganup Formation

The Yoganup Formation directly overlies the Leederville Formation and Cattamarra Coal Measures. Occasionally it extends close to the surface at the eastern margin of the study area, but in general it is unconformably overlain by colluvium, Bassendean Sand, and more extensively the Guildford Clay. It extends west from the Darling Scarp, however the distance it extends can be quite variable. South of the South Dandalup River it extends west to the Ascot Formation, roughly in line with the Murray River. However to the north it is more heavily eroded, but generally interpreted to extend west to the Gnangara Sand.

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 ferruginized 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 were sometimes found near the top (Deeney 1989).

The thickness of the formation is highly variable (1 – 25 m), generally being most thick at the Darling Scarp. The spatial interpretation of the surface of the Yoganup Formation in the study area with upper surface contours in m AHD is presented in Figure 4-6.

Guildford Clay

Guildford Clay is predominantly of fluvial origin and is generally constrained to within 5 – 10 km of the Darling Scarp. It unconformably overlies the Yoganup Formation and the Ascot Formation. In the study region it interfingers to the west with the Bassendean Sand, and Gnangara Sand, and possibly with the upper layer of the Rockingham Sand. It is unconformably overlain by aeolian Bassendean Sand in many places.

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 are probably remnant deposits of the Yoganup and Ascot Formations (Davidson and Yu 2008).

It appears that recent studies have used the term Guildford Clay to define a broad range and area of clays, sandy clays, and clayey sands within the study area. This increasingly broad interpretation of the term Guildford Clay has resulted in clayey portions of the Yoganup Formation being misinterpreted. Further, care is required in the west as there are clays associated with the upper few metres of the Rockingham Sand (Morgan 1969), and estuarine clays and silts associated with the modern day rivers and floodplains. During this study a careful determination based on consistency, colour, and location has been used to differentiate the clays on the eastern area of the plain. In the western areas of the plain the mapping and interpretation of the clay lenses is an ongoing process as their occurrence in bores can be quite sporadic, even within closely-spaced bores. The thickness of the Guildford Clay has been interpreted to be less than 10 m in most places. The interpreted thinness of the clay is the result of the observed measurements and the interpretation method employed (see section 4.5). The spatial interpretation of the surface and extent of the Guildford Clay in the study area with upper surface contours in mAHD is presented in Figure 4-7.

Gnangara Sand

The Gnangara Sand is described as consisting of pale grey, fine to very coarse grained, very poorly sorted, sub-rounded to rounded quartz and abundant feldspar. It can be of bimodal consistency, 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.

This study interprets the Gnangara Sand to interfinger with the Guildford Clay on its western edge, and overlies the Ascot Formation to the south and the Rockingham Sand and Leederville Formation to the north. The connection of the Gnangara Sand with the Tamala Limestone is poorly resolved, and has been modelled as an abrupt change in this study. Within the study region it is difficult to separate sections of lithological logs into Rockingham, Bassendean or Gnangara Sand due to their similar characteristics. Deeney (1989) interpreted much of the sand overlying the Ascot Formation south of the Murray River as the Guildford Sand Member, a title never formally adopted. However recent publications are inconsistent with the re-interpretation of this title, classifying it as either Bassendean Sand (URS 2009) or Gnangara Sand (Pennington Scott 2009). The spatial interpretation of the surface and extent of the Gnangara Sand in the study area with upper surface contours in mAHD is presented in Figure 4-8.

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). The grains tend to be sub-rounded to rounded quartz that commonly has an upward fining progression in grain size (Davidson and Yu 2008). A layer of friable, mostly weakly limonite cemented sand known as ‘coffee rock’ is commonly present at or near the watertable.

It is interpreted to exist as a thin veneer and the uppermost layer over much of the study region east of the Tamala Limestone, however it is up to 30 m thick in the central area due to stranded dunes. It interfingers with, and in many places overlies, the Guildford Clay, indicating that it has been deposited during an alternating fluvial, estuarine and shallow-marine environment (Davidson and Yu 2008). Aeolian processes continue to shift the Bassendean Sand across the landscape, especially where stranded dunes have been stripped of protective vegetation.

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, sub-angular to rounded, frosted, and limonite stained (Davidson and Yu 2008). The limestone contains numerous solution channels that form a karst aquifer. Below approximately +3 mAHD the formation predominantly 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 between the Serpentine River and the coast and at Point Grey between the Peel Inlet and Harvey Estuary. Depending on its location in the study region it may overlie the Rockingham Sand, 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.

Safety Bay Sand

The Safety Bay Sand was a named proposed by Passmore (1970) for an extensive band of Holocene age dunes. 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 dunes west of the Tamala Limestone between Mandurah to Rockingham.

The Safety Bay Sand comprises fine to medium grained aeolian quartz grains with a large portion of shell debris. The formation also contains interbedded humic and carbonaceous material.

Alluvium, estuarine and swamp deposits

The alluvium, estuarine and swamp deposits are associated with the many rivers, lakes and wetlands that exist within the study area. These deposits consist of clays, silts and sand, which 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 organic rich. The distribution of the alluvium, estuarine and swamp deposits are displayed in Figure 4-9.

Clay lenses

In the study area it is not uncommon to encounter lenses of clay, sandy clay and clayey sands within the profile. They are often less than 2 m in thickness and tend to be found between 2 – 4 mBGL in the interdunal flats and 2 – 6 mBGL elsewhere. The relationship of these clay lenses to the surrounding formations is not well understood, and they may relate to marl beds of the Rockingham Sand, outcrops of Guildford Clay, clayey portions of the Bassendean Sand and Holocene estuarine and alluvium deposits. Within this boundary the clay lenses will vary in depth, thickness and will not occur in some places. Analysis of the clay lenses is continuing to improve the understanding of their extent, provenance, and importance to the hydrogeology.

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 thickness of the colluvium is highly variable but rarely exceeds 5 m.

4.4 Geological interpretation

As a result of the data analysis, the extent and interconnection of post-Cretaceous formations within the study region has been interpreted. A significant finding from the work is the extension of the paleochannel associated with the Rockingham Sand Aquifer. The mapped extension of the Rockingham Paleochannel runs east to west under the Nambeelup area, ranging from 55 – 65 m deep. Two new observation bores were drilled (July 2009) through the paleochannel until the Leederville Formation was reached using sonic push probe. The core from this drilling has been kept thus enabling detailed stratigraphic information to a depth of 70 m to be gathered. The paleochannel lithology is typically light grey, medium to coarse grained, mainly sub-angular quartz with minor silt and clay. Feldspar grains are common, with some bands containing very coarse angular grains. A band of dense, grey, coarse grained sandy clay around 1.5 m thick, followed by Bassendean Sand overlaid the Rockingham Sand in one drill hole. The other had a sharp unconformity from Rockingham to Bassendean Sand. At the bottom of the channel a medium to coarse grained dark green silty-sand was found. No clay beds were found within the Rockingham Sand that could be expected to significantly retard groundwater flow.

South of the Murray River the Yoganup Formation has been interpreted to have a similar extent and connection with the Ascot Formation as that interpreted by Deeney (1989). Within the remaining part of the study area the Yoganup Formation has not previously been mapped. For this study, it has been interpreted to taper under the Gnangara Sand. The Gnangara, Bassendean or Rockingham Sands are difficult to distinguish in some places. Generally much more detail is required in lithology logs than is usually given to distinguish them. The Rockingham Sand is identifiable in detailed drill logs by its poorly sorted, medium-coarse and almost entirely angular to subangular grain size and shape. Gnangara Sand is often identified as being bi-modal, subrounded and relatively feldspar rich compared to the Bassendean Sand. Bassendean Sand is generally moderately sorted, fine to medium grained and logs commonly make reference to samples containing dark minerals. Importantly, the sands encountered within this region will generally exhibit similar hydraulic parameters for modelling purposes.

The Guilford Clay is interpreted to be thinner in the study area than that illustrated by Deeney (1989). This partly results from the interpretation method employed during the GIS analysis (refer to Section 4.5). The Guildford Clay is still interpreted to be widespread on the eastern plain although in many areas it less than 3 m thick. The low permeability mining related clay bottomed evaporation and storage dams in the east have been separately classified as ‘Mine Clays’.

The extent of the Safety Bay Sand and Tamala Limestone have been interpreted from existing mapping, as outlined in Section 3. The Bassendean Sand has been used to fill the area above the top of the underlying stratigraphy and the surface, between the Tamala Limestone and the Colluvium. This helps develop a natural profile of Bassendean Dunes and a thin veneer of Bassendean Sand that is found over Guildford Clay in much of the eastern area.

In the deeper geology the Cretaceous sediments around Pinjarra contain several interesting components. In this area the lithology descriptions commonly refer to sand and shells in association with granite boulders and dark grey clays. Bore HS080-2A cored to 40.5 m in July 2009 found green sandy clay, angular pieces of granite, cemented shell bed material, chalk-like remnant shell material and dark grey silty sands and clays underlying the Ascot Formation. Preliminary investigation indicates these are related to the Mariginiup Member, although further investigation is required to confirm this.

Table 4-1: *Stratigraphy of the Peel-Harvey Region (Based on Deeney 1988, Pennington Scott 2009)*

Era	Period	Epoch	Date (Ma)	Stratigraphy	
Cenozoic	Quarternary	Holocene	0 - 0.01	Alluvium, esturaine and swamp deposits	
				Safety Bay Sands	
					UNCONFORMITY
		Middle to late Pleistocene	0.01 - 1.0	Tamala Limestone	Bassendean Sand
				UNCONFORMITY	
		Early to late Pleistocene	1.0 - 1.8	Gnangara Sand	Guildford Clay
				UNCONFORMITY	
		Late Pliocene to early Pleistocene	1.0 - 3.0	Ascot Formation	Yoganup Formation
				UNCONFORMITY	
	Tertiary	Pliocene to early Pleistocene	1.8 - 5.3	Rockingham Sand	
				UNCONFORMITY	
Mesozoic	Cretaceous	Late	91 - 113	Osborne Formation	
				UNCONFORMITY	
		Early	119 - 127	Leederville Formation	
			125 - 138	South Perth Shale	
				UNCONFORMITY	
	Jurassic	Early	181 - 200	Cattamarra Coal Measures	

4.5 Conceptual geology

The three-dimensional representation of the geology was based on interpretation of bore logs available in the Access™ database, discussed in Section 4.2. For each formation classified within the database, a point layer was exported, including the maximum elevation in mAHD of the top of the formation for that borehole. Based on the lateral extent of the formation as identified in the bore logs and historical geological survey in the area, a bounding polygon was defined for each individual formation. For example, the Leederville formation was confined to the area west of the Darling Scarp, and the Ascot formation was confined to the south east of the modelling area (Figure 4-5).

The model was built from the base of the Leederville formation upwards. The base of the Leederville was approximated as the top of the South Perth Shale formation, and was modelled to slope from the base of the Superficial Formation near the scarp, to -200 mAHD at the coastline.

For each of the lower formations, the discretised spline interpolation program ANUDEM 4.6.3 (Hutchinson 1988, 1989) was used to generate a surface representative of the top of that layer, limited to the bounding polygon. Where the edge of the layer was located within the modelling boundary, it was forced to drop gradually to the top of the layer immediately below.

Where the surface elevation of a lower layer was interpolated to be higher than the layer above, priority was given to the lower layer, and the layer above was set to null (deemed to not exist in that area). This is evident for example in the patchiness of the Guildford Clay and Gnangara Sands.

The lateral extent of surface geological formations was defined by the Department of Agriculture and Food WA Soil - Landscape Mapping Units, which is at a scale of better than 1:25 000 in the study area. The extent of surface formations was verified from the bore data across the modelling area.

The Bassendean Sand, Tamala Limestone, Safety Bay Sand, Mining Clay and colluvium were modelled as existing between the surface elevation, and the maximum elevation of all layers beneath. Alluvium, estuarine and swamp sediments were also defined from the soil mapping. These layers were burnt into the existing superficial layers to a depth of 1 m.

Geologic cross sections are displayed in Figures 4-10 to 4-14. In some areas with deeply incised river valleys, the modelled formation surfaces were modified to either follow the surface topography, or were assumed to have been eroded through, and therefore not exist in those areas. This is best illustrated near the Murray River in cross-section E (Figure 4-13).

The model maintains logical consistency, in that there is no intersection between the formations. All surfaces were generated at 10 m pixel resolution. A three-dimensional representation of the block model is presented in Figure 4-17. The horizontal resolution of the three dimensional block model is 10 m.

Table 4.1 summarises the order of layering, the method used to define the lateral extent of the layer, and indicates which method was used to define the surface and base of the formation.

Sources of error

The block model and surfaces generated within the modelling area are a conceptual representation of the regional lithology. Heterogeneity within the superficial sediments will not be completely represented within the model. The purpose is to capture the coarse variability within the superficial formations with sufficient accuracy to enable realistic calibration of the numerical model.

Table 4-2: *Layering methodology information for the block model interpretation*

Layer	Order	Number of Bores	Extent	Surface	Base
Estuarine Sediments	1	na	Soil Mapping	LiDAR DEM	1m below surface elevation
Swamp Sediments	1	na	Soil Mapping	LiDAR DEM	1m below surface elevation
Alluvium	1	na	Soil Mapping	LiDAR DEM	1m below surface elevation
Mining Clay	2	na	Soil Mapping/Aerial Photography	LiDAR DEM	Top of lower layers
Colluvium	2	na	Soil Mapping	LiDAR DEM*	Top of lower layers
Safety Bay Sand	2	na	Soil Mapping	LiDAR DEM*	Top of lower layers
Bassendean Sand	2	na	Soil Mapping	LiDAR DEM*	Top of lower layers
Tamala Limestone	2	na	Soil Mapping	LiDAR DEM*	Top of lower layers
Guildford Clay	3	116	Bore Interpretation	Bore Interpretation	Top of lower layers
Gnangara Sands	4	48	Bore Interpretation	Bore Interpretation	Top of lower layers
Yoganup Formation	5	81	Bore Interpretation	Bore Interpretation	Top of lower layers
Ascot Formation	6	44	Bore Interpretation	Bore Interpretation	Top of lower layers
Rockingham Sands	7	72	Bore Interpretation	Bore Interpretation	Top of Leederville
Leederville Formation	8	203	Bore Interpretation	Bore Interpretation	Top of South Perth Shale

**Note, where alluvium, swamps or estuarine sediments were present, the surface of these layers were lowered by 1m.*

There are several potential sources of error associated with the block model development that should be considered.

- Where not specified, the surface elevations for bores used in the lithological interpretation were estimated from a 1 m resolution LiDAR DEM with +/- 0.15 m vertical accuracy. Many bores in the WIN database were not accurately surveyed for location and/or elevation. Particularly in areas with more complex terrain, significant errors in elevation were likely to occur. Estimated LiDAR elevations were compared only with bores that had previously been surveyed, and elevation values in AHD were largely consistent, and within 0.3 m error.
- Different bores were used for different layers, depending on occurrence of the formation, and the depth of the bore (e.g. fewer bores are deep enough to intersect the Leederville than the Yoganup).
- Where layer surfaces conflicted the surface of the lower layer was given priority (which may not truly represent the stratigraphy). This problem is a result of less bores being used for interpolation of the deeper layers.
- The accuracy of the model is dependent on the interpretation and classifications of the lithological logs, and the original stratigraphic description of the log.

5 Hydrogeology

Within the study area, the sedimentary deposits of the Swan Coastal Plain can be divided into four main aquifers: the Superficial, Leederville, Rockingham and Cattamarra. The Yarragadee Aquifer also underlies the northern end of the study region but it is sufficiently separated by the overlying Jurassic and Cretaceous formations not to warrant inclusion for this study.

Phreatic and potentiometric surface analysis

The location and trends for long-term bores within the Superficial and Rockingham Aquifer are displayed in Figure 5-1. The time-series plot for the water levels in each of these bores is displayed in Appendix C. A watertable contour map covering the Murray Study area was developed, which was useful for estimating the depth to the water table. The watertable was completed using head measurements taken on June 16 2009, from bores screened in the regional Superficial Aquifer. The interpretation was aided by use of topography, previous groundwater studies, constant head boundaries (such as the Peel Harvey estuary, Serpentine estuarine lakes, and lower Murray River) and regional groundwater contours. The contour map representing the phreatic surface in June 2009 is displayed in Figure 5-2.

Location and trends for bores in the Leederville Aquifer are displayed in Figure 5-3. The time-series plot of each of the Leederville Aquifer bores is displayed in Appendix D. A contour map of isopotentials has also been constructed for the Leederville Aquifer based predominantly on data from the beginning of the winter in 2008, and the beginning of summer 2009 (Figure 5-4 and Figure 5-5). South of the Murray River measurements taken several years ago at the equivalent time of year were used due to the lack of recent data. This is likely to result in a slight over prediction of heads in that area due to the consistent head decrease over time.

5.1 Superficial Aquifer

Characteristics

In the study area, the Superficial Aquifer is synonymous with the Quaternary superficial formations, and therefore it is characterised by clayey deposits in the east and sandy deposits in the west. The Superficial Aquifer overlies a thin section of the Cattamarra Aquifer along the Darling Fault, the Leederville Aquifer in the central and eastern areas, and the Rockingham Aquifer in the west.

In large parts of the study area, the watertable tends to lie within 3 m of the surface, rising in winter by 2 – 4 m in the eastern plain and a more subdued 0.5 – 1.2 m in the central and western areas of the plain. This fluctuation reflects the topography as well as the low conductivity clays in the east and the high conductivity sands in the west (Deeney 1989, Davidson 1995). This variation in the water table is an important driver of the wetting and drying cycles of the wetlands in the study area. Temporary surface saturation is also thought to be related to localised sandy-clay lenses in some areas. 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. During the course of this study the effect of these drains on local and regional hydrology will become more fully understood.

In general, the Superficial Aquifer is considered to be unconfined; however head differences illustrated in Figure 5-6 demonstrate that localised semi-confined conditions are not uncommon. This is partly due to the aquifers anisotropic nature, with vertical flow considered to be an order of magnitude less than the horizontal flow (Davidson and Yu 2008). However, localised clay layers are known to exist in the study area. Analysis of nested piezometers that had a head difference found several had clayey sand layers, generally less than 2 m thick. However, the influence of the clay lenses is inconsistent, as the presence of this layer did not result in a head difference in all locations.

Recharge

Superficial Aquifer recharge predominantly occurs via direct rainfall on the Swan Coastal Plain, particularly in areas with a sandy profile. Guildford Clay acts as a minor aquitard on the eastern side reducing recharge; 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, although this is likely to be minimal due to the presence of the Rockingham Aquifer in the west. The potential for upward leakage from the Leederville to the Superficial Aquifer occurs around the southern edge of the Peel Inlet, and along the Murray River. The positive head differential along the Murray River is a result of the drawdown in the Superficial Aquifer caused by the incision of the Murray River channel draining the aquifer. There is no equivalent response seen in the hydraulic head of the Leederville Aquifer, although the sparse number of monitored bores would make this difficult to identify.

For the majority of the study area, recharge to the superficial groundwater is through free-draining sandy-soils. In most areas, the groundwater table is close to the surface (1 – 5 mBGL), and has small horizontal gradients. Flow through the unsaturated zone is likely to be vertical and lateral movement in the unsaturated zone will be negligible.

In most of the study area, no long term decreasing trends are discernable in the superficial monitoring bores, however in the northwest a cluster of bores does show a decreasing trend (Figure 5-1) In this area it is possible the concentration of domestic bores extracting groundwater is developing a cone of depression that impacts the regions hydraulic heads. The increased heads recorded at three locations may be caused by imported irrigation water or by a change in land use.

Hydrodynamics

Groundwater flow in the Superficial Aquifer is driven by gravity from east to west across the study area, although the rivers dissecting the plain cause a deviation of flow in some areas. The phreatic head reduces from over 60 mAHD along the Darling Scarp to 0 mAHD at the lower Serpentine River, lower Murray River, and Peel Inlet. The Murray River has eroded through the Guildford Formation and now collects discharge from the Guildford Clay and Yoganup and Ascot Formations. Likewise the Serpentine River intercepts the east to west flow in the northern part of the study region. The study area incorporates two regional flow systems, flows in the Waroona Flow System travel north to the Murray River and west to the Peel-Harvey Estuary, and the Serpentine Flow System flows west until it is intercepted by either the Murray or Serpentine Rivers (Davidson 1984, Deeney 1989). The installation of numerous new bores near Nambeelup Brook have served to illustrate that the brook is acting as another important groundwater discharge point in the region. The numerous 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 water levels measured in June as the drainage channels are higher than the water table.

The groundwater hydraulic gradient rapidly decreases on the eastern margin. In the central plain the gradient is low, represented by the increased distance between lines of equipotential. The equipotential contours illustrate that the streams are gaining groundwater from the Superficial Aquifer. The North Dandalup River is the one major exception. An investigation by Davidson (1982) found that the hydraulic potential is from the river to the water table, but due to the high clay content of the Guildford Clay exchange of water was minimal. The low hydraulic gradient and shallow water table mean the water balance will have high vertical fluxes and small lateral fluxes.

An outline of the average horizontal and vertical hydraulic conductivity, as well as the average specific yield of each superficial formation member is outlined in Section 7-2.

Discharge

Groundwater discharge from the Superficial Aquifer occurs via several mechanisms; surface drains, rivers, downward leakage, evapotranspiration, wetland related pond evaporation, abstraction, and marine discharge. Assuming a steady state condition, as water flows across the plain the losses to these discharge points are offset by recharge, maintaining equilibrium where the change in storage is zero.

Downward leakage will only occur where a negative (downward) head gradient exists and no confining layer is present. Figure 5-7 shows the potentiometric head difference between the Leederville and Superficial Aquifers. It can be seen in this figure that the area between Nambeelup Brook and North Dandalup River has a head differential of up to 15 m. This region corresponds to an area of lower heads in the Leederville Aquifer, potentially induced by several large licensed abstractions between AM65A and AM66A or possibly water discharging into the eastern extension of the Rockingham Sand paleochannel. Marine discharge for most of the Superficial Aquifer is likely to be via by the Rockingham Aquifer, as a downward gradient and hydraulic connection exists between these aquifers. Also much of the salt water interface is located within the Rockingham Aquifer itself. Flow-net analysis to estimate lateral flow in the Superficial Aquifer is discussed in Section 7-3.

5.2 Rockingham Aquifer

Characteristics

The Rockingham Aquifer extends northwards from the Peel Inlet to the Rockingham district (Figure 4-3). As previously discussed its eastern boundary has been redrawn during this study to include a channel that extends under Lakes Rd, Nambeelup. It is a locally important aquifer, occupying a paleochannel around 60 m deep in the study area that has eroded into Leederville Formation. It consists of coarse sands with a high average hydraulic conductivity estimated to be around 20 meters per day, it is in direct hydraulic connection with the overlying Superficial Aquifer, the surrounding Leederville Aquifer, as well as the ocean interface. In places discontinuous clay lenses on top of the formation separate the Rockingham Aquifer from the Superficial Aquifer, forming localised semi-confined conditions (Passmore 1970).

Recharge

Recharge to the Rockingham Aquifer occurs from the Superficial and Leederville Aquifer. 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. The confluence of the Leederville Aquifer isopotentials towards the paleochannel indicate that it may be a major recharge source to the Rockingham Aquifer. Davidson (1995) calculates that recharge to the Rockingham Aquifer occurs above the saltwater-freshwater interface, at -64 m AHD several kilometres inland. Quantitative estimates of recharge using flow-net analysis conducted by Davidson (1995) estimated 14 300 kL/d, or about 2.17% of rainfall over its mapped area becomes recharge. The Leederville contributed about 3300 kL/d, however decreasing heads in the Leederville since 1995 and the reinterpreted extent of the aquifer will alter this value.

Hydrodynamics

Hydraulic heads in the top of the Rockingham Aquifer are similar to those recorded in the Superficial Aquifer. The area west of the Serpentine River in the north-west of the study area has a decreasing hydraulic head trend of around 0.03–0.05 m/yr and is illustrated in Figure 5-1. This area coincides with a high concentration of abstraction bores. Hydraulic heads in the Rockingham Aquifer are thought to mimic those of the overlying Superficial Aquifer.

Early investigations of the Rockingham Aquifer recognised seawater intrusion as a threat to water quality (Passmore 1970). A salt water interface was identified between 65–75 m BGL several kilometres inland (Davidson 1995), although since this time the interface may have moved in response to a dual function of reduced recharge due to changing climate, and increased abstraction. The salt water interface is also prone to upcoming in areas of high extraction rates. This process may already have affected some users as the transition from fresh to brackish water has been noted in some bores (C. Johnston, *personal communication 2009*).

Discharge

As the Superficial and Leederville Aquifer interfaces are determined to be recharge boundaries, discharge can only occur across the salt water wedge or via anthropogenic abstraction.

5.3 Leederville Aquifer

Characteristics

Within the study area the Leederville Aquifer is synonymous with the Leederville Formation, of which only the Wanneroo Member and Mariginiup Member are extensively present in the area. It is a major confined aquifer within 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: 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 Archean basement rocks of the Yilgarn Block, or in places the thin exposure of the Cattamarra Aquifer. The aquifer extends extensively north and south of the study area and westwards to a fault underlying the ocean (Pennington Scott 2008). It rapidly increases in thickness from its tapered eastern boundary to greater than 200 m thick near the coast. Within the study area the Leederville Aquifer is overlain by the Superficial and Rockingham Aquifers. Underlying the Leederville Aquifer is the South Perth Shale, which acts as an aquitard between the Leederville and Cattamarra Aquifers.

Recharge

Within the study region recharge occurs predominantly via downward vertical leakage from the Superficial Aquifer along the eastern margin, 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 Yoganup Formation may act as preferential recharge flow paths. The potential for recharge extends west from the Darling Scarp to Nambeelup and is illustrated in Figure 5-7. Due to the decreasing heads in the Leederville Aquifer the recharge area is extending further west over time. Currently the isopotentials shown in Figure 5-5 illustrate that the Rockingham Aquifer is a discharge boundary, however with heads decreasing in the Leederville, yet mostly remaining stable in the Rockingham Aquifer, this situation may eventually reverse during the summer. Notably, measured heads at AM67A have already begun to drop below 0 m AHD in summer.

Hydrodynamics

The flow system underlying the study area is generally east to west, with isopotentials running parallel to the Darling Scarp. The potentiometric heads reduces from around 60 mAHD in the east to between 0 – 4 mAHD at the coast. Seasonal head fluctuations are in the order of 5 – 7 m in the east, and around 2 m in the west. The lower hydraulic gradients in the west reflect the increasing thickness and transmissivity of the Wanneroo Member. The increase in abstraction is also increasing the seasonal fluctuation of the potentiometric head. For example, the potentiometric head in bore AM62A varied around 0.5 m seasonally in the early 1980’s, and in recent years the fluctuation has been between 1.5 – 2.5 m. The average horizontal conductivity of the aquifer is around 3.0 m (see Table 7.1),. The average vertical conductivity is constrained to around $1x10^{-5}$ m/d, due mainly to the interbedded shale and siltstone.

Discharge

As groundwater flow is east to west within the study area approximately half of the through flow is intercepted by the Rockingham Aquifer (Davidson 1995). Where the Rockingham Aquifer is not present the flows continue westward to discharge offshore via a saltwater interface. Some through flow may discharge vertically to the Superficial Aquifer where upward vertical gradients are present; however the latter is constrained by the Rockingham Aquifer and estuarine clays around the Peel Inlet.

5.4 Cattamarra Aquifer

Due to the limited extent and interaction of the Cattamarra Aquifer in the study area only a brief summary is given.

Within the study area the Cattamarra Aquifer is analogous to the Cattamarra Coal Formation. It is present immediately below the superficial formations along a narrow section immediately adjacent the Darling Scarp (Figure 4-16). Within 2 km west of the scarp the South Perth Shale aquitard begins, disconnecting the Cattamarra Aquifer from Leederville Aquifer. Generally the hydraulic conductivities observed in the upper Cattamarra Aquifer are slightly higher than those in the Leederville Aquifer, ranging up to 10 m/d. However, the presence of clayey sediments in the eastern areas of the superficial formation acts to reduce recharge to the aquifer. Low recharge rates are indicated by the rapidly increasing salinity with depth (Davidson 1995).

The flow system underlying the study area is generally east to west, radiating out from the recharge area. The potentiometric heads in the recharge area of the Cattamarra Aquifer have reduced from approximately 26.5 m AHD to 20.5 mAHD since 1990. On the western margin heads have reduced from around 11 mAHD to 3.5 mAHD. Seasonally fluctuations are generally less than 2 m in the east, and approximately 0.2 m in the west.

6 Wetlands

6.1 Introduction

Wetlands of the Perth Region have been defined as 'areas of seasonally, intermittently or permanently waterlogged soils or inundated land, whether natural or otherwise, fresh or saline; e.g. waterlogged soils, ponds, billabongs, lakes, swamps, tidal flats, estuaries, rivers and their tributaries' (Tiner 1999).

Within the study area, key wetlands have been selected to have their EWR defined, which involves a detailed assessment of the water regime required to maintain the ecological values of the wetlands. It is to be based primarily on the water requirements of the wetland vegetation. In order to assess the EWR component, a detailed hydrological assessment of the key wetlands is necessary, including conceptual representation of the wetlands (surface and sub-surface), calibrated water level and flow modelling (surface and groundwater) of the key wetlands, and expected change in water level under various climate and land use scenarios.

6.2 Selection of key wetlands

The selection process of key wetlands for the EWR analysis involved members from the DWB, WSB and Allocation Branch's of the DoW, the Wetlands Section of the Department of Environment and Conservation, specialist vegetation scientists from the wetland EWR contractor GHD, local landowners and local environmental consultants.

The process began in April 2008, when DWB, local Mandurah Regional officers and Department of Environment and Conservation officers undertook an initial assessment of the wetlands in the Murray DWMP area, using aerial photography and classification from the Department of Environment and Conservation's Geomorphic Wetlands dataset. Wetlands classed "conservation category" (CCW) were prioritised (wetlands that have been classified according to their remnant high ecological values), but wetlands classed "resource enhancement" were considered if they had high potential ecological values. The desktop assessment was followed by a site visit in June 2008, where a preliminary list of suitable wetlands was constructed. In April 2009, the assessment was extended, and involved officers from various government agencies, the contractor GHD (undertaking the EWR component of the study), land owners and local environmental consultants. An attempt was made to select wetlands from a range of soil types, and hydrological locations (floodplain wetlands, clay-pan wetlands). However, due to degradation issues, only wetlands on sandy soils were eventually chosen, and these were mainly damplands and sumplands. Issues such as site access for drill rigs, entry permissions, and drilling permissions were investigated and also taken into consideration.

A final list of eight wetlands was selected in the Murray DWMP area which will form the basis of the EWR component of the DWMP. The following criteria were satisfied by each of the selected key wetlands:

- All stakeholders agreed that the wetland was of high ecological value, appropriate for the EWR study
- Wetlands were accessible by drill rig
- Land access and drilling permissions could be obtained
- All wetlands were within the Murray DWMP study area.

All sites selected were typical “circular type” wetlands, so a “linear wetland” (the Dandalup River) was also selected and the EWR of this River are to be assessed by the Allocation Branch of the Department of Water during the course of the Murray DWMP study. Figure 6-1 displays the location of the key wetlands that form the EWR component of the DWMP. The Department of Environment and Conservation (DEC) has a geomorphic wetlands database which identifies each wetland on the Swan Coastal Plain with a four digit unique feature identifier (UFI). Key wetlands will be identified by their UFI from the geomorphic wetlands database, and by the colloquial name given to them for the Murray DWMP project.

6.3 Wetland hydrology and hydrogeology

All key wetlands in the EWR study are ephemeral, and do not usually contain free standing water between the months January – April. In general, wetlands on the Swan Coastal Plain can be broadly divided into three categories. Those that receive groundwater over the whole of their bottom surface are known as ‘discharge’ wetlands; those that release wetland water to the aquifer over the whole of their bottom surface are called ‘recharge’ wetlands; and those that receive water and release water over different parts of their bottoms surface are called ‘flow-through’ wetlands. Most of the wetlands that have been studied in detail on the Swan Coastal Plain appear to act as ‘flow-though’ wetlands, which capture groundwater on their up-gradient side and discharge wetland water on their down-gradient side (Townley et al 1993). However, smaller wetlands, which may include some of the EWR wetlands in the Murray region, can act as discharge or recharge wetlands depending on the time of year.

Wetlands in the Murray Study area are usually (but not always) connected to the drainage network. This adds further complications to the hydrological regime, as wetlands can receive additional fluxes through surface drainage from surrounding land, and can be limited in capacity and water level by drains which convey water away from the wetland.

Within each circular wetland, the water surface is horizontal, thus the piezometric head at the bed of the lake 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 water body itself provides less resistance to flow than an aquifer, so groundwater tends to rise towards a wetland on the up-gradient side, travel though the wetland and then discharge to the aquifer at the down-gradient side. The water body acts as a conduit or a short circuit in the wetland-aquifer system. It causes flow to deviate from being essentially horizontal, i.e. it induces significant upward and downward components of flow. It is this fact which 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 water bodies 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 surface water body, 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 though the sediments.

In the Murray study area a veneer of sand (Bassendean Sands) in the first few metres of the surface generally (but not always) overly a layer of lower permeability sediments. The low-permeability layer is usually present 2 – 6 mBGL. In the western part of the catchment, the low permeability layer generally consists of grey sandy clays, which are alluvial and associated with the Serpentine River flow system. In the eastern side of the catchment, clays and sandy clays which form the low permeability layer are associated with the Guildford Clay (Figure 4-7). Throughout the catchment, the Bassendean Sand often contains a layer of coffee rock. This layer is commonly present at or near the watertable, and potentially has the ability to form a low permeability layer, particularly in regions where the coffee rock is heavily cemented. Most of the recent drilling in the Murray region has encountered coffee rock that is easily friable (can be easily broken up by bare hands), and is unlikely to cause an aquitard layer. Drilling has indicated that in some regions a low permeability clay or coffee rock layer does not exist, and in other regions it may act as an impedance layer or aquitard. This layer is likely to affect the hydrological fluxes within certain wetlands systems, and needs to be considered in the wetland hydrological conceptualisation.

Understanding and quantifying the processes controlling water level fluctuations in wetlands are vital to understanding wetland regimes. Determining wetland hydrology is therefore important for understanding how the wetland system functions and for predicting its response to natural and anthropogenic hydrological change.

6.4 Key wetlands

Wetland UFI 3945 (Barragup Swamp)

Barragup Swamp (wetland UFI 3945 in the DEC geomorphic wetlands database) is located in the west of the catchment, approximately 2 km east of the Peel Estuary. The wetland is colloquially known as Barragup Lake or Barragup Swamp, and is surrounded by a largely semi-rural community (classified as Special Rural) with some low-level commercial development along Pinjarra Road (Figure 6-2). The wetland was dry in May 2009, with the exception of a drainage sump in the eastern corner of the lake that remains inundated year round, due to the connection with groundwater.

At the time of this report, three wells had been drilled in the proximity of the wetland. Well HS087-2 encountered sands overlying 1 – 2 m of relatively impervious gravely clay at approximately 7 mBGL which was underlain by clayey sands. The other two bores encountered cemented sands or gravely clays at approximately 3.5 mBGL. In each case the water level was above the lower-permeability layers, at approximately sea level (0 mAHD). The base of the wetland was also very close to sea level (0 mAHD). The wetland exhibited halophyte vegetation, indicating saline water, also evident in salinity data.

Barragup Swamp receives surface water drainage from the surrounding semi-rural community through a large drain in the south-west of the wetland as well as road runoff through a piped network. It is possible that the wetland could become a recharging wetland at some times during the year due to surface water runoff into the wetland from the surrounding land. Water level analysis throughout the winter of 2009 will assist in the determination and validation of the local wetland hydrological processes.

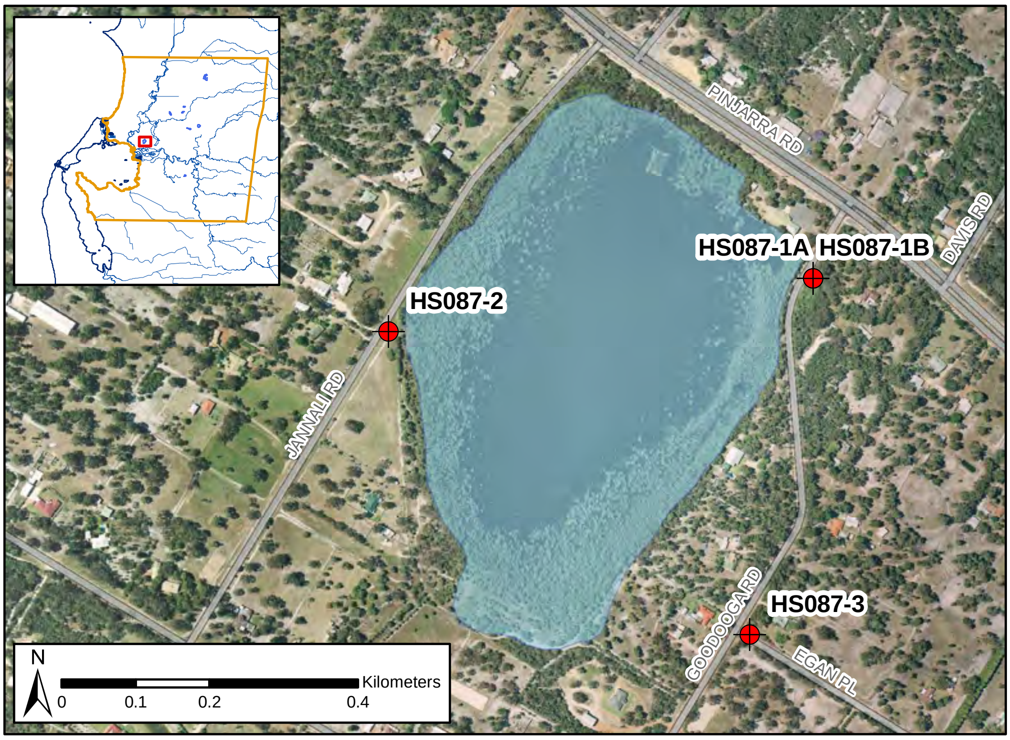

Figure 6-2: *Barragup Swamp (wetland UFI 3945) and associated bore locations*

Wetland UFI 4835 (Airfield wetland)

The Airfield Wetland (wetland UFI 4835 in the DEC geomorphic wetlands database) is bisected by Lakes Road, and is adjacent to a private aerodrome. The wetland is seasonally inundated, and there are elevated culverts adjacent to Lakes Road, connecting the surface water of the northern and southern portion of the wetlands. Six bore locations are drilled in the vicinity (Figure 6-3).

Water level analysis was likely to be affected from the Water Corporation dewatering a large drain for the installation of a water pipeline under Lakes Road, during the period of drilling and initial measurements. This would have affected the groundwater levels recorded in the early period. Readings taken on the 19 June 2009 showed that significant head differences occurred between shallow and intermediate bore levels in HS104-2 A and B (approx 1.5 m difference), indicating the possible presence of a perched surficial groundwater table in the vicinity. However, this head difference was not present in the bore HS104-3A and B, and may have been caused by dewatering activities. It is therefore difficult to ascertain whether the wetland is perched on a low permeability layer, or is an expression of the superficial groundwater. Parsons Brinkerhoff investigated shallow groundwater levels in the Nambeelup Strategic Industrial Area (Parsons Brinkerhoff, 2008), which included Airfield Wetland. The report suggests that seasonally inundated areas are a surface expression of the groundwater, and the winter groundwater contours in the report suggest that the wetland is inundated by superficial groundwater in winter months.

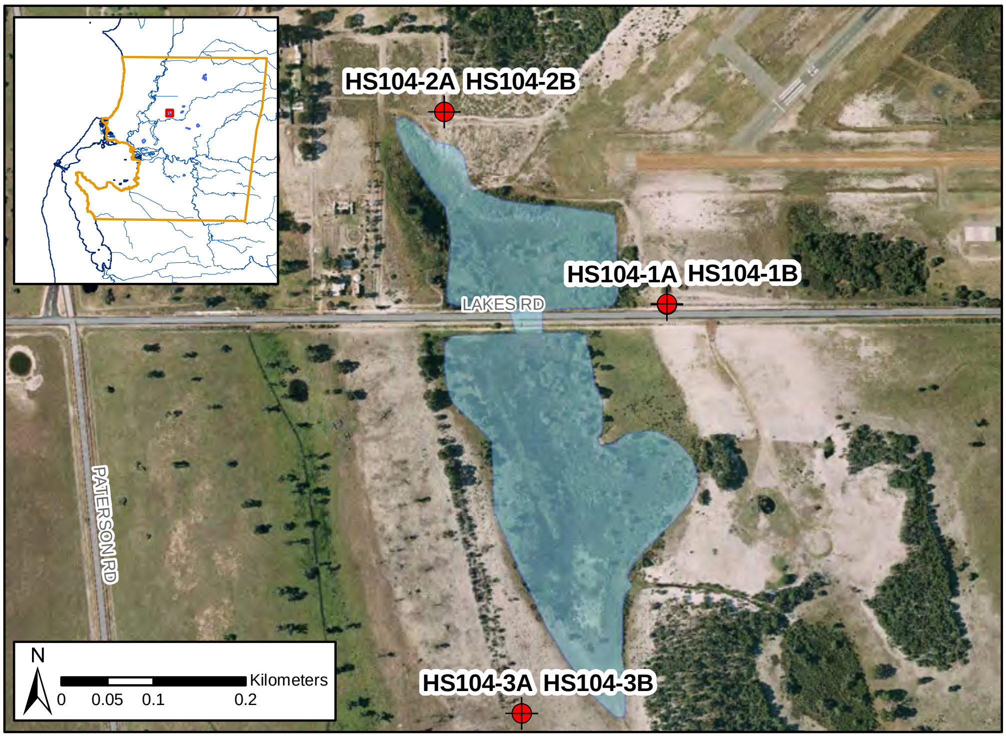

Figure 6-3: *Airfield Wetland (wetland UFI 4835) and associated bore locations*

Surface water is likely to drain from the runway of the north/west facing aerodrome and enter the wetland, and while there is a drain at the southern end of the wetland leading to Nambeelup Brook, its invert is so high that outflow from the Airfield wetlands will flow to the north-west and west.

The elevated culverts that join the northern and southern portions of the wetland have been temporarily blocked during the installation of the water pipeline along Lakes Road. Therefore Airfield Wetland is monitored as two wetlands north and south of Lakes Road (Airfield North and Airfield South) due to the pipeline construction blocking water flowing between the wetlands, and partially to ensure that the wetland systems are linked.

Wetland UFI 5032 (Greyhound Road Wetland)

Greyhound Road Wetland (wetland UFI 5032 in the DEC geomorphic wetlands database) is located north of Greyhound Road, immediately north east of Lakes Road Wetland. The wetland is located on private property, is heavily vegetated and seasonally inundated, being dry during summer months. Four bores have been drilled in the vicinity: north-east, south and north-west of the wetland (Figure 6-4). The southern bore (HS108-2) has a nested shallow and deeper bore, with screening depths of approx 1.5 – 3.5 m and 6 – 8 m respectively.

Initial readings from LiDAR elevations indicate minor head differences between HS108-2A and B. The wetland receives surface water inflows through a drain entering the western edge of the wetland. There is a discharge drain to the south of the wetland (draining an area of approximately 1 km^2) which is likely to constrain the maximum water level in the wetland. According to the head differences in the nearby bores, groundwater flows tend to be in north-south direction towards Nambeelup Brook. This flow pattern is not supported by the regional groundwater contours defined by the DoW's minimum groundwater level coverage. However, finer scale local groundwater investigations agree that there is a tendency for regional groundwater to flow towards south in this region (Parsons Brinkerhoff, 2008, Bowman Bishaw Gorham, 2006), and the regional superficial groundwater flow pattern around Nambeelup Brook is reflected in the phreatic surface, presented in Figure 5-2.

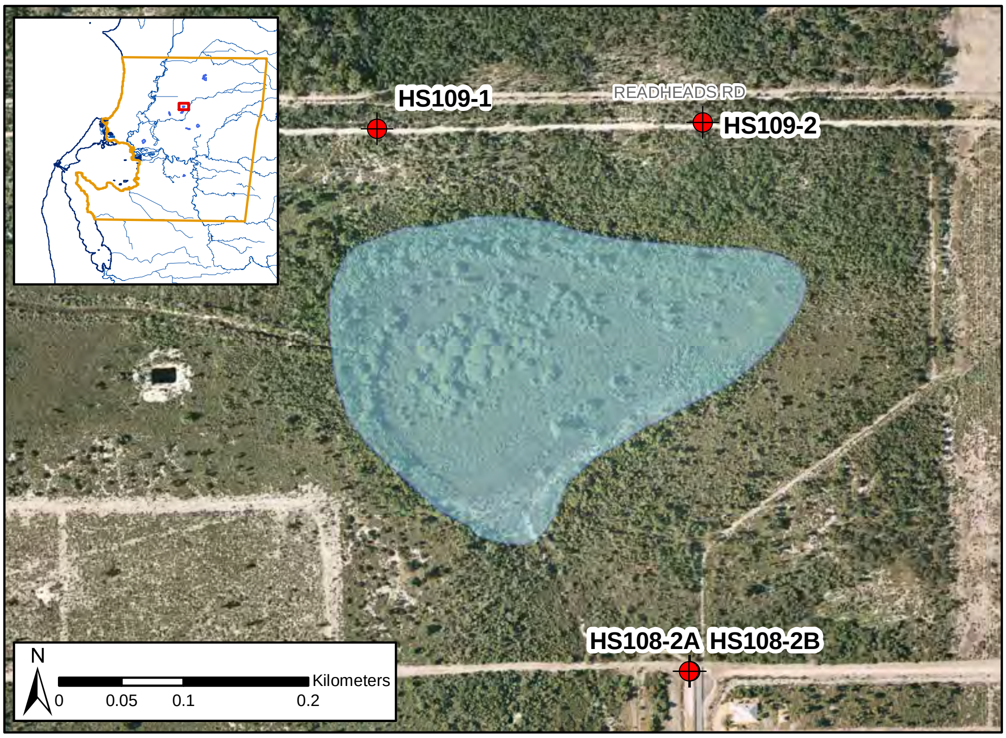

Figure 6-4: *Greyhound Road Wetland (wetland UFI 5032) and associated bore locations*

Wetland UFI 5033 (Lakes Road Wetland)

Lakes Road Wetland (wetland UFI 5033 in the DEC geomorphic wetlands database) is approximately 1.5 km south of Greyhound Road Wetland and is also located on private property, is heavily vegetated and seasonally inundated (Figure 6-5). It is adjacent to a larger conservation-category wetland (wetland UFI 13305) that covers most of the land between Lakes Road Wetland and Greyhound Road Wetland and the bushland to the north west of Lakes Road wetland. The wetland is cut by Lakes Road in its south, and has three paired sets of bores in the vicinity. This includes a shallow and deep bore drilled to the east (screened at approx 1 – 2.5 mBGL and 13 – 16 mBGL), and two sets of nested shallow and deep bores to the north and west (HS105B and A are screened at 2 – 5 m and 11 – 14 m respectively).

Significant head differences were observed in bores HS108-2A and B (approx 0.6 m), however the proximity of the regional groundwater level to the base of the wetland indicates that the wetland is not likely to be perched. The wetland is drained by a channel in its north-east which joins to a main channel and drains to Nambeelup Brook, approximately 1km downstream. There is a small elevated culvert that drains water south across Lakes Road when the wetland water level is greater than approximately 0.5 m above ground level. Groundwater flow is likely to be eastward towards Nambeelup Brook, as indicated by the superficial bore water levels, and is supported by studies completed by Parsons Brinkerhoff (2008) and Bowman Bishaw Gorham (2006).

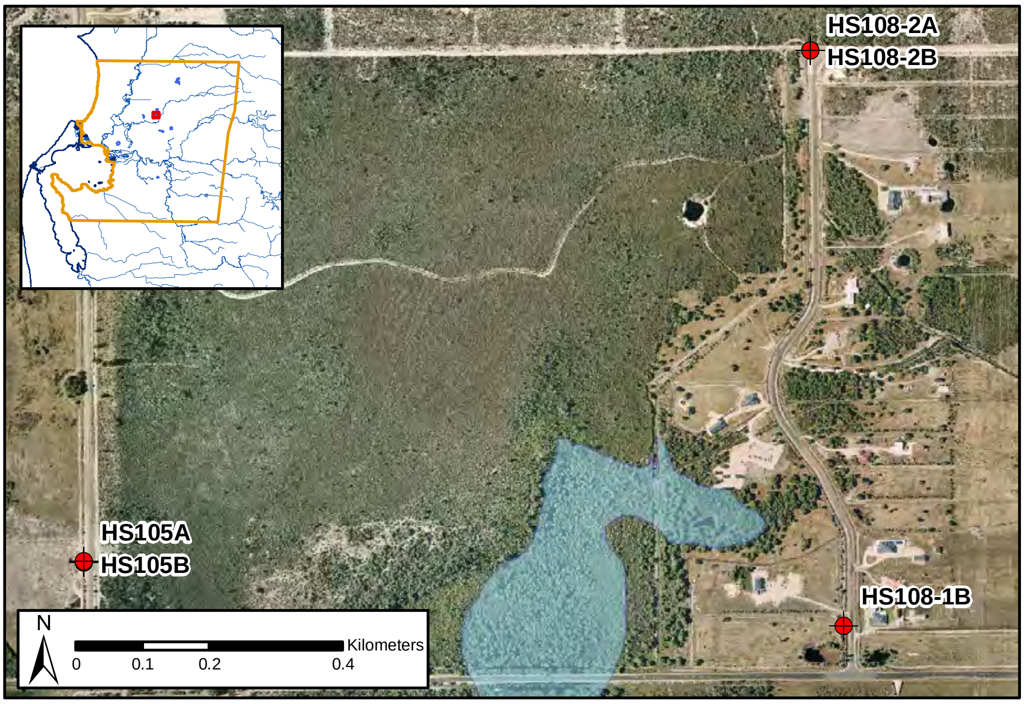

***Figure 6-5**: Lakes Road Wetland (wetland UFI 5033) and associated bore locations*

Wetland UFI 5056 (Phillips Road Wetland)

Phillips Road Wetland (wetland UFI 5056 in the DEC geomorphic wetlands database) is located in the south of the catchment, adjacent to the Pinjarra Golf Course, a caravan park, and the Pinjarra light industrial area. It is seasonally inundated in medium to high-rainfall years. Three superficial bores are drilled in the vicinity (Figure 6-6). The wetland appears to be highly disturbed, and is bisected by a high-voltage power line easement. In regions the wetland is sparsely vegetated, however it receives its 'conservation category' rating due to the presence of a critically endangered plant species. The water levels (June 2009) in each of the bores range between 1.0 – 2.0 m below the base of the wetland. The wetland receives surface water drainage from the nearby caravan park, from surrounding rural residential land uses south west of the wetland, and from the light industrial area to the east of the wetland. Moores Road bounds the wetland to the south, and on the southern side of this road is a deep drain with an invert deeper than the bottom of the wetland. The southern drain is connected to the wetland via a drain and culvert to the south of the wetland. It is likely that Phillips Wetland is a recharge wetland, and receives water from surface water inflows and direct recharge from rainfall, and discharges to the superficial water table and to the southern drain adjacent to Moores Road. Water level and chemistry analysis over the winter of 2009 will assist in determining the hydrological processes. During the winter of 2008 the wetland had standing water in the lower lying areas, but these were not extensive.

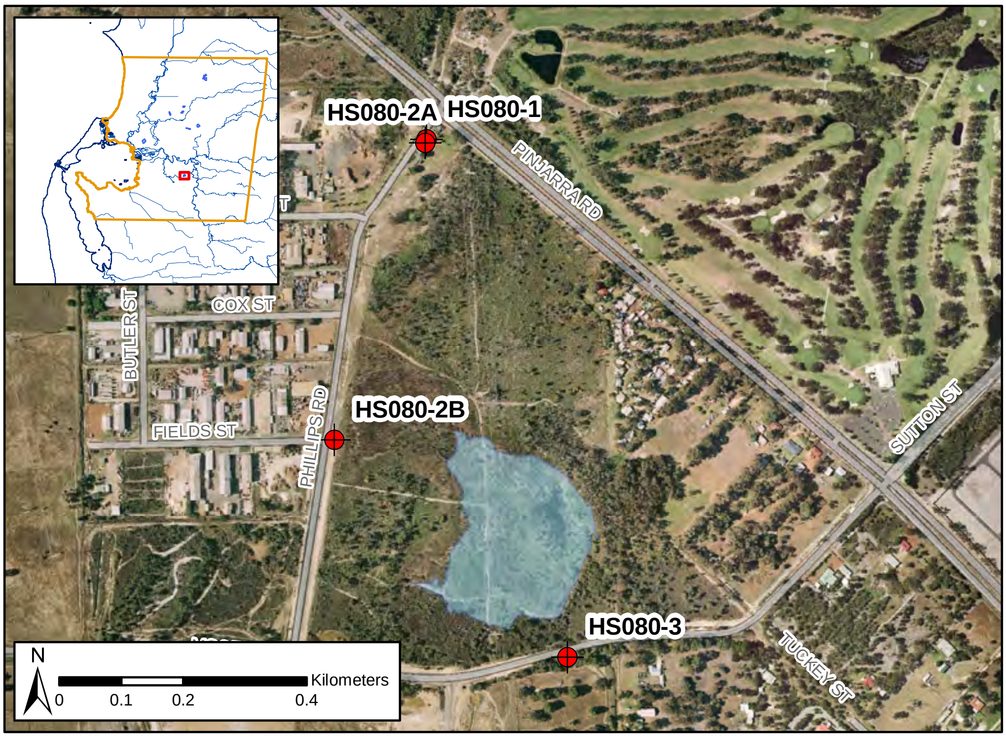

Figure 6-6: *Phillips Road Wetland (wetland UFI 5056) and associated bore locations*

Wetland UFI 5180 (Scott Road Wetland)

Scott Road Wetland (wetland UFI 5180 in the DEC geomorphic wetlands database) is located close to the centre of the study area (Figure 6-7). It has received a "resource enhancement" classification from the Department of Environment and Conservation's geomorphic wetlands dataset, but was included as a key wetland for the EWR study due to the high level of vegetation diversity, quality and health that was observed during the site visit. The wetland is seasonally inundated, and is dry in summer months.

At the time of reporting, there were three bores drilled in the vicinity, two north and one south of the wetland. According to the water levels in the bores, groundwater flow is in a southerly direction, toward the Murray River. A set of nested bores is drilled approximately 700 m north of the wetland (HS98A and B), which display very little head difference. Local data exists from the Bowman Bishaw Gorham report (2006), and may be used in subsequent analysis. The wetland receives a small amount of surface water drainage from surrounding paddocks. A drainage channel is present south of the wetland which drains to the upper reaches of Winter Brook and eventually to the Murray River.

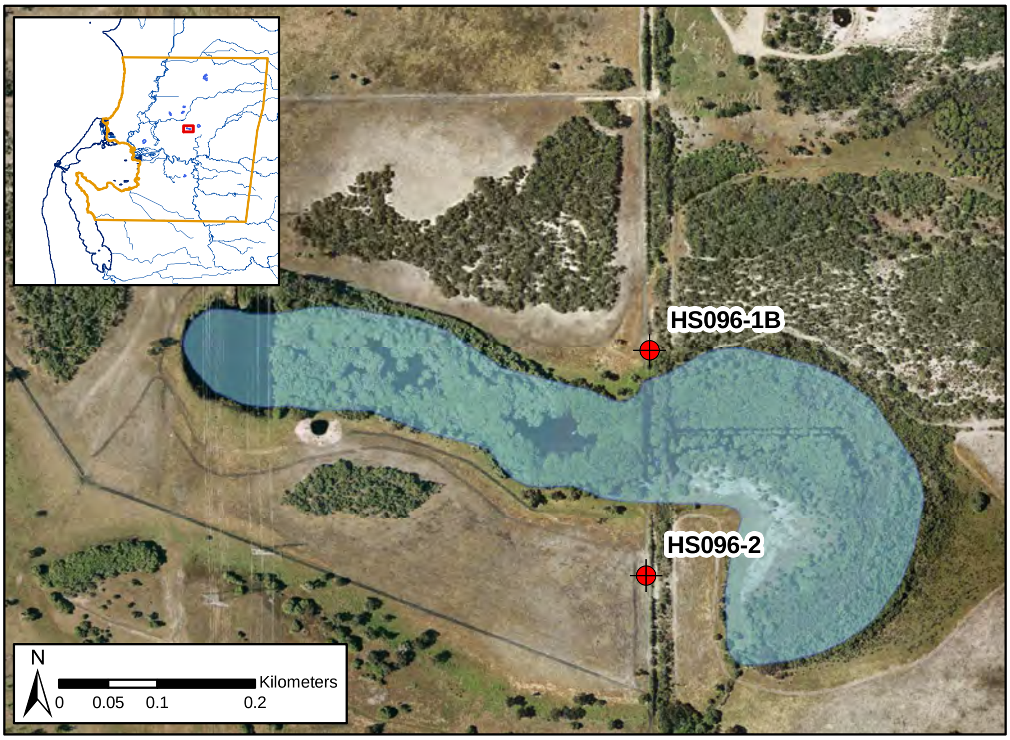

Figure 6-7: *Scott Road Wetland (Wetland UFI 5180) and associated bore locations*

Benden Road Wetland (wetland UFI 5724)

Benden Road Wetland (wetland UFI 5724 in the DEC geomorphic wetlands database) is located approximately 1.2 km north east of Scott Road Wetland. There are two sets of nested bores to the north and to the north west of the catchment (Figure 6-8).

Very minor differences in head levels in nested bores indicates that the wetland is not likely to be located on a perched aquifer, and the proximity of the water levels to the base of the wetland indicates that the wetland is likely to be an expression of the regional groundwater. This conclusion agrees with the Bowman Bishaw Gorham Report (2006), which investigated the regional groundwater in the southern Nambeelup Region (including Benden Road Wetland), and determined areas of potential inundation from the superficial groundwater table during winter months.

The wetland does not appear to receive water from surface water drains, nor does it discharge water to adjacent drains. It is seasonally inundated, and dry in late summer and early autumn.

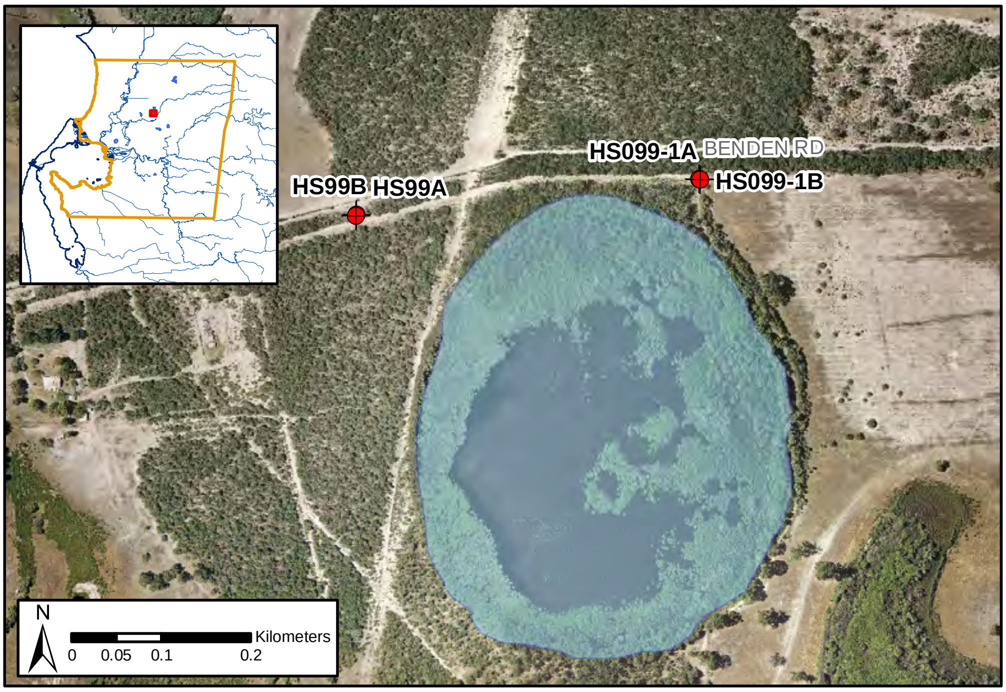

Figure 6-8: *Benden Road Wetland (wetland UFI 5724) and associated bore locations*

Wetland UFI 7046 (Elliot Road Wetland)

Elliot Road Wetland (wetland UFI 7046 in the DEC geomorphic wetlands database) is located in the north of the Murray DWMP area. The wetland is adjacent to an aquaculture farm to the east, is bounded by a ridge of vegetated sand dunes to the west, which mark the boundary of the Murray DWMP area. There are three proposed bores in the vicinity of the wetland, and a set of bores immediately to the north on Elliot Road.

Only the eastern ridge of the wetland receives a conservation category rating, however the entire wetland has been included for the EWR study. Elliot Road Wetland is bounded artificially in the east by a levee bank, and two drains in the northern and southern portions of the levee bank which connects the wetland to a network of drains. The drains convey the water south towards Nambeelup Brook. Relative water level analysis and lithology is not yet available from the nearby bores, however, according to the inferred regional groundwater surface (Figure 6-9), the regional water table is very close to the base of the wetland at the start of winter, and the wetland is likely to be an expression of the regional water table. The water level in the wetland is likely to be limited by the drain levels that intersect the wetland.

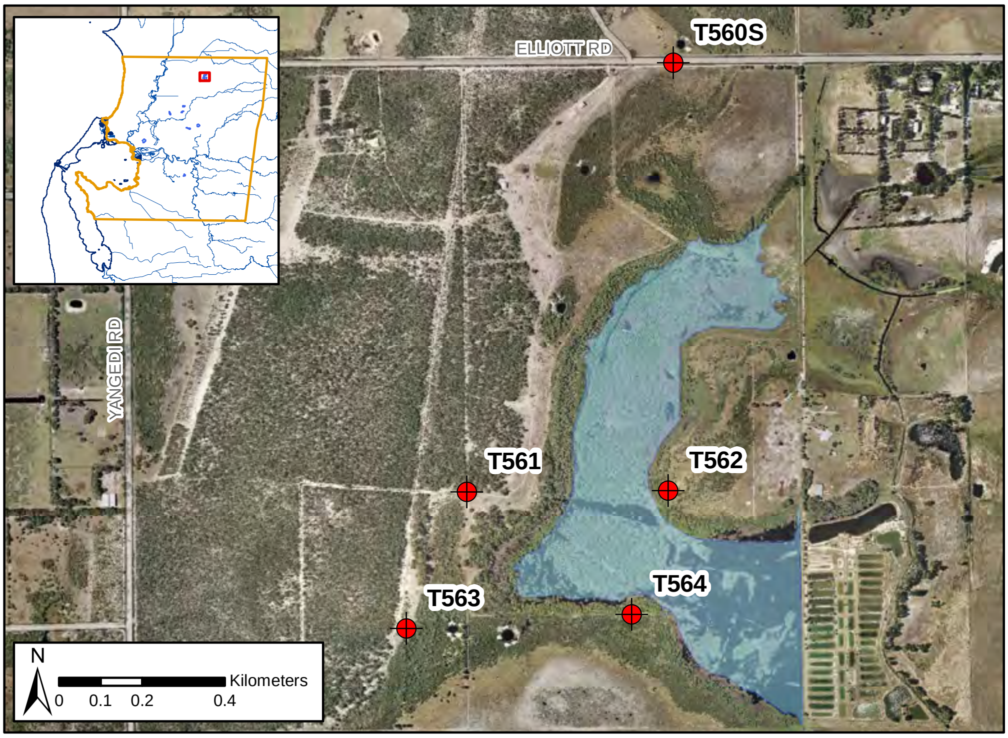

Figure 6-9: *Elliot Road Wetland (wetland UFI 7046) and associated proposed bore locations*

6.5 Wetland conceptual water balance

Analysis of the depth to groundwater, based on the superficial phreatic head computed for the Murray study area (Figure 5-2) indicates that the base of all wetlands with the exception of Phillips Wetland are within 0.7 m of the regional groundwater table. Based on the nearby long term superficial monitoring bores (Appendix B), the seasonal amplitude of the regional groundwater table in the central and western part of the catchment is approximately 1.2 m. Therefore, in an average year, all wetlands Phillips Wetland are expected to become seasonally inundated by regional groundwater.

Phillips Road Wetland has a depth to watertable of approximately 2 m, and the surrounding long term superficial monitoring bores have seasonal amplitude of approximately 1.2 m. It is therefore unlikely that the regional watertable will recharge the wetland; however it is possible that this may occur in wetter years.

Fluxes that determine the water level in a wetland include direct rainfall, evaporation from the wetland water surface, evapotranspiration from fringing vegetation, vertical leakage through the base of the wetland, regional groundwater inflow and outflow, surface water runoff from the catchment draining to the wetland, and artificial drainage that conveys water away from the wetland. The hydraulic conductivity of the bottom sediments or of any lithological layer between the wetland and the regional groundwater table will affect the rate at which the water perched in the wetland will percolate to the groundwater.

Conceptually, a simple wetland water balance can be applied to approximate wetland levels at a monthly time-step, whereby the water level in the wetland is equal to the sum of:

1. The difference between the regional groundwater table height and the elevation of the base of the wetland, and
2. The height of water in the wetland due to the local hydrological fluxes (i.e., direct rainfall, surface water inflows and outflows, evapotranspiration, vertical leakage and direct evaporation).

The conceptual wetland water regimes expected to be encountered in the Murray study area are presented in Figure 6-10. If the surface water catchment of the wetland is small, and the wetland contains few surface water drain inflows (e.g. Wetland 5724), the water level will be driven by the regional groundwater levels rather than local hydrological fluxes, and the regime will be similar to scenario 1 in Figure 6-10. If, however, there is a large amount of surface runoff (from either a large draining catchment or from large areas of impervious surfaces, e.g. wetland Barragup Swamp), or if the hydraulic conductivity of the bottom sediments or subsurface lithology is high, water levels, particularly at the start of winter after initial rainfall events, will be largely driven by local hydrological fluxes, and the regime will be similar to scenario 2 in Figure 6-10. If the regional groundwater level is always below the wetland base, but the wetland receives large amounts of surface drainage or direct hydrological inputs (e.g. Phillips Road Wetland), then the low permeability material will form an impedance layer, and the wetland water level will be higher than the regional groundwater. In this case the regime will be similar to scenario 3 in Figure 6-10. This type of conceptualisation is used to determine the major driving fluxes of wetland water level, and has obvious implications to wetland modelling and management. The wetland water level is dependent on:

1. the proximity of the regional water table to the wetland surface
2. the surface water catchment of the wetland
3. the rate of runoff for surface water
4. the vertical hydraulic conductivity of the bottom sediments or any impedance layers between the wetland and the superficial groundwater
5. evapotranspiration and rainfall
6. the topography of the wetland
7. invert levels for drains conveying water away from the wetland.

The water level is particularly sensitive to the vertical hydraulic conductivity and to rates of runoff from surface water catchments. Conceptual monthly wetland water levels calculations, including the analysis of the wetland fluxes will be determined once monitoring data from the winter of 2009 has been collected (see section 6.6). It is necessary for one year of wetland water level and surrounding superficial groundwater levels to be collected before a numerical conceptualisation is meaningful.

6.6 Wetland monitoring

The eight key wetlands that are included in the EWR component of the Murray DWMP are being extensively monitored during the winter of 2009. The drilling program for the bores adjacent the wetlands is a component of the monitoring program, and the limited data from these bores is the only data from the wetland monitoring program that could be used in the current conceptual model report.

Water level data for all bores will be collected monthly until at least the end of 2010. In addition, six data loggers will be included in selected bores to measure small time-scale effects of the rise of the regional water table relative to the rise in water level of selected wetlands and the timing of rainfall events. Gauge boards have been installed in the deepest portion of each of the wetlands, and wetland water levels will be monitored monthly.

Water chemistry data will be collected in September 2009 for all monitoring bores, in rainfall and in wetland water bodies. It is desirable to collect water chemistry species monthly, however the water quality monitoring budget allows only for a single snap-shot. The suite of chemicals collected will include major anions and cations, nutrient species and heavy metals in some locations. In addition, pH, dissolved oxygen, and salinity will be measured in-situ. The hydrological conceptualisation of the wetlands will be reviewed upon collection of the water chemistry and the water level data from the winter of 2009.

7 Numerical conceptualisation

The following section provides numerical description of the conceptual model for the Murray study area. The conceptual model is based on the collation of hydrological, hydrogeological, geological, climate and topological information gathered as part of the literature review and the data interpretation process described in the previous chapters. The conceptual model reflects the general understanding of the system, however there are many uncertainties and assumptions within the conceptual model due to data availability. The conceptual model will be refined and improved throughout the modelling process, as more data becomes available or interpretation of available data is improved.

The modelling area covers approximately 720 km^2 on the Swan Coastal Plain from Dirk Brook to south of the Peel Estuary (Figure 1-1). The aim of the numerical conceptualisation is to identify and quantify important aspects of the hydrogeological system. The hydrological processes represented in the conceptual model include groundwater recharge from rainfall and irrigation, evapotranspiration, wetland and drainage interaction with groundwater, and groundwater abstraction. A simplified diagram of the conceptual model is displayed in Figure 7-1.

7.1 Model boundaries

It is important to constrain groundwater flow and recharge using hydrogeological model boundaries. There are two types of external model boundaries: 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 real 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), the hydraulic boundaries need to be defined. Hydraulic boundaries are derived from the groundwater flow-net and are therefore "artificial" boundaries. In the case of the Murray study area, the eastern and western boundaries are physical boundaries and the northern and southern are hydraulic boundaries.

The eastern boundary is the Darling Fault where no flow condition applies to all groundwater layers. There will be input to the surface water at this boundary however, and waterways that discharge from the scarp will be included into the model, with daily discharge rates taken from the surface water model SQUARE (Kelsey 2010). The western boundary of the model is the coastline of the Indian Ocean and of the Peel Harvey Estuary which is affected by tidal variations. Tidal variations occur at various time-scales; there are daily, monthly and seasonal fluctuations in water levels. There is a seasonal signal in sea-level in the Peel Estuary and Indian Ocean varying up to 0.4 m in annual monthly average over the course of a year. Boundary heads will affect groundwater heads, particularly in nearby bore locations. Figure 7-2 displays the monthly average tidal values at the Peel and Harvey estuaries. The value at the Peel Estuary is used for the time-varying head for the western boundary of the model, as it is most representative of the model boundary in the Murray study area.

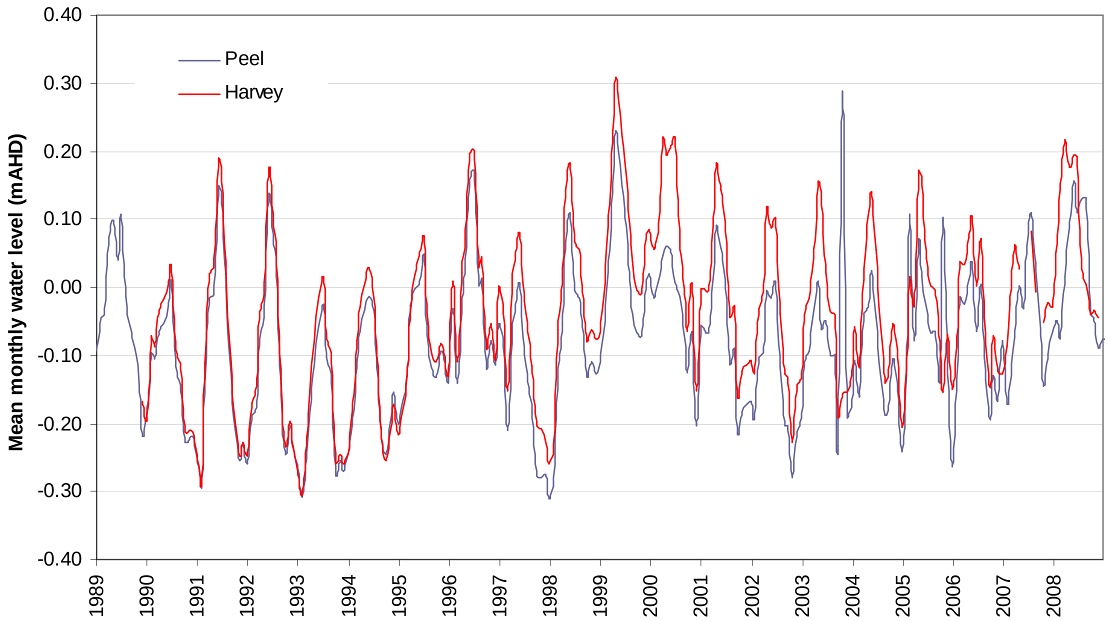

Figure 7-2: *Monthly tidal variations in the Peel and Harvey estuaries*

The northern boundary is at Dirk Brook / Punrack Drain, and follows along a stream line, across which no flow is occurring. This ensures that there is likely to be minimal water exchange through this boundary throughout the modelling timeframe. The southern boundary is also a hydraulic boundary, which crosses a mound between the Murray River and the Harvey estuary. The groundwater gradient of the mound is small on the southern boundary, and exchange across the model boundary is likely to be minimal.

7.2 Parameters

Groundwater parameters

The conceptual model consists of 11 geological units. Each unit is distinguished by regions of distinct hydrogeological properties representing different formations, and is represented spatially in the block model (Figure 4-18).

Average values for the hydraulic groundwater parameters are presented Table 7-1. They are the result of collating and then averaging values from a wide variety of sources, including: values obtained from pump tests, slug tests, literature reviews such as Davidson (1995), localised investigations such as URS (2002) for the Iluka Resources Ltd mineral sands mine, and modelling calibrations for PRAMS and PHRAMS. Over coming months more pump and slug test analysis will become available providing further constraint on the average values. Alluvial sediments are often associated with layers of silt or ironstone which cause the vertical hydraulic conductivity to be smaller than the horizontal hydraulic conductivity. Davidson and Yu (2008) estimated vertical conductivity to be 1/10th the value of the horizontal conductivity for most stratigraphy types in the Superficial Aquifer. The 1/10th rule was used to estimate vertical hydraulic conductivity values in the superficial formations for the Murray study.

Table 7-1: *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_H m/day	K_Z m/day	S_Y	S_S
Estuarine/Swamp	(refer Guildford)	1.0	0.1	0.07	$5x10^{-5}$
Bassendean	5 to 15	9.2	0.9	0.21	$1x10^{-6}$
Tamala	7 to 1000	120.0	12.0	0.27	$1x10^{-6}$
Safety Bay	15	15.0	1.5	0.22	$1x10^{-6}$
Guildford	0.0001 to 2	1.0	0.1	0.07	$5x10^{-5}$
Colluvium	1	2.0	0.2	0.05	$5x10^{-5}$
Gnangara	20	20.0	2.0	0.22	$1x10^{-6}$
Yoganup	0.1 to 10	6.5	0.7	0.10	$1x10^{-6}$
Ascot	1 to 28	9.5	1.0	0.23	$1x10^{-6}$
Rockingham	20	20.0	2.0	0.25	$1x10^{-6}$
Leederville	0.1 to 10	3.0	$1x10^{-5}$	0.01	$5x10^{-5}$

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, i.e. not flowing under pressure. The Manning Equation was developed for uniform steady state flow, and uses the coefficient *n* which describes the channel roughness.

Work by the U.S. Bureau of Reclamation and other government agencies indicates that the Manning Roughness factor should be increased (by approximately 10 – 15%) for hydraulic radii greater than 3 m. The loss in capacity of large channels is due to the roughening of the 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 7-2.

Table 7-2: *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

7.3 Hydrogeological processes

The numerical model will be required to simulate major hydrological process and to calculate the water balance of the aquifer system. The conceptual hydrological processes represented in the model include groundwater recharge from rainfall, evapotranspiration, surface water runoff, groundwater abstraction, lateral groundwater flow, groundwater recharge from irrigation returns and leakage to and from deeper aquifers. For the Murray study area, where there is generally no long-term trend in superficial groundwater level (see Appendix A), the water balance model should satisfy the following flux equation:

$$RE_G - \Delta Ly - \Delta D - EVT - \Delta Lz + I_{re} - A = 0$$

Where:

RE_G = gross recharge from rainfall to the Superficial Aquifer (ML/yr)

ΔLy = net horizontal flow of groundwater across the model boundaries (ML/yr)

ΔD = net drainage from groundwater to surface water (ML/yr)

EVT = evapotranspiration from the groundwater (ML/yr)

ΔLz = net leakage to confined aquifers (ML/yr)

A = groundwater abstraction (ML/yr)

I_{re} = groundwater recharge return from irrigation (ML/yr)

That is the sum of the fluxes on an annual time-step is approximately zero. All fluxes vary in space and time. Some values can be measured directly, for example, the discharge from extraction wells, 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 assist in determining the relative importance of specific drivers of groundwater levels in the Murray study area. Each of the flux estimation techniques are described in the following sections and a summary of the flux quantities is presented in Section 7.4.

Gross recharge from rainfall to the Superficial Aquifer

The groundwater recharge to the Superficial Aquifer is the proportion of rainfall over the land surface that reaches the watertable. The amount of recharge depends on the rainfall (intensity, frequency an duration), land use, depth to watertable, and soil and geological conditions.

Recharge of the Murray superficial groundwater system occurs principally from direct rainfall infiltration, although overland flow from waterways that drain from the scarp to the coastal plain will also contribute a small amount of recharge from outside of the study area. For most of the study area, recharge to the superficial groundwater table is through free-draining sandy-soils. In most areas, the groundwater table is close to the surface (1 – 5 mBGL). Flow through the unsaturated zone is likely to be vertical and lateral movement in the unsaturated zone will be negligible.

Conceptual recharge for the Murray Region can be calculated by using an empirical relationship derived from WAVES modelling (Xu *et* al 2009) for sites in the Armadale area with annual rainfall (1975 – 2000, average 842 mm) and evaporation similar to the Murray study area, and soil representing both sandy and clay profiles. The WAVES model estimates annual recharge versus annual rainfall for the Superficial Aquifer. The model uses Richards equation to simulate saturated flow in one dimension and returns a maximum annual recharge using annual rainfall, and a monthly breakdown of recharge values.

The maximum recharge is based on freely draining sandy soils, and can be represented by the following equation:

$$RE_{GM} = 0.8(R - 350)$$

Where:

RE_{GM} = maximum gross recharge for freely draining sandy soils

R = Annual rainfall

Using this formula, the gross infiltration to the Superficial Aquifer in the Murray study area is estimated to be 440 mm/yr, which is 49% of the annual rainfall. Evapotranspiration (EVT) from the superficial groundwater system will be likely to reduce this quantity significantly, and the net recharge will be significantly less than this value. The assumption is that superficial soils in the Murray Study area are free draining. This formula is likely to be an overestimation in the Murray study area, where surface water regularly reaches the ground surface, and any extra rainfall will not infiltrate, and hence is included in recharge calculations. This figure represents an upper limit in the gross recharge to the superficial aquifer.

Horizontal groundwater flow

Horizontal or lateral through-flow 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 through-flow, flow-net analysis of the study area has been undertaken. A flow-net is a graphical representation of two-dimensional steady-state flow through an aquifer. It is created through the combination of hydraulic head contours and flow-lines, where a flow-line is an estimate of the path a molecule of groundwater 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 through-flow to be calculated using Darcy’s law.

For the Murray study region the flow-lines were hand-drawn over a hydraulic head contour map to develop smooth curve-linear lines. The hydraulic head contours were based on late dry season (June 2009) measurements as this better satisfies the assumption of steady-state conditions (minimal rainfall recharge), and due to the limited number of wet season head measurements available. Transmissivity was calculated using the saturated thickness multiplied by the relevant hydraulic conductivity for each geological formation. This was completed using the block model discussed earlier, and the hydraulic conductivities presented in Table 7-1. The length and width of each cell was measured accurately using GIS. The flow-net and results of calculations of lateral through-flow for each of the flow channels are displayed in Appendix E. Estimates of annual flow rates from the flow-net analysis are presented in Table 7-3.

Table 7-3: *Flow-net derived estimates of lateral groundwater flow for various outlets within the Murray study area.*

Outlet	Q_{out} (ML/day)	Q_{out} (GL/Year)
Serpentine River	7.4	30.2
Murray River	11.6	42.4
Peel Estuary	2.6	9.5
Indian Ocean	8.6	3.2

The flow-net analysis estimated flows of 30.2 GL/yr flows to the Serpentine River, 42.4 GL/yr flows to the Murray River, 9.5 GL/yr flows to the Peel Inlet, and 3.2 GL/yr for the Indian Ocean. These values are likely to be an underestimation of the annual volume of lateral through-flow, as higher rates are likely to occur during winter late-winter / spring months.

Drainage from groundwater to surface water

The Murray study area has a series of waterways and channels which drain the superficial groundwater system. The two largest rivers in the catchment are the Murray and Serpentine Rivers, which drain groundwater year round, and are significantly deeper than the other water bodies in the region (depth of rivers are 5 – 10 m compared with 1 – 2 m for most minor rivers and drains, see Appendix B). The groundwater drainage component to the main channels of the Murray and Serpentine rivers has been estimated using flow-net (see the previous section). 30.2 GL/yr is estimated to discharge to the Serpentine River annually, and 42.4 GL/yr is estimated to discharge to the Murray main channel annually. The other waterways of the catchment are seasonal, but are likely to drain significant quantities of groundwater throughout the winter to early summer.

The groundwater component of the surface flows can be estimated using baseflow separation techniques. Baseflow separation uses the time-series record of streamflow to derive the baseflow signature. Filtering methods for baseflow separation (Eckhardt 2005) process the entire stream hydrograph to derive a baseflow hydrograph, the only requirement being a daily hydrograph.

Daily hydrographs for all waterways in the Murray study area have been estimated by a surface water modelling project that was undertaken by the Water Science Branch of the Department of Water using the Streamflow Quality for Rivers and Estuaries (SQUARE) model (Kelsey 2010). SQUARE is a physically-based conceptual model driven by meteorological and land-cover inputs. It was developed specifically to model hydrology and nutrients in large-scale catchments, and has the ability to deal with the hydrological characteristics of the Swan Coastal Plain (sandy duplex and seasonally waterlogged soils with ephemeral waterways), and uses a daily time-step.

Calibration of the hydrological component of the SQUARE model was undertaken independently from the nutrient modules. The hydrological component has 32 parameters that are calibrated against observed data extracted from all flow gauging stations listed in Section 3.2, and the Nash-Sutcliffe estimator (NSE) is used to determine the efficiency of the calibration. Table 7-4 gives the NSE values for the modelled flows at the gauging stations in the Murray study area, and the corresponding observed verses modelled cumulative flow (the cumulative values are for days where there is both a predicted and observed flow value, and does not reflect an average annual value, or a cumulative flow over a period of years).

Table 7-4: *Daily and monthly Nash-Sutcliffe efficiency values for observed versus SQUARE predicted flows, and observed versus predicted cumulative flows for flow-gauging stations within the Murray study area*

Station ID (AWRC)	Daily NSE	Monthly NSE	Observed cumulative flow (mm)	Predicted cumulative flow (mm)
614063	0.87	0.95	1443.1	1452.6
614094	0.68	0.84	921.3	1075.1
614065	0.75	0.95	19096.9	19134.0
614028	0.55	0.71	3853.9	2918.3
614009	0.45	0.75	1530.6	1985.3
613032	0.55	0.75	1460.7	1229.2
616030	0.53	0.75	824.1	685.7
616029	0.36	0.48	1323.4	1476.9

Average annual flows derived from the SQUARE model for the water bodies which discharge into the Estuary from the years 1985 – 2008 are displayed in Table 7-5. Drainage quantities into and out of the Murray study area are displayed in Table 7-6. This does not include the main channels of the Serpentine and Murray Rivers, as there are no flow calibration stations in the downstream ends of these Rivers, where they are likely to receive large quantities of baseflow. The baseflow to these rivers was determined using flow-net analysis, described in the previous section.

Table 7-5: *Average annual flows in GL (1985 – 2007) for the major waterways in the Murray study area, derived from SQUARE modelling*

Year	Nambeelup Brook	Upper Serpentine River	Murray River	North/South Dandalup Rivers	Dirk Brook	Caris/Coolup Drains
1985	23.3	76.1	411.6	40.4	16.8	12.1
1986	18.7	96.5	318.8	32.6	13.4	9.2
1987	18.7	73.8	300.6	25.2	10.8	5.9
1988	37.1	144.8	713.0	64.4	31.2	22.1
1989	20.6	71.9	394.8	46.5	20.1	13.7
1990	16.4	73.5	431.3	48.7	20.2	14.1
1991	44.8	163.9	621.0	56.1	25.8	19.4
1992	30.4	132.8	624.4	49.8	21.1	16.0
1993	15.3	55.9	358.1	35.4	14.4	9.5
1994	22.7	58.7	404.2	33.1	14.2	10.2
1995	23.9	60.7	523.7	49.2	22.5	15.6
1996	29.6	99.3	791.8	56.7	25.8	19.6
1997	19.4	66.5	358.4	42.7	17.6	12.8
1998	16.2	62.1	380.4	47.0	19.6	13.7
1999	26.2	86.6	528.8	68.6	31.0	22.7
2000	28.2	112.1	497.4	50.1	21.0	16.6
2001	4.9	28.6	228.2	28.6	10.8	6.3
2002	17.7	53.3	352.5	39.1	17.9	12.3
2003	25.4	91.5	450.3	37.8	16.7	10.9
2004	18.1	50.5	427.5	38.1	17.2	11.8
2005	24.6	88.8	499.2	53.7	25.0	16.4
2006	3.9	20.1	210.1	18.5	7.0	4.7
2007	20.0	68.1	387.9	36.4	16.4	11.1
Average	**22.0**	**79.8**	**444.1**	**43.4**	**19.0**	**13.3**

Table 7-6: *Average annual inflows, outflows and net total flows for major surface water bodies in the Murray study area (not including main channel of the Murray and Serpentine Rivers).*

Model	**Total in (GL/yr)**	**Total out (GL/yr)**	**Net (GL/yr)**
Estuary	9.6	31.0	21.4
Murray tributaries	18.8	50.0	31.2
Nambeelup	0.0	22.1	22.1
Dirkbrook	16.6	18.7	2.1
Lower Serpentine tributaries	0.0	11.9	11.9
Total	**45.0**	**133.8**	**88.8**

The groundwater component of the surface flows was estimated using baseflow separation (Eckhart 2005) for hydrographs of the waterways entering and discharging the Murray study area. Results of the baseflow separation are displayed in Appendix A, and were applied to the major waterways in the Murray study area. The monthly baseflow contributions of each of the major waterways are displayed in Table 7-7. The baseflow contribution to the Murray River main channel and to the Serpentine River main channel has not been included in this analysis; the values of the groundwater contribution to these rivers were calculated using flow-net analysis in the previous section.

Table 7-7: *Monthly net baseflow contribution (GL) for major surface water bodies in the Murray study area.*

Month	Nambeelup (GL)	Estuary (GL)	Murray[1] (GL)	Dirk Brook (GL)	Lower Serpentine[1] (GL)	TOTAL (GL)
Jan	0.0	0.1	0.2	0.0	0.1	0.3
Feb	0.0	0.0	0.0	0.0	0.0	0.1
Mar	0.0	0.0	0.0	0.0	0.1	0.1
Apr	0.0	0.0	0.0	0.0	0.1	0.2
May	0.0	0.1	0.1	0.0	0.1	0.3
Jun	0.2	0.3	0.4	0.0	0.1	1.0
Jul	1.2	1.2	1.5	0.1	0.4	4.4
Aug	1.6	1.3	2.4	0.1	0.6	6.1
Sep	1.0	0.7	2.0	0.2	0.6	4.5
Oct	0.5	0.3	1.7	0.1	0.5	3.1
Nov	0.0	0.2	0.6	0.1	0.3	1.1
Dec	0.0	0.1	0.1	0.0	0.1	0.2
Annual	**4.5**	**4.4**	**8.1**	**0.6**	**2.5**	**20.1**

[1] Waterways modelled do not include the main channel

Monthly baseflow separation analysis estimates the total surface water drainage of the groundwater system to be 20.1 GL/yr. In addition, groundwater contributes 30.2 GL/yr to the Lower Serpentine River, and 42.4 GL/yr for the Lower Murray River, based on flow-net calculations. A total of 92.4 GL/yr contributes to surface water drainage from groundwater flows. The baseflow quantities for the annual and monthly breakdown of each of the waterways, and the architecture of the SQUARE models and subcatchments is displayed in Appendix F.

Evapotranspiration from groundwater

Evapotranspiration (EVT) from the superficial groundwater in the Murray study area is related to depth to groundwater, soil type and vegetation. The annual pan evaporation can be assigned from the relevant climate station data and distributed on a monthly basis (Table 7-8). SILO pan evaporation data from the Pinjarra rainfall station (9596) for the years 1900 – 2008 were used for the analysis displayed in Table 7-6.

Table 7-8: *SILO pan evaporation, monthly distribution of evapotranspiration and Penman-Monteith evapotranspiration (FAO56) for shallow rooted vegetation at Pinjarra (9596).*

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Evaporation (mm)	256	215	185	113	76	58	60	72	91	133	178	230	1668
Evaporation (%)	15	13	11	7	5	3	4	4	5	8	11	14	100
FAO56 (mm)	193	162	143	94	64	47	49	62	81	117	147	180	1340

* FAO56 = Potential Evapotranspiration calculated using the FAO Penman-Monteith formula as in FAO Irrigation and Drainage paper 56

The evapotranspiration flux can be split into regions of the catchment which contain deep rooted vegetation that draws from the regional groundwater, and shallow rooted vegetation / bare soil. For the shallow rooted vegetation or bare soil, the evapotranspiration flux discharging from the groundwater can be determined by the Penman-Montieth evaporation rate and the extinction depth whereby the evaporation rate decreases linearly based on the depth to water table. The Penman-Monteith method refers to the use of an equation for computing evapotranspiration from vegetated surfaces (Howell and Evett 2005). The values for Penman-Monteith evaporation are available from the Bureau of Meteorology in the SILO dataset, and are presented in Table 7-8 (FAO56 is the FAO Penman-Monteith formula as in FAO Irrigation and Drainage paper 56, Allen et al. 1998). The evaporation rate from the watertable is equal to the corrected pan evaporation rate where the watertable intersects the land surface and is zero when the watertable depth is equal to the extinction depth. The pan correction factor of 0.75 was used to correlate the pan to a body of water. Due to the uniform veneer of Bassendean sands overlying vast majority of the Murray study area, a uniform extinction depth of 2 m was used, common for medium-coarse grained sands (Shah *et al* 2007).

For the deep-rooted vegetation, the evapotranspiration can be approximated to be equal to the pan evaporation times by a vegetation factor. For the Murray area, the vegetation factor is equal to 1.1 for the months March – 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 0.2 is applied to the pan evaporation.

An annual total of 197.3 GL was estimated to be lost from the superficial groundwater to evapotranspiration. Of this 82.8 GL (42%) was from deep-rooted vegetation, 33.9 GL (17%) is from waterlogged regions, 20.2 GL (10%) is evapotranspiration from grasses, and 60.4GL (30.6%) is evaporation from the soil profile, deeper than 0.3 mBGL. A summary of the monthly evapotranspiration figures and calculations are presented in Appendix G.

Groundwater leakage to confined aquifers

The recharge to confined aquifers can be represented by the vertical leakage model (Darcey's Law). The difference between the Leederville and superficial heads is displayed in Figure 5-7. Areas potentially discharging from the Leederville Aquifer to the Superficial Aquifer are in the west or the study region and along the main river channels. Areas that are potentially recharging the Leederville Aquifer are in the scarp and along the eastern margin of the study area. The vertical conductance of the confining beds between the superficial and Leederville Aquifers is estimated to be approximately $1x10^{-5}$ m/d (Davidson 1995). Using this value and the heads displayed in Figure 5-7, the total annual flux between the superficial and Leederville Aquifers is approximately 5.3 GL/yr leakage from the superficial to Leederville Aquifers (7.0 GL recharging the Leederville in the east, and 1.7 GL discharging from the Leederville to superficial in the west).

Groundwater abstraction – licensed abstraction

Groundwater in Western Australia is used for reticulated scheme-supply to households and industry by Water Corporation, self-supply for agriculture and various industries, domestic, park and recreation uses by licensed private bores, and home garden use by unlicensed garden bores. Licensed entitlement and actual usage are not the same. Davidson (1995) employed a usage and entitlement ration of 0.8 for data between 1985 and 1995. Aquaterra

(2001) and Yu (2002) used an average ration of 0.92 to calculate the usage data from the licensed entitlement data. Water Corporation records monthly metering data for their production bores, but most other licensed allocations do not record historical usage data.

Abstraction occurs within the Murray study area from the superficial, Leederville, Cattamarra and Rockingham Aquifers. Table 7-9 displays the allocation limits reported in the Department of Waters WRL database. The locations of the draw-points from the respective aquifers and the relative quantities of groundwater abstraction are displayed in Appendix H.

Table 7-9: *Estimated groundwater abstraction allocations for the four aquifers within the Murray study area.*

Aquifer	No of drawpoints	Total allocation amount (GL/yr)	Maximum allocation amount for single drawpoint (GL/yr)	Average allocation per drawpoint (ML/yr)
Superficial	963	8.3	0.47	8.6
Rockingham	110	1.5	0.23	13.4
Leederville	166	12.1	3.69	72.7
Cattamarra Coal Measures	14	4.6	0.50	327.8
Unlicensed Superficial	5955	4.8	0.00	0.8
Total	**1253**	**26.4**	**3.69**	**21.1**

Abstraction from the Cattamarra Coal Measures is primarily from the region surrounding the Pinjarra Refinery. This region is outside of the Murray DWMP area, but large abstraction levels may affect groundwater levels (particularly the Leederville Aquifer) within the DWMP area. The groundwater abstraction applied to the model will be based on the historical license entitlements with an estimated yearly cycle of abstraction with higher abstraction rates over the summer period for irrigation bores and a uniform pattern for industrial bores.

Groundwater abstraction – unlicensed abstraction

Western Australian residential properties do not require licenses for bores for domestic garden watering. The average garden bore pumps about 800 kL/yr in the Perth metropolitan area (Davidson and Yu 2006). 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 3-10), there are 19,850 residential premises in the Murray Study area, the vast majority west of the Serpentine river, outside of the Murray DWMP area. Using figures derived for the Perth metropolitan region (30% of houses with bores, extracting an average of 800 kL/yr), a total of 4.75 GL/yr of water can be estimated to be extracted by unlicensed residential premises in the Murray study area.

Groundwater recharge from irrigation

Most of the licensed abstractions are for irrigation purposes, although some large extractions 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 and Yu 2008); however studies are required to improve the understanding of irrigation on the Swan Coastal Plain. The Murray study area is outside of the Harvey irrigation area, and thus does not import water from outside of the study area for irrigation purposes. The recharge return from irrigation is estimated to be 3.84 GL/yr, which comprises only 1.2% of the total recharge.

7.4 Water balance

Annual water balance

An annual water balance can be applied to describe the flow of water in and out of the system. The summaries of the annual flux inputs and exports are displayed in Table 7-10, and in Figure 7-3 below.

Table 7-10: *Annual conceptual flux summaries for the Superficial Aquifer in the Murray study area.*

Input/output	Flux	Quantity (GL)	Quantity (mm)	(%)
Inputs	Gross recharge from rainfall	318	441	98.8%
	Groundwater recharge from irrigation returns	4	5	1.2%
Outputs	Evapo-transpiration from superficial groundwater	197	273	-61.2%
	Net drainage from groundwater to surface water	93	128	-28.7%
	Abstraction from superficial groundwater	15	20	-4.5%
	Net horizontal through-flow across model boundary	12	17	-3.8%
	Verticle leakage to deeper aquifers	5	7	-1.6%

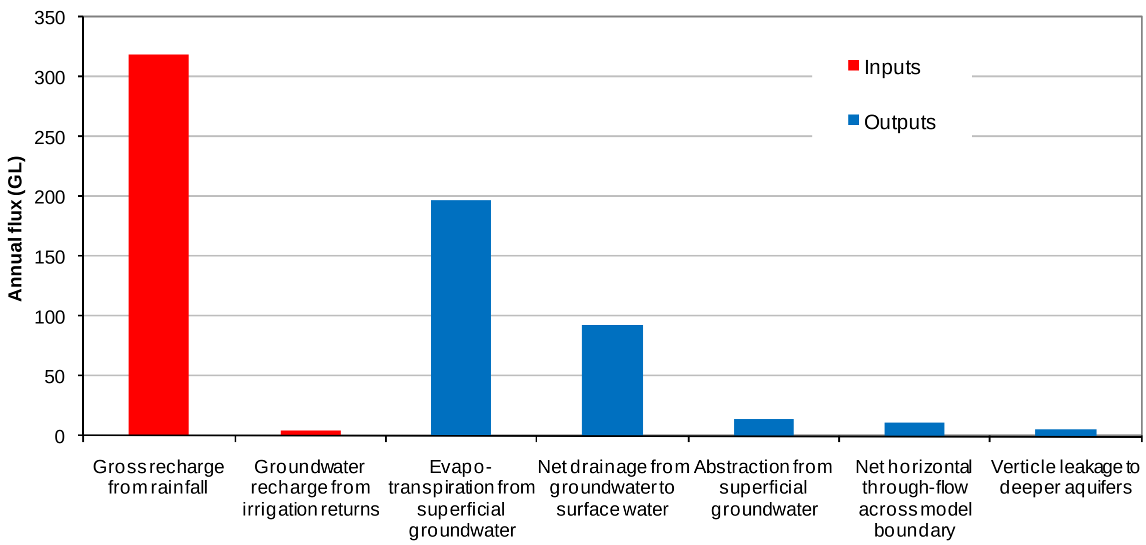

Figure 7-3: *Annual conceptual flux quantities for the Superficial Aquifer in the Murray study area*

The difference between inflows and outflows is estimated to be -1 GL/yr. This figure reflects the change in storage, and is an estimate of the uncertainty in the water balance component estimates. Uncertainty is expected due to estimation techniques and simplifications of the conceptual fluxes (particularly when estimating evapotranspiration). However, the small magnitude of uncertainty indicates that the flux calculations satisfy the water balance equation, given that there is very little change in long term Superficial Aquifer levels. Figure 7-3 displays the magnitude of each of the input and output fluxes. Irrigation returns comprise an less than 1 per cent of the gross recharge from rainfall, and are negligible on a regional scale. The major outflow fluxes are evapotranspiration and drainage to surface water bodies. The drainage flux is estimated to be 5 – 10 times higher than the abstraction flux, which is a contrast to the Perth region, where abstraction is much higher than surface water drainage. Surface water drainage is a much larger flux than abstraction and lateral flow (to the estuary and ocean) combined. The magnitude of the drainage flux highlights the importance of accurately quantifying drainage in the numerical model.

The vertical leakage flux represents the net exchange between the Leederville and Superficial Aquifers, and is the least significant of the output fluxes. The leakage to the Leederville is a small component of the water balance and can be ignored without introducing significant error or uncertainty. Consequently, there is little value investing large amounts of time and effort estimating this component of the water balance.

Monthly water balance

The monthly water balance describes the flow of water in and out of the Superficial Aquifer on a monthly basis. Some of the hydrological fluxes were calculated on monthly bases (groundwater drainage from SQUARE, evapotranspiration, recharge), whereas others were calculated annually (lateral groundwater flow, irrigation returns, vertical leakage and abstraction). For abstraction and irrigation returns, it was assumed that the annual flux would be divided evenly between the months November – April (which is when abstraction for irrigation generally occurs). For vertical leakage and lateral flow, a constant rate was applied. Although this is not likely to be correct, as higher rates of will be likely to occur in winter months for these fluxes, it is reasonable for first order conceptualisation. A summary of the fluxes are displayed in Table 7-11.

The net flux is the sum of the inputs minus the outputs on a monthly basis. The storage in the superficial groundwater could be calculated by determining the cumulative net fluxes over the year. The storage was set to a minimum of zero (April), and is the cumulative of the fluxes for subsequent months. The monthly conceptual storage time-series in the Superficial Aquifer is displayed in Figure 7-4.

Table 7-11: *Groundwater abstraction allocations for the four aquifers within the Murray study area.*

Month	Rainfall	Surface water drainage (overland flow and groundwater drainage)	Gross recharge from rainfall	Evapo-transpiration from superficial groundwater	Abstraction from superficial groundwater	Net drainage from groundwater to surface water	Verticle leakage from superficial to deeper groundwater	Horizontal groundwater flow across model boundary	Groundwater recharge from irrigation returns	Net fluxes	Storage
	GL	GL	GL	GL	GL	GL	GL	GL	GL	GL	GL
January	7.4	7.5	5.7	13.8	2.4	6.4	0.4	1.0	0.6	-17.7	35.6
February	9.5	5.8	5.1	9.4	2.4	6.2	0.4	1.0	0.6	-13.8	21.9
March	14.2	6.1	7.0	15.9	2.4	6.2	0.4	1.0	0.6	-18.2	3.6
April	34.1	7.0	17.4	12.6	2.4	6.2	0.4	1.0	0.6	-4.6	0.0
May	92.6	11.1	43.1	10.0	0.0	6.4	0.4	1.0	0.0	25.3	25.3
June	136.6	21.4	62.5	9.4	0.0	7.1	0.4	1.0	0.0	44.5	69.8
July	129.2	37.0	61.6	11.4	0.0	10.5	0.4	1.0	0.0	38.3	108.0
August	97.6	41.4	48.2	16.1	0.0	12.1	0.4	1.0	0.0	18.6	126.6
September	62.8	31.6	33.4	23.2	0.0	10.5	0.4	1.0	0.0	-1.9	124.8
October	39.3	19.2	18.1	28.1	0.0	9.2	0.4	1.0	0.0	-20.7	104.1
November	18.1	12.6	12.4	30.0	2.4	7.2	0.4	1.0	0.6	-28.0	76.0
December	8.9	9.6	4.0	17.2	2.4	6.3	0.4	1.0	0.6	-22.7	53.3
Total Annual	**650.5**	**210.1**	**318.5**	**197.3**	**14.5**	**92.7**	**5.3**	**12.1**	**3.8**	**-1.0**	

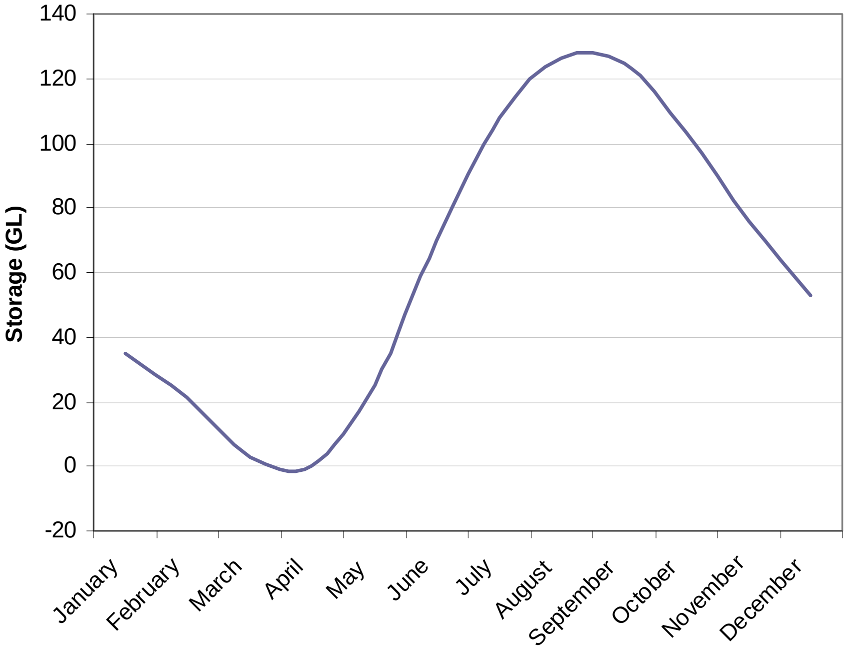

Figure 7-4: *Monthly storage in the Superficial Aquifer for the Murray study area*

7.5 Numerical model selection

Mike SHE will be used to develop the numerical groundwater model. Mike SHE is a modelling tool that 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 impacts, environmental flows assessment and water quality.

Mike SHE (Refsgaard and Storm 1995) 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 combined depending on the scope of the study (DHI 2005). 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 discretizing the catchment into a large number of elements or grid squares and solving the equations for the state 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 is a fully-distributed physically-based catchment model which 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 (DHI), 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 run off. 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 from 1985 – 2000 and validated from 2000 – 2009. Model calibration will be undertaken using a manual iterative technique. The results of the calibration/verification 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 Modelling Guidelines (Middlemis 2000). The following calibration targets are expected to be achieved:

- Root mean square error between measure hydraulic-head and simulated hydraulic head of less than 5% of the measured hydraulic-head drop across the model area. Final calibration results will report the root mean square error, the mean absolute error and the mean error.
- The root mean squared 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 root mean squared 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%.

7.6 Knowledge gaps

Gaps in knowledge and data include lack of testing for hydraulic properties of geological units, particularly in the Leederville Aquifer, and the poor quality of historical data.

The study region lies south of the PRAMS model boundary, and north of the SWAMS modelling boundary. The PRAMS and SWAMS models involved extensive drilling programs, with a number of superficial and confined aquifer monitoring bore transects drilled to deliver the required data for the models. The lack of overlap between the two models has lead to a large area of very sparse data in the centre of the modelling region. In response to this a drilling program was initiated by the Department of Water in July 2008. Whilst this provides an adequate spatial representation of data, the lack of historical data throughout the catchment remains an issue as long term bores are limited to the few Thompson Lake Bores in the north of the study area and the few Harvey Shallow bores in the south.

There is a lack of small time-scale (daily or sub-daily) measurement of groundwater levels in the study area, and a lack of sub-daily rainfall data. It is thus difficult to assess the response times of the groundwater hydrograph to rainfall events. This knowledge gap has been addressed by the installation of a pluviograph in Ravenswood [509 – 646] in April 2009, and by the installation of six data loggers for selected superficial bores within the Murray DWMP area. The data from the bore loggers and pluviographs will be analysed when it is completed, and will be available for the final model calibration.

There is a lack of water chemistry data in the catchment, in particular chloride measurements in bores, and major anions and cations in key wetlands. Water chemistry (major cation and anions) is extremely useful in determining flow-paths in wetlands, and in determining water balances at a regional or sub-regional scale. This is being addressed by a monitoring program which is beginning in the winter of 2009, and will be available before the final calibration of the model.

As mentioned in Section 3.2, there is a lack of surface flow gauging in the Murray DWMP area, particularly for drains that have their headwaters within the Murray DWMP area. Two flow gauging stations have been commissioned as part of the monitoring program Winter Brook (6140127) and Buchanans Drain (6140128), (Figure 3-9) to assist in the hydrological conceptualisation of drains within the Murray DWMP area.

The hydrological conceptualisation of the regional surface water and groundwater systems, and the key wetlands will be reviewed upon collection of the water level, water chemistry, and surface water flow data from the winter of 2009, and amendments will be made where necessary, prior to the final calibration of the regional hydrological model.

8 Glossary

Abstraction	pumping groundwater from an aquifer
Australian height datum (AHD)	height datum used within the study. Where Level (AHD) = mean seal level (MSL) + 0.026m
Alluvium	detrital material which is transported by streams and rivers and deposited
anisotropy	the degree of variation of hydraulic conductivity between the vertical and horizontal directions at a point in an aquifer
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
semi-unconfined	intermediated between semi-confined and unconfined, when the upper semi-permeable layer ea
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
colloid	suspended microscopic particles in water
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 – 135 million years ago
delta (deltaic)	sediments deposited at the mouth of a river where it enters a lake or the ocean
density	the mass of water per unit volume, usually stated in g/cm3
discharge (groundwater)	all water leaving the saturated part of an aquifer
doline	synonym for sinkhole (karst feature)
effective porosity	drainable pore space, considered synonymous with specific yield of unconfined aquifer
Electrical conductivity	Electrical conductivity or specific conductance is a measure of a material's ability to conduct an electric current
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
eustatic	pertaining to worldwide changes of sea level that affect all the oceans

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
formation (geological)	a group of rocks or sediments which have certain characteristics in common and which were deposited 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. Such a system is designed to capture, store, update, manipulate, analyse and display the geographic information. A GIS 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 groundwater 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
hypersaline	excessively saline; with a salinity substantially greater than that of sea water (> 35,000 mg/L)

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 – 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 – 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
paleo lake	ancient lake
palynology	study of pollen of seed plants and spores of other embryophytic plants, whether living or fossil, including their dispersal and applications in stratigraphy and palaeoecology
paralic	pertaining to interfingered marine and continental deposits laid down on the landward side of the coast or in a shallow water (lagoonal or littoral) subject to marine invasion
percolation	movement of water from the land surface to the watertable after infiltration
penecontemporaneious	almost at the same time
permeable	ability to permit water movement
pH	the negative decimal logarithm of hydrogen ion concentration. For example, pure water at $25^{O}C$ contains 10^{-7} g/L of H+ ion; its pH is 7.00
piedmont	a plain or foothill at the base of a mountain range
plain	tract of flat or level terrain
plateau	an extensive land region considerably elevated (more than 150 m in altitude) above the adjacent country or above sea level
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
puggy	plasticine-like consistency
Quaternary	The latest period in the Canozoic era
recharge (groundwater)	all water reaching the saturated part of an aquifer (artificial or natural)
reducing	remove oxygen or undergo addition of electrons

salinity	a measure of the concentration of total dissolved solids (TDS) in water 0 – 500 mg/L, fresh 500 – 1500 mg/L, fresh to marginal 1500 – 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 water table
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
surfactant	substance which reduces surface tension
swale	a slight depression, sometimes swampy, in generally level land
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
type (locality, section)	the place at which a stratotype is situated and from which it derives its name
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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Figures

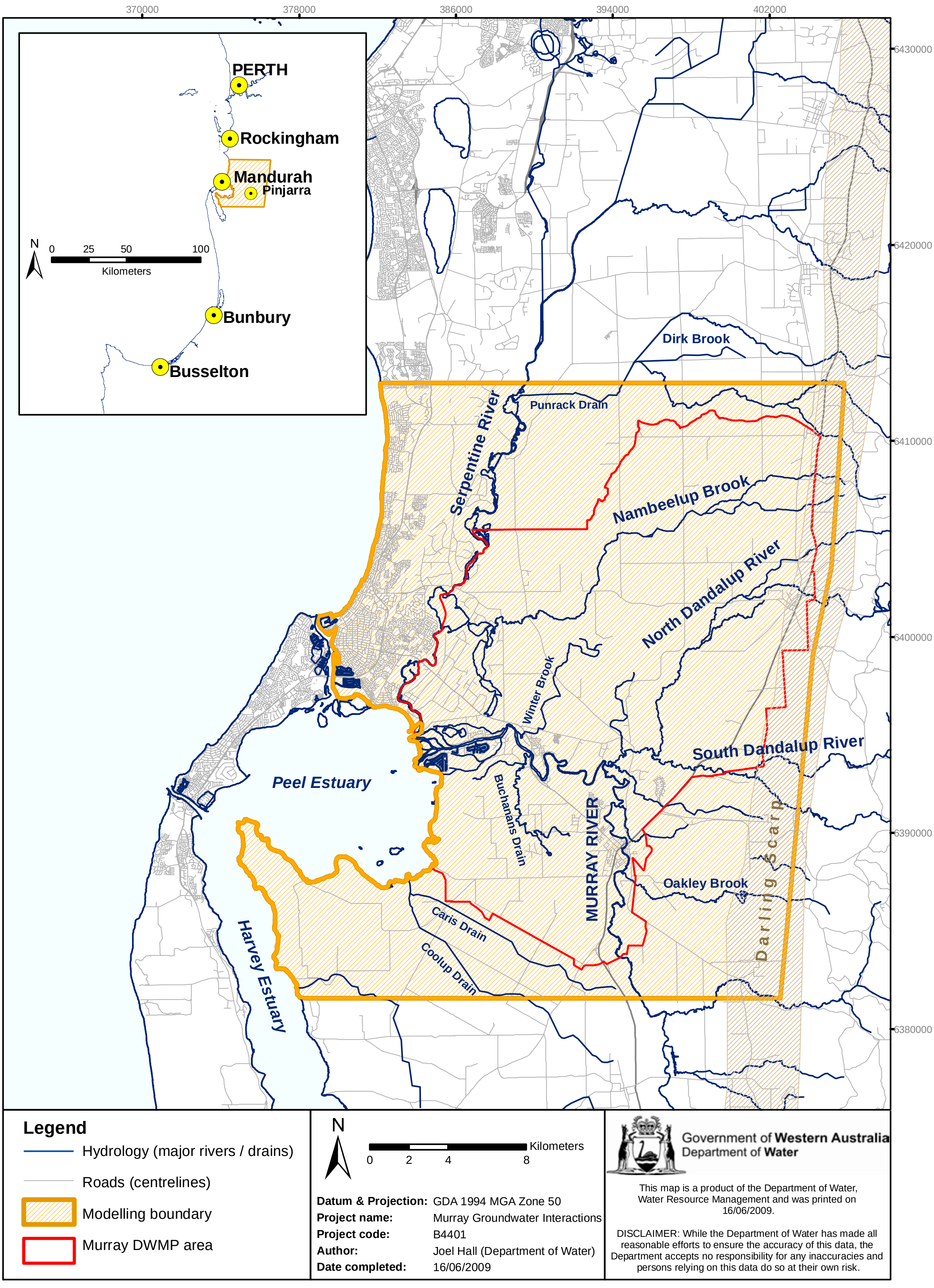


***Figure 1-1:** Murray study area boundary and Murray DWMP boundary*

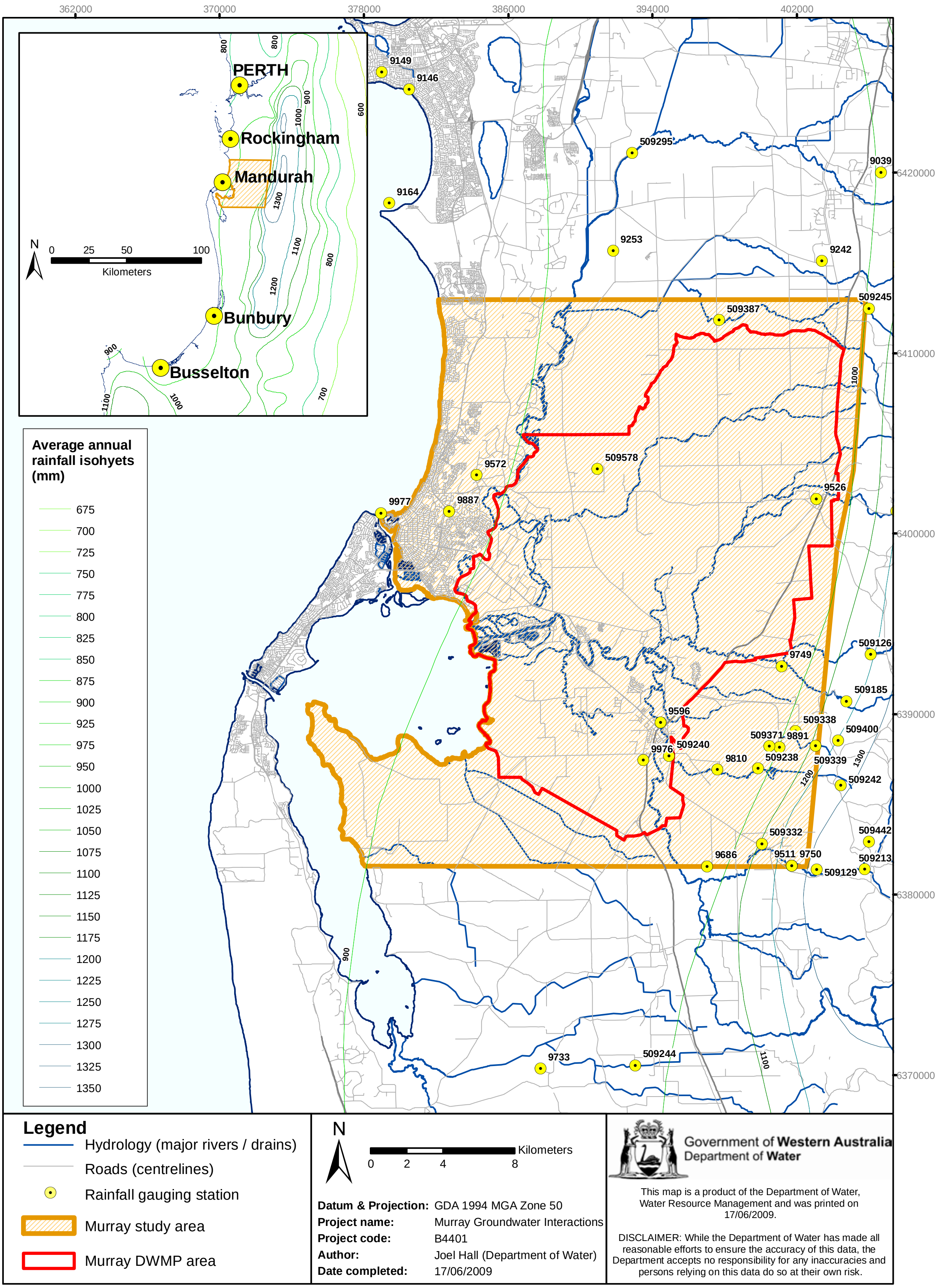


Figure 3-1: *Average annual rainfall isohyets and rainfall gauging station locations*

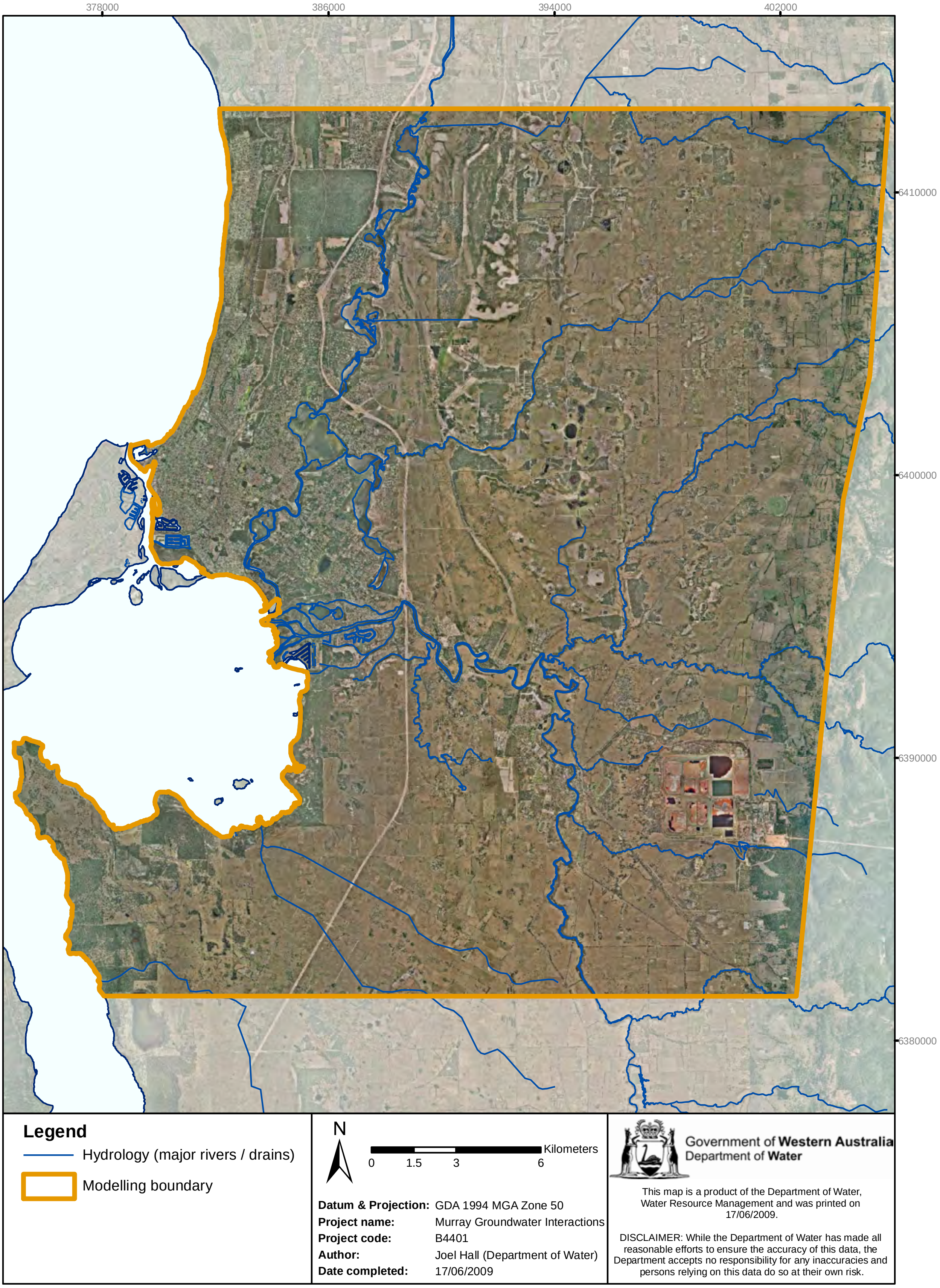


***Figure 3-6**: Aerial photograph (2005) of the Murray study area*

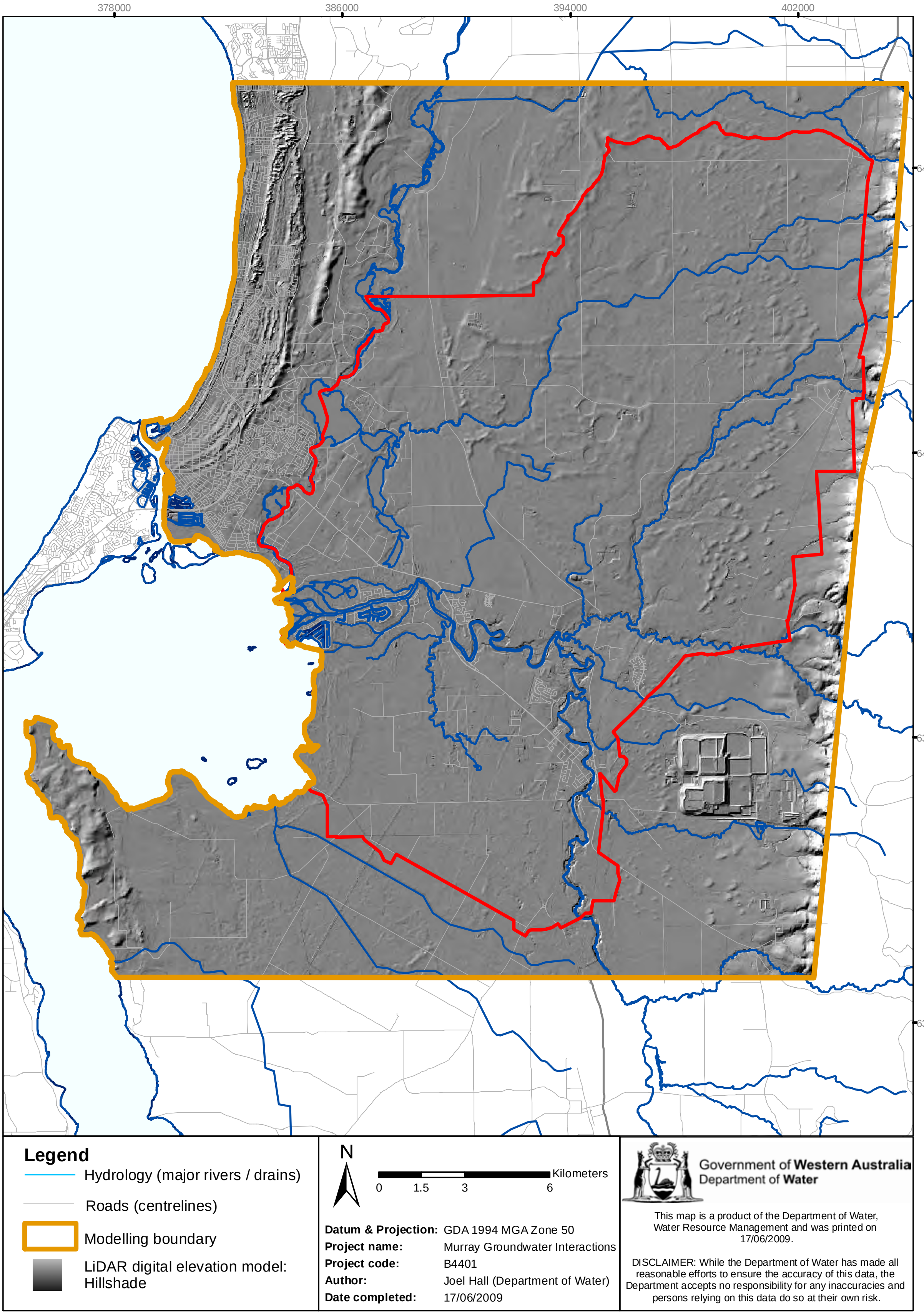


Figure 3-7: *LiDAR topography (2008) of the Murray study area*

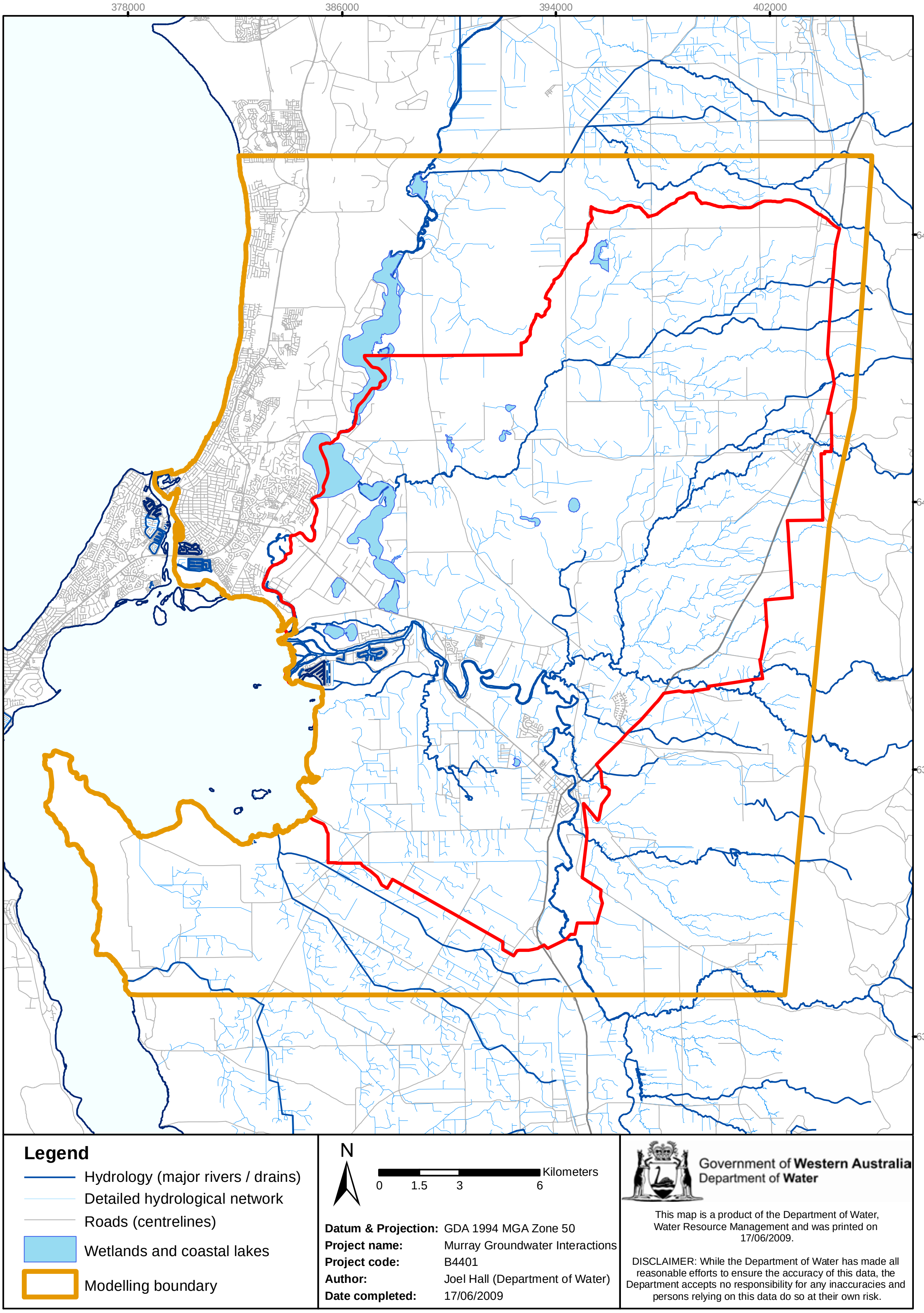


***Figure 3-8:** Detailed hydrological network in the Murray study area*

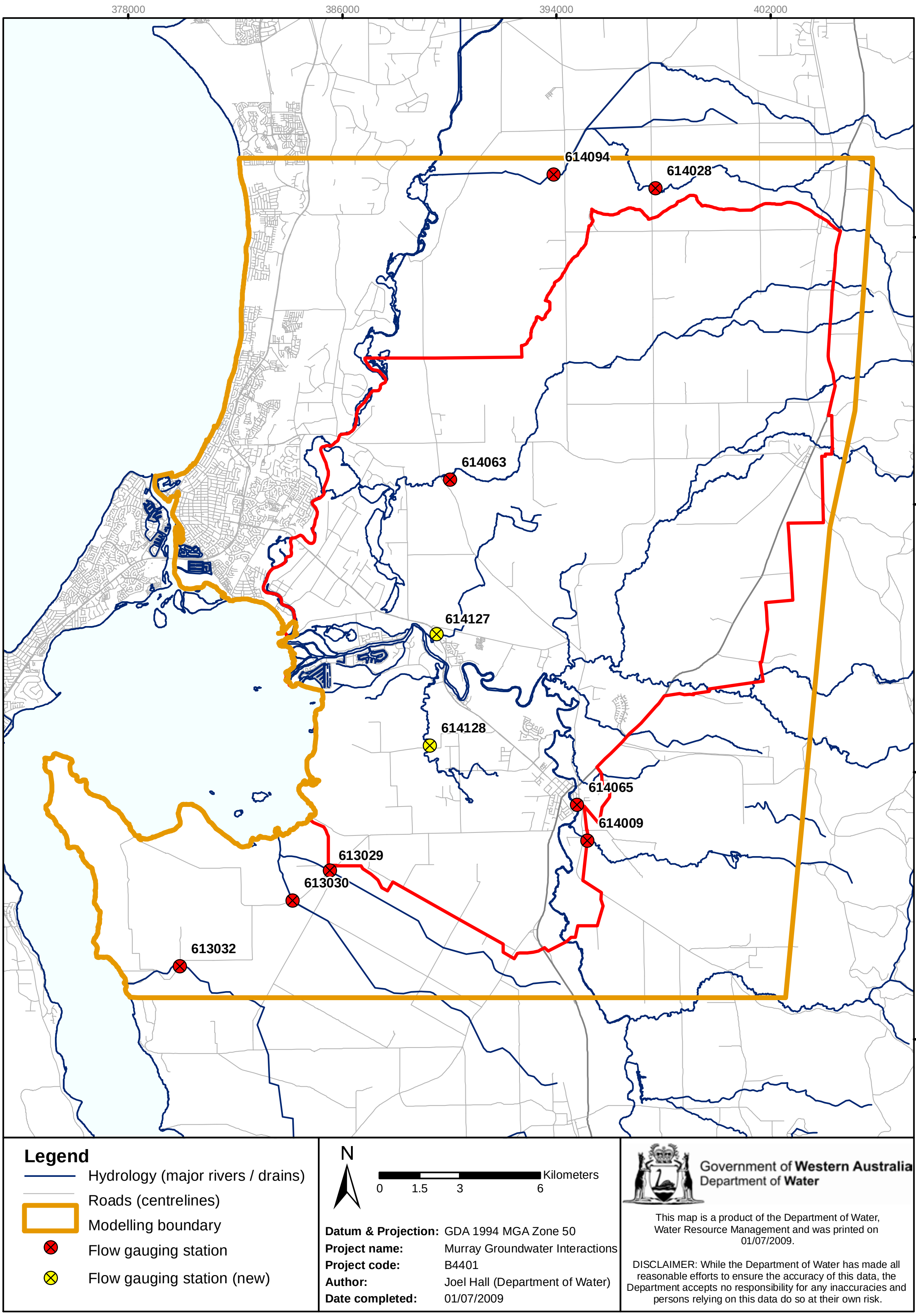


Figure 3-9: *Flow gauging station locations for the Murray study area*

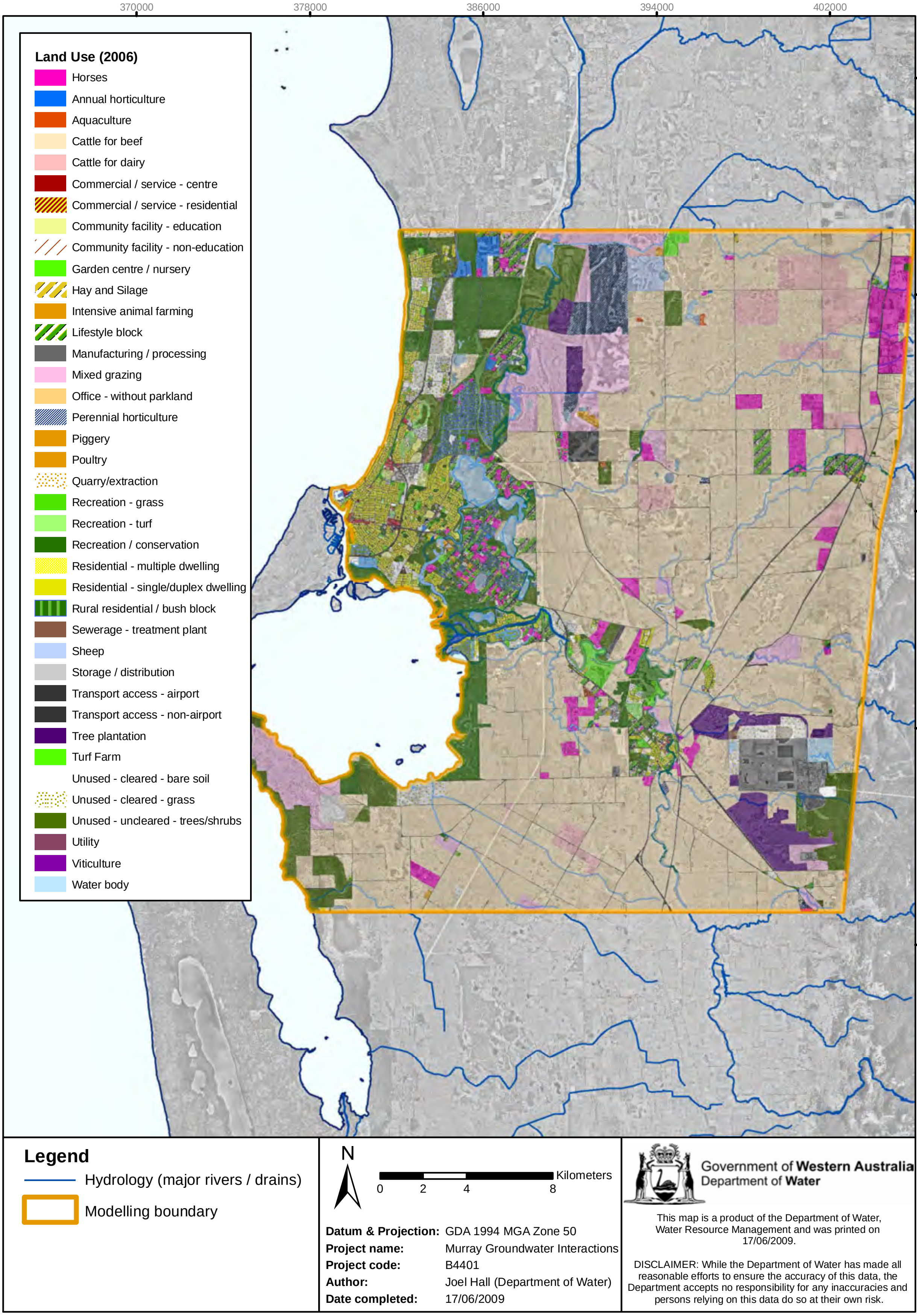


Figure 3-10: *Land use by cadastral parcel for the Murray study area*

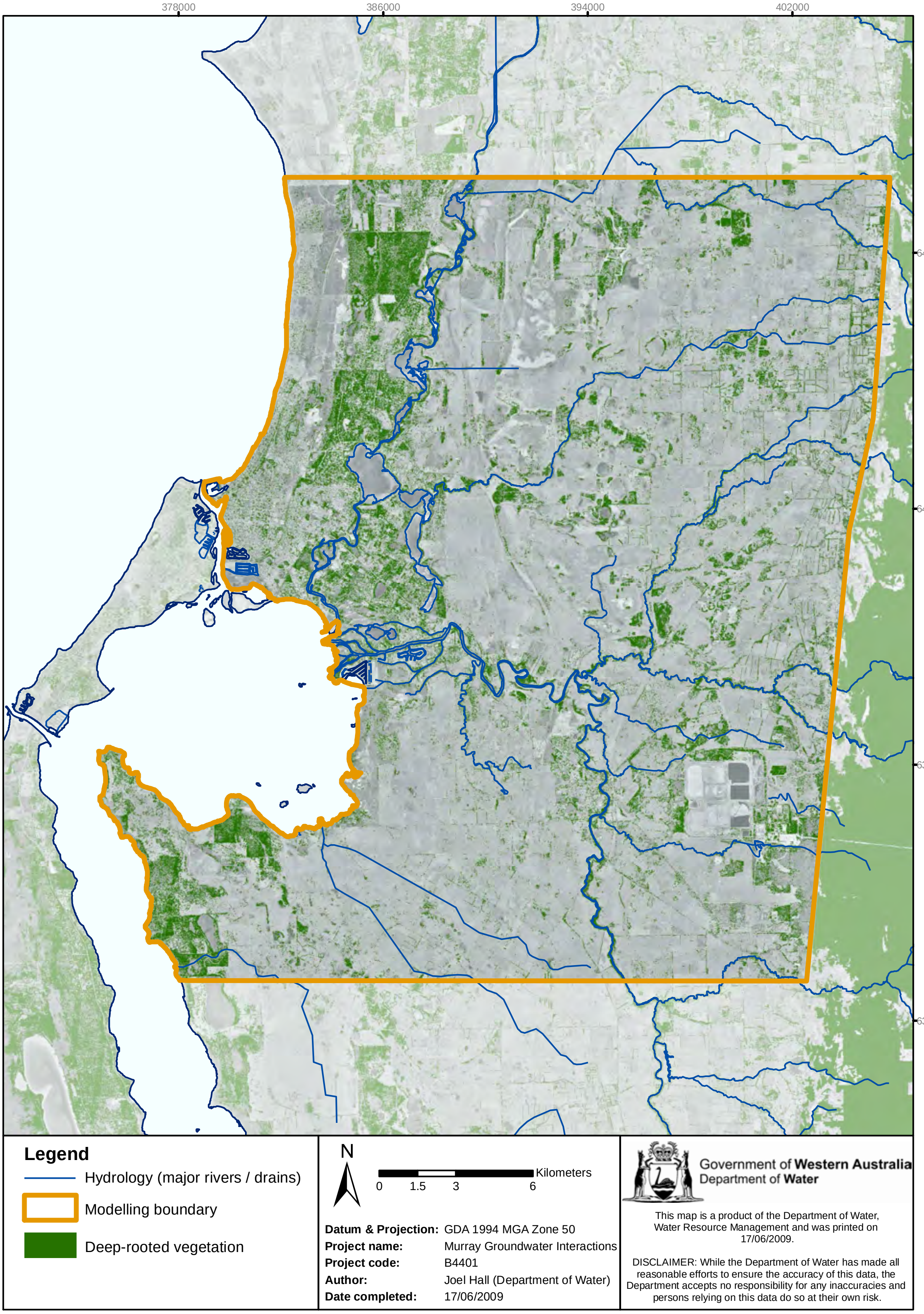


Figure 3-11: *Deep-rooted vegetation coverage in the Murray study area*

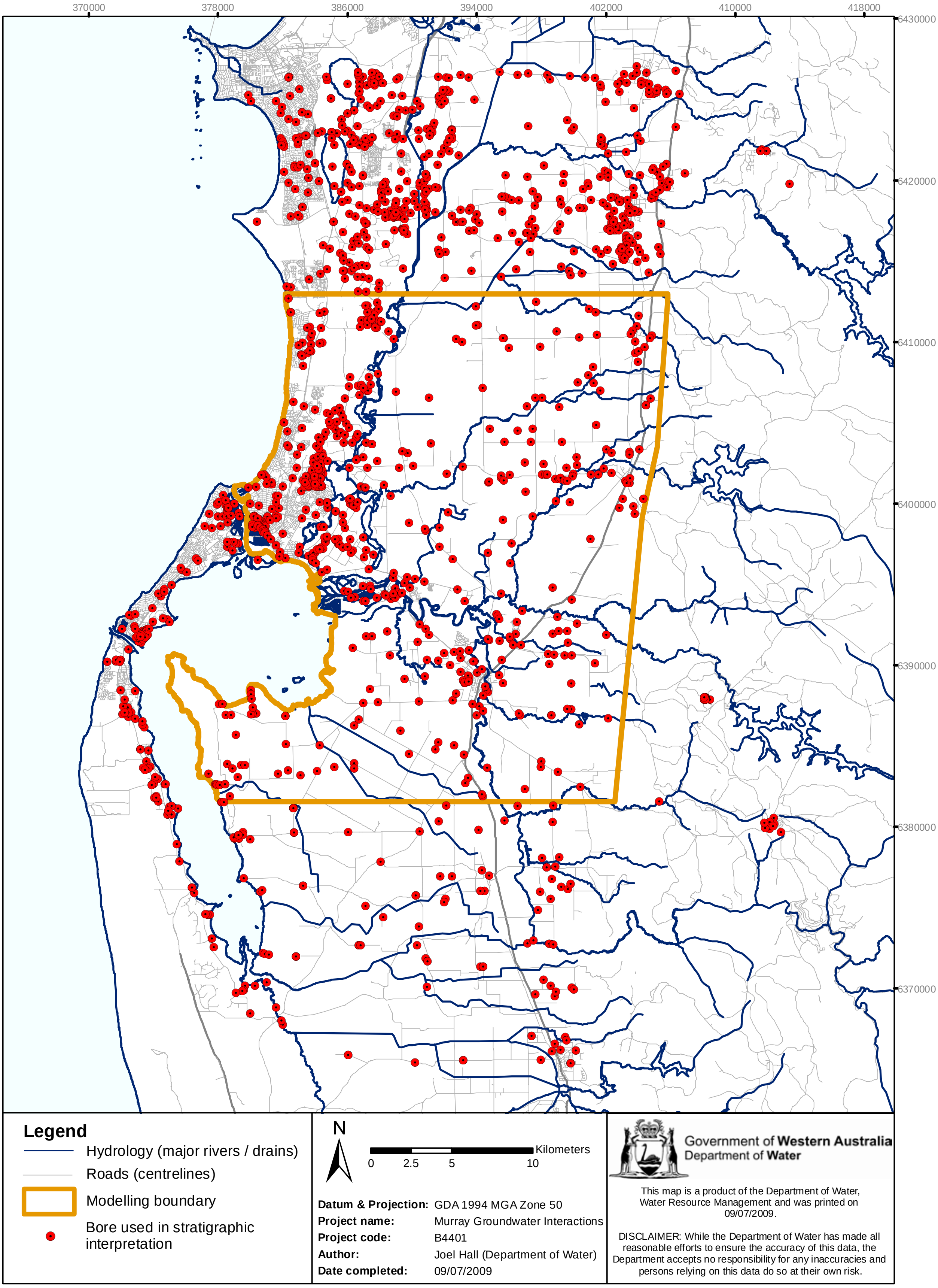


Figure 4-1: *Bores used in stratigraphic interpretation for the Murray study area*

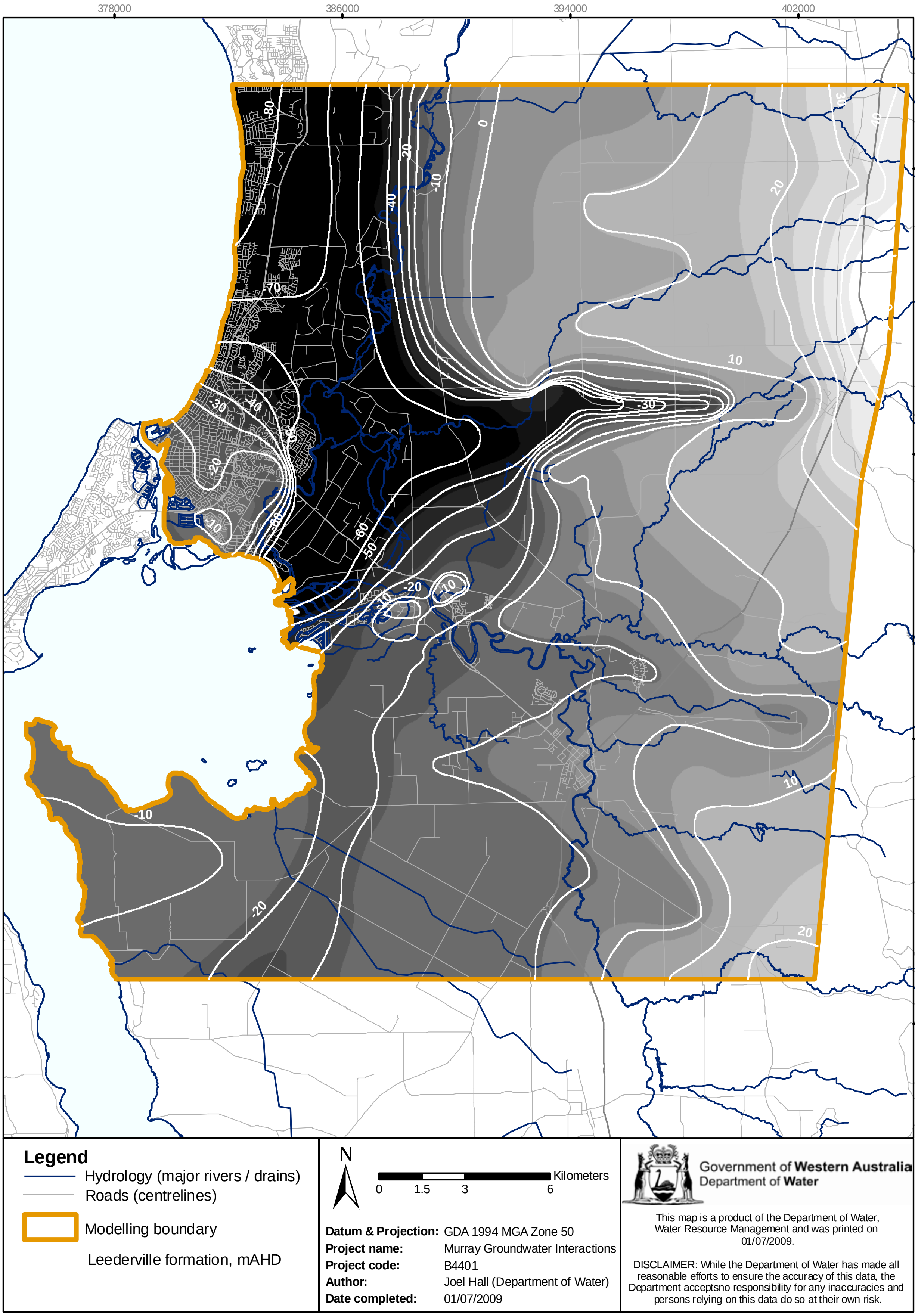


***Figure 4-2:** Leederville formation: contours at the surface of unit*

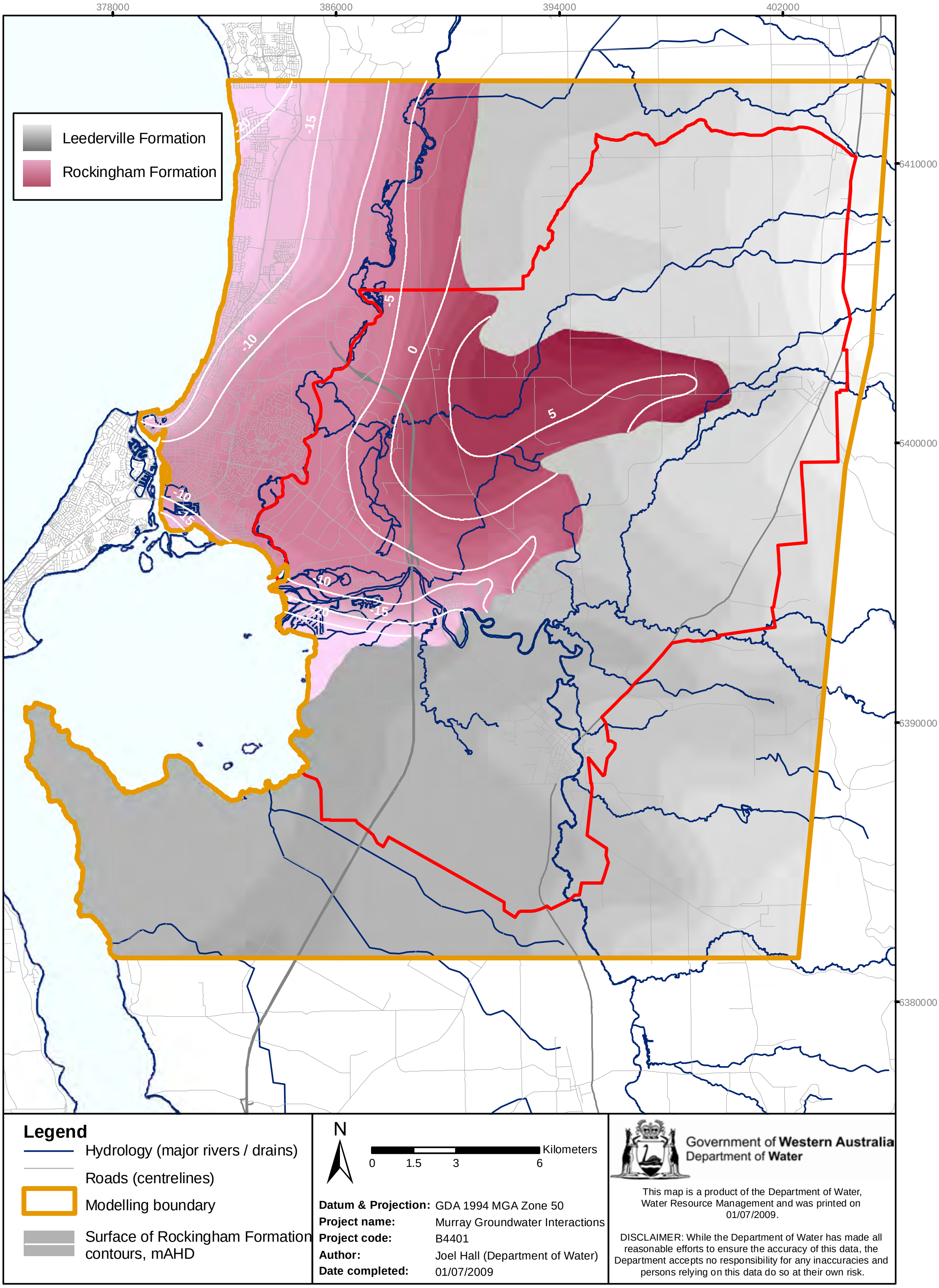


***Figure 4-3**: Rockingham formation: contours at the surface of unit*

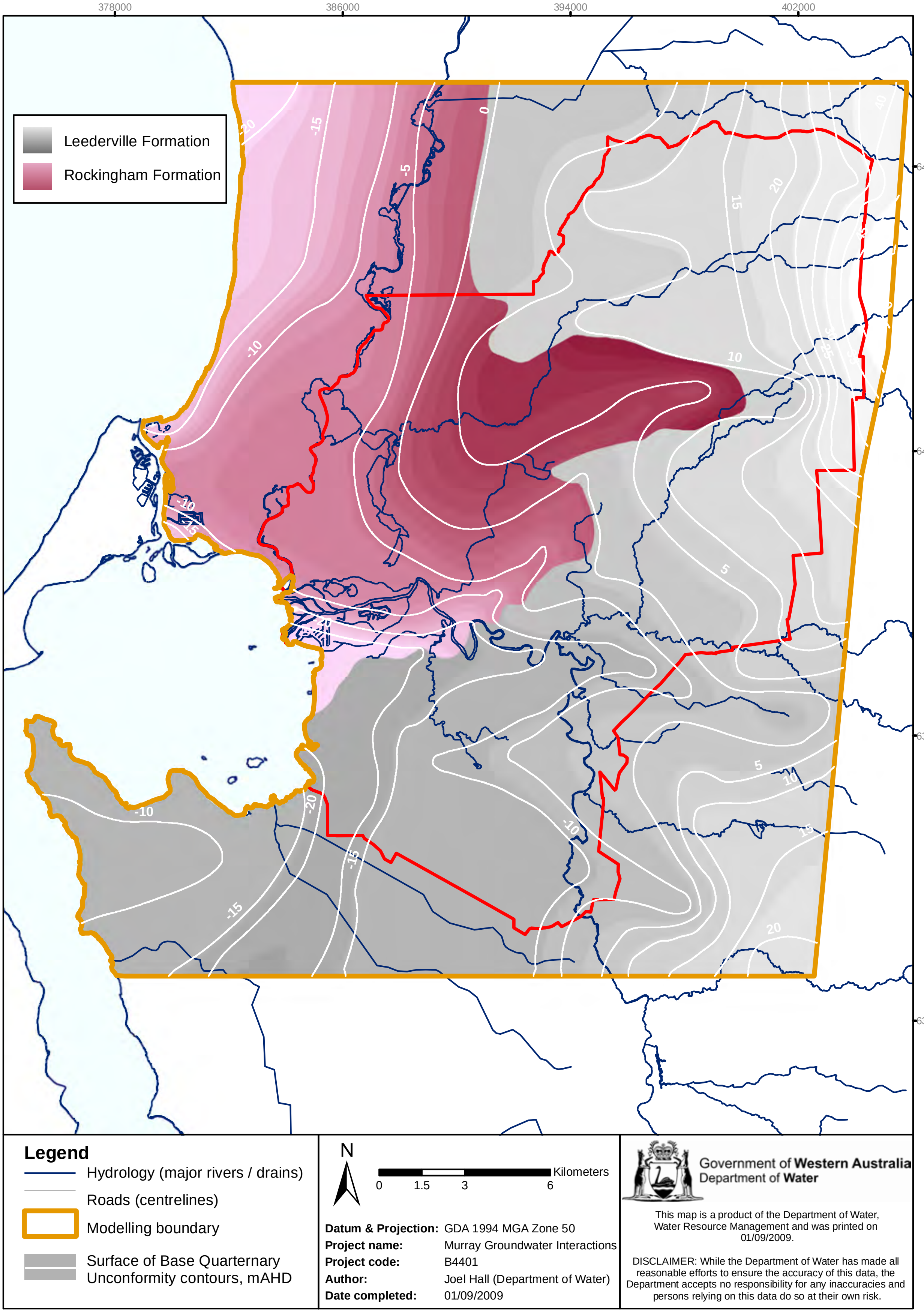


Figure 4-4: *Base Quaternary Unconformity contours*

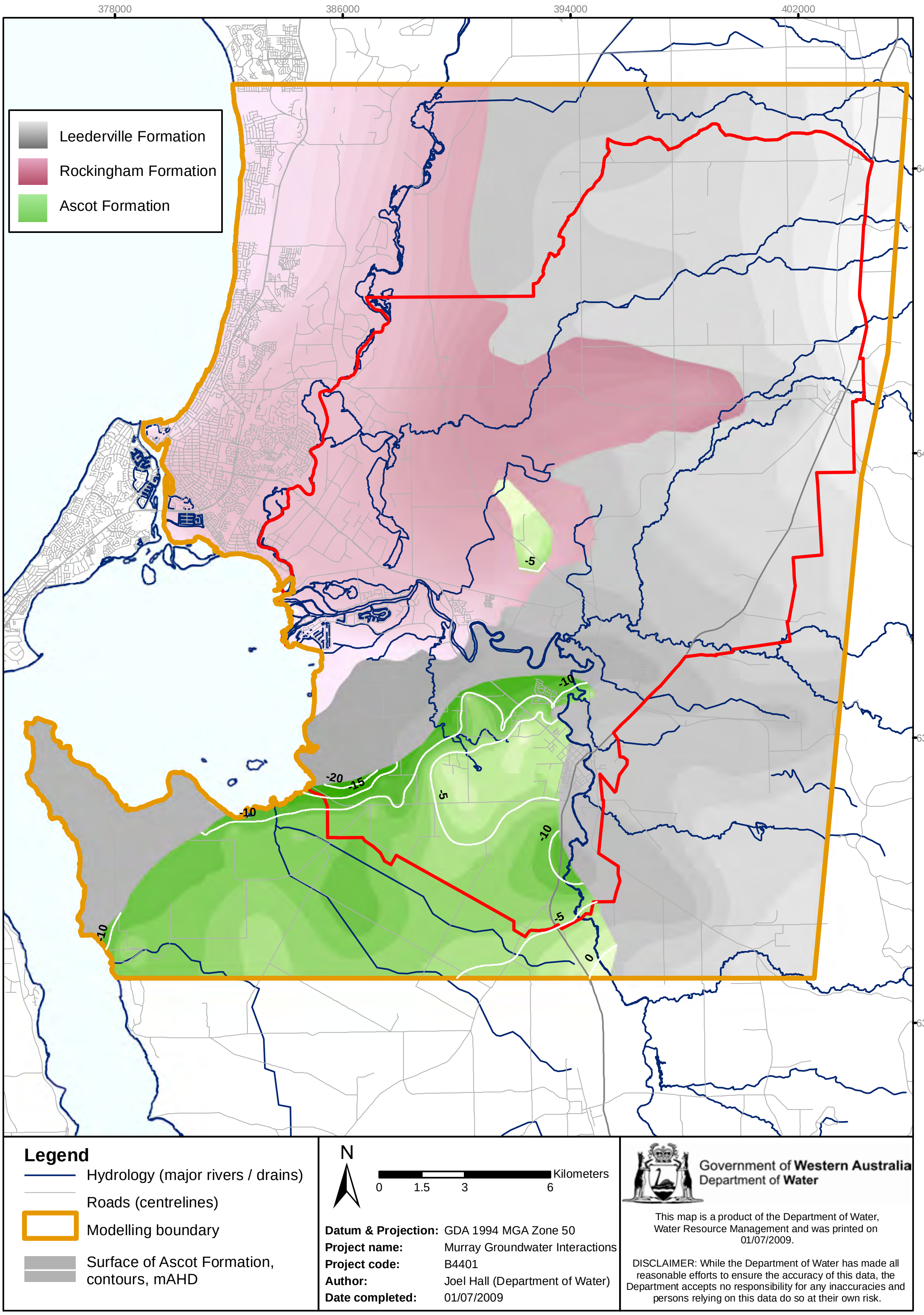


***Figure 4-5**: Ascot formation: contours at the surface of unit*

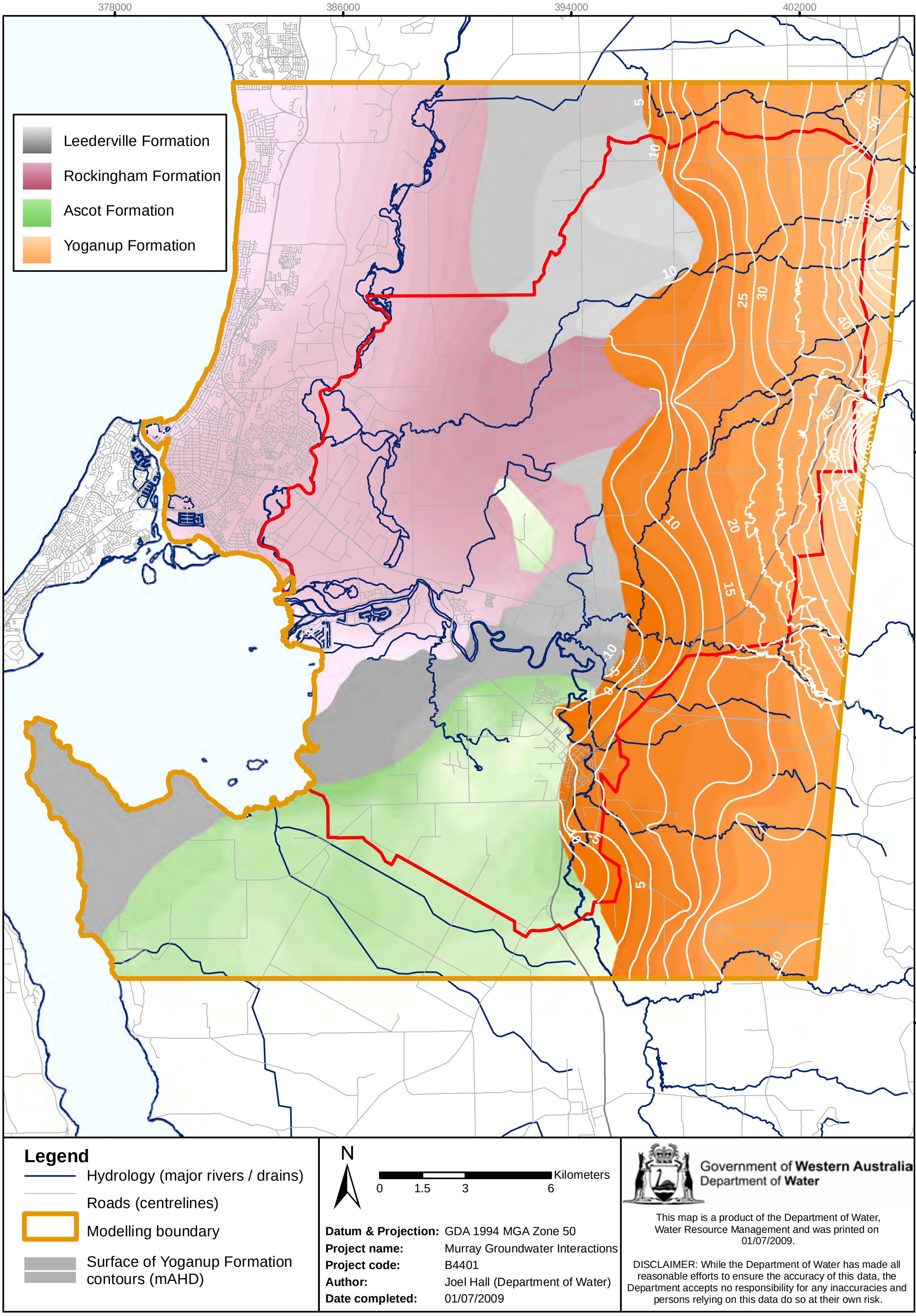


***Figure 4-6**: Yoganup formation: contours at the surface of unit*

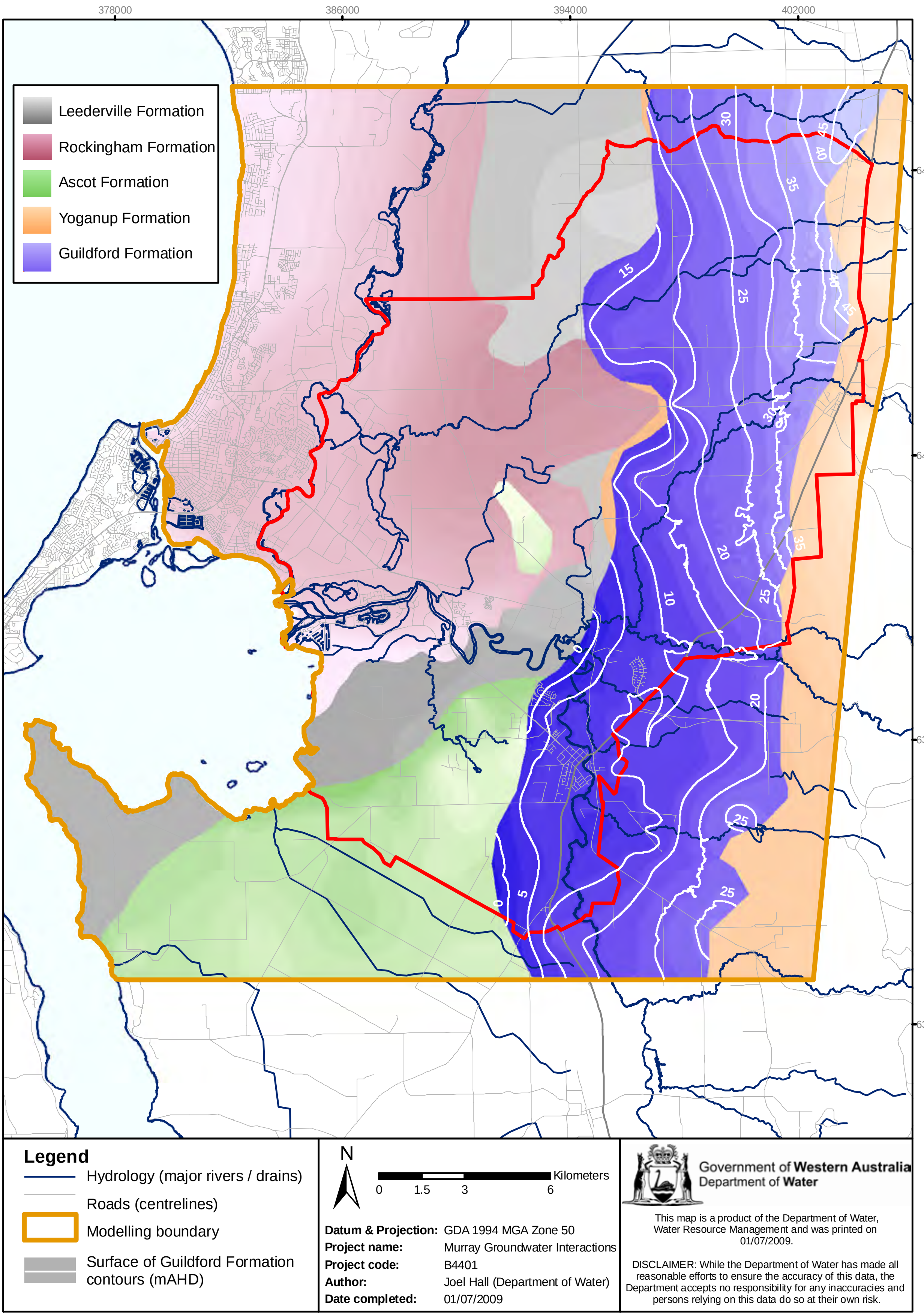


***Figure 4-7**: Guildford formation: contours at the surface of unit*

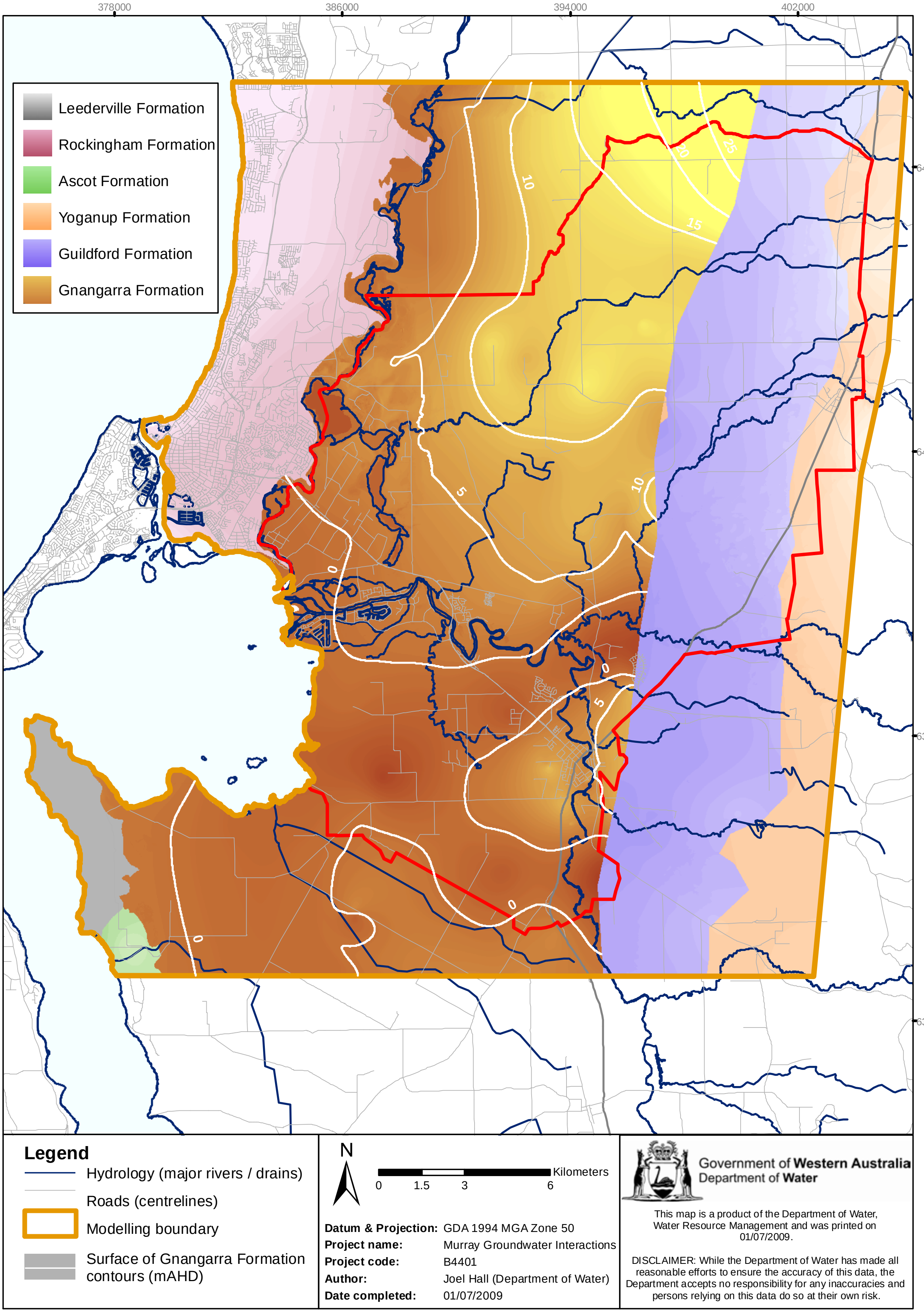


***Figure 4-8**: Gnangara formation: contours at the surface of unit*

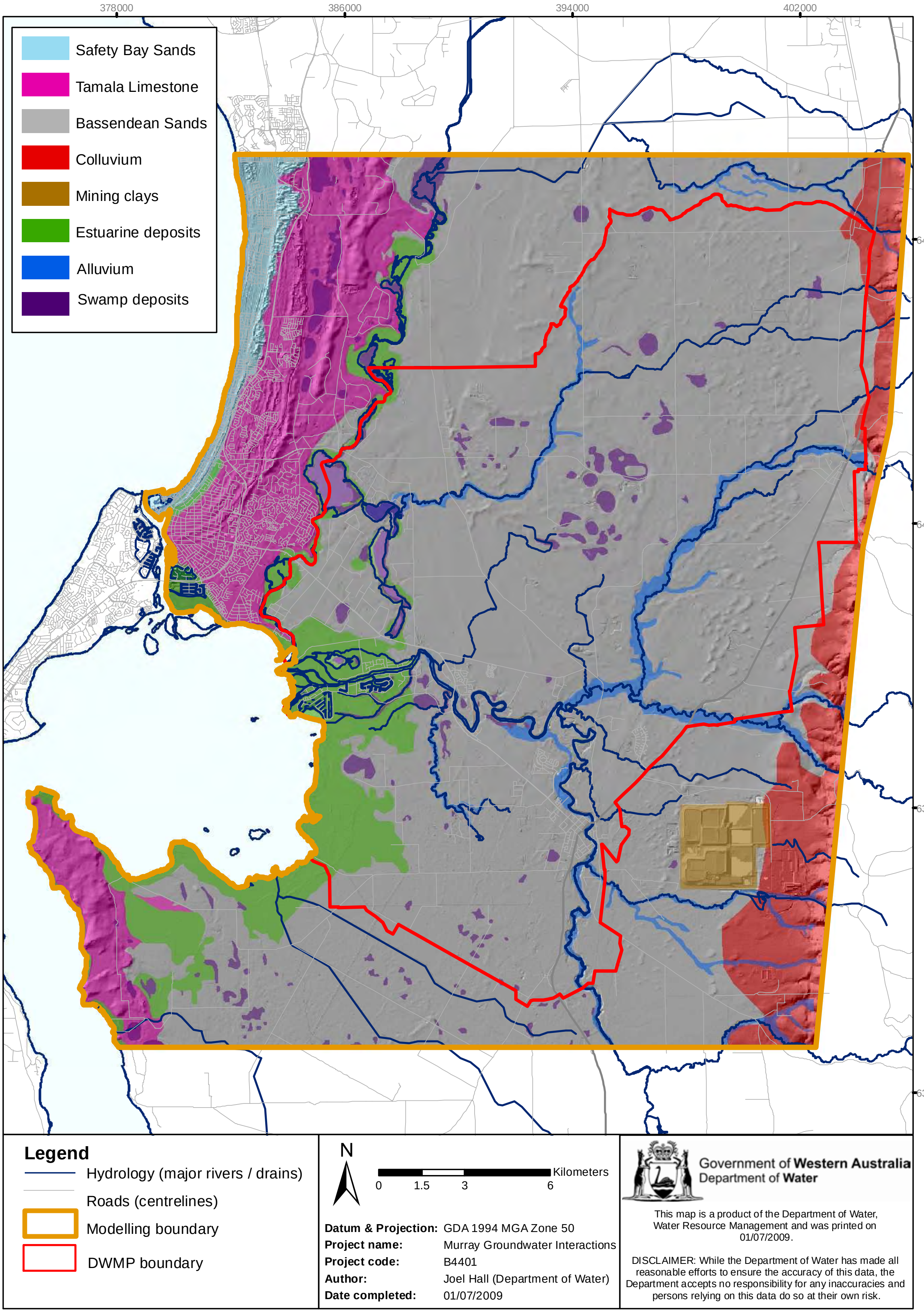


***Figure 4-9:** Surface geology in the Murray study area*

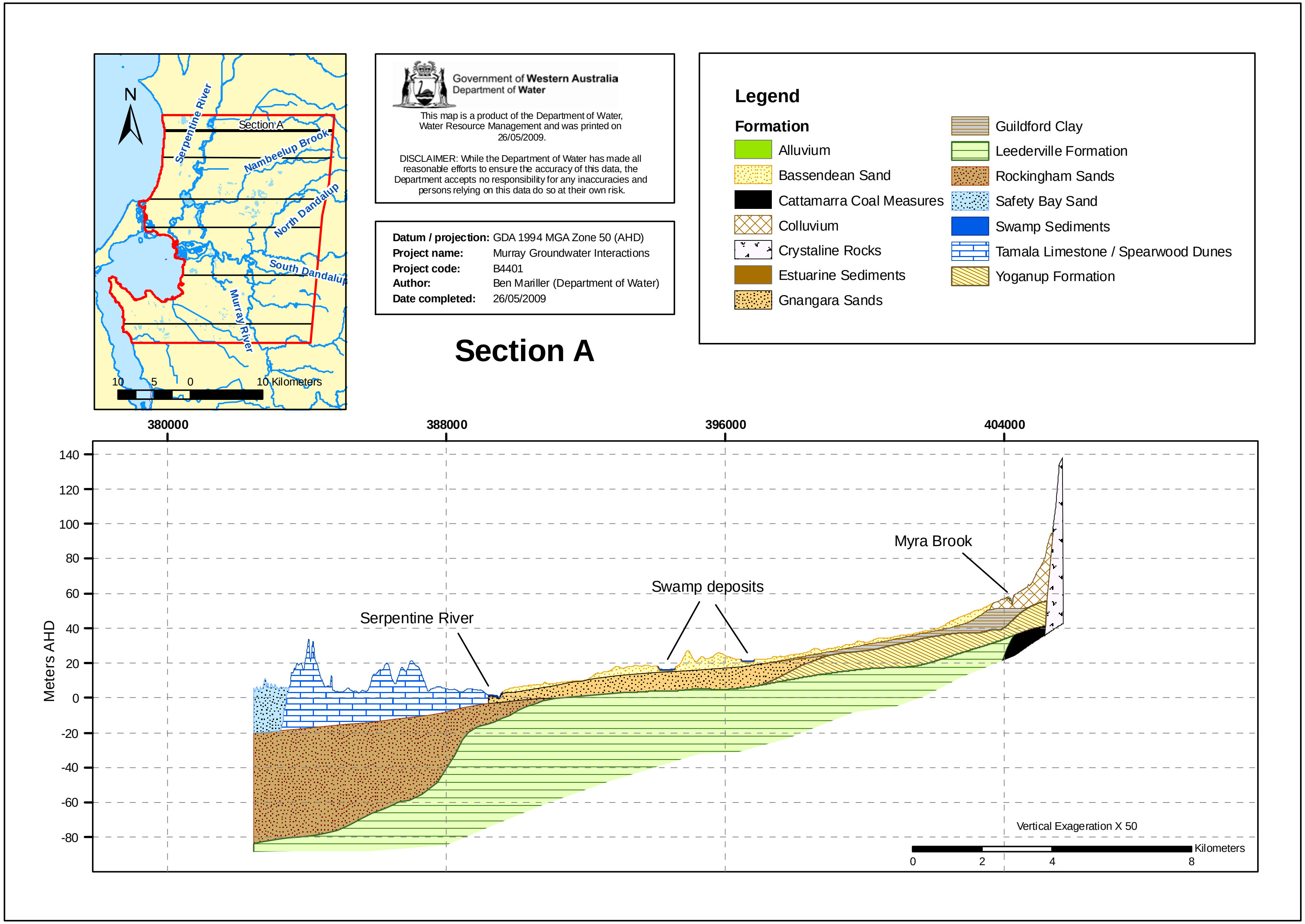
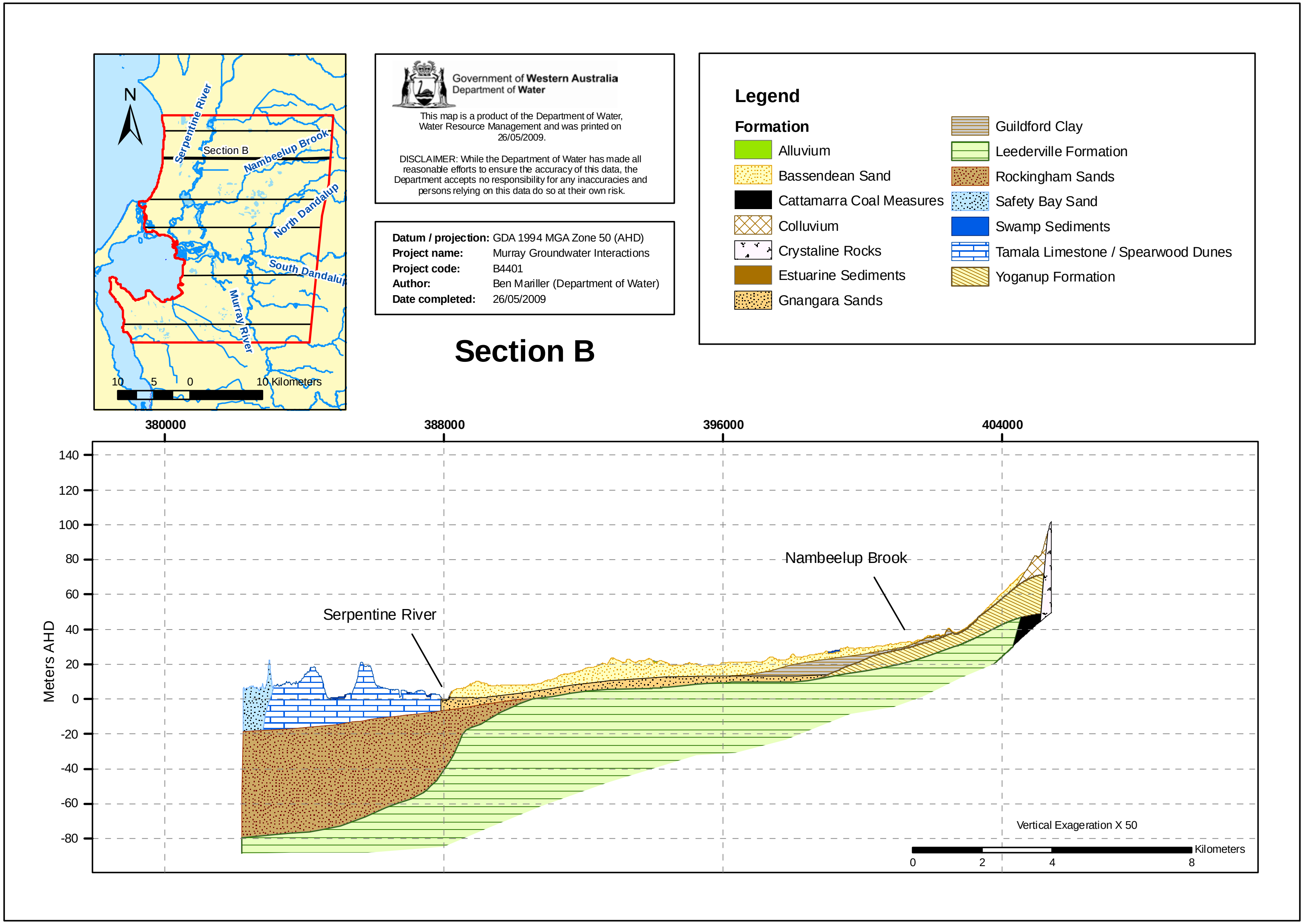


Figure 4-10: Cross section A: Superficial, Cattamarra and Leederville formations

Figure 4-11: Cross section B: Superficial, Cattamarra and Leederville formations



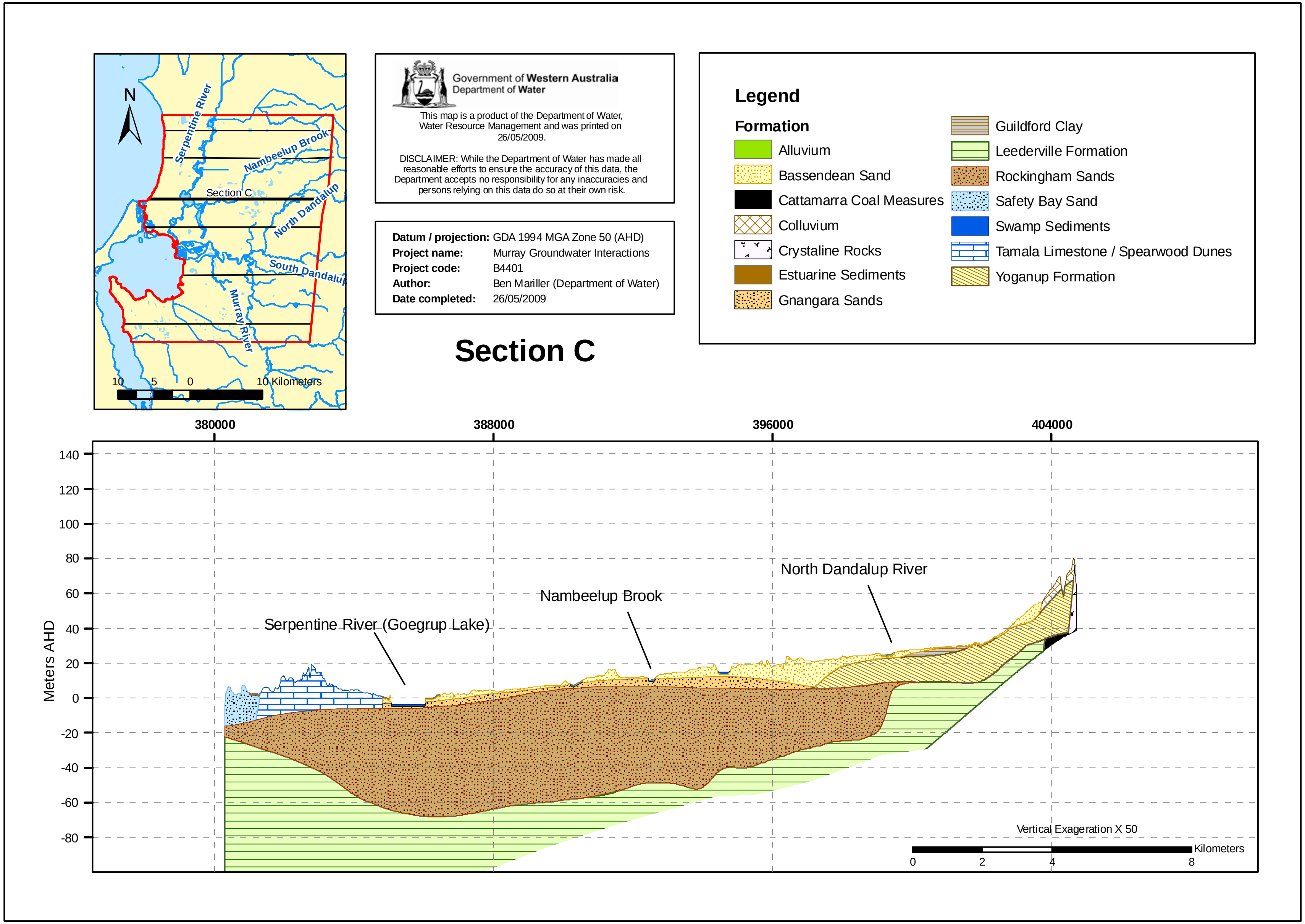


Figure 4-12: *Cross section C: Superficial, Cattamarra and Leederville formations*

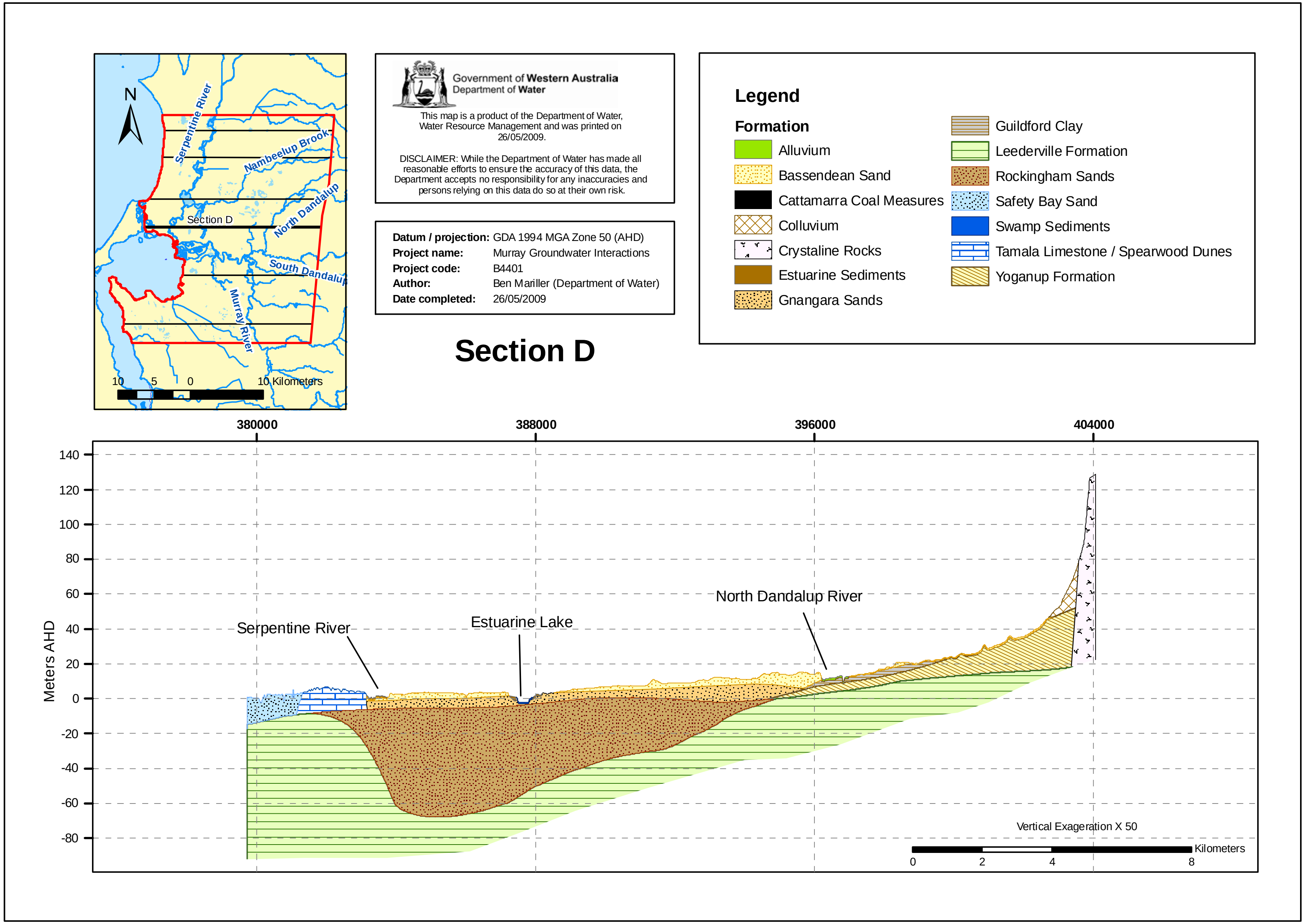


Figure 4-13: Cross section D: Superficial and Leederville Formations

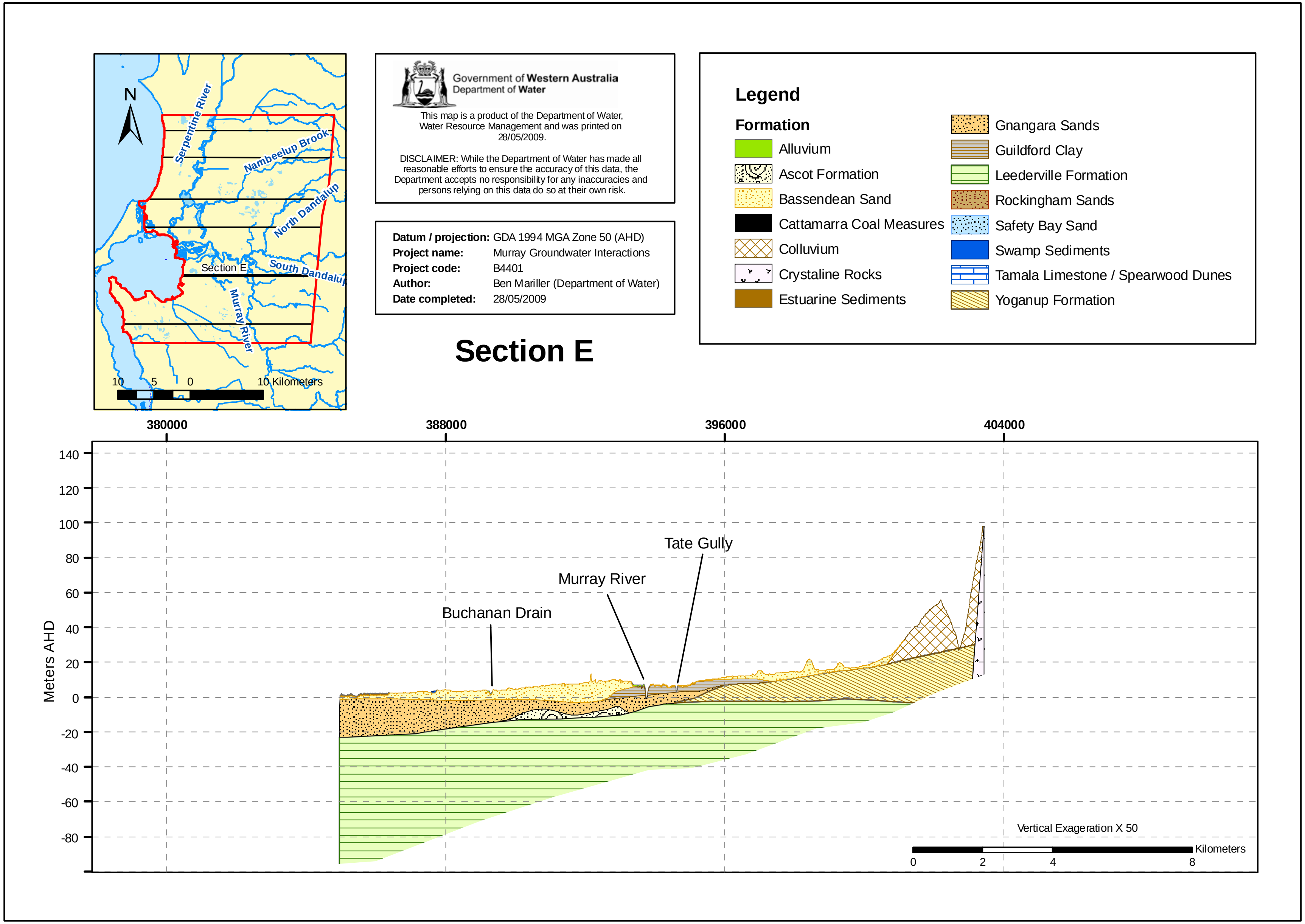


Figure 4-14: Cross section E: Superficial and Leederville Formations

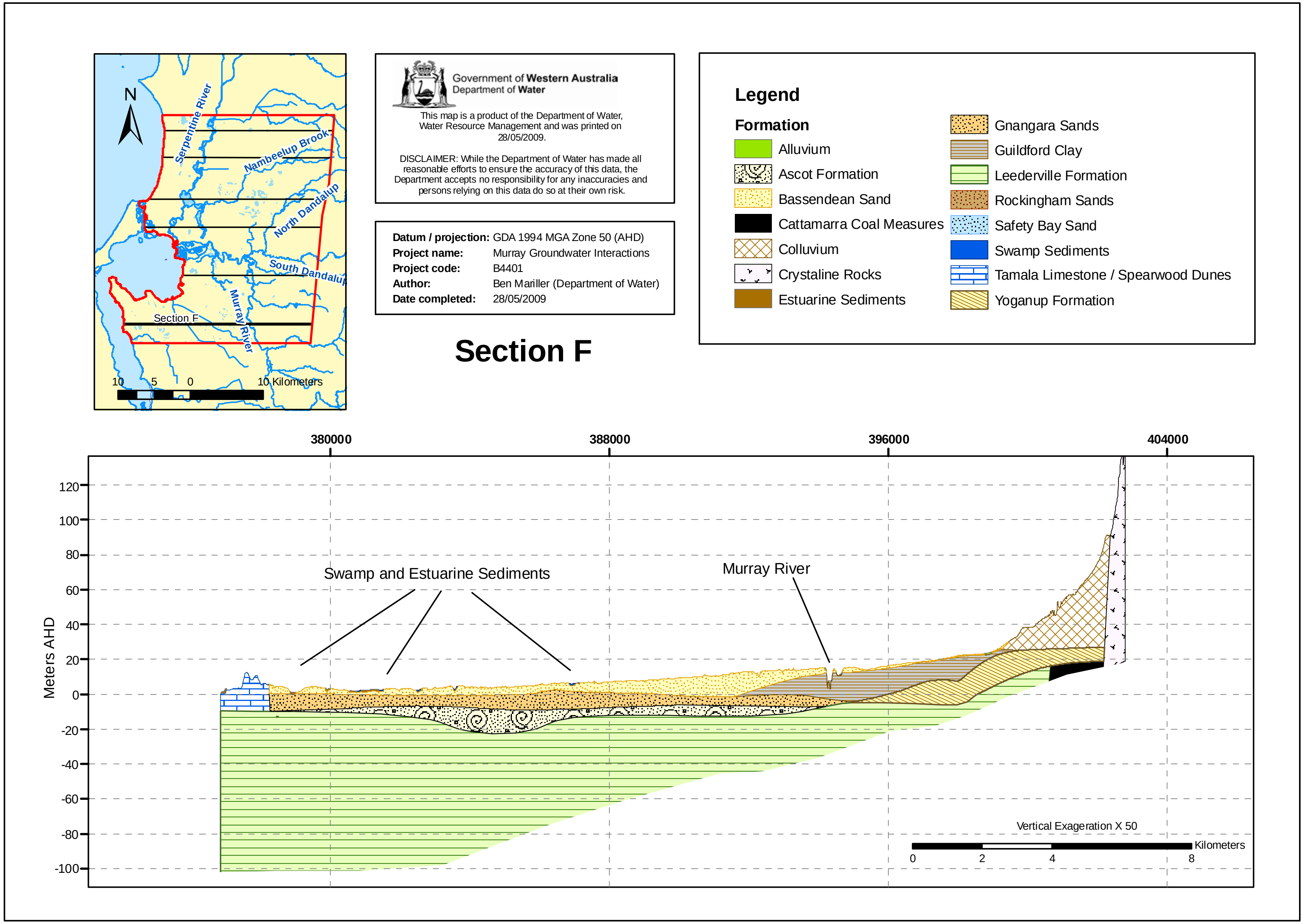
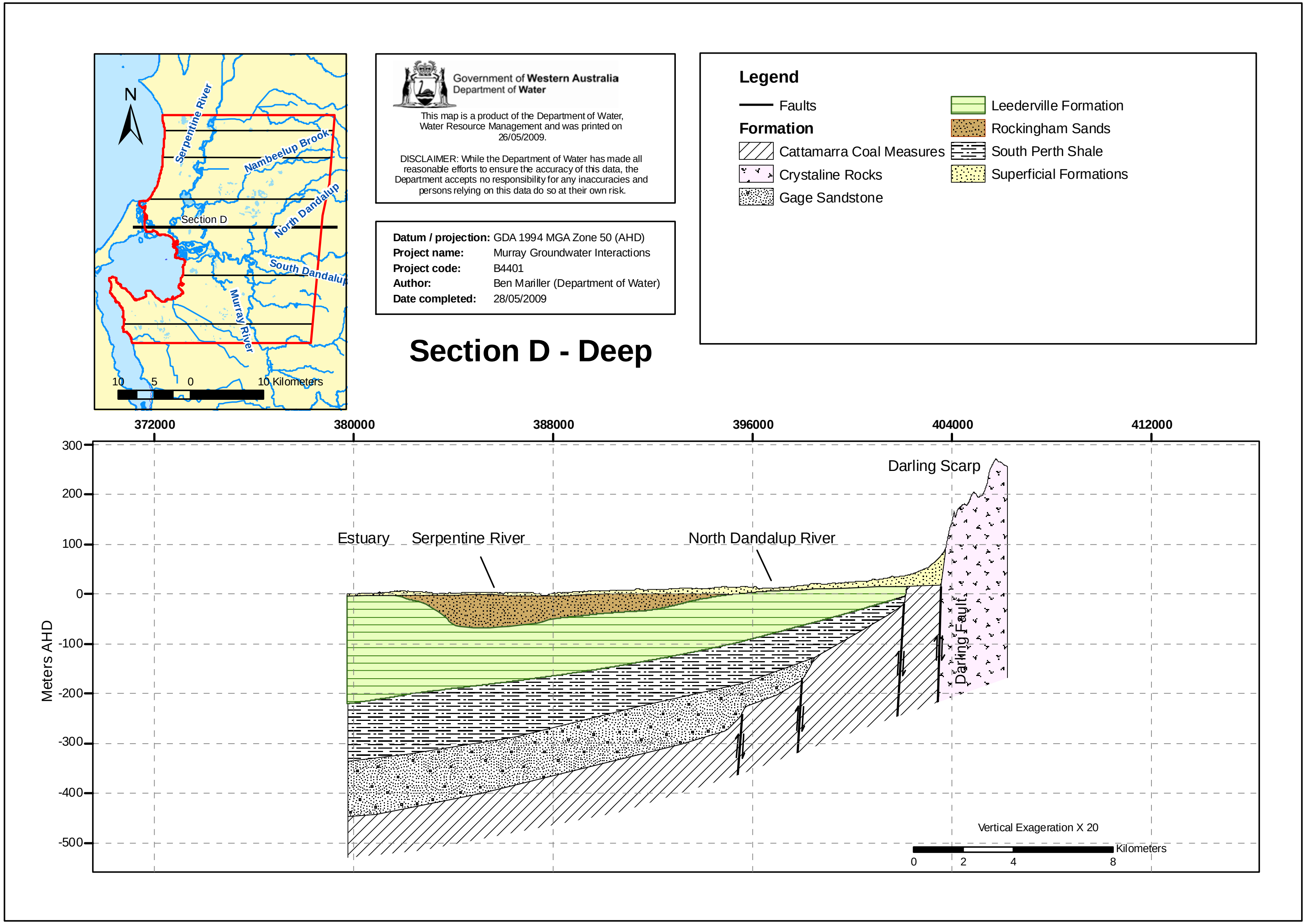


Figure 4-15: Cross section F: Superficial, Cattamarra and Leederville Formations

Figure 4-16: Cross section D: Deeper formations



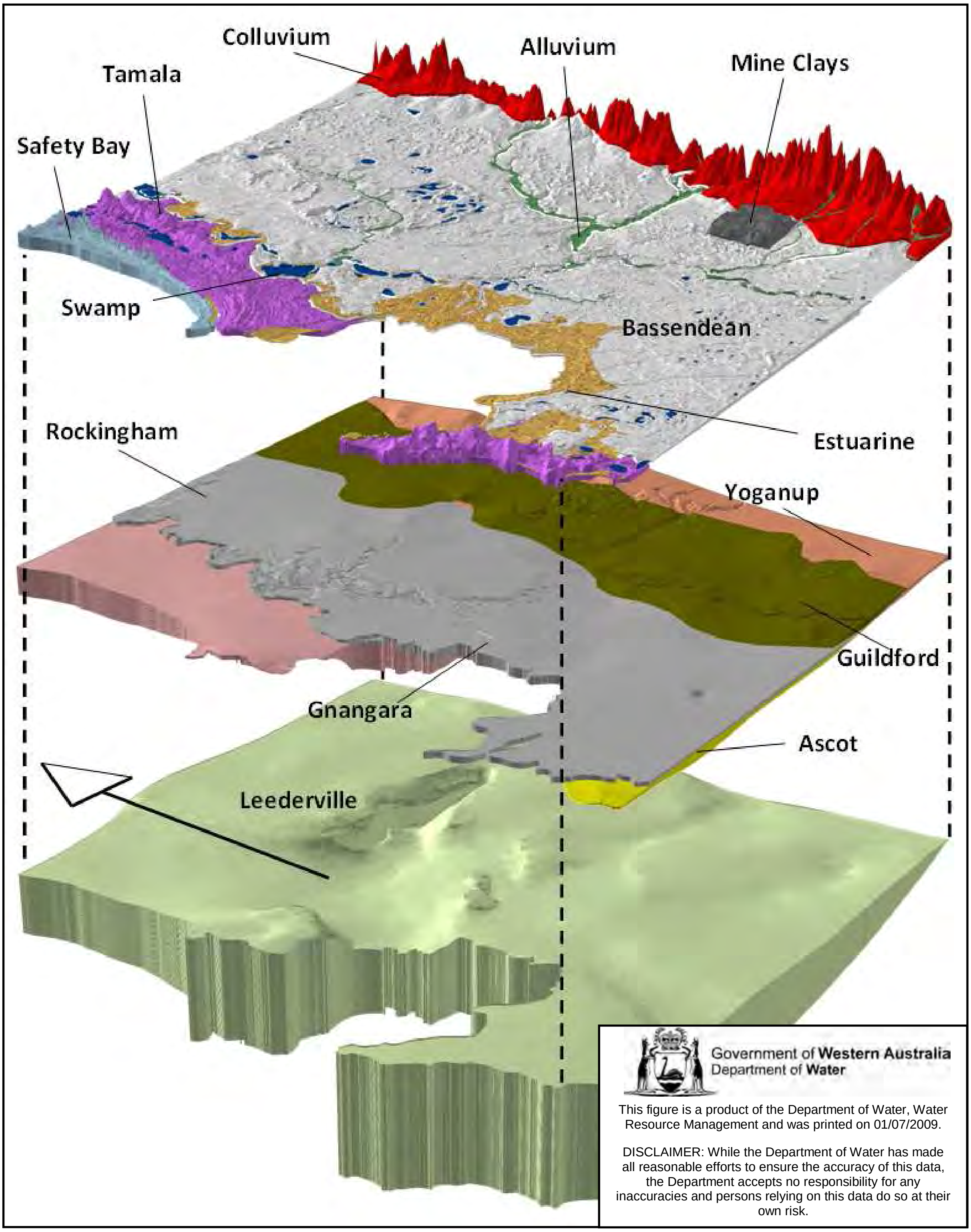


Figure 4-17: *Three-dimensional representation of geological units*

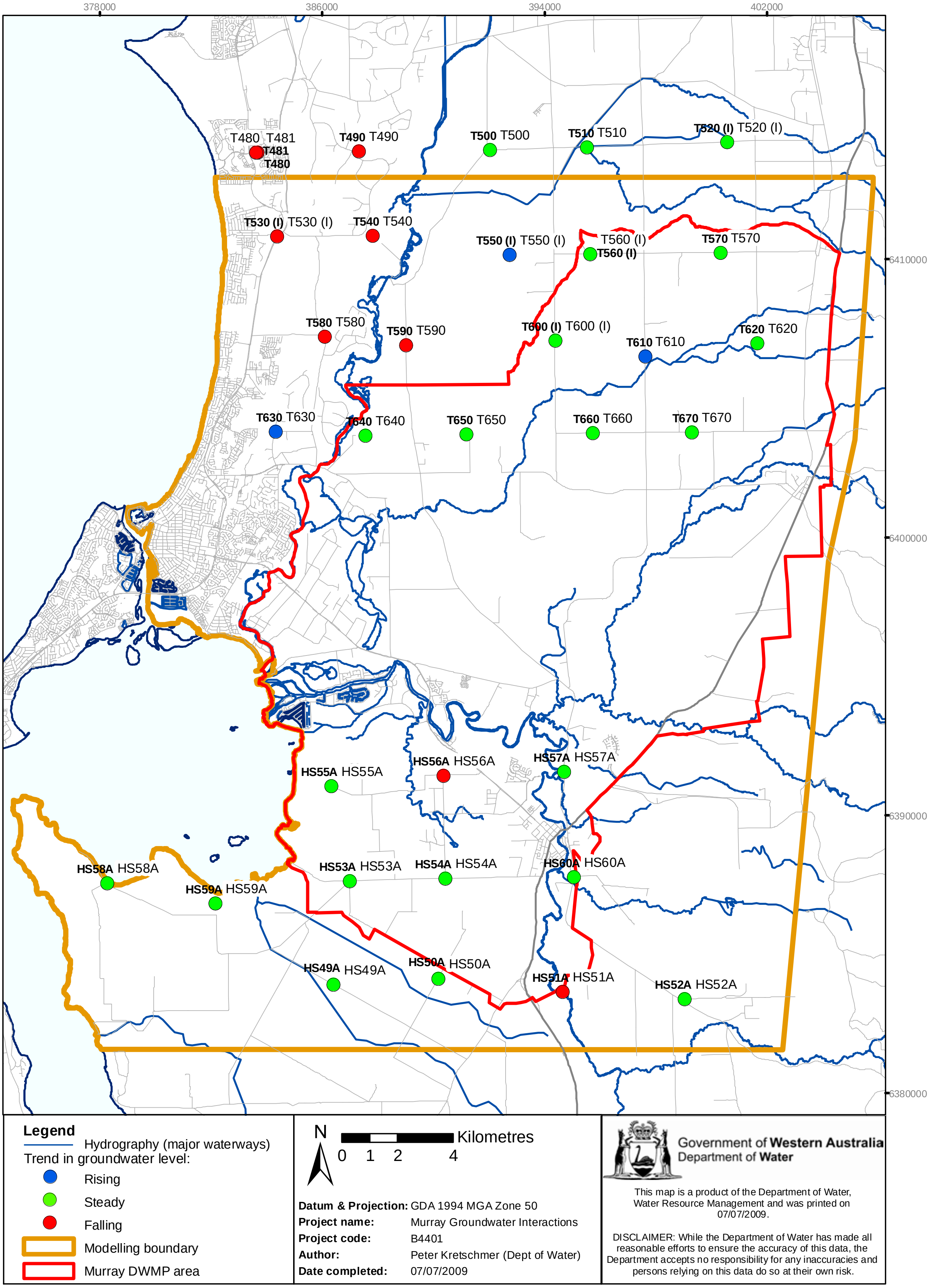


***Figure 5-1**: Long-term superficial monitoring bore locations and water level trends*

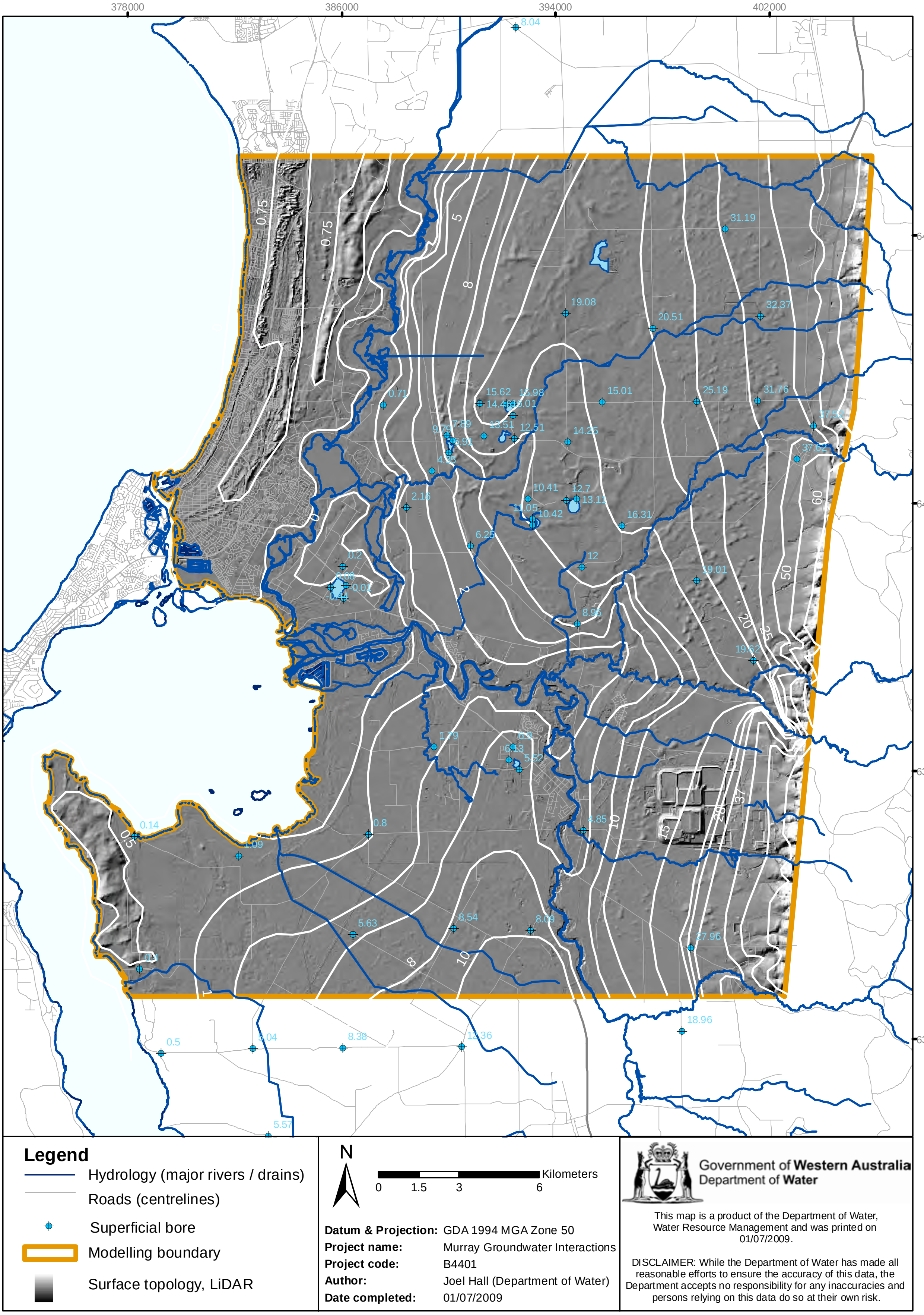


Figure 5-2: *Regional superficial groundwater levels, June 2009 (mAHD)*

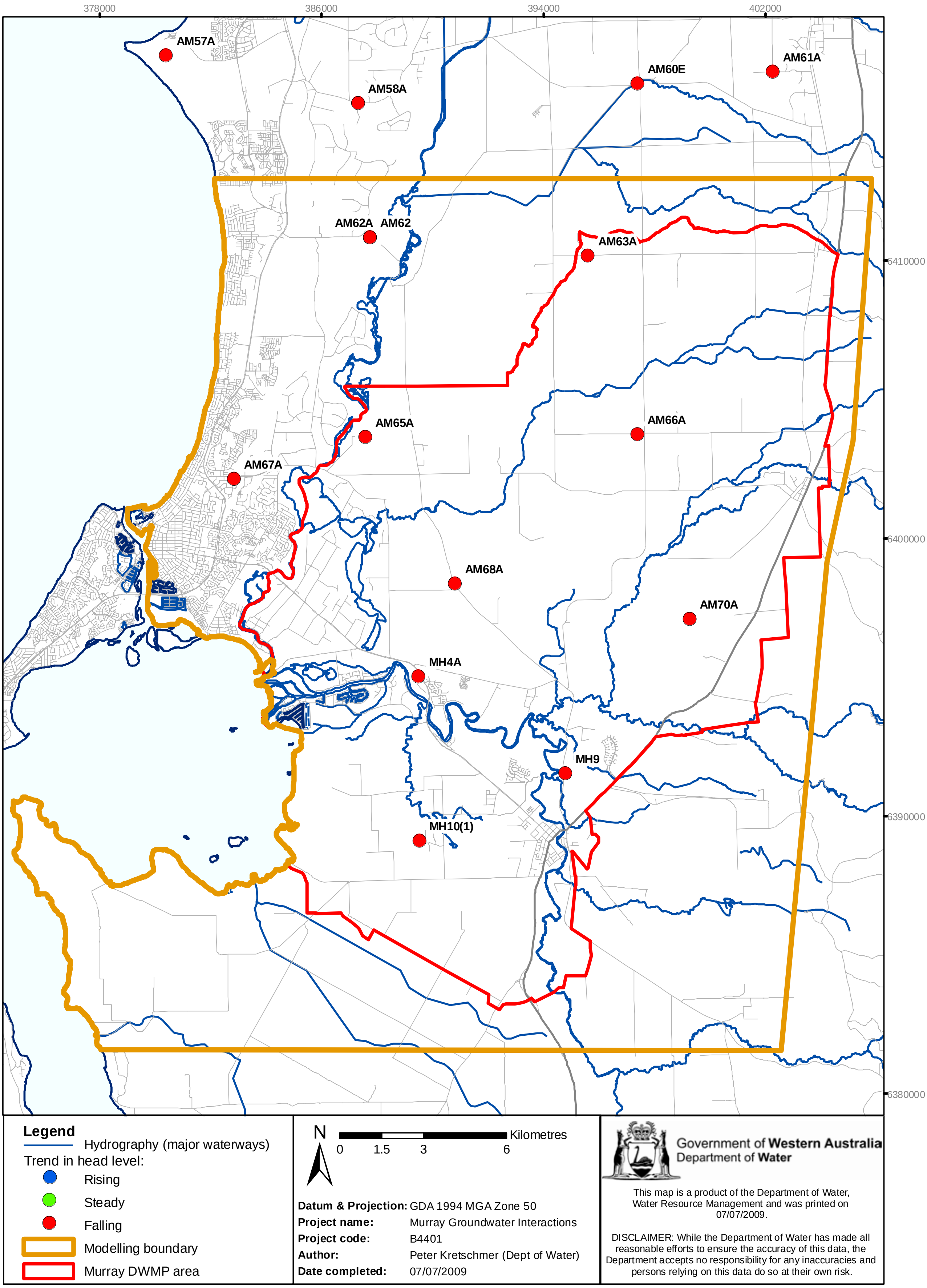


***Figure 5-3:** Leederville bore locations and trends in potentiometric head*

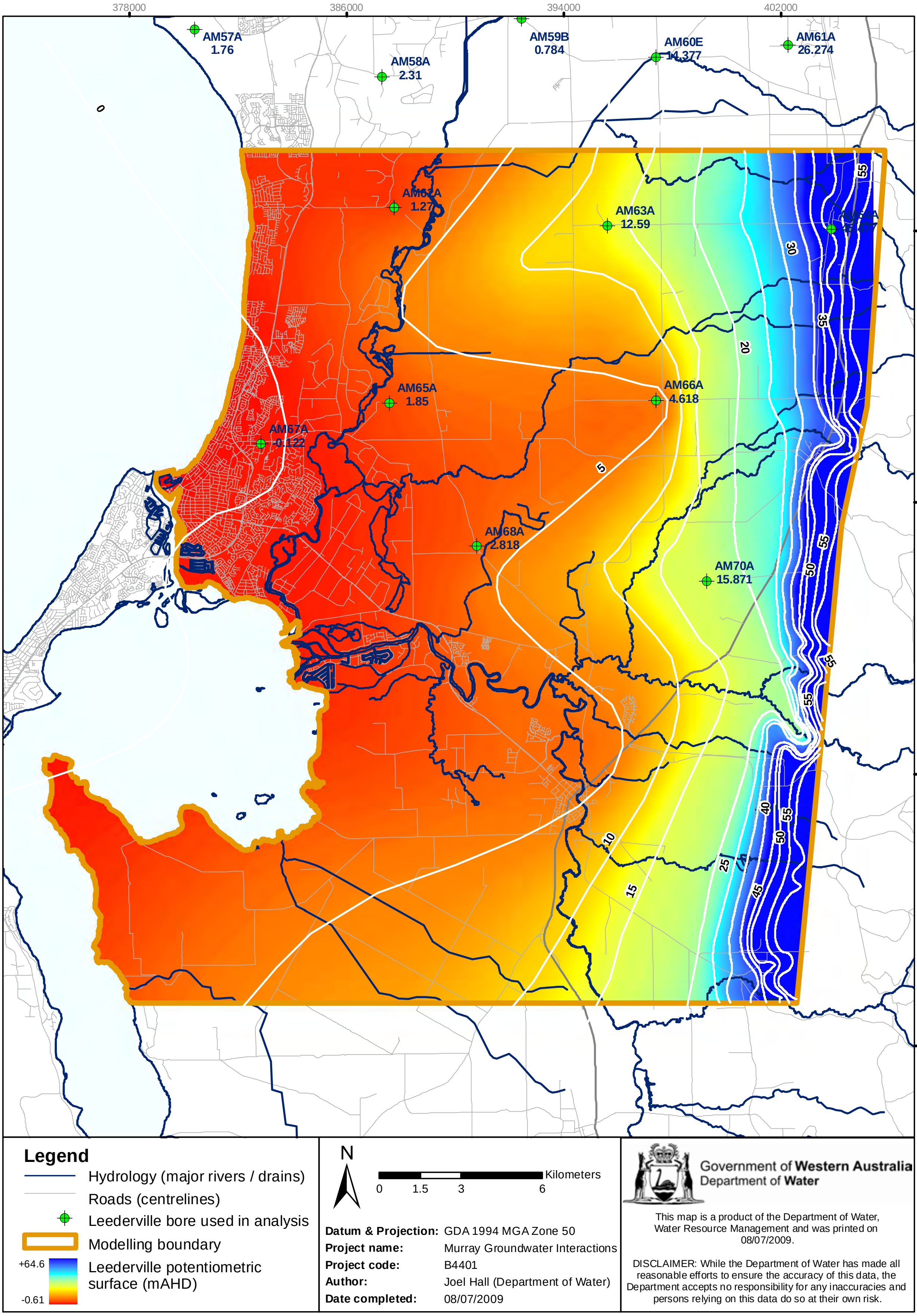


***Figure 5-4**: Leederville isopotentials: March 2008*

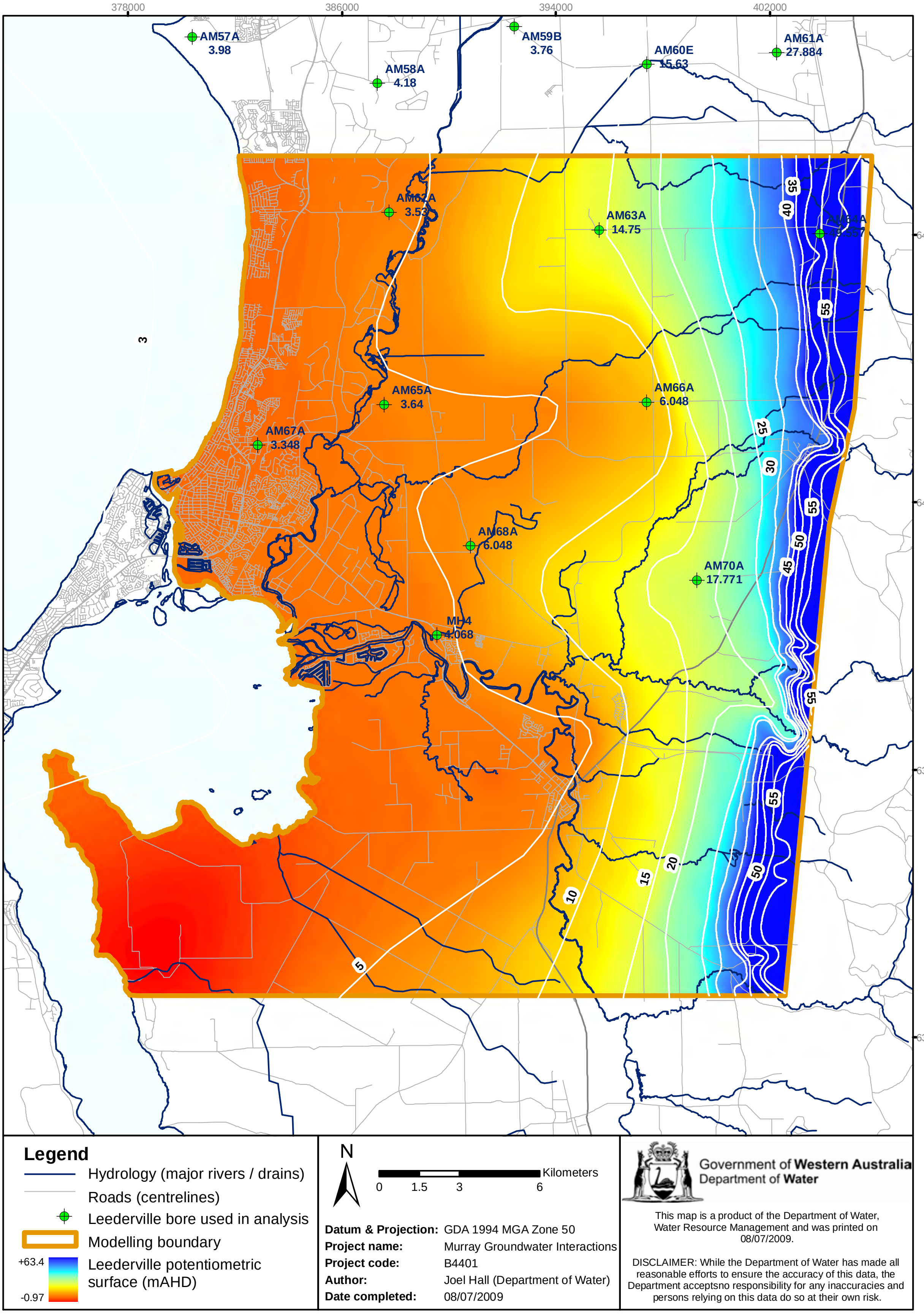


***Figure 5-5:** Leederville isopotentials: September 2008*

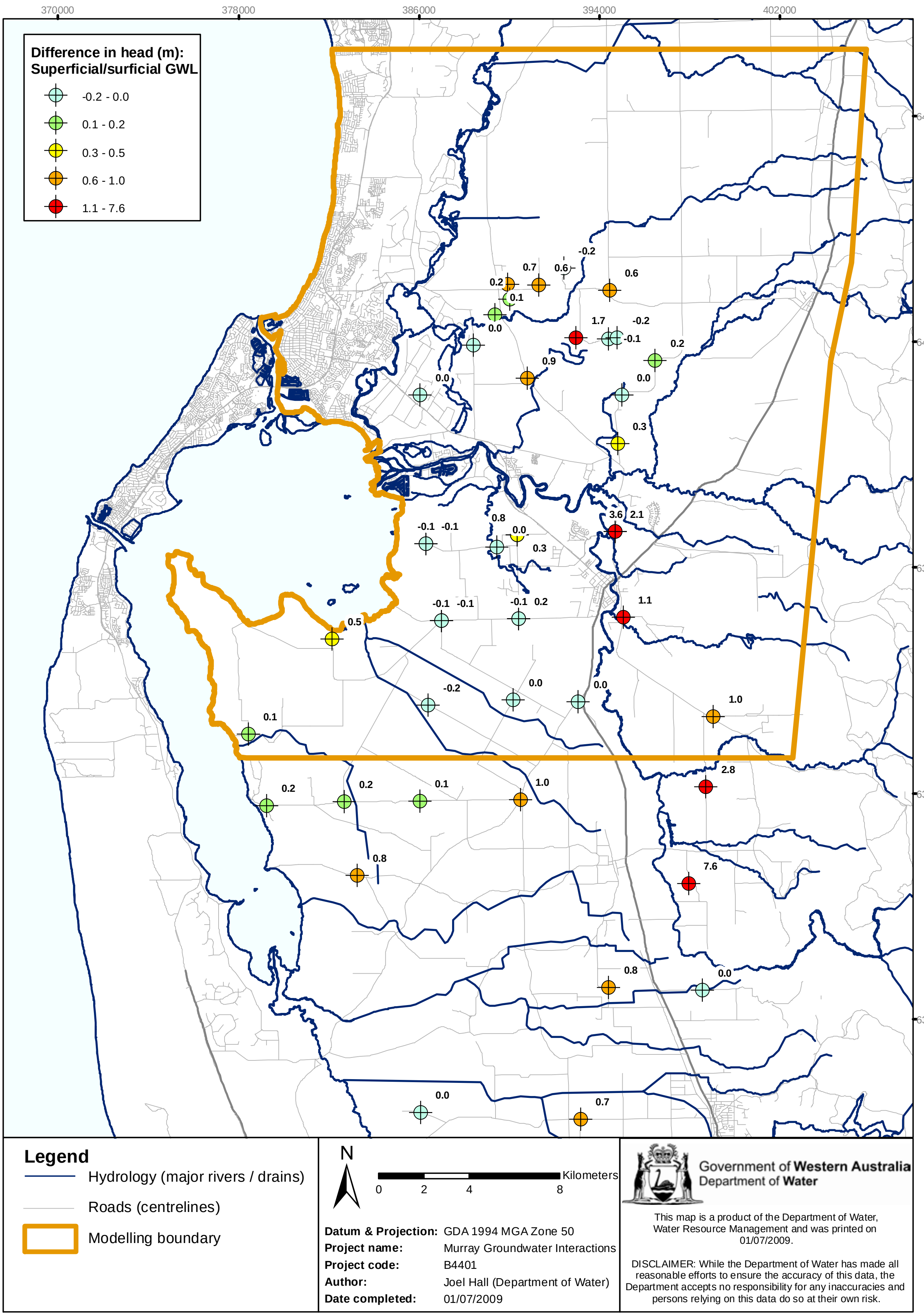


***Figure 5-6**: Potentiometric head differences recorded in nested superficial piezometers*

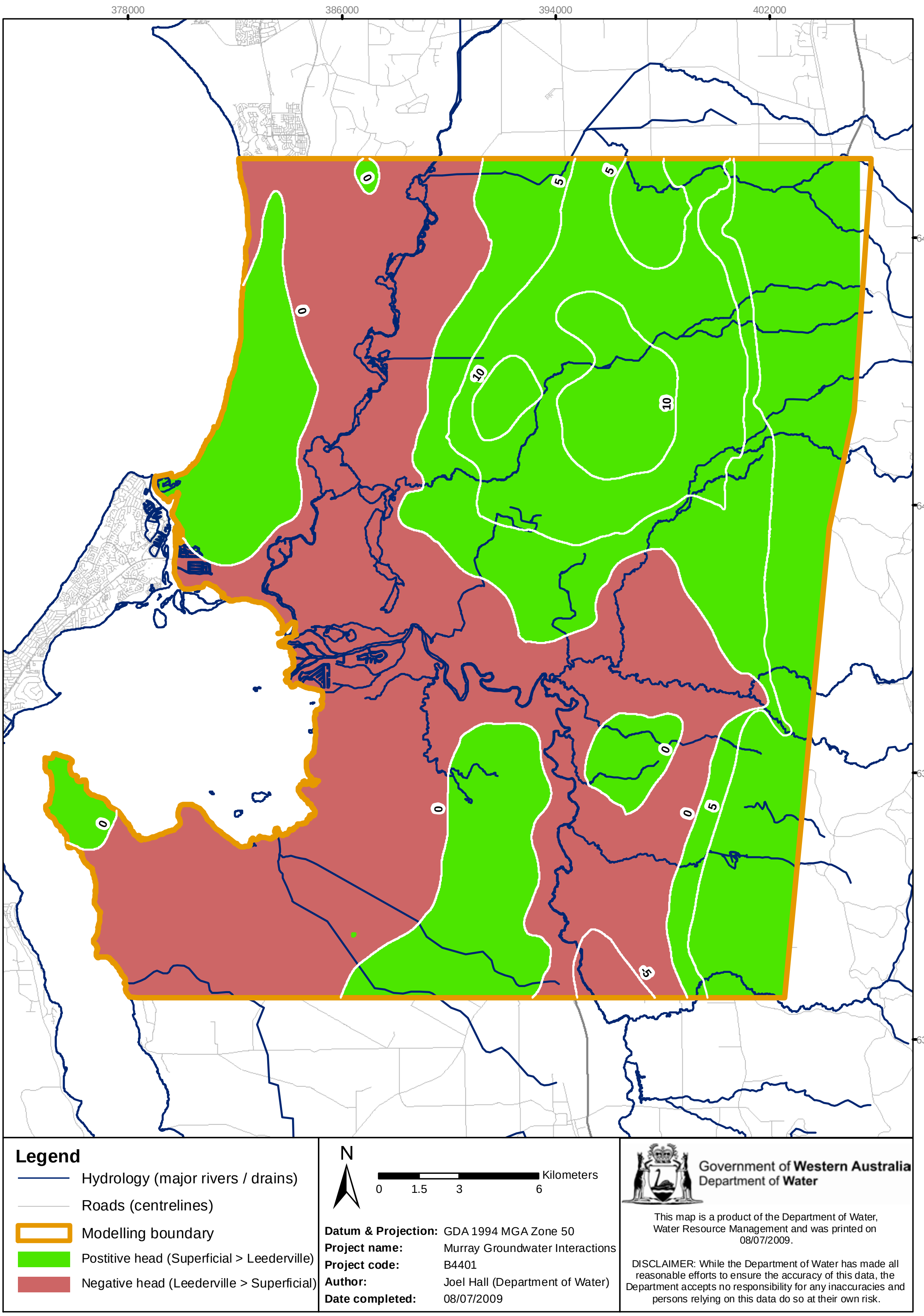


***Figure 5-7:** Potentiometric head differences: Leederville and Superficial Aquifers*

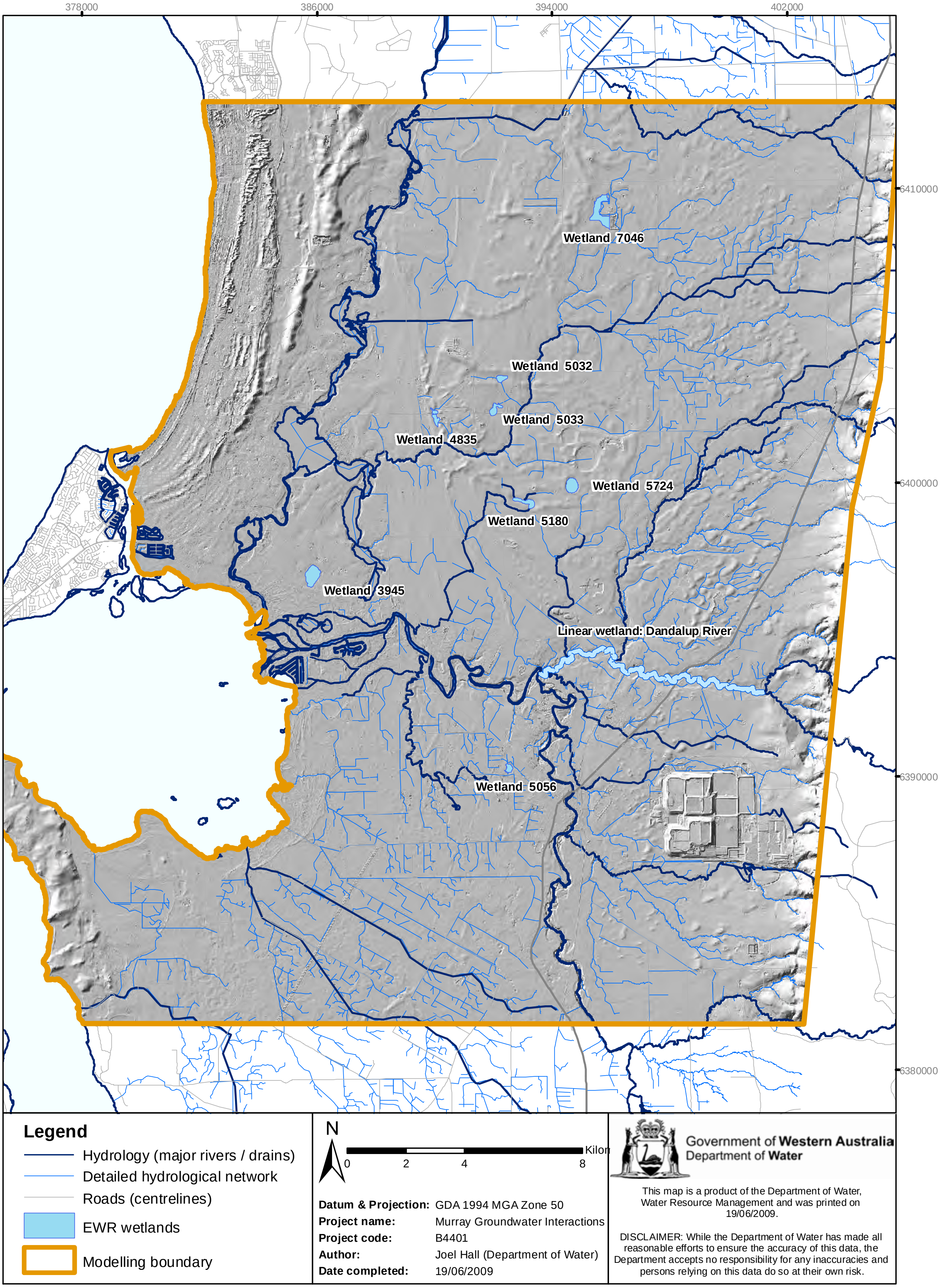


Figure 6-1*: Selected EWR wetland locations and numbers*

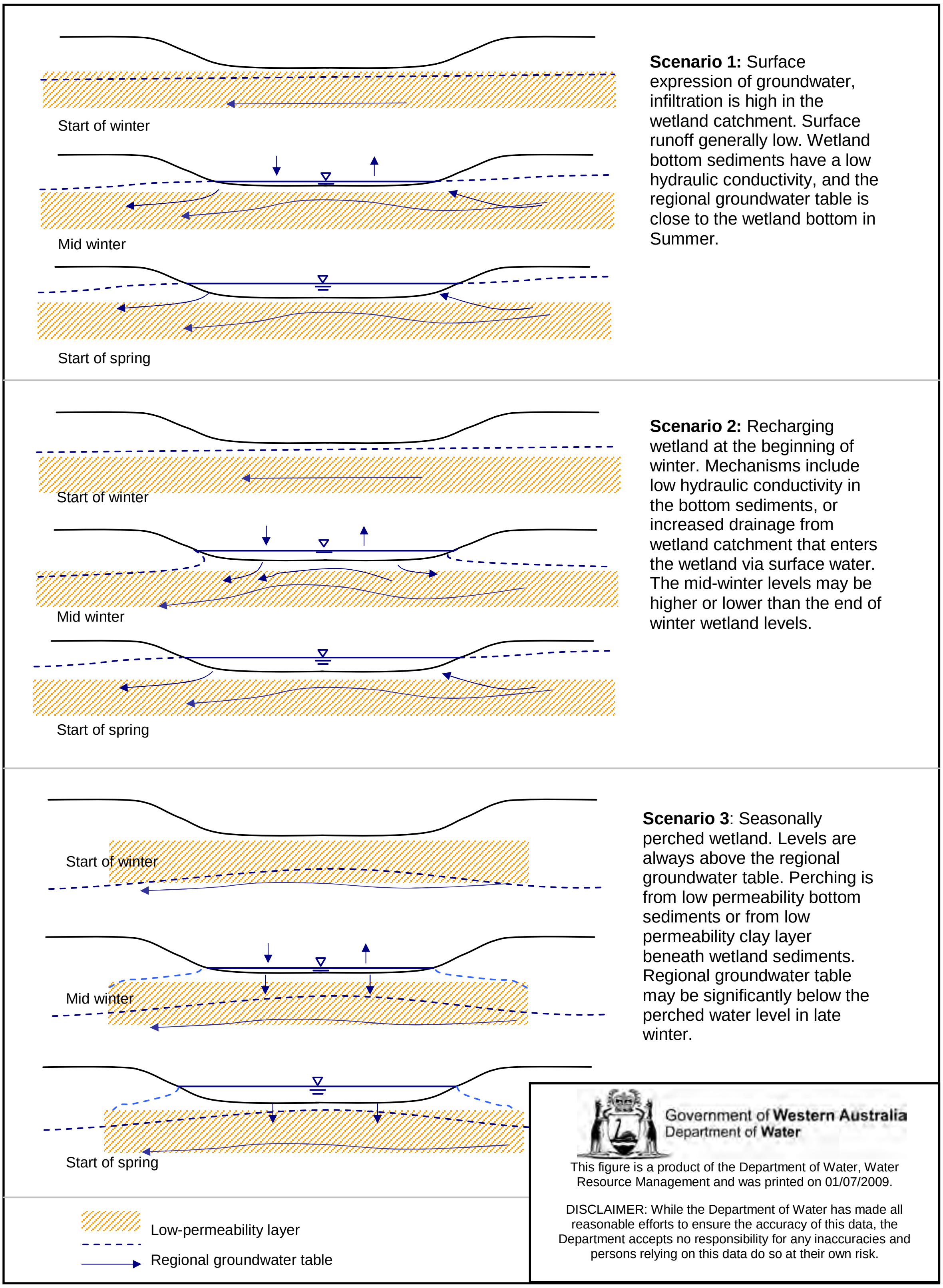
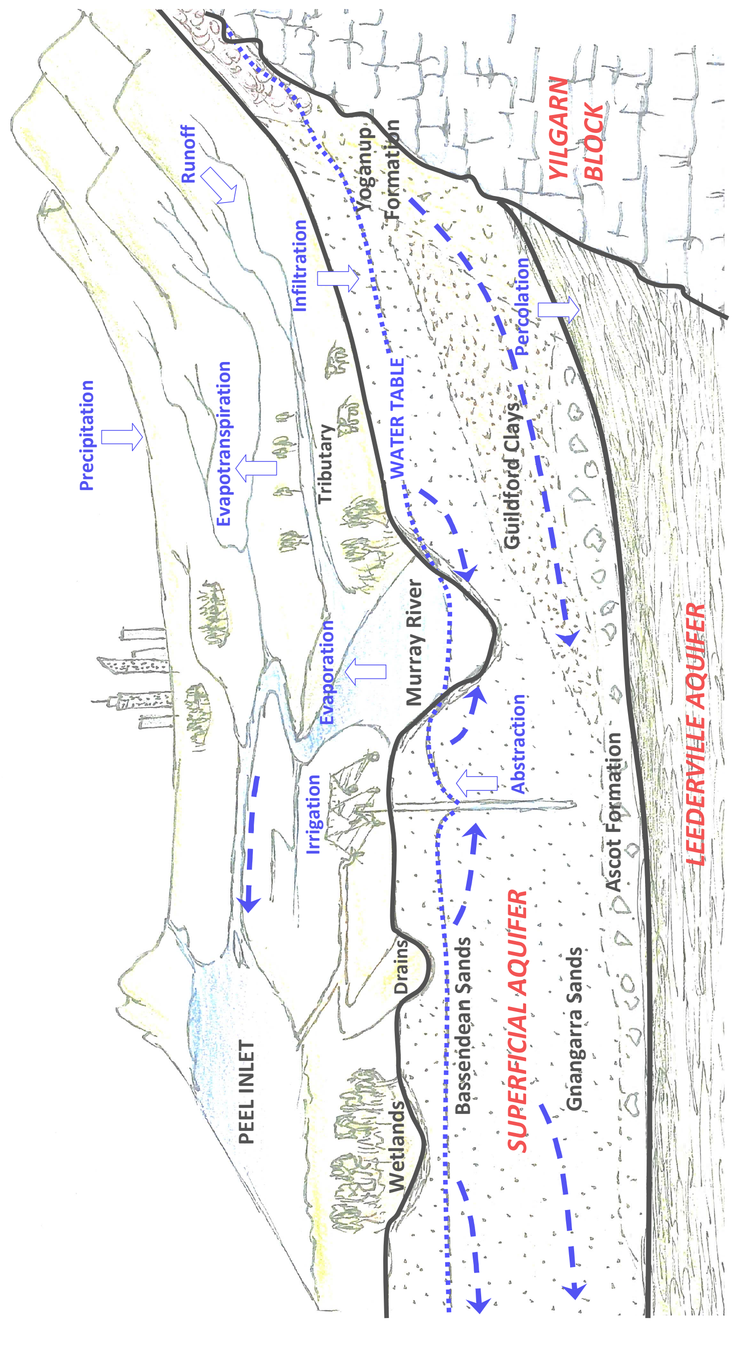


***Figure 6-10:** Wetland conceptual scenarios*



Legend

Hydrological Process

Superficial groundwater level

Direction of flow

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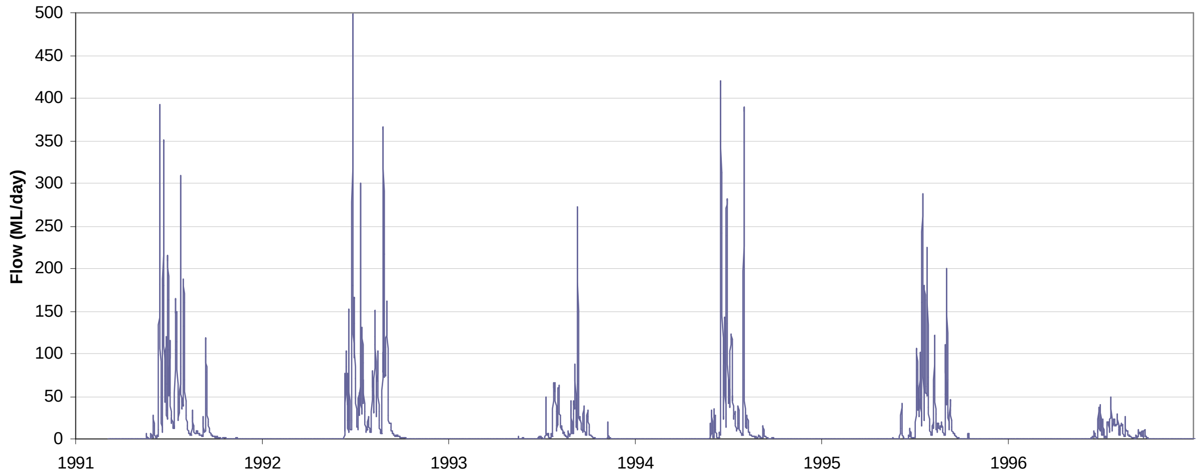
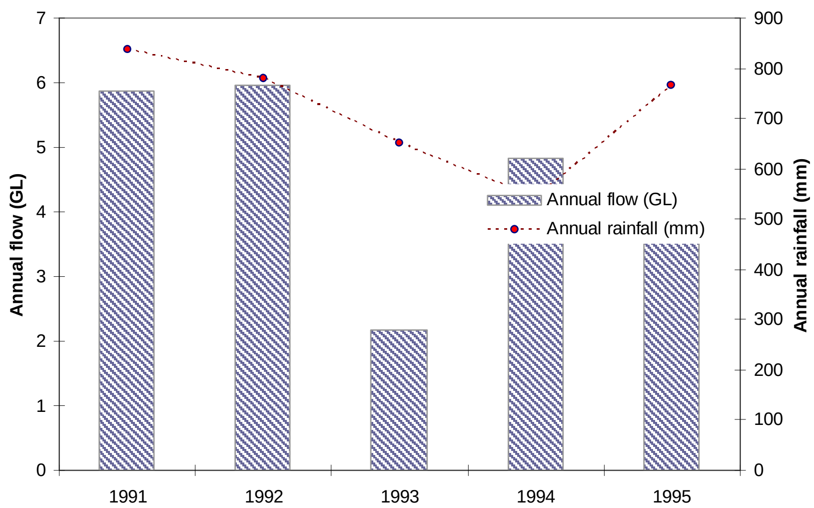
***Figure 7-1**: Conceptual model and hydrological processes*

Appendix A — Surface water analysis

613029 (Caris Drain, Greenlands Road)

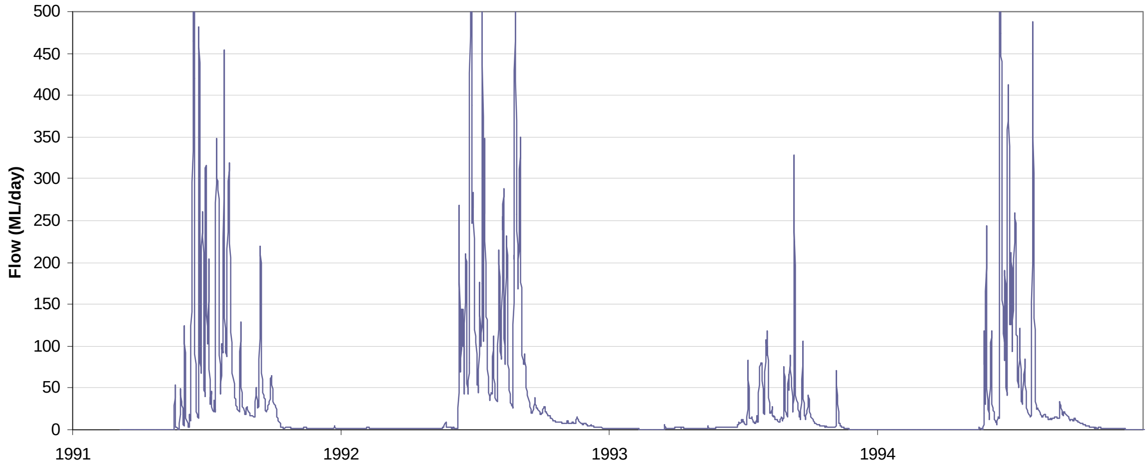
Year	Flow Count	Flow (GL)	Rainfall (mm)	*CR*
1991	301	5.9	837	37.3%
1992	366	6.0	781	40.6%
1993	365	2.2	652	17.8%
1994	365	4.8	543	47.3%
1995	365	3.7	765	25.5%
Average		4.2	716	33.7%
Catchment area (sqkm)		*18.8*		

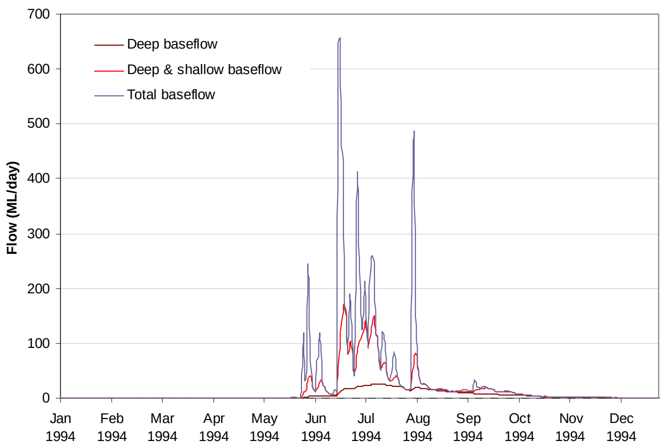


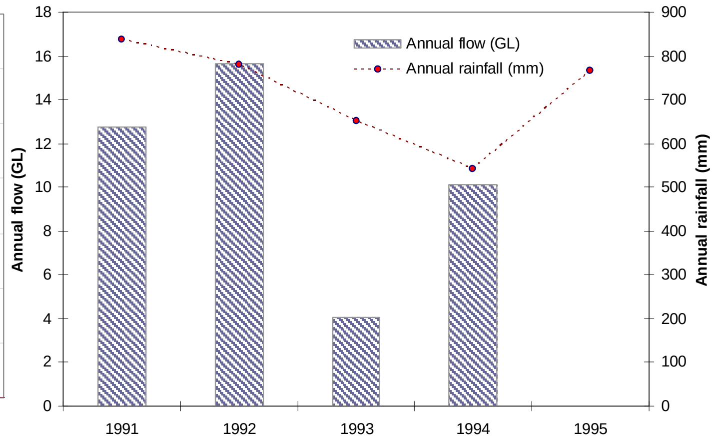


613030 (Coolup Main Drain, Paul Road)

Year	Flow Count	Flow (GL)	Rainfall (mm)	*CR*
1991	300	12.8	837	29.9%
1992	366	15.6	781	39.3%
1993	365	4.0	652	12.1%
1994	365	10.1	543	36.5%
1995	119	0.0	765	-
Average		7.4	716	29.3%
Catchment area (sqkm)		*51.0*		

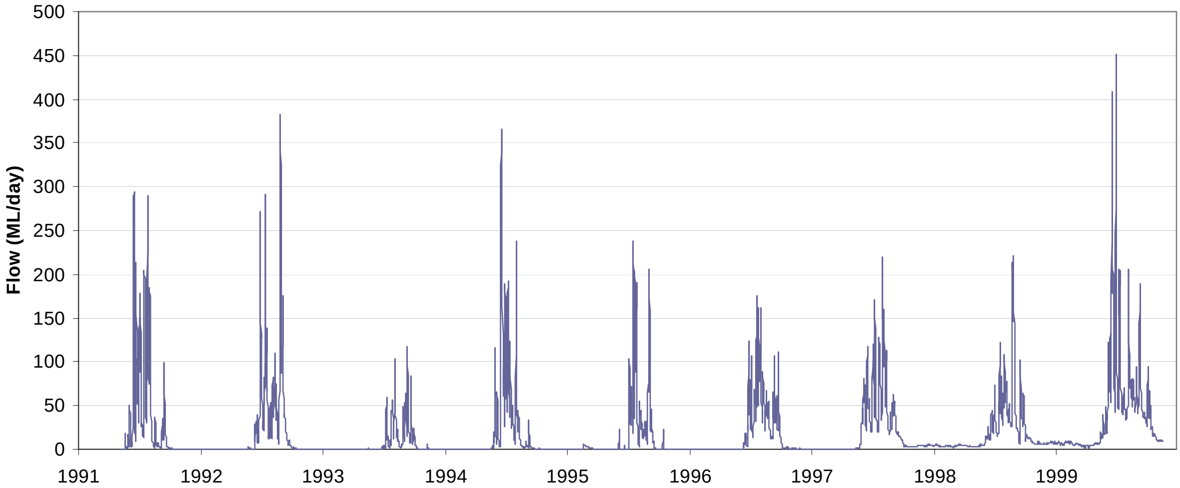


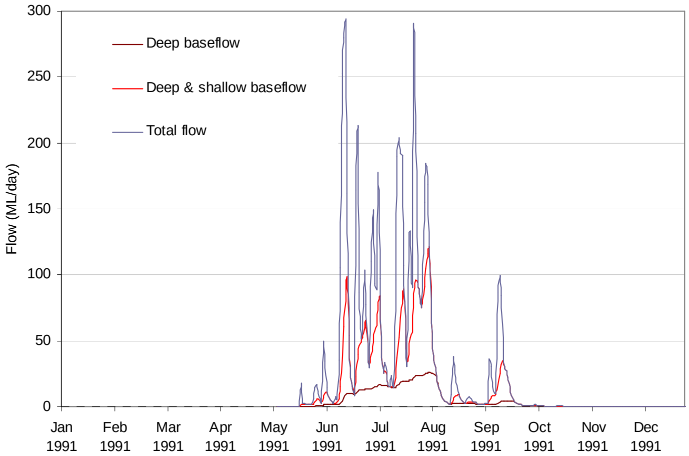


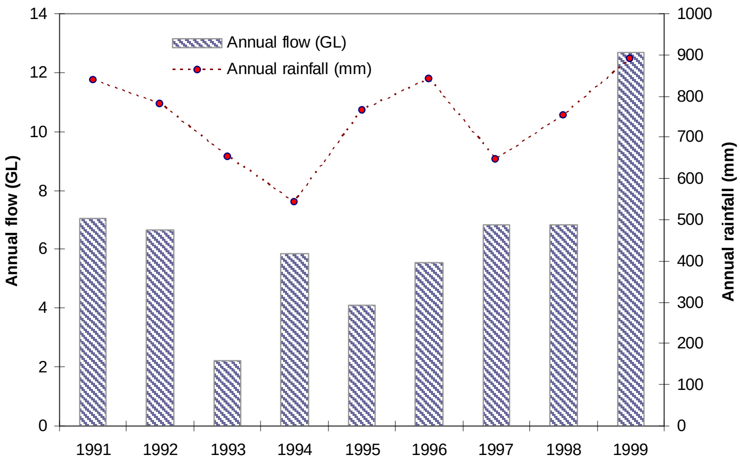


613032 (Mealup Drain, Mealup Road)

Year	Flow Count	Flow (GL)	Rainfall (mm)	*CR*
1991	239	7.0	837	32.4%
1992	366	6.7	781	32.8%
1993	365	2.2	652	13.0%
1994	365	5.8	543	41.3%
1995	365	4.1	765	20.7%
1996	366	5.5	840	25.3%
1997	365	6.8	645	40.7%
1998	365	6.8	752	34.8%
1999	325	12.7	890	-
Average		5.4	745	29.5%
Catchment area (sqkm)		*26.0*		

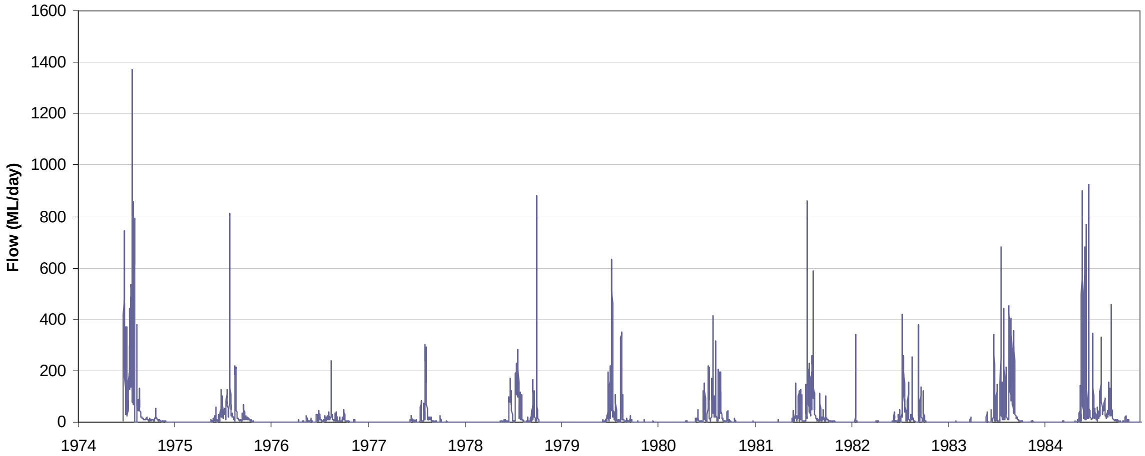


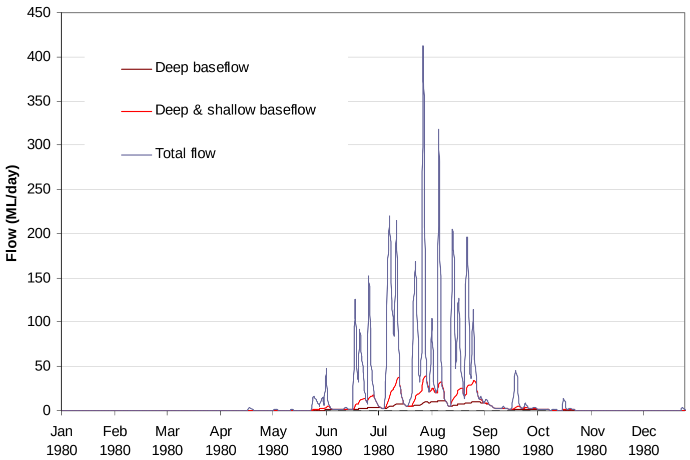


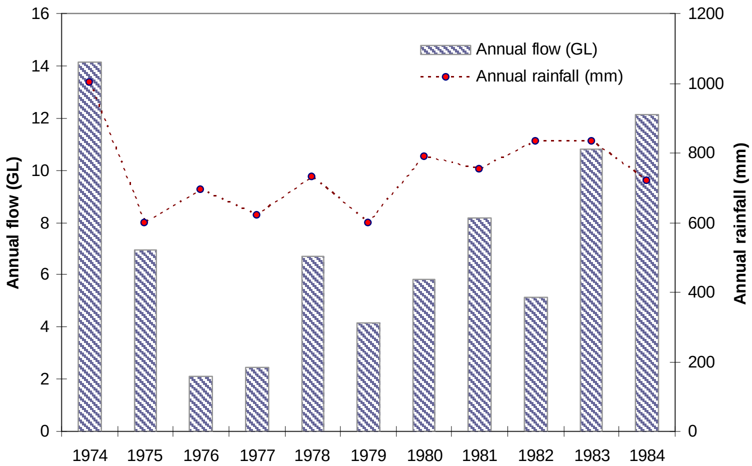


614009 (Oakley Brook, Pinjarra South)

Year	Flow Count	Flow (GL)	Rainfall (mm)	*CR*
1974	184	14.1	1002	-
1975	365	6.9	597	32.5%
1976	366	2.1	694	8.5%
1977	365	2.4	619	11.0%
1978	358	6.7	732	25.5%
1979	365	4.1	597	19.4%
1980	364	5.8	788	20.6%
1981	365	8.2	752	30.4%
1982	365	5.1	834	17.1%
1983	365	10.8	834	-
1984	366	12.1	721	-
Average		6.4	743	20.6%
Catchment area (sqkm)		*35.8*		

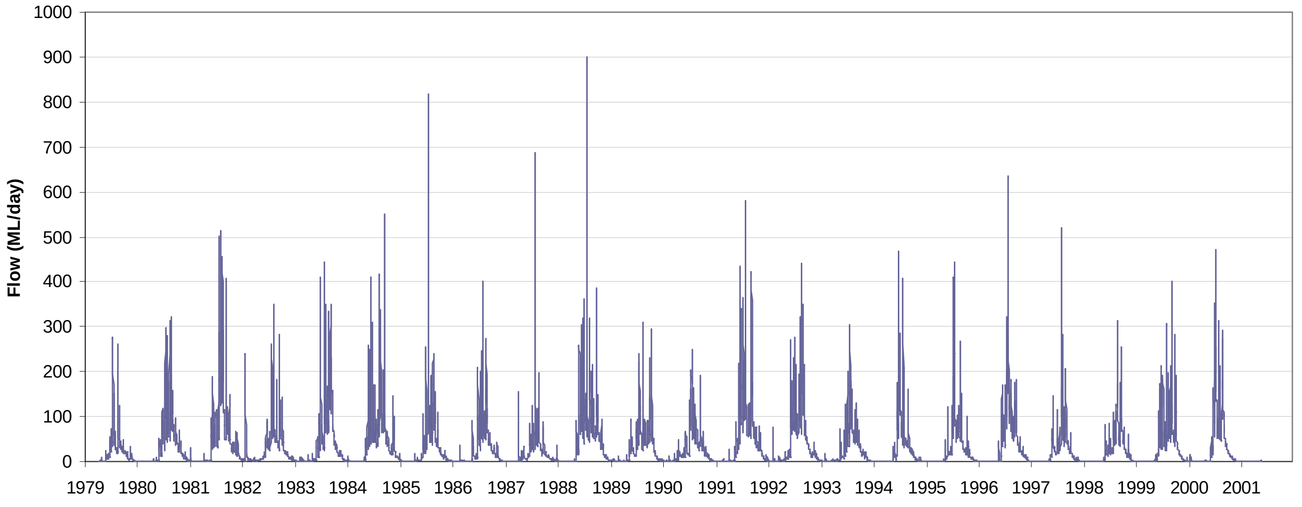


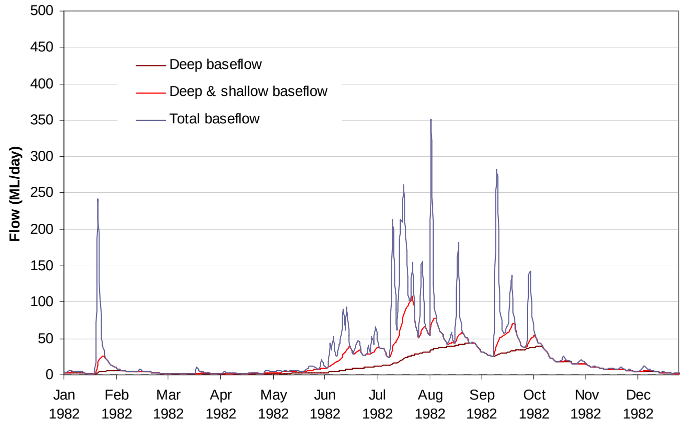


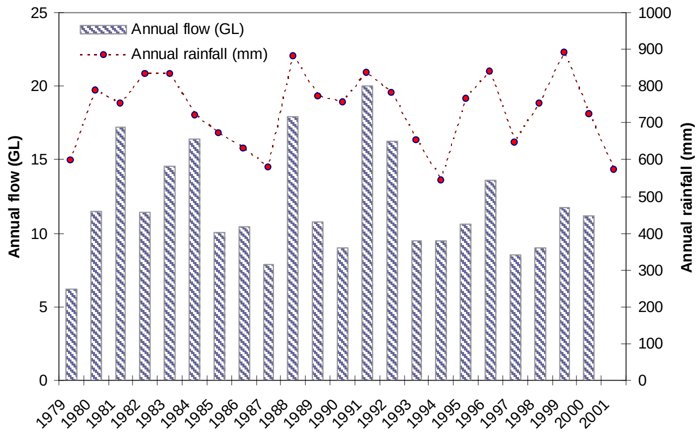


614028 (Dirk Brook, Hopelands Road)

Year	Flow Count	Flow (GL)	Rainfall (mm)	*CR*
1979	271	6.2	597	-
1980	366	11.5	788	22.9%
1981	365	17.2	752	35.9%
1982	365	11.4	834	21.5%
1983	365	14.6	834	27.4%
1984	366	16.4	721	35.6%
1985	365	10.1	673	23.5%
1986	365	10.4	629	26.0%
1987	365	7.8	579	21.2%
1988	366	17.9	881	31.8%
1989	365	10.8	772	21.9%
1990	365	9.0	757	18.7%
1991	365	20.0	837	37.5%
1992	366	16.2	781	32.6%
1993	365	9.5	652	22.8%
1994	365	9.5	543	27.4%
1995	365	10.6	765	21.8%
1996	366	13.5	840	25.3%
1997	365	8.5	645	20.6%
1998	365	9.0	752	18.8%
1999	365	11.7	890	20.7%
2000	366	11.2	725	24.1%
2001	149	0.0	571	-
Average		12.2	723	25.6%
Catchment area (sqkm)		*63.9*		

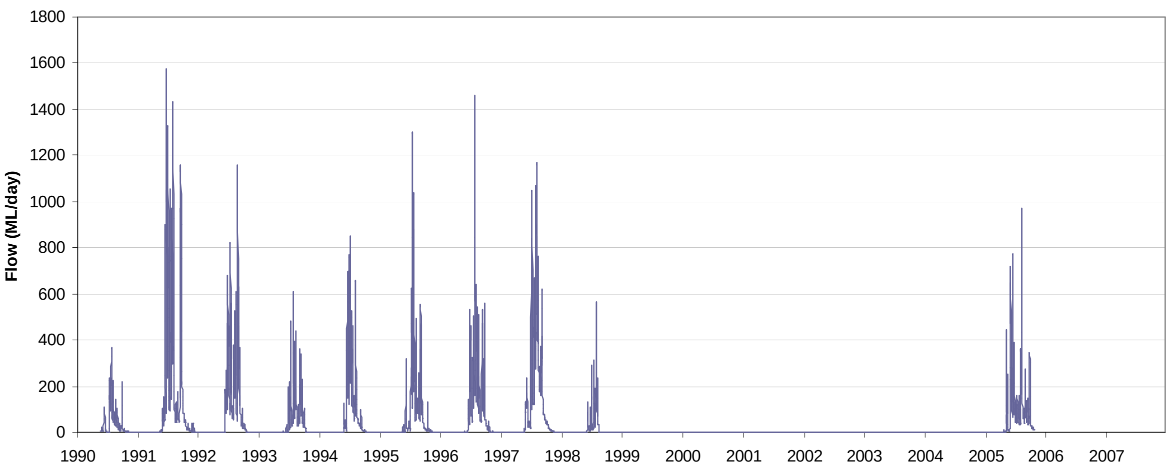


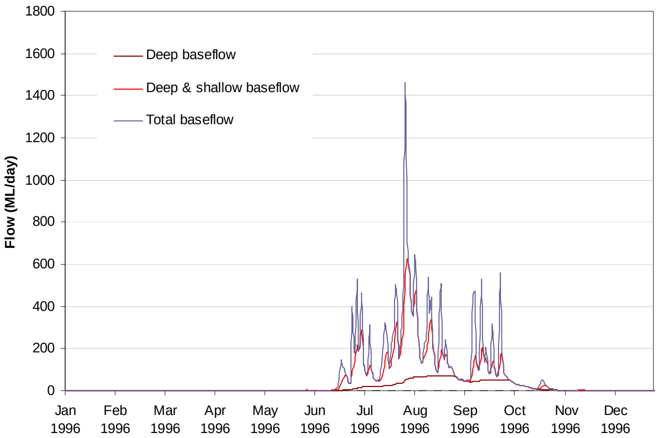


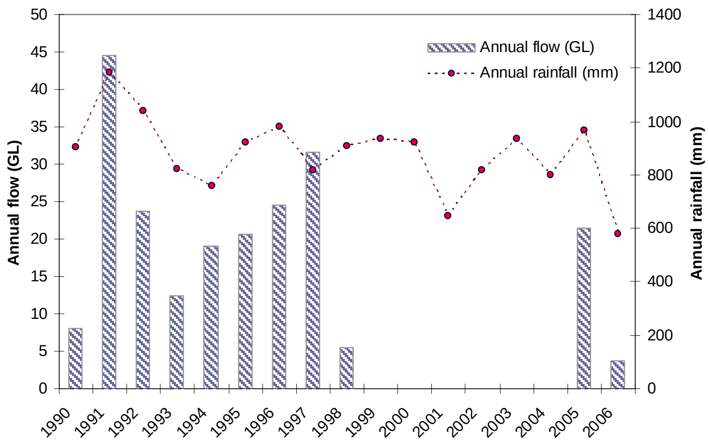


614063 (Nambeelup Brook, Keilman)

Year	Flow Count	Flow (GL)	Rainfall (mm)	*CR*
1990	224	8.1	905	-
1991	365	44.5	1185	32.5%
1992	366	23.6	1040	19.7%
1993	365	12.4	820	13.1%
1994	365	19.1	760	21.8%
1995	365	20.7	923	19.4%
1996	366	24.5	982	21.6%
1997	365	31.7	818	33.5%
1998	228	5.5	907	-
1999	-	-	933	-
2000	-	-	923	-
2001	-	-	648	-
2002	-	-	819	-
2003	-	-	936	-
2004	-	-	798	-
2005	285	21.4	969	-
2006	365	3.7	576	5.5%
2007	129	0.0	892	-
Average		24.7	880	20.9%
Catchment area (sqkm)		*115.5*		

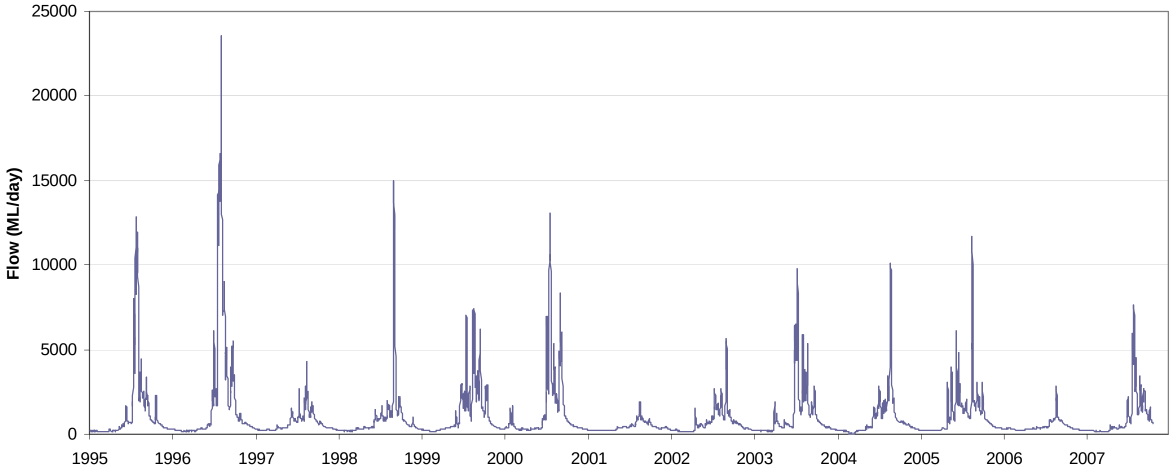


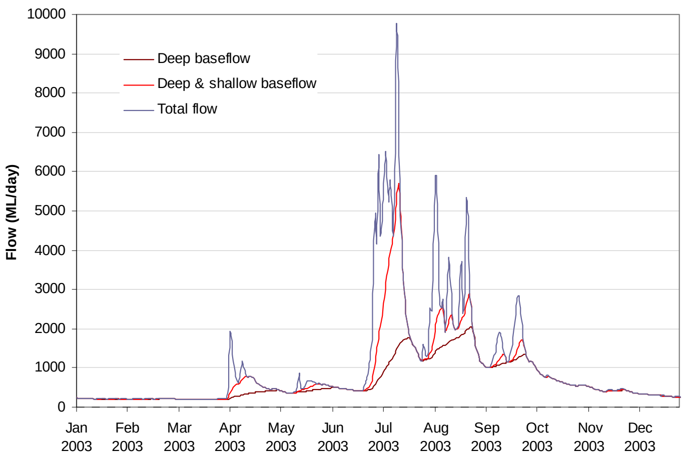


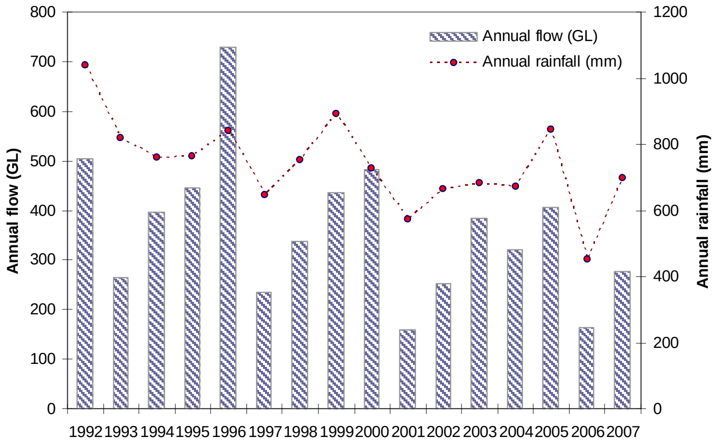


614065 (Murray River, Pinjarrra)

Year	Flow Count	Flow (GL)	Rainfall (mm)	*CR*
1992	193	504.5	1040	-
1993	261	264.6	820	-
1994	365	396.7	760	7.4%
1995	365	444.4	765	8.2%
1996	366	727.9	840	12.3%
1997	365	235.6	645	5.2%
1998	365	336.5	752	6.4%
1999	365	436.0	890	7.0%
2000	366	481.0	725	9.4%
2001	365	158.0	571	3.9%
2002	365	251.9	663	5.4%
2003	365	384.5	682	8.0%
2004	366	321.0	671	6.8%
2005	365	406.4	844	6.8%
2006	365	163.8	452	5.1%
2007	297	276.0	699	-
Average		364.9	739	7.1%
Catchment area (sqkm)		*7044.3*		

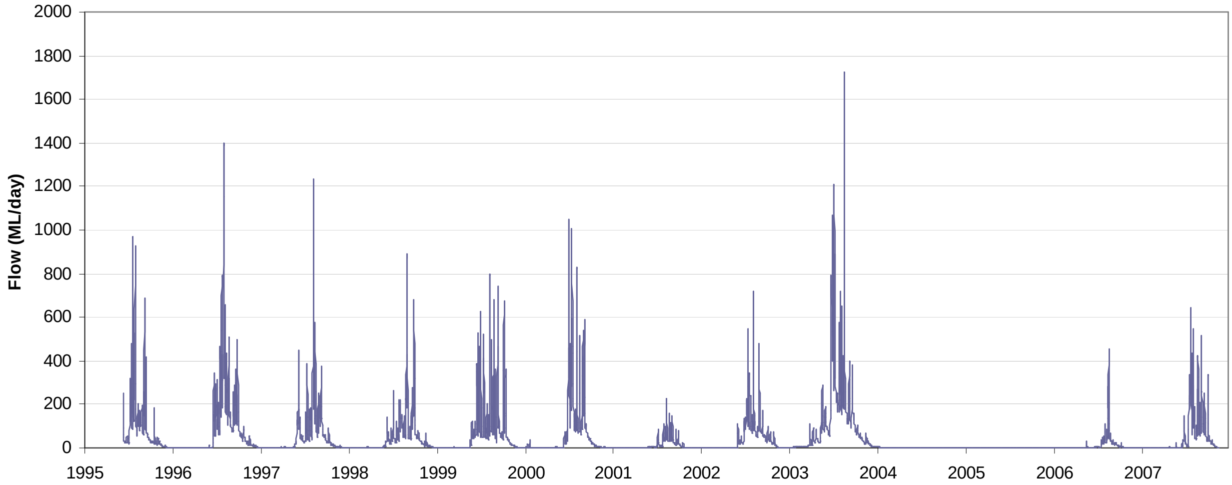


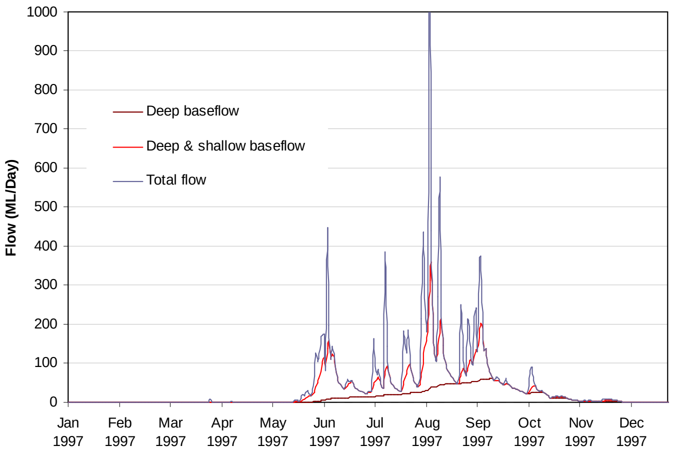


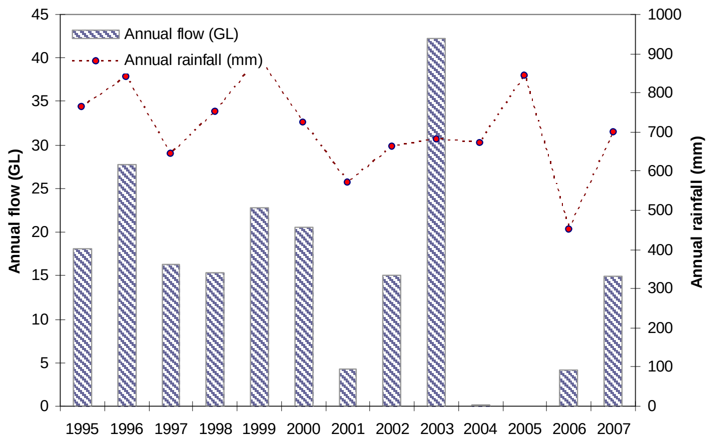


614094 (Punrack Drain, Yangedi Swamp)

Year	Flow Count	Flow (GL)	Rainfall (mm)	*CR*
1995	206	18.1	765	-
1996	366	27.8	840	26.9%
1997	365	16.3	645	20.5%
1998	365	15.3	752	16.6%
1999	365	22.7	890	20.8%
2000	366	20.6	725	23.1%
2001	365	4.3	571	6.1%
2002	365	15.0	663	18.4%
2003	365	42.2	682	50.4%
2004	96	0.1	671	-
2005			844	-
2006	282	4.2	452	-
2007	325	15.0	699	17.4%
Average		19.9	708	22.3%
Catchment area (sqkm)		*122.9*		







Appendix B — Hydraulic cross-sections for major waterways

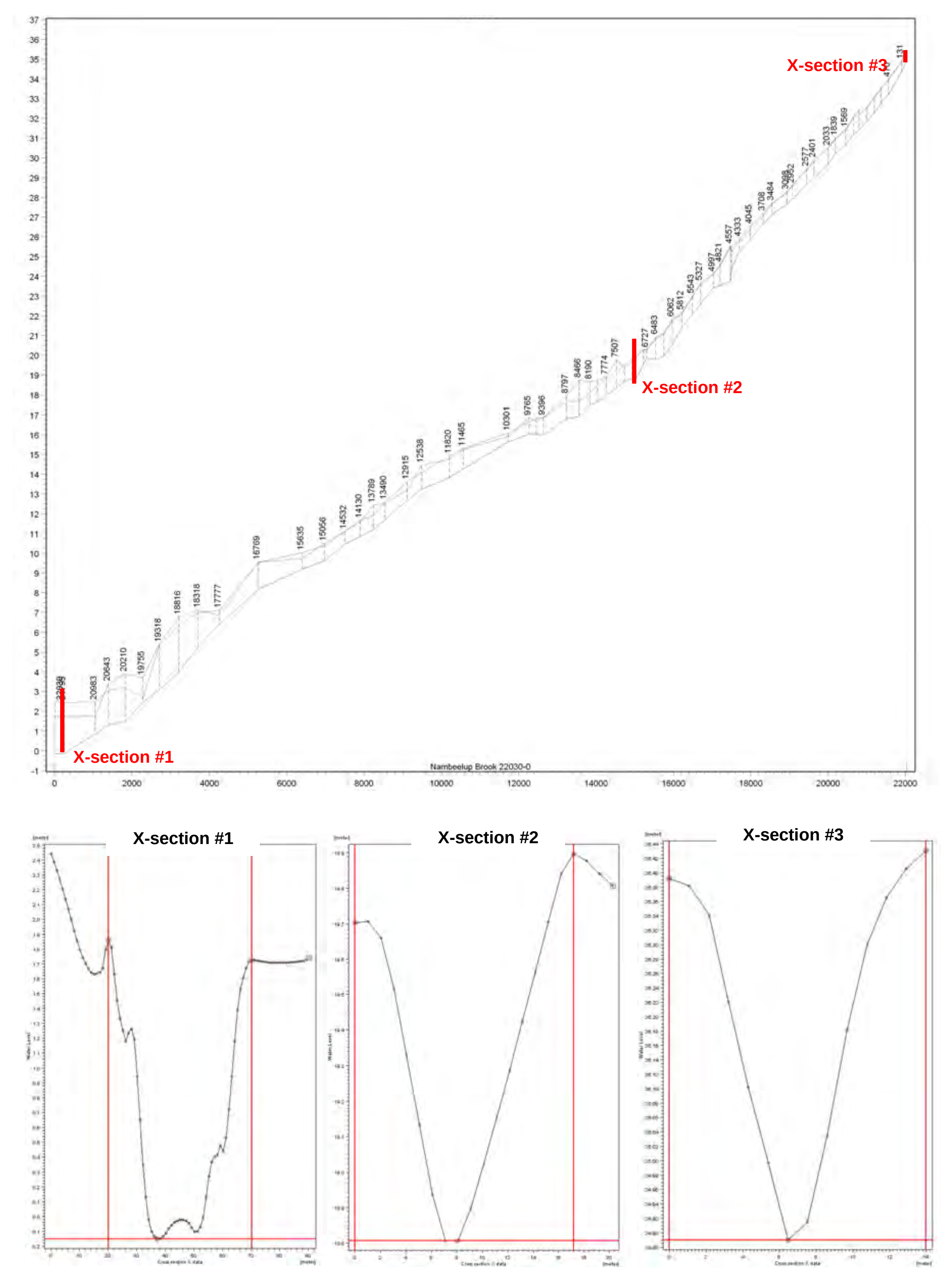


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Figure B-1: *Nambeelup Brook*

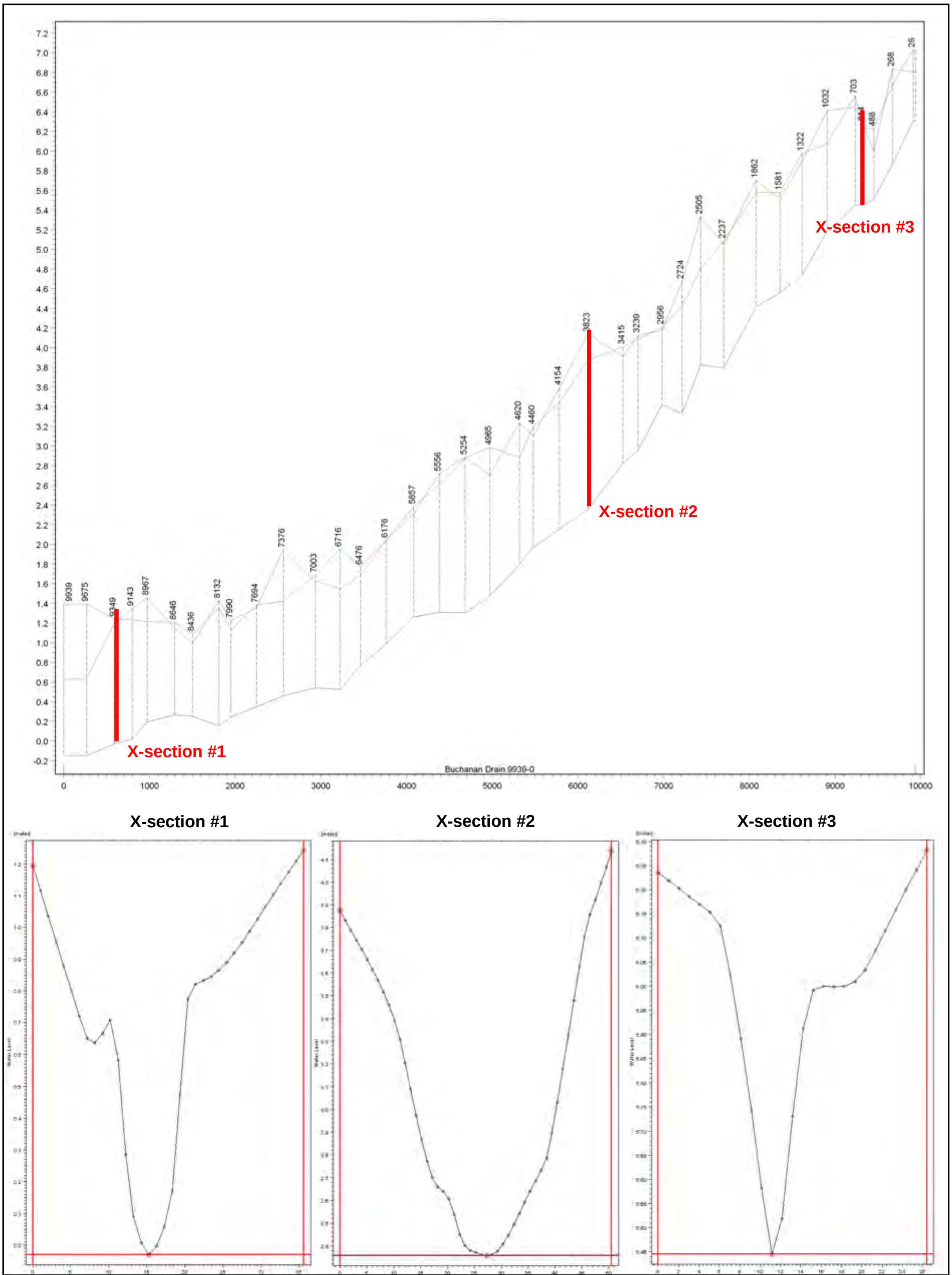

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Figure B-2: *Buchanans Drain*

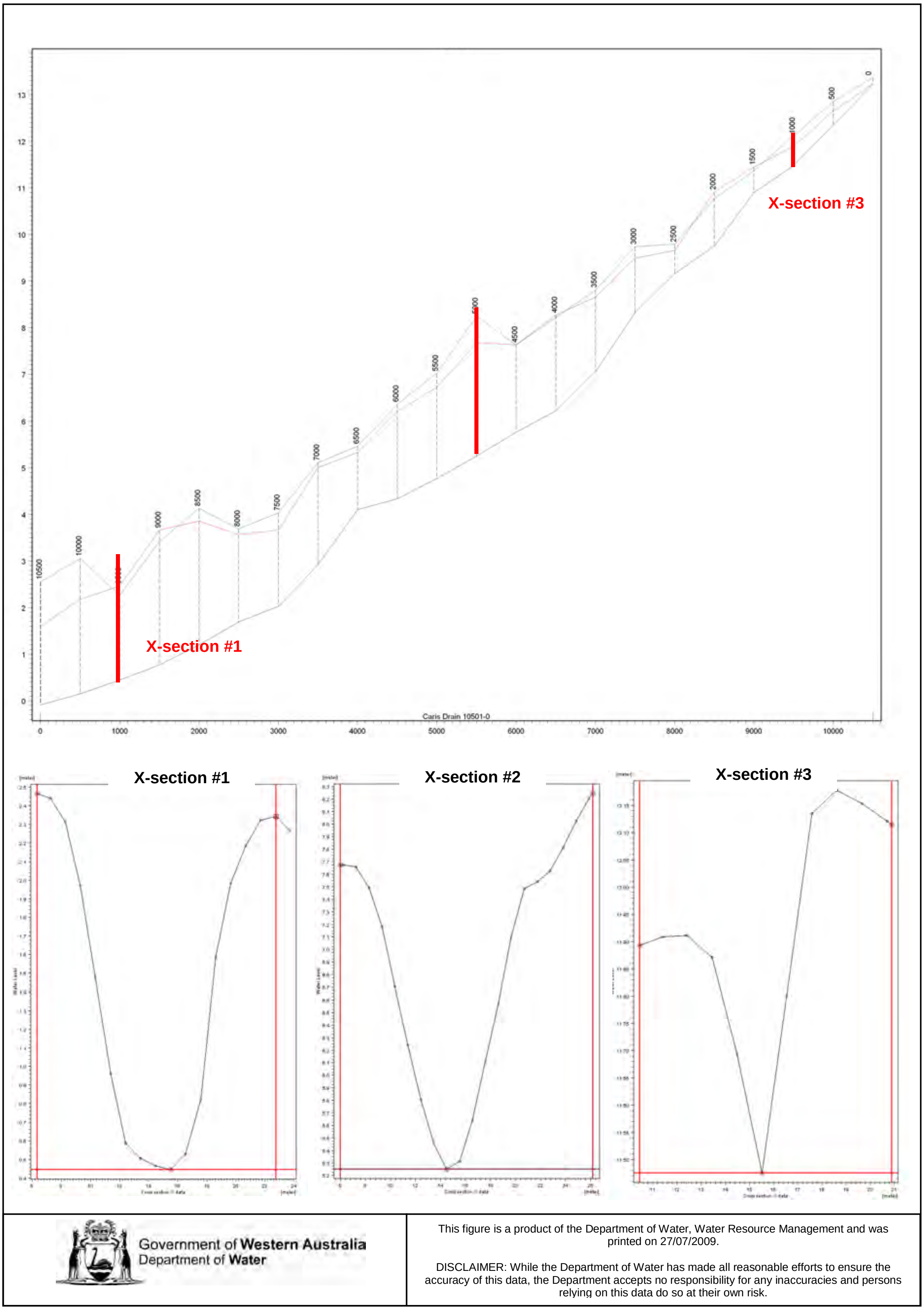

Figure B-3: *Caris Drain*

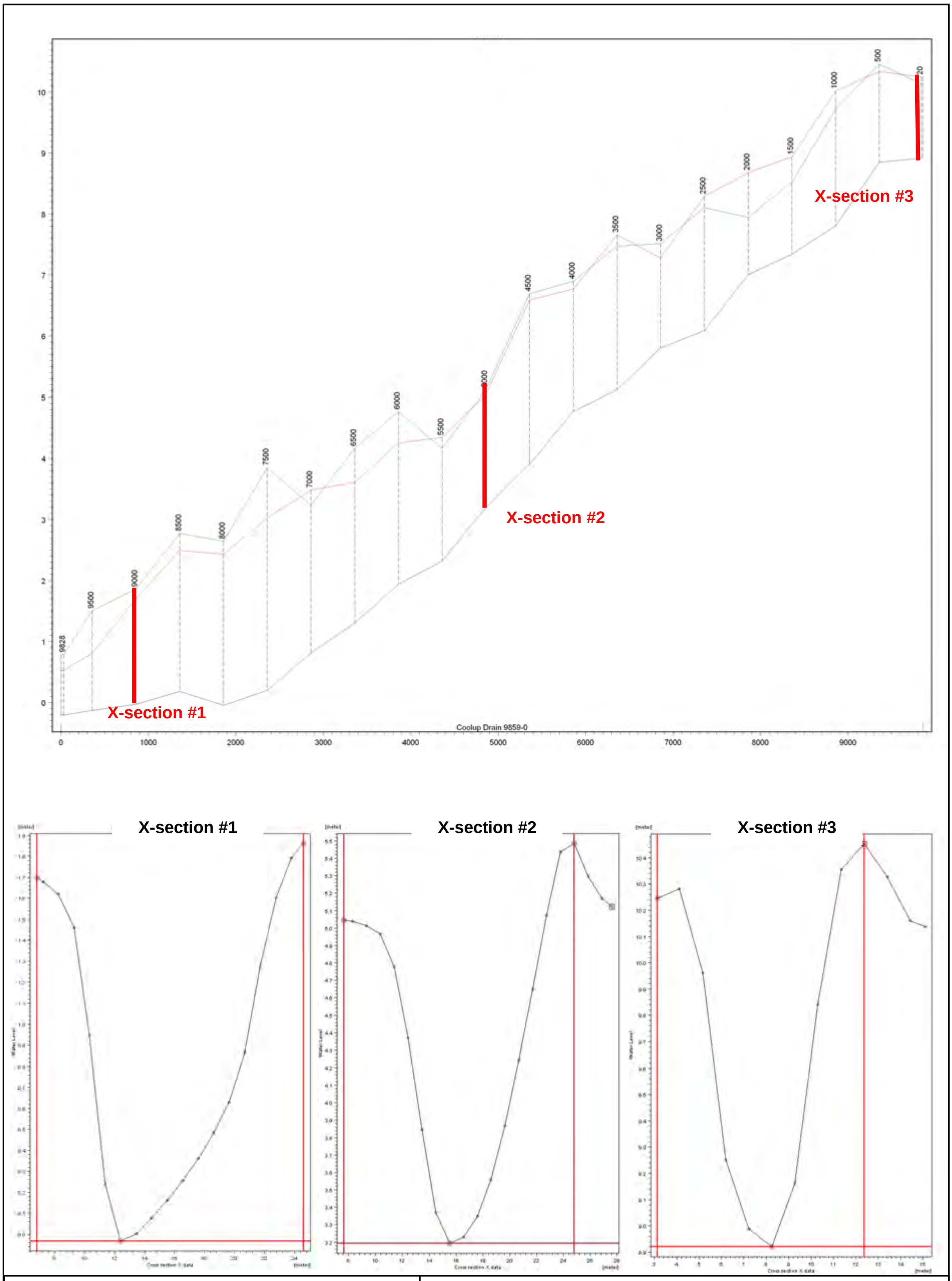

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Figure B-4: *Coolup Drain*

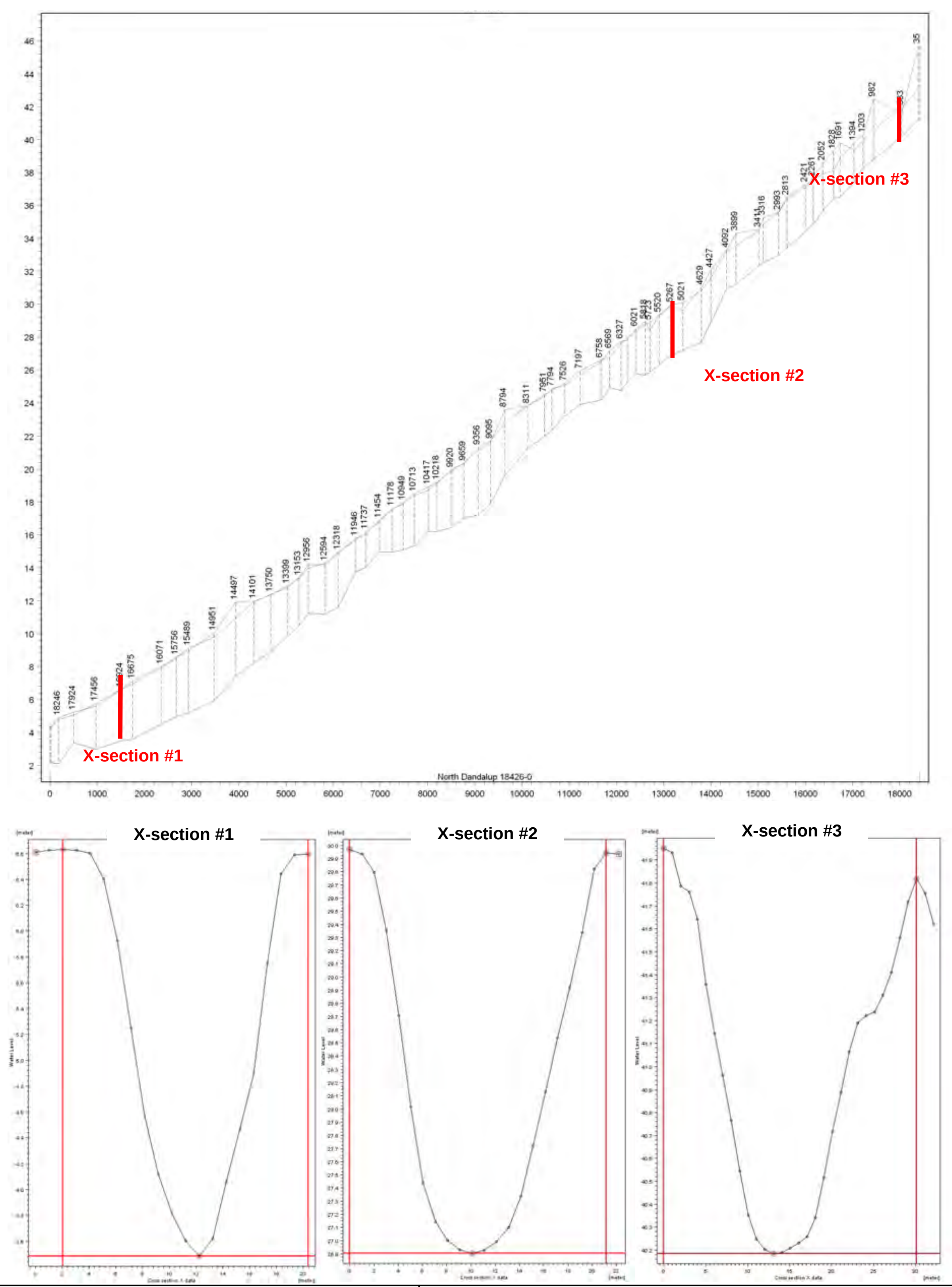

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***Figure B-5:** North Dandalup River*

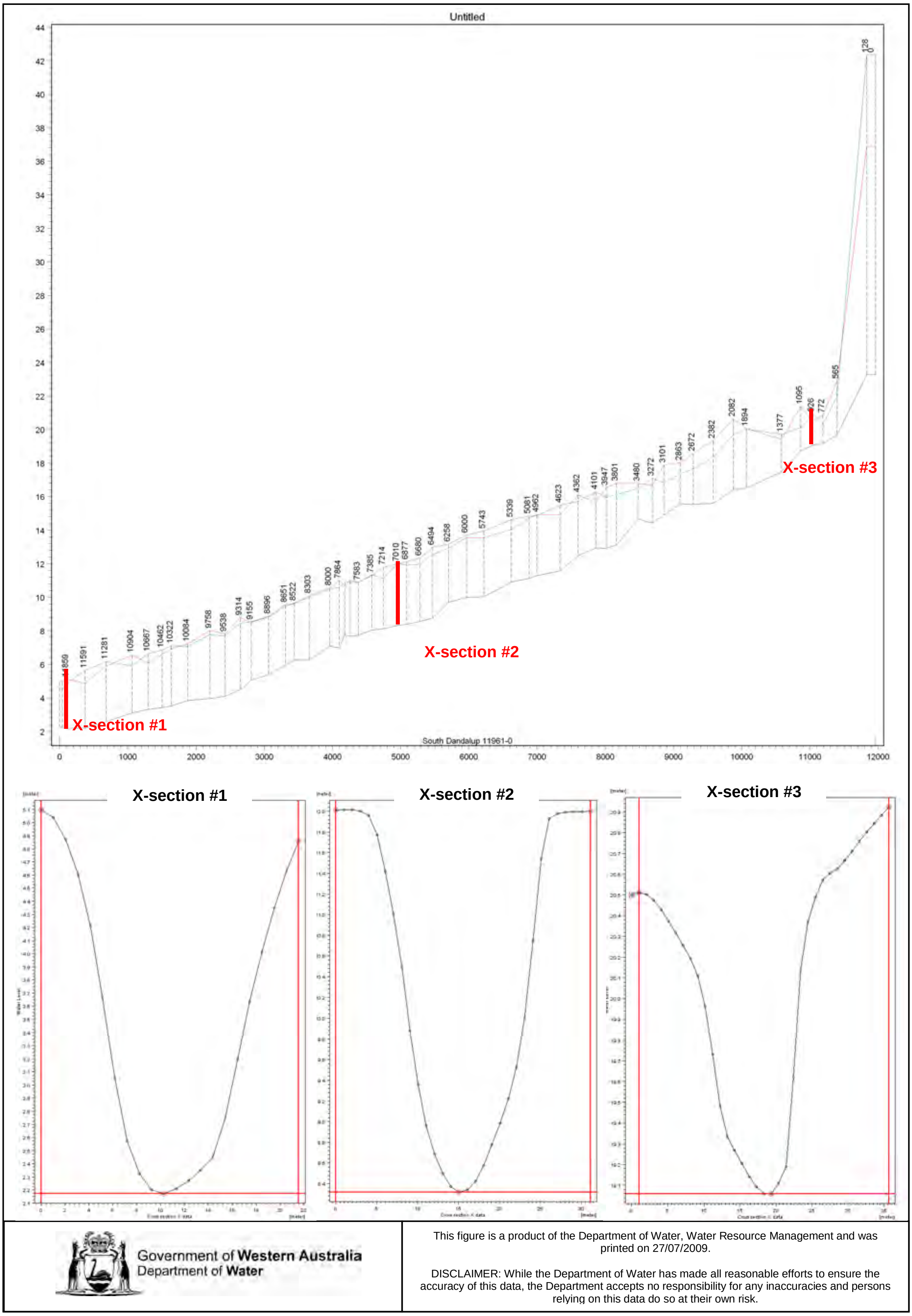

Figure B-6: *South Dandalup River*

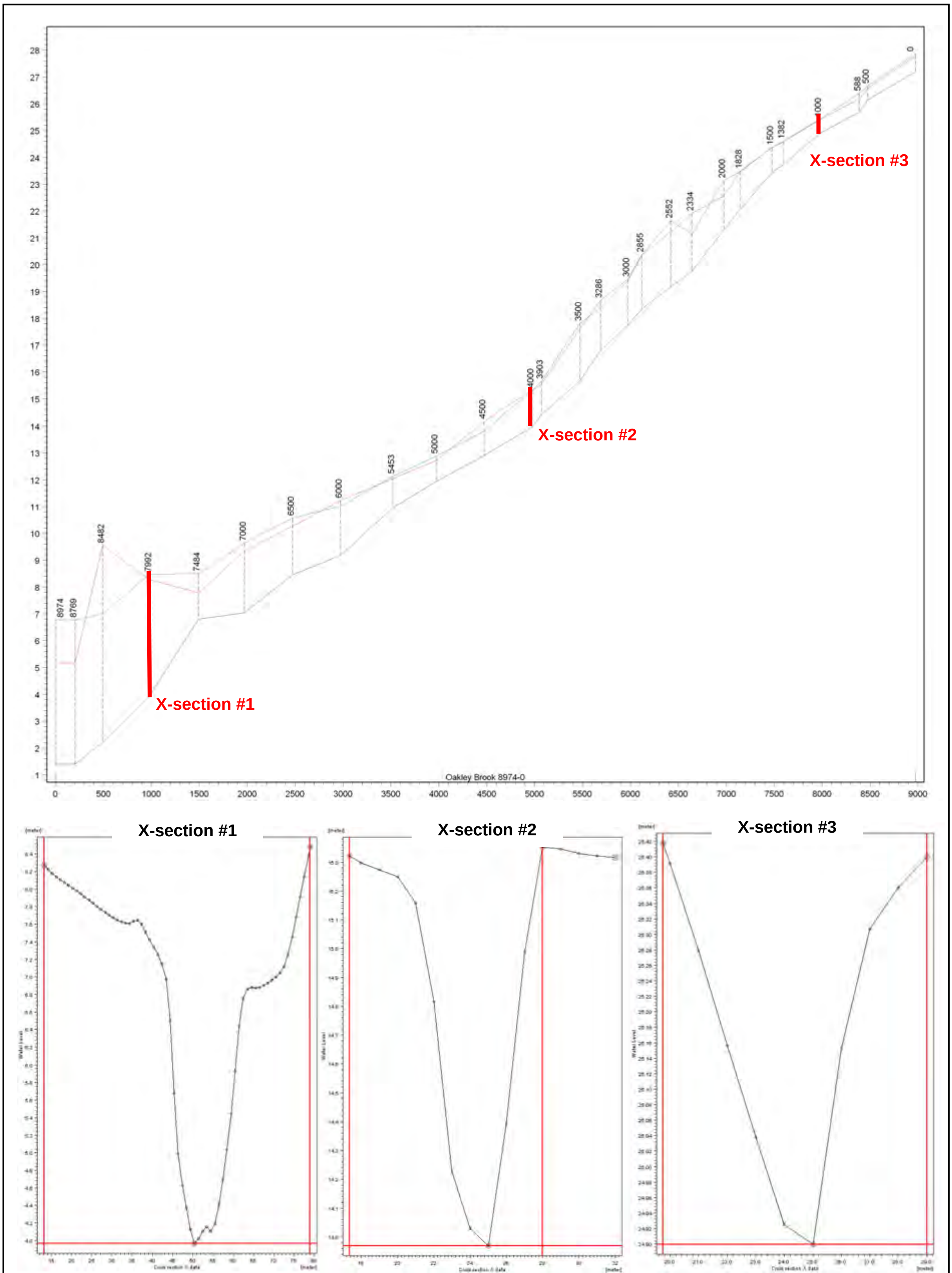

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Figure B-7: *Oakley Brook*

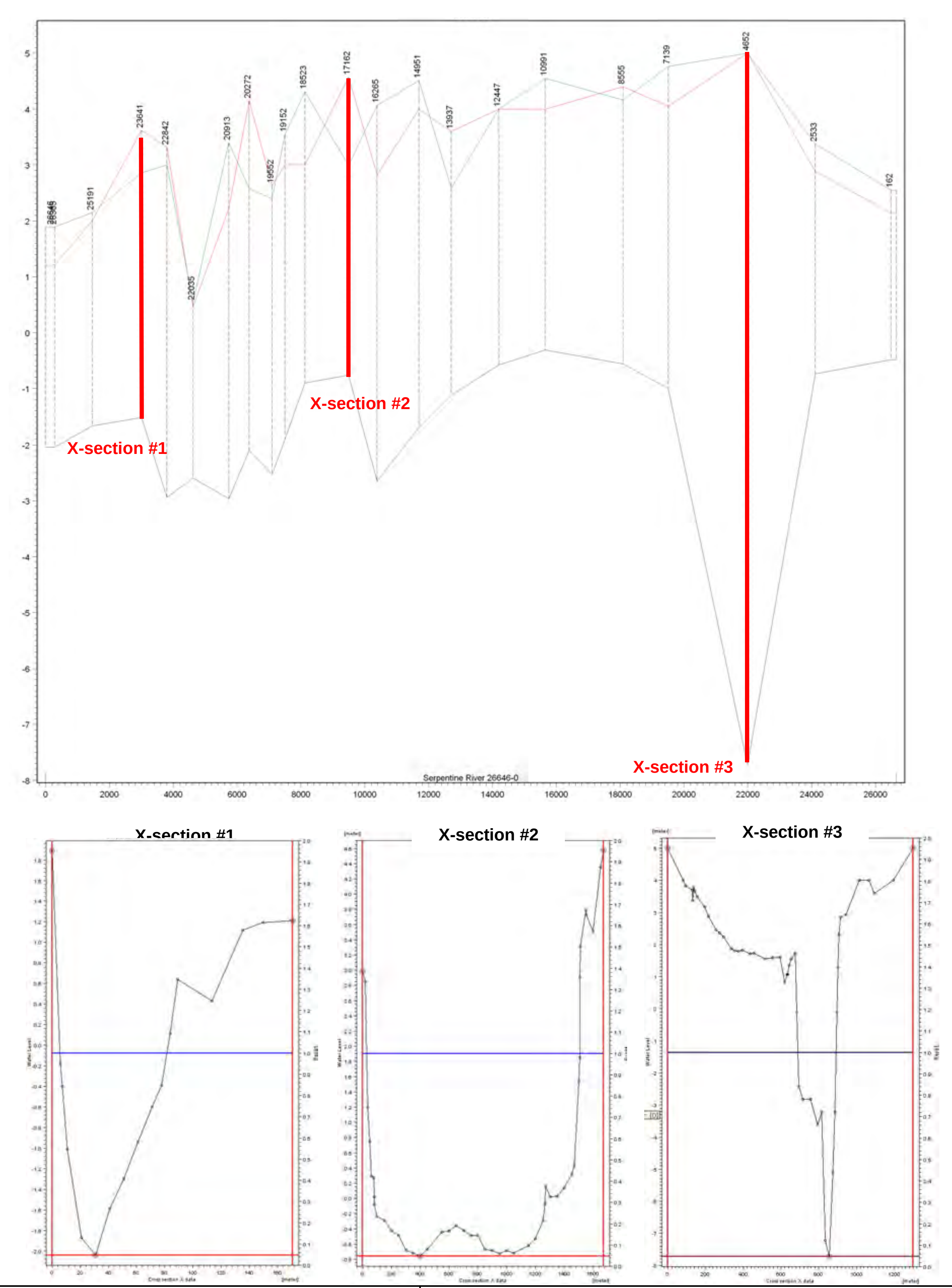

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Figure B-8: *Serpentine River*

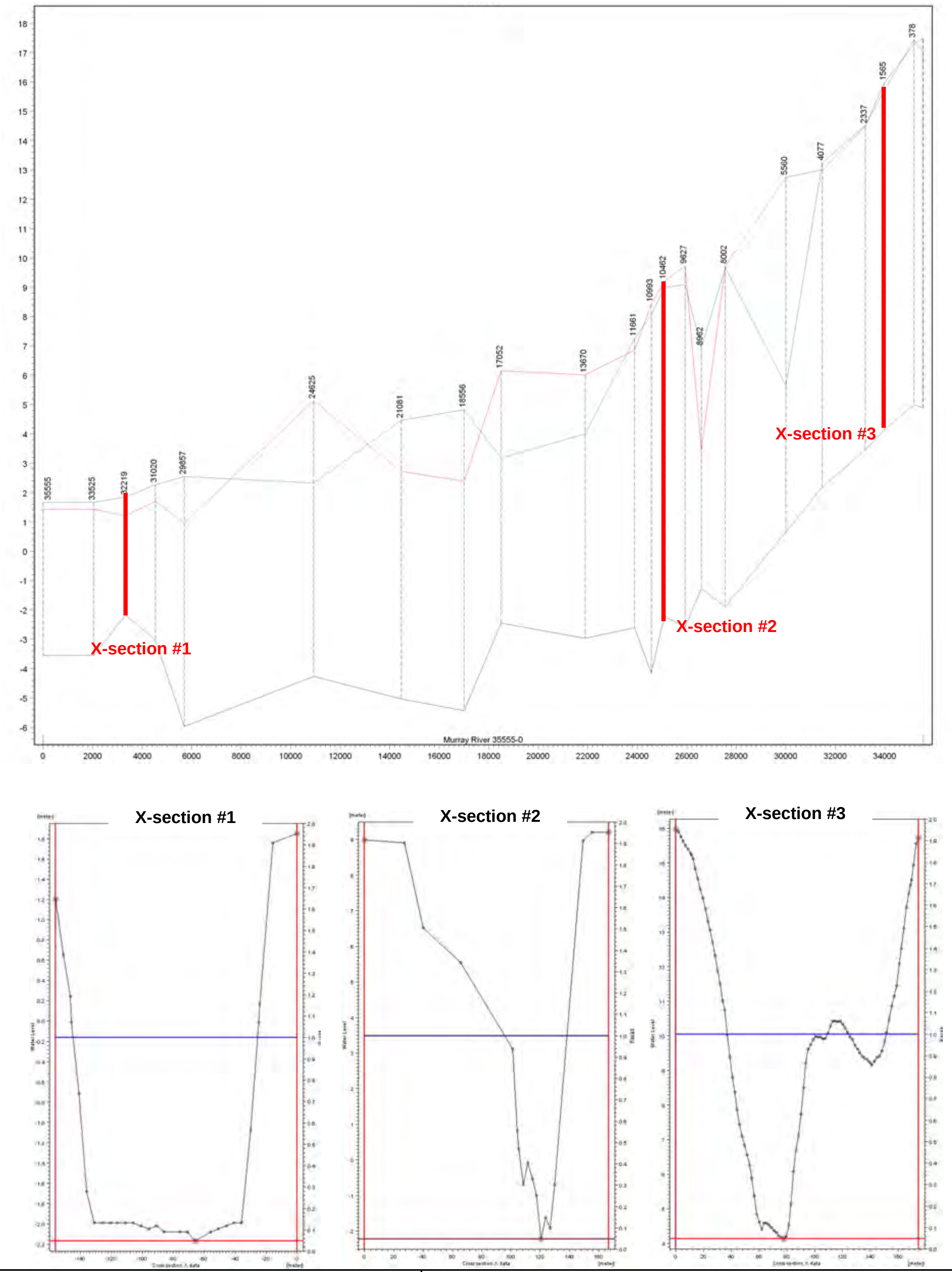

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Figure B-9: *Murray River*

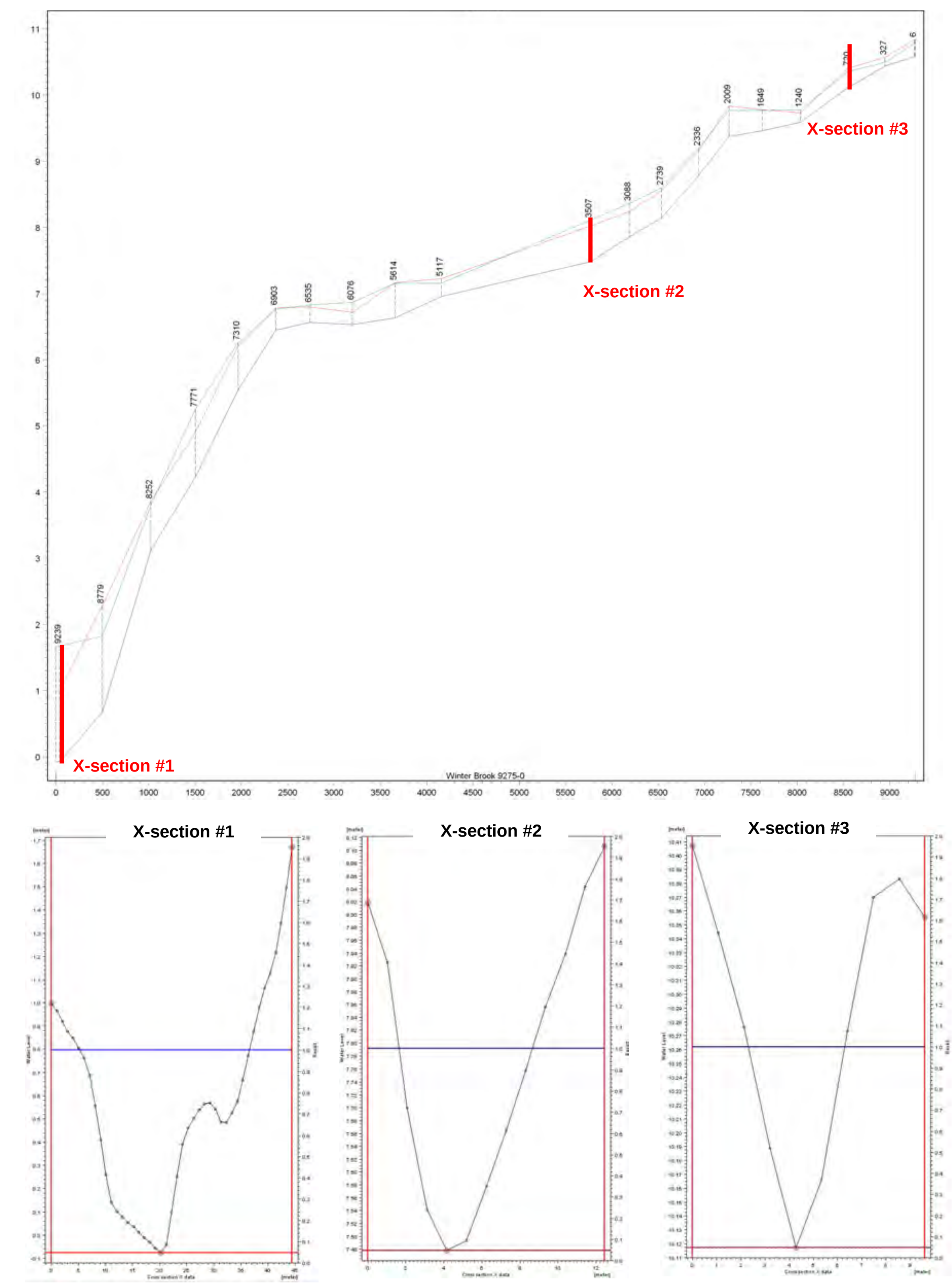

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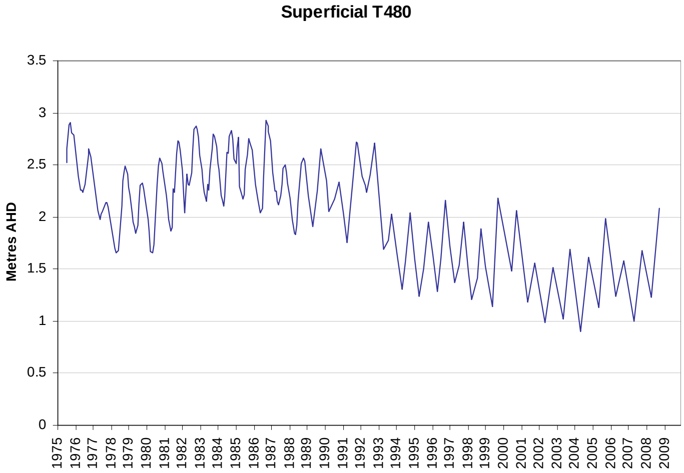
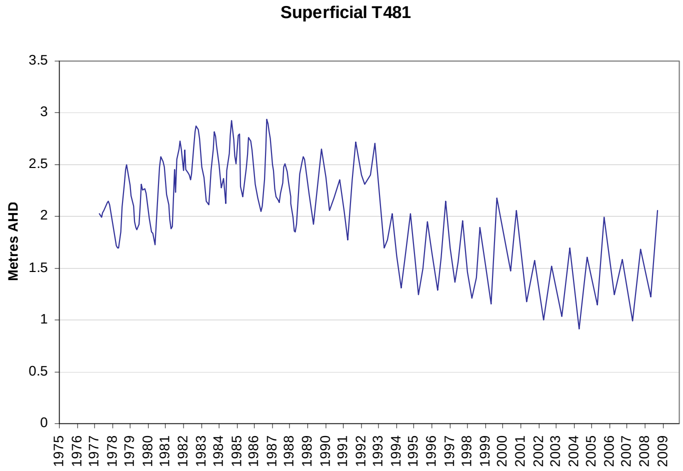
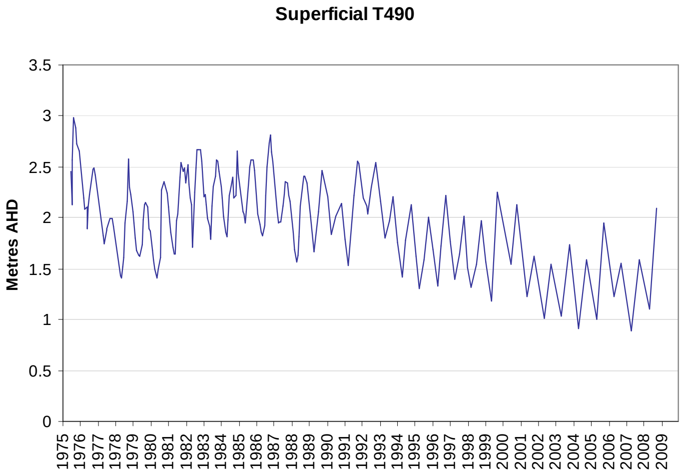
Figure B-10: *Winter Brook*

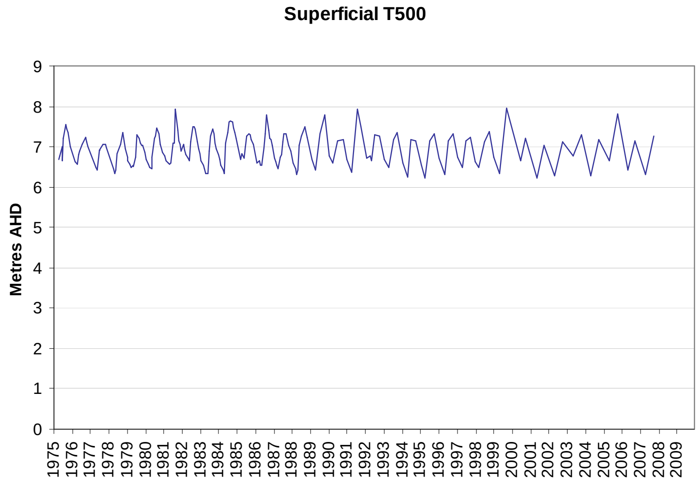
Appendix C — Time series for monitoring bores: Superficial aquifer

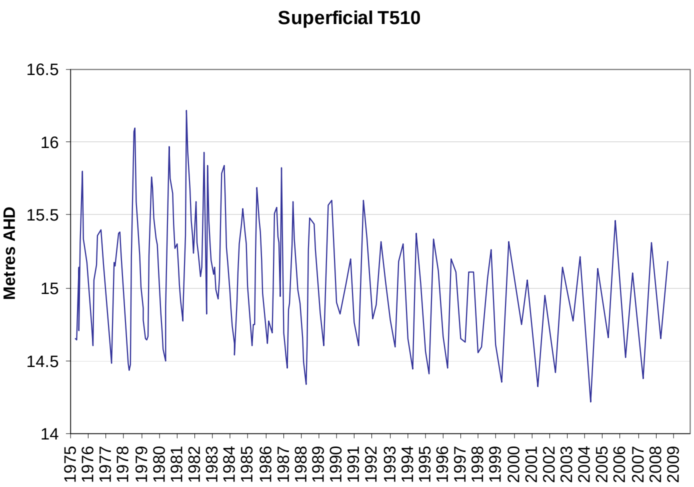
T-series monitoring bores

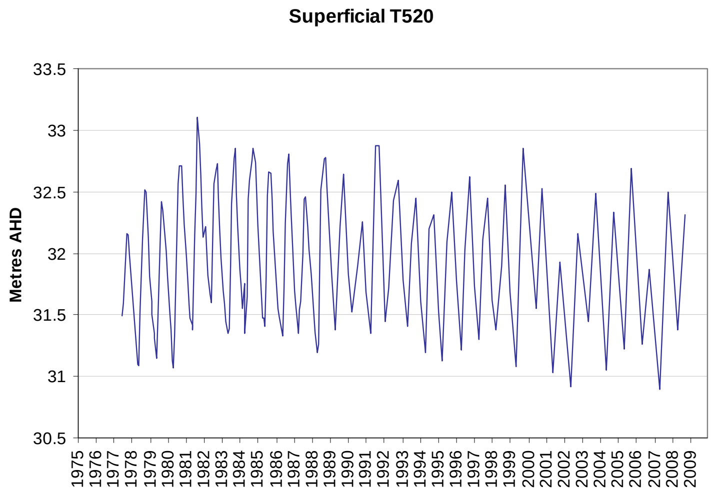






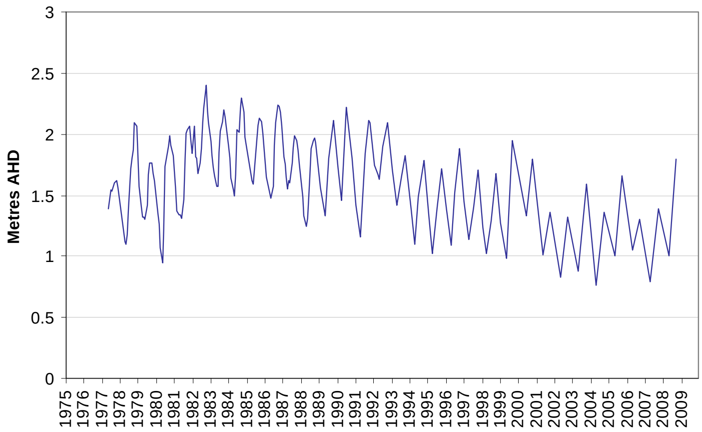






T-series monitoring bores (continued…)

Superficial T530



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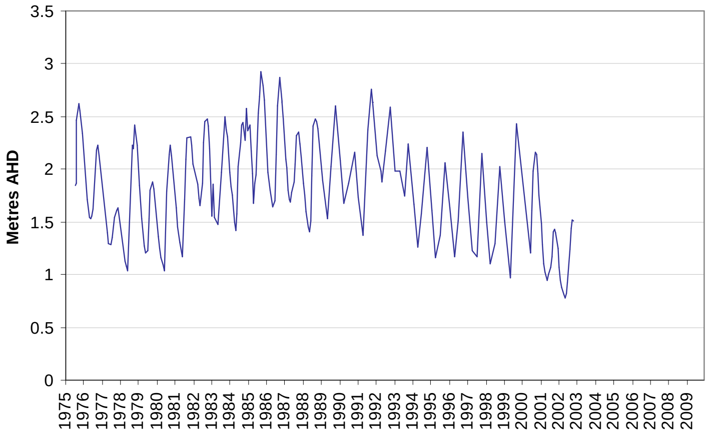

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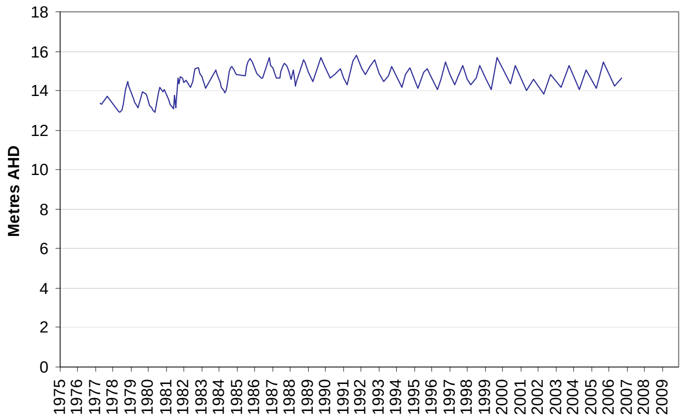

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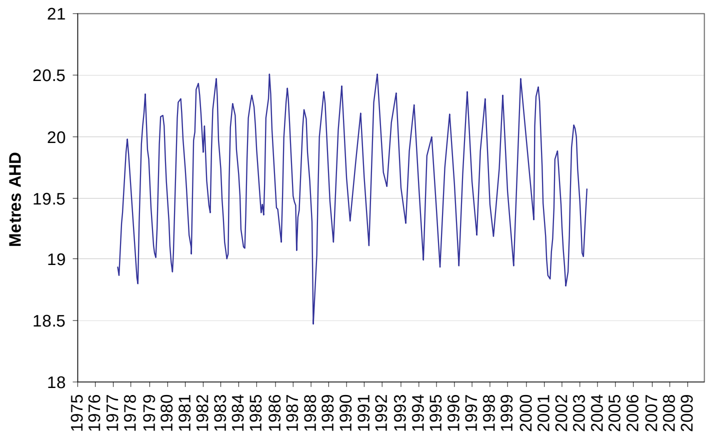

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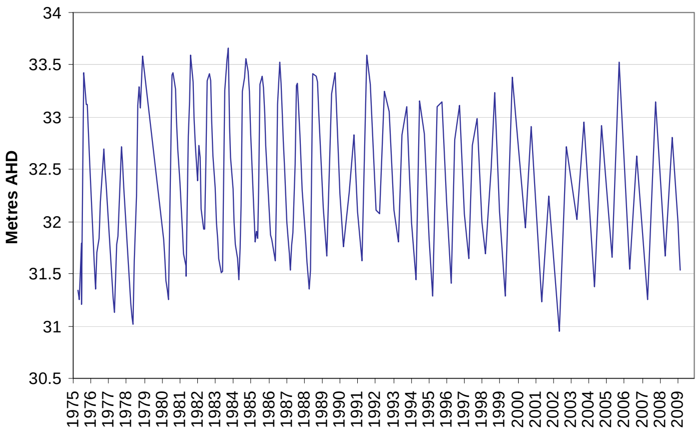

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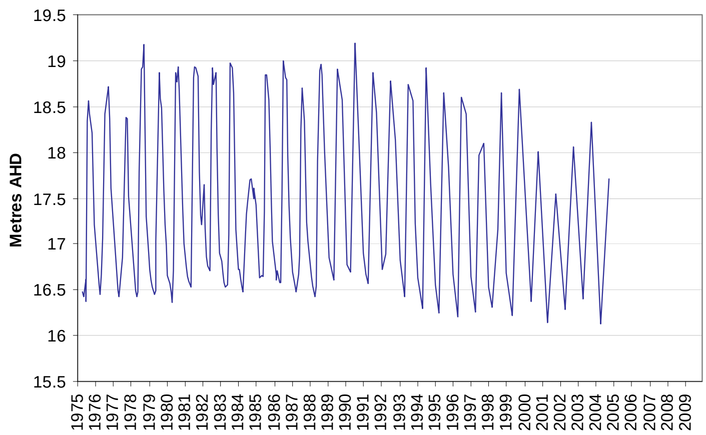
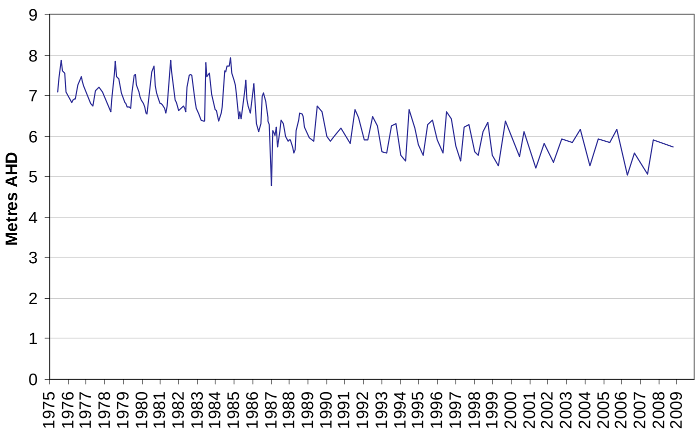


T-series monitoring bores (continued…)

Superficial T590



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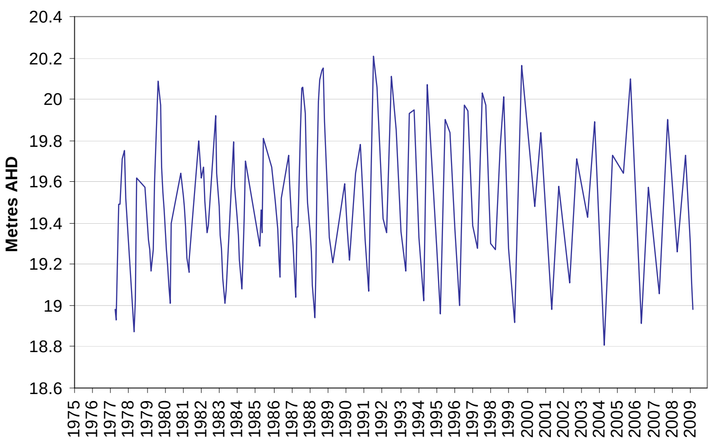

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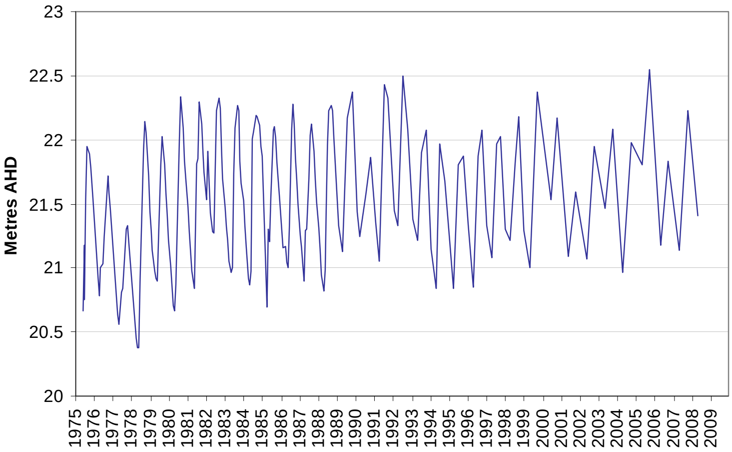

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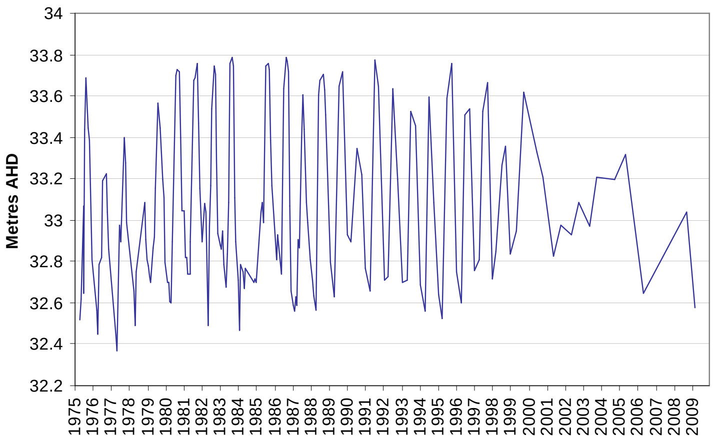

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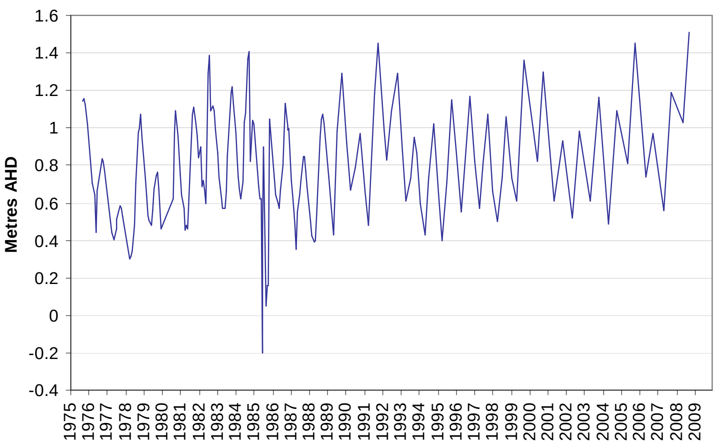

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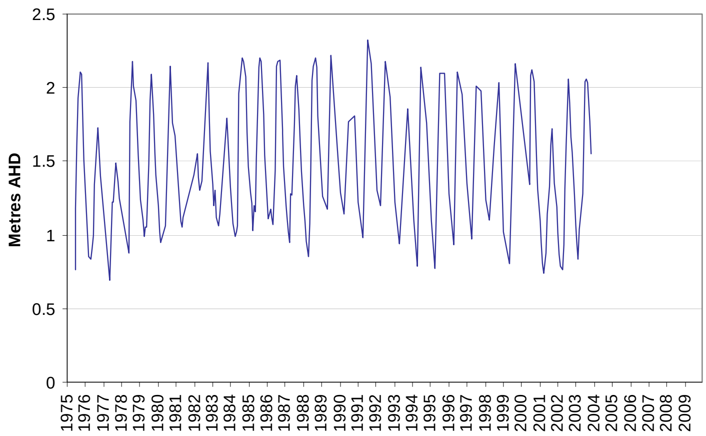
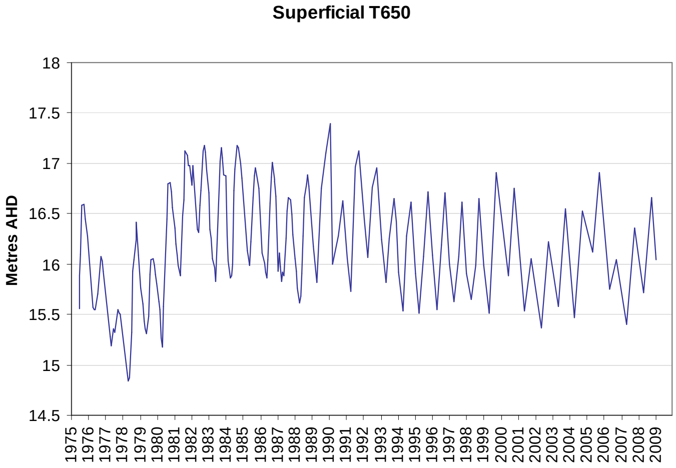
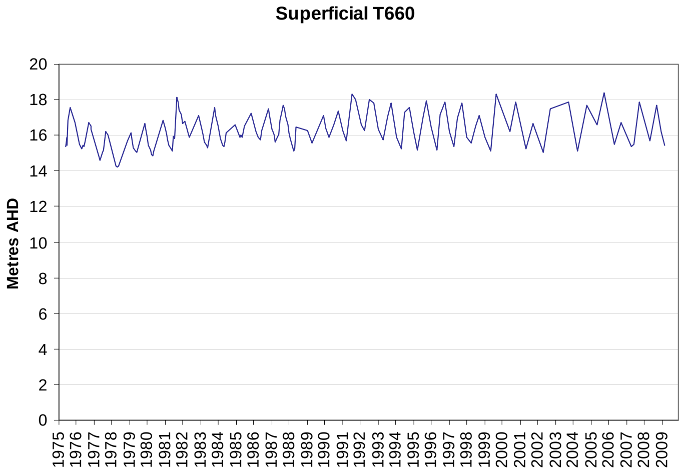
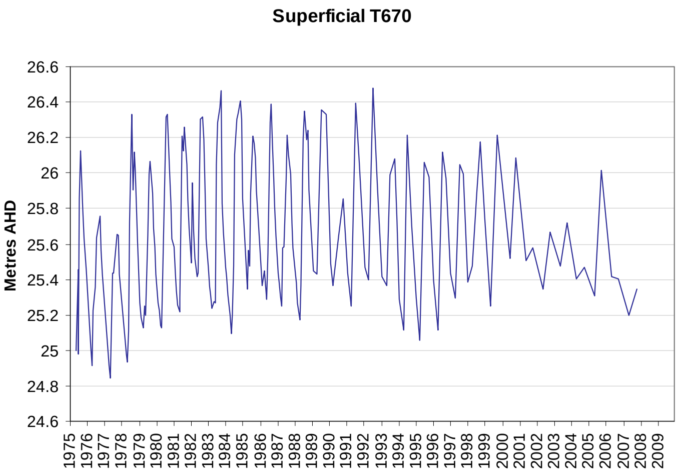


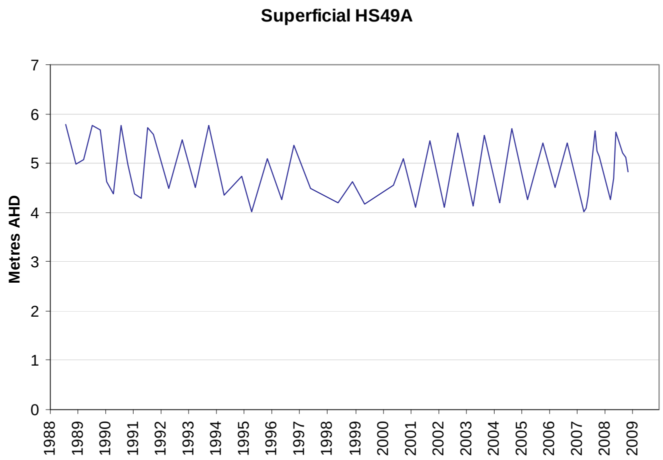
T-series monitoring bores (continued…)

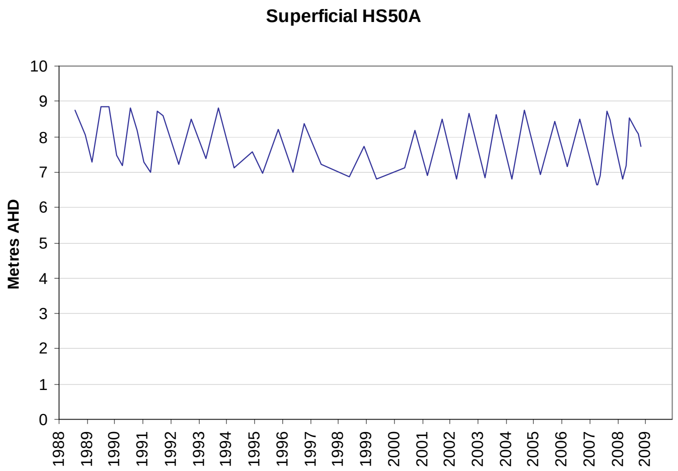


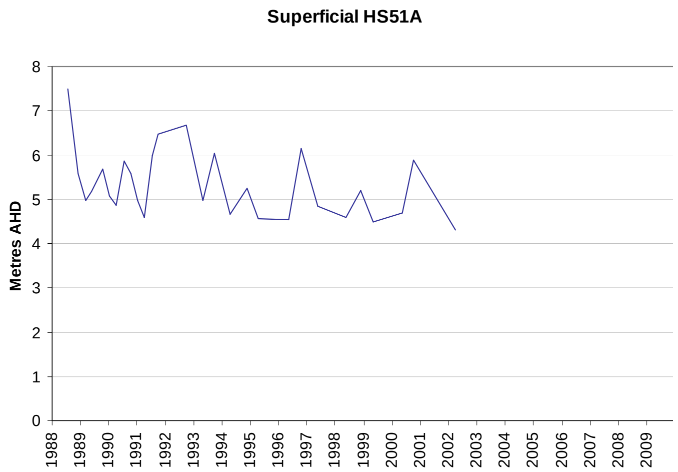


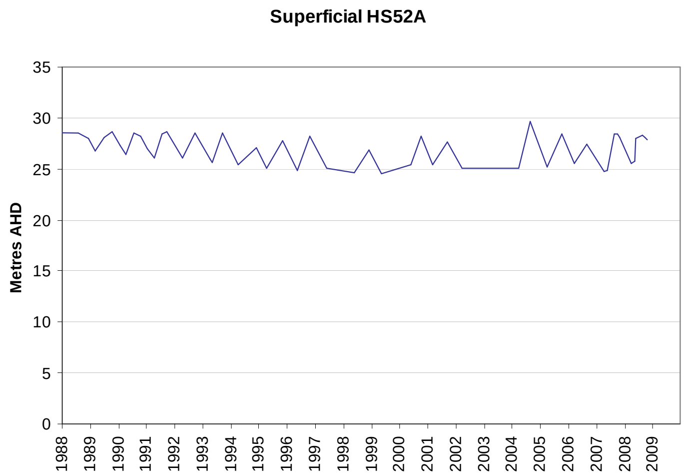


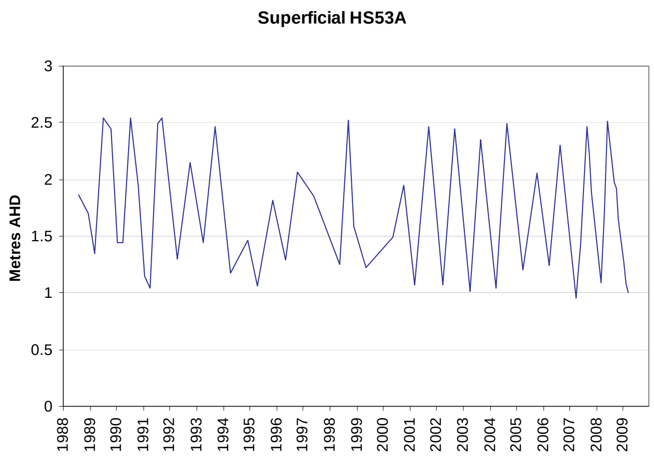
Harvey shallow (HS) series monitoring bores

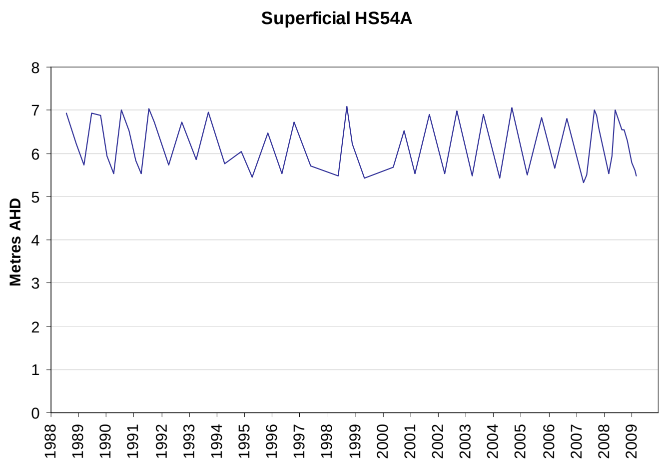






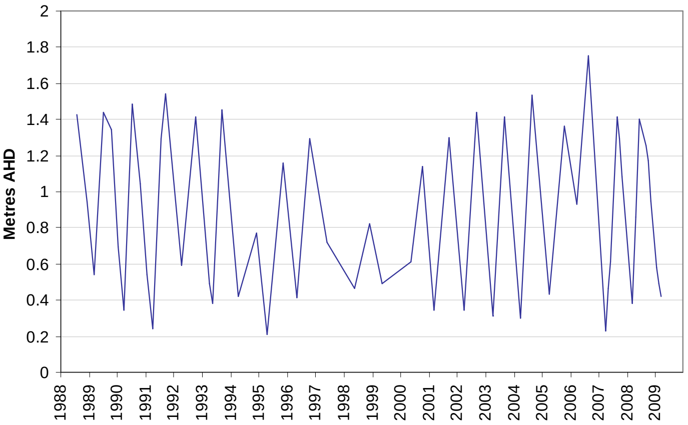






Harvey shallow (HS) series monitoring bores (continued…)

Superficial HS55A



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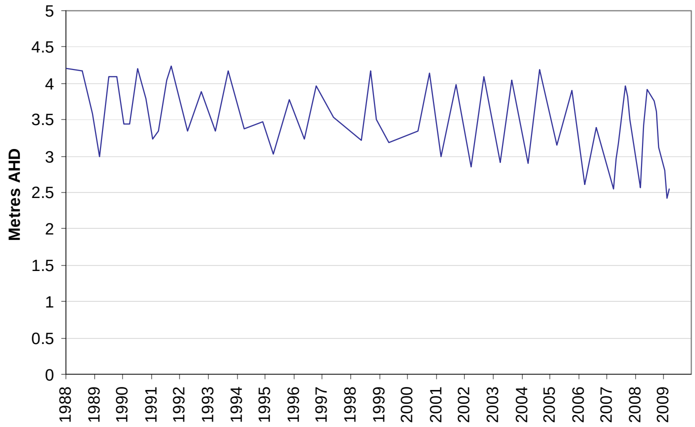

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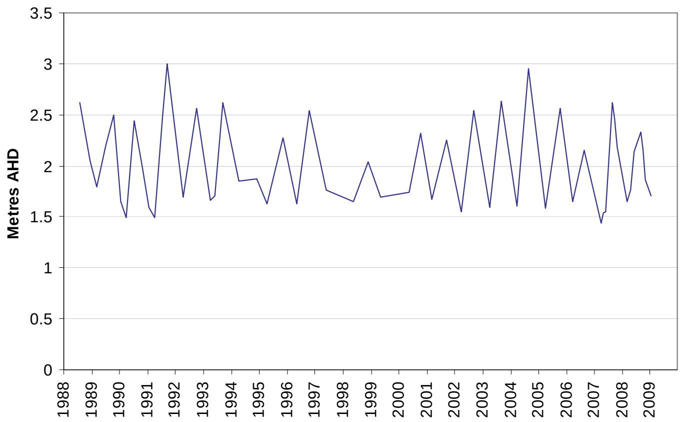

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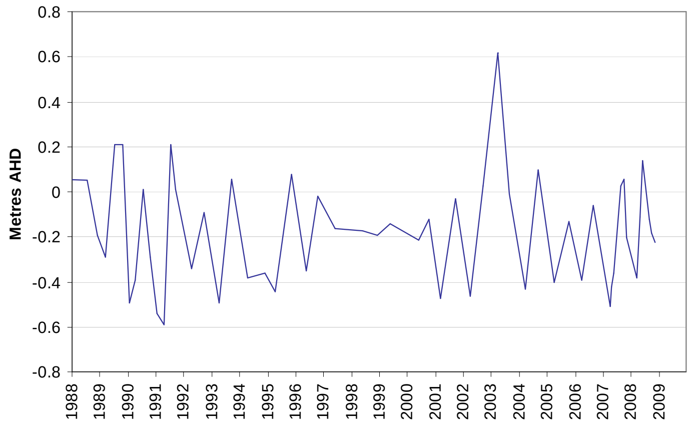
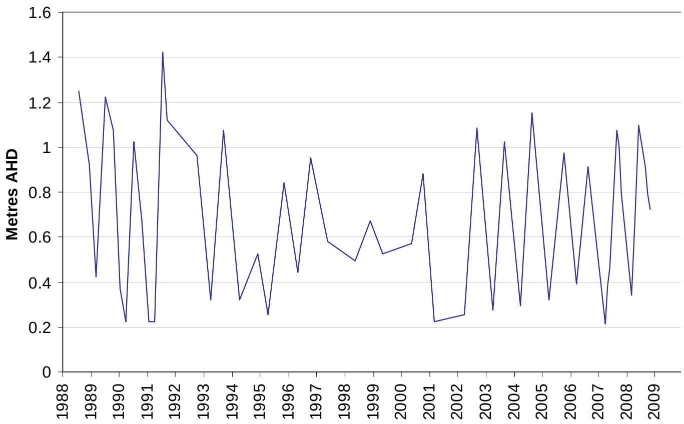
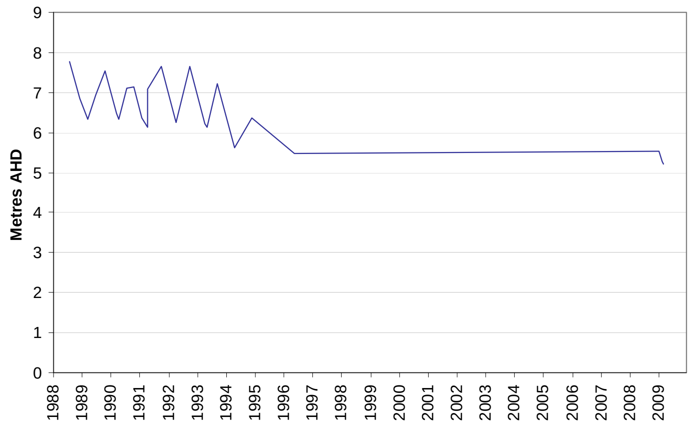


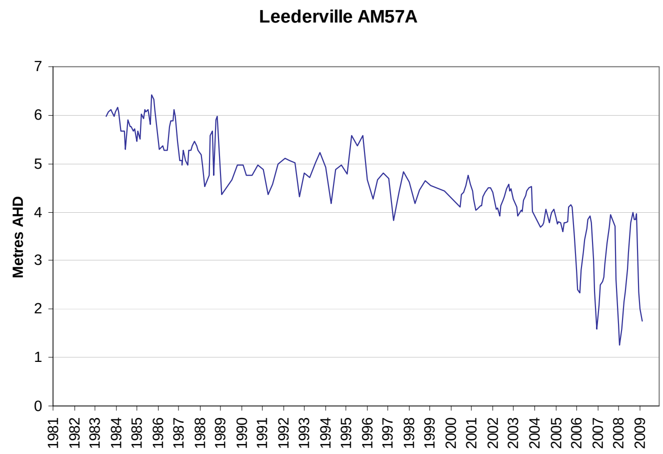
Superficial HS59



Superficial HS60A



Appendix D — Time series for monitoring bores: Leederville Aquifer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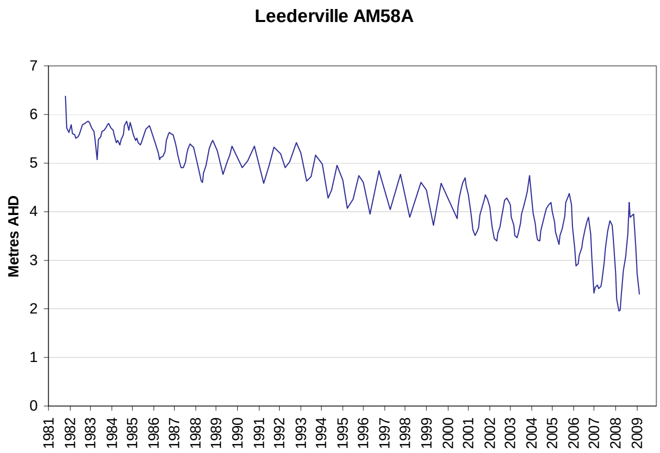
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009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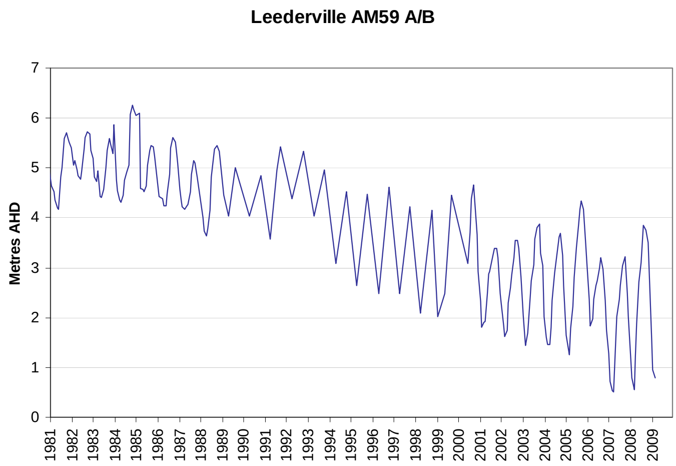
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009


Leederville AM59 A/B
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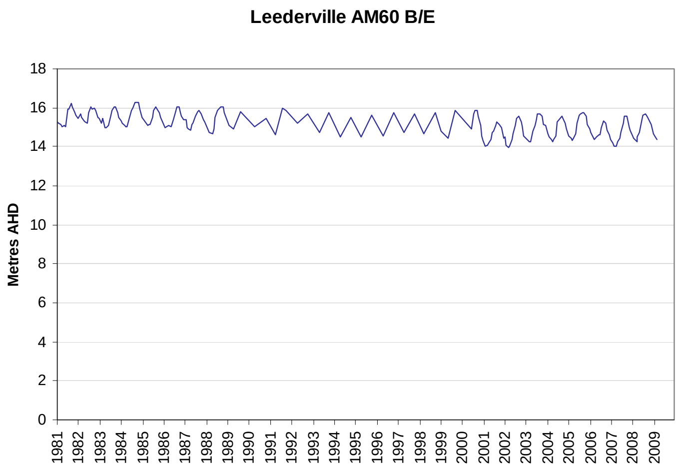
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009


Leederville AM60 B/E
Metres AHD
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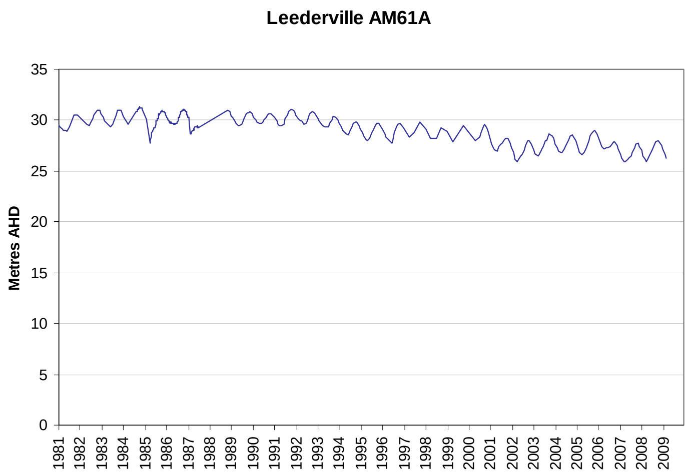
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009


Leederville AM61A
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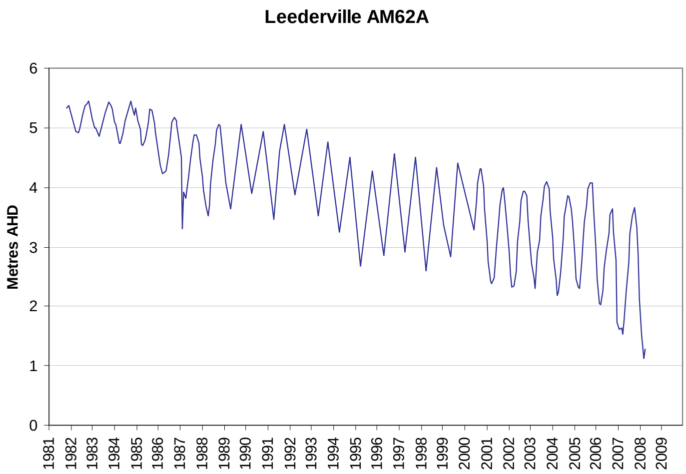
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009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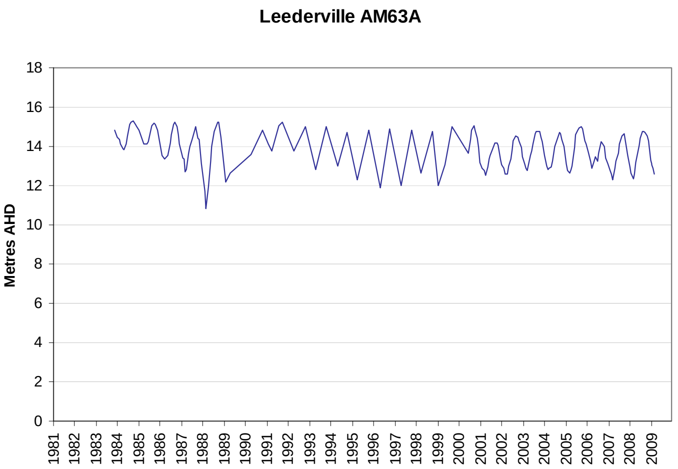
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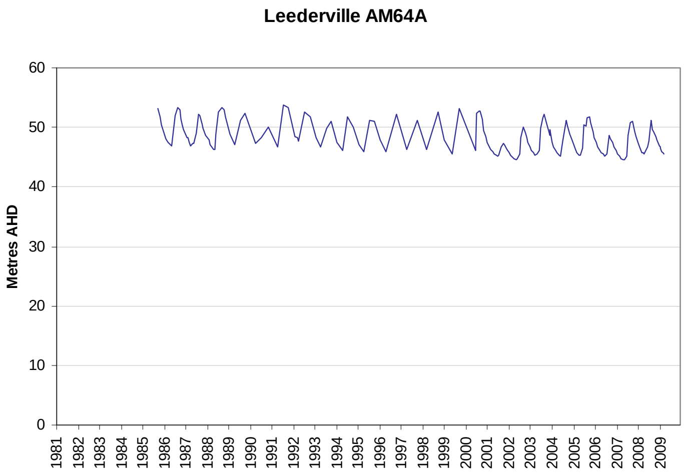
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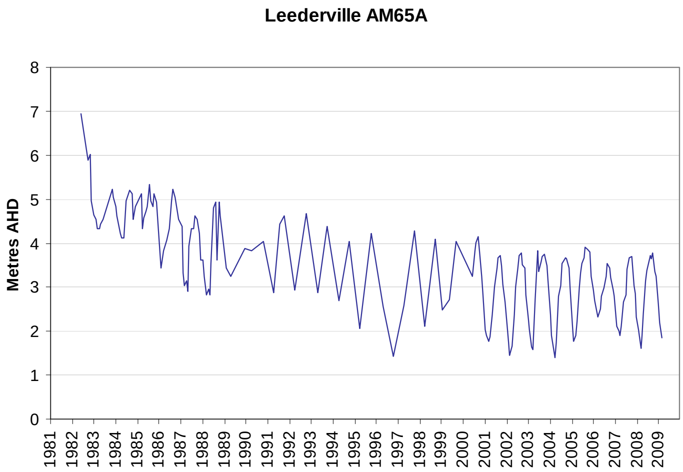
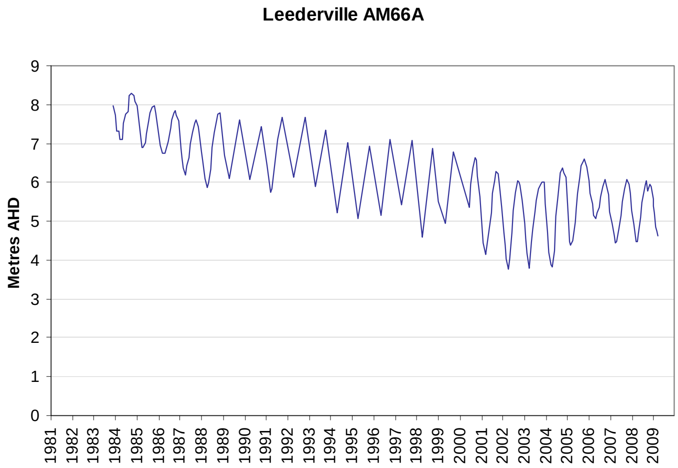
Metres AHD


Leederville AM65A
Metres AHD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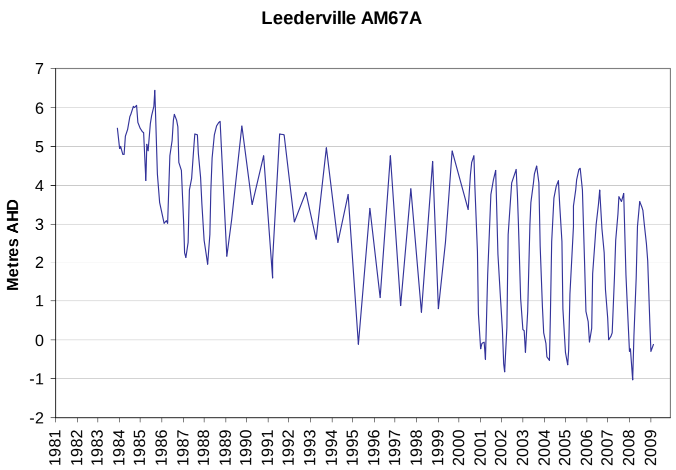
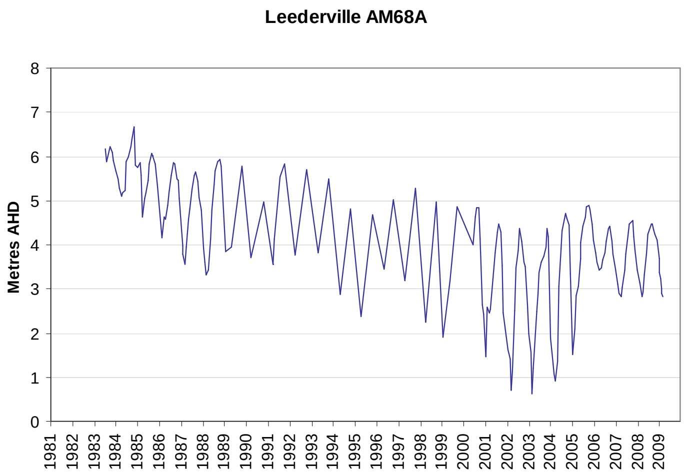
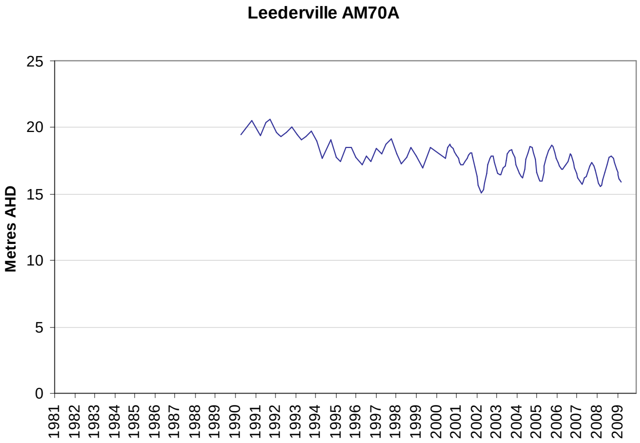
Metres AHD


Leederville AM67A
Metres AHD


Leederville AM68A
Metres AHD


Leederville AM70A
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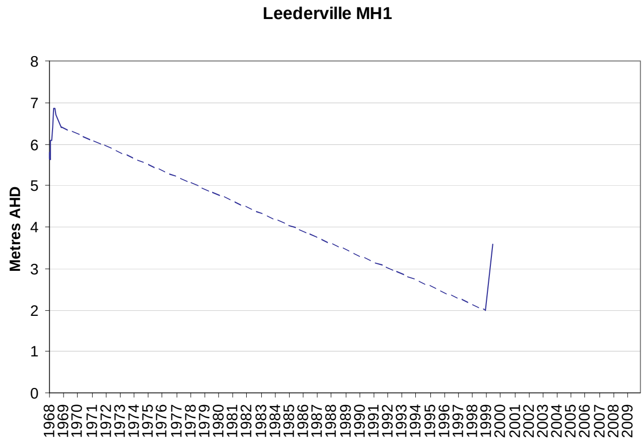
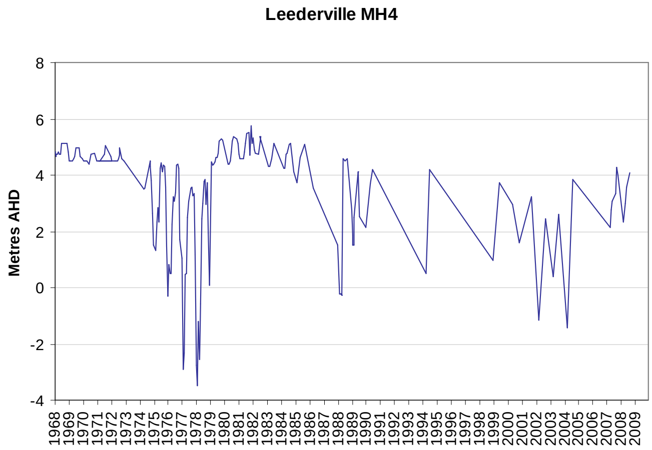
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009


Leederville MH1
Metres AHD
0 1 2 3 4 5 6 7 8
1968 1969 1970 1971 1972 1973 1974 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


Leederville MH4
Metres AHD
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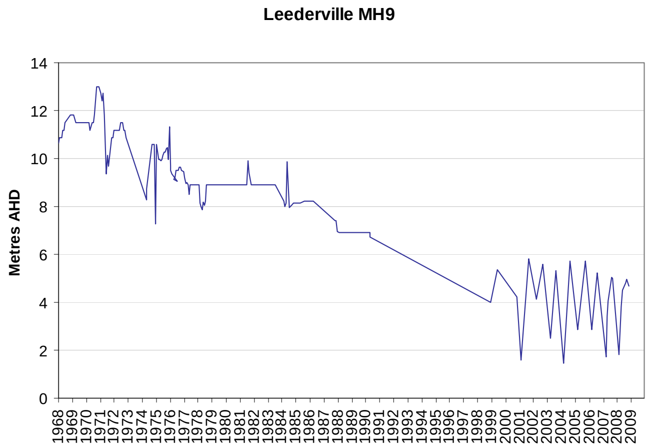
1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009


Leederville MH9
Metres AHD
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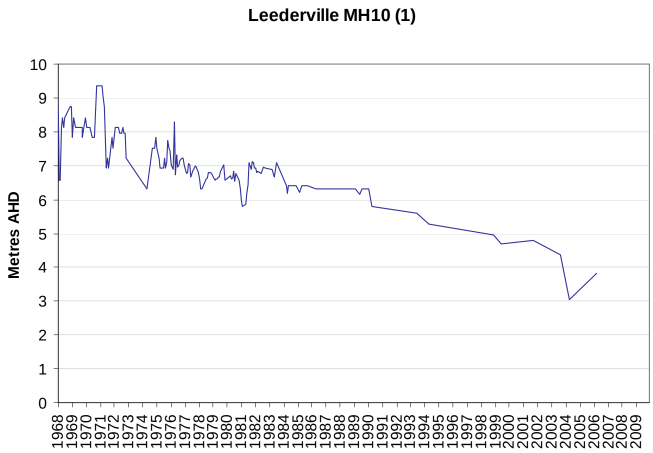
1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009


Leederville MH10 (1)
Metres AHD
0 1 2 3 4 5 6 7 8 9 10
1968 1969 1970 1971 1972 1973 1974 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

Appendix E — Flow-net analysis for horizontal groundwater flow

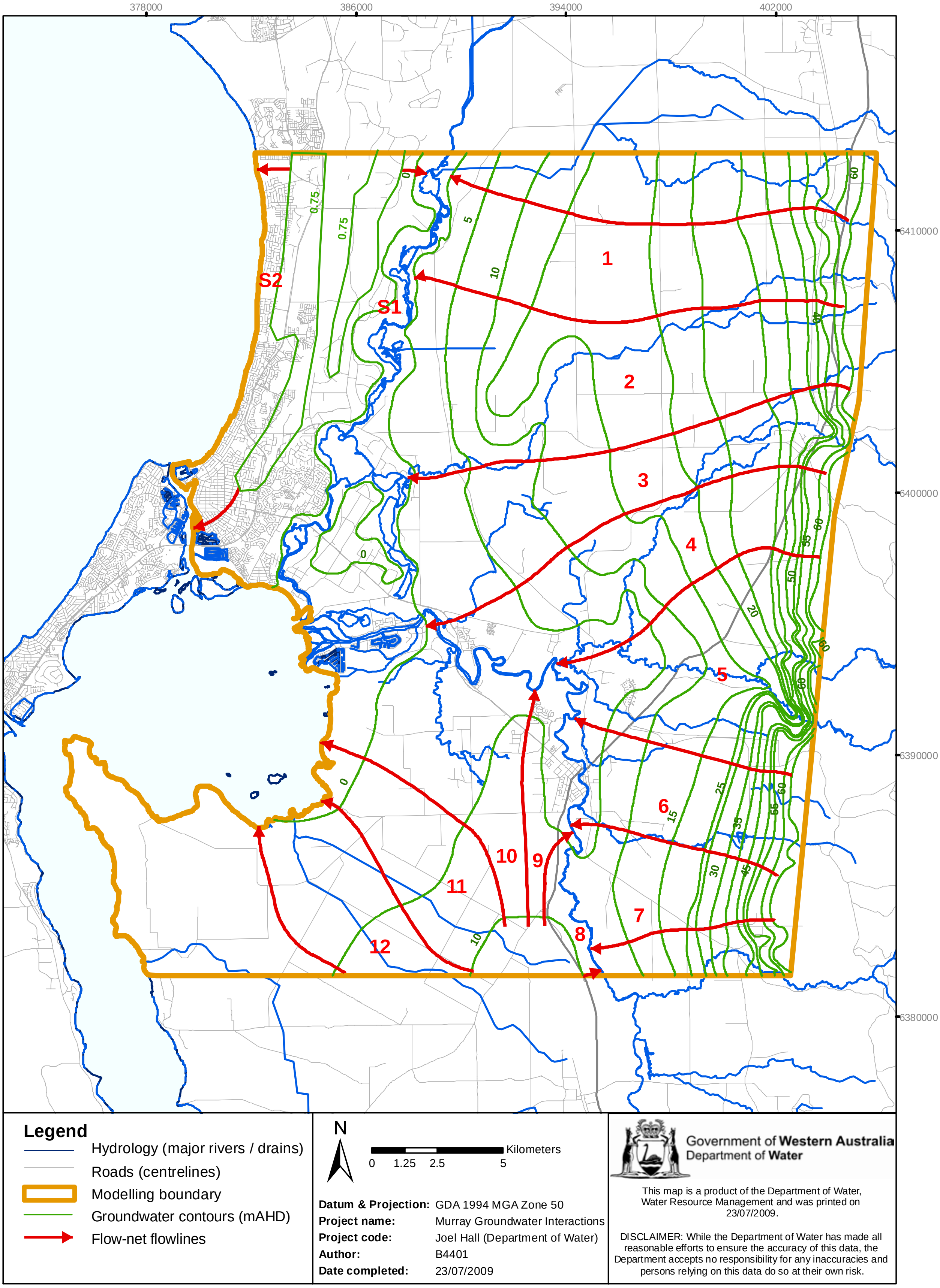


Figure E-1: *Flow-net contours and flow lines for the lateral flow analysis.*

Table E-1: *Flow-net analysis and flow calculations for Murray study area – east of the Serpentine River.*

Flow-net Channel	Flow channel width (m)	Average length (m)	Upper level (mAHD)	Upper level (mAHD)	Change height (m)	Hydraulic gradient	Transmissivity (m^2/day)	Q_{Do} (m^3/day)
1	4850	1880	5	0	5	0.0027	150	1935
2	8650	1930	5	0	5	0.0026	150	3361
3	6300	2230	5	0	5	0.0022	150	2119
4	8780	2950	5	0	5	0.0017	150	2232
5	4200	2400	5	1	4	0.0017	50	350
6	6300	680	5	3	2	0.0029	50	926
7	6500	1900	10	7	3	0.0016	50	513
8	7100	1175	10	7	3	0.0026	75	1360
9	10200	700	5	1	4	0.0057	75	4371
10	14000	2800	5	0	5	0.0018	150	3750
11	2150	4500	5	0	5	0.0011	150	358
12	2600	5450	5	0	5	0.0009	150	358

Table E-2*: Flow-net analysis and flow calculations for Murray study area – west of the Serpentine River*

Flow-net Channel	Flow channel width (m)	Average length (m)	Upper level (mAHD)	Upper level (mAHD)	Change height (m)	Hydraulic gradient	Transmissivity (m^2/day)	Q_{Do} (m^3/day)
S1	23000	1000	0.75	0	0.75	0.0008	500	8.63
S2	23000	1000	0.75	0	0.75	0.0008	500	8.63

Table E-3: *Flow-net analysis and flow calculations for Murray study area – flow entering the southern boundary of the study area*

Flow-net Channel	Flow channel width (m)	Average length (m)	Upper level (mAHD)	Upper level (mAHD)	Change height (m)	Hydraulic gradient	Transmissivity (m^2/day)	Q_{Do} (m^3/day)
8	3600	4200	10	5	5	0.0012	150	0.64
9	1325	4650	15	10	5	0.0011	150	0.21
10	1325	4650	15	10	5	0.0011	150	0.21
11	2965	4000	15	10	5	0.0013	150	0.55

Appendix F — Modelled surface water flows and baseflow analysis

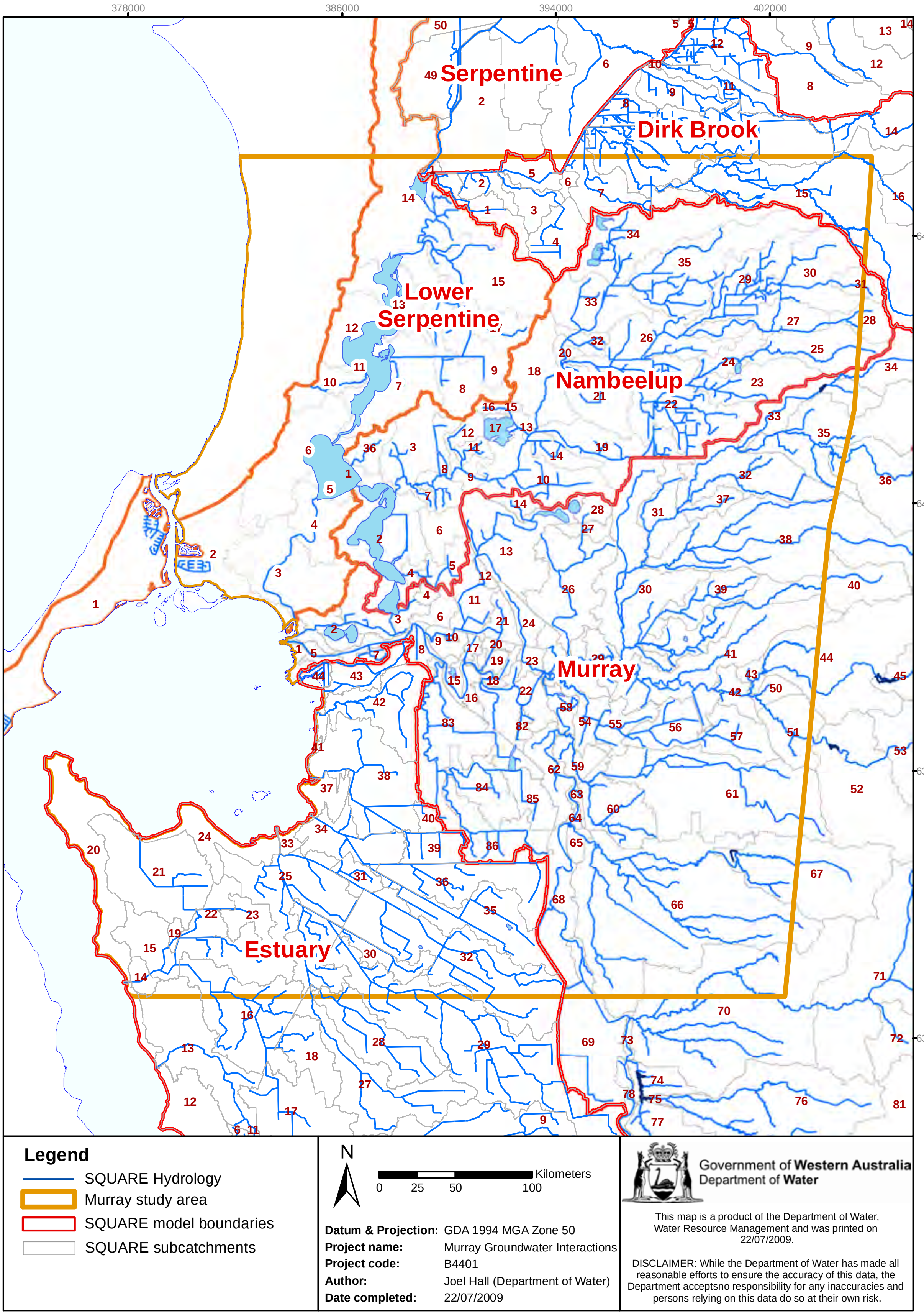


***Figure F-1**: SQUARE hydrology and subcatchments in the Murray study area*

Table F-1: *Subcatchments from various SQUARE models which flow into and drain from the Murray study area.*

Estuary		Murray		Nambeelup		Dirk Brook		Lower Serpentine	
In	Out	In	Out	In	Out	In	Out	In	Out
29	14	34	9	-	1	7	1	-	1
28	20	36	25						2
16	21	45	65						3
	24	52	83						4
	25	71							5
	33	69							6
	34								7
	37								10
	38								11
	41								12
	42								13
	43								14
	44								15

Table F-2: *Inflows, outflows and net annual flows (GL) from SQUARE models in the Murray study area*

Model	Total in	Total out	Net
Estuary	9.6	31.0	21.4
Murray	18.8	50.0	31.2
Nambeelup	0.0	22.1	22.1
Dirkbrook	16.6	18.7	2.1
Lower Serpentine	0.0	11.9	11.9
Total	**45.0**	**133.8**	**88.8**

Table F-3: *Net average monthly flows (GL) from SQUARE models in the Murray study area*

Month	Nambeelup	Estuary	Murray	Dirk Brook	Lower Serpentine	TOTAL
Jan	0.02	0.20	0.22	0.02	0.26	0.72
Feb	0.00	0.13	0.10	0.01	0.17	0.41
Mar	0.00	0.13	0.12	0.01	0.19	0.46
Apr	0.02	0.18	0.35	0.01	0.32	0.88
May	0.31	0.67	1.69	0.06	0.72	3.45
Jun	3.01	3.70	4.72	0.24	1.45	13.12
Jul	7.96	7.08	8.05	0.47	2.54	26.10
Aug	6.82	5.61	7.97	0.51	2.69	23.60
Sep	3.17	2.69	5.00	0.39	2.01	13.27
Oct	0.72	0.67	2.02	0.23	0.93	4.57
Nov	0.07	0.23	0.77	0.10	0.46	1.62
Dec	0.00	0.14	0.18	0.04	0.19	0.56
Annual	**22.09**	**21.43**	**31.19**	**2.10**	**11.94**	**88.76**

Nambeelup Brook – Annual and monthly subcatchment flows (GL) and baseflow contribution

Subcatchment Year	In 1
1975	19.53
1976	9.03
1977	8.54
1978	28.92
1979	11.47
1980	28.62
1981	34.33
1982	18.31
1983	30.44
1984	34.05
1985	23.34
1986	18.67
1987	18.68
1988	37.07
1989	20.62
1990	16.35
1991	44.81
1992	30.42
1993	15.28
1994	22.65
1995	23.94
1996	29.59
1997	19.41
1998	16.19
1999	26.15
2000	28.22
2001	4.87
2002	17.72
2003	25.37
2004	18.08
2005	24.56
2006	3.85
2007	20.01
Average	**22.09**
Net	**22.09**

Month	Average Flow	% Baseflow	Baseflow
Jan	0.02	46.6%	0.01
Feb	0.00	31.6%	0.00
Mar	0.00	4.6%	0.00
Apr	0.02	8.7%	0.00
May	0.31	5.5%	0.02
Jun	3.01	7.2%	0.22
Jul	7.96	14.7%	1.17
Aug	6.82	23.8%	1.62
Sep	3.17	32.3%	1.02
Oct	0.72	63.3%	0.45
Nov	0.07	58.1%	0.04
Dec	0.00	29.9%	0.00
Annual	**22.09**	**20.40%**	**4.51**

Estuary – Annual and monthly subcatchment flows (GL) and baseflow contribution

Subcatchment	Out													In		
Year	**14**	**20**	**21**	**24**	**25**	**33**	**34**	**37**	**38**	**41**	**42**	**43**	**44**	**16**	**28**	**29**
1975	4.70	0.78	1.92	0.36	11.38	0.09	3.02	0.16	1.92	0.89	0.87	0.35	0.32	3.51	1.14	3.71
1976	3.18	0.46	1.28	0.21	7.92	0.06	2.09	0.09	1.29	0.57	0.56	0.24	0.32	2.40	0.80	2.60
1977	3.56	0.54	1.44	0.25	8.80	0.07	2.33	0.11	1.45	0.65	0.64	0.27	0.30	2.68	0.89	2.88
1978	6.20	1.10	2.57	0.52	14.75	0.12	3.93	0.23	2.54	1.20	1.17	0.47	0.37	4.59	1.47	4.79
1979	3.18	0.50	1.29	0.23	7.78	0.06	2.06	0.10	1.29	0.58	0.57	0.24	0.28	2.38	0.78	2.54
1980	5.40	0.89	2.22	0.42	13.05	0.11	3.47	0.18	2.21	1.02	1.00	0.41	0.39	4.03	1.31	4.25
1981	6.36	1.15	2.64	0.54	15.02	0.13	4.01	0.24	2.60	1.23	1.20	0.48	0.39	4.69	1.50	4.87
1982	5.92	1.02	2.44	0.47	14.20	0.12	3.78	0.21	2.42	1.13	1.10	0.45	0.43	4.40	1.42	4.62
1983	8.29	1.55	3.46	0.73	19.47	0.16	5.20	0.33	3.39	1.62	1.58	0.63	0.44	6.10	1.94	6.31
1984	5.02	0.83	2.06	0.38	12.17	0.10	3.23	0.17	2.05	0.94	0.93	0.38	0.37	3.75	1.22	3.97
1985	4.97	0.80	2.03	0.37	12.12	0.10	3.21	0.16	2.03	0.93	0.92	0.37	0.36	3.72	1.22	3.96
1986	3.79	0.61	1.55	0.28	9.20	0.08	2.44	0.12	1.55	0.71	0.69	0.29	0.30	2.83	0.93	3.00
1987	2.35	0.33	0.95	0.15	5.86	0.05	1.55	0.06	0.96	0.42	0.41	0.18	0.25	1.78	0.59	1.92
1988	9.46	1.79	3.95	0.84	22.13	0.19	5.92	0.38	3.87	1.86	1.82	0.71	0.50	6.94	2.20	7.17
1989	5.70	0.96	2.35	0.45	13.69	0.11	3.64	0.20	2.32	1.08	1.06	0.43	0.38	4.24	1.37	4.46
1990	5.89	1.03	2.43	0.48	14.08	0.12	3.75	0.21	2.40	1.13	1.10	0.45	0.40	4.37	1.41	4.58
1991	8.27	1.54	3.45	0.73	19.37	0.16	5.18	0.33	3.38	1.62	1.58	0.63	0.45	6.08	1.93	6.27
1992	6.75	1.23	2.81	0.58	15.96	0.13	4.26	0.26	2.76	1.31	1.28	0.51	0.41	4.98	1.59	5.18
1993	3.84	0.59	1.56	0.27	9.47	0.08	2.50	0.12	1.56	0.70	0.69	0.29	0.32	2.89	0.96	3.10
1994	4.27	0.74	1.76	0.35	10.22	0.08	2.72	0.15	1.74	0.82	0.80	0.32	0.27	3.17	1.02	3.32
1995	6.59	1.20	2.74	0.57	15.55	0.13	4.15	0.25	2.69	1.28	1.25	0.50	0.39	4.86	1.55	5.05
1996	8.39	1.58	3.51	0.75	19.60	0.17	5.25	0.34	3.43	1.65	1.61	0.64	0.45	6.16	1.95	6.34
1997	5.36	0.92	2.21	0.43	12.85	0.11	3.42	0.19	2.19	1.03	1.00	0.40	0.35	3.98	1.29	4.18
1998	5.65	0.93	2.32	0.43	13.66	0.11	3.63	0.19	2.31	1.07	1.05	0.42	0.39	4.22	1.37	4.45
1999	9.67	1.82	4.04	0.86	22.66	0.19	6.06	0.39	3.95	1.90	1.85	0.73	0.50	7.11	2.26	7.34
2000	7.12	1.34	2.98	0.63	16.60	0.14	4.44	0.28	2.91	1.40	1.36	0.54	0.38	5.22	1.65	5.37
2001	2.49	0.33	1.03	0.15	6.31	0.05	1.66	0.06	1.01	0.44	0.43	0.19	0.26	1.90	0.64	2.07
2002	5.09	0.86	2.19	0.40	12.28	0.10	3.26	0.18	2.08	0.96	0.95	0.38	0.34	3.79	1.23	3.99
2003	4.48	0.74	2.00	0.34	10.86	0.09	2.89	0.15	1.83	0.84	0.82	0.34	0.32	3.35	1.09	3.53
2004	4.95	0.86	2.21	0.40	11.82	0.10	3.15	0.18	2.02	0.94	0.93	0.38	0.33	3.67	1.19	3.83
2005	6.83	1.17	3.07	0.54	16.41	0.14	4.37	0.24	2.79	1.30	1.27	0.51	0.44	5.08	1.65	5.33
2006	1.89	0.27	0.86	0.12	4.70	0.04	1.24	0.05	0.77	0.34	0.33	0.15	0.18	1.43	0.48	1.54
2007	4.56	0.73	2.06	0.34	11.10	0.09	2.95	0.15	1.86	0.85	0.83	0.34	0.33	3.41	1.12	3.61
Average	**5.46**	**0.94**	**2.28**	**0.44**	**13.06**	**0.11**	**3.48**	**0.20**	**2.23**	**1.04**	**1.02**	**0.41**	**0.36**	**4.05**	**1.31**	**4.25**
Total Out	**31.04**															
Total In	**9.61**															
Net	**21.43**															

Month	14	20	21	24	25	33	34	37	38	41	42	43	44	16	28	29	Total	% Baseflow	Baseflow
Jan	0.05	0.01	0.02	0.00	0.12	0.00	0.03	0.00	0.02	0.01	0.01	0.00	0.01	0.04	0.01	0.04	0.20	33%	0.06
Feb	0.03	0.01	0.01	0.00	0.08	0.00	0.02	0.00	0.01	0.01	0.01	0.00	0.00	0.02	0.01	0.02	0.13	26%	0.03
Mar	0.03	0.01	0.01	0.00	0.08	0.00	0.02	0.00	0.01	0.01	0.01	0.00	0.00	0.02	0.01	0.03	0.13	29%	0.04
Apr	0.05	0.01	0.02	0.00	0.11	0.00	0.03	0.00	0.02	0.01	0.01	0.01	0.01	0.03	0.01	0.04	0.18	27%	0.05
May	0.17	0.02	0.07	0.01	0.41	0.00	0.11	0.00	0.07	0.03	0.03	0.02	0.02	0.13	0.04	0.14	0.67	13%	0.09
Jun	0.94	0.17	0.39	0.08	2.26	0.02	0.60	0.03	0.39	0.18	0.18	0.07	0.06	0.70	0.23	0.74	3.70	9%	0.32
Jul	1.80	0.34	0.76	0.16	4.23	0.04	1.13	0.07	0.74	0.36	0.35	0.13	0.09	1.33	0.42	1.37	7.08	17%	1.23
Aug	1.43	0.26	0.60	0.12	3.40	0.03	0.91	0.05	0.58	0.28	0.27	0.11	0.07	1.06	0.34	1.10	5.61	23%	1.30
Sep	0.69	0.10	0.28	0.05	1.72	0.01	0.45	0.02	0.28	0.13	0.12	0.05	0.05	0.52	0.17	0.56	2.69	28%	0.75
Oct	0.17	0.02	0.07	0.01	0.45	0.00	0.12	0.00	0.07	0.03	0.03	0.01	0.03	0.13	0.04	0.15	0.67	51%	0.34
Nov	0.06	0.01	0.02	0.00	0.14	0.00	0.04	0.00	0.02	0.01	0.01	0.01	0.01	0.04	0.01	0.04	0.23	69%	0.16
Dec	0.04	0.01	0.02	0.00	0.08	0.00	0.02	0.00	0.01	0.01	0.01	0.00	0.01	0.03	0.01	0.03	0.14	35%	0.05
Annual	**5.46**	**0.94**	**2.28**	**0.44**	**13.06**	**0.11**	**3.48**	**0.20**	**2.23**	**1.04**	**1.02**	**0.41**	**0.36**	**4.05**	**1.31**	**4.25**	**21.43**	**21%**	**4.43**

Murray River catchment – Annual and monthly subcatchment flows (GL) and baseflow contribution

Subcatchment	Out				In				
Year	**9**	**25**	**65**	**83**	**34**	**36**	**45**	**52**	**71**
1975	1.87	26.69	5.87	2.95	0.55	0.87	3.89	3.88	4.72
1976	1.75	24.93	5.57	2.82	0.51	0.81	3.63	3.62	4.41
1977	1.79	25.41	5.62	2.83	0.52	0.83	3.70	3.68	4.49
1978	2.72	39.29	8.57	4.25	0.82	1.30	5.80	5.78	7.01
1979	1.62	23.07	5.11	2.59	0.48	0.75	3.35	3.34	4.07
1980	2.56	36.68	8.11	4.04	0.77	1.21	5.43	5.40	6.58
1981	2.88	41.67	9.06	4.49	0.87	1.37	6.13	6.10	7.41
1982	2.52	36.07	7.99	3.99	0.75	1.18	5.28	5.27	6.42
1983	3.54	51.39	11.18	5.49	1.08	1.70	7.64	7.60	9.23
1984	2.27	32.60	7.17	3.59	0.68	1.07	4.78	4.77	5.79
1985	2.19	31.45	6.92	3.45	0.65	1.03	4.61	4.60	5.59
1986	1.80	25.57	5.66	2.85	0.53	0.83	3.72	3.71	4.52
1987	1.42	20.02	4.47	2.28	0.41	0.65	2.90	2.89	3.52
1988	4.30	62.88	13.58	6.62	1.33	2.09	9.42	9.37	11.33
1989	2.69	38.77	8.50	4.22	0.81	1.28	5.72	5.70	6.93
1990	2.71	39.09	8.57	4.25	0.81	1.29	5.76	5.74	6.98
1991	3.53	51.16	11.11	5.47	1.07	1.69	7.60	7.56	9.17
1992	2.86	41.33	9.05	4.48	0.86	1.36	6.11	6.08	7.39
1993	1.89	26.92	5.97	3.00	0.55	0.88	3.92	3.90	4.76
1994	1.84	26.33	5.76	2.88	0.55	0.87	3.86	3.84	4.67
1995	3.05	44.12	9.60	4.75	0.92	1.46	6.53	6.50	7.88
1996	3.57	51.69	11.23	5.53	1.08	1.71	7.65	7.61	9.23
1997	2.28	32.85	7.19	3.57	0.68	1.08	4.84	4.82	5.85
1998	2.65	38.05	8.34	4.15	0.79	1.25	5.60	5.58	6.79
1999	4.23	61.87	13.38	6.53	1.31	2.06	9.27	9.22	11.16
2000	2.87	41.40	9.02	4.46	0.87	1.37	6.12	6.09	7.39
2001	1.40	19.80	4.42	2.25	0.41	0.64	2.87	2.86	3.48
2002	2.33	33.55	7.34	3.65	0.70	1.10	4.93	4.91	5.97
2003	2.18	31.21	6.86	3.44	0.65	1.02	4.57	4.55	5.54
2004	2.27	32.48	7.12	3.55	0.68	1.07	4.78	4.76	5.78
2005	3.33	48.15	10.50	5.16	1.01	1.59	7.17	7.13	8.65
2006	0.95	13.06	2.94	1.53	0.27	0.42	1.86	1.85	2.26
2007	2.25	31.77	6.99	3.51	0.66	1.04	4.64	4.62	5.62
Average	**2.49**	**35.80**	**7.84**	**3.90**	**0.75**	**1.18**	**5.28**	**5.25**	**6.38**
Total Out	**50.03**								
Total In	**18.83**								
Net	**31.19**								

Month	9	25	65	83	34	36	45	52	71
Jan	0.02	0.24	0.05	0.03	0.00	0.01	0.03	0.03	0.04
Feb	0.01	0.10	0.03	0.02	0.00	0.00	0.01	0.01	0.02
Mar	0.01	0.12	0.03	0.02	0.00	0.00	0.02	0.01	0.02
Apr	0.03	0.36	0.09	0.05	0.01	0.01	0.05	0.05	0.06
May	0.14	1.88	0.46	0.24	0.04	0.06	0.29	0.28	0.35
Jun	0.39	5.46	1.23	0.61	0.12	0.19	0.84	0.83	1.01
Jul	0.65	9.36	2.03	1.00	0.20	0.31	1.40	1.39	1.69
Aug	0.63	9.22	1.97	0.96	0.19	0.30	1.35	1.34	1.63
Sep	0.39	5.76	1.24	0.61	0.12	0.19	0.84	0.84	1.02
Oct	0.15	2.26	0.48	0.24	0.04	0.07	0.31	0.32	0.38
Nov	0.06	0.85	0.19	0.10	0.02	0.03	0.12	0.12	0.15
Dec	0.01	0.19	0.04	0.02	0.00	0.01	0.02	0.02	0.03
Annual	**2.49**	**35.80**	**7.84**	**3.90**	**0.75**	**1.18**	**5.28**	**5.25**	**6.38**

Month	%Baseflow (hills)	Baseflow (Hills)	% Baseflow (plain)	Baseflow (Plains)	Net Baseflow
Jan	3%	0.00	46.6%	0.16	0.15
Feb	16%	0.01	31.6%	0.05	0.04
Mar	2%	0.00	4.6%	0.01	0.01
Apr	3%	0.01	8.7%	0.05	0.04
May	3%	0.03	5.5%	0.15	0.12
Jun	6%	0.18	7.2%	0.55	0.37
Jul	8%	0.41	14.7%	1.92	1.51
Aug	14%	0.67	23.8%	3.04	2.37
Sep	21%	0.62	32.3%	2.59	1.96
Oct	25%	0.28	63.3%	1.98	1.71
Nov	33%	0.14	58.1%	0.70	0.56
Dec	32%	0.03	29.9%	0.08	0.05
Annual	**11%**	**2.14**	**20.40%**	**10.21**	**8.06**

Dirk Brook– Annual and monthly subcatchment flows (GL) and baseflow contribution

Subcatchment	Out	In
Year	**1**	**7**
1975	14.28	12.67
1976	13.72	12.16
1977	13.72	12.17
1978	20.55	18.25
1979	12.54	11.12
1980	19.22	17.08
1981	21.62	19.17
1982	20.08	17.82
1983	25.65	22.78
1984	17.54	15.56
1985	16.79	14.88
1986	13.43	11.90
1987	10.84	9.62
1988	31.24	27.75
1989	20.12	17.85
1990	20.20	17.92
1991	25.81	22.92
1992	21.07	18.69
1993	14.35	12.72
1994	14.24	12.64
1995	22.48	19.97
1996	25.81	22.92
1997	17.60	15.62
1998	19.63	17.42
1999	31.05	27.59
2000	20.99	18.63
2001	10.76	9.54
2002	17.87	15.85
2003	16.66	14.78
2004	17.19	15.25
2005	24.95	22.14
2006	6.98	6.17
2007	16.37	14.51
Average	**18.65**	**16.55**
Total Out	**18.65**	
Total In	**16.55**	
Net	**2.10**	

Month	1	7	Total	% Baseflow	Baseflow
Jan	0.19	0.16	0.02	48%	0.01
Feb	0.10	0.09	0.01	33%	0.00
Mar	0.09	0.08	0.01	19%	0.00
Apr	0.17	0.16	0.01	16%	0.00
May	0.74	0.68	0.06	13%	0.01
Jun	2.44	2.20	0.24	9%	0.02
Jul	4.28	3.82	0.47	13%	0.06
Aug	4.48	3.96	0.51	27%	0.14
Sep	3.32	2.93	0.39	43%	0.17
Oct	1.80	1.57	0.23	65%	0.15
Nov	0.78	0.67	0.10	71%	0.07
Dec	0.27	0.23	0.04	87%	0.03
Annual	**18.65**	**16.55**	**2.10**	**28%**	**0.58**

Lower Serpentine - Annual and monthly subcatchment flows (GL) and baseflow contribution

Subcatchment	Out												
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**10**	**11**	**12**	**13**	**14**	**15**
1975	1.74	1.09	0.74	0.45	0.23	1.09	1.16	0.12	0.01	0.25	0.27	1.22	1.09
1976	1.86	1.15	0.72	0.45	0.26	1.10	1.08	0.11	0.01	0.23	0.23	1.03	0.98
1977	1.66	0.97	0.62	0.39	0.21	0.94	0.92	0.10	0.01	0.20	0.20	0.90	0.84
1978	2.31	1.45	1.08	0.61	0.34	1.50	1.82	0.18	0.02	0.38	0.43	1.95	1.75
1979	1.60	1.01	0.65	0.40	0.21	0.97	0.96	0.10	0.01	0.21	0.22	0.96	0.88
1980	2.34	1.59	1.19	0.69	0.40	1.69	2.08	0.20	0.03	0.43	0.48	2.16	1.98
1981	2.58	1.55	1.17	0.68	0.37	1.67	2.15	0.21	0.03	0.44	0.50	2.27	2.08
1982	2.71	1.66	1.19	0.71	0.42	1.79	2.24	0.20	0.03	0.43	0.49	2.14	2.14
1983	2.95	1.73	1.23	0.72	0.39	1.77	2.32	0.23	0.03	0.48	0.55	2.50	2.27
1984	2.16	1.31	0.92	0.57	0.30	1.41	1.56	0.15	0.02	0.33	0.36	1.59	1.48
1985	2.10	1.42	1.02	0.62	0.36	1.53	1.91	0.18	0.02	0.38	0.43	1.93	1.82
1986	1.87	1.14	0.82	0.47	0.26	1.15	1.24	0.13	0.01	0.26	0.28	1.25	1.16
1987	1.50	0.94	0.62	0.38	0.19	0.93	0.87	0.10	0.01	0.20	0.20	0.88	0.79
1988	2.78	2.01	1.74	1.02	0.55	2.49	3.52	0.35	0.06	0.73	0.84	3.90	3.48
1989	2.29	1.52	1.11	0.70	0.39	1.72	2.13	0.21	0.03	0.44	0.50	2.25	2.06
1990	2.41	1.48	1.00	0.62	0.35	1.53	1.86	0.18	0.02	0.38	0.42	1.90	1.77
1991	3.13	2.12	1.60	0.98	0.51	2.41	3.32	0.34	0.05	0.70	0.80	3.68	3.29
1992	2.61	1.71	1.21	0.78	0.43	1.90	2.48	0.24	0.04	0.51	0.58	2.65	2.40
1993	1.78	1.15	0.69	0.46	0.25	1.14	1.21	0.12	0.01	0.26	0.27	1.21	1.13
1994	1.54	0.81	0.53	0.36	0.18	0.86	0.87	0.09	0.01	0.20	0.20	0.90	0.81
1995	2.33	1.08	0.81	0.51	0.27	1.23	1.35	0.14	0.02	0.30	0.32	1.44	1.28
1996	2.50	1.31	1.08	0.65	0.36	1.60	1.97	0.20	0.03	0.41	0.46	2.11	1.90
1997	1.79	0.87	0.63	0.42	0.23	1.02	1.11	0.11	0.01	0.24	0.25	1.13	1.04
1998	1.84	0.98	0.66	0.42	0.22	1.01	1.01	0.10	0.01	0.22	0.22	0.98	0.93
1999	2.53	1.30	0.87	0.53	0.30	1.29	1.49	0.15	0.02	0.31	0.34	1.52	1.41
2000	1.89	1.14	0.84	0.51	0.30	1.25	1.45	0.15	0.02	0.31	0.34	1.53	1.38
2001	1.28	0.78	0.44	0.28	0.11	0.67	0.48	0.07	0.01	0.13	0.11	0.49	0.41
2002	1.63	1.05	0.64	0.39	0.22	0.95	0.97	0.10	0.01	0.20	0.21	0.96	0.89
2003	1.97	1.27	0.80	0.48	0.28	1.17	1.27	0.13	0.01	0.26	0.29	1.29	1.19
2004	1.87	1.11	0.66	0.40	0.21	0.98	0.98	0.10	0.01	0.21	0.22	0.98	0.79
2005	2.90	1.70	1.07	0.62	0.38	1.53	1.81	0.17	0.02	0.35	0.41	1.94	1.32
2006	1.31	0.76	0.39	0.24	0.09	0.62	0.41	0.06	0.00	0.11	0.10	0.53	0.24
2007	2.12	1.29	0.75	0.45	0.24	1.12	1.08	0.11	0.01	0.23	0.25	1.19	0.64
Average	**2.12**	**1.29**	**0.89**	**0.55**	**0.30**	**1.33**	**1.55**	**0.16**	**0.02**	**0.32**	**0.36**	**1.62**	**1.44**
Total Out	**11.94**												

Month	1	2	3	4	5	6	7	10	11	12	13	14	15	Total	% Baseflow	Baseflow
Jan	0.06	0.03	0.02	0.01	0.00	0.03	0.03	0.00	0.00	0.01	0.01	0.03	0.03	0.26	33%	0.08
Feb	0.04	0.02	0.01	0.01	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.02	0.01	0.17	26%	0.04
Mar	0.05	0.03	0.02	0.01	0.00	0.02	0.02	0.00	0.00	0.01	0.00	0.02	0.01	0.19	29%	0.06
Apr	0.09	0.05	0.03	0.02	0.00	0.04	0.02	0.00	0.00	0.01	0.01	0.03	0.02	0.32	27%	0.09
May	0.22	0.13	0.07	0.04	0.01	0.10	0.04	0.01	0.00	0.02	0.01	0.05	0.03	0.72	13%	0.10
Jun	0.32	0.19	0.12	0.07	0.03	0.18	0.15	0.02	0.00	0.04	0.04	0.16	0.13	1.45	9%	0.12
Jul	0.40	0.25	0.19	0.11	0.07	0.27	0.35	0.03	0.00	0.07	0.08	0.37	0.34	2.54	17%	0.44
Aug	0.38	0.24	0.19	0.11	0.08	0.28	0.40	0.04	0.01	0.08	0.09	0.42	0.39	2.69	23%	0.62
Sep	0.28	0.18	0.14	0.08	0.06	0.21	0.31	0.03	0.00	0.05	0.07	0.31	0.29	2.01	28%	0.56
Oct	0.15	0.09	0.07	0.04	0.03	0.10	0.14	0.01	0.00	0.02	0.03	0.13	0.13	0.93	51%	0.47
Nov	0.10	0.06	0.03	0.02	0.01	0.05	0.05	0.01	0.00	0.01	0.01	0.05	0.05	0.46	69%	0.32
Dec	0.04	0.02	0.01	0.01	0.00	0.02	0.02	0.00	0.00	0.01	0.01	0.03	0.02	0.19	35%	0.07
Annual	**2.12**	**1.29**	**0.89**	**0.55**	**0.30**	**1.33**	**1.55**	**0.16**	**0.02**	**0.32**	**0.36**	**1.62**	**1.44**	**11.94**	**21%**	**2.47**

Appendix G —Evapotranspiration calculation figures and tables

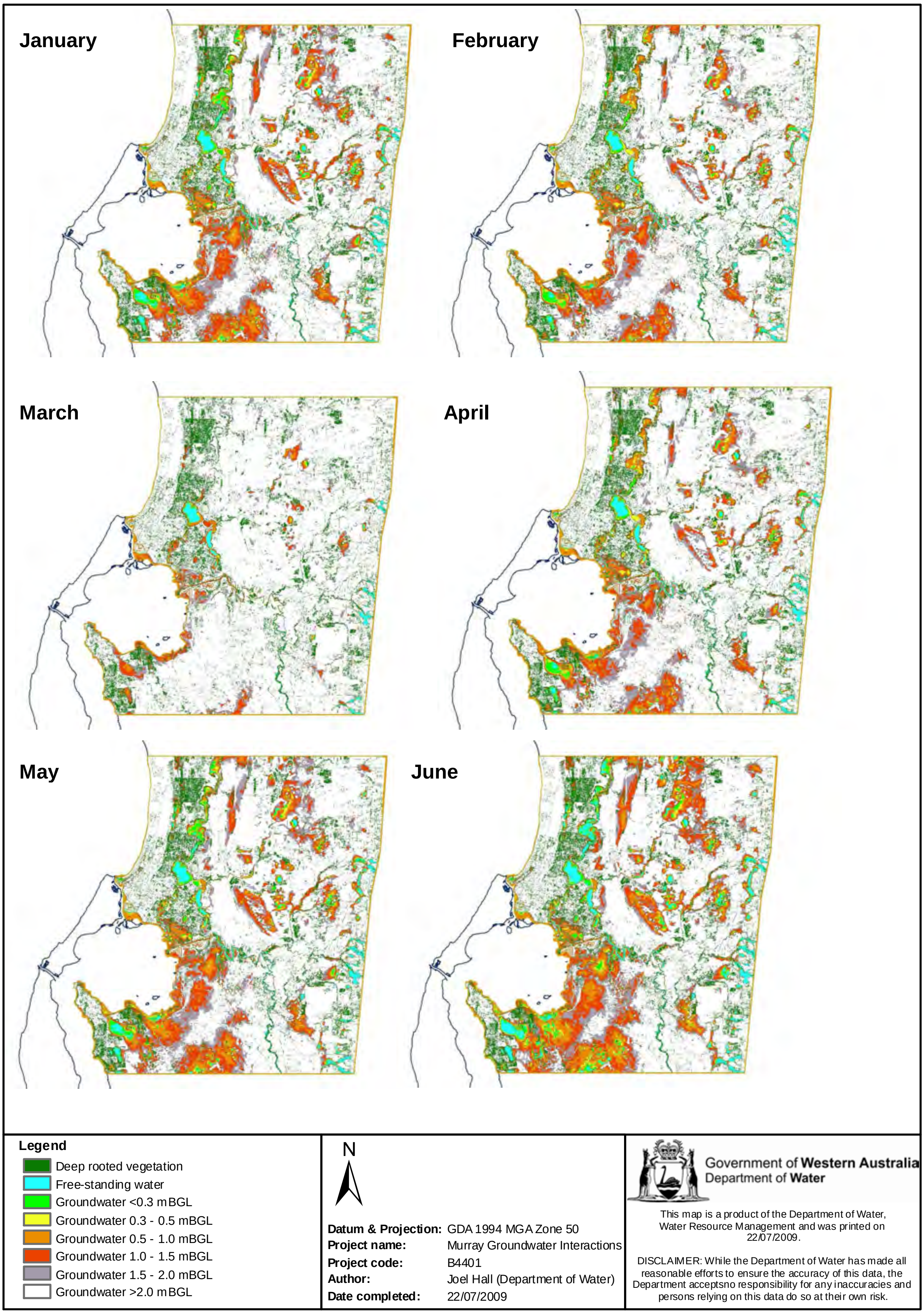


***Figure G-1**: Distance to groundwater and deep-rooted vegetation, January – June.*

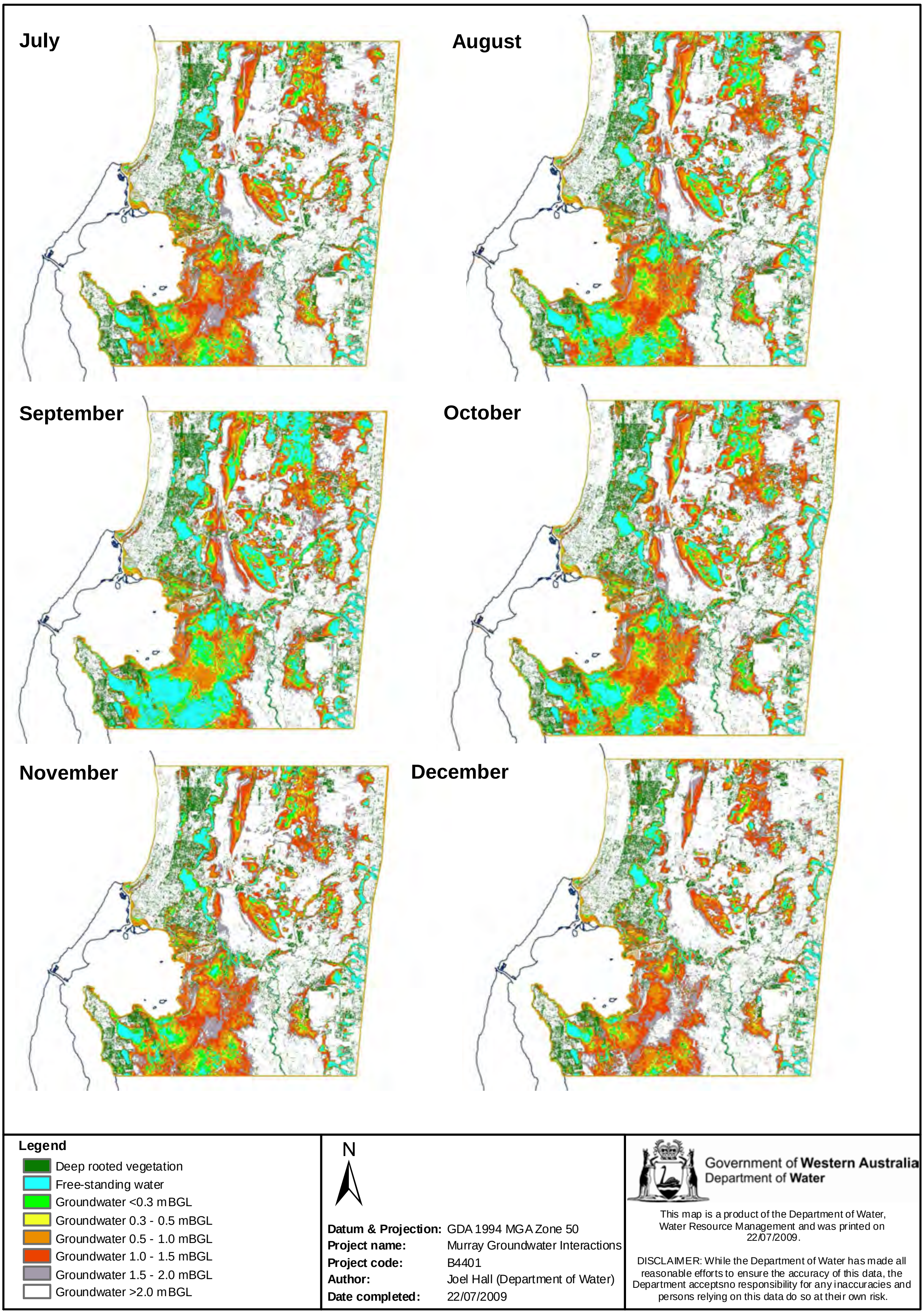


Figure G-2: *Distance to groundwater and deep-rooted vegetation, July - December.*

Table G-1: *Total area for classes of various depths to watertable*

Month	Rainfall (mm)	Pan Evaporation (mm)	Penman Monteith (mm)	Area (sqkm)							
				Deep Rooted Veg	Water logged	<0.3m	0.3 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	>2.0
Jan	15.1	255.8	193.4	86.1	13.6	9.1	8.2	34.6	57.9	71.4	440.8
Feb	13.3	215.4	162.0	86.1	9.8	6.1	6.3	24.8	42.8	60.8	485.1
March	18.6	184.9	143.1	86.1	5.3	0.7	1.2	7.0	14.8	21.1	585.6
April	46.0	112.8	93.6	86.1	9.8	6.1	6.3	24.8	42.8	60.8	485.1
May	113.7	75.7	63.6	86.1	13.6	9.1	8.2	34.6	57.9	71.4	440.8
June	164.8	58.1	46.6	86.1	20.8	12.5	12.7	51.8	71.2	71.5	395.3
July	162.5	60.2	48.7	86.1	32.2	21.6	20.5	66.9	74.3	67.1	353.1
August	127.1	71.9	62.4	86.1	56.8	33.0	26.2	72.9	69.7	63.0	314.2
September	88.0	90.6	81.5	86.1	94.6	39.4	27.8	70.6	64.4	61.7	277.1
October	47.6	133.3	117.2	86.1	56.8	33.0	26.2	72.9	69.7	63.0	314.2
November	32.8	177.6	147.1	86.1	32.2	21.6	20.5	66.9	74.3	67.1	353.1
December	10.5	229.8	179.8	86.1	20.8	12.5	12.7	51.8	71.2	71.5	395.3
Total Annual	**840.1**	**1666.0**	**1338.9**								

Table G-2: *Evapotranspiration for classes of various distances to watertable*

Month	Rainfall	Pan Evaporation	Penman Monteith	Evapotranspiration flux (GL)								
				Deep Rooted Veg	Water logged	<0.3m	0.3 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	>2.0	TOTAL EVT
Jan	15.1	255.8	193.4	3.5	2.6	1.8	1.3	3.1	1.4	0.1	0.0	13.8
Feb	13.3	215.4	162.0	3.0	1.7	1.0	0.8	1.9	1.0	0.1	0.0	9.4
March	18.6	184.9	143.1	14.0	0.8	0.1	0.1	0.5	0.4	0.0	0.0	15.9
April	46.0	112.8	93.6	8.5	0.9	0.6	0.4	1.1	1.0	0.1	0.0	12.6
May	113.7	75.7	63.6	5.7	0.8	0.6	0.4	1.0	1.4	0.1	0.0	10.0
June	164.8	58.1	46.6	4.4	1.0	0.6	0.4	1.1	1.7	0.1	0.0	9.4
July	162.5	60.2	48.7	4.6	1.6	1.1	0.7	1.5	1.8	0.2	0.0	11.4
August	127.1	71.9	62.4	5.5	3.3	2.1	1.1	2.1	1.7	0.3	0.0	16.1
September	88.0	90.6	81.5	6.9	6.9	3.2	1.5	2.7	1.6	0.5	0.0	23.2
October	47.6	133.3	117.2	10.1	6.1	3.9	2.1	4.0	1.7	0.3	0.0	28.1
November	32.8	177.6	147.1	13.5	4.6	3.2	2.2	4.6	1.8	0.2	0.0	30.0
December	10.5	229.8	179.8	3.2	3.8	2.2	1.7	4.4	1.7	0.1	0.0	17.2
Total Annual	**840.1**	**1666.0**	**1338.9**	**82.8**	**33.9**	**20.2**	**12.9**	**28.1**	**17.2**	**2.2**	**0.0**	**197.3**

Extinction depth:	2.00
Pan correction:	0.75
Vegetation factor:	1.1
Vegetation factor (summer):	0.2

Appendix H – Groundwater abstraction figures

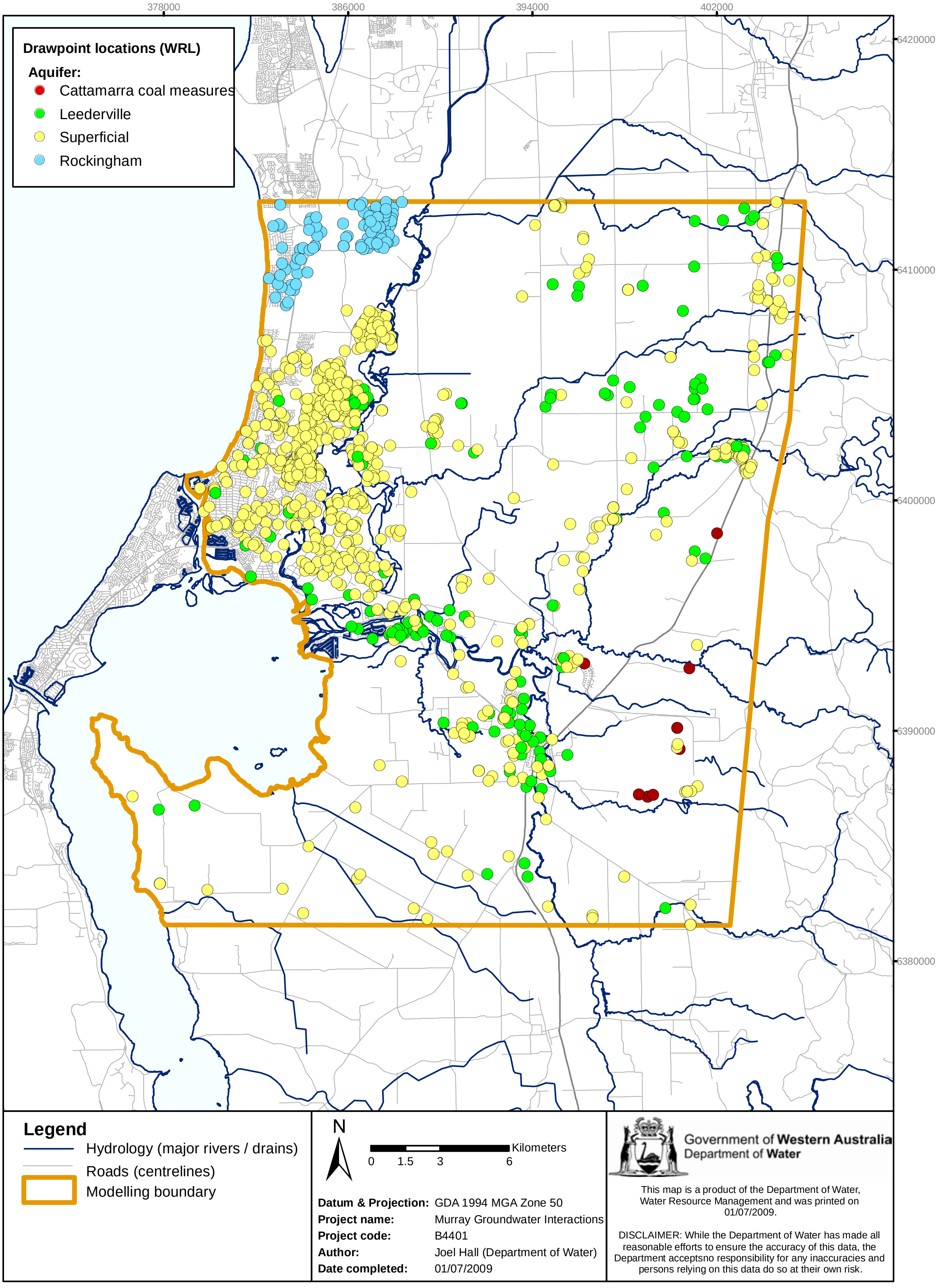


***Figure H-1:** WRL draw-points from various aquifers in the Murray region*

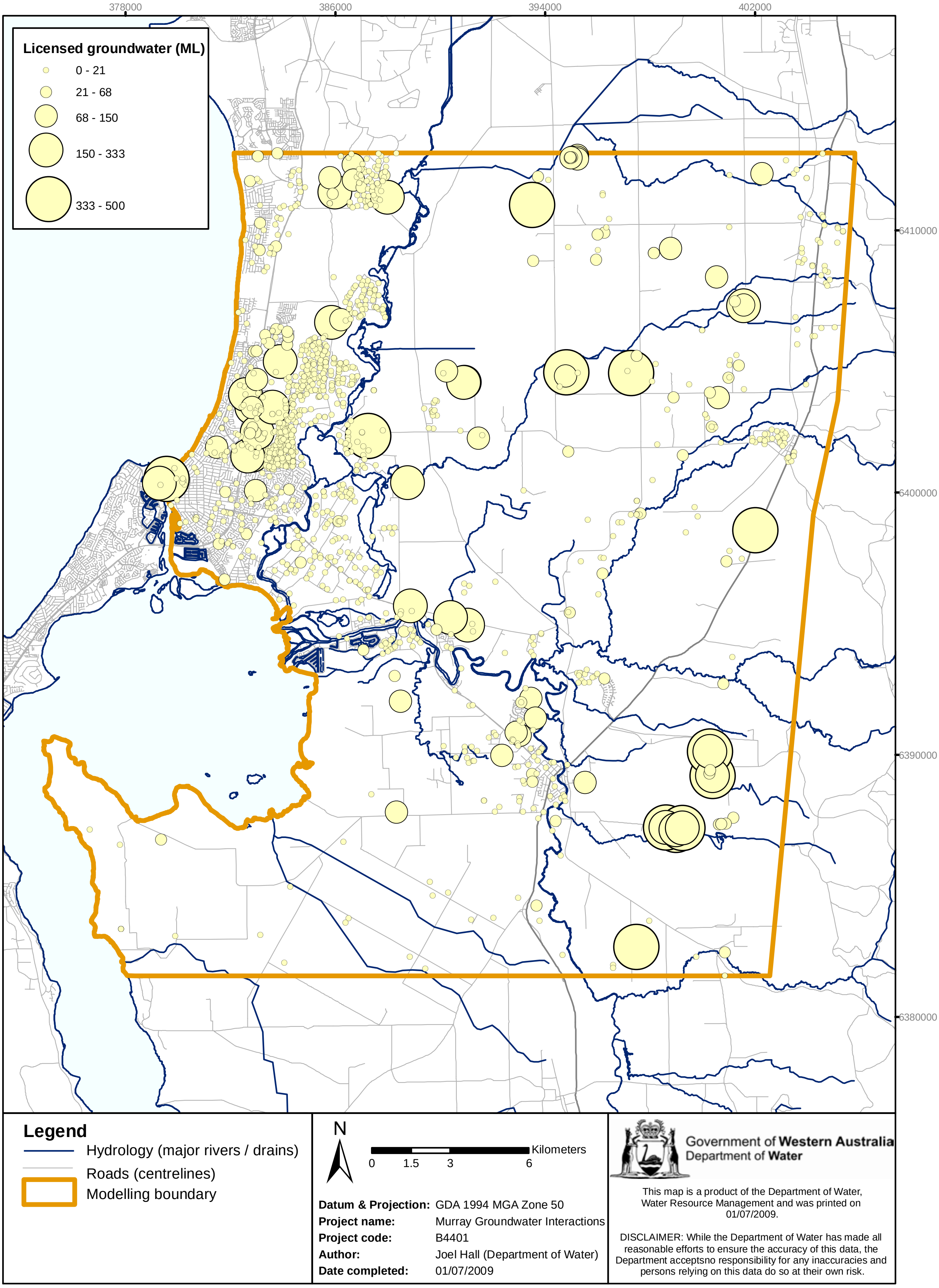


Figure H-2: *WRL draw-points quantities in the Murray region*

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