Government of Western Australia
Department of Water

# Lower Serpentine hydrological studies

## Model construction and calibration report

Looking after all our water needs

Water*Science* technical series

Report no. WST 46
March 2012

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*Cover photograph: Aerial view of rural properties and drainage near Mundijong, Ben Marillier, 2011*

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# Summary

This construction and calibration report is the second in a series of three attached to the *Lower Serpentine hydrological studies*, a project initiated to support future drainage and water management plans for the region.

This report outlines the process of converting the conceptual model, described in the first report in the series (Marillier et al. 2012), to a regional transient surface water and groundwater model over the Lower Serpentine study area. It includes detailed discussion on the following topics:

- the model code and component models used
- construction of the numerical model based on the conceptual model
- model inputs
- the calibration and validation process, and discussion of results
- calibrated model parameters and limitations associated with the final model
- water balances for the modelled system
- sensitivity and uncertainty assessment for model parameters and stress datasets
- recommendations for future modelling in the area based on the construction and calibration process.

The Lower Serpentine regional model was constructed with the Mike SHE 2011 modelling framework, using available geological, hydrogeological, hydrological, soil and land use information. The model simulates the following processes: rainfall and evapotranspiration, unsaturated zone, saturated zone, channel flow, overland flow and abstraction.

The model simulation period is from 1970 to 2010 inclusive, with the years 1980 to 2004 used for calibration and 2005 to 2010 reserved for validation. The model calibration of the Superficial, Leederville and Rockingham aquifers satisfied the criteria (Middlemis 2000) of a water balance error <0.05%, an iteration residual error <0.1% and a scaled root mean square (RMS) error <5%. The scaled RMS error for the Superficial Aquifer in the calibration period was 1.5%. The average absolute error for the Superficial Aquifer was 0.45 m. Calibration of the Leederville and Rockingham aquifers achieved a scaled RMS of 3.8% and an average absolute error of 0.80 m.

The average Nash-Sutcliffe coefficient of efficiency achieved at surface water flow-gauging stations was 0.77, with a -7% average cumulative flow error. Observed versus modelled flows showed that both low flows and peak flows were realistically simulated.

Most of the simulated heads in the Superficial Aquifer had a response consistent with measured data. In some parts of the model, the observed trends in groundwater level were not well replicated. The areas of significant error or uncertainty within the model include:

- The area to the west of Jandakot Mound and the Spectacles Wetlands at the interface of the Tamala Limestone and Bassendean Sand. The geology in this area is complex, as sandy sediments transition to a region of karstic limestone.

- The area along the model's northern boundary, where changes in groundwater levels outside of the model boundary may have an impact internally. This area is also subject to abstraction of scheme water by the Water Corporation.
- The area around Mundijong and Byford where groundwater levels are over-predicted for the last 10 years of the simulation period. These areas show declining trends in observed groundwater levels, most likely due to abstraction. The abstraction dataset available for the model did account for this flux, and is likely to be inaccurate.

Trends and levels in the Leederville and Rockingham aquifers were well replicated in the model's western and central parts. However, AM50Z shows an under-prediction of 2.5 m and a failure of the model to replicate the artesian conditions observable in the hydrograph for this area before 1995, indicating a deficiency in the conceptualisation. The declining trend of AM50X near Byford was not replicated by the model, possibly due to insufficient abstraction data, or too much recharge from the Superficial Aquifer. The area around AM60E in the south of the model is sensitive to abstraction and shows a declining trend from the mid 1990s greater than that shown by the observed data.

The model predicted gross recharge of 33% of rainfall and net recharge of 18% calculated for 1975 to 2010. Net recharge is considerably less than gross recharge as a result of evapotranspiration from shallow groundwater over the low-lying parts of the study area.

Sensitivity analysis showed that parameters associated with recharge in the unsaturated zone were the most important for achieving model calibration. These included root depth and soil parameters including water content at saturation, field capacity, wilting point and saturated conductivity. Leaf area index was not a sensitive parameter. In the Superficial Aquifer, horizontal conductivity within different geological units was less sensitive than parameters associated with recharge. The Leederville Aquifer was most sensitive to changes in vertical and horizontal conductivity in the Wanneroo and Pinjar members.

The Lower Serpentine regional model has a spatial resolution of 200 m, a temporal resolution of one day, and three computational layers. Based on the model's structural limitations, and the uncertainty and error associated with the calibration, the model is appropriate for:

- Evaluating changes to the Superficial Aquifer water balance related to land use, climatic and drainage changes (e.g. changes in recharge, drainage, evapotranspiration, horizontal flows etc.).
- The relative assessment of regional and subregional impacts due to changes in drainage and abstraction from the Superficial Aquifer.
- District-scale groundwater-level evaluation (average annual maximum groundwater level etc.) under various climate scenarios. This includes determining areas of seasonal waterlogging and inundation. However, the inherent model error needs to be considered when using groundwater levels derived from the regional model. If the error is deemed too large for the purpose of the application, a localised model with a finer grid should be constructed and re-calibrated to achieve appropriate model error. The use of additional locally sourced field data and a revised conceptual model may also be necessary.

The model should not be used for fine-scale wetland, river and lake modelling, flood modelling or detailed drainage modelling. The model is not recommended for abstraction or sustainable yield analysis in the Leederville and Rockingham aquifers due to errors in calibration and the level of uncertainty in conceptualisation of the Leederville.

# 1 Introduction

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

- protection of significant environmental assets – including meeting their water requirements and managing the potential impacts of development
- water demand – including supply options, opportunities for conservation and demand management measures, as well as wastewater management
- surface runoff – including both peak event (flood) management and water saving urban design 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, possible effects on the environment and the potential to use groundwater as a resource
- water quality management – including source control of pollution inputs by catchment management, acid sulfate soil management, control of contaminated discharges from industrial areas and management of nutrient exports from surface runoff and groundwater through structural measures.

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

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

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

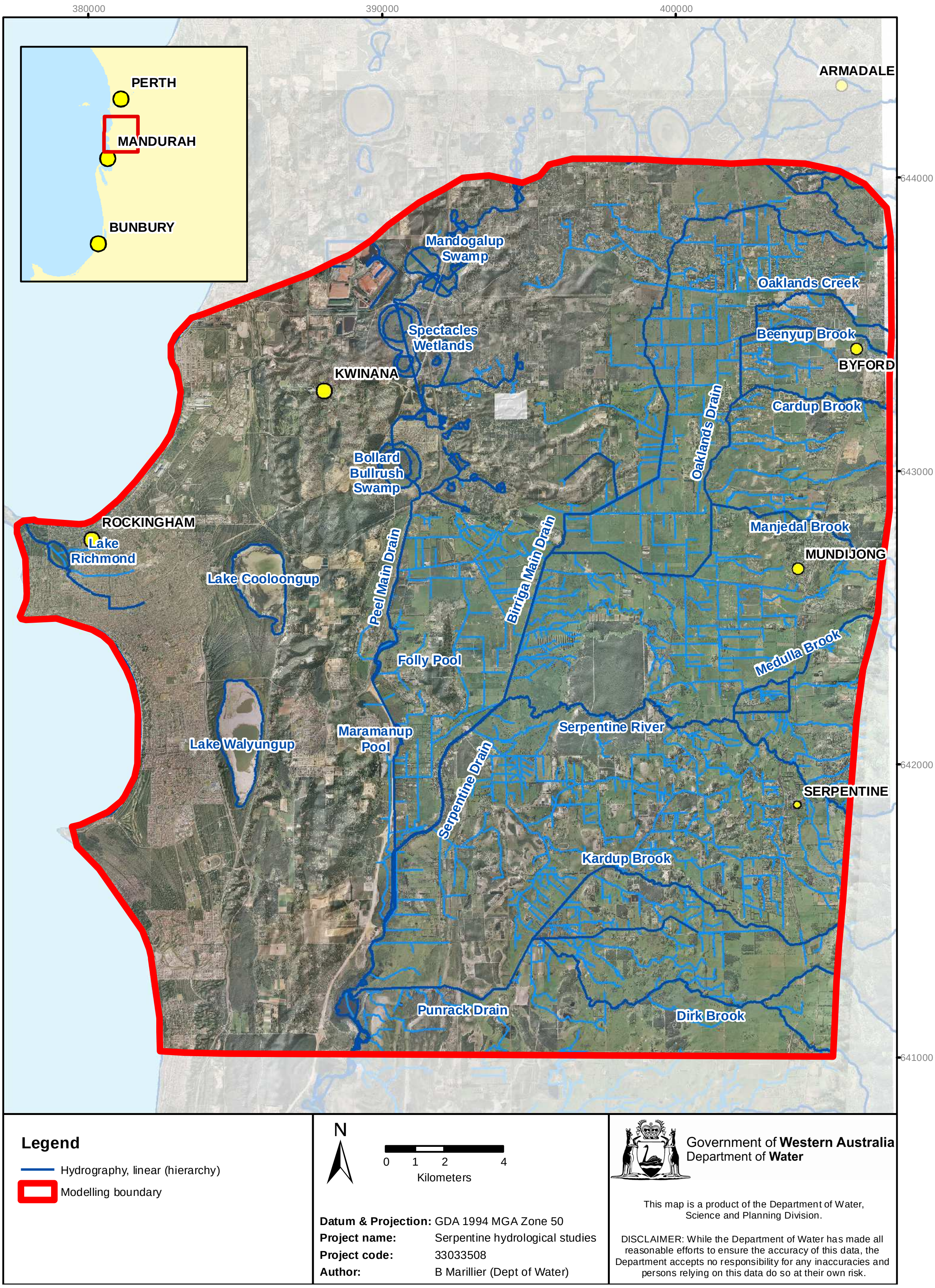



*Figure 1-1 Modelling boundary for the Serpentine region*

## 1.1 Project objective

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

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

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

The project requires the modelling results to determine the following:

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

## 1.2 Scope of work

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

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

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

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

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

3 Create a suite of scenarios to determine the change to water budgets and groundwater levels under various land use and climate scenarios. The Department of Water's Urban Water Management Branch will select scenarios for the Water Science Branch to model. These will fit into the following broad categories:

a **Land development scenarios:** these will be based on likely areas of urban development within the study area (to be provided by WAPC).

b **Drainage scenarios:** these will examine the influence of subsurface drainage on groundwater levels, surface water flows and the water balance within areas of future development.

c **Climate scenarios:** a range of future climate scenarios will be simulated to account for various possibilities in changing rainfall and evapotranspiration. These will be based on Intergovernmental Panel on Climate Change (IPCC) predictions, including predicted changes in rainfall and evapotranspiration. Results from appropriate global circulation models will be used to determine scenario inputs.

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

# 2 Selection of Mike SHE component models for the Lower Serpentine study area

Mike SHE was selected as the numerical model to simulate the Lower Serpentine study area. Mike SHE is a flexible modelling framework that enables different component models representing aspects of the hydrological cycle to be combined. Mike SHE is a physically based model able to be run in fully distributed and partially-distributed modes depending on the selection of component models.

The following component models were used to implement the Lower Serpentine conceptual model (Marillier et al. 2012) within Mike SHE:

- overland flow model (rainfall/runoff)
- channel flow model (Mike 11) (river and drain flows)
- unsaturated zone model (soil processes in the vadose zone)
- evapotranspiration model (vegetation evapotranspiration)
- saturated zone model (groundwater flow).

Each of the component models can interact with each other where appropriate; for example, groundwater exchanges to and from river channels. Each component model and the reasons for its selection are discussed in more detail below.

### Overland flow

Overland flow simulates the movement of water over the land surface, and can calculate flow across a floodplain and into streams and rivers. The route of overland flow is determined by the surface topography and resistance of the land surface, which are defined within Mike SHE. This module acts to simulate the rainfall runoff processes described in Section 3.2 of the conceptual model (Marillier et al. 2012).

The overland flow model available within Mike SHE solves the diffusive wave approximation of the Saint Venant equations, which ignores momentum losses due to local and convective acceleration and lateral inflows perpendicular to the flow direction.

Two types of solver are available for use with the overland flow module:

- successive over-relaxation (SOR)
- explicit numerical.

The choice of method is a trade-off between solution time and model accuracy. SOR will generally find a solution more quickly than the explicit method, at the cost of accuracy, and with the possibility of mass errors.

For the Lower Serpentine model the SOR solver was used for shorter run-times and it did not result in unacceptable mass errors.

The overland flow model interacts with the saturated zone model, the unsaturated zone model and the channel flow model. When the phreatic surface is above the topographic surface, groundwater is converted to overland flow. If rainfall intensity exceeds the saturated conductivity in the unsaturated zone, then water will pool at the surface and add to overland flow. Flow will continue along the land surface until it reaches local depressions, where it may evaporate or infiltrate, or may spill to the river, drainage network or model boundary.

The Manning number (Manning's *M*) and detention storage are the two parameters requiring calibration for the overland flow module.

### Channel flow

Channel flow is simulated within Mike SHE using the one-dimensional hydraulic model Mike 11. The Mike SHE/Mike 11 coupling enables the following processes to be simulated:

- one-dimensional simulation  of river flows and water levels using the fully dynamic Saint Venant equations
- hydraulic control structures such as culverts, weirs and bridges
- dynamic overland flooding to and from the Mike 11 network
- dynamic coupling subsurface flow processes in Mike 11 and Mike SHE.

The Mike 11 module simulates the river and drain flows described in Section 3.2 of the conceptual model report (Marillier et al. 2012).

Mike 11 contains several solution methods for the conservation of momentum equations, including the fully dynamic wave (full Saint Venant equations), the diffusive wave equation (ignores the momentum term) and the kinemetic wave (ignores pressure and momentum terms). The latter two methods are numerically less intensive and therefore faster, and are appropriate in situations with fast-moving bodies of water, steep bed gradients and no backwater or tidal effects. In the Serpentine area, the presence of very low hydraulic gradients requires the use of the fully dynamic wave solution.

The riverbed roughness (Manning's *n*) and the riverbed leakage coefficient are the two parameters requiring calibration for the Mike 11 model.

### Unsaturated flow/evapotranspiration model

The unsaturated flow model and evapotranspiration model are coupled within Mike SHE. The model's main function is to estimate actual evapotranspiration and recharge to the saturated zone. There are three methods in Mike SHE to calculate unsaturated flow:

1. Richards equation: used when detailed unsaturated zone water-content profile is required or if the soils have significant capillary potential.
2. Gravity flow: used when the main purpose of the unsaturated zone is to provide recharge and overland flow, and if the soils are predominantly coarse.
3. Two-layer water balance: useful when the watertable is 'shallow' and a simple water balance of the unsaturated zone is required. 'Shallow' is when the infiltration time is less than or close to the groundwater timestep.

The two-layer water balance method is an alternative to more complex unsaturated flow processes, and is suitable for the Lower Serpentine model. It was used to simulate evapotranspiration as described in Section 6.3 of the conceptual model (Marillier et al. 2012).

The two-layer model divides the unsaturated zone into a root zone, from which evapotranspiration can occur, and a zone below the root zone, where evapotranspiration does not occur. The module is particularly useful for areas with a shallow groundwater table, such as swamps or wetland areas, where the actual evapotranspiration rate is close to the potential rate. In areas with deeper or drier unsaturated zones, the model does not realistically represent the flow dynamics in the unsaturated zone. The model only considers average conditions and does not account for the relation between unsaturated hydraulic conductivity and soil moisture content – and thereby the soil's ability to transport water to the roots. The two-layer approach simply assumes that if sufficient water is available in the root zone, then the water will be available for evapotranspiration.

The calculation of evapotranspiration uses meteorological and vegetation data to predict the total evapotranspiration and net rainfall due to:

- canopy interception
- drainage from the canopy to the soil surface
- evaporation from the canopy surface
- evaporation from the soil surface and from the subsurface above the extinction depth
- uptake of water by plant roots and transpiration, based on soil moisture in the unsaturated zone.

In MIKE SHE, the evapotranspiration processes are split and modelled in the following order:

1 a proportion of the rainfall is intercepted by the vegetation canopy, from which part of the water evaporates

2 the remaining water reaches the soil surface, producing either surface water runoff or infiltrating to the unsaturated zone

3 part of the infiltrating water is evaporated from the upper part of the root zone or transpired by the plant roots

4 the remainder of the infiltrating water recharges the groundwater in the saturated zone while water content remains above the soil field capacity.

The two 'layers' in the approach represent average conditions in the unsaturated zone. The vegetation is described in terms of leaf area index (LAI) and root depth (RD). LAI describes the area of leaves above the unit area of the ground surface. Generalised time-varying functions of the LAI for most crops and types of vegetation are available in the literature. In Mike SHE, the temporal variation in LAI for each vegetation type is required. RD is defined as the maximum depth of active roots in the root zone. The soil properties include saturated hydraulic conductivity and soil moisture content at the wilting point, field capacity and saturation. The output is an estimate of actual evapotranspiration and groundwater recharge.

### Saturated flow

The saturated zone component of Mike SHE calculates the saturated subsurface flow in the catchment. Mike SHE allows for a fully three-dimensional flow in a heterogeneous aquifer to shift between unconfined and confined conditions. The spatial and temporal values of the hydraulic head are described mathematically by the three-dimensional Darcy equation and solved numerically by an iterative implicit finite difference technique. Mike SHE allows the subsurface geologic model to be developed independently of the numerical model. The parameters for the numerical grid are interpolated from the grid's independent values during pre-processing.

The saturated flow model was used to implement the groundwater flow within and between the aquifers described in the conceptual model (Marillier et al. 2012).

The geologic model can include both geologic layers and lenses. The former cover the entire model domain and the latter may exist only in parts of the model area. Geologic layers and lenses are assigned geologic parameters as either distributed values or as constant values. The geologic model is interpolated to the model grid during pre-processing by a two-step process:

1. the horizontal geologic distribution is interpolated to the horizontal model grid
2. the vertical geologic distribution is interpolated to the vertical model grid.

The upper boundary of the top layer is always the infiltration/exfiltration boundary, which in Mike SHE is calculated by the unsaturated zone component. The lower boundary of the bottom layer is always considered as impermeable. In Mike SHE, the rest of the boundary conditions can be divided into two types: internal and outer. If the boundary is an outer boundary then it is defined on the boundary of the model domain. Internal boundaries, on the other hand, must be inside the model domain.

### Interaction processes

Mike 11 and Mike SHE are coupled via river links located on the edges of adjacent grid cells. The river link network is created by the pre-processor, based on the Mike 11 coupling reaches (a coupling reach is a Mike 11 river reach that has been selected to interact with the Mike SHE model). The entire river system is always included in the hydraulic model, but Mike SHE will only exchange water with the coupling reaches. Mike 11 will exchange water with both the saturated zone model and the overland flow model. This occurs by a two-way gradient-driven dynamic flow exchange based on the Darcy approximation. It includes the degree of hydraulic contact expressed through distributed river-lining leakage coefficients. Loosing and gaining stream reaches will vary spatially and temporally. The interaction between Mike SHE and Mike 11 can simulate the baseflow component of the river and drain flows described in Section 6.3 of the conceptual model (Marillier et al. 2012).

The overland flow model will calculate the surface runoff and provide lateral runoff to the rivers in the Mike 11 network. The overland flow model will also interact with the unsaturated zone model, and infiltration and evapotranspiration is calculated from overland flow and the unsaturated zone model at each timestep.

The saturated zone component calculates the recharge/discharge between ponded water and the saturated zone without the unsaturated zone, if the phreatic surface is above the ground surface. Otherwise the saturated zone receives recharge from the unsaturated zone model. All model flux processes and algorithms are documented in the Mike SHE technical reference guide (DHI 2011).

# 3 Model construction

Model construction involves the transformation of the conceptual model (Marillier et al. 2012) into a mathematical form that can be used to simulate groundwater heads and flows, surface water and river flows. The required outcome is an interactive model with features to represent the hydrogeological framework, hydraulic properties, hydrological processes and boundary conditions as defined in the conceptualisation stage.

## 3.1 Simulation periods

The model simulation period is from 1 January 1970 to 31 December 2010, which is 40 years. The years 1980 to 2004 were used for model calibration, which includes both wet and dry sequences and incorporates long-term trends in groundwater level. The years 2005 to 2010 were used for model validation.

## 3.2 Model domain

The model was configured using a grid resolution of 200 x 200 m over the extent of the study area defined in the conceptual model report (Marillier et al. 2012). Mike SHE uses a regular grid, and it is possible to configure smaller, nested models within a larger model by using boundary conditions from previous simulations. The model consists of 17 688 internal cells and 527 boundary cells, as shown in Figure 3-1. Coordinate details for the model domain and grid are shown in Table 3-1. The model domain has been configured using a non-Universal Transverse Mercator (UTM) grid with no rotation; however, coordinate values are consistent with GDA 1994 MGA Zone 50 (GDA: Geocentric Datum of Australia; MGA: Map Grid of Australia) and model input and resulting grids can be displayed and analysed in this projection.

*Table 3-1 Model domain and grid values*

| | |
|---|---|
| **Cell size** | 200 m |
| **Projection** | non-UTM |
| **X minimum** | 377553 m |
| **X maximum** | 407353 m |
| **Y minimum** | 6410035 m |
| **Y maximum** | 6440635 m |
| **Total model area** | 727.6 $km^2$ |
| **Number of cells (X)** | 149 |
| **Number of cells (Y)** | 153 |
| **Computational layers** | 3 |

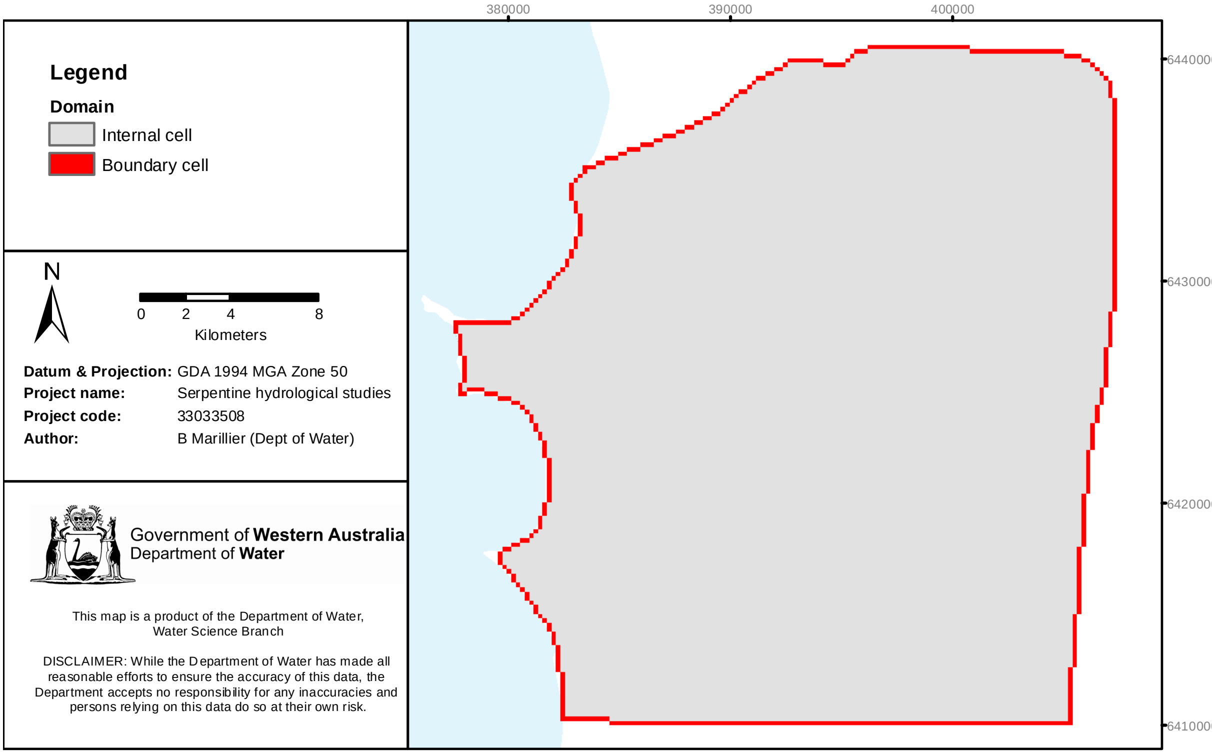



*Figure 3-1 Model domain*

## 3.3 Topography

The topography is the layer most used in the Mike SHE model. It is the upper layer for the saturated zone and unsaturated zone models, and it is used to determine the flow direction and velocity in the overland flow model.

The 2008 Department of Water LiDAR (light detection and ranging) dataset was re-sampled to a 200 m grid size using bilinear interpolation to generate the topographic surface used within the model. The Kwinana Freeway was included in the topographic dataset using more recently flown LiDAR (May 2010). The resampling process leads to some generalisation, which introduces error into the model. The resulting topography is shown in Figure 3-2.

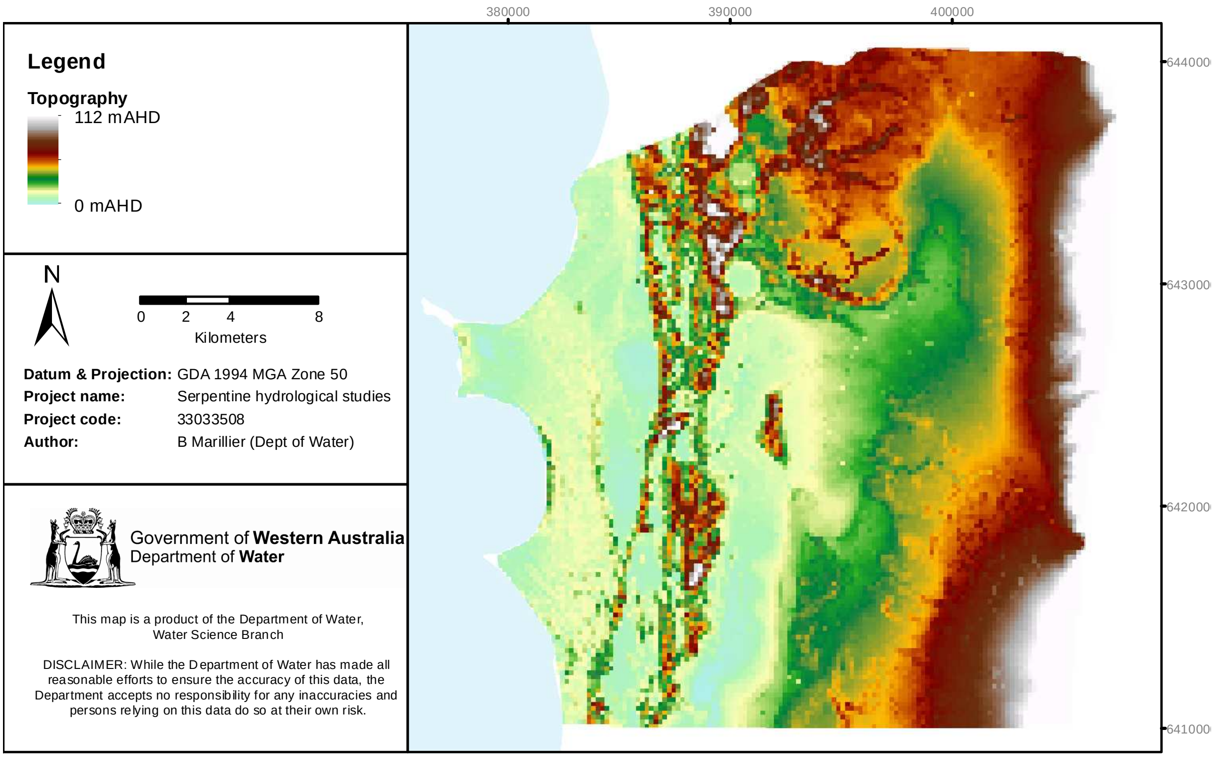



*Figure 3-2 Topography*

## 3.4 Rainfall and evapotranspiration

Rainfall and potential evapotranspiration (PET) are the primary hydrologic drivers of the Mike SHE model. Spatially, they can either be homogeneous over the entire catchment, or they can vary by assigning a rainfall and PET file to separate climate zones. Within the Lower Serpentine model, an increasing trend in rainfall moving to the south-east is occurring, as described in the conceptual model (Marillier et al. 2012). This variation in rainfall was captured within the model using SILO gridded data (QDERM 2011) across nine grid cells. The model area was divided into nine climate zones to enable input rainfall and PET time-series to be distributed. A 10th zone was added over Alcoa's containment ponds in the catchment's north. This area was set to receive no rainfall, so that recharge does not occur beneath the ponds.

The climate zones are shown spatially in Figure 3-3. A comparison of average annual rainfall and FAO56 Penman-Monteith PET data for all climate zones and the Serpentine meteorological station are shown in Figure 3-4. (FAO: the United States' Food and Agriculture Organization.)

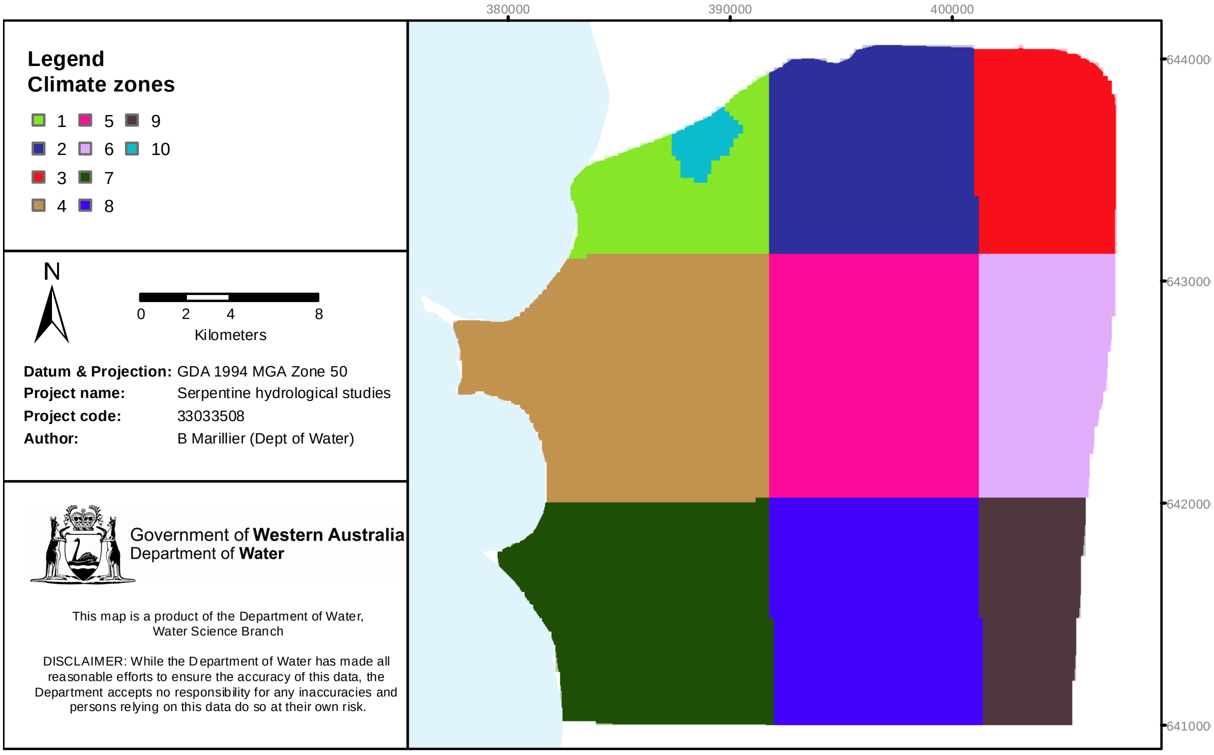



*Figure 3-3 Climate zones*

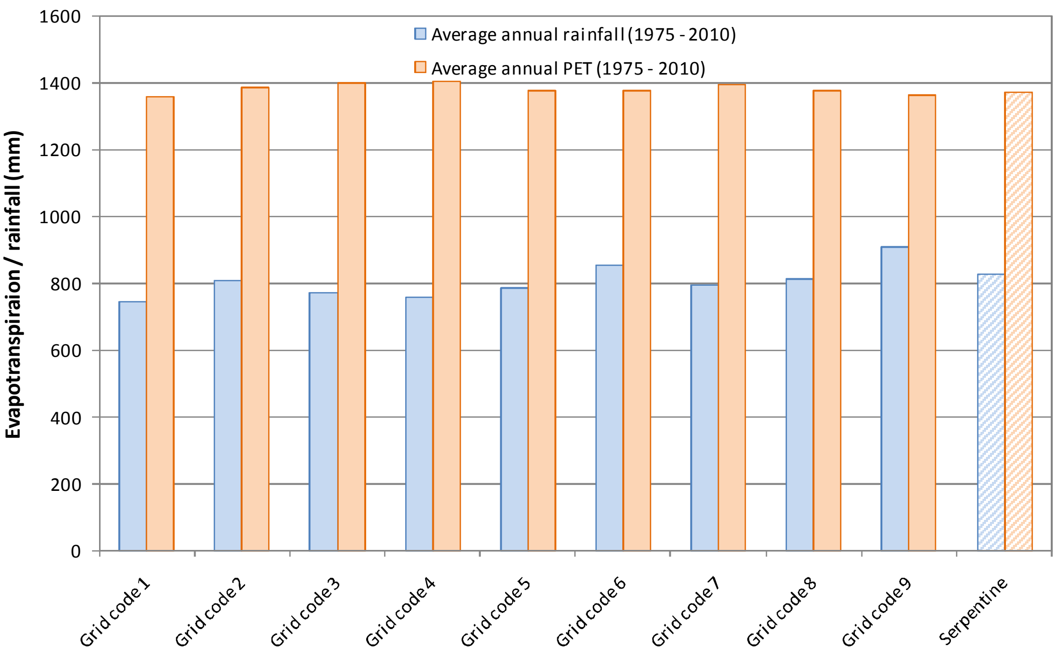



*Figure 3-4 Average annual rainfall and FAO56 potential evapotranspiration (1975–2010) for SILO gridded data and the Serpentine meteorological station (9039)*

## 3.5 Evapotranspiration model

The parameters for the evapotranspiration model include RD and LAI. The catchment's land use was divided into six categories, each with corresponding values for LAI and RD. Land use for the Serpentine study area was taken from the conceptual model report, and re-categorised into six groupings (Figure 3-5). Initial parameter values were based on the calibrated values used in the Murray regional model (Hall et al. 2010), as shown in Table 3-2. These are consistent with ranges defined in the conceptual model.

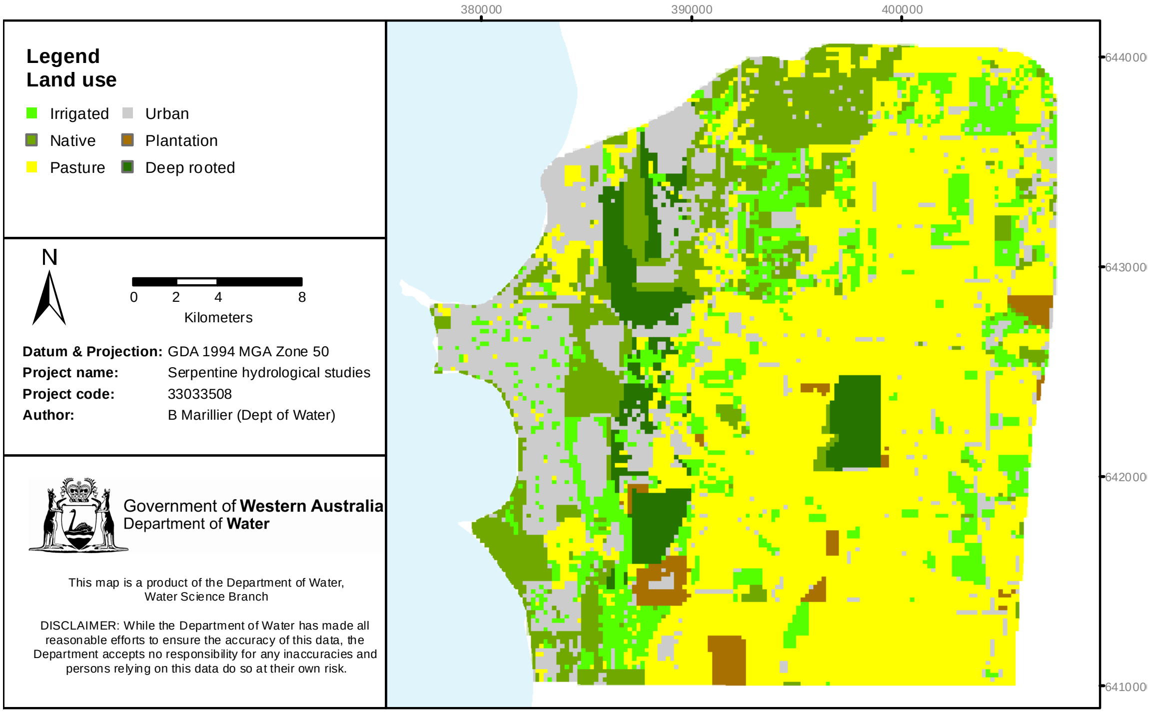



*Figure 3-5 Land use*

*Table 3-2 Initial unsaturated zone land use parameters (Hall et al. 2010)*

| Murray land use | Serpentine land use | LAI ($m^2/m^2$) | RD (mm) |
|---|---|---|---|
| Bare / urban | Urban | 1 | 1000 |
| Plantation | Plantation | 1.8 | 2000 |
| Native vegetation | Native vegetation | 1.3 | 2000 |
| N/A | Native vegetation - deep rooted | 2 | 4000 |
| Grazing (irrigated) | Irrigated | 3 | 1200 |
| Grazing (non-irrigated) | Pasture | 0 to 3 | 800 to 1300 |

With the exception of pasture, all land use classes have a constant LAI and RD throughout the simulation. The values for LAI are subject to calibration in the model within the bounds defined in the conceptual model. For pasture, a monthly trend of LAI and RD is assigned that follows normal pasture growth and senescence in monthly increments (Xu et al. 2009). The annual LAI and RD profile for pasture is shown in Figure 3-6.

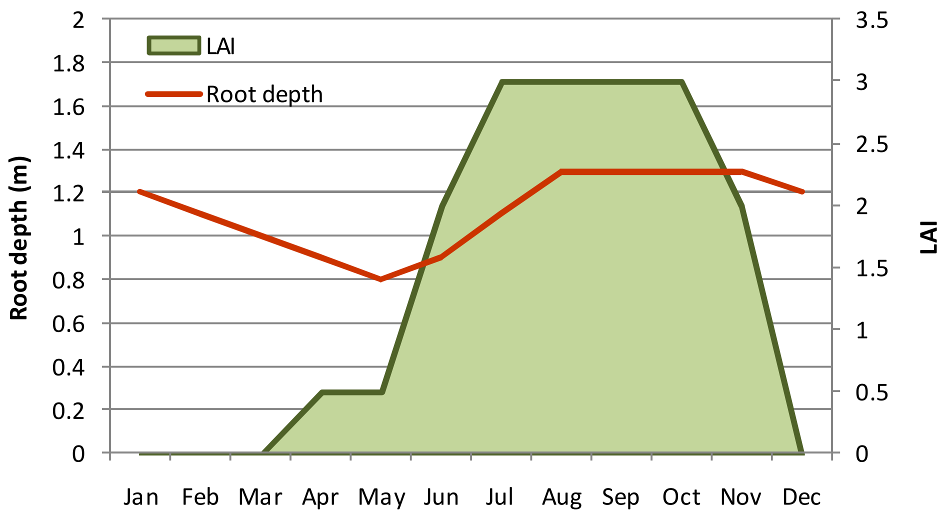



*Figure 3-6 Monthly root depth and leaf area index for the grazing land use*

# 3.6 Channel flow model (Mike 11)

Mike 11 is the channel flow model used by Mike SHE. It is a one-dimensional model and consists of a set of nodes along a river reach. Water will flow from node to node, and nodes are linked together to form the river network. At channel nodes physical properties such as river cross-section geometry, floodplain topography, channel and floodplain roughness and/or structure geometry can be assigned. Time-series data can be stored at the nodes, including boundary conditions (Q-h, flow time-series, constant head etc.) or calibration data. The Mike 11 simulation file for the Lower Serpentine model requires four physical data editors: a river network editor, cross-section editor, boundary file editor and hydraulic parameter editor.

## River network

The Mike 11 river network editor was used to implement drainage within the model, and included all of the major waterways shown in Table 3-3, as described in the conceptual model report (Marillier et al. 2012). The drainage network consists of the following components:

- digitisation of points and connection of river branches
- definition of weirs, culverts and other hydraulic structures
- definition of interaction processes between the river network and the overland flow and saturated zone models.

The extent of the hydrological network, as defined by the river network file used in the Lower Serpentine model, is shown in Figure 3-7. A fine-scale network of agricultural drains was modelled using drain codes, as described in Section 3.9 under *Drainage (saturated zone)*.

The leakage coefficient, which determines the rate at which water is exchanged between the river network and groundwater, was set to 1 x $10^{-7}$ based on the recommended range provided by the Danish Hydrological Institute (DHI) of between 1 x $10^{-6}$ for high hydraulic contact and 1 x $10^{-7}$ for low hydraulic contact. The leakage method was set to 'riverbed only' which means the leakage coefficient is the only user-defined parameter controlling flow between the river and groundwater (note that modelled river stage and groundwater head also determine the rate of exchange for each timestep).

It is possible to configure Mike 11 to allow interaction between channel and overland flow using either overbank spilling or flood codes. For the Lower Serpentine model, the flood code option was used at the Bollard Bullrush Swamp, the Spectacles Wetlands and Mandogalup Swamp. Flood codes relate water elevation in flood areas (in this case the wetland areas) to the river stage in the Mike 11 model. Mike SHE grid points within the wetland area are linked to the nearest h-point in Mike 11. Surface water stages are calculated in Mike SHE by comparing the water levels in the h-points with the surface topographic elevations in the flooded area. This is the most computationally efficient way to model inundated areas situated within the river network. The extent of the areas defined by flood codes are shown in Figure 3-7. See the Mike SHE reference guide (DHI 2011) for further detail on the interaction between Mike 11 reaches and flooded areas.

The Mike 11 timestep was set to 1.5 minutes, which enabled effective simulation without numerical instabilities at low flow.

The Mike 11 network for the Lower Serpentine model consists of 21 branches, 269 h-points (stage calculation) and 248 Q-points (discharge calculation). Only the major rivers and drains were modelled using the Mike 11 model, although smaller drains were included using the drainage option specified within the saturated zone module (see Section 3.9). No hydraulic structures were included in the model, as Mike 11's primary role is to drain superficial groundwater and direct overland flow to the appropriate river system. River and groundwater interactions are unlikely to be influenced by hydraulic structures within the study area. Cross-section spacing constrains computational points to every 500 to 1000 m.

A longitudinal profile view for each branch in the Mike 11 network is shown in Appendix A.

*Table 3-3 Rivers and drains simulated in the Mike 11 network*

| Reach name | Start chainage (m) | End chainage (m) | Reach name | Start chainage (m) | End chainage (m) |
|---|---|---|---|---|---|
| Beenyup Brook | 0 | 7354 | Oaklands Drain 2 | 0 | 7668 |
| Berriga Drain 1 | 0 | 22464 | Peel Main Drain | 0 | 28982 |
| Berriga Drain 2 | 0 | 5307 | Punrack Drain 1 | 0 | 11278 |
| Cardup Brook | 0 | 5792 | Punrack Drain 2 | 0 | 336 |
| Dirk Brook 1 | 0 | 3115 | Punrack Drain 3 | 0 | 7773 |
| Dirk Brook 2 | 0 | 11823 | Serpentine Drain 1 | 0 | 6935 |
| Karnet Brook | 0 | 8915 | Serpentine Drain 2 | 0 | 5714 |
| Manjedal Brook | 0 | 7111 | Serpentine Drain 3 | 0 | 2675 |
| Medulla Brook | 0 | 7829 | Serpentine River 1 | 0 | 6295 |
| Myara brook | 0 | 2936 | Serpentine River 2 | 0 | 11741 |
| Oaklands Drain 1 | 0 | 4358 | | | |

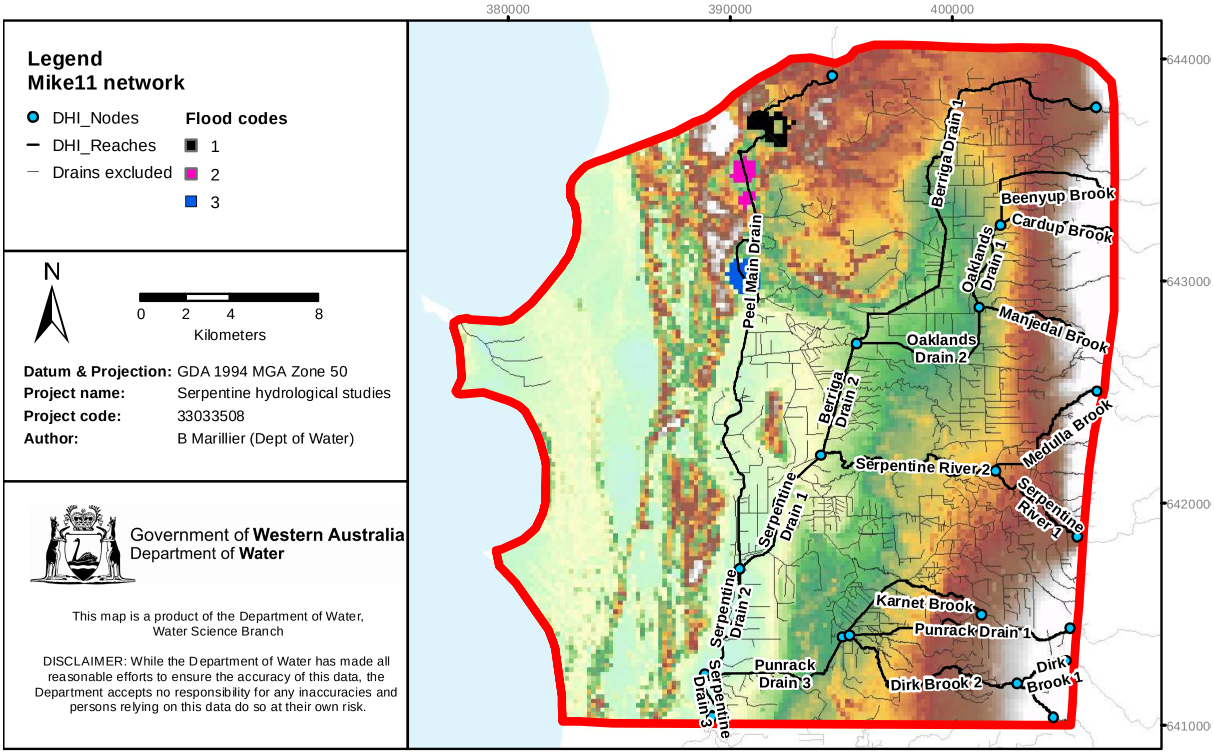



*Figure 3-7 Mike 11 network: fine grey lines show drainage that was not included in the network (these drains were included in the saturated zone drainage model)*

## Cross-sections

The river cross-section data comprises both raw and processed data. The raw data describes the physical shape of a cross-section using (x, z) coordinates. Raw cross-section data was extracted across the study area using the Department of Water 1 m resolution LiDAR dataset. Cross-sections were spaced to capture major changes in channel shape and hydraulic gradient within the river and drain network, which usually resulted in a spacing between cross-sections of 500 to 1000 m. Each cross-section was examined for erroneous data, and conveyance was calculated using the ‘equidistant’ method within the Mike 11 cross-section editor.

## Boundaries

The boundary conditions in Mike 11 are defined by the combined use of time-series data and specifications made on locations of boundaries. Two types of boundary conditions were used in the Mike 11 model:

- **Inflow boundaries:** included at the upper end of each reach that extended beyond the model boundary (i.e. received inflows from outside of the model domain). At each such reach, a time-series of daily discharge was derived from Streamflow Quality for Rivers and Estuaries (SQUARE) modelling (Kelsey et al. 2010) of the relevant catchment. Each SQUARE model was re-calibrated using the appropriate SILO gridded data, so that the inflow boundary data was consistent with the Lower

Serpentine Mike SHE model data, which is important for future climate scenarios. Nine reaches were configured with dynamic inflows including the Beenyup, Cardup, Manjedal, Medulla, Dirk and Myara brooks, Serpentine River, and Punrack and Peel main drains. See Appendix B time-series information.

- **Water level boundaries:** implemented at the downstream end of the Serpentine River. The water level was set at 0 mAHD to approximate mean sea level.

### Hydrodynamics

The hydrodynamic editor allows for user-specified parameters for hydrodynamic calculations. The most important consideration is the wave approximation technique, which determines whether the fully dynamic wave, diffusive wave or kinematic wave solution is used. For the Lower Serpentine model, the slower, more stable fully dynamic wave solution was required by the low hydraulic gradients and backwater effects in the channel network.

The Manning's roughness coefficient was set to a global value of 0.033 as defined in the conceptual model.

## 3.7 Overland flow model

The SOR method was used for calibration of the Lower Serpentine regional model. The Manning *M* (inverse of Manning *n*) value was set globally as 30 $m^{1/3}/s$, which is appropriate for pasture and low grass (Gupta 2008). The detention storage parameter was set to 1 mm to account for sub-grid-cell storage of water before overland flow will occur.

## 3.8 Unsaturated flow model

Soil zones for the unsaturated flow model were developed for the numerical model as defined in Section 3.4 of the conceptual model report (Marillier et al. 2012). The classification of soils was constrained by the existing soil units in the Department of Agriculture and Food's Soil Landscape Units dataset. The sandy units of the study area consist of the Bassendean, Spearwood and Quindalup soil units (generally associated with the Bassendean, Tamala and Safety Bay Sand geologic units). The Pinjarra soils, generally associated with the Guildford Clay and alluvium, consist of duplex soils with higher quantities of clay. The Vasse soil unit (swamp, alluvium and estuarine) also consists of higher quantities of clay and organic matter associated with estuarine and wetland deposits. The Forrestfield soil unit located along the scarp consists of colluvial clays. The locations of the model's six unsaturated zone soil units are shown in Figure 3-8.

The unsaturated zone model had four parameters to calibrate:

- Water content at saturation: the maximum water content of the soil, which is approximately equal to the porosity.
- Water content at field capacity: the water content at which vertical flow becomes negligible. In practice, this is the lower soil water content for free drainage. The difference between the water content at saturation and the water content at field capacity should be approximately equal to the specific yield of the corresponding

geological layer. Mike SHE calculates the first computational layer's specific yield directly from the unsaturated zone parameters specified.

- Water content at wilting point: the lowest water content whereby plants can extract water from the soil. The difference between the water content at field capacity and the water content at wilting point is the plant-available moisture.
- Saturated hydraulic conductivity: this is equal to the vertical infiltration rate of the soil.

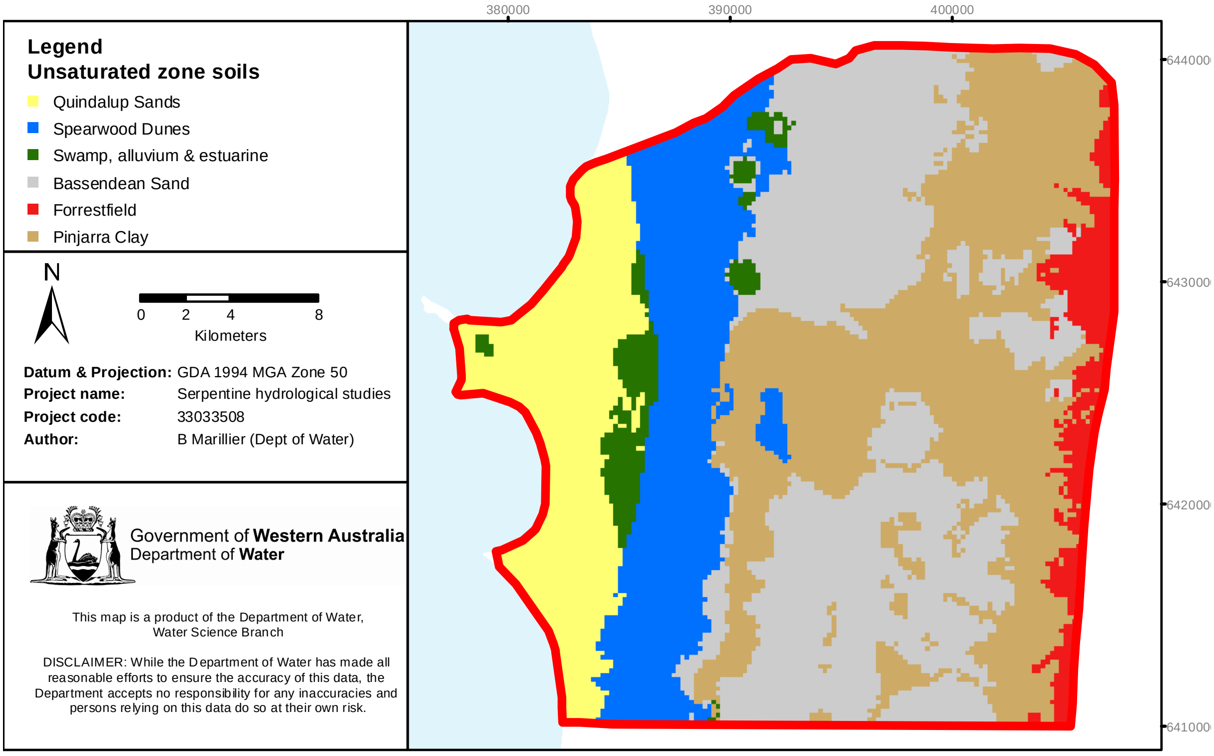



*Figure 3-8 Unsaturated zone soil units*

## Wastewater infiltration - irrigation module

The irrigation module within Mike SHE was used to simulate infiltration of wastewater near the Spectacles Wetlands (Figure 1-1) from the Kwinana wastewater treatment plant. The wastewater creates a local groundwater mound near the Spectacles monitoring bore SP1-1D – causing superficial groundwater to move in an easterly direction, counter to the regional movement of groundwater (Shams 2000).

The Water Corporation provided monthly discharge data for the infiltrated water, which was used to generate an irrigation time-series for input to the model. Average infiltration rates of 3386 kL/day were reported for the period 2001 to 2011. Infiltration began in 1975 and it was assumed that discharge rates increased linearly from no discharge in 1975 to 1600 kL/day in 2000. For the period 2001 to 2010 the discharge rates provided by the Water Corporation were used as time-series input in the model, with a reduction factor of 30% applied to account for evaporative losses within the ponded area. The reduction factor is necessary as the grid size prevents the ponds being modelled explicitly, and infiltration rates are therefore over-estimated by the model. The resulting time-series is shown in Figure *3-9* in units of mm/day. The discharge is applied over a single grid cell of 200 x 200 m using the irrigation module. Thus the discharge rate in ML/day from the treatment plant is the product of the irrigation rate in mm/day, the cell area in metres and 0.7.

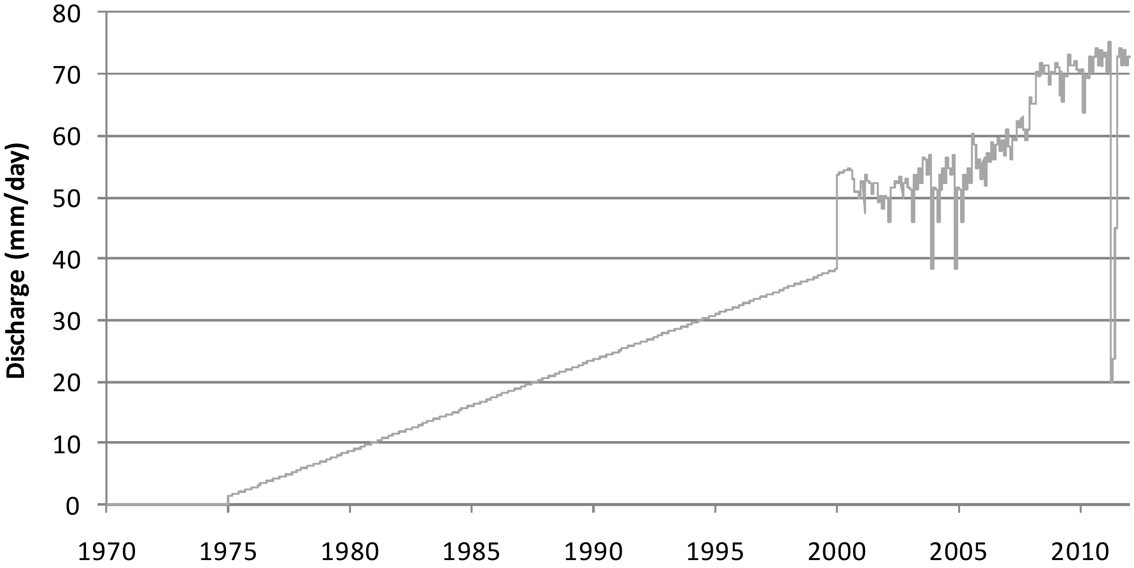



*Figure* 3-9 *Time-series of wastewater infiltration rates near the Spectacles Wetlands*

## 3.9 Saturated flow model

The saturated flow model is based on the conceptual hydrogeology described in sections 4.0 and 5.0 of the conceptual model report (Marillier et al. 2012). Each of the geological units described in the conceptual model was converted into units within the computational model. The gridded data defining the upper, lower and lateral extent of the units were re-sampled to the 200 m grid size used by the numerical model. The units were distributed within three ‘geological layers’, which are defined by the extent of the superficial formations, the Pinjar Member and Kardinya Shale, and the Wanneroo Member and Rockingham Member (proposed), as discussed in the following section. Note that the Rockingham Member (proposed) is equivalent to the formation previously called the Rockingham Sands. As the term Rockingham Member has not been formally adopted by the Department of Water it will be referred to as (proposed) in this report. Mike SHE was configured such that the extent of the geological layers was coincident with the extent of the computational layers. As such, the construction of the saturated zone numerical model is a direct translation of the three-dimensional geology shown in the conceptual model report (Marillier et al. 2012) in Section 4.3 and includes the Superficial, Rockingham and Leederville aquifers.

### Geological layers

In Mike SHE, each geological aquifer is required to span the entire model domain, and is entered as a ‘geological layer’. Three geological layers were entered into the model:

- **Superficial** which includes the sediments that comprise the Superficial Aquifer

- **Pinjar and Kardinya** which includes the Pinjar Member of the Leederville Formation, and also the Kardinya Shale Member of the Osborne Formation
- **Wanneroo** which includes the Wanneroo Member and Rockingham Member (proposed) of the Leederville Formation.

The detailed conceptual geology and hydrogeology was later entered as geological lenses within Mike SHE.

## Geological units

The Lower Serpentine model was configured with a total of 16 geological units. Using geological units, it is possible to completely distribute aquifer parameters within the computational layers, such that the numerical model represents as closely as possible the actual geology interpreted in the conceptual model. The block model shown in the conceptual model report (Marillier et al. 2012) identifies the extent of these layers. Calibration of the numerical model identified some deficiencies in the conceptual hydrogeology. As such, the conceptual model was updated with three additional units to improve geological resolution. These included the Tamala Sand on the Jandakot Mound’s western edge, lake sediments around lakes Walyungup and Cooloongup, and basal clays at the base of the Safety Bay Sand. The numerical model was updated to reflect the revised conceptualisation. Each geological unit is defined by a lateral extent, and upper and lower levels, and is consistent with the geology defined in Section 4 of the conceptual model report (Marillier et al. 2012). The units contained within the model are listed below:

- The **Safety Bay Sand** is a fine- to medium-grained quartz sand with numerous shell fragments. It is present as a band of low-lying dunes to the west of the Tamala Limestone, and is up to 25 m thick in some locations. The extent of the Safety Bay Sand is shown in Figure 3-10. The **basal clay** unit (Figure 3-11) was inserted beneath the Safety Bay Sand underneath Rockingham, where the Safety Bay Aquifer is effectively disconnected from the underlying Rockingham Aquifer. The basal clay layer is up to 3 m thick in some areas and is discussed by Passmore (1970).
- The **Tamala Limestone** is composed of limestone, calcarenite and sand, with minor clay and shell beds. The limestone contains numerous solution channels that form a karst aquifer. Below approximately 3 mAHD the formation contains marine and lacustrine sediments. 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. The top and base of the Tamala Limestone formation, as represented in the numerical model, is shown in Figure 3-12. Within the model, the Tamala Limestone is divided into eastern and western sections. The **Tamala Sand** unit (Figure 3-13) was introduced to the model close to the Spectacles Wetlands, to account for lower hydraulic conductivities associated with lithified calcarenite. The extent of this unit is approximated by the *Perth groundwater atlas* (DEC 2004) surface geology (Geol. code Qpcs), west of the Spectacles Wetlands.
- **Bassendean Sand** covers most of the study area. Bassendean Sand is pale grey to white and occasionally brown, moderately-sorted, fine- to medium-grained quartz sand with traces of heavy minerals. A layer of friable, mostly weakly limonite

cemented sand known as 'coffee rock' is commonly present at or near the watertable. The formation 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 Jandakot Mound. The top and base of the Bassendean Sand formation, as represented in the numerical model, is shown in Figure 3-14.

- The **Guildford Clay** is predominantly of fluvial origin and is generally constrained to within 5 to 10 km of the Darling Scarp. Guildford Clay is described as pale grey, blue, but mostly brown, silty and slightly sandy clay. The top and base of the Guildford Clay, as represented in the numerical model, is shown in Figure 3-15.
- The **Ascot Formation** exists beneath the Bassendean Sand within the Jandakot Mound in the study area's north. It consists of grey, poorly sorted, medium-grained sands with shell remains throughout. The top and base of the Ascot Formation, as represented in the numerical model, is shown in Figure 3-16.
- The **alluvium, estuarine and swamp** deposits are associated with the many rivers, lakes and wetlands 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 2008). Peaty and sandy swamp deposits are associated with the numerous wetlands, often having a dark brown, grey to black colour and being organic rich. The distribution of the alluvium, estuarine and swamp deposits, as represented in the numerical model, is shown in Figure 3-17. The extent of this unit was insufficient to capture sediments associated with lakes Cooloongup and Walyungup, so an additional **Lake Sediments** unit (Figure 3-18) was introduced to account for lower vertical conductivity in the area. The presence of clay and calcareous deposits and their influence as a partial confining layer to groundwater beneath the lakes is outlined by Passmore (1970).
- A layer of **colluvium**, which lies along the edge of the Darling Scarp, is identifiable as fragments of granite, laterite and clays unconformably overlying the Guildford Clay and Precambrian rocks. The grain size can range from coarse pebbly sand to poorly sorted silty sand and clay. The colluvium's thickness is highly variable but rarely exceeds 5 m. The distribution of colluvium, as represented in the numerical model, is shown in Figure 3-19.
- The **Quaternary Sand** consists of a pale grey to grey-brown, fine- to very-coarse-grained quartz sand. It is interpreted to occur throughout the central parts of the study area beneath the Guildford Clay and Bassendean Sand, as shown in Figure 3-20.
- The Osborne Formation is found in the centre of the syncline at the study area's northern end (Figure 3-21). Mainly consisting of the **Kardinya Shale** Member, it is composed of siltstone, shale and clay. It acts as a confining layer between the Superficial and Leederville aquifers.
- The **Rockingham Member (proposed)** is equivalent to the Wanneroo Member on the western side of the syncline (Kretschmer et al. 2011). It consists of medium- to coarse-grained feldspathic quartz sand of yellow, brown and pale grey colour. The

maximum thickness of the Rockingham Member (proposed) within the study area is around 150 m in the west. The extent of the formation is shown in Figure 3-22.

- The **Pinjar Member** is found in the central area of the syncline between the Mandurah and Serpentine faults. It consists of alternating layers of sand and clays and obtains its maximum thickness of around 100 m at the study area's northern edge. It acts as an aquitard between the Superficial and Leederville aquifers. The extent of the Pinjar Member is shown in Figure 3-23.
- The extent and elevation of the **Wanneroo Member** shows it was deposited in a syncline that is down-faulted between the Mandurah and Serpentine faults, and is up to 150 m thick within the study area. It consists of interbedded sands and siltstones. The Wanneroo is separated from the underlying Mariginiup Member by a green-clay bed, which acts as an aquitard between the upper and lower Leederville aquifers. The extent of the Wanneroo Member is shown in Figure 3-24.

The available data for the above formations within the Superficial Aquifer – in the Lower Serpentine regional model domain – were reviewed as part of the conceptual model. That review is summarised in Table 3-4, which shows the initial value of hydraulic conductivity and specific yield for the selected formations. In previous modelling studies (Xu et al. 2009; Hall et al. 2010) a horizontal to vertical hydraulic conductivity ratio of 10:1 was used to define the value for vertical hydraulic conductivity, and in the absence of field observations, was used to estimate vertical conductivity in some geological units. These ranges represent best estimates of the upper and lower bounds for aquifer properties that may be assigned during calibration.

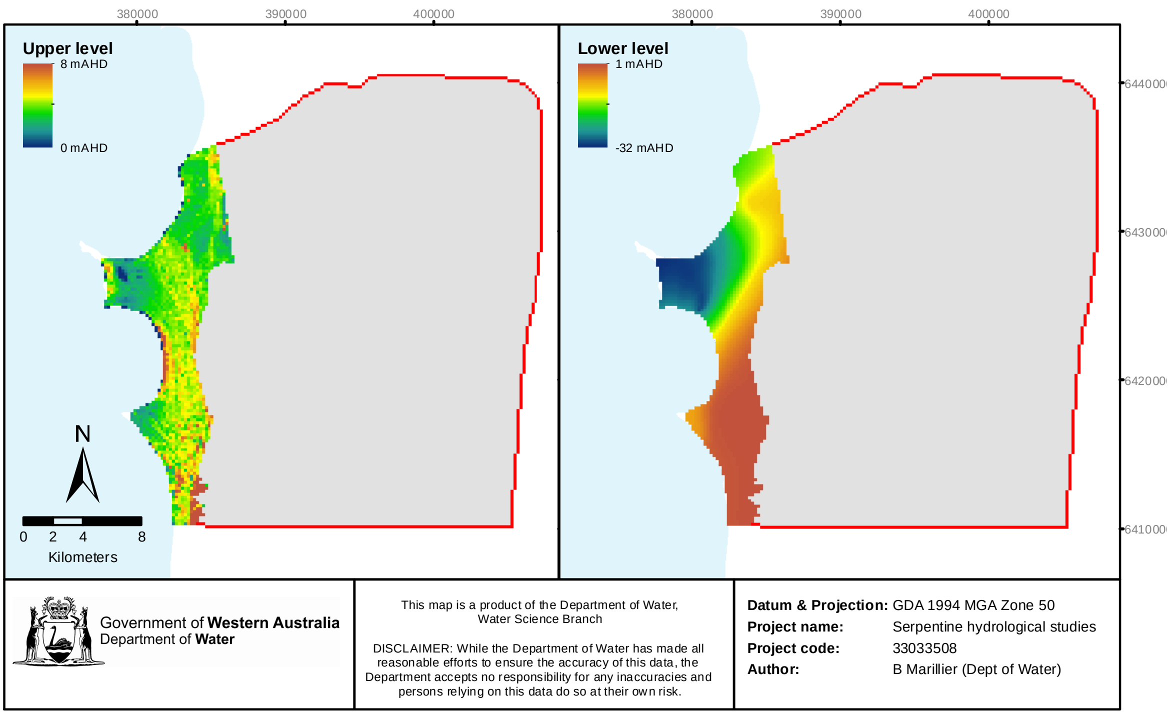



*Figure 3-10 Safety Bay Sand*

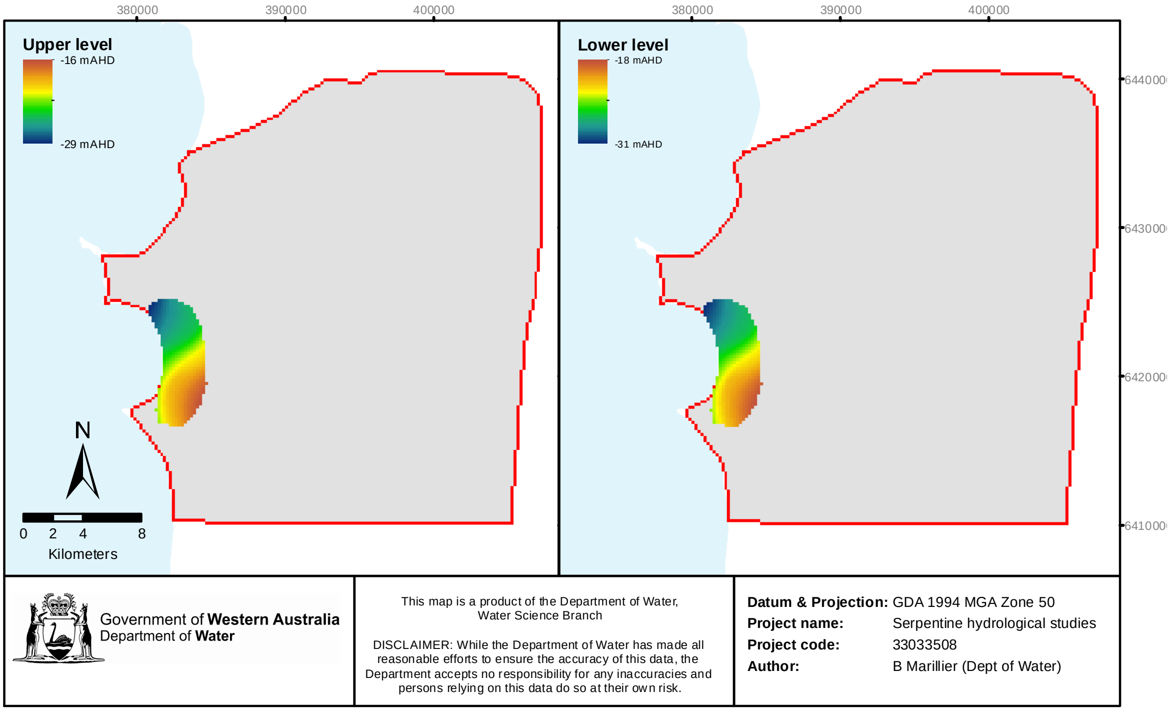



*Figure 3-11 Basal clay*

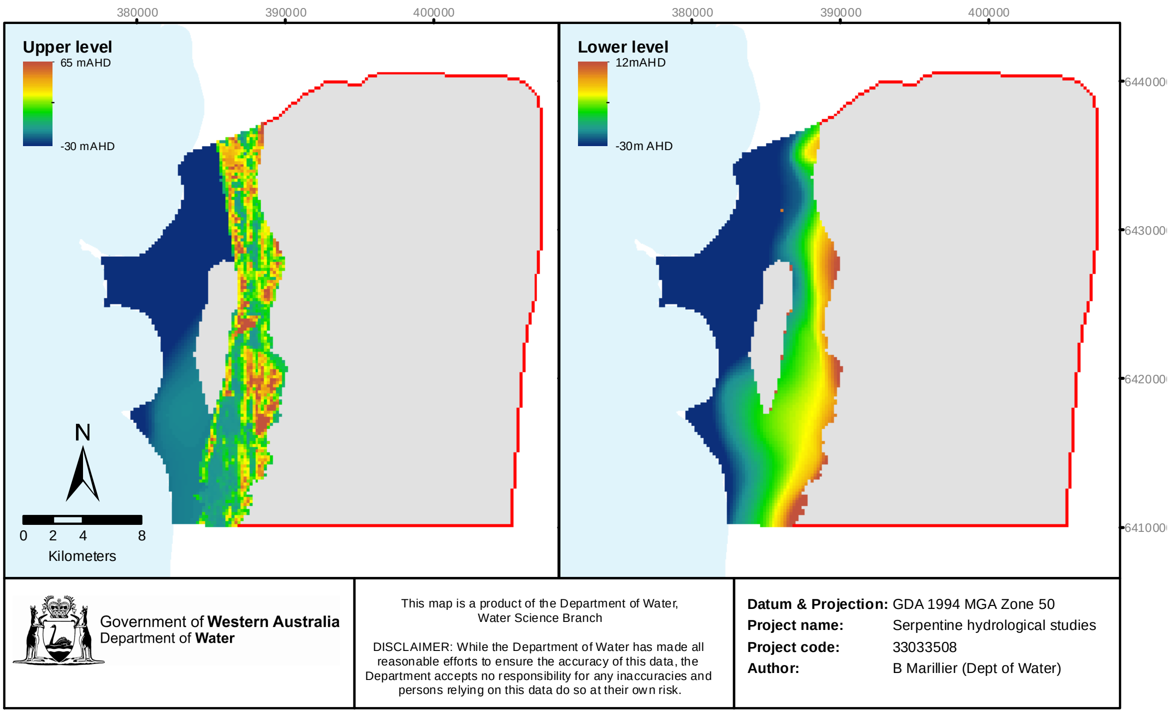



*Figure 3-12 Tamala Limestone*

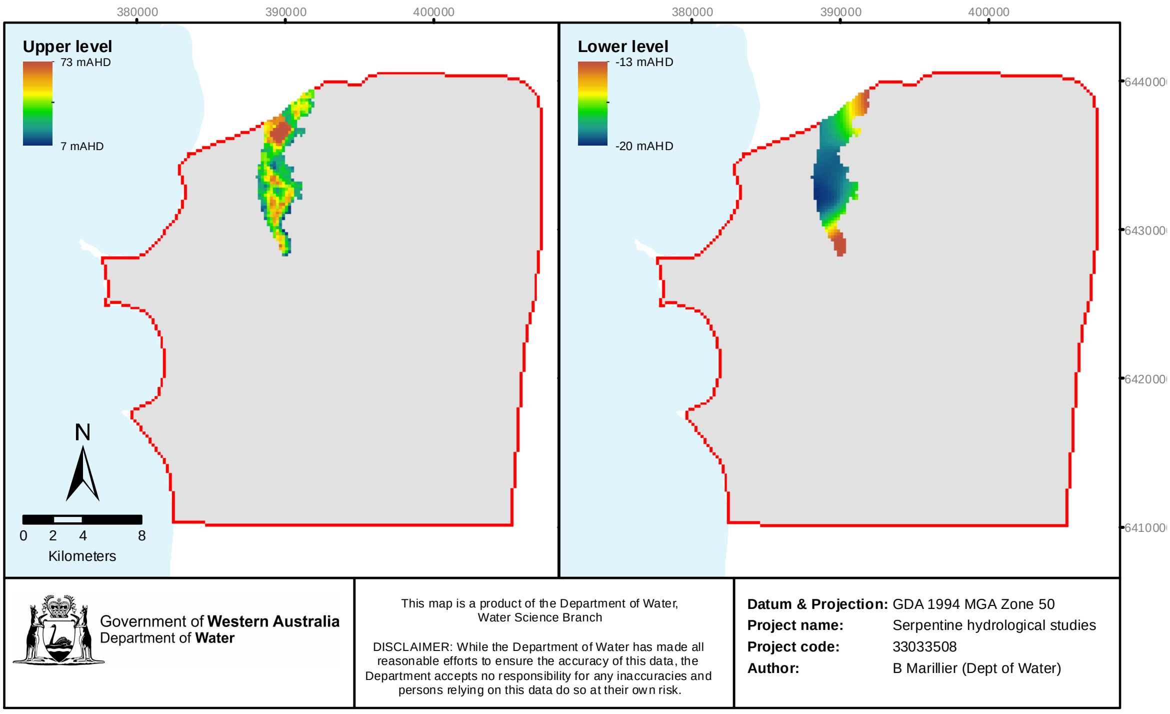



*Figure 3-13 Tamala Sand*

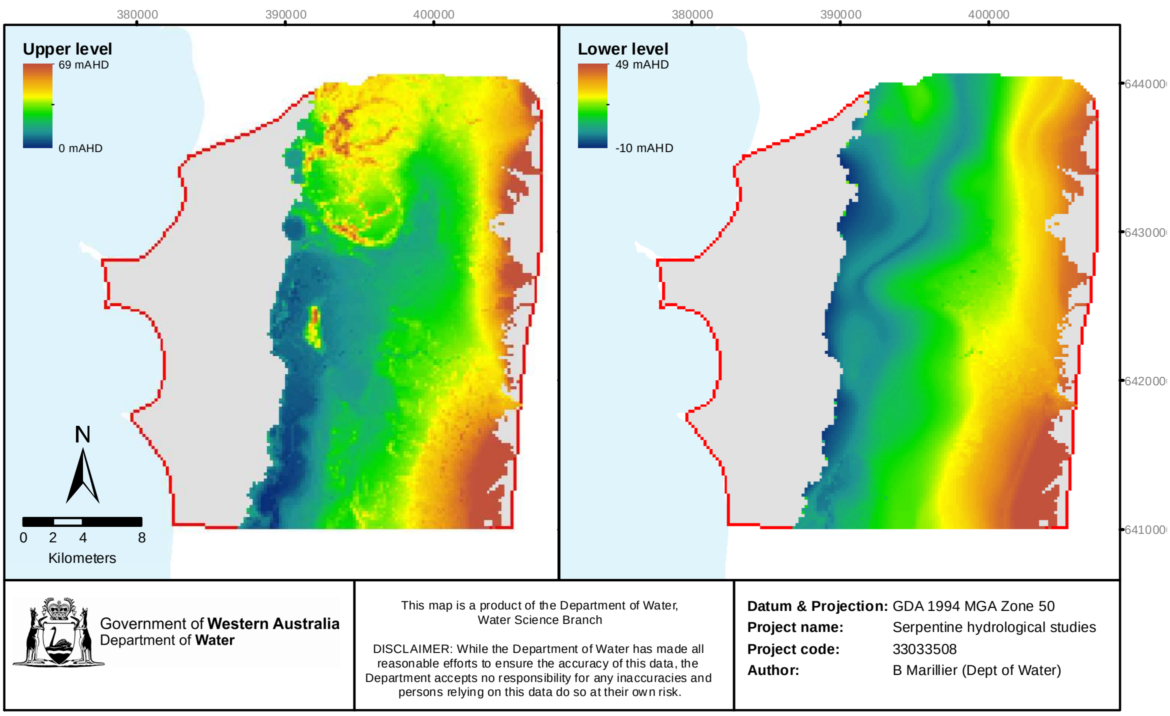



*Figure 3-14 Bassendean Sand*

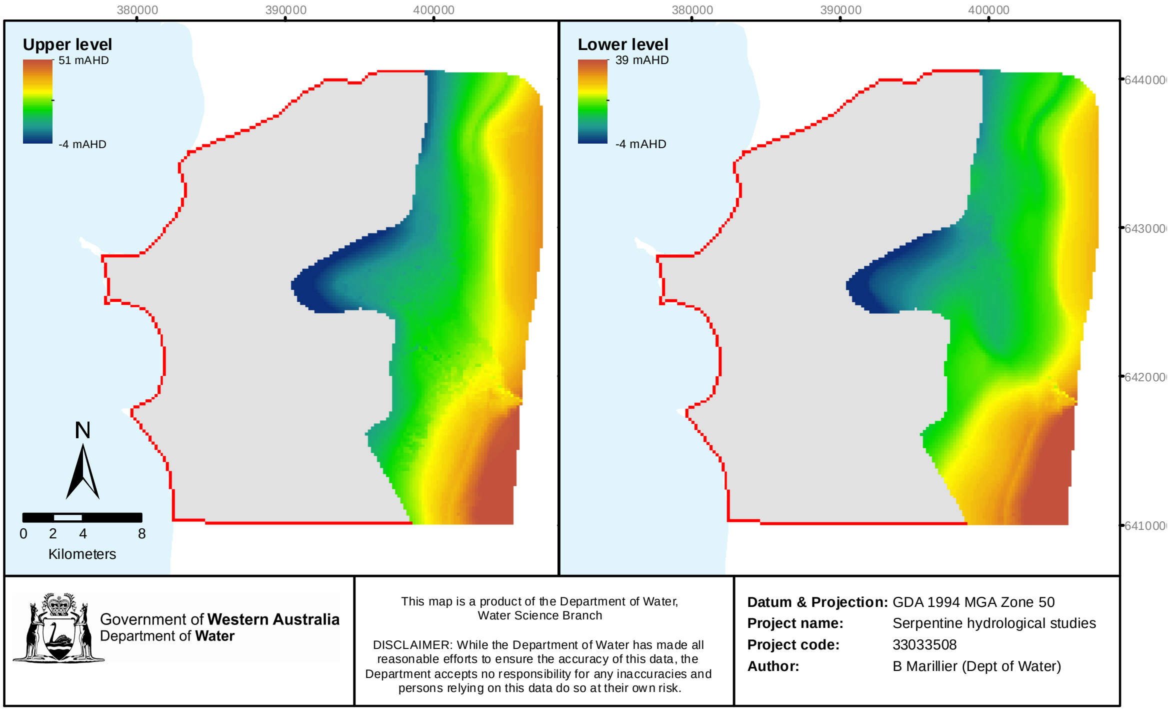



*Figure 3-15 Guildford Clay*

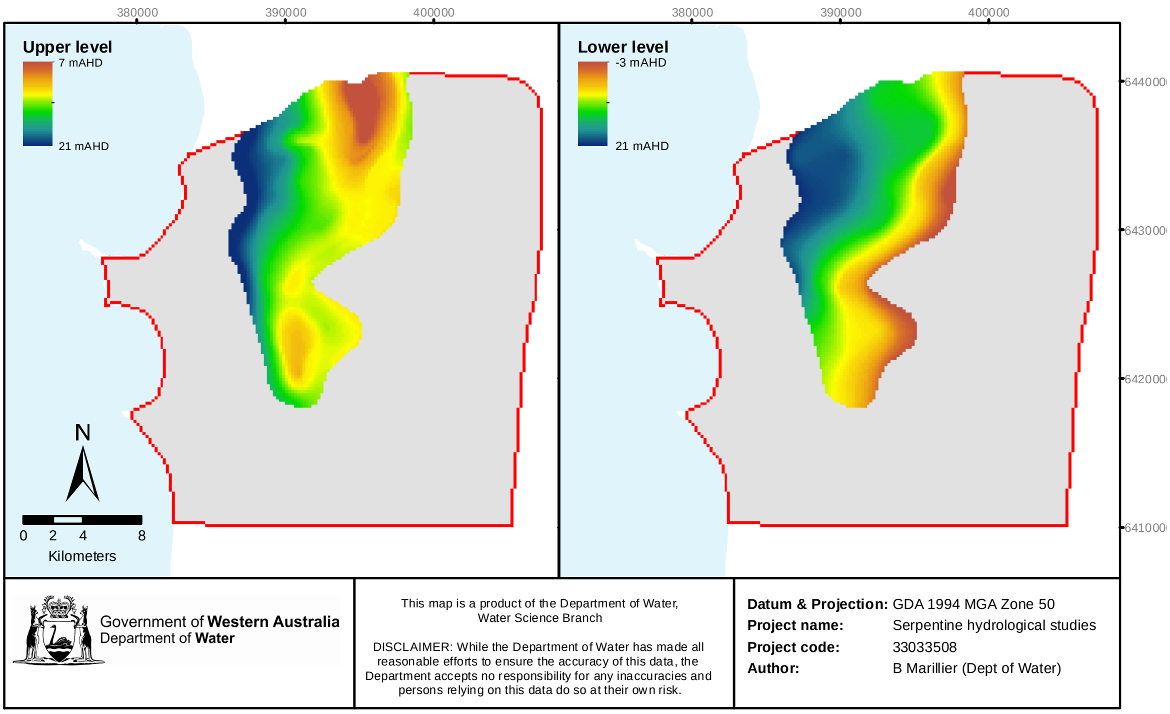



*Figure 3-16 Ascot Formation*

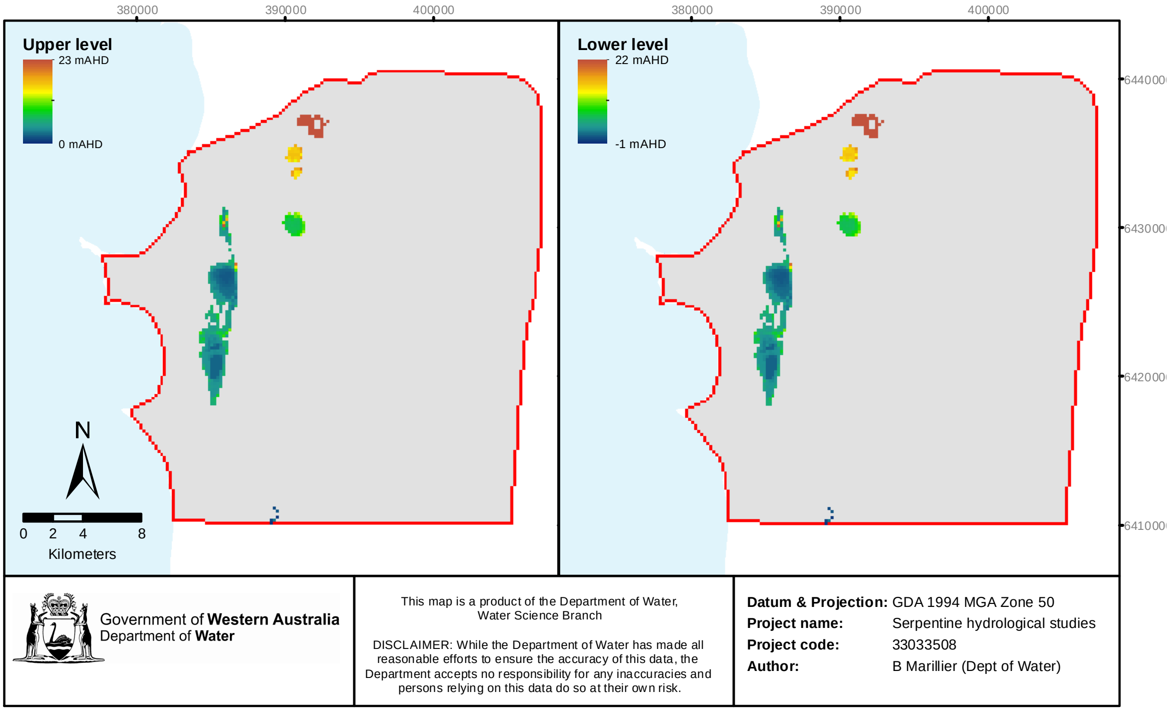



*Figure 3-17 Alluvium, estuarine and swamp sediments*

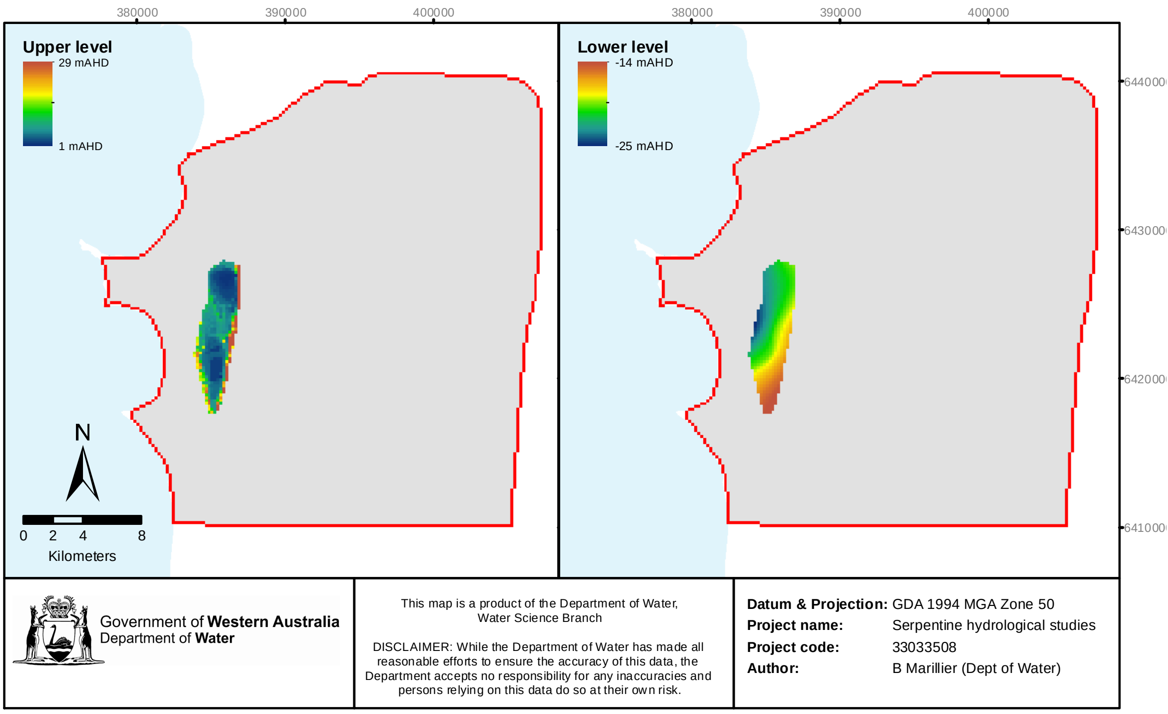



*Figure 3-18 Lake sediments*

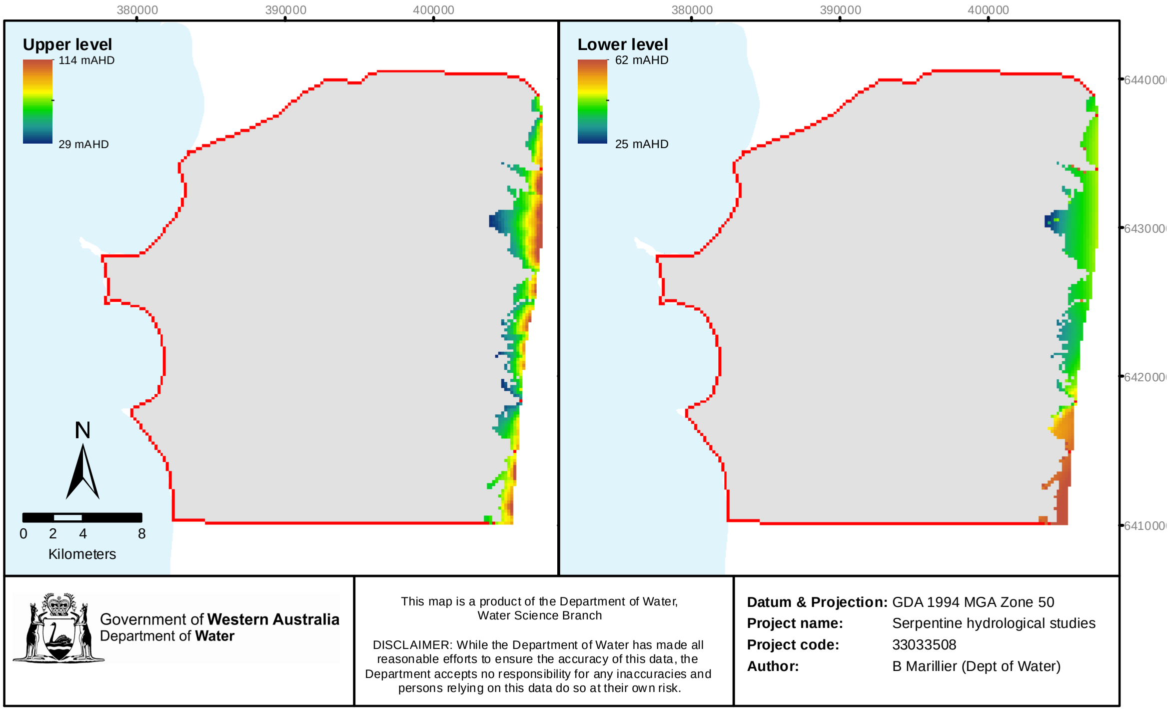



*Figure 3-19 Colluvium*

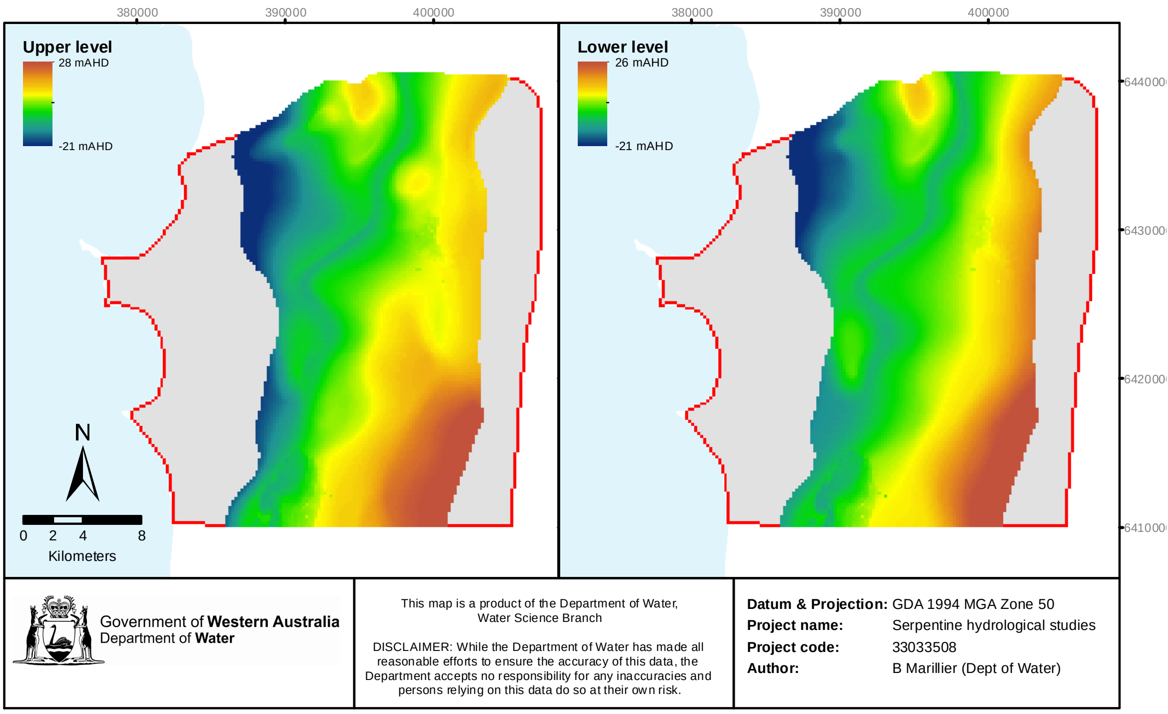



*Figure 3-20 Quaternary sands*

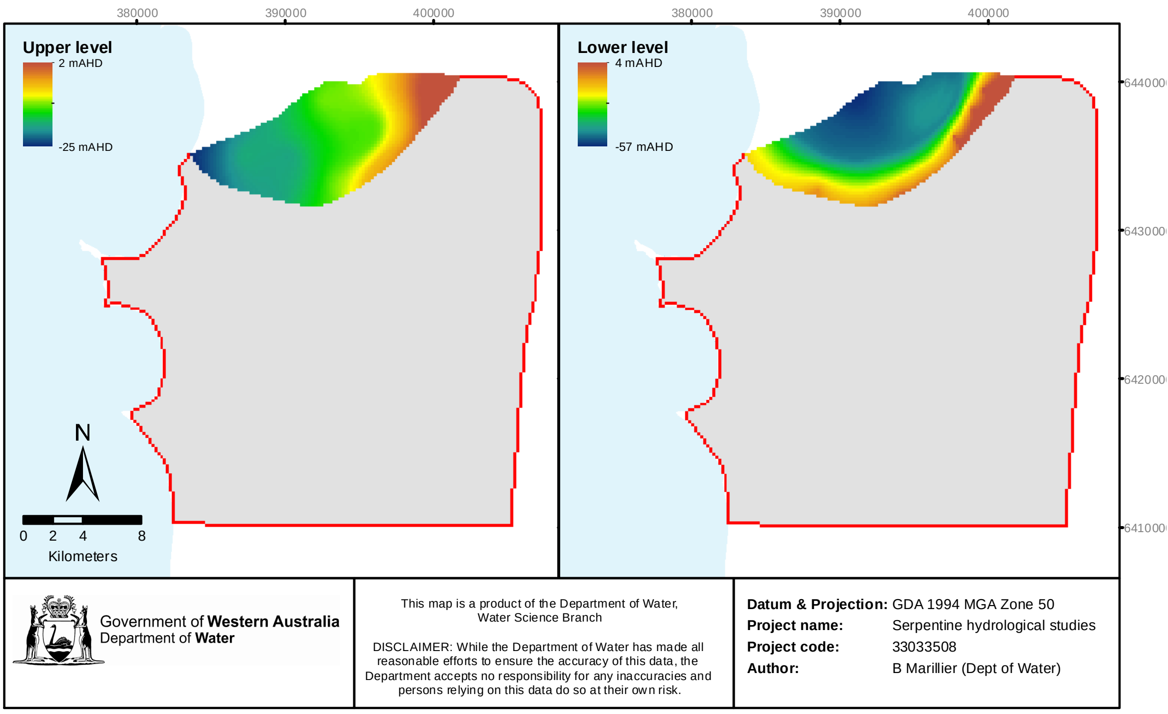



*Figure 3-21 Kardinya Shale*

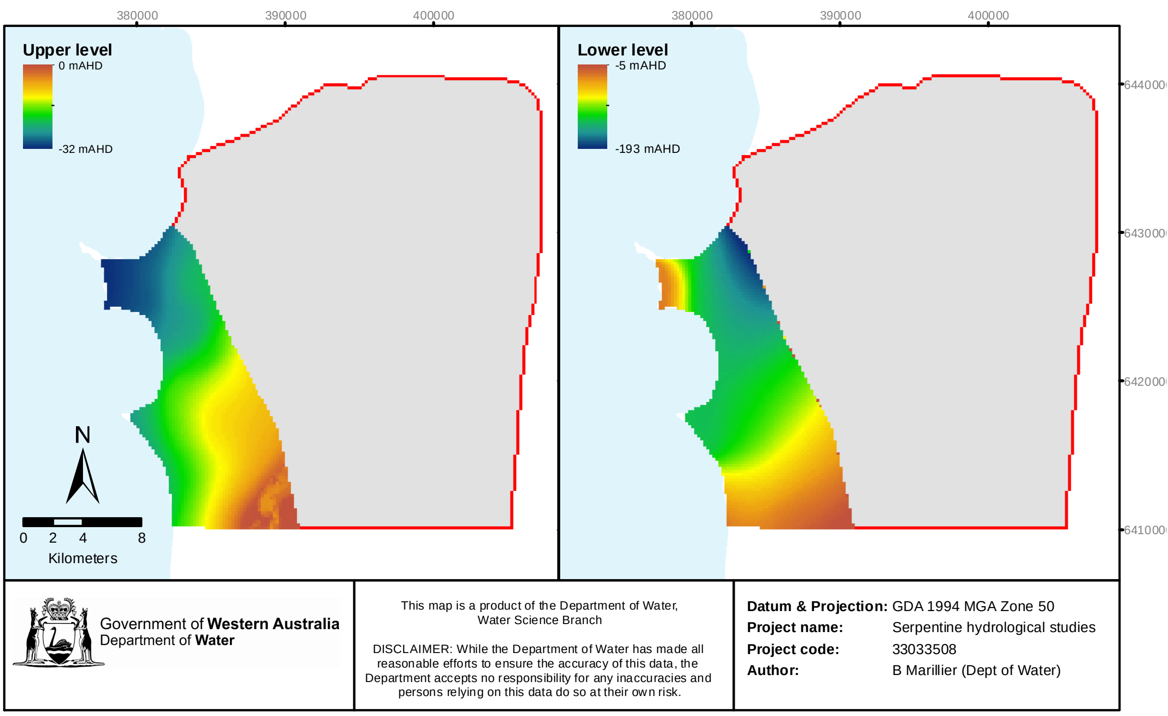



*Figure 3-22 Rockingham Member (proposed)*

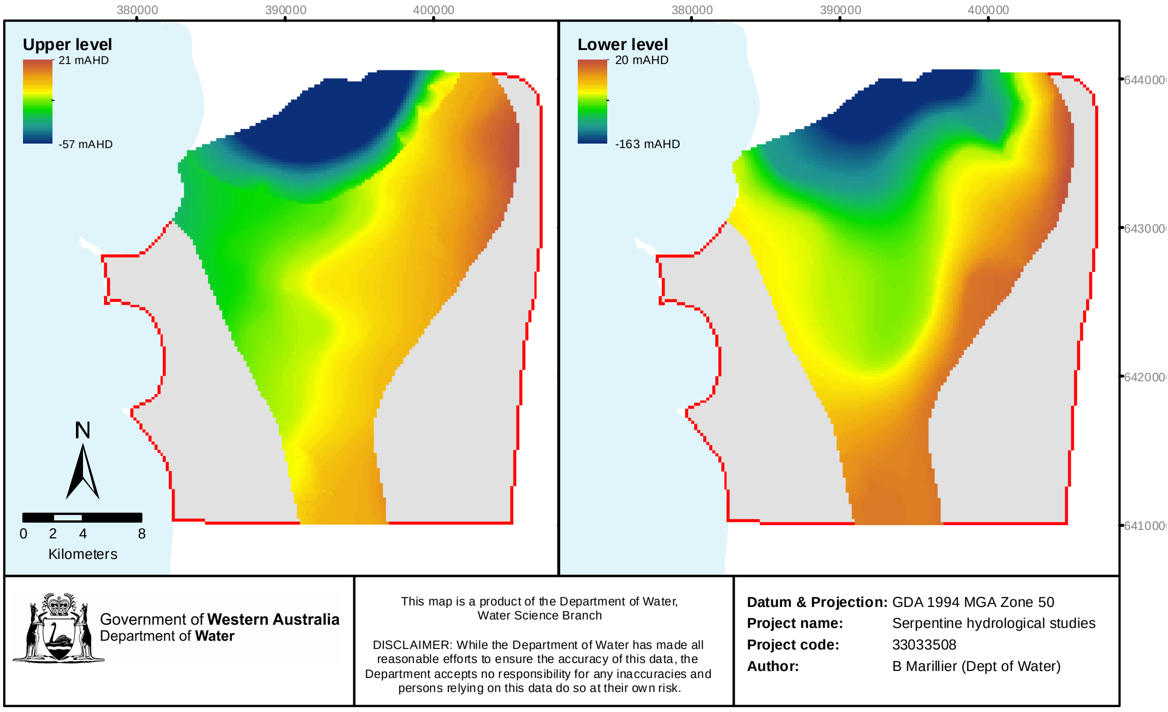



*Figure 3-23 Pinjar Member*

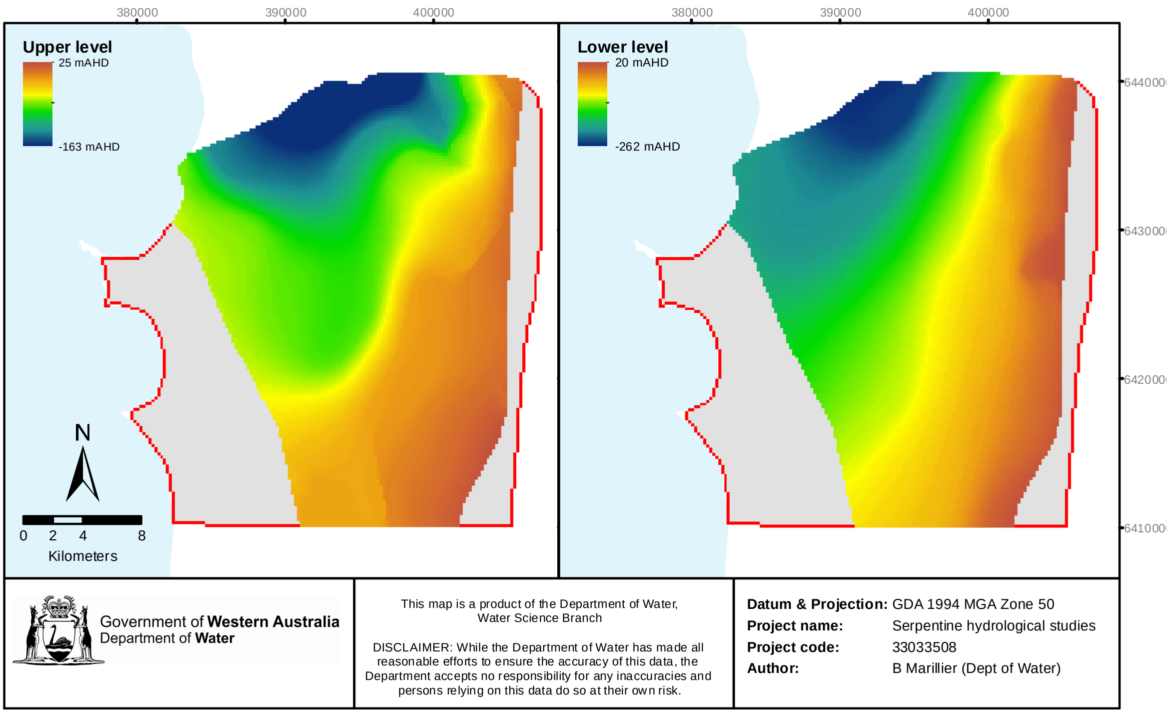



*Figure 3-24 Wanneroo Member*

*Table 3-4 Hydraulic parameter ranges for geological units within the Superficial, Rockingham and Leederville aquifers*

| Stratigraphy | $K_H$ (range) m/day | initial | $K_z$ (range) m/day | initial | $S_Y$ (Range) | initial | $S_c$ | initial |
|---|---|---|---|---|---|---|---|---|
| Lake sediments | 0.1 to 10 | 10 | 0.01 to 1.0 | 0.1 | 0.05 to 0.15 | 0.15 | $5\times10^{-5}$ | $1\times10^{-6}$ |
| Basal clay | 1 to 0.001 | 0.001 | 0.1 to 0.0001 | $5\times10^{-4}$ | 0.05 to 0.15 | 0.15 | $5\times10^{-5}$ | $1\times10^{-6}$ |
| Estuarine/swamp | 0.1 to 10 | 10 | 0.01 to 1.0 | 1 | 0.05 to 0.15 | 0.15 | $5\times10^{-5}$ | $1\times10^{-6}$ |
| Bassendean | 5 to 50 | 15 | 0.5 to 5.0 | 1.5 | 0.10 to 0.28 | 0.2 | $1\times10^{-6}$ | $1\times10^{-6}$ |
| Tamala Sand | 1 to 20 | 5 | 0.1 to 2 | 0.5 | 0.10 to 0.28 | 0.2 | $1\times10^{-6}$ | $1\times10^{-6}$ |
| Tamala Limestone | 100 to 1000 | 200 | 10 to 100 | 20 | 0.1 to 0.3 | 0.2 | $1\times10^{-6}$ | $1\times10^{-6}$ |
| Safety Bay | 10 to 15 | 15 | 1.0 to 1.5 | 1.5 | 0.10 to 0.28 | 0.2 | $1\times10^{-6}$ | $1\times10^{-6}$ |
| Guildford | 0.1 to 10 | 2 | 0.01 to 1.0 | 0.02 | 0.05 to 0.15 | 0.15 | $5\times10^{-5}$ | $1\times10^{-6}$ |
| Colluvium | 1 to 10 | 2 | 0.1 to 1.0 | 0.05 | 0.05 to 0.15 | 0.15 | $5\times10^{-5}$ | $1\times10^{-6}$ |
| Quaternary sands | 5 to 20 | 8 | 0.5 to 2.0 | 1.2 | 0.15 to 0.32 | 0.2 | $1\times10^{-6}$ | $1\times10^{-6}$ |
| Ascot | 1 to 28 | 10 | 0.1 to 2.8 | 1.2 | 0.15 to 0.32 | 0.2 | $1\times10^{-6}$ | $1\times10^{-6}$ |
| Kardinya Shale | $1\times10^{-4}$ to $1\times10^{-6}$ | $1\times10^{-5}$ | $1\times10^{-6}$ to $1\times10^{-7}$ | $1\times10^{-6}$ | 0.05 to 0.15 | 0.15 | $5\times10^{-5}$ | $1\times10^{-6}$ |
| Leederville: Rockingham | 5 to 50 | 15 | 0.5 to 5.0 | 1.5 | 0.2 to 0.35 | 0.2 | $1\times10^{-6}$ | $1\times10^{-6}$ |
| Leederville: Pinjar Member | 1 to 2 | 2 | $5\times10^{-4}$ to 0.2 | 0.005 | 0.01 to 0.2 | 0.2 | $1\times10^{-6}$ | $1\times10^{-6}$ |
| Leederville: Wannaroo Member | 1 to 21 | 4 | $5\times10^{-4}$ to 2.1 | 0.009 | 0.01 to 0.2 | 0.1 | $1\times10^{-6}$ | $1\times10^{-6}$ |

**Parameters based on conceptual model (Marillier et al. 2012)*

## Groundwater abstraction

Groundwater abstraction was modelled for the Leederville and Superficial aquifers, as it was shown to be an important flux in conceptual water balance calculations. Both licensed and unlicensed (garden bore) abstraction was included within the model, and are discussed separately below.

### *Licensed abstraction*

The Department of Water maintains a record of licensed abstraction of groundwater within the area. This dataset was used to develop an historical abstraction time-series for each drawpoint within the model domain. As metered data for every drawpoint was not available, the following method was used to convert licensed allocation to modelled historical abstraction:

1. The Department of Water's Water Resources Licensing (WRL) database was interrogated to extract a time-series of all licences that were historically or are currently enforced. Due to the disjunct nature of the licensing database, this was smoothed to a representative, estimated history of abstraction in the area.
2. The dataset was used to determine the long-term trend in abstraction on a yearly basis, using a usage to entitlement ratio of 0.8.
3. The current allocation at drawpoints was determined using the WRL database, and was hind-cast using the trends identified in step 2.
4. At each drawpoint, groundwater extraction was determined at a daily timestep, using the monthly variation in abstraction identified in the conceptual model report.

5 Each drawpoint and abstraction time-series was included within the model, with a screen depth specified according to the aquifer the bore was reported to be screened within.

This methodology does not represent an ideal dataset, as drawpoint locations are likely to change through time, and very rarely will intra-annual use patterns be consistent between users. However, given the lack of reliable metered data for the majority of bores, this was the best dataset able to be produced within the constraints of the project. The resulting abstraction time-series for the combined Rockingham and Superficial aquifers, and Leederville Aquifer, are shown in Figure 3-25. Note that the pumping time-series shows the intra-annual variation in abstraction, not the absolute volume abstracted. In Mike SHE the pumping time-series is adjusted to 0.8 times the allocation limit of each drawpoint.

### *Unlicensed abstraction*

As discussed in the conceptual model report (Marillier et al. 2012), unlicensed abstraction was identified using land use mapping within the study area. It was assumed that 30% of residential properties had garden bores, which used 800 kL/year. Population growth within the study area was used as an analogue for historical unlicensed abstraction, using data sourced from the Australian Bureau of Statistics. Each garden bore was inserted into the model individually, and groundwater abstraction was scaled on a monthly basis. The abstraction time-series for unlicensed users is shown in Figure 3-26.

### *Abstraction in Mike SHE*

A total of 6005 abstraction points are contained in the model: 1073 are from the Superficial and Rockingham aquifers, 4259 are unlicensed garden bores (note that garden bores within each 200 m grid cell were lumped as a single drawpoint) and 673 are from the Leederville Aquifer. Note that drawpoints with an allocation of less than 1500 kL/yr were excluded from the model because the volume extracted is negligible.

Within Mike SHE, the spatial distribution of ‘wells’ is defined by a well file, which defines the ‘xyz’ location of the well and the screen level. The location of the bores was determined using the WRL drawpoint dataset, and each bore was configured to extract water from the computational layer corresponding to the appropriate aquifer. The well file is also used to define a ‘fraction’ which relates the indicative pumping time-series (discussed above) to the actual abstraction from that well. Thus it is possible to distribute total borefield pumping to individual drawpoints. The allocation limit for each drawpoint was used as the fraction and applied to the time-series.

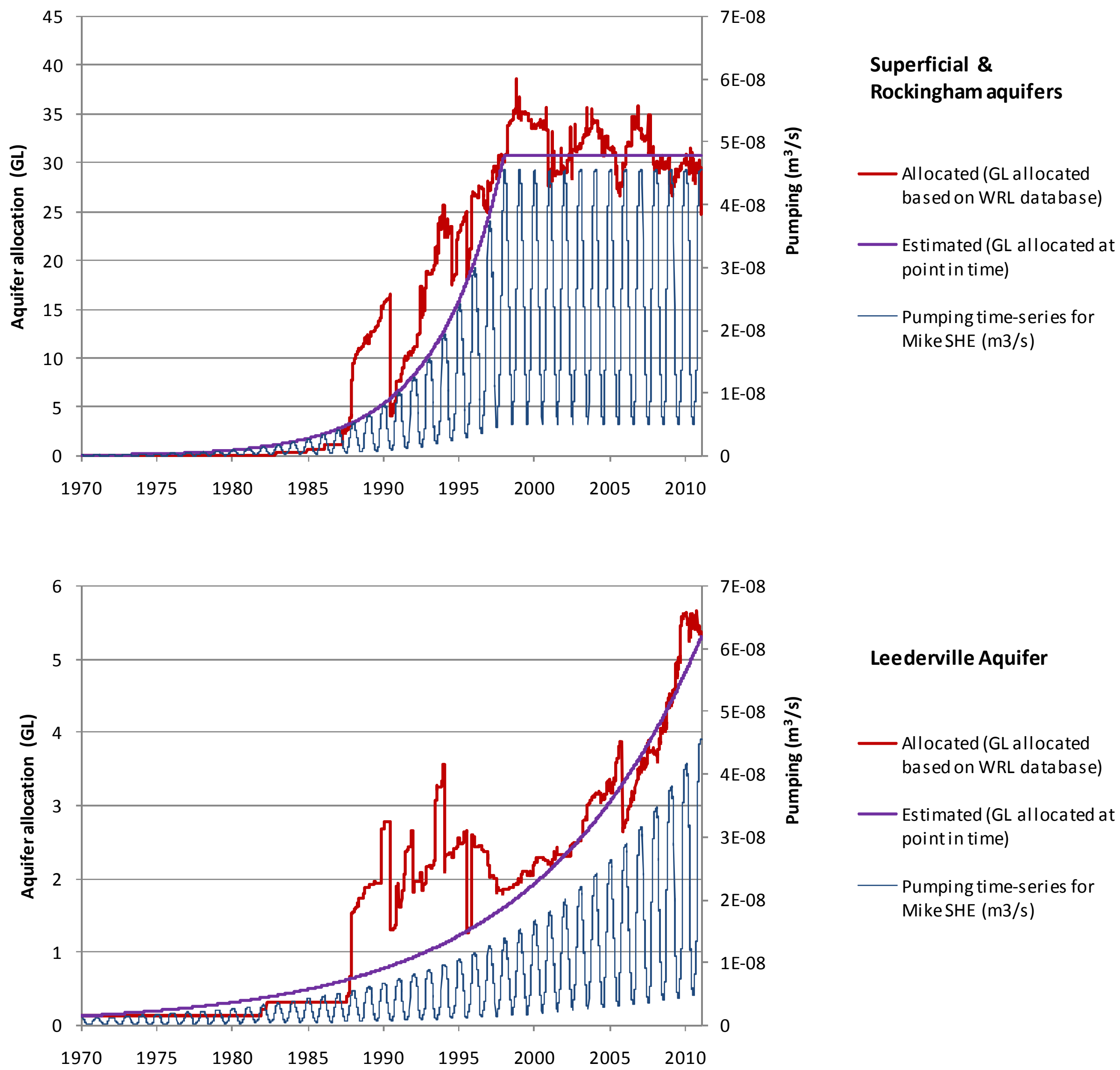



*Figure 3-25 Time-series of licensed abstraction for the Rockingham and Superficial, and Leederville aquifers*

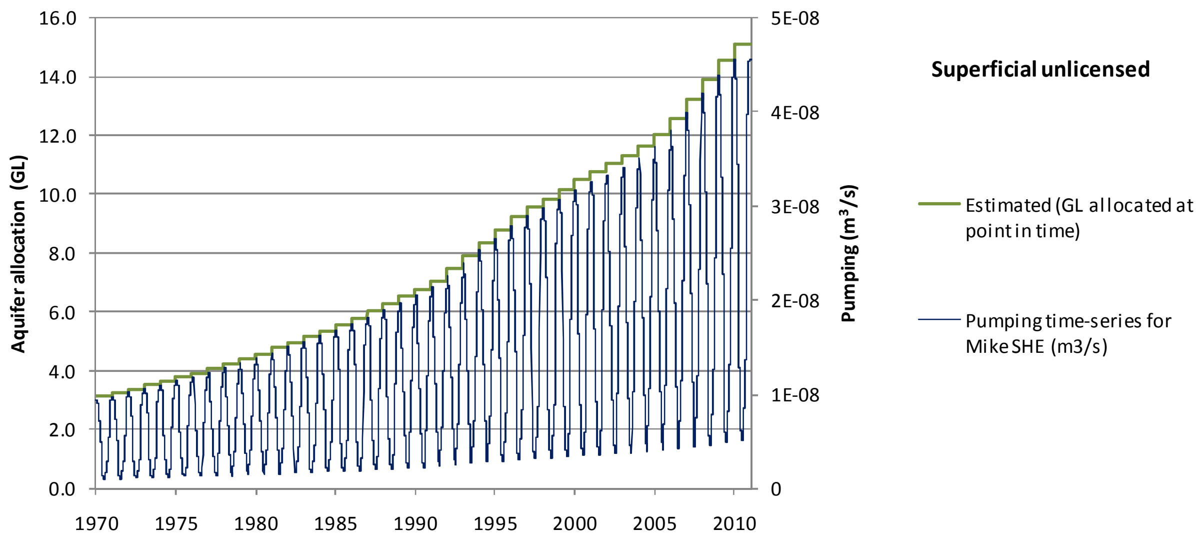



*Figure 3-26 Time-series of unlicensed abstraction from the Superficial Aquifer*

## Computational layers (vertical discretisation)

The model consists of three computational layers (Figure 3-27), representing the Superficial Aquifer, the confining layers of the Pinjar Member and Kardinya Shale, and the Rockingham and Leederville aquifers (Wanneroo Member only). The geological lenses discussed in the previous section are used to distribute hydraulic parameters within each computational layer. For example, the east to west increase of hydraulic conductivity from the Guildford Clay, to the Bassendean Sand, to the Tamala Limestone is represented in the computational layer using each unit. Where the units overlap, the parameters are averaged within the computational layer based on relative thickness, and thus the transition between geological units with different hydraulic parameters is accounted for.

The extent of the computational layers was developed as follows:

- **Computational layer 1** is located between the surface topography and the base Quaternary unconformity. It includes all of the superficial sediments and approximates the Superficial Aquifer.
- **Computational layer 2** is located between the base Quaternary unconformity and the base of the Pinjar Member and Kardinya Shale. In areas where these formations do not exist, the layer includes 0.5 m of the Wanneroo or Rockingham Member (proposed), depending on the location. This computational layer acts as a confining layer between the Leederville and Superficial aquifers.
- **Computational layer 3** is located between the base of the Pinjar Member and the Kardinya Shale, and the green-clay marker bed at the base of the Rockingham Member (proposed) and Wanneroo Formation.

In the study area's east where the Superficial Aquifer overlays the Cattamarra Aquifer, computational layers 1 and 2 are set to 0.5 m thick, as the Cattamarra Aquifer is not included within the model.

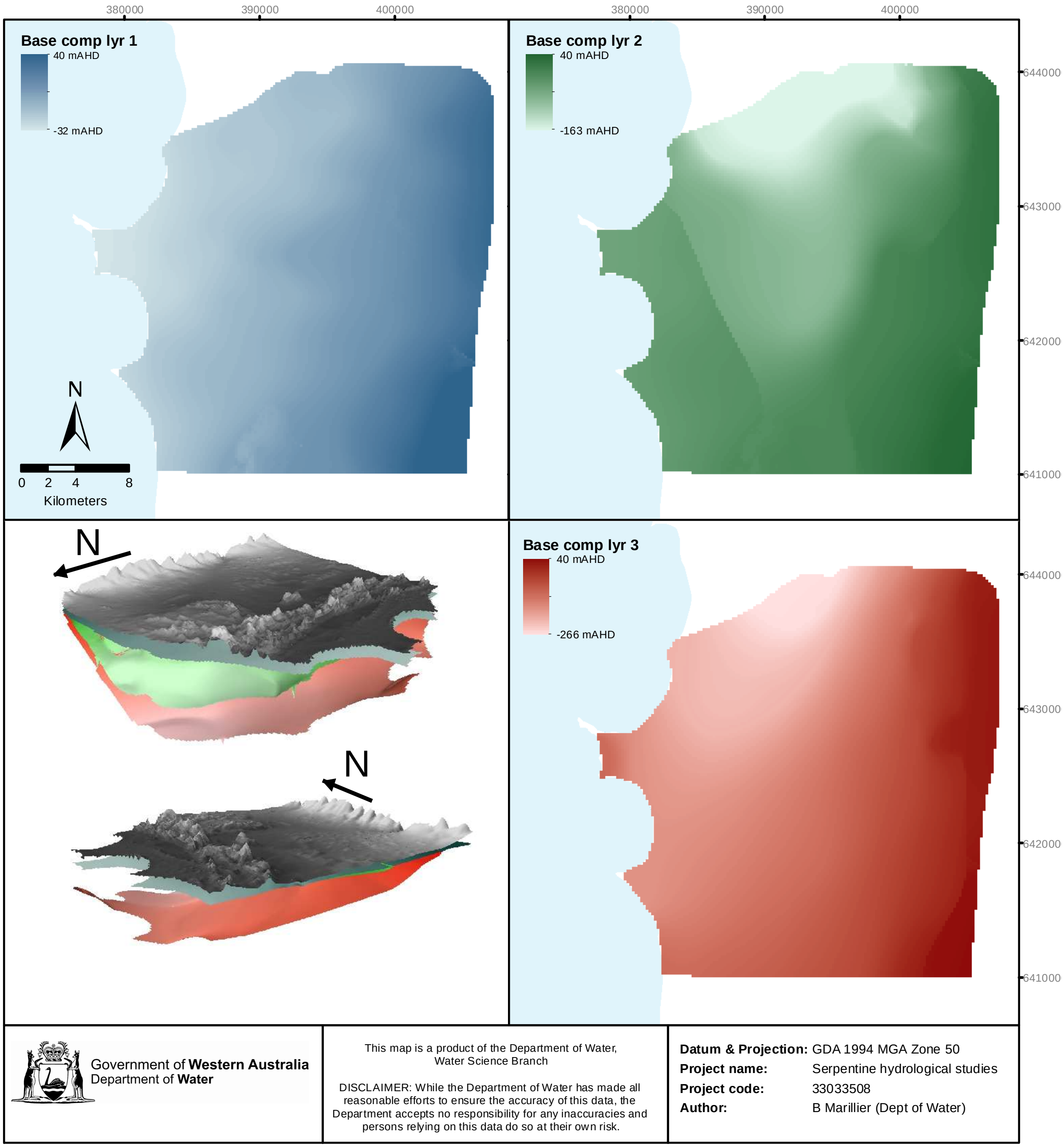



*Figure 3-27 Computational layers*

### Boundary conditions

Hydrogeological model boundaries are important considerations in a numerical groundwater model. Within the Lower Serpentine study area, it was not possible to select physical boundary conditions while maintaining a high-resolution numerical model. The influence of these boundary conditions is discussed in Section 6 – Sensitivity analysis.

#### *Superficial Aquifer boundary conditions (computational layer 1)*

The Superficial Aquifer boundary conditions were separated into five distinct sections as follows:

- The **western** edge of the model uses the ocean as a fixed-head boundary set at 0 mAHD.
- The **southern** boundary was set as no-flow, as it is approximately perpendicular to the superficial groundwater contours in the area.
- The **eastern** boundary was set as a no-flow boundary representing the hydraulic barrier of the Darling Fault.
- The **north-eastern** boundary was configured as no-flow, as it is approximately perpendicular to the superficial groundwater contours in the area. However, flow-paths are complex in this area, and are liable to change under varying climatic conditions. As such, this boundary condition was selected given the spatial constraints of the model.
- The **north-western** and **northern** boundary were configured as a time-varying fixed-head, using observed data from bores CSG3 and T95 (O) (Figure 3-30). The time-series for these were developed by fitting a trend and amplitude varying sinusoidal function to the observed data to derive a daily variation in head (Figure 3-28). This was necessary to replicate the steep gradient in groundwater to the west of the Spectacles Wetlands.

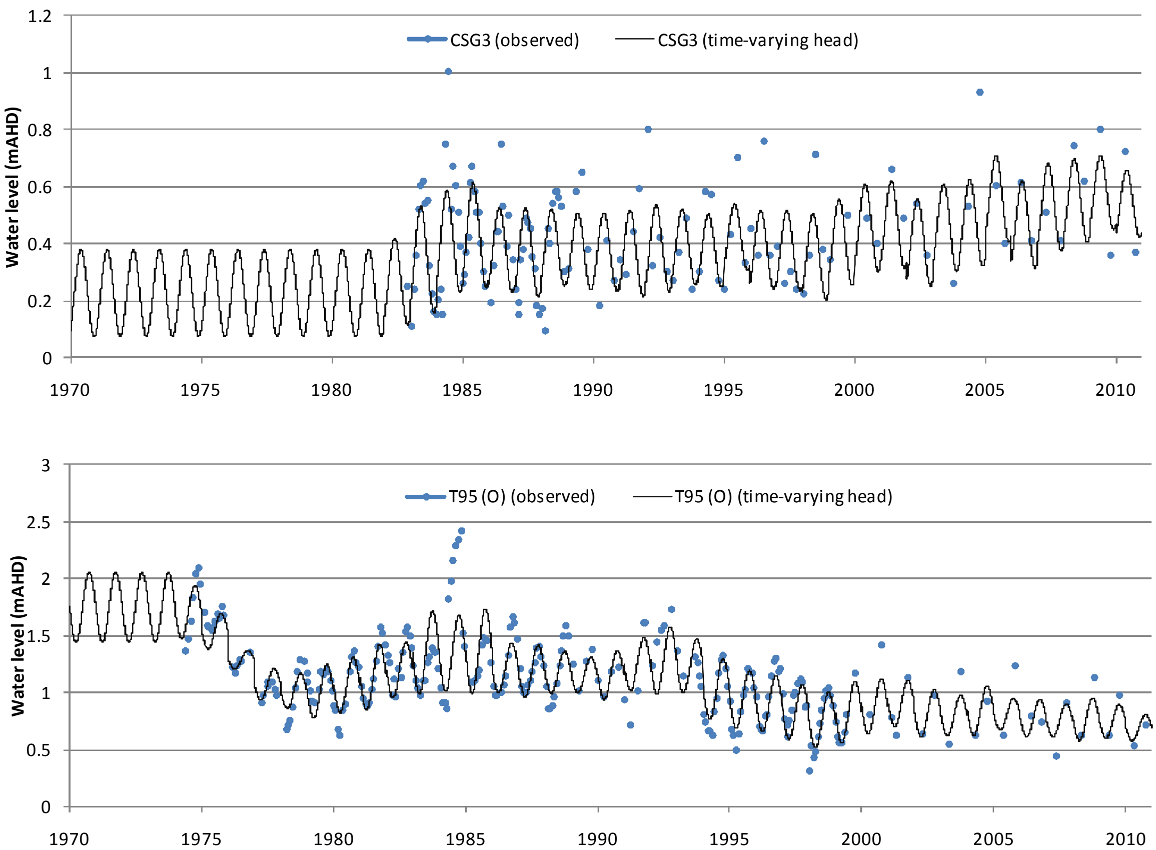


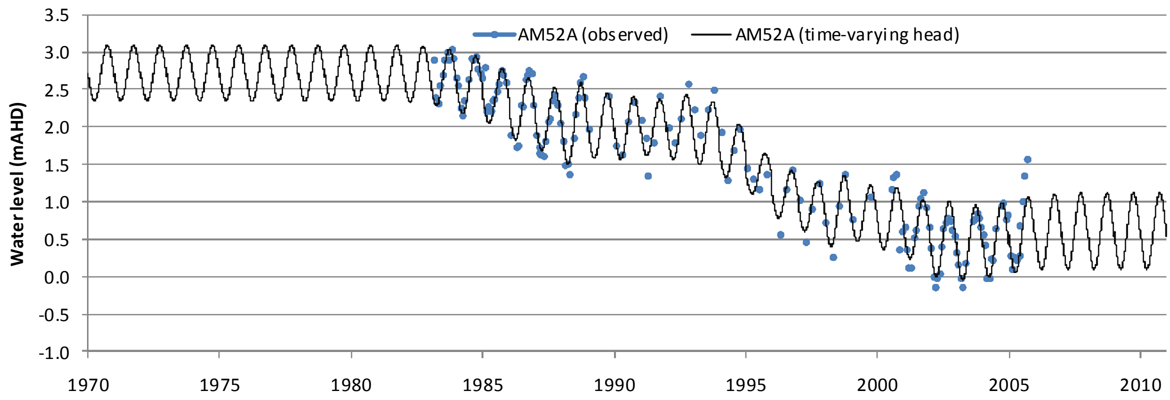

*Figure 3-28 Time-varying specified heads for the north-western and north boundaries in the first computational layer*

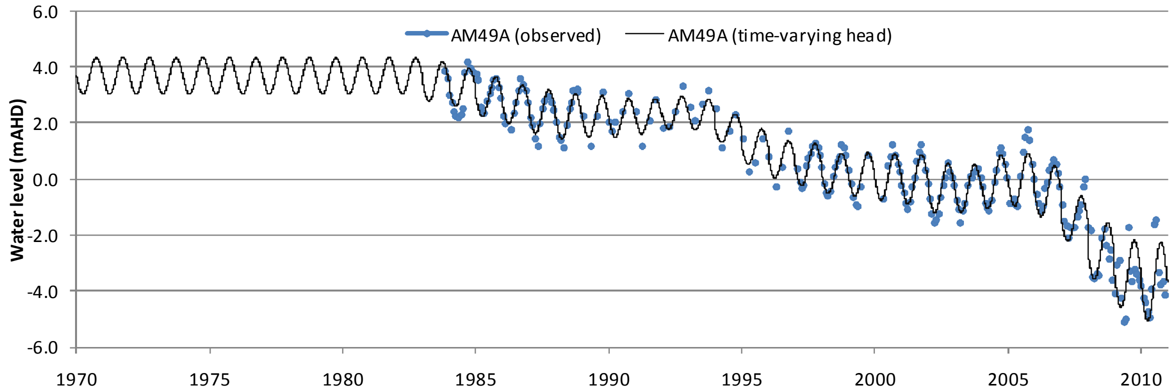
## *Leederville Aquifer boundary conditions (computational layers 1 and 2)*

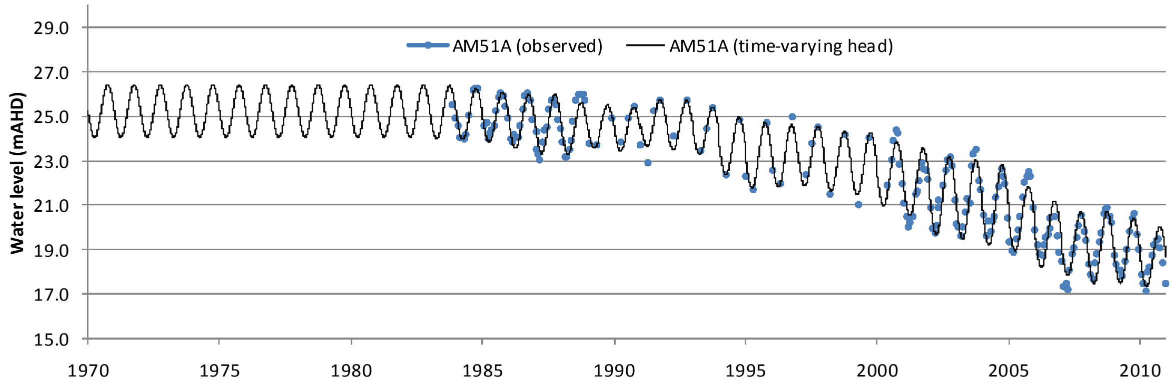
The Leederville Aquifer boundary conditions were configured in four distinct sections as follows:

- The **western** edge of the model uses the ocean as a fixed-head boundary set at 0 mAHD.
- The **southern** boundary was set as no-flow, as it is approximately perpendicular to the Leederville potentiometric contours in the area.
- The **eastern** boundary was set as a no-flow boundary representing the hydraulic barrier of the Darling Fault.
- The **northern** boundary was divided into eleven sections. This was set as a time-varying fixed-head boundary using observed data from bores AM52A, AM49A and AM51A (Figure 3-30), with interpolated values used for sections of the boundary between these bores. The time-series for these were developed by fitting a trend and amplitude varying sinusoidal function to the observed data to derive a daily variation in head (Figure 3-28).

The extent of each boundary condition is shown in Figure 3-30.



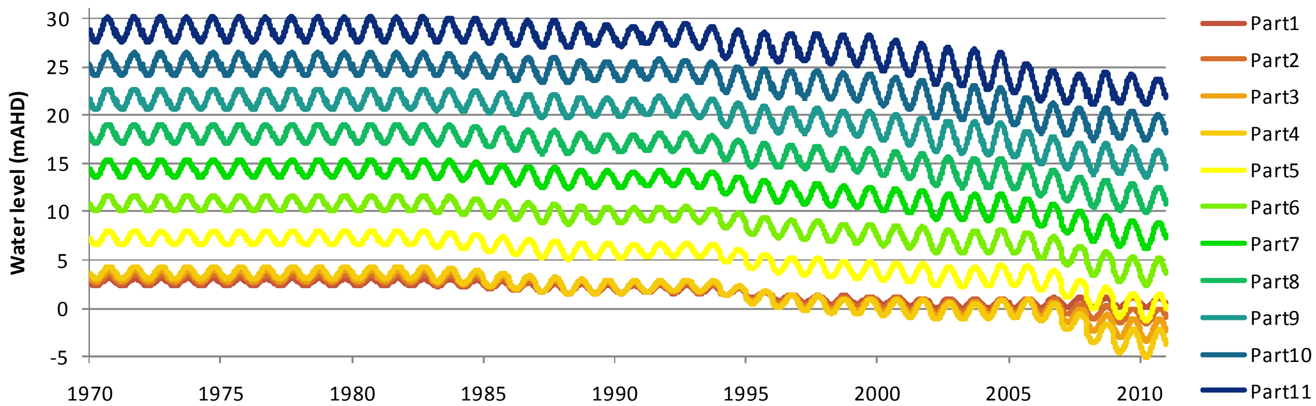




*Figure 3-29 Time-varying specified heads for the northern boundary for the second and third computational layer*

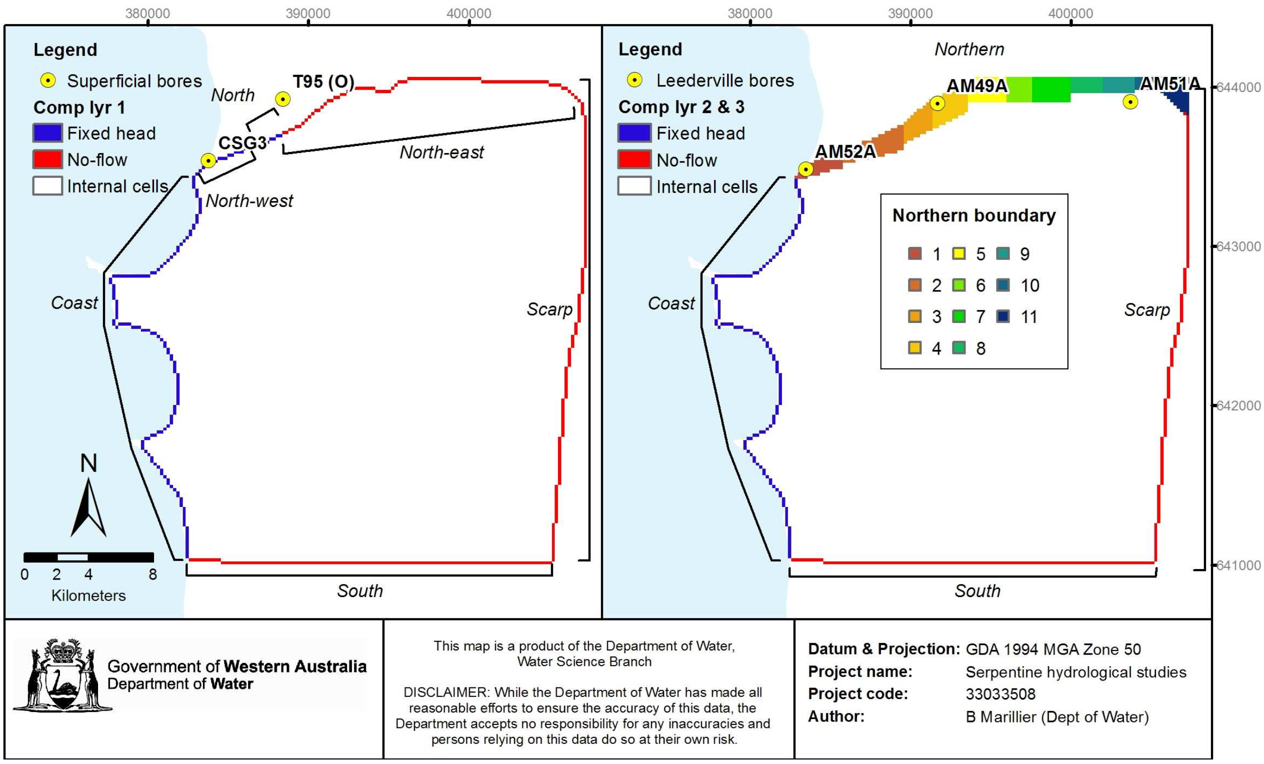



*Figure 3-30 Spatial extent of boundary conditions for the three computational layers*

## Drainage (saturated zone)

In addition to the drainage in the Mike 11 channel flow model, the saturated zone model also has a drainage option. The drainage option is configured with a set level below the ground surface (the surface of the saturated zone model), a drain constant and a spatial distribution of drain codes. When the groundwater level is above the drain level of a drainage cell, then the water will drain to the nearest Mike 11 Q-point at a rate according to the drain time constant. As the Mike 11 model comprised only major drains and rivers, it was necessary to include a comprehensive drainage network using the saturated zone drainage model.

This drainage network represents shallow agricultural drains that were not modelled with the Mike 11 network. The drainage network was configured by adding a gridded dataset of drain codes, where each drain is assigned a unique code. This grid is based on a comprehensive dataset of agricultural drains originally mapped by Kelsey et al. (2010). The drainage level can be configured with a depth below the topographic surface that represents the approximate depth of the drain, and a drain time constant, which determines how quickly the drains convey water. The initial parameters of the drainage network were set to a depth of 0.5 m below the surface, and time constant of $1 \times 10^{-5}$ to reflect the drain depths and gradients as outlined in the conceptual model. The drainage network, which is represented by the drain codes and the Mike 11 network, is shown in Figure 3-31.

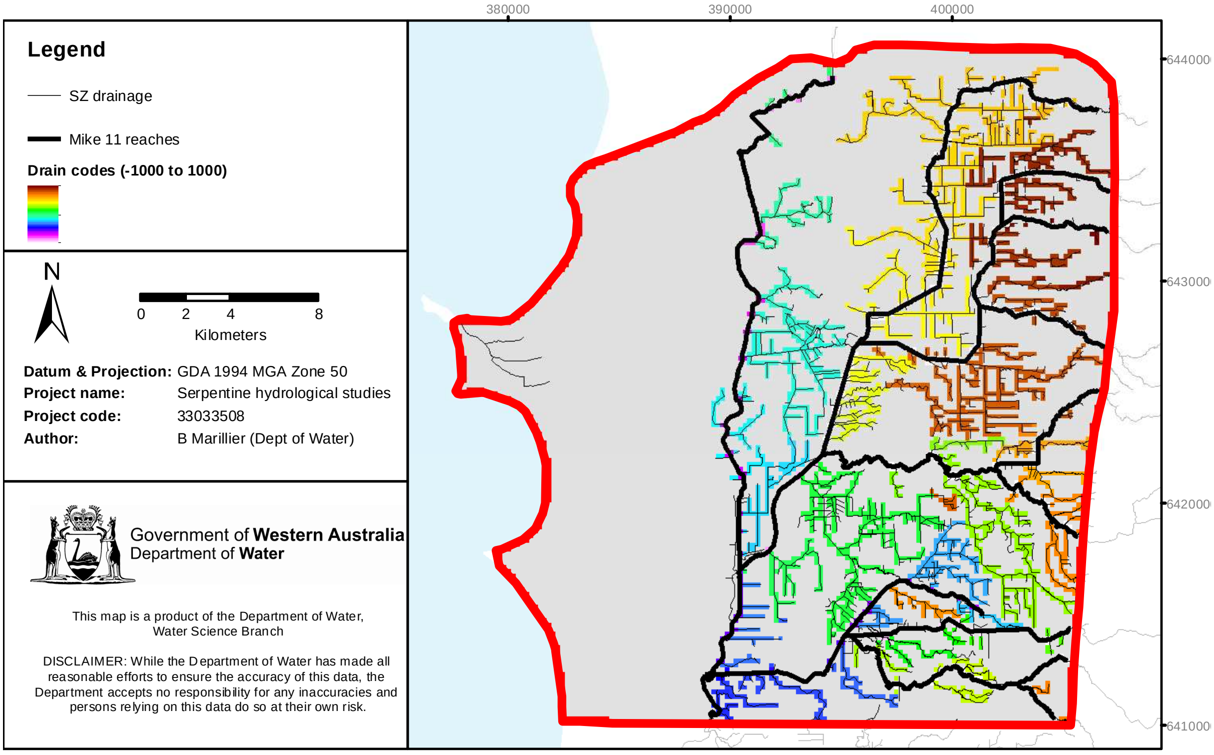



*Figure 3-31 Saturated zone drainage and Mike 11 coupling reaches*

## 3.10 Model input data audit

The source of all input data used for the Lower Serpentine model's construction and calibration is listed in Table 3-5 below. For references related to parameter values, see the conceptual model report (Marillier et al. 2012).

*Table 3-5 Summary of all data used in model construction*

| Dataset used in modelling | Format | Units | Dates | Source |
|---|---|---|---|---|
| **Topography** | | | | |
| 1m LiDAR dataset, resampled to 200m | Gridded | mAHD | 2006 to 2008 | Department of Water, see Fugro (2008) |
| **Climate** | | | | |
| Rainfall and referance evapotranspiration | Daily time-series | mm | 1970 to 2010 | SILO, see QDERM (2011) |
| Climate zone grid | Gridded | Grid codes | na | Derived from SILO gridded data coordinates |
| **Vegetation** | | | | |
| Land use grid | Gridded | Land use class | 2006 | Derived from Peel-Harvey land use dataset developed by Kelsey et al. (2010) |
| **Infiltration** | | | | |
| Kwinana wastewater treatment plant infiltration data | Variable time-series | mm | 1975 to 2000 estimated 2000 to 2010 observed | Provided by the Water Corporation |
| **Rivers and Lakes - Mike 11** | | | | |
| Flood codes | Gridded | Grid codes | na | Derived from aerial photography |
| Mike 11 reaches | Mike 11 nwk11 | mAHD | 2006 to 2008 | Derived from 1m LiDAR |
| Mike 11 cross-sections | Mike 11 xns11 | mAHD | 2006 to 2008 | Derived from 1m LiDAR |
| Mike 11 boundary inflows | Daily time-series | Flow ML/day | 1970 to 2010 | SQUARE modelled flows, Kelsey et al. (2010) |
| Mike 11 calibration data | Daily time-series | Flow ML/day | 1979 to 2010 | Department of Water hystra database |
| **Unsaturated zone** | | | | |
| Soil zones | Gridded | Soil class | na | Derived from DAFWA soil mapping |
| **Saturated zone** | | | | |
| Geological lenses | Gridded | mAHD | na | See conceptual model report, Marillier et al. (2012) |
| Drainage network | Gridded | Grid codes | Current | Dervied from the drainage network used by Kelsey et al. (2010) for the Peel Harvey catchment |
| **Abstraction** | | | | |
| Licensed abstraction data (timeseries) | Daily time-series | kL | 1970 to 2010 | Derived from Department of Water WRL abstraction database |
| Licensed abstraction data (locations) | Shapefile | na | 2011 | Based on Department of Water WRL drawpoint locations |
| Unlicensed abstraction data (timeseries) | Daily time-series | kL | 1970 to 2010 | Derived from Water Corporation estimates of garden bore abstraction and census population data |
| Unlicensed abstraction data (locations) | Shapefile | na | 2006 | Based on location of residential properties using 2006 land use mapping |
| **Groundwater calibration & validation data** | | | | |
| T series, AM series, SE series and Jandakot Mound bore data | Variable time-series | head elevation (mAHD) | 1974 to present | Department of Water |
| Wetland and lake water levels | Variable time-series | water level (mAHD) | 1927 to present | Department of Water |

# 4 Model calibration and validation

Calibration is the process by which the independent variables (parameters and fluxes) of a model are adjusted within realistic limits to produce the best match between simulated and measured data (e.g. groundwater level and surface flow monitoring). Calibration aims to solve a problem inversely by adjusting the unknown (parameters) until the solution matches the known (heads).

The calibration performance is presented in qualitative and quantitative terms in comparison with agreed target criteria. The model calibration and validation methods are based on the *Murray Darling Basin Commission groundwater flow modelling guidelines* (Middlemis 2000). The four calibration criteria described below have been used to assess the calibration result:

- **Water balance**: the single maximum cumulative error of the water balance of the Superficial Aquifer of less than 1%. The difference between the total modelled inflow and the total modelled outflow (water balance error) will be less than 0.1%. Note that this is a computational requirement and not a calibration target.
- **Iteration residual error**: the iteration convergence criterion should be one or two orders of magnitude smaller than the head resolution. Here the criterion is <0.1%. Note that this is a computational requirement and not a calibration target.
- **Qualitative measures**:
  - modelled versus measured groundwater hydrographs for each calibration bore
  - residual error plot for each calibration bore
  - scattergram of measured versus modelled heads (for each aquifer).
- **Quantitative measures**:
  - RMS error between measured hydraulic head and modelled hydraulic head will be less than 5% of the measured hydraulic head drop across the model area. The error will not be spatially biased. Final calibration results will report the RMS error, mean absolute error, the mean error and the coefficient of determination.
  - Final calibration for each bore will report mean error, mean absolute error, RMS error, standard deviation of residuals, correlation coefficient (R), and Nash-Sutcliffe efficiency (NSE) (R2).
  - For surface water flow gauges, the average NSE shall be better than 0.7 and the average cumulative flow error less than 10%.

## 4.1 Calibration methods

Calibration was for the 25-year period from 1 January 1980 to 31 December 2004. The validation period was the six years from 1 January 2005 to 31 December 2010.

Modelled and measured groundwater levels were compared over the selected calibration time-period. Selected model parameters were adjusted manually to minimise the difference between the modelled and measured data. The manual iterative technique was continued until the results of the calibration criteria were achieved.

The calibration was undertaken in three phases. Firstly, the volume of groundwater drained through the drainage and Mike 11 network was calibrated using the base un-calibrated model. Secondly, parameters affecting recharge were calibrated to satisfy the water balance. Thirdly, aquifer parameters were calibrated to adjust groundwater levels, trend and amplitude. Parameters associated with the Superficial Aquifer were calibrated before those associated with the Leederville and Rockingham aquifers. The following processes were used to calibrate the model across these phases:

1. Initial manual sensitivity analysis was undertaken to determine the model's response to changes in model parameters (e.g. vertical hydraulic conductivity, horizontal hydraulic conductivity, LAI, RD and unsaturated zone parameters).
2. Review of water balances to determine validity of recharge, evapotranspiration, drainage and horizontal flow.
3. Review of the error in predicted water levels in the calibration bores, and discharge at surface water gauging sites.
4. Adjustment of saturated zone model parameters, land use parameters and unsaturated zone model over a 10-year period (1990–2000) within reasonable ranges as identified in the conceptual model. Return to step three to review the model.
5. When the amplitude in the groundwater levels was close to the measured groundwater amplitude, and the water balance was close to the conceptual water balance, the model was simulated from 1970 to 2004, using the period 1980 to 2004 to calculate calibration statistics, with changes in the land use and hydraulic parameters undertaken to reduce error in bores. Repeat steps three and four.
6. When the calibration criteria was achieved and most remaining errors were small or intractable (did not respond to changes in model parameters), the calibration process was complete.

Model calibration results were assessed using the calibration measures (targets) outlined above.

## 4.2 Calibration and validation bores

Hydrographs from 81 bores were selected for model calibration. The calibration bores were selected based on the quality and quantity of the water level data, the depth at which the bores were completed, and an assessment of whether the bores adequately reflected regional water levels. These consisted of 45 'T series' bores, eight Jandakot Mound 'JM series' bores, 14 'SE series' bores, eight wetland gauge boards and six 'AM series' bores screened in the Leederville Aquifer. The location of the calibration bores is shown in Figure 4-1. Most bores were sampled biannually, quarterly or monthly.

Paired bores were not included within the Superficial Aquifer, which is represented by a single computational layer. Where two bores existed in one location, the shallower screened bore was selected for calibration, given the model is being developed primarily to identify areas of shallow watertable.

For calibration, bores were split into two datasets according to the computational layer, and therefore aquifer they were screened in. The two datasets include the Leederville and Rockingham aquifer bores (third computational layer) and the Superficial Aquifer (first computational layer). The Superficial Aquifer bores were the primary focus of calibration.

The same bores were used for calibration and validation where data were available for the respective periods.

## 4.3 Calibration flow gauges

Five flow gauges were deemed appropriate for calibration within the study area. These are well distributed throughout the Mike 11 channel network, as shown in Figure 4-2. The available time-series data for these gauges are summarised in Table 4-1.

Two additional gauges with recorded data starting after 2004 were used for validation purposes. These include the Karnup Road station on Peel Main Drain, which has recorded reliable data since April 2009; and the Lightbody station on Oaklands Drain, which has recorded data since May 2010.

*Table 4-1 Flow gauge summary information*

| AWRC Ref | Gauge name | River name | Start date | End date | Notes | Mike 11 branch name | Mike 11 Q-point chainage (m) |
|---|---|---|---|---|---|---|---|
| **614114** | Lowlands | Serpentine River | 16/06/1998 | Current | DoW gauge | Serpentine River 2 | 9411 |
| **614030** | Dog Hill | Serpentine River | 22/02/1979 | Current | DoW gauge | Serpentine Drain 1 | 1804 |
| **614028** | Hopelands Road | Dirk Brook | 5/04/1979 | 29/05/2001 | DoW gauge | Dirk Brook 2 | 10630 |
| **614094** | Yangedi Swamp | Punrack Drain | 9/06/1995 | Current | DoW gauge | Punrack Drain 3 | 2045 |
| **614013** | Hope Valley | Peel Main Drain | 16/06/1976 | 21/05/2001 | Water Corp. gauge | Peel Main Drain | 4874 |
| **614129** | Lightbody Road | Oaklands Drain | 12/05/2010 | Current | DoW gauge | Oaklands Drain 2 | 3657 |
| **614121** | Karnup Road | Peel Main Drain | 19/03/2005 | Current | DoW gauge (ADVM* installed from 2005) | Peel Main Drain | 28460 |

**ADVM: Acoustic doppler velocity meter*

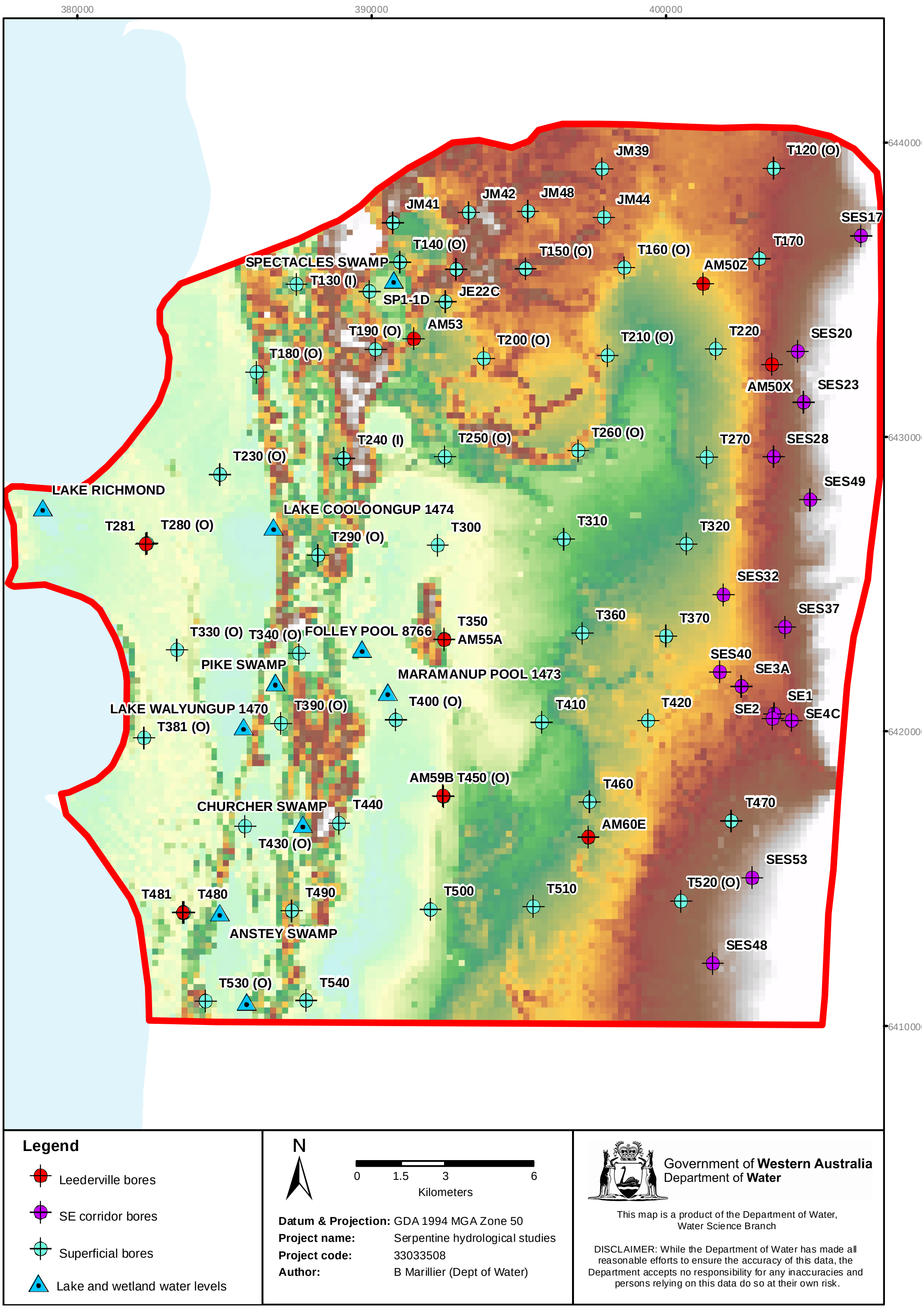



*Figure 4-1 Calibration and validation bores and gauge boards*

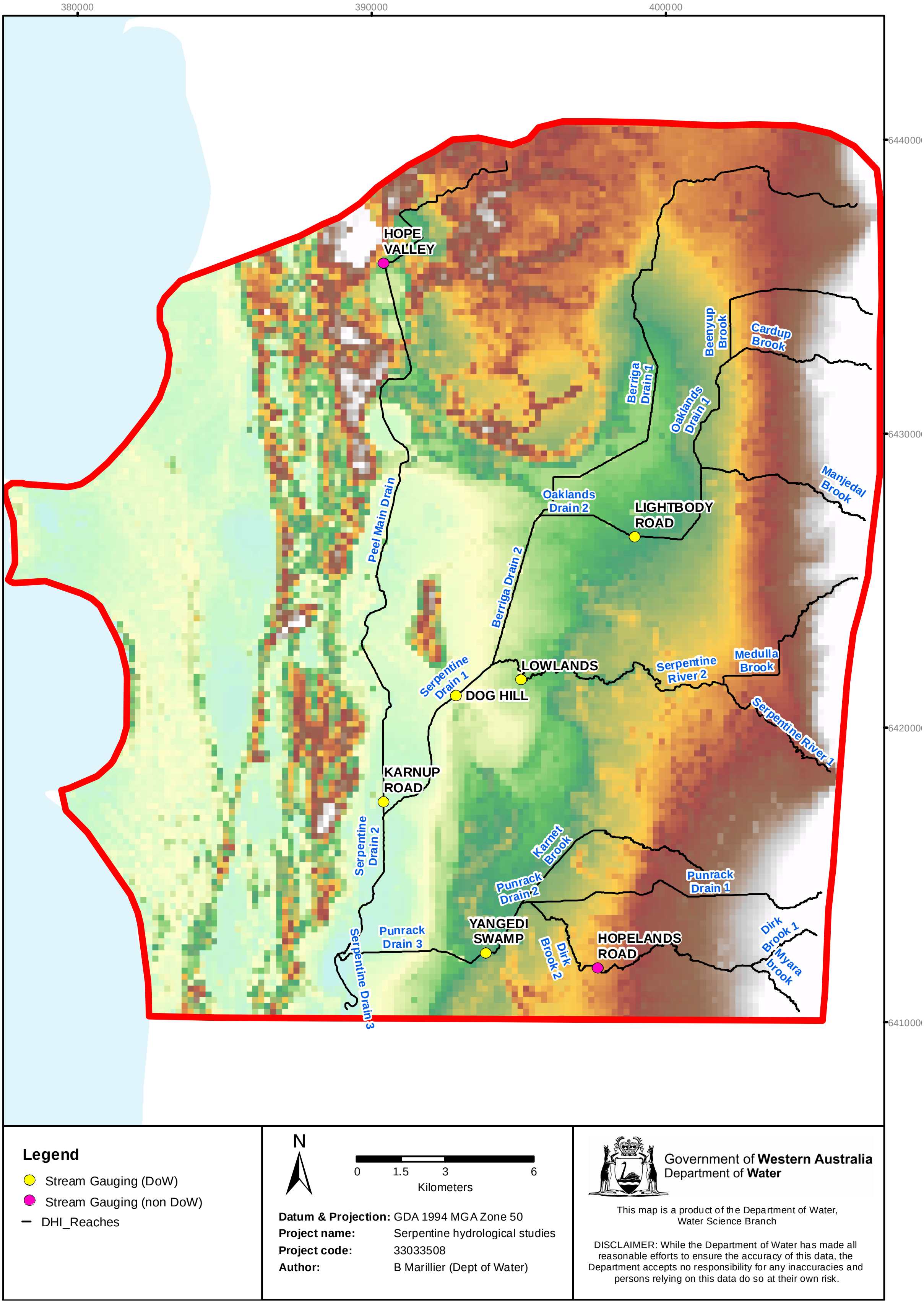



*Figure 4-2 Flow gauges used in calibration*

## 4.4 Calibration results

The simulation period for the calibration was from 1 January 1980 to 31 December 2004, a total of 25 years. The calibration targets outlined were achieved for the Superficial Aquifer with a scaled mean sum of residuals (MSR) of 1.10% (0.45 m) and a scaled RMS of 1.50% (0.62 m). For the Leederville Aquifer, the scaled MSR was 2.64% (0.80 m) and the scaled RMS was 3.85%, which is within the calibration target, although less accurate than the calibration in the Superficial Aquifer. When considering the Superficial and Leederville aquifers together, the scaled MSR was 1.20% (0.50 m) and the scaled RMS was 1.72% (0.71 m).

An average NSE of 0.77 was achieved across the flow gauges, which is within the 'acceptable' calibration range of 0.7 to 0.8 as specified in Ladson (2008), with a negative cumulative flow error of 7% (underestimation). Statistics for individual calibration gauges are discussed in subsequent sections.

This shows that a satisfactory calibration was achieved for superficial groundwater levels, with error statistics well within the Murray Darling Basin Commission (MDBC) guidelines. The model as a whole is also within the MDBC calibration guidelines; however, calibration of the Leederville Aquifer was less successful compared with the Superficial. Calibration statistics are presented for each of the aquifers and for surface water in the following sections.

Observed and modelled heads for all calibration bores are shown in Appendix C.

### Superficial Aquifer and wetland levels

*Table 4-2 Calibration statistics for modelled versus observed heads for the Lower Serpentine Mike SHE model – Superficial Aquifer*

| Description | Observed | Modelled | Residual | Abs residual |
|---|---|---|---|---|
| average (mAHD) | 11.51 | 11.54 | -0.03 | 0.45 |
| median (mAHD) | 9.52 | 9.69 | -0.02 | 0.34 |
| min (mAHD) | -0.32 | 0.00 | -3.15 | |
| max (mAHD) | 41.17 | 41.38 | 2.34 | |
| range (m) | 41.49 | 41.38 | 5.50 | |

| Description | Symbol | Value |
|---|---|---|
| Count | n | 10473 |
| Sum of squares ($m^2$) | SSQ | 4040 |
| Mean sum of squares ($m^2$) | MSSQ | 0.39 |
| Root mean square (m) | RMS | 0.62 |
| Scaled root mean square (%) | SRMS | 1.50 |
| Sum of residuals (m) | SUMR | 4763.3 |
| Mean sum of residuals (m) | MSR | 0.45 |
| Scaled mean sum of residuals (%) | SMSR | 1.10 |
| Coefficient of determination () | CD | 1.00 |

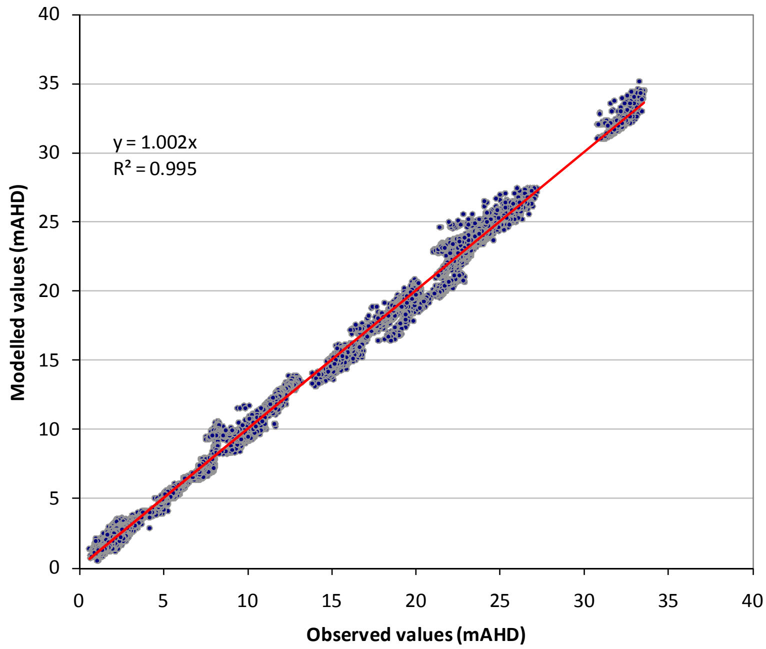



*Figure 4-3  Scatter plot of observed versus modelled heads in the Lower Serpentine Mike SHE model – Superficial Aquifer*

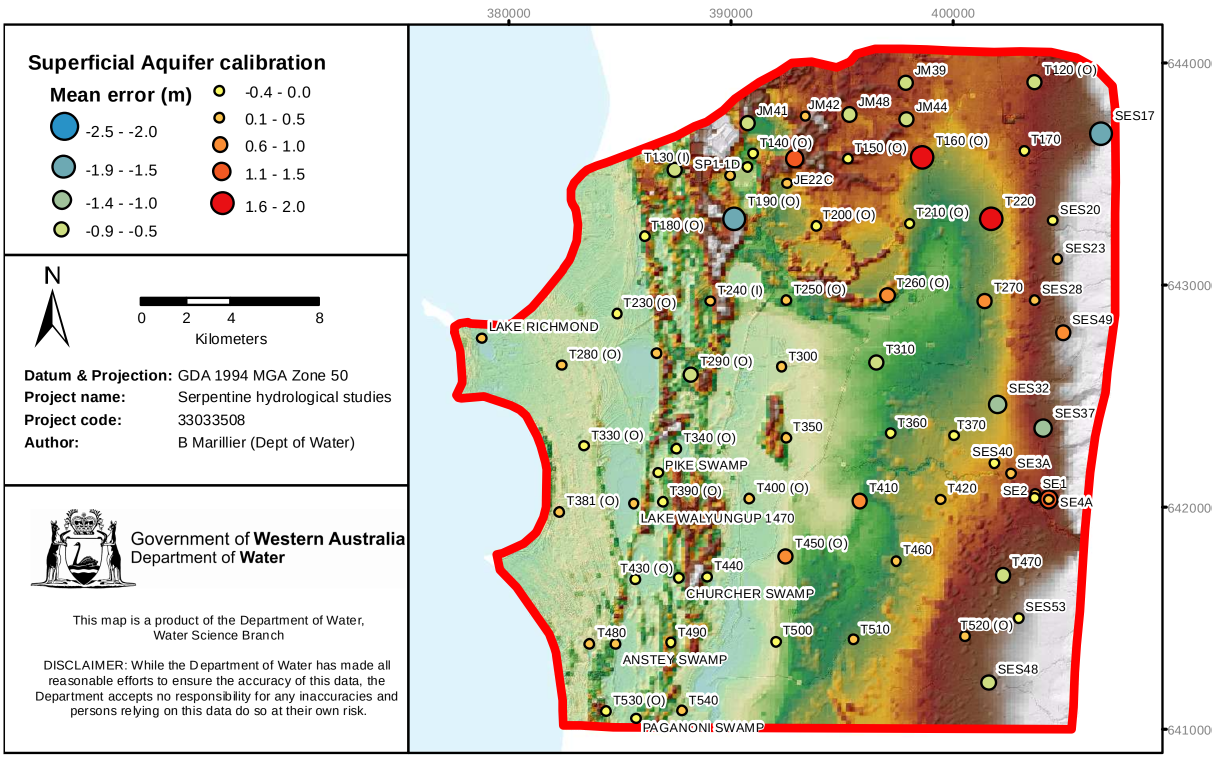



*Figure 4-4  Distribution of mean error (observed minus modelled heads) for the Superficial Aquifer for the calibration period*

## Leederville and Rockingham aquifers

*Table 4-3 Calibration statistics for modelled versus observed heads for the Lower Serpentine Mike SHE model – Leederville and Rockingham aquifers*

| Description | Observed | Modelled | Residual | Abs residual |
|---|---|---|---|---|
| average (mAHD) | 9.92 | 9.57 | 0.35 | 0.80 |
| median (mAHD) | 3.71 | 3.77 | 0.16 | 0.49 |
| min (mAHD) | -0.34 | 0.76 | -2.13 | |
| max (mAHD) | 29.91 | 29.83 | 3.98 | |
| range (m) | 30.26 | 29.07 | 6.11 | |

| Description | Symbol | Value |
|---|---|---|
| Count | n | 1514 |
| Sum of squares ($m^2$) | SSQ | 2047 |
| Mean sum of squares ($m^2$) | MSSQ | 1.35 |
| Root mean square (m) | RMS | 1.16 |
| Scaled root mean square (%) | SRMS | 3.84 |
| Sum of residuals (m) | SUMR | 1208.8 |
| Mean sum of residuals (m) | MSR | 0.80 |
| Scaled mean sum of residuals (%) | SMSR | 2.64 |
| Coefficient of determination () | CD | 0.99 |

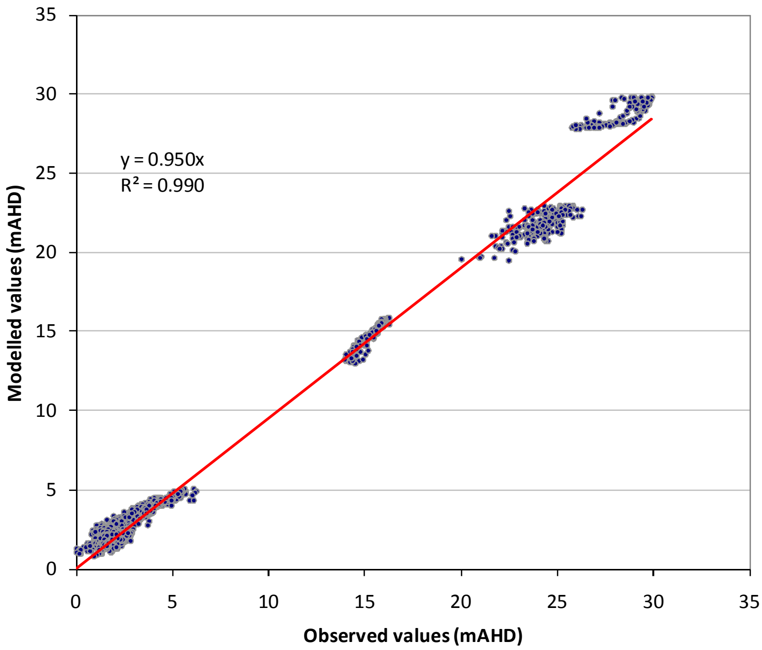



*Figure 4-5 Scatter plot of observed versus modelled heads in the Lower Serpentine Mike SHE model – Leederville and Rockingham aquifers*

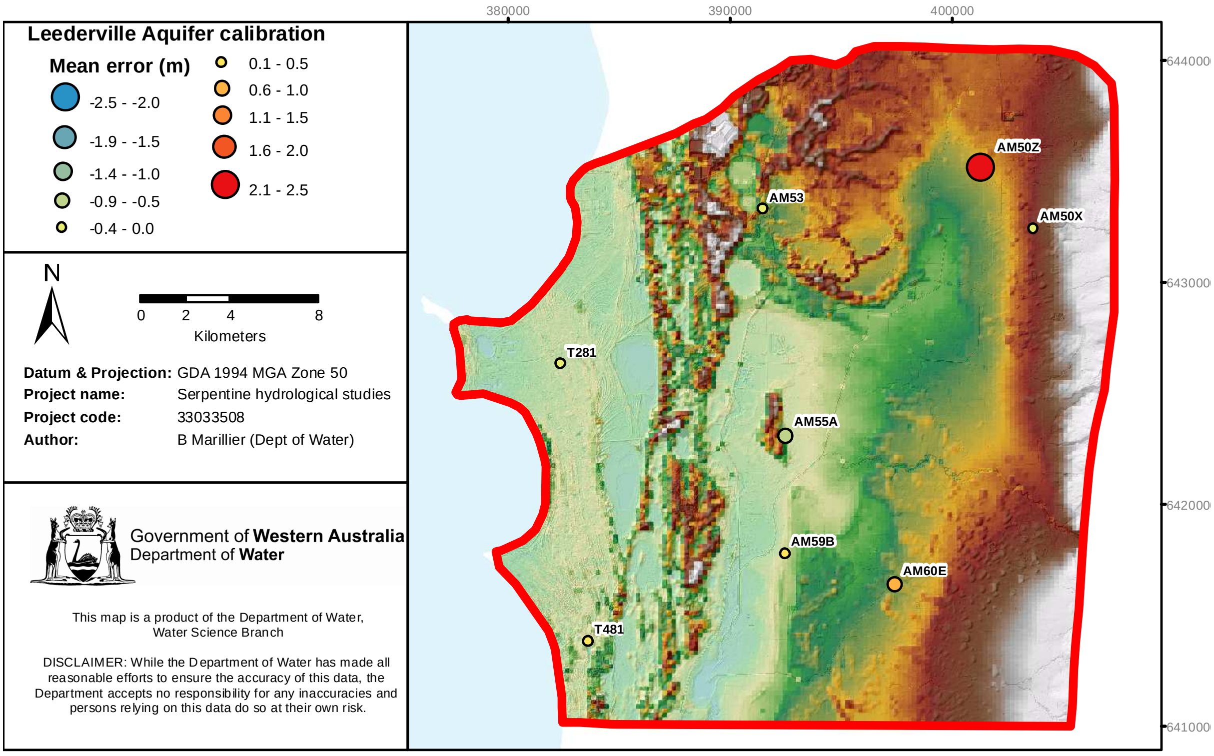



*Figure 4-6 Distribution of mean error (observed minus modelled heads) for the Leederville and Rockingham aquifers for the calibration period*

## Validation results

Validation was undertaken for the six-year period from 1 January 2005 to 31 December 2010. Results of validation were worse than those for calibration, with an MSR of 0.70 m (scaled MSR of 2.13%) for the Superficial Aquifer bores, and 1.26 m (scaled MSR of 4.03%) for the Leederville Aquifer bores.

In the Superficial Aquifer, the validation errors are highest near the study area's northern boundary, where external forcing from outside the model boundary (due to abstraction) is probably influencing groundwater heads. Notable problem bores include T120 (O), T170, JM39 and JM44, as presented in Appendix C.

## Superficial Aquifer and wetland levels

*Table 4-4 Validation statistics for modelled versus observed heads for the Lower Serpentine Mike SHE model – Superficial Aquifer*

| Description | Observed | Modelled | Residual | Abs residual |
|---|---|---|---|---|
| average (mAHD) | 13.29 | 13.60 | -0.30 | 0.70 |
| median (mAHD) | 11.86 | 12.18 | -0.10 | 0.43 |
| min (mAHD) | 0.07 | 0.00 | -5.35 | |
| max (mAHD) | 33.12 | 34.41 | 1.61 | |
| range (m) | 33.05 | 34.41 | 6.95 | |

| Description | Symbol | Value |
|---|---|---|
| Count | n | 1525 |
| Sum of squares ($m^2$) | SSQ | 1566 |
| Mean sum of squares ($m^2$) | MSSQ | 1.03 |
| Root mean square (m) | RMS | 1.01 |
| Scaled root mean square (%) | SRMS | 3.07 |
| Sum of residuals (m) | SUMR | 1073.7 |
| Mean sum of residuals (m) | MSR | 0.70 |
| Scaled mean sum of residuals (%) | SMSR | 2.13 |
| Coefficient of determination () | CD | 0.99 |

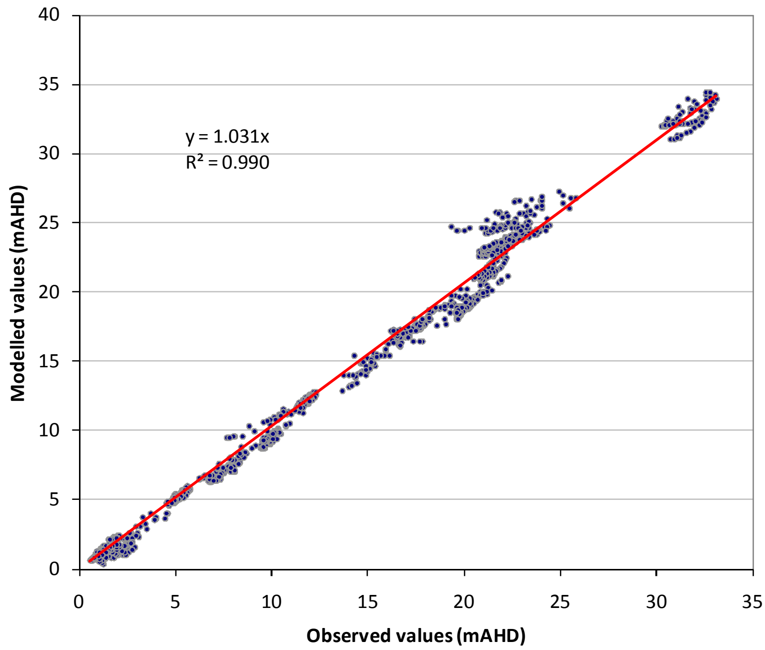



*Figure 4-7 Scatter plot of observed versus modelled heads in the Lower Serpentine Mike SHE model – Superficial Aquifer*

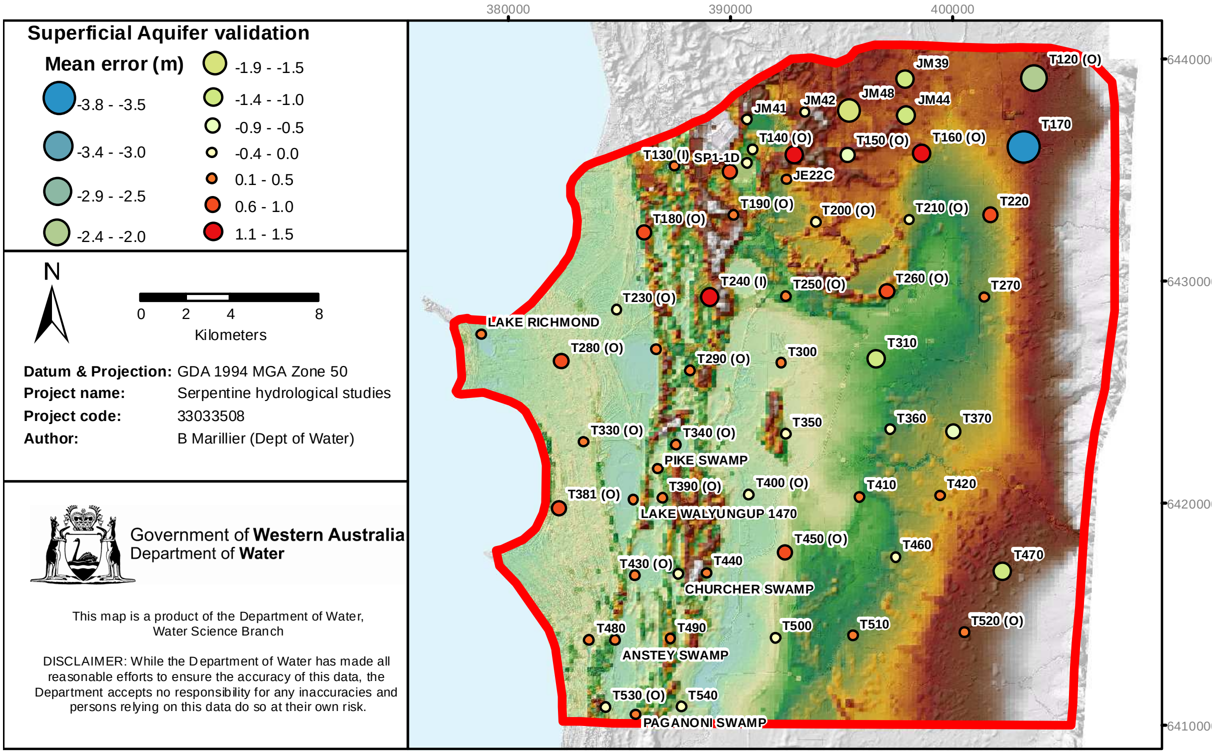



*Figure 4-8 Distribution of mean error (observed minus modelled heads) for the Superficial Aquifer for the validation period*

## Leederville and Rockingham aquifers

*Table 4-5 Validation statistics for modelled versus observed heads for the Lower Serpentine Mike SHE model – Leederville and Rockingham aquifers*

| Description | Observed | Modelled | Residual | Abs residual |
|---|---|---|---|---|
| average (mAHD) | 8.70 | 9.45 | -0.75 | 1.26 |
| median (mAHD) | 2.01 | 2.70 | -0.89 | 1.09 |
| min (mAHD) | -2.26 | -0.33 | -4.15 | |
| max (mAHD) | 28.97 | 29.75 | 2.60 | |
| range (m) | 31.24 | 30.09 | 6.75 | |

| Description | Symbol | Value |
|---|---|---|
| Count | n | 352 |
| Sum of squares ($m^2$) | SSQ | 837 |
| Mean sum of squares ($m^2$) | MSSQ | 2.38 |
| Root mean square (m) | RMS | 1.54 |
| Scaled root mean square (%) | SRMS | 4.94 |
| Sum of residuals (m) | SUMR | 442.8 |
| Mean sum of residuals (m) | MSR | 1.26 |
| Scaled mean sum of residuals (%) | SMSR | 4.03 |
| Coefficient of determination () | CD | 0.98 |

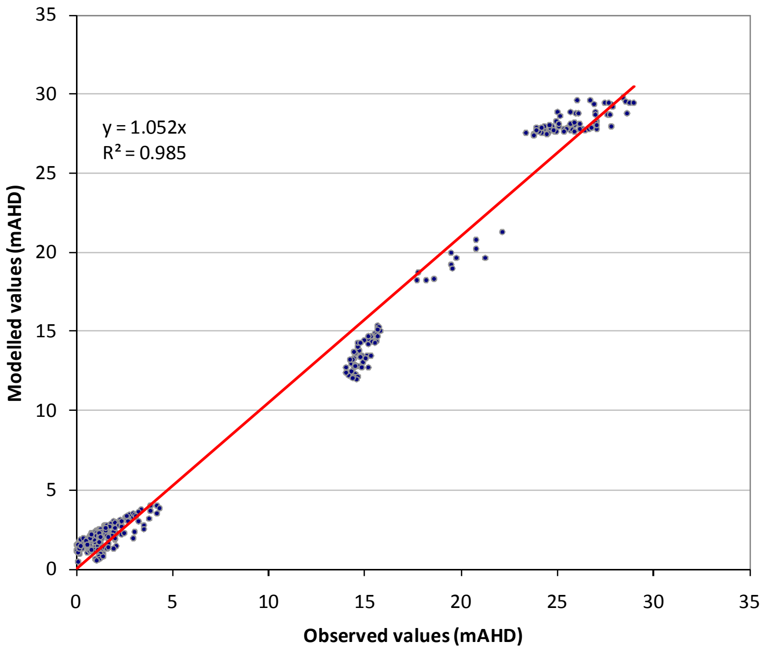



*Figure 4-9 Scatter plot of observed versus modelled heads in the Lower Serpentine Mike SHE model – Leederville and Rockingham aquifers*

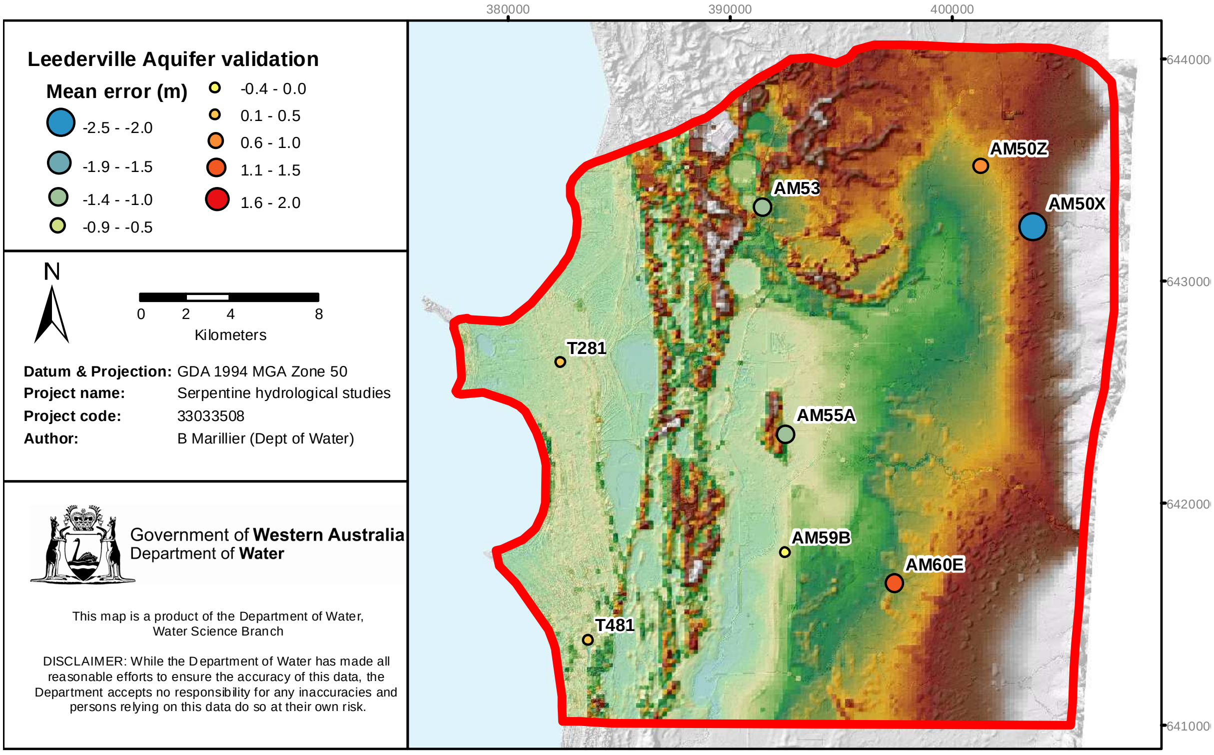



*Figure 4-10 Distribution of mean error (observed minus modelled heads) for the Leederville and Rockingham aquifers for the validation period*

### Surface water calibration

Surface water statistics are shown in Table 4-6. All calibration gauges achieved an NSE of greater than 0.70, with an average across all gauges of 0.77 – indicating a satisfactory overall model performance in modelling river flows, based on model performance criteria outlined by Ladson (2008). The average cumulative flow error was a 7% under-prediction.

Observed versus modelled flows and flow duration curves are shown in Figure 4-11 to Figure 4-17 for each gauge. Peak and low flows were well replicated. The main prediction error is associated with very low flows, with the model generally predicting a very small baseflow component in all waterways year-round (often less than 0.001 m/s), whereas the waterways in the area are generally ephemeral.

*Table 4-6 Surface water statistics (for all gauging data from 1970–2010)*

| Flow Gauge | Nash-sutcliffe | Cumulative flow error |
|---|---|---|
| **Calibration** | | |
| Dog Hill - Serpentine Drain | 0.80 | -8% |
| Hope Valley (Peel Main Drain) | 0.70 | -24% |
| Hopelands (Dirk Brook 2) | 0.83 | 5% |
| Lowlands (Serpentine River 2) | 0.78 | 12% |
| Yangedi (Punrack Drain 3) | 0.76 | -21% |
| *Average* | 0.77 | -7% |
| **Validation only** | | |
| Karnup (Peel Main Drain) | 0.76 | 12% |
| Lightbody (Oaklands Drain 2) | 0.61 | 78% |

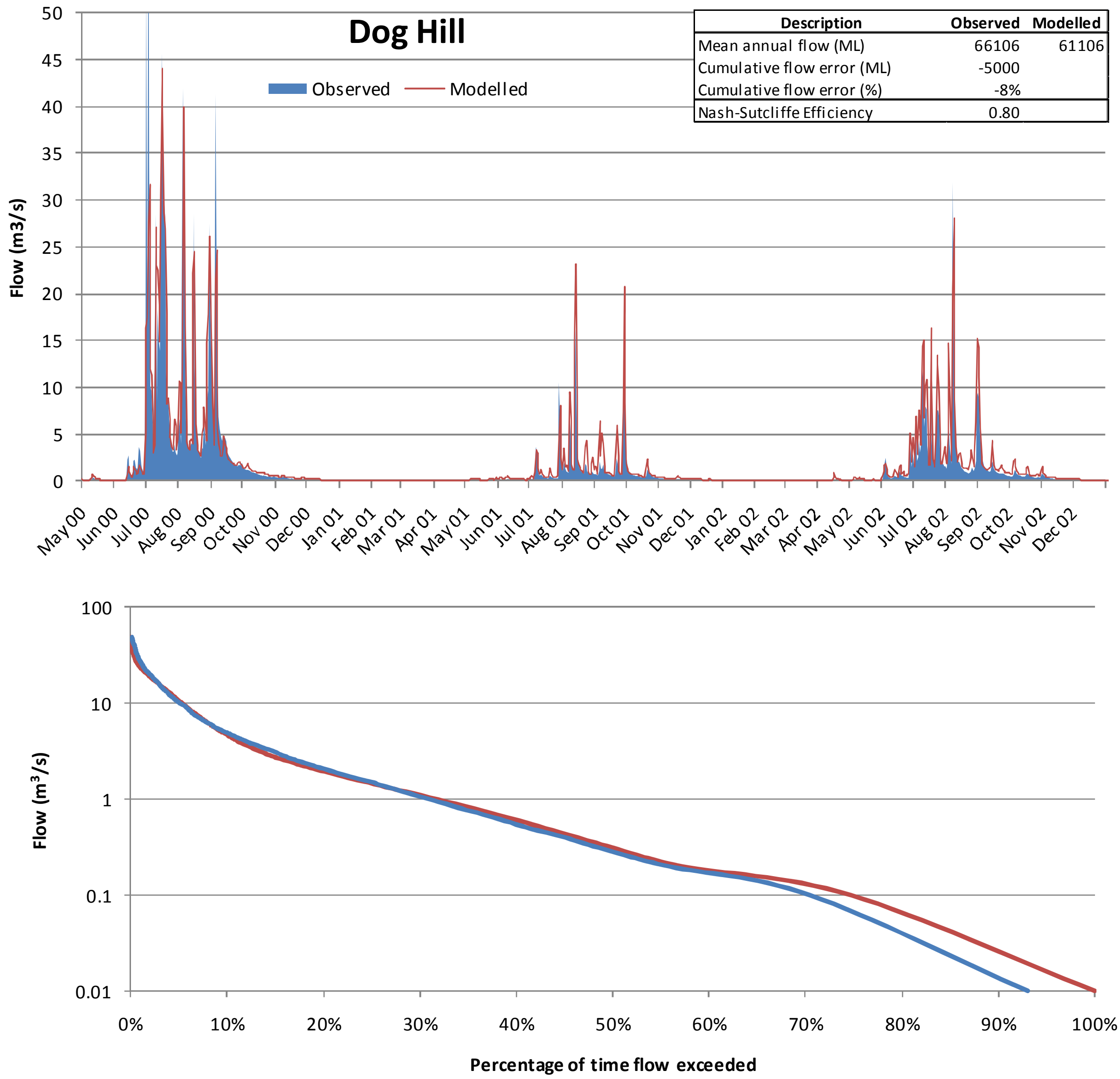



*Figure 4-11 Dog Hill – modelled versus observed flow for three years and summary statistics*

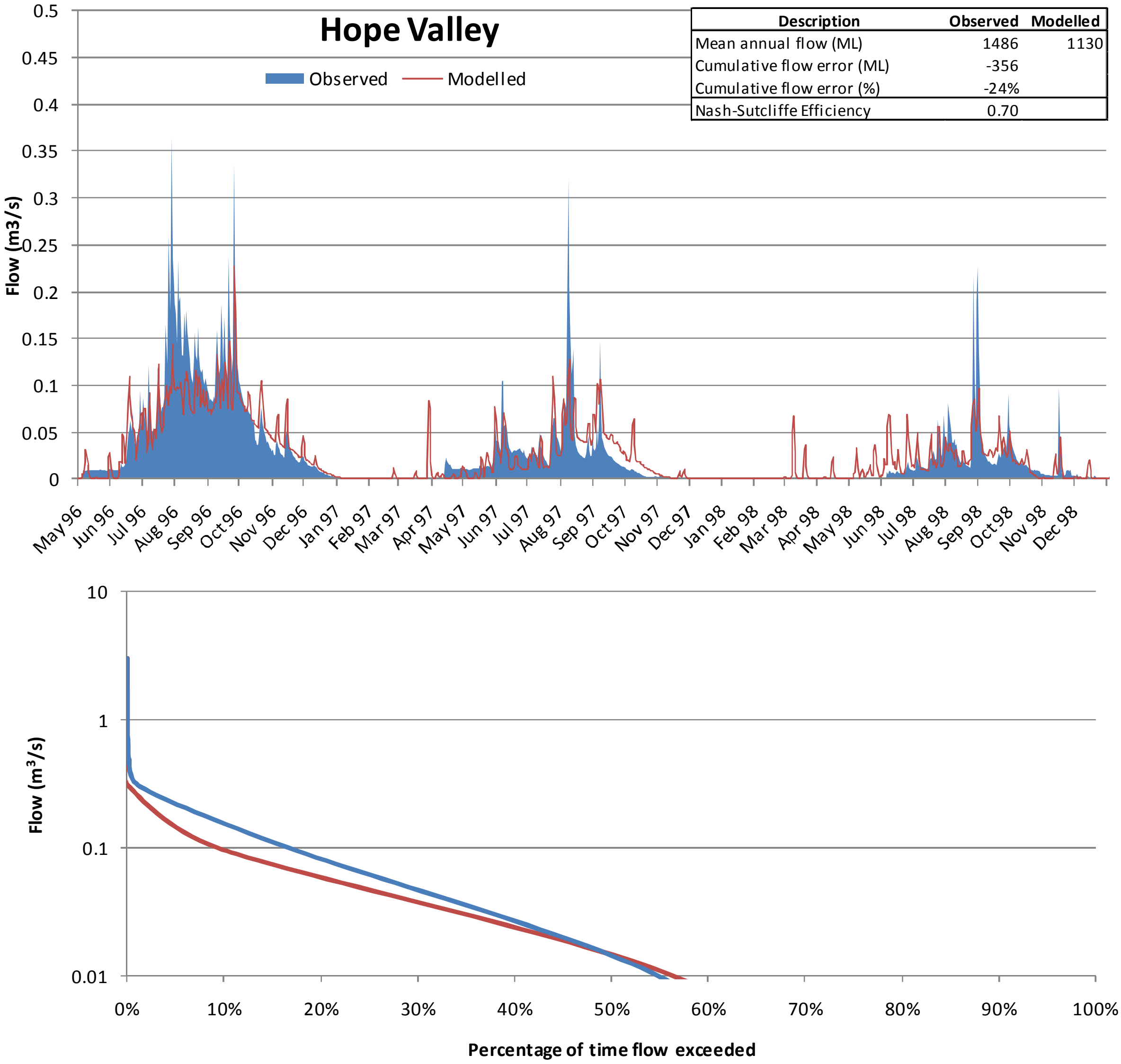
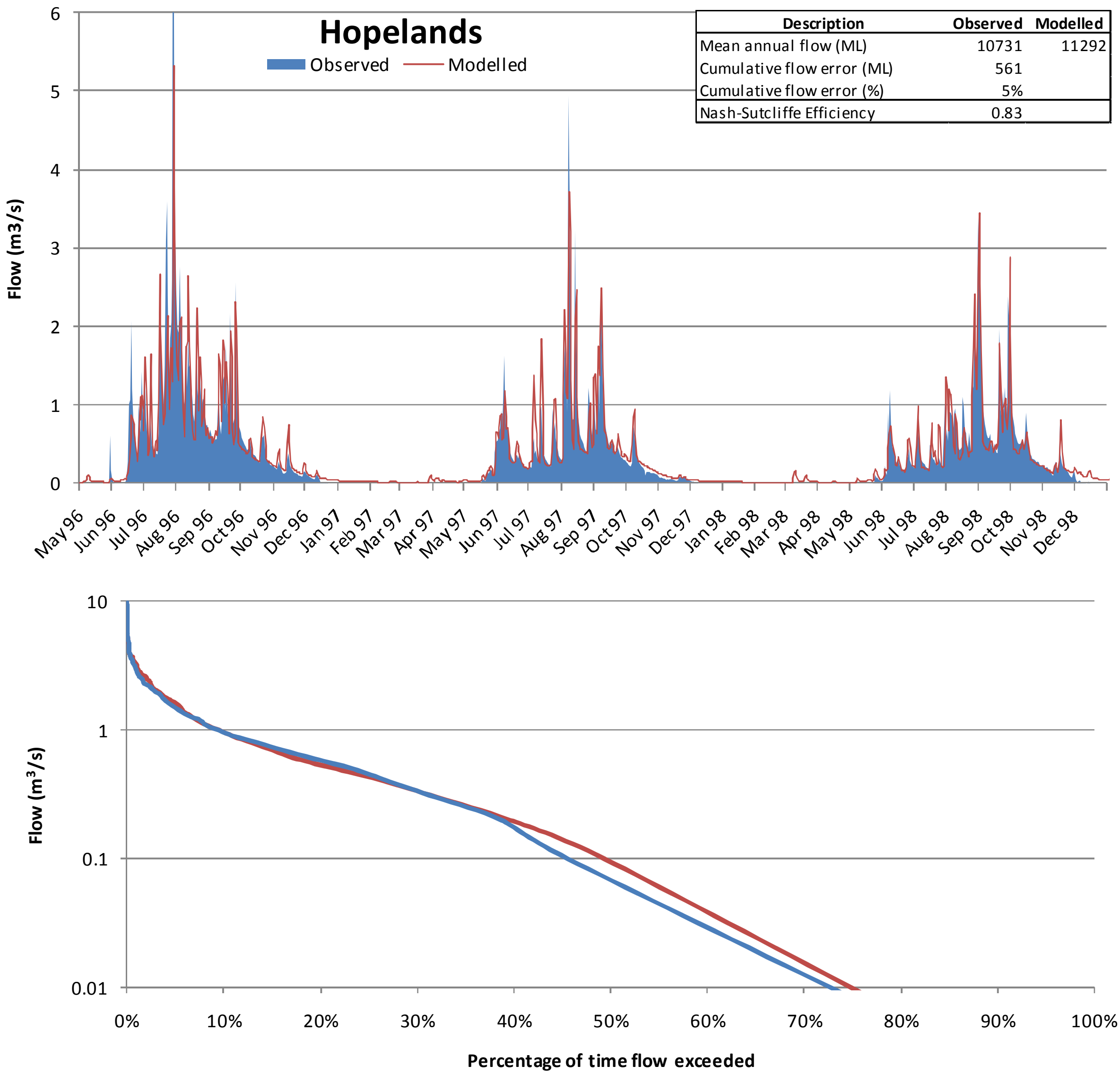



*Figure 4-12 Hope Valley – modelled versus observed flow for three years and summary statistics*




| Description | Observed | Modelled |
|---|---|---|
| Mean annual flow (ML) | 10731 | 11292 |
| Cumulative flow error (ML) | 561 | |
| Cumulative flow error (%) | 5% | |
| Nash-Sutcliffe Efficiency | 0.83 | |

*Figure 4-13   Hopelands – modelled versus observed flow for three years and summary statistics*

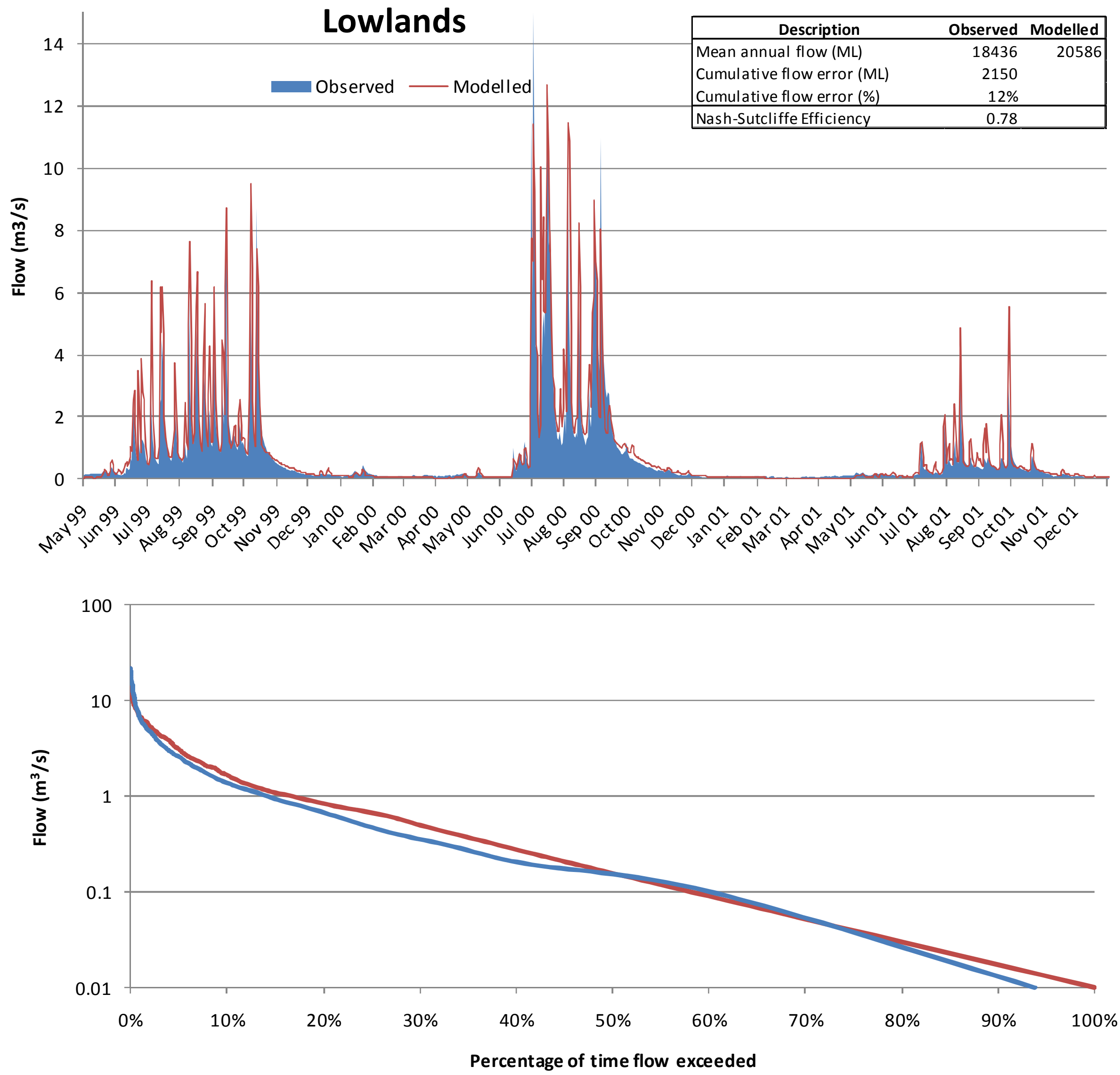



*Figure 4-14 Lowlands – modelled versus observed flow for three years and summary statistics*

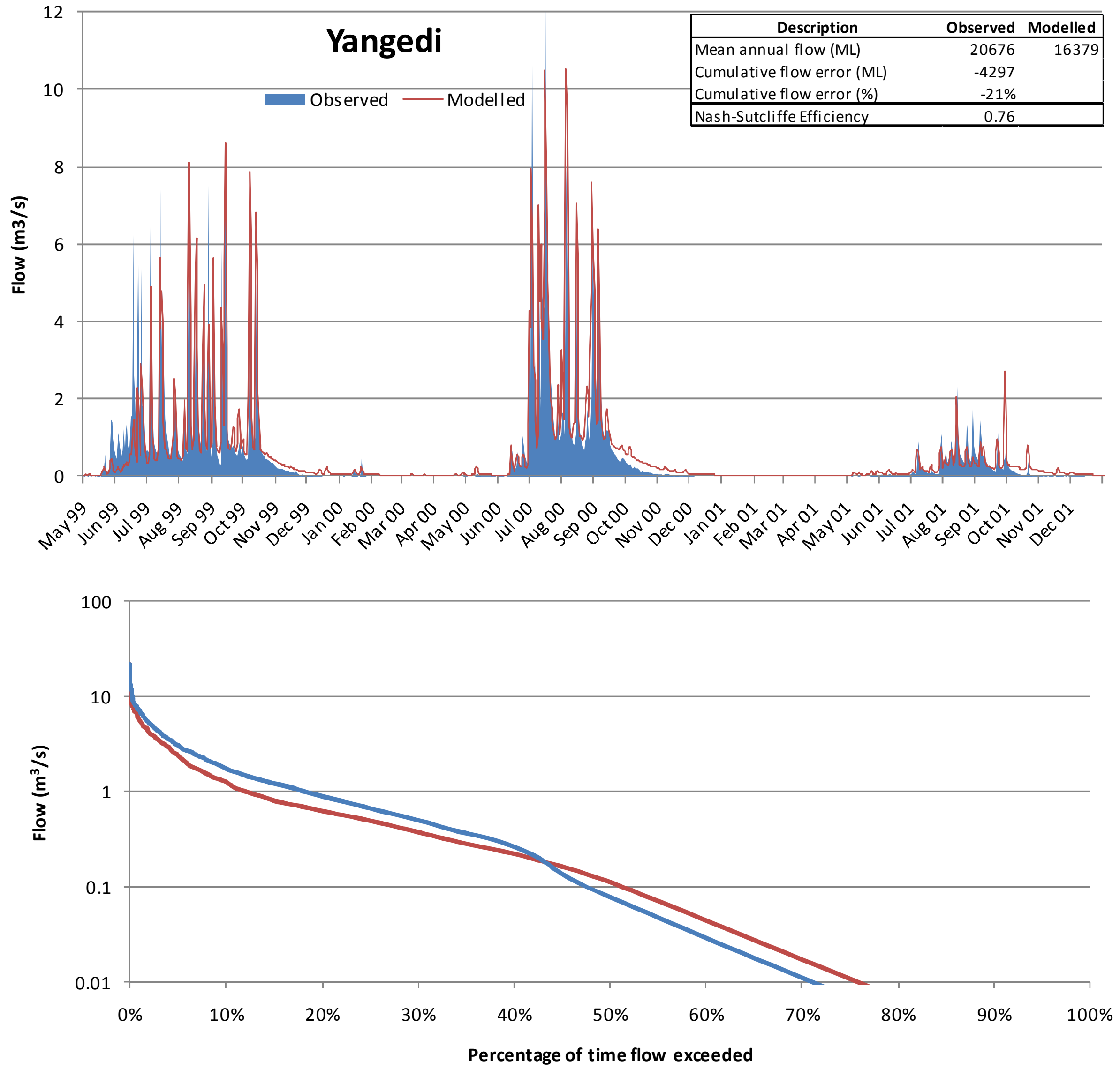



*Figure 4-15 Yangedi – modelled versus observed flow for three years and summary statistics*

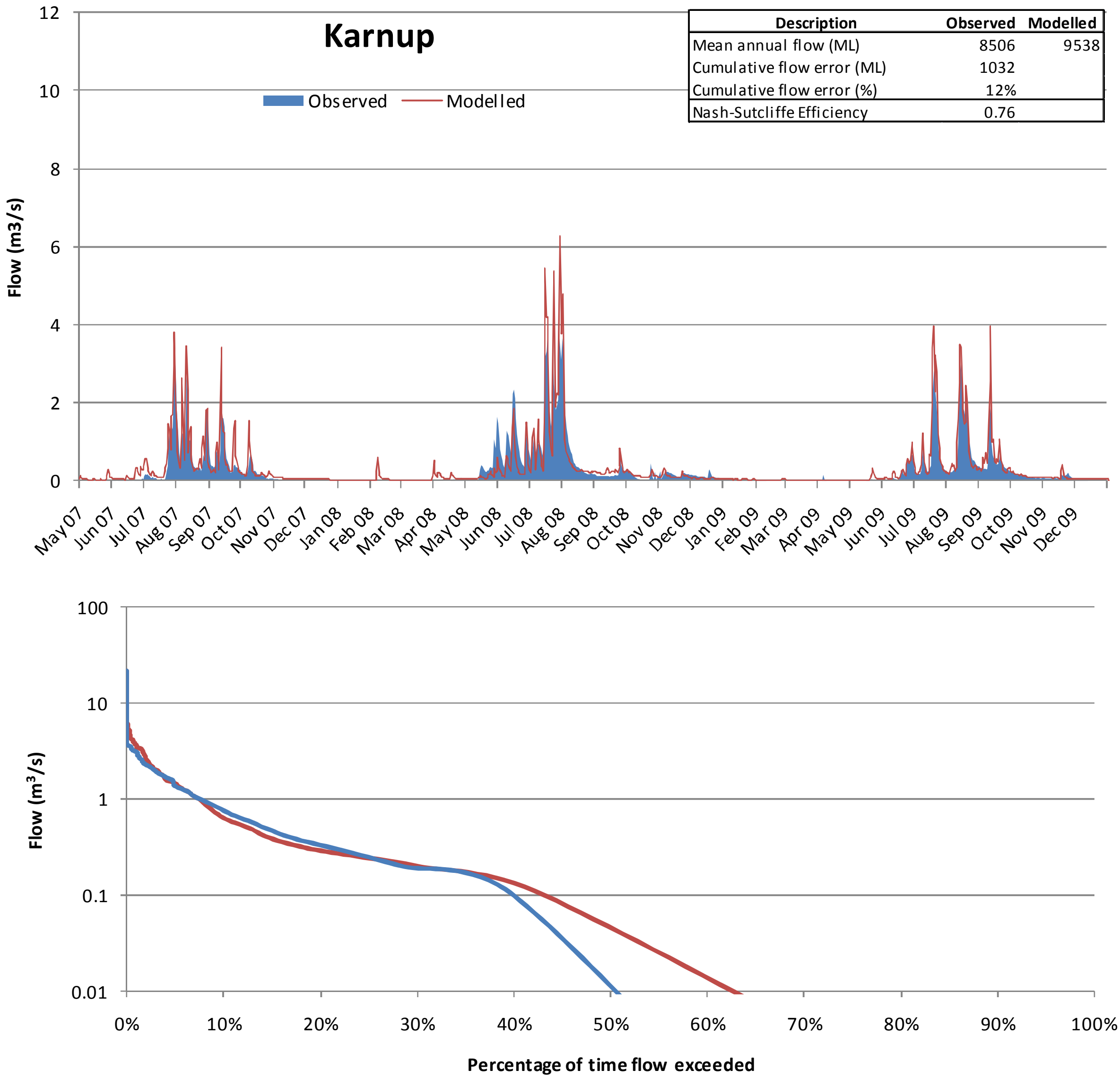
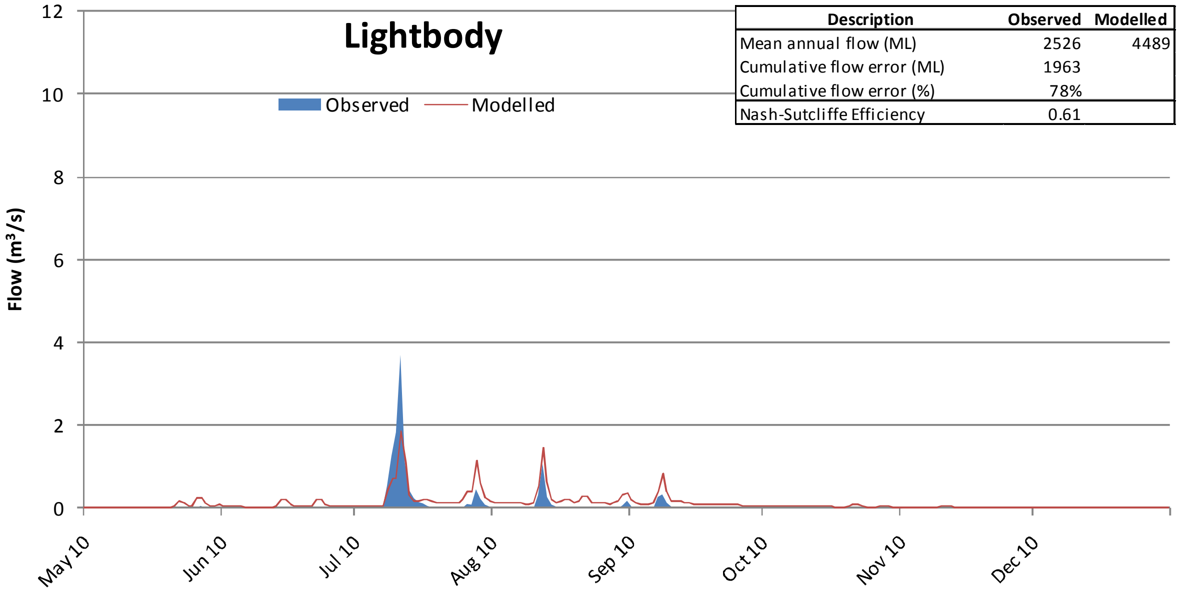



*Figure 4-16 Karnup – modelled versus observed flow for three years and summary statistics*




| Description | Observed | Modelled |
|---|---|---|
| Mean annual flow (ML) | 2526 | 4489 |
| Cumulative flow error (ML) | 1963 | |
| Cumulative flow error (%) | 78% | |
| Nash-Sutcliffe Efficiency | 0.61 | |

*Figure 4-17 Lightbody – modelled versus observed flow for one year and summary statistics*

## 4.5 Calibrated parameters

The calibrated model parameters are the result of manual adjustments to achieve best fit between observed and modelled groundwater levels and surface water flows, within the limits imposed in the conceptual model.

Parameters from the unsaturated zone model (including LAI and RD), the overland flow model, the saturated zone model, and from the Mike 11 model were adjusted for calibration. A summary of the calibrated parameters for each of the Mike SHE component models is presented below.

### Unsaturated zone parameters

The unsaturated zone parameters were important for calibration of the Superficial Aquifer, as they controlled the amount of recharge to the first computational layer. The two-layer soil model was selected for use in the Lower Serpentine model because it is numerically efficient and appropriate for areas with shallow groundwater tables. However, in some parts of the model (e.g. close to the Darling Scarp and along the Spearwood Dunes) groundwater is at significant depth and the unsaturated zone is generally drier. As such, the two-layer model may not realistically represent the flow dynamics in the unsaturated zone. As such, unsaturated zone soil parameters have been calibrated outside the ranges specified in the conceptual model for some soil zones – and may not be appropriate for use in other areas with shallow groundwater tables. Calibrated parameters for each soil zone are shown in Table 4-7.

The Quindalup and Bassendean soil zones have parameter values consistent with the conceptual model. The water content at field capacity (Wfc) and wilting point (Wwp) are close, which increases recharge, and implies low plant-available water. The specific yield – water content at saturation (Wcs) minus Wfc – for the Quindalup zone is 0.28 and the Bassendean zone 0.24. The saturated vertical conductivity (Ksat) is 5 m/day for both zones, implying rapid infiltration and little surface runoff under free-draining conditions.

The Spearwood soil zone has parameter values consistent with the conceptual model, with the exception of the Wfc, which is set to 0.16. This is to increase plant-available water in the soil profile, as recharge was being over-estimated in the Spearwood soil zone within the model using lower values of Wfc. The specific yield for the Spearwood soil zone is 0.26, which is within an appropriate range.

The Vasse, Forrestfield and Pinjarra soil zones all have calibrated parameter sets consistent with sandy clay soils. Note that the specific yield of the Pinjarra and Forrestfield soil zones is low (0.08 and 0.06 respectively). These values were necessary to replicate the amplitude of the groundwater signal on the Pinjarra Plain and Darling Scarp. The saturated conductivity of these soil zones was set to 0.05 m/day, and this parameter was important for determining the magnitude of peak flows in the Mike 11 channel network, as it directly influences the amount of overland flow.

The evapotranspiration surface depth parameter was set to 0.2 m, which is appropriate for sandy soils.

*Table 4-7 Unsaturated zone model (two-layer model) calibrated parameters*

| Unsaturated zone soils | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Soil zone** | **Parameter** | **Value** | **Units** | **Soil zone** | **Parameter** | **Value** | **Units** |
| Quindalup | Wcs | 0.34 | | Bassendean | Wcs | 0.3 | |
| | Wfc | 0.06 | | | Wfc | 0.06 | |
| | Wwp | 0.045 | | | Wwp | 0.04 | |
| | Ksat | 5 | m/day | | Ksat | 5 | m/day |
| Spearwood | Wcs | 0.41 | | Forrestfield | Wcs | 0.26 | |
| | Wfc | 0.15 | | | Wfc | 0.2 | |
| | Wwp | 0.02 | | | Wwp | 0.12 | |
| | Ksat | 1 | m/day | | Ksat | 0.05 | m/day |
| Vasse | Wcs | 0.3 | | Pinjarra | Wcs | 0.26 | |
| | Wfc | 0.16 | | | Wfc | 0.18 | |
| | Wwp | 0.1 | | | Wwp | 0.12 | |
| | Ksat | 0.05 | m/day | | Ksat | 0.05 | m/day |

## Land use parameters

Calibrated parameters for the evapotranspiration model are shown in Table 4-8. Calibrated parameters for LAI and RD are fairly consistent with those used by Hall et al. (2010). The main difference is the introduction of a deep-rooted-vegetation land use to account for the large trees along the Spearwood Dunes and around Lowlands. RD for the ‘native trees’ land use class was set to 2000 mm, and is probably limited by watertable depth in parts of the study area.

*Table 4-8 Evapotranspiration model calibrated parameters*

| Unsaturated zone land use | | | |
|---|---|---|---|
| **Class** | **Parameter** | **Value** | **Units** |
| Urban | LAI | 1 | |
| | RD | 1000 | mm |
| Pasture | LAI | 0-3 | |
| | RD | 800-1300 | mm |
| Irrigated | LAI | 3 | |
| | RD | 1200 | mm |
| Native trees | LAI | 1.3 | |
| | RD | 2000 | mm |
| Plantation | LAI | 1.8 | |
| | RD | 2000 | mm |
| Deep rooted | LAI | 2 | |
| | RD | 4000 | mm |

## Channel flow parameters

The channel flow model (Mike 11) uses two main parameters: the bed resistance (Manning’s *n*) and the leakage coefficient between the saturated zone to the channel bed. Calibrated parameter values are shown in Table 4-9.

During calibration, distributed *n* values were tested; however, river flows were relatively insensitive to the parameter, and in some cases a variable *n* introduced numerical instabilities into the Mike 11 model. Given the satisfactory calibration achieved with a global value, and the similarity in bed material and shape of major channels, the original value of 0.033 s/m$^{1/3}$ was assigned to all reaches.

The leakage coefficient was set to a universal value of 1 x $10^{-7}$ in units of 1/s except for the northern end of Peel Main Drain, which was assigned a leakage coefficient of 5 x $10^{-7}$, as the drain intercepts the relatively sandy sediments of the Jandakot Mound in this area. The bed-only leakage option was used, which means the rate of exchange between aquifer and bed is determined by the leakage coefficient only, and aquifer properties are not considered in the calculation. The leakage coefficient was an important parameter for calibrating river baseflow.

The fully dynamic wave approximation was used as the solution method for the Mike 11 channel network.

*Table 4-9 Calibrated Mike 11 parameters*

| | Mike 11 parameter | | |
|---|---|---|---|
| **Class / layer** | **Parameter** | **Value** | **Units** |
| Universal | Leakage coefficient | 1.00E-07 | |
| | Manning's n | 0.033 | s/m$^{2/3}$ |

## Overland flow parameters

Table 4-10 shows the calibrated overland flow parameters. For the overland flow model, a resistance parameter (Manning's *M*) of 30 m$^{1/3}$/s was used. This is a typical value for pasture or sparse native vegetation, which makes up most of the catchment. Detention storage was set to 1 mm. The model was relatively insensitive to the overland flow parameters because overland flow is a small component of the water balance in the model.

*Table 4-10 Calibrated overland flow parameters*

| | Overland flow | | |
|---|---|---|---|
| **Class / layer** | **Parameter** | **Value** | **Units** |
| Universal | Manning's M | 30 | m$^{1/3}$/s |
| | Detention storage | 1 | mm |
| | Initial water depth | 0 | m |

## Saturated zone parameters

Calibrated saturated zone parameters are shown for all geological units in Table 4-11. It is important to note that while each geological unit has associated parameters, these are distributed throughout each computational layer according to the spatial distribution of the units. As such, parameters are averaged within the computational layers based on the distribution of the geological units.

FiguresFigure 4-18 to Figure 4-20 show the distributed parameter values for each computational layer after the Mike SHE pre-processer has run, which defines the numerical model's hydraulic properties.

In the first computational layer, specific yield is determined based on the unsaturated zone parameters, as discussed previously. In the second and third computational layers, specific yield is not required because these are confined in the model calculations. In the first computational layer, the storage coefficient is not considered given the aquifer is unconfined. As such, only the relevant parameters are reported in Table 4-11.

The saturated zone parameters were within the bounds specified in the conceptual model. The following changes in model parameters were important for achieving calibration:

- Low vertical conductivity in the basal clay unit of 0.0005 m/day was important to achieve calibration of the Safety Bay Mound and reduce downward leakage to the Rockingham Aquifer.
- The horizontal conductivity of the Bassendean Sand was set to the relatively low value of 10 m/day, as higher values resulted in flatter gradients on the Jandakot Mound that did not match observed heads. In some locations near wetlands on the Jandakot Mound the horizontal conductivity was assigned a lower value of 2 m/day to increase groundwater gradients and achieve calibration (see Figure 4-8).
- Low horizontal conductivity of 5 m/day for the Safety Bay Sand was necessary to achieve the calibration of the Safety Bay Mound.
- A combination of higher horizontal conductivity through the Tamala Limestone of up to 200 m/day, and lower conductivity in the Tamala Sand (3 m/day), was required to replicate the steep groundwater gradient to the Jandakot Mound's west.
- Distributed vertical conductivity in the Pinjar Member was necessary to achieve calibration of the Leederville bores. To the east of the Serpentine Fault, higher conductivity of $1.15 \times 10^{-3}$ m/day was applied, as the bore AM50X follows closely the trends in the Superficial water levels in this area. To the west of the Serpentine Fault, vertical conductivity was set to $7 \times 10^{-6}$ m/day to prevent vertical leakage through central parts of the study area, where AM53, AM55A and AM59B do not show evidence of connection between the Superficial and Leederville aquifers.
- Vertical conductivity in the Wanneroo Member was an important parameter for controlling recharge to the Leederville Aquifer. It was set to $8 \times 10^{-4}$ m/day, indicating low connectivity with the Superficial Aquifer in places where the Quaternary sediments are underlain by the Wanneroo Member.
- Horizontal conductivity in the Wanneroo Member was important when calibrating the level of the 'AM series' bores in the study area's west, and this was assigned as a distributed parameter with conductivity increasing from 0.1 m/day near the Darling Scarp, to 3 m/day near the Rockingham Member (proposed).

*Table 4-11 Calibrated saturated zone parameters*

| Saturated zone | | | | |
|---|---|---|---|---|
| **Layer** | **Kh (m/day)** | **Kz (m/day)** | **Sy** | **Sc** |
| Estuarine, swamp | 10 | 0.5 | **Refer to unsaturated zone parameters** | na |
| Lake sediments | 15 | 0.1 | | na |
| Basal clay | 0.001 | 0.0005 | | na |
| Bassendean | 10* | 1 | | na |
| Safety Bay | 5 | 0.5 | | na |
| Tamala Sand | 3 | 0.5 | | na |
| Tamala east | 200 | 20 | | na |
| Tamala west | 5 to 100 | 8 | | na |
| Quaternary sands | 8 | 1.2 | | na |
| Guildford Clay | 1 | 0.1 | | na |
| Colluvium | 1 | 0.1 | | na |
| Ascot | 10 | 1.2 | | na |
| Kardinya Shale | $1x10^{-5}$ | $1x10^{-6}$ | na | $1x10^{-5}$ |
| Rockingham Member | 15 | 0.5 | na | $5x10^{-6}$ |
| Pinjar Member | 0.1 to 1 | $7x10^{-6}$ to $1.15x10^{-3}$ | na | $1x10^{-5}$ |
| Wanneroo Member | 0.1 to 3 | $8x10^{-4}$ | na | $5x10^{-6}$ |

** set to 2 m/day in some grid cells*

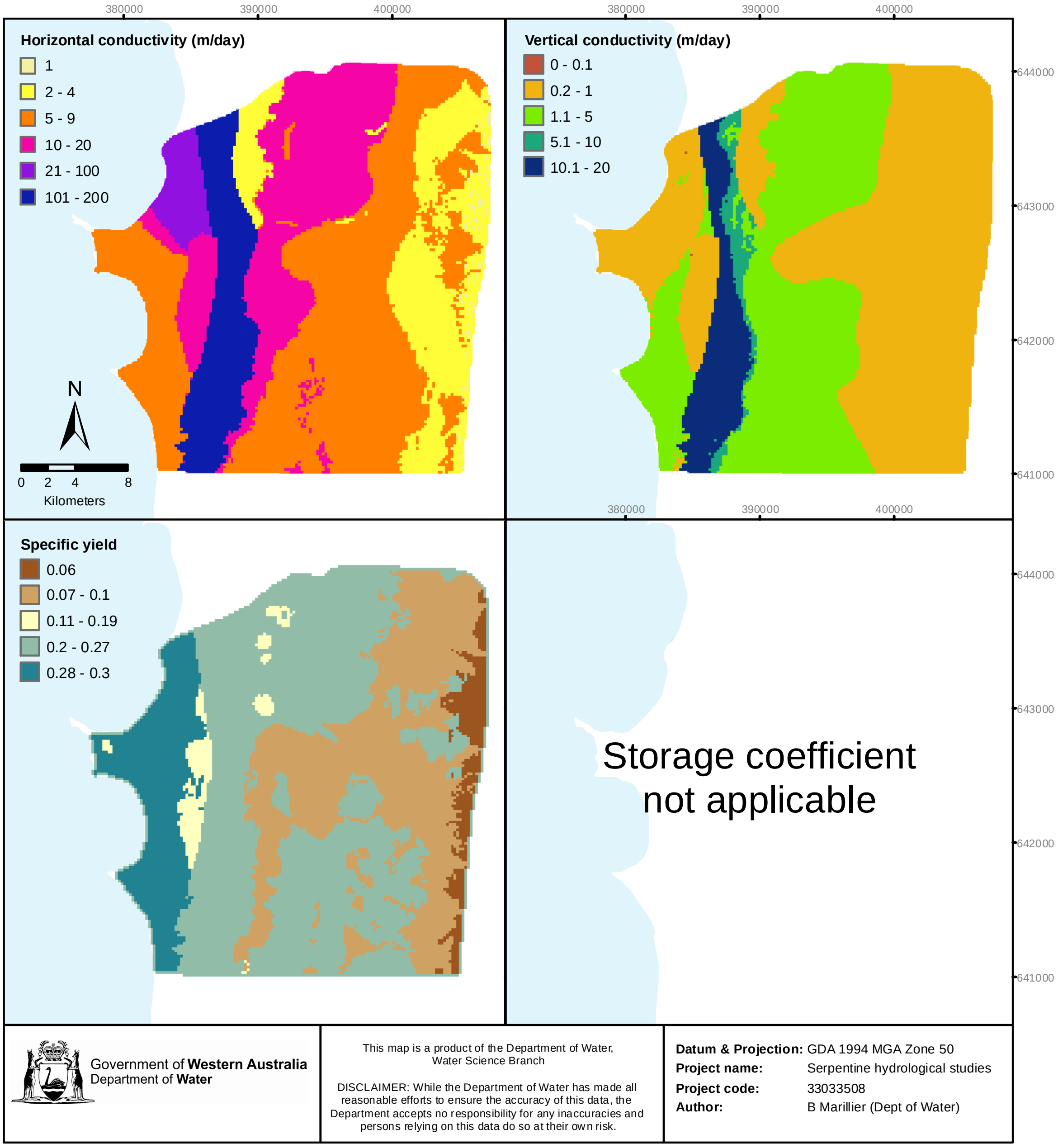



*Figure 4-18 Distributed hydraulic parameters for the first computational layer (Kh, Kz, Sy)*

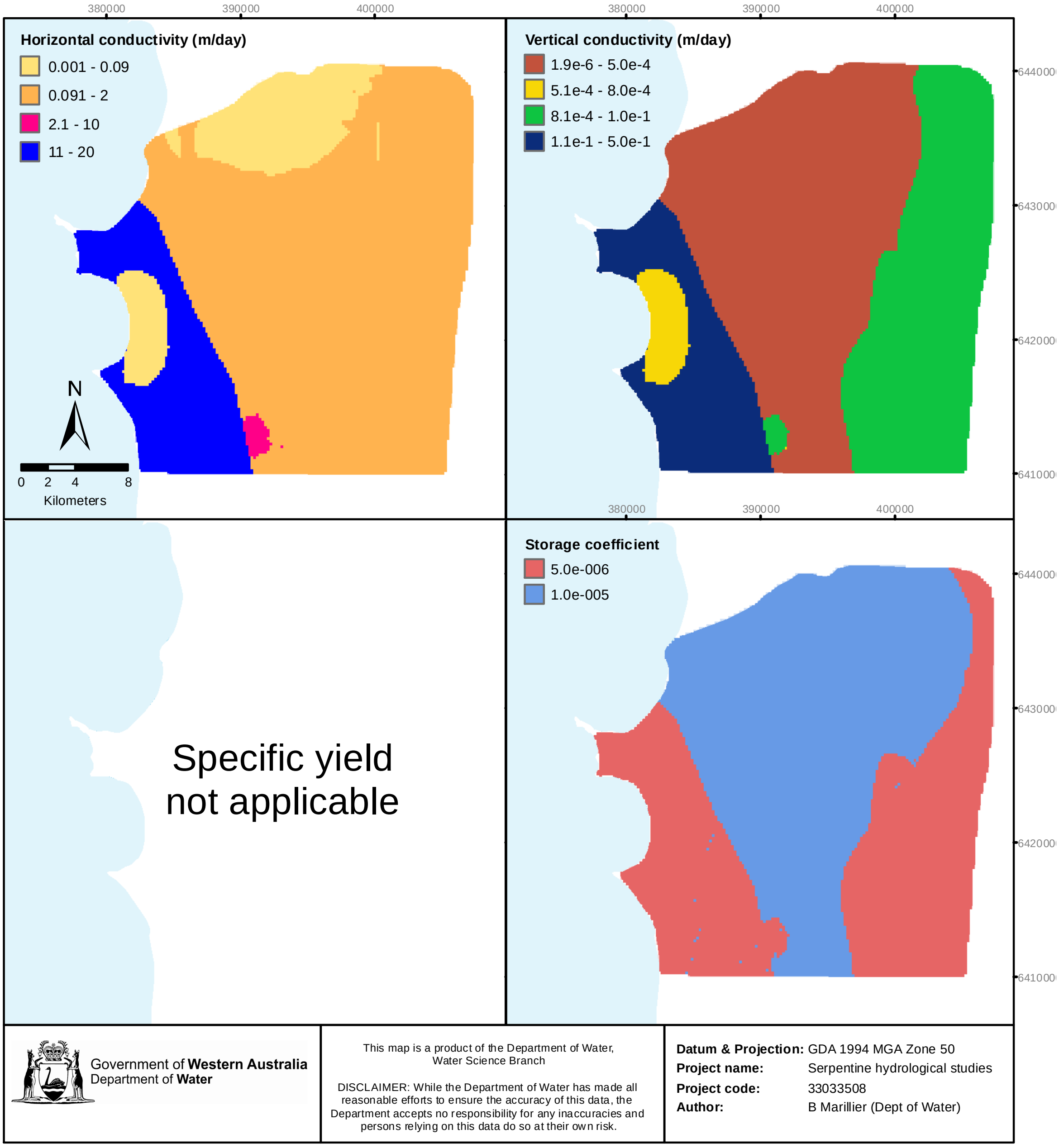



*Figure 4-19 Distributed hydraulic parameters for the second computational layer (Kh, Kz, Sc)*

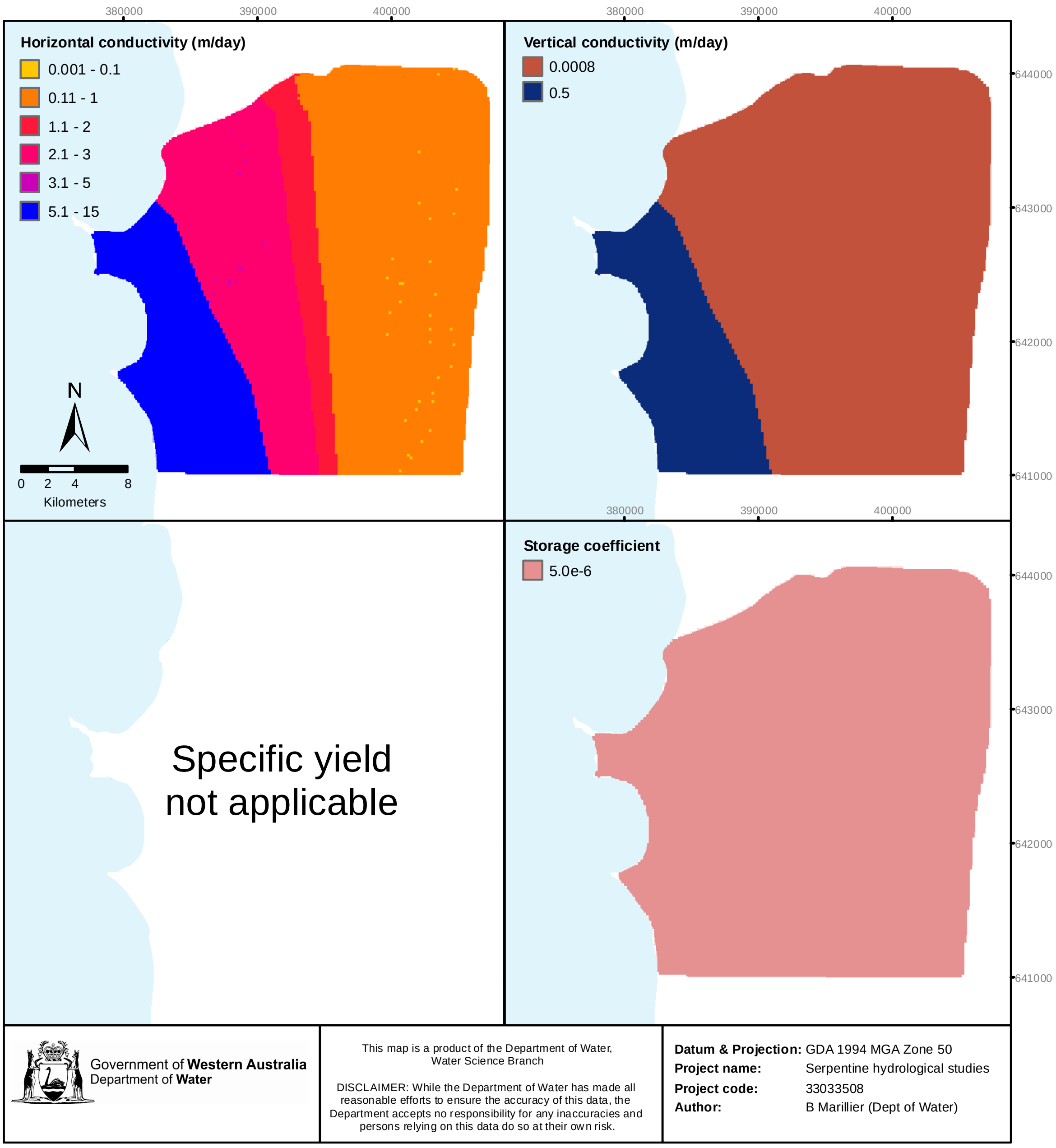



*Figure 4-20 Distributed hydraulic parameters for the third computational layer (Kh, Kz, Sc)*

### Saturated zone drainage parameters

The drainage network within the saturated zone routes water to the Mike 11 river network within the model. Two parameters are adjusted to meet the model water balance and observed flows in the river network. These are the drain level, which was set to 0.2 mbgl; and the drain time constant, which was set to 1 x $10^{-5}$/s. The drain level is important for determining the upper limit of the phreatic surface near drains, and influences the baseflow component in the river network. The depth used represents an approximation of the average depth of small agricultural drains in the area. The drain time constant determines the rate at which water moves through the drain network to the Mike 11 channels, and influences the shape of the flow hydrograph, in particular the ‘flashiness’ of peak flows. Calibrated parameters are shown in Table 4-12.

*Table 4-12 Calibrated drainage parameters*

| Drainage parameters | | |
|---|---|---|
| Level | 0.2 | mbgl |
| Time constant | $1x10^{-5}$ | /s |

## 4.6 Calibration discussion

The Lower Serpentine model has a domain area of 728 km$^2$ and three computational layers. Most of the simulated heads at the monitoring bores have responses that are consistent in amplitude and level with the measured data. However, a model of this size will have various inherent errors due to the simplifications required to produce a large-scale numerical model. The errors are deficiencies in either the calibration process or the conceptual model. Deficiencies in the conceptual model can result in localised areas of high error, systematic errors over large areas, and errors that are intractable or insensitive to parameter variations.

The main errors associated with the conceptual model and the available input datasets are highlighted below:

- **Vertical model resolution:** a single computational layer was used for the Superficial Aquifer, precluding the model from simulating head differences within the aquifer.
- **Horizontal model resolution:** the size of the area modelled limits the detail with which the real world can be represented. Model run-times determine an upper limit on cell size, which in this case was 200 m. Variation in groundwater head at a scale of less than the cell size cannot be simulated, which introduces some inherent error, particularly in areas of steep hydraulic gradient.
- **Heterogeneity in geology:** it was assumed that parameter values were consistent within each of the geological units specified, with the exception of the Tamala Limestone and Pinjar and Wanneroo members, which were assigned distributed parameter values. In reality, most of the formations have significant variations in stratigraphy; for example, the Pinjar and Wanneroo members consist of interbedded sands and siltstones, which are not realistically represented by single geological units.

- **Inadequate conceptualisation of the Leederville Aquifer:** the extent of the Pinjar and Wanneroo members was based on the geological interpretation of Davidson (1995), which formed the basis of the Perth Regional Aquifer Modelling System (PRAMS) 3.0. This interpretation does not capture the shape of the formations in detail. This was the best conceptualisation available, but the difficulty in calibrating the Leederville Aquifer has highlighted potential problems with and uncertainty around the conceptualisation.
- **Groundwater abstraction:** a large amount of data processing was required to generate the input abstraction dataset for the Lower Serpentine model, including licensed and unlicensed data. However, in areas of the model there is clear evidence of groundwater pumping resulting in declining groundwater levels. This is most evident on the Jandakot Mound immediately to the south of the Water Corporation production bores, and around the townships of Byford and Mundijong, which contain numerous horse properties and lifestyle blocks that may be significant water users. It appears the abstraction dataset used in the model does not accurately reflect the true abstraction of groundwater in all areas. This results in poor replication of declining trends in groundwater in some parts of the model. The lack of metering for most consumers of groundwater makes it impossible to accurately model abstraction.
- **Vertical leakage to the Cattamarra:** there is evidence of connectivity between the Superficial, Leederville and Cattamarra aquifers between the Darling Scarp and the Serpentine Fault (Leggette et al. 1971; WAWA 1987). However, vertical leakage to the Cattamarra Aquifer was ignored in this model because it was deemed to be too small a flux to warrant inclusion. However, downward leakage to the Cattamarra may have a significant influence on water levels in the Leederville and Superficial aquifers close to the Darling Scarp. Insufficient hydrogeological data is available in this area to generate a reliable conceptual model, and this area requires further study given its likely importance as a recharge zone for the Cattamarra Aquifer.
- **Boundary conditions:** the time-varying fixed-head boundaries along the model's northern boundary are approximations of the likely hydraulic head in these areas, and spatial variation along the boundary is not well represented. In addition, it appears the model's northern section in the Superficial Aquifer is probably influenced by abstraction from the Jandakot Mound, from outside the model area, which is not accounted for using a no-flow boundary in the north. Sensitivity analysis shows the Superficial Aquifer is not sensitive to the Leederville Aquifer boundary conditions within the range tested.

### Calibration bores

Most bores within the model achieved good calibration, with the seasonal variation in groundwater level and long-term trend well replicated. However, some areas of the model and some bores in particular did not calibrate well. The best-calibrated areas of the model were the low-lying areas of the Pinjarra Plain, the Spearwood Dunes, and associated rivers and wetlands. Generally, steeper-sloped areas adjacent to the Darling Scarp and on the Jandakot Mound were less accurately simulated, as were bores with significant abstraction-related trends. Problem bores and areas are discussed in detail below, with possible causes of error suggested.

The calibration has been compared for each problem bore with the PRAMS 3.0 calibration results (Cymod 2009), which gives some indication as to whether the error is related to conceptualisation, parameterisation or the observed data itself. Problem bores can be clearly identified in the calibration error distribution maps (figures 4-4 and 4-5). See Appendix C for observed versus modelled graphs showing groundwater head for all calibration bores.

The Superficial monitoring bore with the worst positive calibration error (model over-prediction) is associated with **T190 (O)** located 1 km to the south of the Spectacles Wetlands in the Spearwood Dune system. Observed data at this bore show a groundwater hydrograph between 1974 and 2010 with no significant trend, an amplitude of around 0.5 m and a level of 8.5 m. The model shows groundwater heads at 11 m, with an amplitude of 1 m. The up-gradient bore at T200 (O) and the down-gradient bore at T180 (O) calibrated well. PRAMS 3.0 also over-predicts groundwater levels at this bore, although to a lesser degree. This bore is in an area with a steep hydraulic gradient, which is related to the Jandakot Mound and the interface between the Bassendean Sand, Tamala Sand and Tamala Limestone. The likely source of the error is insufficient detail in the geological model representing the formations in this area.

Water levels in the central and western parts of the Jandakot Mound around **T150 (O)** and **JM48** are generally over-predicted, as are water levels in the Spectacles Wetlands. Again, this is probably due to inadequate conceptualisation of the area's geology; however, water levels beyond the northern modelling boundary probably influence water levels in the area. There is evidence of this in the declining groundwater trends and increasing seasonal amplitude in bores **JM39, JM44** and **JM48**, indicating the influence of groundwater abstraction. It is also possible that recharge is over-estimated in this area, which would contribute to the over-estimation of groundwater level.

The largest negative calibration error (model under-prediction) is associated with bore **T220 (O)** located on the Pinjarra Plain near Byford. The maximum groundwater level is correctly simulated but the amplitude is over-estimated and therefore minimum groundwater levels are around 1.5 m too low. As such, areas of inundation near T220 (O) should be fairly well replicated, yet the average and minimum groundwater levels in this area will be under-predicted.

The model under-predicts the groundwater level near **T160 (O)** on the Jandakot Mound's eastern edge. There is a head difference of around 0.5 m between T160 (O) and T160 (I), the latter of which is screened at depth. Logging of this bore indicates a coffee rock layer, and it is possible that resistance to vertical flow is occurring within the Superficial Aquifer in this area, which is not captured by the model. PRAMS 3.0 under-predicts this bore by more than 3 m, which indicates the aquifer may have some localised hydraulic properties that are not captured by regional-scale modelling.

Another area of model error is near bores **T120 (O)** and **T170** north of Byford. For the calibration period until around 1993 groundwater levels are accurately modelled (see Appendix C). However, from 1993 onwards, observed data show a marked downward trend in groundwater level in the Superficial Aquifer that is not captured by the model. The downward trend is accompanied by an increase in seasonal amplitude, which implies an abstraction signal. Given the area has experienced significant population growth since 1990 particularly around horse and lifestyle blocks, it is possible the error is related to incorrect abstraction data in this area, or abstraction from beyond the model boundary to the north. It is also possible this trend is a result of downward leakage to the Cattamarra Aquifer, which has not been included in the model, as groundwater levels in the Cattamarra have declined over a similar period of time in this area.

The abstraction simulated within the model appears to have introduced error around Rockingham and Kwinana, with some bores showing less long-term decline in head than predicted by the model. There is evidence of this around **T330 (O)**, **T240 (I)**, **T130 (I)** and **T180 (O)**. A revision of the abstraction data-series in these areas would probably improve calibration.

Bores screened in the Leederville Aquifer generally had worse calibration statistics than for the Superficial. **AM50X** shows a very similar trend and model error compared with the Superficial bore **T170**. The model fails to simulate the declining trend in hydraulic head in this area, and it is possible abstraction from the Leederville is under-estimated in this area, which would explain the over-prediction in both AM50X and T170 (through underestimation of downward leakage).

**AM50Z** has the worst RMS error of the Leederville bores, and the model failed to simulate the artesian conditions (before 1993) of the Leederville Aquifer in this location. In this area the Pinjar Member is poorly conceptualised, and the thickness is probably over-estimated. A conceptualisation based more closely on Berliat's (1963) work would probably yield better results. Berliat shows the Wanneroo Member, beneath the Quaternary sediments near Byford, dipping westward into the syncline beneath the Pinjar Member, which would create artesian conditions at AM50Z under the required groundwater regime. The conceptualisation used in the Lower Serpentine model was based on Davidson (1995), which shows the Pinjar Member below the Quaternary sediments in this area, with very little thickness in the Wanneroo Member underneath.

**AM60E** was well calibrated until after 2000, when the model simulates a declining trend due to abstraction that is not present in the observed hydraulic head. The most likely reason for this is the bore's proximity to the model's southern boundary, which means this part of the model is sensitive to abstraction because it does not receive lateral inflows of groundwater from beyond the southern boundary. This is best illustrated in Figure 6-10, which shows that the third computational layer is most sensitive to abstraction in the area around AM60E.

### Rivers and lakes

Calibration of the surface water component involved matching observed discharge at surface water gauging sites with observed water levels at wetland and lake monitoring sites. Lake and wetland levels were included as part of the Superficial Aquifer dataset, and included observations from eight long-term monitoring sites throughout the study area. Five flow gauges were included in the calibration dataset, with two used in validation.

All of the lake and wetland levels were simulated accurately, with seasonal inundation and absolute water level matching observations in most or all years. An RMS error of 0.50 m or less was achieved for all of the eight gauge boards. Calibration in the Spectacles Wetlands was the worst, with an RMS error of 0.50 m, due to a slight over-prediction in water level. The Spectacles Wetlands are in the most complex part of the model, and the error is likely to be associated with the over-prediction in groundwater level around bores JM41 and JM42. Water levels in Lake Richmond are under-predicted by around 0.42 m, which is probably due to surface water drainage to the wetland that was not captured in the Mike SHE drainage model. Scale effects may also play a part in errors associated with wetland water levels, as 200 m is too coarse a resolution to accurately represent the smaller wetlands.

The calibration targets were achieved for the flow gauges used in calibration. The plots of observed versus modelled flow for each of the calibration and validation gauges show that peak and baseflows are realistically simulated for all of the main waterways. Accurate replication of the peak flows show the overland flow component of the Mike SHE model, and soil properties (particularly saturated conductivity), are realistically representing landscape runoff processes. Accurate prediction of baseflow is important because drainage is a significant component of the water balance. The seasonal winter baseflow component shows a close match to observed data at all locations.

The main point of error in the model's channel flow component is that a very small baseflow is present year-round (often less that 0.001 m/s). This is unlikely to skew water balance calculations, but may influence calculations for ecological water requirements that relate to low-flow conditions. This flow is probably an artefact of a low-flow stability control called a 'slot' in Mike 11. The slot extends Mike 11 cross-sections using a narrow slot at the base of the channel. This improves stability at low flow, but may also introduce very small quantities of baseflow that are unrealistic.

### Limitations and uncertainties

Achieving calibration statistics in an integrated surface water/groundwater model does not guarantee it is a realistic representation of real-world hydrological and hydraulic phenomena. The selection and implementation of an appropriate conceptual model is more important than achieving a small error in calibration statistics. Application of the model to scenario analysis is therefore limited by the accuracy and intent of its conceptualisation.

The Serpentine model has a spatial resolution of 200 m and a temporal resolution of one day. Based on the model's structural limits and the errors discussed previously, the model **is suitable** for the following applications:

- **Evaluating changes to the Superficial Aquifer water balance** related to land use, as well as climatic and drainage changes (e.g. changes in recharge, drainage, evapotranspiration, horizontal flows etc.).
- **The relative assessment of regional and subregional impacts** due to changes in drainage and abstraction from the Superficial Aquifer.
- **District-scale groundwater-level evaluation (AAMaxGL, AAMinGL etc.) under various climate scenarios**. This includes determining areas of seasonal waterlogging and inundation. However, the inherent model error needs to be considered when using groundwater levels derived from the regional model. If the error is deemed too large for the purpose of the application, a localised model with a

finer grid should be constructed and re-calibrated to achieve appropriate model error, with improved conceptualisation based on local data.

The Lower Serpentine model **is not suitable** for the following applications:

- **Wetland and lake assessment:** when features are similar in scale to the horizontal and vertical resolution of the model, they are not suitable for evaluation using the Lower Serpentine regional model. However, the model shows accurate simulation of surface water/groundwater interactions, and can form the basis of higher-resolution subregional and local models more appropriate for these types of evaluations.
- **Flood modelling:** the Lower Serpentine model was developed to simulate the groundwater and drainage system at an appropriate timestep. As such, the configuration of the model and timestep used is not appropriate for flood modelling. Culverts and bridges were not included in the Mike 11 model, and average recurrence interval (ARI) flood events were not calibrated to. At present the Department of Water and GHD are developing several Mike flood models within the region, designed for the explicit purpose of flood modelling.
- **Detailed drainage modelling:** this includes the detailed modelling of individual subsurface drains, and potential development drainage scenarios. Drainage cannot be modelled at a grid scale finer than that of the saturated zone model (200 m), so any drainage that is likely to be at a finer scale than 200 m is not considered a suitable scenario for the Lower Serpentine regional model.
- **Abstraction and sustainable yield calculations from the Leederville Aquifer:** the Leederville was modelled as a single computational layer within the Lower Serpentine model; however, a poor calibration was achieved, and there is considerable uncertainty around the calibrated parameters and model conceptualisation (especially along the Serpentine Fault). The intent of including the Leederville Aquifer was to account for downward leakage from the Superficial Aquifer, and lateral flow into the Rockingham Aquifer. With improved parameterisation derived from field observations, and an updated conceptualisation, the model may be re-calibrated at a later stage for abstraction analysis, but it is not appropriate with the current version.

# 5 Water balance

The average annual water balance for the Lower Serpentine regional model was calculated for the period from January 1975 to December 2010 inclusive. The water balance is presented here in two ways: a total ‘system’ water balance showing every flux in the numerical model, and an aquifer water balance showing only the fluxes related to groundwater. The system water balance is reported in Table 5-1. The aquifer water balance is reported for the first computational layer – which represents the Superficial Aquifer (Table 5-2) – and is shown in comparison with the conceptual water balance (Marillier et al. 2012) in Table 5-3. The third computational layer represents the combined Rockingham and Leederville aquifers (Table 5-4). Note that the second computational layer (Pinjar Member and Kardinya Shale) has not been reported in the following water balance calculations, as it was included in the model as a confining layer, and not as part of the Leederville or Rockingham aquifers.

*Table 5-1 System water balance for the model domain*

| | Superficial Aquifer water balance (1975-2010) | | | |
|---|---|---|---|---|
| **Flux** | **mm** | **mm/yr** | **GL/yr** | **%*** |
| **Gross recharge** | 9521 | 264 | 192.5 | 96% |
| **Horizontal flow in** | 16 | 0 | 0.3 | 0% |
| **Vertical flow in** | 389 | 11 | 7.9 | 4% |
| **Recharge from river** | 0 | 0 | 0.0 | 0% |
| **EVT (GW)** | 4526 | 126 | 91.5 | 44% |
| **Horizontal flow out** | 464 | 13 | 9.4 | 5% |
| **Vertical flow out** | 1490 | 41 | 30.1 | 15% |
| **Baseflow to rivers** | 388 | 11 | 7.8 | 4% |
| **Drainage** | 2531 | 70 | 51.2 | 25% |
| **Abstraction** | 792 | 22 | 16.0 | 8% |
| **Error** | 6 | 0 | 0.1 | na |
| **Δ Storage (SZ only)** | -259 | -7 | -5.2 | na |

**Percentage as a proportion of total losses or gains*

The system water balance is useful for reporting surface water components of the model. Note that surface water inflows from the Mike 11 channel boundary conditions are not included within the water balance. The sum of the baseflow, drainage and overland flow components of the water balance equate to the discharge from the channel network. This is equal to 67.5 GL/year, from which a coefficient of runoff of 12% can be calculated (total streamflow divided by total rainfall). This is a low value for the Swan Coastal Plain (typically around 20%), which can be attributed to the lack of drainage features on the Jandakot Mound and west from the Spearwood Dunes, with these areas having significant depth-to-watertable. Most of the drainage water is derived from the Pinjarra Plain area of the model, which has shallow groundwater and clayey soils.

Table 5-2 Superficial Aquifer water balance

| Flux | mm | mm/yr | GL/yr | %* |
|---|---|---|---|---|
| | Superficial Aquifer water balance (1975-2010) | | | |
| **Gross recharge** | 9521 | 264 | 192.5 | 96% |
| **Horizontal flow in** | 16 | 0 | 0.3 | 0% |
| **Vertical flow in** | 389 | 11 | 7.9 | 4% |
| **Recharge from river** | 0 | 0 | 0.0 | 0% |
| **EVT (GW)** | 4526 | 126 | 91.5 | 44% |
| **Horizontal flow out** | 464 | 13 | 9.4 | 5% |
| **Vertical flow out** | 1490 | 41 | 30.1 | 15% |
| **Baseflow to rivers** | 388 | 11 | 7.8 | 4% |
| **Drainage** | 2531 | 70 | 51.2 | 25% |
| **Abstraction** | 792 | 22 | 16.0 | 8% |
| **Error** | 6 | 0 | 0.1 | na |
| **Δ Storage (SZ only)** | -259 | -7 | -5.2 | na |

**Percentage as a proportion of total losses or gains*

Table 5-3 Comparison between conceptual and numerical water balance

| Flux | Numerical model water balance mm | % | Conceptual model water balance mm | % |
|---|---|---|---|---|
| Gross recharge | 264 | 96% | 349 | 99% |
| Horizontal flow in | 0 | 0% | 0 | 0% |
| Vertical flow in | 11 | 4% | 3 | 1% |
| Recharge from river | 0 | 0% | 0 | 0% |
| EVT (GW) | 126 | 44% | 227 | 61% |
| Horizontal flow out | 13 | 5% | 7 | 2% |
| Vertical flow out | 41 | 15% | 23 | 6% |
| Drainage & river baseflow | 81 | 29% | 69 | 19% |
| Abstraction | 22 | 8% | 45 | 12% |
| Δ Storage (SZ only) | -7 | | -5 | |

**Percentage as a proportion of total losses or gains*

The Superficial Aquifer water balance describes the largest and most complex fluxes within the modelled system. Gross recharge was calculated as 264 mm/year, which is 33% of rainfall. This is less than the estimated value of 42% in the conceptual model, and the difference can be attributed to recharge rejection due to inundation, which was not accounted for in the conceptual flux calculations. Evapotranspiration from groundwater was the largest outward flux from the aquifer, accounting for 44% of losses: this is less than estimated in the conceptual model (61%) and the difference is due to uncertainties in depth-to-groundwater calculations used in conceptual calculations. Net recharge, which is gross recharge subtract evapotranspiration from groundwater is equal to 18% or rainfall.

The combined volume of drainage water and baseflow to rivers is 59.0 GL/year, which is more than the 49.9 GL/year calculated through baseflow separation in the conceptual model. However, the total flow estimated from drainage in the system water balance is 67.5 GL/year, which is only 5% less than that estimated in the conceptual model (70.7 GL/year).

For the Superficial Aquifer, vertical leakage accounted for 7.9 GL/year of inflows, and 30.1 GL/year of outflows. This results in a net loss from the Superficial Aquifer to the Rockingham and Leederville aquifers of 22.2 GL/year. This volume is greater than the 14.4 GL/year estimated in the conceptual water balance. However, there was a large amount of uncertainty in the simple vertical flux calculations of the conceptual model, particularly leakage from the Superficial Aquifer to the Rockingham.

Abstraction accounted for 8% of losses from the Superficial Aquifer, but it is important to note that abstraction has increased substantially during the past 10 to 15 years, so a water balance for the period 2005 to 2010 would show a much higher proportion of losses related to abstraction – closer to the 12% estimated in the conceptual model.

The Superficial Aquifer water balance is consistent with the conceptual water balance, which shows that the numerical model is functioning as intended. Evapotranspiration and drainage are the largest fluxes within the aquifer; however, all components of the water balance were significant – accounting for 4% or more of losses. Note that horizontal flow from the Superficial Aquifer is around twice the volume estimated in the conceptual model, and this is due to the high transmissivity assigned to the Tamala Limestone in the north-west section of the model.

*Table 5-4 Rockingham and Leederville aquifers' water balance for the periods 1975 to 2010 and 2005 to 2010*

**Rockingham and Leederville water balance (1975-2010)**

| Flux | mm | mm/yr | GL/yr | %* |
|---|---|---|---|---|
| Horizontal flow in | 36 | 1 | 0.7 | 2% |
| Vertical flow in | 1428 | 40 | 28.9 | 98% |
| Horizontal flow out | 949 | 26 | 19.2 | 65% |
| Vertical flow out | 361 | 10 | 7.3 | 25% |
| Abstraction | 156 | 4 | 3.2 | 11% |
| Error | 6 | 0 | 0.1 | na |
| Δ Storage (SZ only) | -1 | 0 | 0.0 | na |

**Percentage as a proportion of total losses or gains*

**Rockingham and Leederville water balance (2005-2010)**

| Flux | mm | mm/yr | GL/yr | %* |
|---|---|---|---|---|
| Horizontal flow in | 5 | 1 | 0.6 | 2% |
| Vertical flow in | 221 | 37 | 26.8 | 98% |
| Horizontal flow out | 113 | 19 | 13.7 | 50% |
| Vertical flow out | 45 | 8 | 5.5 | 20% |
| Abstraction | 68 | 11 | 8.3 | 30% |
| Error | 1 | 0 | 0.1 | na |
| Δ Storage (SZ only) | -1 | 0 | -0.1 | na |

**Percentage as a proportion of total losses or gains*

The Rockingham and Leederville aquifers' water balance contains relatively few fluxes as there is no interaction with the surface water and evapotranspiration components of the water balance. The water balance for the period 1975 to 2010 shows the main inflows are from vertical recharge totalling 28.9 GL/year, although 7.3 GL/year is lost through vertical discharge in some areas of the model. Horizontal flow is the main loss from the aquifer, which includes flow westwards through the Rockingham Aquifer to the ocean, and flow through the north-west boundary, where heads in the Leederville Aquifer have declined substantially. Abstraction accounts for 11% of losses for the period 1975 to 2010. However, recalculation of the water balance for the years 2005 to 2010 shows that abstraction accounts for 30% of losses, with horizontal flow accounting for 50% and vertical flow 20%. The water balance for the more recent period is consistent with the conceptual water balance calculations, which were based on recent and not historical data.

# 6 Sensitivity analysis

Sensitivity analysis describes the procedure for quantifying the impact on an aquifer's simulated response due to an incremental variation in a model parameter or a model stress. The aim of a sensitivity analysis is to identify those parameters that are most important in determining aquifer, river or wetland behaviours. If parameters can be ranked in order of importance, then priorities can be set for focusing field investigations on key parameters to reduce model uncertainty. A sensitivity analysis is undertaken by systematically changing calibrated aquifer parameters and determining the effect these changes have on observed data (i.e. bores where the model has been calibrated to measured heads).

Middlemis (2000) recommends that for highly complex models only a limited sensitivity analysis is performed after calibration is completed. Post-calibration sensitivity was performed for the Lower Serpentine model for all parameters that could feasibly be tested within the Mike SHE framework (see Section 6.1).

A stress dataset refers to an external stress imposed on the numerical model. Stress datasets including boundary conditions, rainfall, potential evaporation, abstraction and river flows were included in a separate quantitative sensitivity analysis (see Section 6.2).

This sensitivity analysis aims to identify parameters that are important to model function, and should be targeted by future field investigations to reduce model uncertainty. The sensitivity analysis is also useful to guide re-calibration of the Lower Serpentine model if required in future, and gives some indication of important parameters to consider in subregional models in the area.

## 6.1 Sensitivity of model parameters

The Mike Zero sensitivity analysis tool AUTOCAL was used to perform sensitivity analysis on the 73 model parameters listed in Table 6-1. AUTOCAL is a generic tool for performing automatic calibration, parameter optimisation, sensitivity analysis and scenario management of Mike SHE's numerical modelling engines. The methodology is described in detail in the Mike user guide (DHI 2011). AUTOCAL produces a result file that contains the calculated sensitivity coefficients of each parameter with respect to the different output measures and objective functions.

The sensitivity coefficient is calculated by comparing the relative impact of perturbing each parameter value compared with a base model run that uses a set of initial unperturbed parameters. The sensitivity coefficient is scaled by the degree of parameter perturbation. As a general rule, parameters are said to be insensitive if their scaled sensitivity coefficient is less than about 0.01 to 0.02 times the maximum scaled sensitivity coefficient (absolute value).

Several configuration options are available in AUTOCAL for the perturbation of parameter values used in the sensitivity analysis. The following options were used for analysis of the Lower Serpentine model:

- **difference approximation**: backward – initial parameter values were perturbed negatively (e.g. initial Kh = 10 m/day, perturbed Kh = 9.5 m/day)

- **perturbation option**: fraction of initial parameter
- **perturbation fraction**: 0.05 (linear), 0.50 (logarithmic, approx.) – the fraction by which the initial value is perturbed
- hydraulic conductivity, storage coefficient and leakage coefficient parameters were perturbed logarithmically, all other parameters were perturbed linearly.

The following procedure was used in the AUTOCAL sensitivity analysis:

1 Calibrated model parameters were tabulated, and a perturbed value was assigned for each parameter, as listed in Table 6-1.

2 Using AUTOCAL, simulations were run of each parameter in turn using the perturbed value.

3 Scaled sensitivity coefficients were compared for all parameters, and sensitive parameters were identified.

Several objective functions were configured to identify sensitivity in different aspects of the model. The objective function is used to determine the sensitivity coefficients of each parameter. Therefore it is important to select an objective function representative of important components of the model. An aggregate objective function can combine different measures to give an overall measure of model sensitivity. The following objective functions and their relative weight in the aggregate objective function are as follows:

- **RMS error of Leederville screened bores**: weight 5%, includes all ‘AM series’ bores
- **RMS error of Superficial screened bores**: weight 75%, includes all Superficial Aquifer bores
- **RMS error of select surface water gauging stations**: weight 20%, includes Dog Hill, Hopelands and Yangedi gauges.

Ten years of simulation were run, from 1990 to 1999. The period 1993 to 1999 was used to calculate the objective functions, which allows three years for the model to respond to new parameters.

The results of the sensitivity analysis for the aggregate objective function and Superficial Aquifer objective function are shown in Figure 6-1 below, while Figure 6-2 shows results for the surface water (Mike11) and Leederville Aquifer objective functions. Only parameters for which the objective function was ‘sensitive’ (greater than 0.02 times the maximum scaled sensitivity value) are shown in these figures.

*Table 6-1 Parameters and values used in sensitivity analysis*

| Parameter | $Val_i$ | $Val_p$ | Units | Parameter | $Val_i$ | $Val_p$ | Units |
|---|---|---|---|---|---|---|---|
| Irrigated_LAI | 3.00 | 2.85 | $m^2/m^2$ | Pinjarra_Ksat | 0.050 | 0.025 | m/day |
| Irrigated_RD | 1200 | 1141 | mm | Estuarine_Kh | 10.000 | 6.429 | m/day |
| Native_LAI | 1.30 | 1.24 | $m^2/m^2$ | Estuarine_Kz | 0.500 | 0.277 | m/day |
| Native_RD | 2000 | 1902 | mm | Lakes_Kh | 15.000 | 9.837 | m/day |
| Pasture_LAI | 1.80 | 1.71 | $m^2/m^2$ | Lakes_Kz | 0.100 | 0.051 | m/day |
| Pasture_RD | 1000 | 951 | mm | Basal_clay_Kh | 1.00E-03 | 4.09E-04 | m/day |
| Urban_LAI | 1.00 | 0.95 | $m^2/m^2$ | Basel_clay_Kz | 5.00E-04 | 1.97E-04 | m/day |
| Urban_RD | 1000 | 951 | mm | Bassendean_Kh | 10.000 | 6.429 | m/day |
| Plantation_LAI | 1.80 | 1.71 | $m^2/m^2$ | Bassendean_Kz | 1.002 | 0.574 | m/day |
| Plantation_RD | 2000 | 1902 | mm | Safety_Bay_Kh | 5.003 | 3.101 | m/day |
| DeepRooted_LAI | 2.00 | 1.90 | $m^2/m^2$ | Safety_Bay_Kz | 0.500 | 0.277 | m/day |
| DeepRooted_RD | 4000 | 3804 | mm | Tamala_sand_Kh | 2.998 | 1.813 | m/day |
| Mannings_M | 30.00 | 28.53 | $m^{1/3}/s$ | Tamala_sand_Kz | 0.500 | 0.277 | m/day |
| Quindalup_Wcs | 0.340 | 0.323 | - | Tamala_East_Kh | 200.000 | 148.232 | m/day |
| Quindalup_Wfc | 0.060 | 0.057 | - | Tamala_East_Kz | 20.000 | 13.242 | m/day |
| Quindalup_Wwp | 0.045 | 0.043 | - | Tamala_West_Kh | 40.003 | 27.460 | m/day |
| Quindalup_Ksat | 5.003 | 3.101 | m/day | Tamala_West_Kz | 8.001 | 5.076 | m/day |
| Spearwood_Wcs | 0.410 | 0.390 | - | Quaternary_sands_Kh | 8.001 | 5.076 | m/day |
| Spearwood_Wfc | 0.150 | 0.143 | - | Quaternary_sands_Kz | 1.201 | 0.694 | m/day |
| Spearwood_Wwp | 0.020 | 0.019 | - | Guildford_clay_Kh | 1.002 | 0.574 | m/day |
| Spearwood_Ksat | 1.002 | 0.574 | m/day | Guildford_clay_Kz | 0.100 | 0.051 | m/day |
| Vasse_Wcs | 0.300 | 0.285 | - | Colluvium_Kh | 1.002 | 0.574 | m/day |
| Vasse_Wfc | 0.160 | 0.152 | - | Colluvium_Kz | 0.100 | 0.051 | m/day |
| Vasse_Wwp | 0.100 | 0.095 | - | Ascot_Kh | 10.000 | 6.429 | m/day |
| Vasse_Ksat | 0.050 | 0.025 | m/day | Ascot_Kz | 1.201 | 0.694 | m/day |
| Bassendean_Wcs | 0.300 | 0.285 | - | Rockingham_Kh | 15.000 | 9.837 | m/day |
| Bassendean_Wfc | 0.060 | 0.057 | - | Rockingham_Kz | 0.500 | 0.277 | m/day |
| Bassendean_Wwp | 0.040 | 0.038 | - | Rockingham_Sc | 5.00E-06 | 2.75E-06 | 1/m |
| Bassendean_Ksat | 5.003 | 3.101 | m/day | Pinjar_Kh | 1.000 | 0.574 | m/day |
| Forrestfield_Wcs | 0.260 | 0.247 | - | Pinjar_Kz | 5.00E-04 | 1.97E-04 | m/day |
| Forrestfield_Wfc | 0.200 | 0.190 | - | Pinjar_Sc | 1.00E-05 | 5.69E-06 | 1/m |
| Forrestfield_Wwp | 0.120 | 0.114 | - | Wanneroo_Kh | 3.000 | 1.813 | m/day |
| Forrestfield_Ksat | 0.050 | 0.025 | m/day | Wanneroo_Kz | 1.00E-03 | 4.09E-04 | m/day |
| Pinjarra_Wcs | 0.260 | 0.247 | - | Wanneroo_Sc | 5.00E-06 | 2.75E-06 | 1/m |
| Pinjarra_Wfc | 0.180 | 0.171 | - | Drainage_level | -0.20 | -0.21 | m |
| Pinjarra_Wwp | 0.120 | 0.114 | - | Drainage_constant | 1.00E-05 | 5.69E-06 | /s |
| Pinjarra_Ksat | 0.050 | 0.025 | m/day | Leakage_coefficient | 1.00E-07 | 4.54E-08 | - |

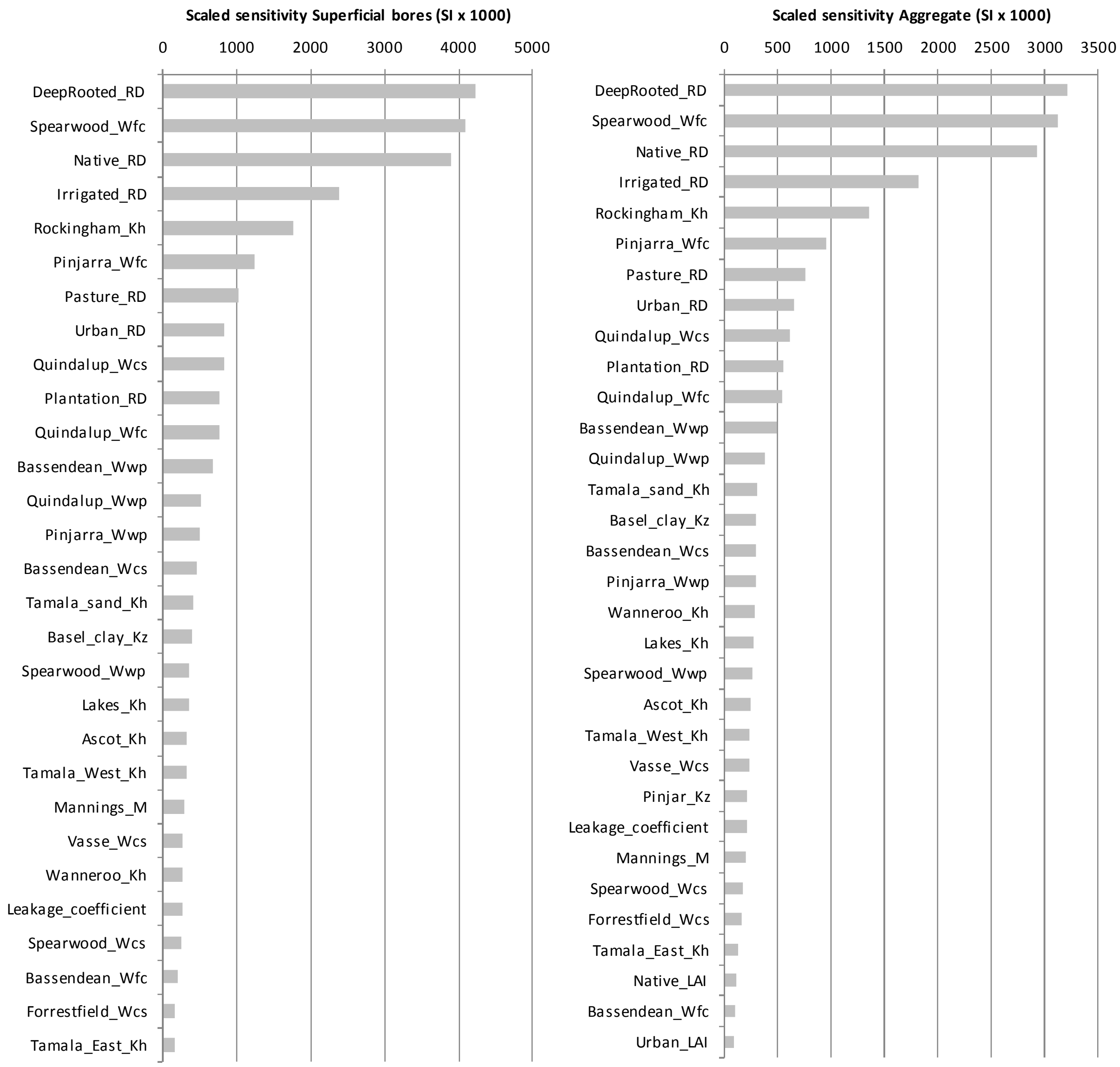



*Figure 6-1 Sensitivity coefficients for the Superficial Aquifer and aggregate function objective functions*

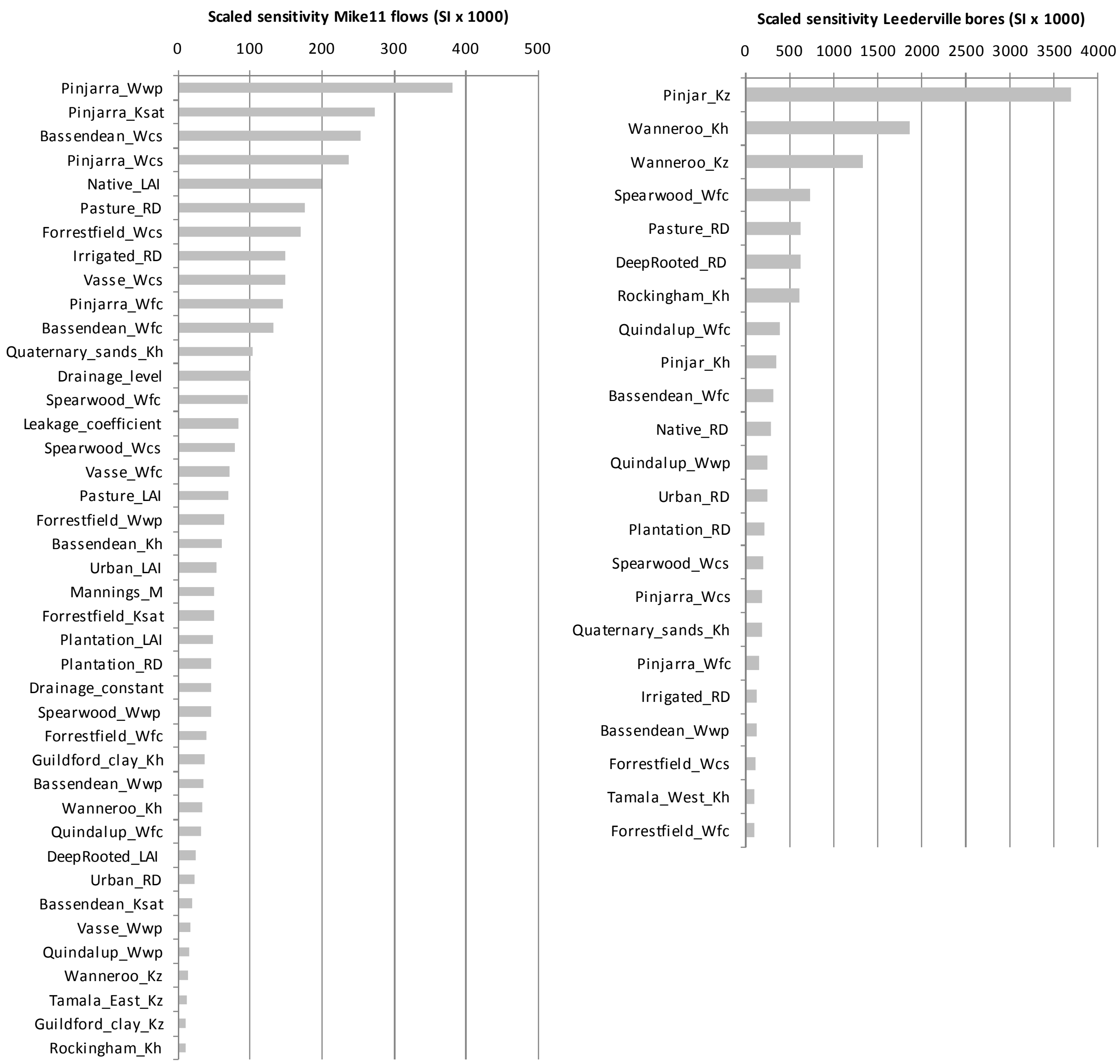



*Figure 6-2 Scaled sensitivity values for the Mike11 and Leederville Aquifer objective functions*

The aggregate objective function and the Superficial objective function show high sensitivity to RD parameters, particularly for the native and deep-rooted vegetation land use categories. The model was sensitive to the Spearwood water content at field capacity (Wfc), which reflects the responsiveness of groundwater heads in the Spearwood Dune area to changes in recharge – which are affected by Wfc. The most sensitive saturated zone parameter was the horizontal conductivity in the Rockingham Member (proposed). This is to be expected given the Rockingham Aquifer is a discharge pathway from the Superficial towards the coast. The model was insensitive to horizontal conductivity of the Bassendean Sand despite this being the main unit within the Jandakot Mound. It is also notable that the Superficial Aquifer objective function is insensitive to parameters that control vertical leakage to the Leederville, including vertical conductivity in the Pinjar and Wanneroo units.

The Leederville objective function was most sensitive to the Kz of the Pinjar Member, as this parameter influences vertical leakage between the Superficial and Leederville aquifers across much of the model area. The objective function was also sensitive to the Kh and Kz of the Wanneroo Member, which influence the amount of leakage to the Leederville and the transmissivity of the aquifer.

The surface water objective function, based on the Mike 11 flow results, was sensitive to recharge-related parameters, as superficial groundwater levels affect both baseflow to the rivers; and also peak flows, as a result of inundated areas. The objective function showed the second-highest sensitivity to the Pinjarra soil zone due to its influence on peak flows through infiltration excess runoff. The Mike11 objective function was moderately sensitive to the drain level and leakage coefficient parameters, with less sensitivity shown for the drain time constant.

Given the complexity and non-linearity of the Lower Serpentine model, an automated sensitivity analysis is unlikely to highlight all sensitive model parameters. As such, the project modeller has undertaken a qualitative assessment of model sensitivity and uncertainty associated with parameters. This summary is presented in Table 6-2 and is based on the experience of calibrating the model and developing the conceptual model. Parameters have been classified as **sensitive (S)** if they are important for the overall model, **locally sensitive (LS)** if they are important in some areas of the model, and **insensitive (I)** if they have little influence anywhere in the model. Sensitivity was considered only within appropriate parameter ranges. Uncertainty is listed as **high** if no, or very little field data or research was used in support of the parameter value or the parameter value is outside appropriate ranges; **medium** if some referenced values were available and the parameter value is inside an appropriate range; and **low** if the parameter value is well documented and inside appropriate ranges.

*Table 6-2 Qualitative assessment of parameter sensitivity and uncertainty*

| LAI | Sensitivity | Uncertainty |
|---|---|---|
| Irrigated_LAI | I | medium |
| Native_LAI | LS | medium |
| Pasture_LAI | I | medium |
| Urban_LAI | I | medium |
| Plantation_LAI | I | medium |
| DeepRooted_LAI | LS | medium |
| **Root depth** | **Sensitivity** | **Uncertainty** |
| Irrigated_RD | LS | medium |
| Native_RD | S | medium |
| Pasture_RD | LS | medium |
| Urban_RD | LS | medium |
| Plantation_RD | LS | medium |
| DeepRooted_RD | S | medium |
| **Overland flow** | **Sensitivity** | **Uncertainty** |
| Mannings_M | I | low |
| **Water content at saturation** | **Sensitivity** | **Uncertainty** |
| Quindalup_Wcs | LS | medium |
| Spearwood_Wcs | S | high |
| Vasse_Wcs | LS | medium |
| Bassendean_Wcs | S | medium |
| Forrestfield_Wcs | LS | medium |
| Pinjarra_Wcs | S | medium |
| **Water content at field capacity** | **Sensitivity** | **Uncertainty** |
| Quindalup_Wfc | LS | medium |
| Spearwood_Wfc | S | high |
| Vasse_Wfc | LS | medium |
| Bassendean_Wfc | S | medium |
| Forrestfield_Wfc | LS | medium |
| Pinjarra_Wfc | S | medium |
| **Water content at wilting point** | **Sensitivity** | **Uncertainty** |
| Quindalup_Wwp | LS | medium |
| Spearwood_Wwp | S | high |
| Vasse_Wwp | LS | medium |
| Bassendean_Wwp | S | medium |
| Forrestfield_Wwp | LS | medium |
| Pinjarra_Wwp | S | medium |
| **Saturated conductivity** | **Sensitivity** | **Uncertainty** |
| Quindalup_Ksat | LS | low |
| Spearwood_Ksat | LS | low |
| Vasse_Ksat | S | low |
| Bassendean_Ksat | LS | low |
| Forrestfield_Ksat | S | low |
| Pinjarra_Ksat | S | low |

| Horizontal conductivity (Superficial) | Sensitivity | Uncertainty |
|---|---|---|
| Lakes_Kh | S | medium |
| Basal_clay_lense_Kh | I | high |
| Tamala_sand_Kh | S | high |
| Bassendean_Kh | LS | low |
| Ascot_Kh | I | low |
| Safety_Bay_Kh | LS | medium |
| Tamala_East_Kh | S | medium |
| Tamala_West_Kh | S | medium |
| Quaternary_sands_Kh | S | high |
| Guildford_clay_Kh | LS | low |
| Colluvium_Kh | I | low |
| Estuarine_Kh | I | low |
| **Vertical conductivity (Superficial)** | **Sensitivity** | **Uncertainty** |
| Lakes_Kz | LS | high |
| Basal_clay_lense_Kz | LS | high |
| Tamala_sand_Kz | I | high |
| Bassendean_Kz | I | low |
| Ascot_Kz | I | low |
| Safety_Bay_Kz | I | medium |
| Tamala_East_Kz | I | medium |
| Tamala_West_Kz | I | medium |
| Quaternary_sands_Kz | I | high |
| Guildford_clay_Kz | I | low |
| Colluvium_Kz | I | low |
| Estuarine_Kz | LS | low |
| **Horizontal conductivity (Leederville)** | **Sensitivity** | **Uncertainty** |
| Rockingham_Kh | S | high |
| Pinjar_Kh | S | high |
| Wanneroo_Kh | S | high |
| **Vertical conductivity (Leederville)** | **Sensitivity** | **Uncertainty** |
| Rockingham_Kz | I | medium |
| Pinjar_Kz | S | high |
| Wanneroo_Kz | S | high |
| **Storage coefficient** | **Sensitivity** | **Uncertainty** |
| Rockingham_Sc | I | high |
| Pinjar_Sc | S | high |
| Wanneroo_Sc | S | high |
| **Drainage & Mike 11** | **Sensitivity** | **Uncertainty** |
| Drainage_level | S | medium |
| Drainage_constant | I | high |
| Leakage coefficient | S | medium |

## 6.2 Sensitivity of stress datasets

Stress datasets are external forces applied to a numerical model to generate a response or prediction. They represent the known (e.g. rainfall, abstraction), while the model predictions represent the unknown (e.g. groundwater head, river baseflow). Stresses to the Serpentine model include climatic datasets (rainfall and reference evapotranspiration), hydrologic datasets (river flows), human induced changes (abstraction) and hydraulic datasets (boundary conditions). Stress datasets are important components of the model, and therefore need to be assessed as part of the sensitivity analysis.

For each of the stress datasets, sensitivity analysis was performed by scaling the input dataset by a factor of 10% forward and backward, with the exception of the boundary conditions that were scaled by 50 cm up and down. Therefore three points in the parameter space of the stress dataset can be assessed, including one model run with the unperturbed stress dataset. The response of the model was assessed in three ways:

- average hydraulic head in the Superficial Aquifer – computational layer 1
- average hydraulic head in the Leederville and Rockingham aquifers – computational layer 3
- average annual flow discharging from the Serpentine River at the southern model boundary.

In this way, the effects of the stress datasets on the Superficial Aquifer, Leederville Aquifer and river flows can be assessed. The period 1990 to 1999 was used for sensitivity analysis of the stress datasets.

### Rainfall

The input rainfall dataset is sourced from gridded SILO data for the Lower Serpentine area. For the period 1990 to 1999 the central grid cell received an average annual rainfall of 814 mm: the scaled average annual rainfalls used for sensitivity analysis is therefore 733 mm and 895 mm.

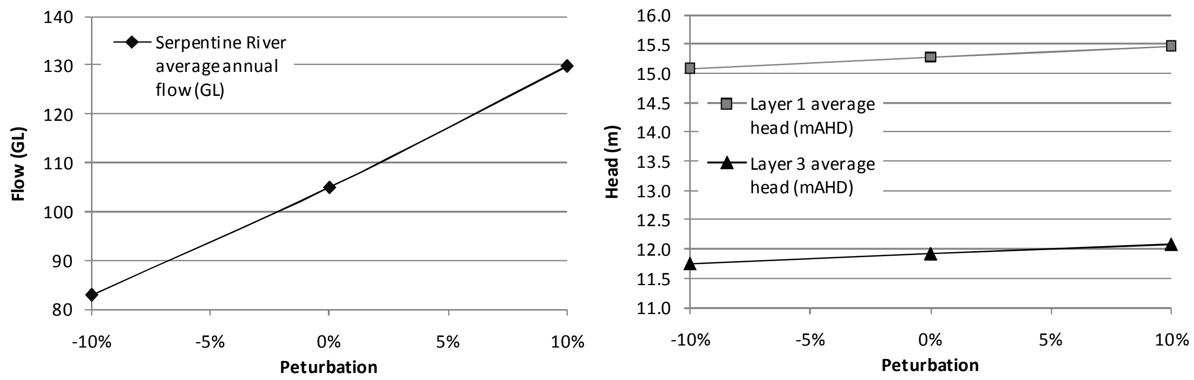



*Figure 6-3 Model sensitivity to rainfall*

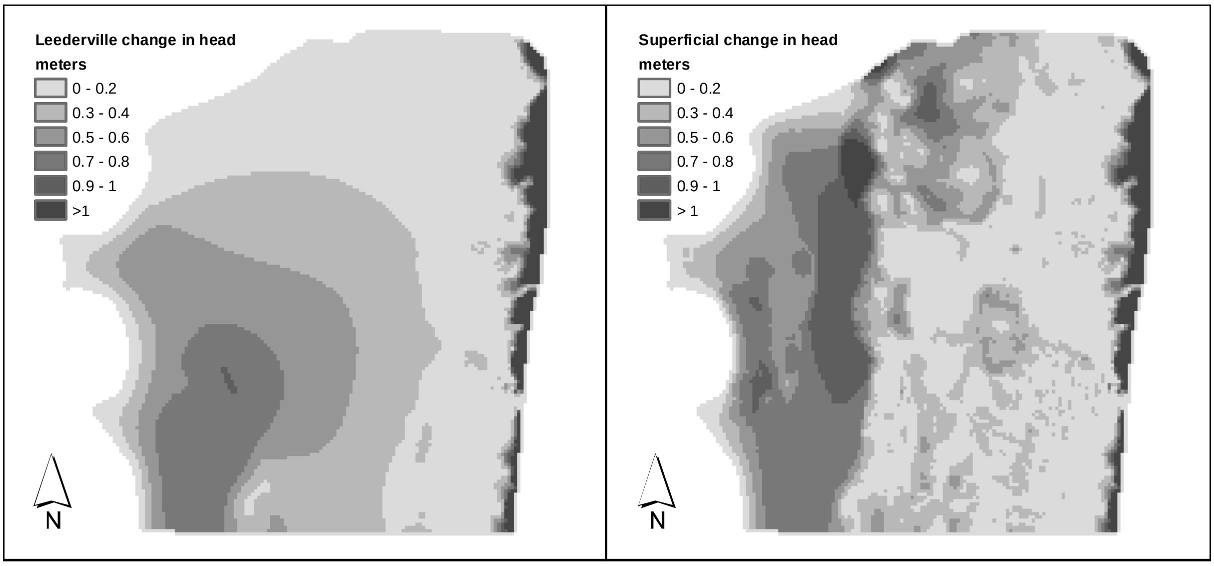



*Figure 6-4 Sensitivity of head to rainfall in the first and third computational layers*

Figure 6-3 shows that both flow and groundwater head are sensitive to changes in rainfall. For the range of perturbation tested, flow is affected by a factor of 20% for every 10% change in rainfall. In the Superficial Aquifer, groundwater head is most sensitive to changes in rainfall in areas with greater depth-to-watertable – around Rockingham and along the Spearwood dunes, on the Jandakot Mound, and along the foothills (see Figure 6-4). The Leederville Aquifer is most sensitive along the foothills, and where it is adjacent to the Rockingham Aquifer.

## Reference evapotranspiration ($ET_0$)

The $ET_0$ dataset used in the Lower Serpentine model was SILO gridded data and calculated using the FAO56 Penman-Monteith method. For the period 1990 to 1999 the central grid cell has an average $ET_0$ of 1403 mm: the scaled average annual $ET_0$ used for sensitivity analysis is therefore 1262 and 1543 mm.

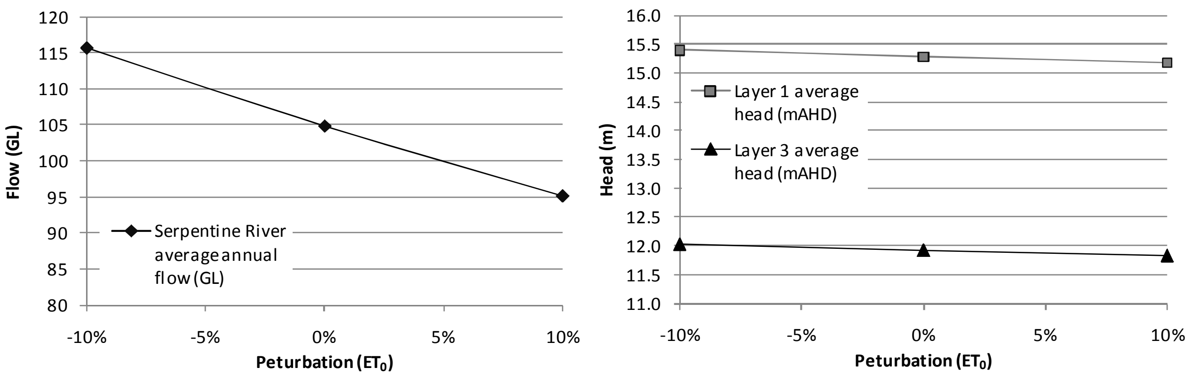



*Figure 6-5 Model sensitivity to $ET_0$*

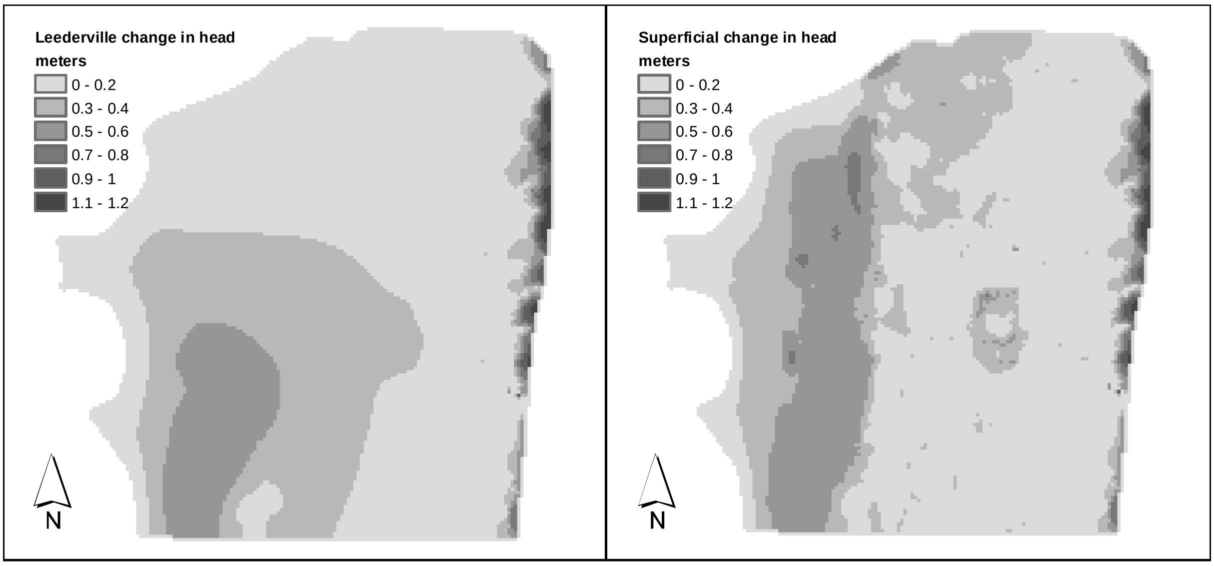



*Figure 6-6 Sensitivity of head to $ET_0$ in the first and section computational layers*

Figure 6-5 shows that river flows are sensitive to changes to $ET_0$ with a linear response. Flow at the model boundary from the Serpentine River changes proportionally to the change in $ET_0$ within the range tested. The response is due to the direct influence of evaporation on pooled water at the surface, and therefore overland flow.

Groundwater heads in both the Superficial, Leederville and Rockingham aquifers varied by around 20 cm between the +10% and -10% $ET_0$ model runs. Figure 6-6 shows spatially the areas where groundwater head is most sensitive to changes in $ET_0$. In the Superficial Aquifer, this includes the areas of the model with a comparatively larger depth-to-groundwater. The seasonally inundated areas show less response. In the Leederville and Rockingham aquifers, the area around the Rockingham Aquifer in connection with the Superficial shows the most extensive response.

## River flows

River flows are applied as a stress dataset via the boundary conditions applied in the Mike 11 component model. These flows are derived from the rainfall/runoff model SQUARE, which provides daily inflows at the model boundary for the simulation period. At each inflow boundary the daily discharge was scaled by a factor of 10% forward and backward.

Figures Figure 6-7 and 6-8 show the saturated zone is insensitive to changes in the river inflow boundaries; however, the Mike 11 channel flows show a change of around 7% in response to a 10% change in flows. Accurate simulation of the flow boundary conditions is important, and therefore climate scenarios will need to be applied to the SQUARE rainfall/runoff models before climate change is simulated in the Lower Serpentine model, so that flows are realistically replicated in Mike 11.

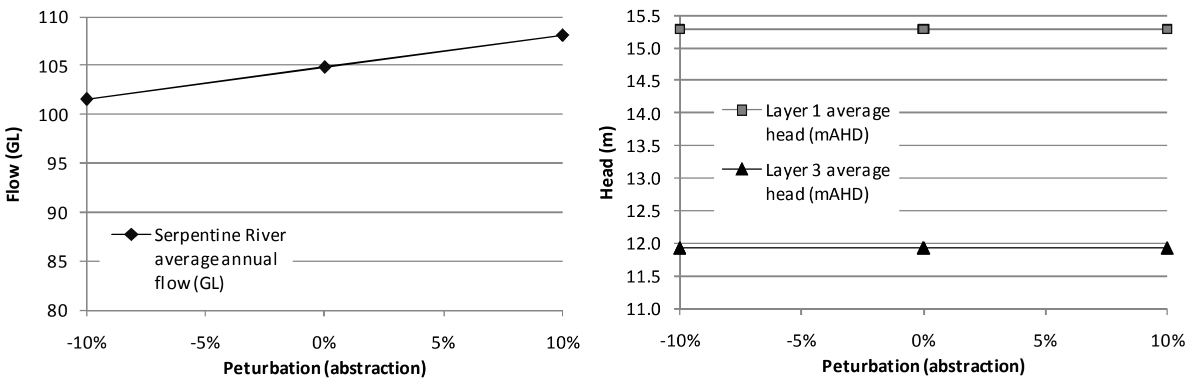



*Figure 6-7 Model sensitivity to boundary river flows*

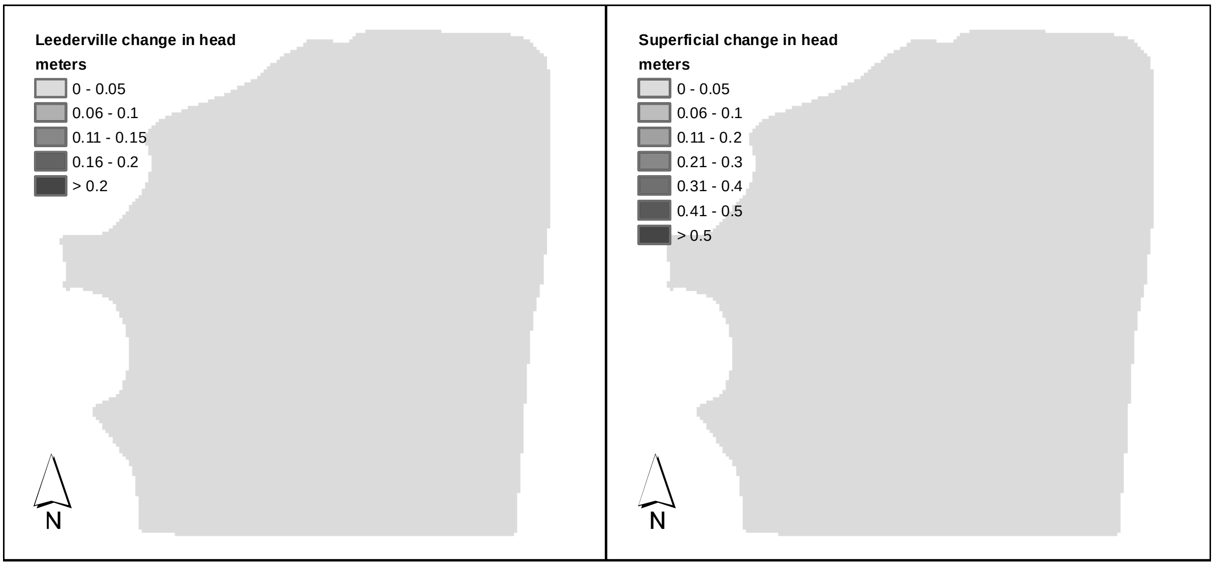



*Figure 6-8 Sensitivity of head to river flows in the first and third computational layers*

## Abstraction

Records of licences to abstract groundwater before 1996 are unreliable, and most current licences do not require metering. In addition, no formal record of unlicensed abstraction from garden bores exists, so an approximation of the location and volume of abstraction was applied as a stress dataset to the model. As such, there is considerable uncertainty in both the temporal and spatial distribution of abstraction within the Lower Serpentine model.

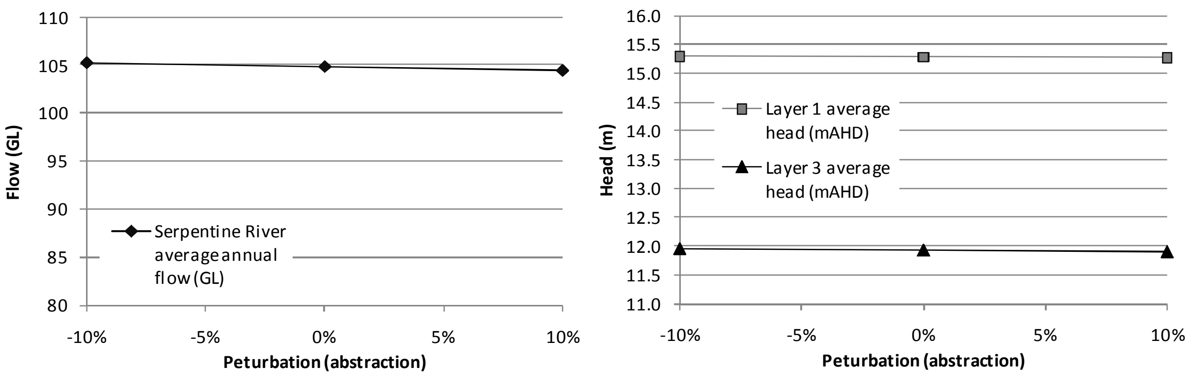



*Figure 6-9 Model sensitivity to abstraction*

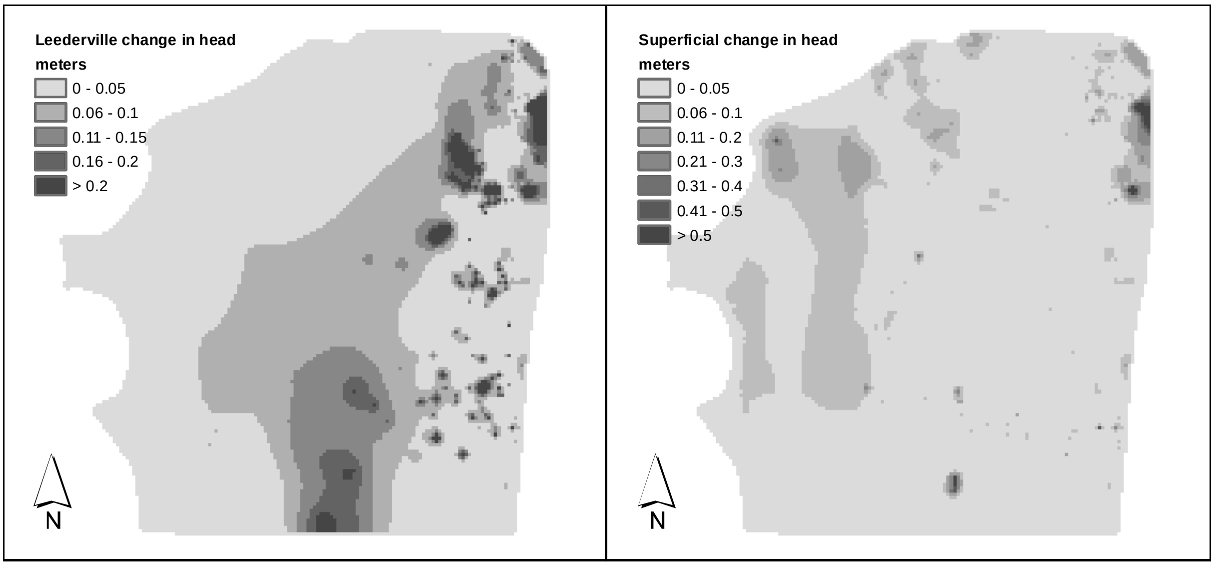



*Figure 6-10 Sensitivity of head to abstraction in the first and third computational layers*

Figure 6-9 shows the response of groundwater heads to changes in abstraction volume on-average was less than 6 cm. In some parts of the model where production bores are concentrated, the response is more significant. Figure 6-10 shows that heads in the Leederville Aquifer are more sensitive to changes in abstraction near Byford, Mundijong and Serpentine, and in the central southern part of the model. For the Superficial Aquifer, modelled heads are most sensitive to changes in abstraction underneath areas of urban development near Kwinana, Rockingham and Byford, and on the Jandakot Mound. Parts of the model with lower hydraulic conductivities generally have more localised sensitivities to abstraction.

## Superficial boundary conditions

The time-varying head boundaries along the model's north-western border for the Superficial Aquifer were assessed as part of the sensitivity analysis. The time-series used in the boundary conditions were scaled forward and backward by 50 cm.

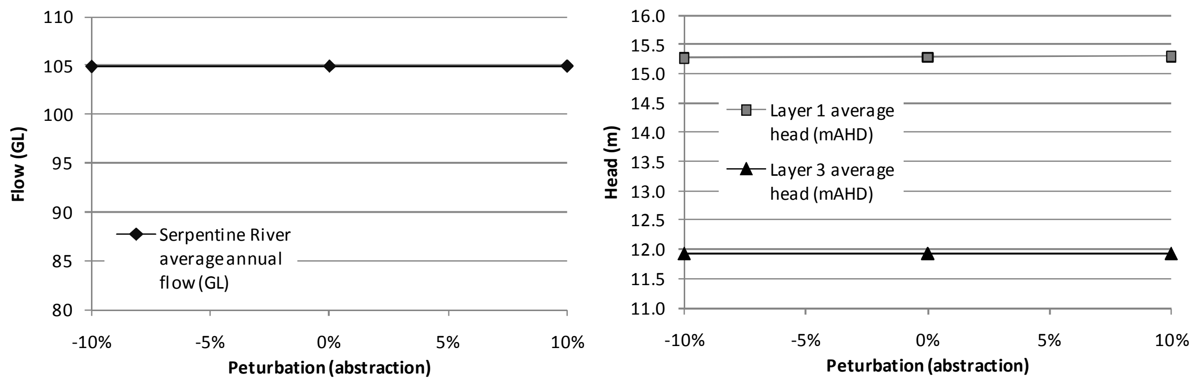



*Figure 6-11 Model sensitivity to Superficial boundary conditions*

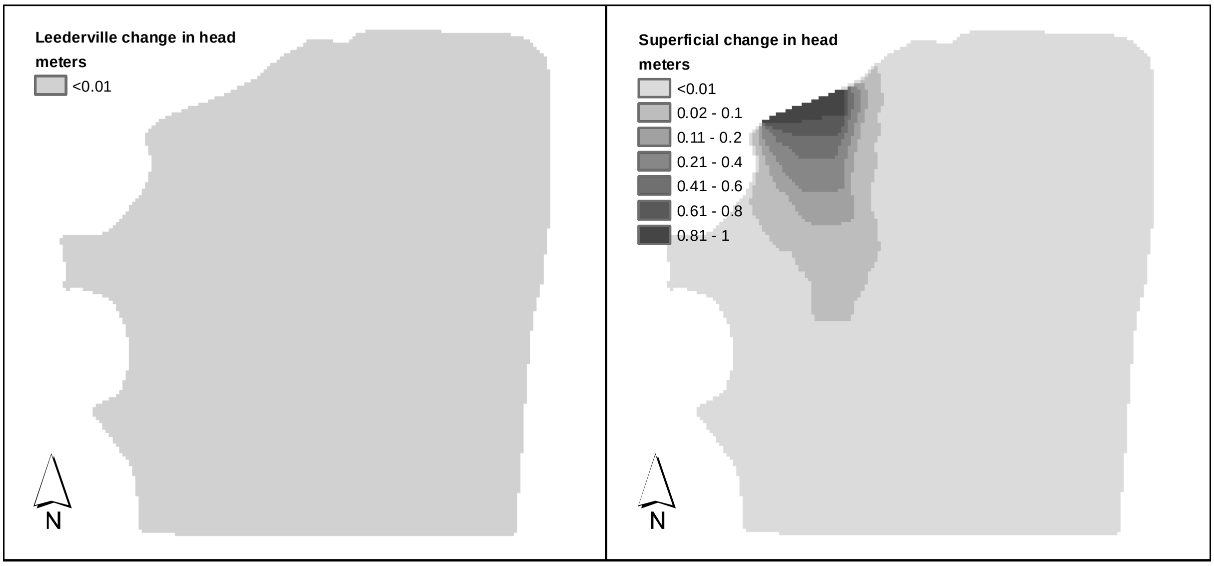



*Figure 6-12 Sensitivity of head to Superficial boundary conditions in the first and third computational layers*

As illustrated in Figure 6-11, model flows and heads on-average are insensitive to changes in the Superficial boundary conditions. However, Figure 6-12 shows that in the north-west immediately adjacent to the time-series boundary, the model is influenced by changes to the boundary condition. The hydraulic conductivity in the first computational layer is close to 200 m/day in this part of the model, and as such the boundary condition influences heads in the Superficial Aquifer between 3 and 7 km from the boundary. Results from this section of the model should therefore be used with caution. However, most of the model area is not sensitive to this boundary condition in the Superficial, and the Leederville and Rockingham aquifers show no response to changes in the boundary condition within the range tested.

## Leederville boundary conditions

The time-varying head boundaries along the model's northern border for the Leederville Aquifer (computational layers 2 and 3) were assessed as part of the sensitivity analysis. The time-series used in the boundary conditions were scaled forward and backward by 50 cm.

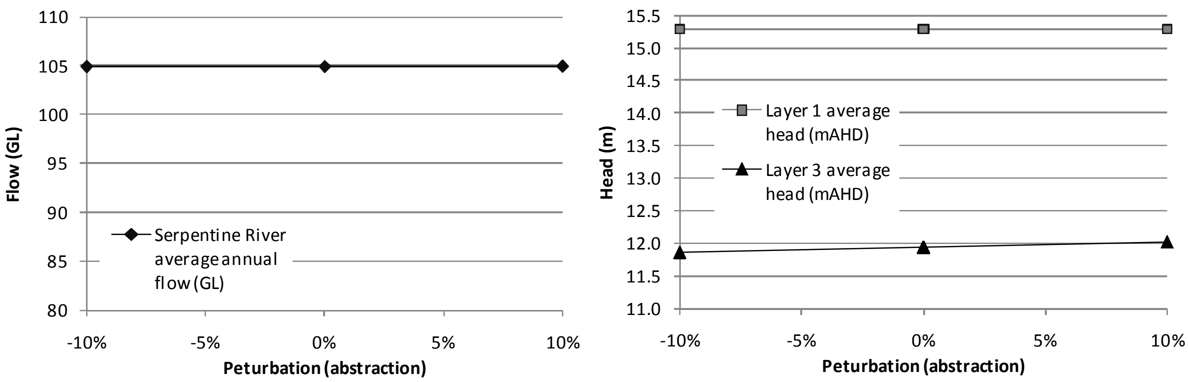



*Figure 6-13 Model sensitivity to Superficial boundary conditions*

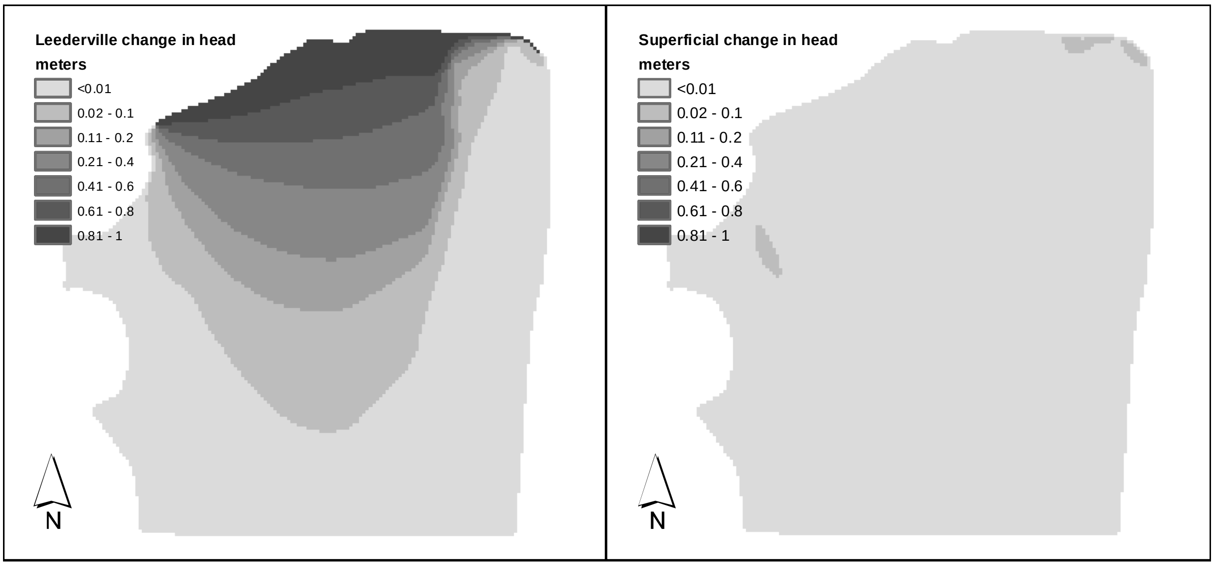



*Figure 6-14 Sensitivity of head to Leederville boundary conditions in the first and third computational layers*

The sections of the Leederville Aquifer at the greatest depth (particularly beneath the Kardinya Shale in the north), and closest to the boundary conditions, show the greatest response to changes in the time-series. This is consistent with the model conceptualisation, which indicated the cause of decline in head in the Leederville Aquifer in the Lower Serpentine area is primarily driven by declining heads beyond the model's northern extent. The influence of the boundary condition on the model declines with distance from the northern border. It is important to note that the Superficial Aquifer is insensitive to changes in the Leederville boundary condition, as illustrated in figuresFigure 6-13 and Figure 6-14. This means that predictive scenarios in the Superficial Aquifer are unlikely to be affected by forecast Leederville Aquifer boundary conditions.

## 6.3 Conclusions of sensitivity analysis

Parameter sensitivity analysis showed that groundwater level in the Superficial Aquifer is most sensitive to parameters associated with the unsaturated zone, particularly soil properties. These parameters have a physical basis and are generally within ranges documented in the literature, and can be viewed with a moderate degree of uncertainty. As such, recharge estimates within the model should be regarded as reliable.

The model was less sensitive to Superficial Aquifer conductivity parameters compared with unsaturated zone parameters. Generally the distribution and calibrated values for these parameters is consistent with the literature; however, the values are not supported by local pump tests, and there is a high level of uncertainty associated with the aquifer properties on the Jandakot Mound’s western edge at the interface of the Tamala Limestone and Bassendean Sand. As such, model results in this area are less reliable compared with the remainder of the model. It is recommended that future studies in this region develop a revised, detailed conceptual model based on local information including pump tests and lithological data.

The Leederville Aquifer was sensitive to conductivity parameters within the associated geology, and there is also a high level of uncertainty associated with these parameters and their distribution. Therefore this aquifer’s conceptualisation and parameterisation should be viewed with a high degree of uncertainty, despite the adequate calibration. It is recommended that a revised interpretation of the Leederville and Rockingham aquifers is undertaken in future regional modelling work. It should be supported by pump testing and additional drilling in the deeper aquifers.

The Leederville Aquifer is sensitive to the time-varying head boundary condition at the model’s northern end. Although this influence is an intentional component of the conceptualisation, it also indicates that boundary conditions used in the scenario analysis need to be carefully selected, as they will have a strong influence on groundwater head within the Leederville Aquifer over much of the model domain. It is worth noting that this study is primarily interested in groundwater head in the Superficial Aquifer, which does not show sensitivity to the Leederville boundary conditions.

The influence of the time-varying head boundary in the Superficial Aquifer in the model’s north-west is confined to a relatively small area. When considering scenario analysis, this portion of the model will be influenced by the boundary condition selected, and the results should be considered in this context.

The Superficial and Leederville aquifers are both sensitive to the abstraction stress dataset when they are near groundwater drawpoints. There is a high uncertainty associated with the spatial and temporal distribution of the abstraction dataset. Model results reported from areas close to large groundwater users will have a higher degree of uncertainty and should be viewed more critically. The scenario analysis will also be affected by the selection of abstraction time-series and this is an important consideration when viewing results.

# 7 Conclusions and recommendations

This construction and calibration report is the second of three reports that comprise the *Lower Serpentine hydrological studies*. The project's purpose was to develop and calibrate a regional-scale groundwater model, and to use the model to run various development, drainage and climate scenarios.

The Lower Serpentine regional model was constructed within the Mike SHE modelling framework based on the conceptual model described in the first report in the series (Marillier et al. 2012). The model was constructed using available geological, hydrogeological, hydrological, soil and land use information. It consists of an unsaturated zone, saturated zone, channel flow and overland flow components. It has a constant grid spacing of 200 m, and covers an area of 728 km$^2$. It consists of three computational layers, and simulates groundwater hydraulic heads in the Superficial, Leederville and Rockingham aquifers.

The model has a 41-year simulation period from 1970 to 2010, was calibrated from 1980 to 2004, and validated from 2005 to 2010. The model calibration satisfied the criteria of a water balance error of <0.05%, an iteration residual error of <0.1% and a scaled RMS error of <5%. The Superficial Aquifer achieved a scaled absolute error of less than 50 cm. The average NSE calculated at calibration flow gauges was 0.77. The model calibration error is summarised in Table 7-1.

*Table 7-1 Calibration error summary for the Lower Serpentine regional model*

| **Groundwater** | **Superficial Aquifer** | **Leederville Aquifer** | **Combined** |
|---|---|---|---|
| Number of observations | 10473 | 1514 | 11987 |
| Average absolute error (m) | 0.46 | 0.8 | 0.5 |
| Average residual error (m) | -0.02 | 0.35 | 0.00 |
| Average RMS error (m) | 0.62 | 1.16 | 0.71 |
| Minimum negative error (m) | -3.15 | -2.13 | -3.15 |
| Maximum positive error (m) | 2.34 | 3.98 | 3.98 |
| Scaled absolute error (%) | 1.1% | 2.6% | 1.2% |
| Scaled RMS (%) | 1.5% | 3.9% | 1.7% |
| **Surface water** | | | |
| Average Nash-Sutcliffe efficiency | 0.77 | | |
| Average cumulative flow error | -7% | | |

Most of the Superficial Aquifer is well calibrated, with simulated heads matching observed heads across most of the calibration bores. The model accurately simulated flows within the rivers and drains in the study area, with no major errors. The Leederville Aquifer was not as well calibrated in comparison with the Superficial, but still achieved the required scaled RMS error.

The areas of significant error in the Superficial Aquifer include:

- The region at the base of the Darling Scarp in the model's north, near Byford and Mundijong, which shows evidence of groundwater abstraction that the model does not account for. These areas tend to show model over-prediction in recent years.

- The area immediately adjacent to the model's northern boundary on the Jandakot Mound, which may be influenced by abstraction beyond the model domain that is not accounted for.
- The Jandakot Mound's western edge through the Spectacles Wetlands and past the Alcoa refinery. The geology in this area was not conceptualised in detail, and it was difficult to replicate the steep groundwater gradients that occur at the interface of the Bassendean Sand and Tamala Limestone. Uncertainty around unlicensed groundwater abstraction has also introduced error in this area.

The areas of significant error in the Leederville Aquifer include:

- the model's north-eastern region near AM50X, which does not show a decline in groundwater after the mid 1990s consistent with observed data.
- the area of the Leederville in the model's central southern part near AM60E, which shows a decline in head not consistent with the observed data.
- there is a much higher degree of uncertainty associated with modelled heads in the Leederville due to the lack of data available for calibration and conceptualisation.

The model predicted a gross recharge rate of 33% of rainfall and a net recharge of 18%. Net recharge is significantly lower than gross recharge due to the large amount of evapotranspiration from shallow superficial groundwater.

Sensitivity analysis shows the model is most sensitive to parameters that control recharge to the Superficial Aquifer – such as the water content at saturation, field capacity and wilting point in the various soil zones, and values of RD and LAI associated with some land uses. The Leederville Aquifer was also sensitive to horizontal and vertical conductivity parameters in the Wanneroo and Pinjar members. River flows were sensitive to similar parameters as the Superficial Aquifer, in addition to the drainage level, riverbed leakage coefficient, and unsaturated zone saturated conductivity in the Pinjarra soil zone.

The numerical model conformed to the conceptual model structurally, with the exception of three additional geological units inserted to account for localised discrepancies in hydraulic properties within the Superficial Aquifer. These included the Tamala Sand unit on the west of the Jandakot Mound; the basal clay unit that limits vertical connectivity between the Safety Bay and Rockingham aquifers; and the lake sediments around lakes Cooloongup and Walyungup, which lowers vertical connectivity between the Superficial and Rockingham aquifers. All of these units are documented in the literature, but were not defined explicitly in the conceptual model. The water balance of the numerical model was consistent with that of the conceptual model, allowing for some variation due to the uncertainty associated with many of the conceptual flux calculations.

Based on the model's structural limitations, and the uncertainty and error associated with the calibration, the Lower Serpentine model is appropriate for:

- Evaluating changes to the Superficial Aquifer water balance related to land use, climatic and drainage changes (e.g. changes in recharge, drainage, evapotranspiration, horizontal flows etc.)

- The relative assessment of regional and subregional impacts due to changes in drainage and abstraction from the Superficial Aquifer.
- District-scale groundwater-level evaluation (AAMaxGL, AAMinGL etc.) under various climate scenarios. This includes determining areas of seasonal waterlogging and inundation. However, the inherent model error needs to be considered when using groundwater levels derived from the regional model. If the error is deemed too large for the purpose of the application, a localised model with a finer grid should be constructed and re-calibrated to achieve appropriate model error.

The model should not be used for fine-scale wetland, river and lake modelling, flood modelling or detailed drainage modelling. The model is not recommended for abstraction or sustainable yield analysis in the Leederville and Rockingham aquifers due to errors in calibration and the level of uncertainty in conceptualisation of the Leederville Aquifer.

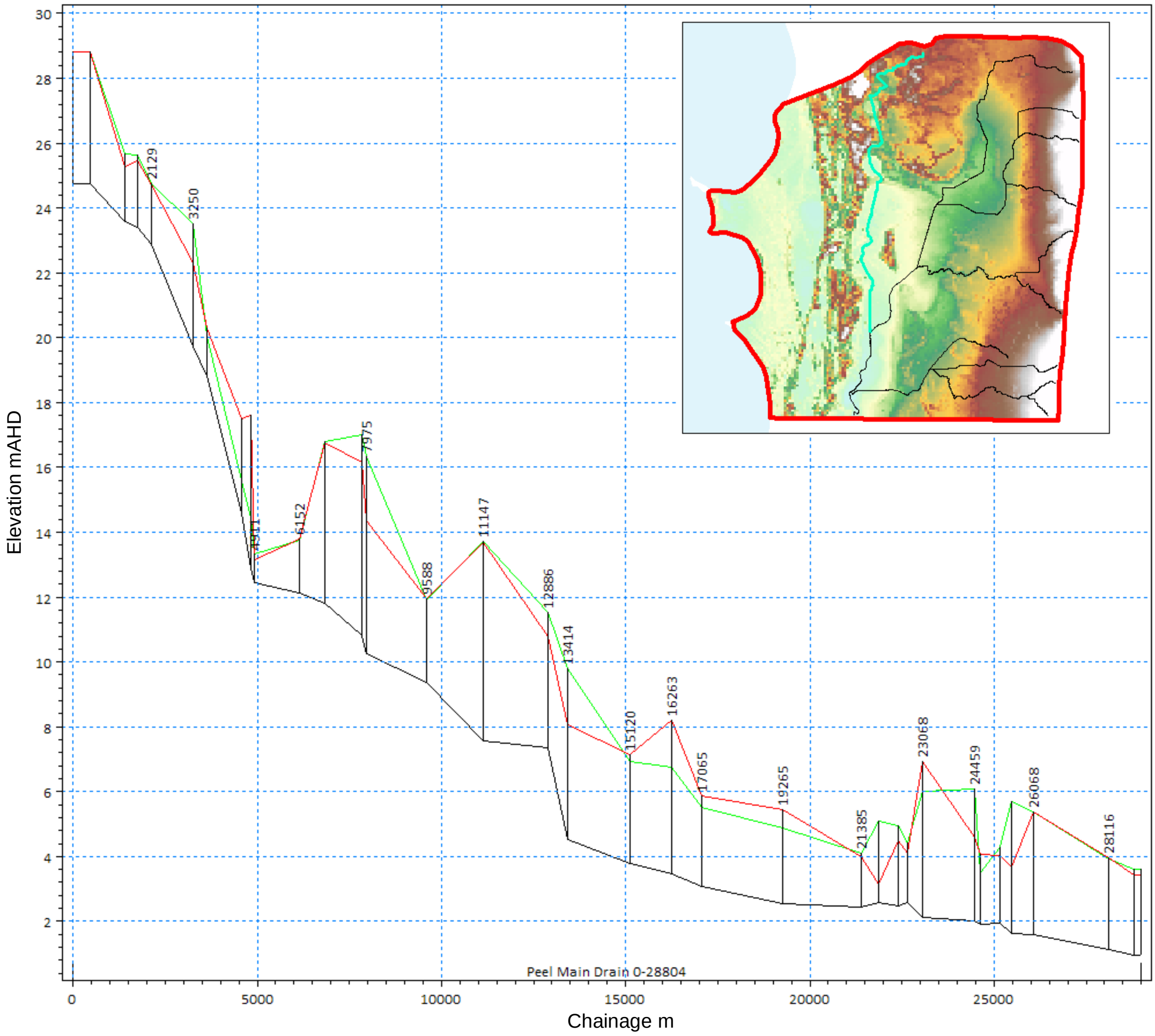
The model could be further improved in the following ways:

- Revised conceptualisation of the Leederville Aquifer and its interaction with the Superficial Aquifer near the Darling Scarp. This should be supported by pump testing and paired bores in the area, where at present only limited groundwater information is available. Interaction between the Superficial and Cattamarra aquifers in this area should also be considered as additional information becomes available.
- Revised conceptualisation of the superficial formations and associated hydrogeology on the Jandakot Mound’s western edge.
- Introduction of additional computational layers (improved vertical discretisation) within the Superficial Aquifer to account for localised differences in superficial groundwater head.
- Detailed analysis of historical and current groundwater abstraction patterns and development of an improved abstraction dataset.
- Assessment of vegetation rooting depth along the Spearwood Dunes to improve unsaturated zone modelling in the area.

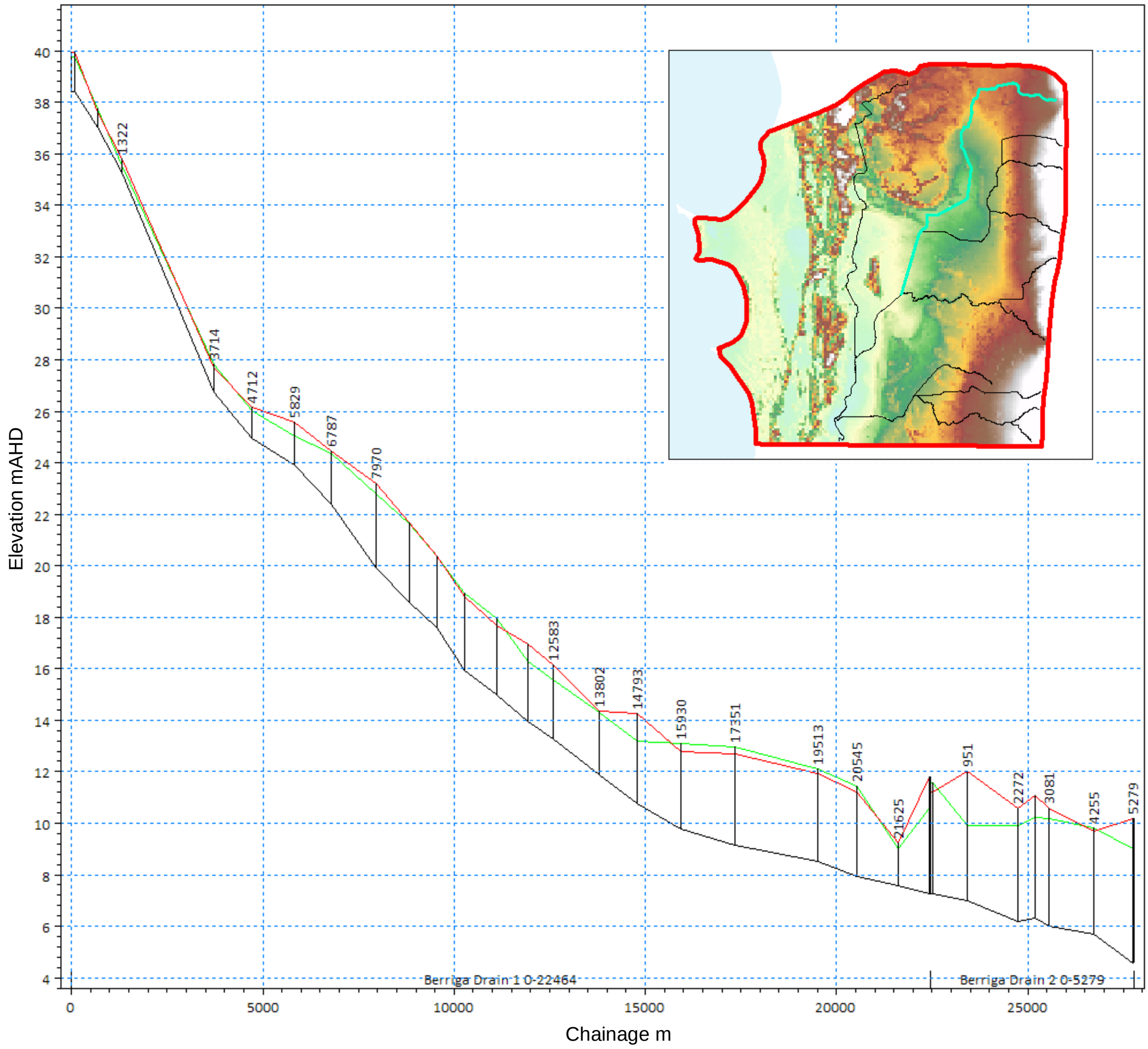
# Appendices

# Appendix A – Mike 11 longitudinal profiles

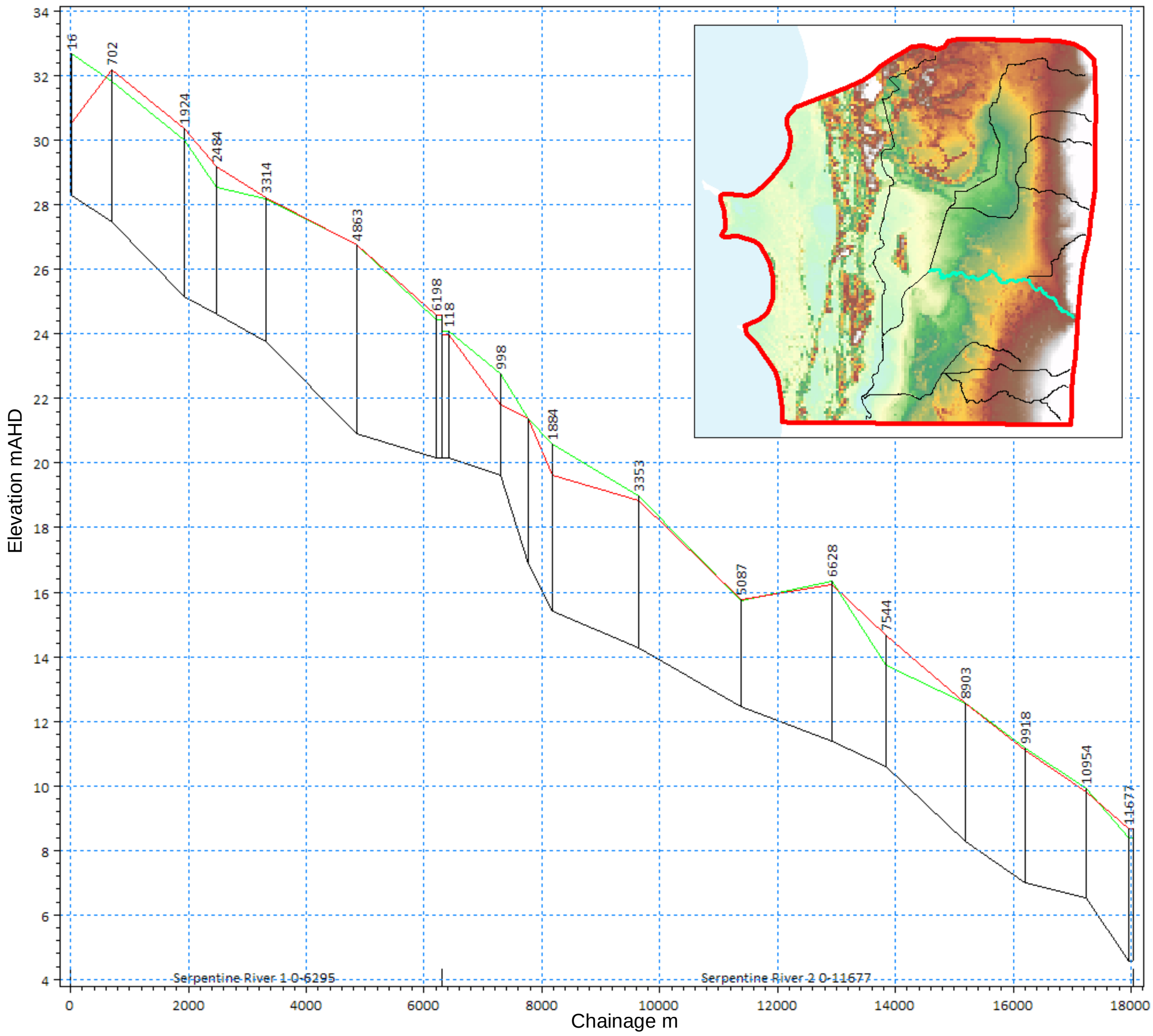
## Peel Main Drain



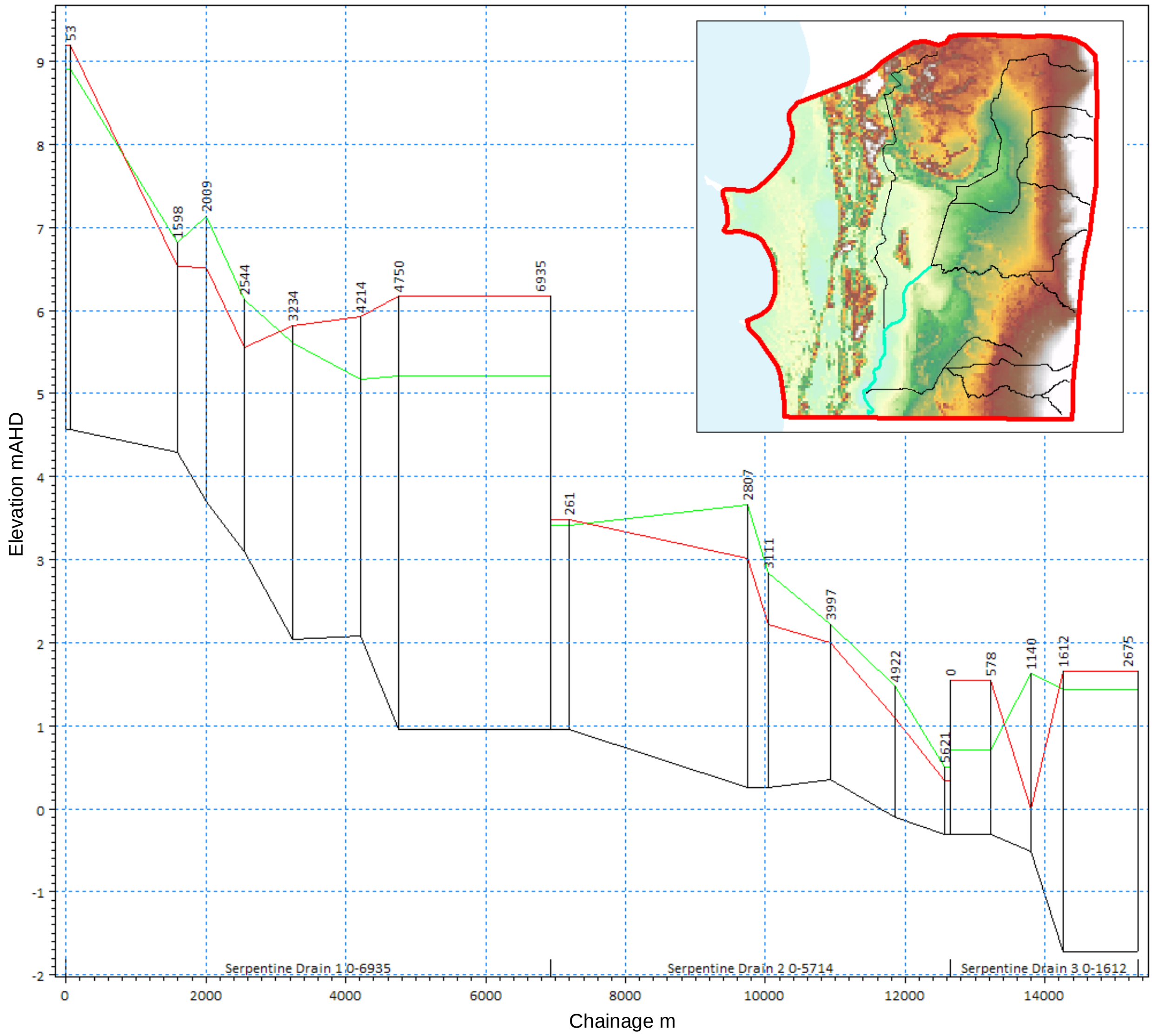
## Birriga Drain 1 & 2



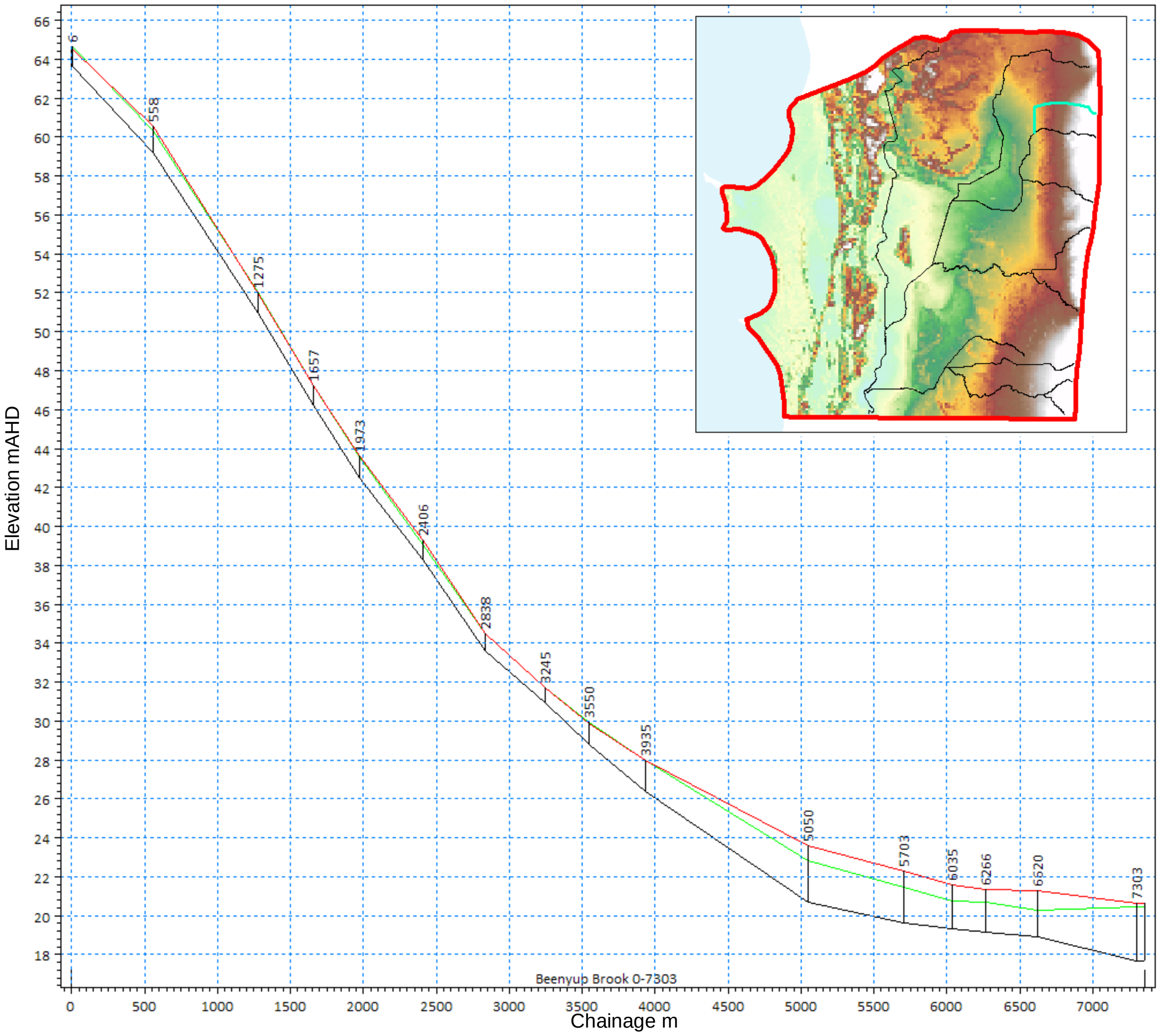
## Serpentine River 1 & 2



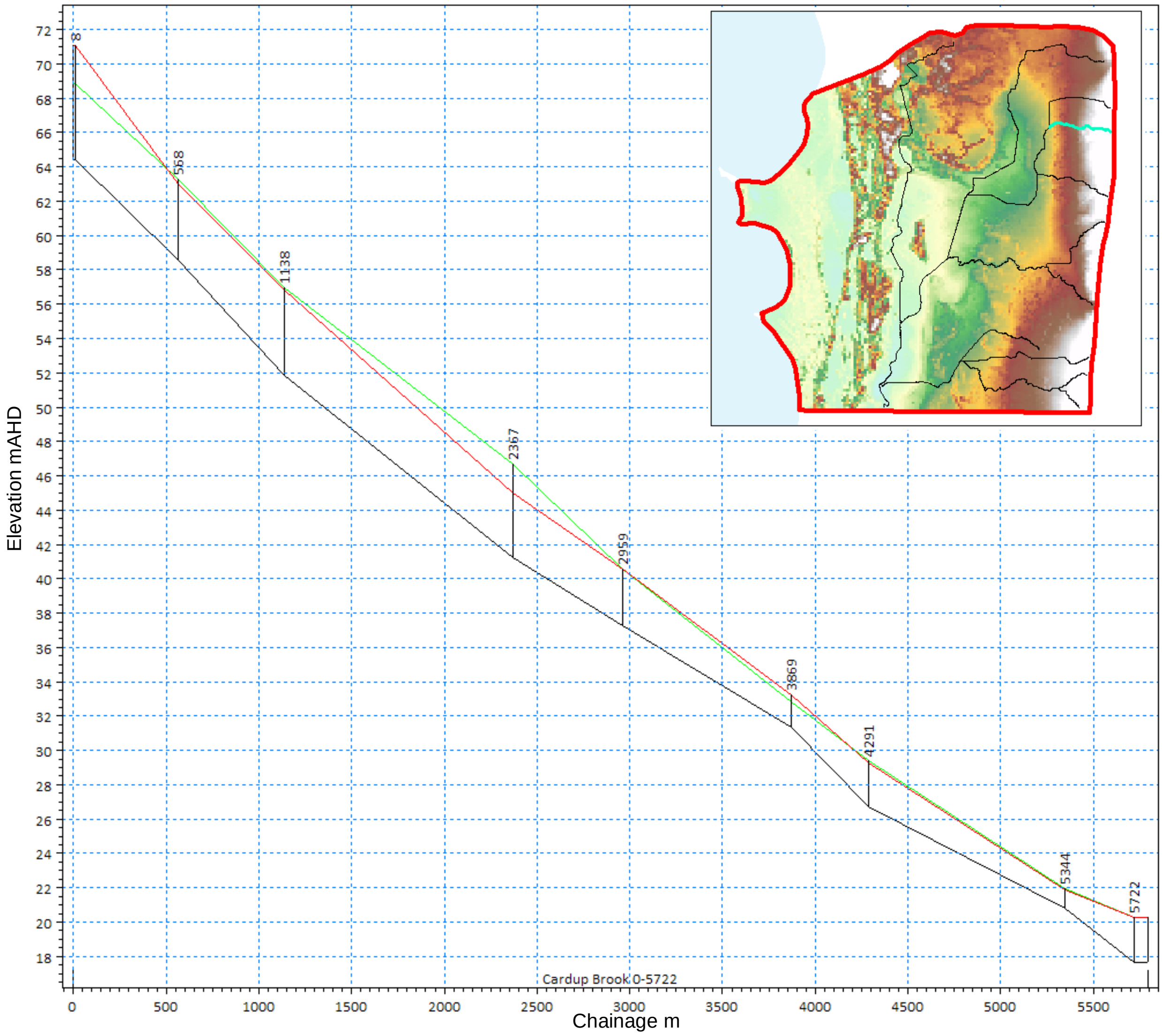
## Serpentine Drain 1, 2 & 3



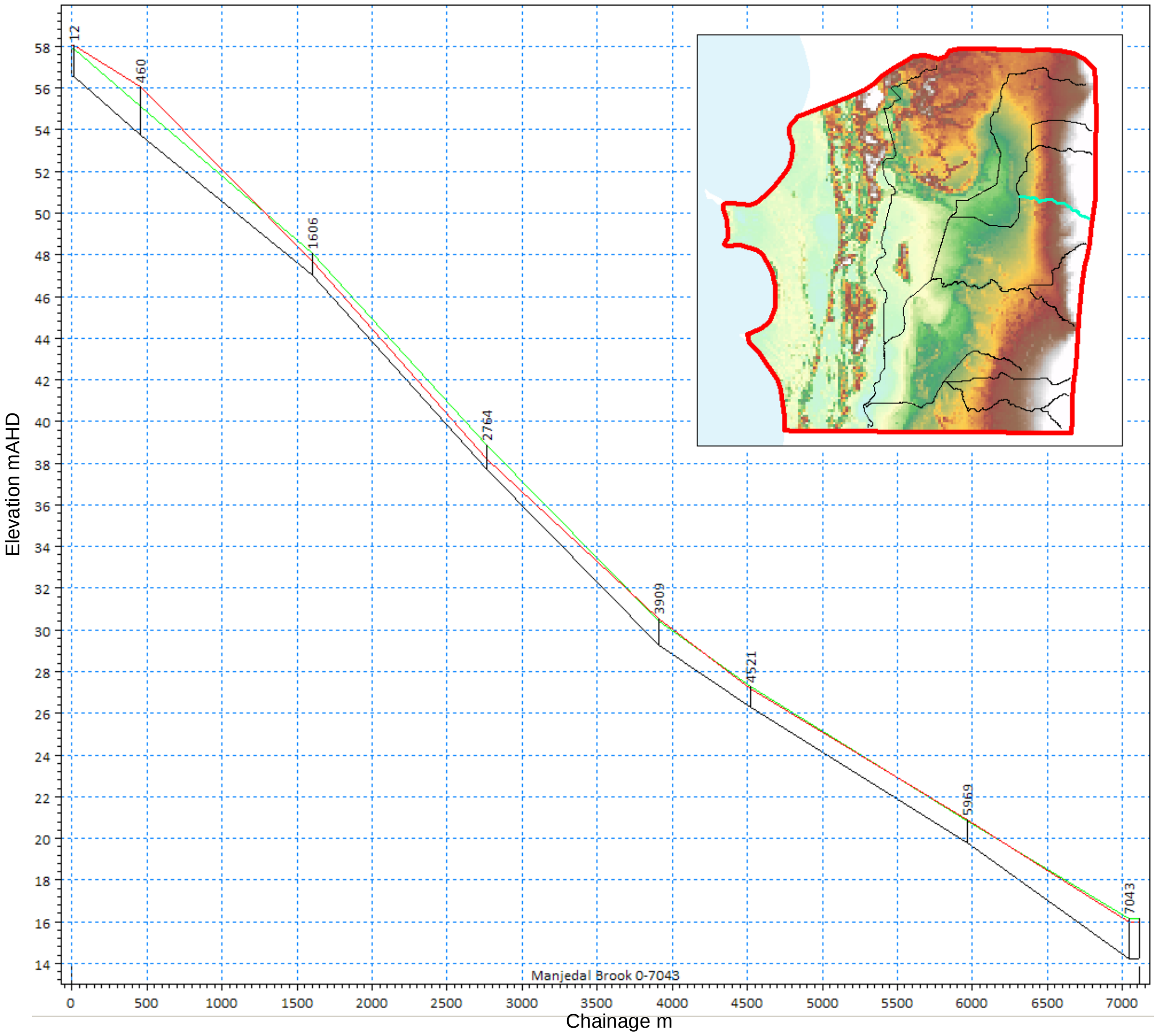
## Beenyup Brook



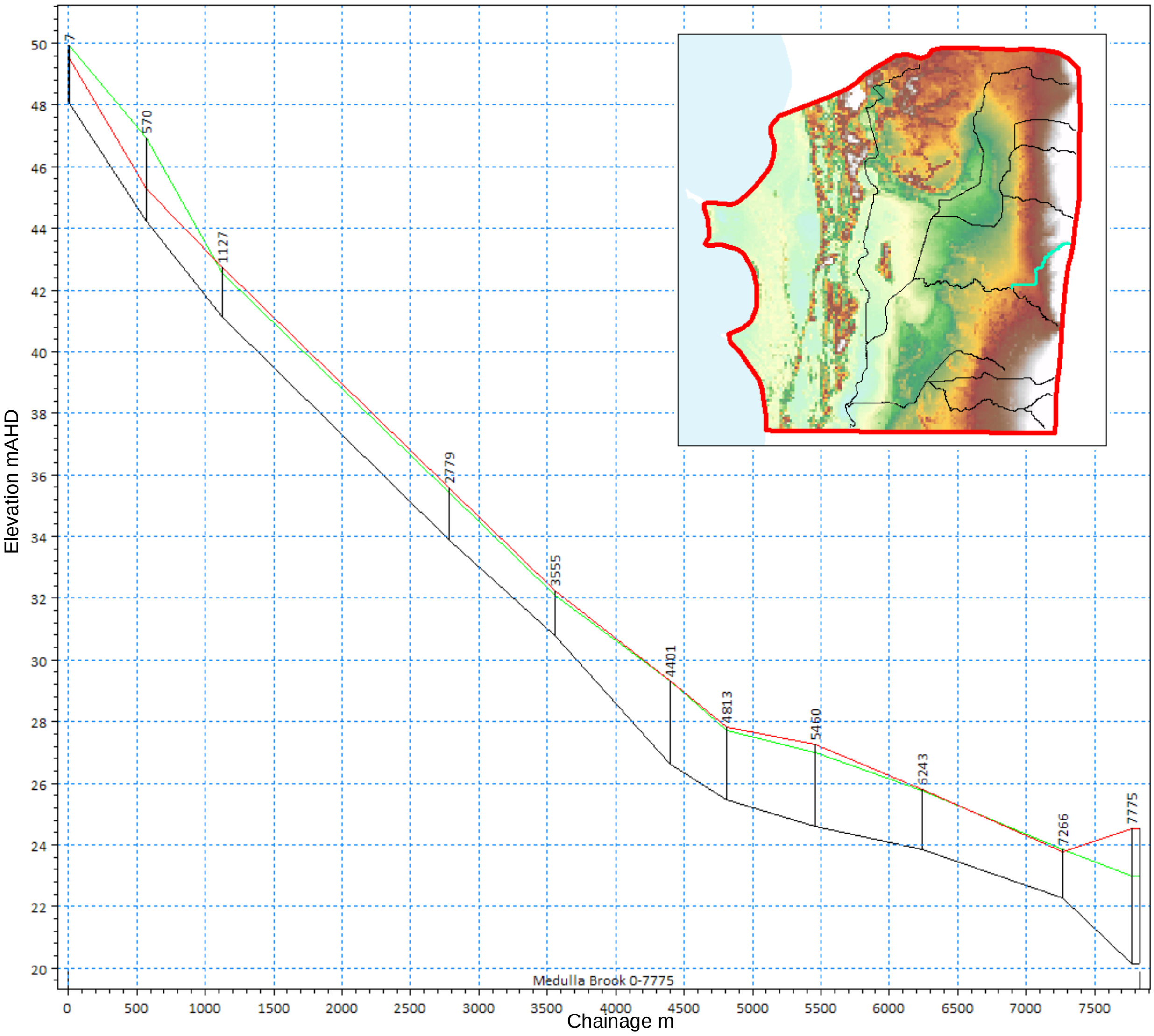
## Cardup Brook



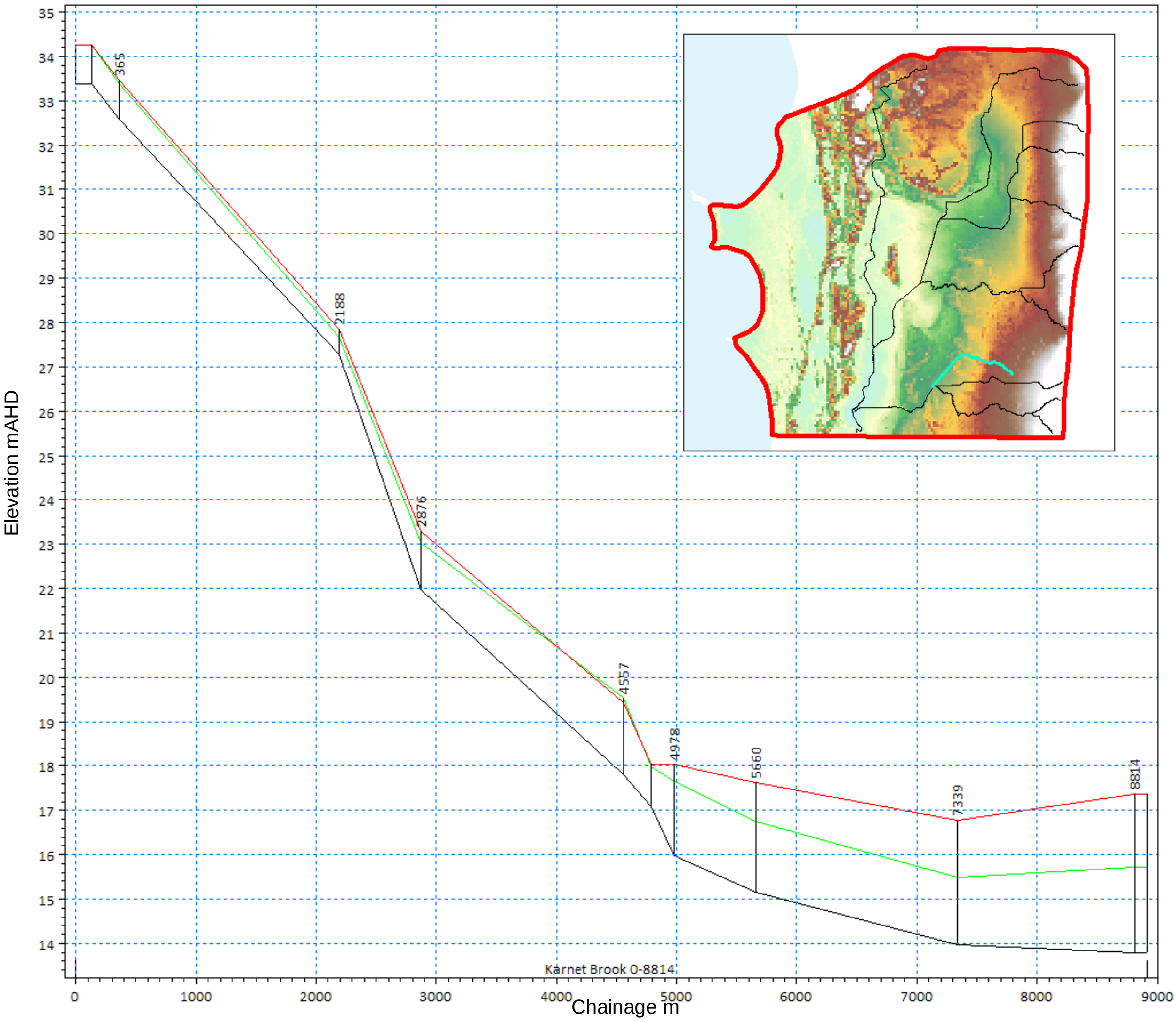
## Manjedal Brook



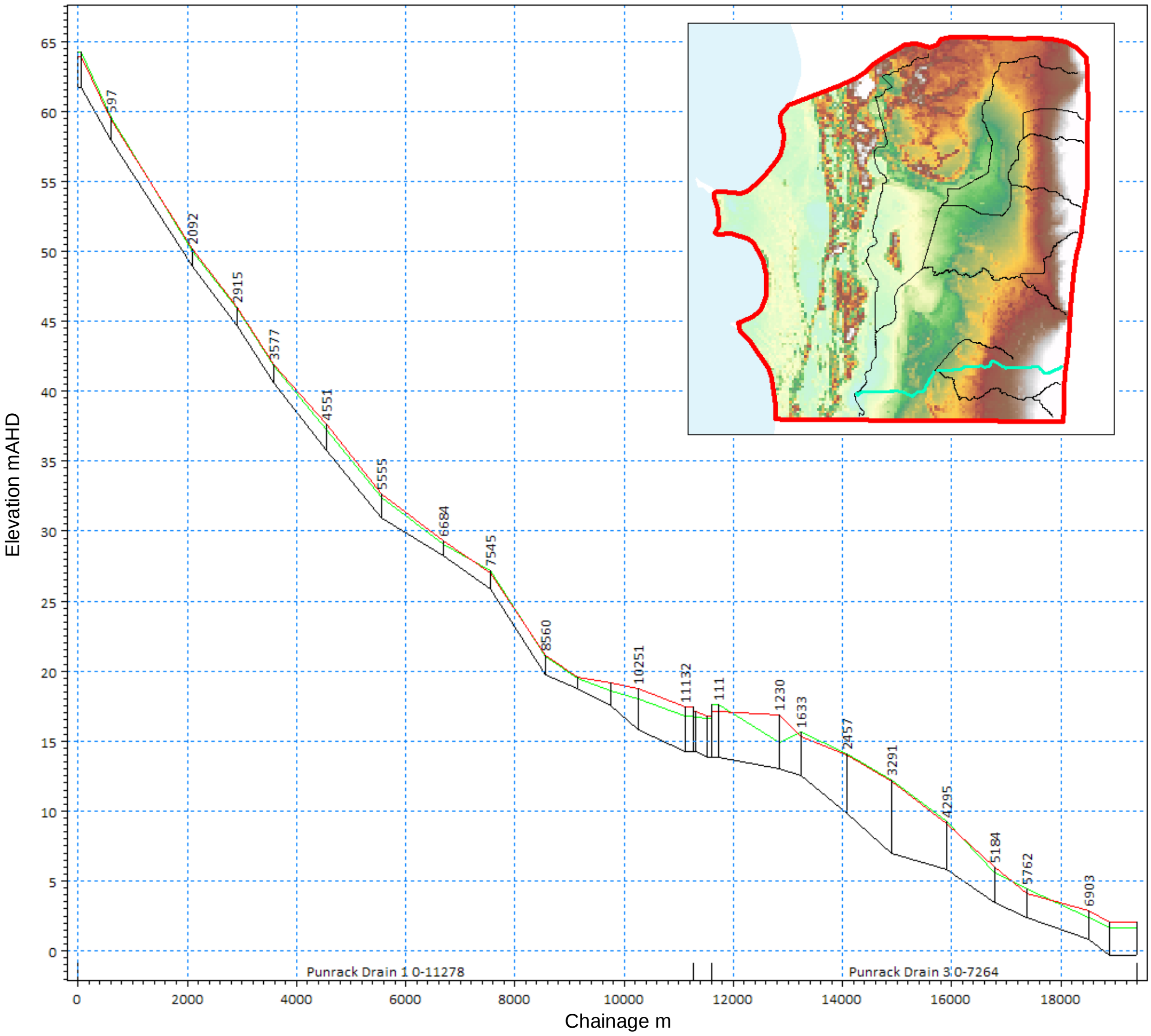
## Medulla Brook



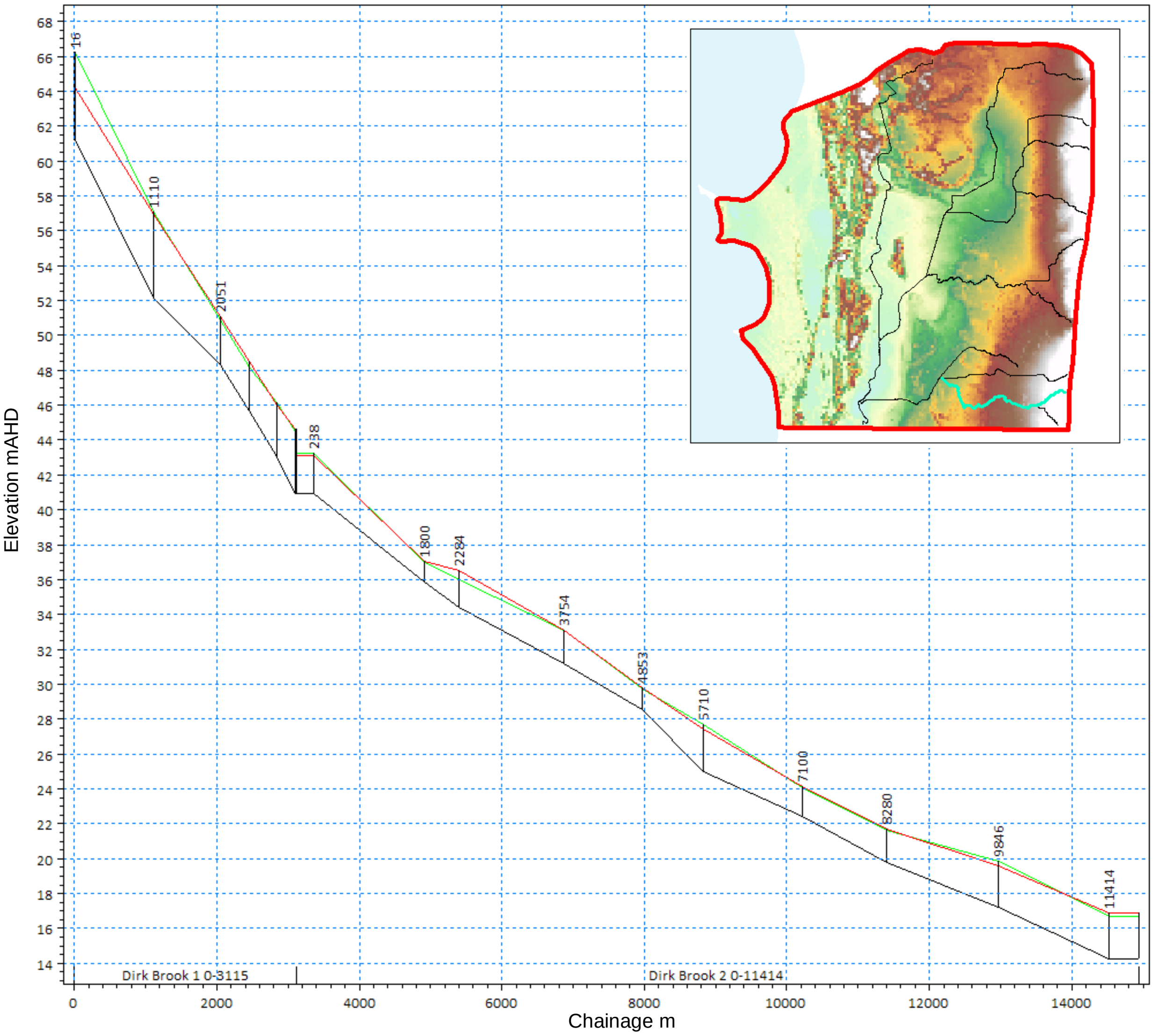
## Karnet Brook



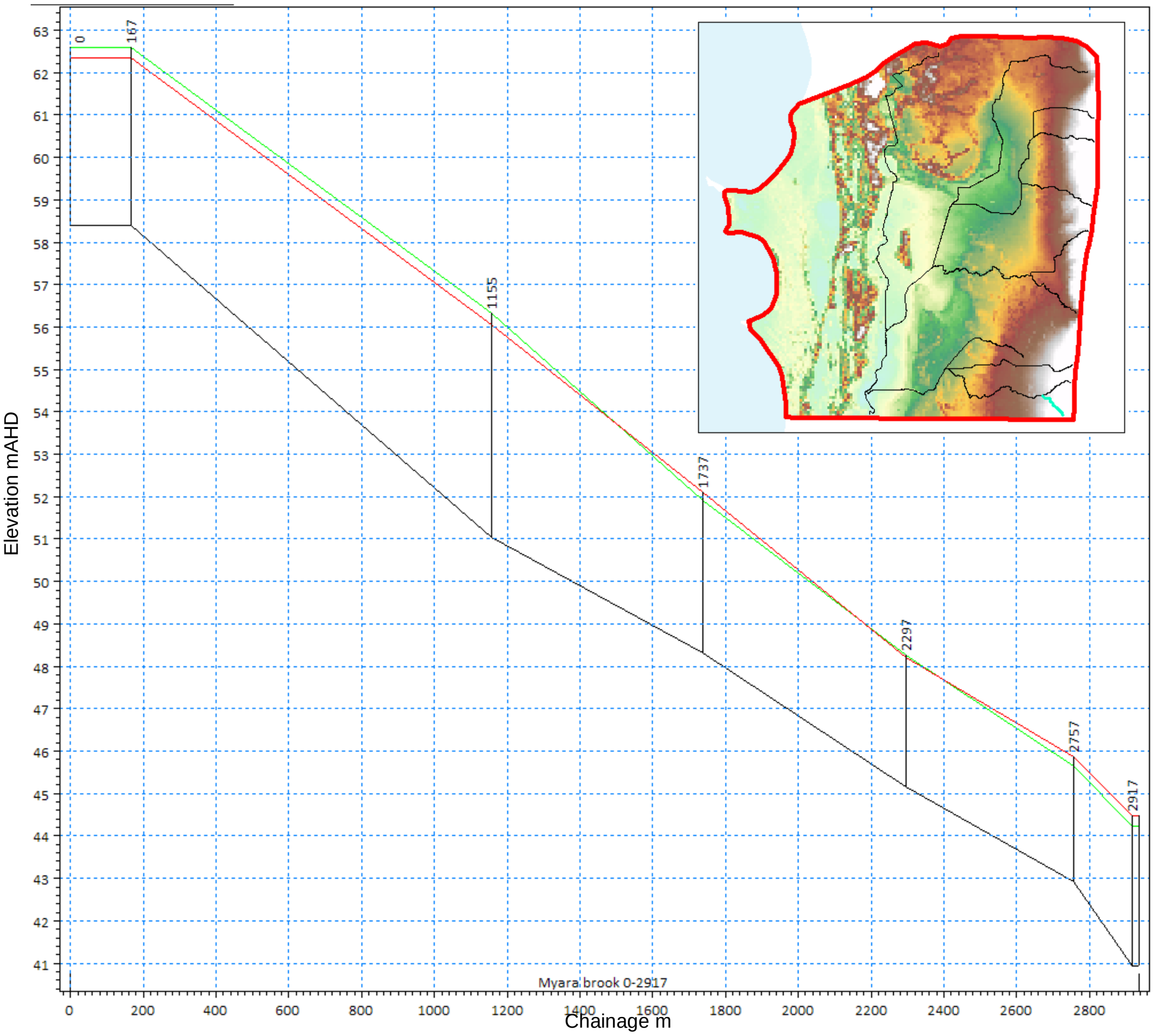
## Punrack Drain , 1, 2 & 3



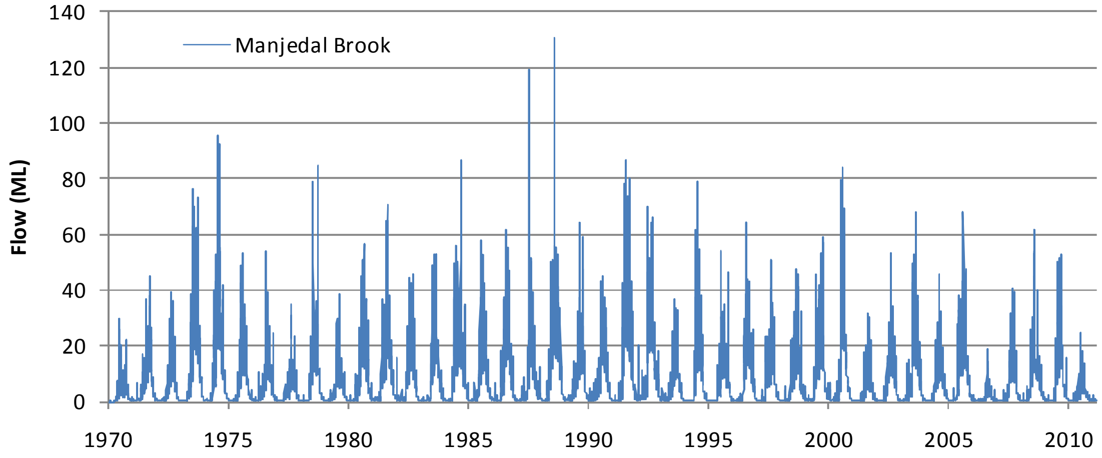
## Dirk Brook 1 & 2

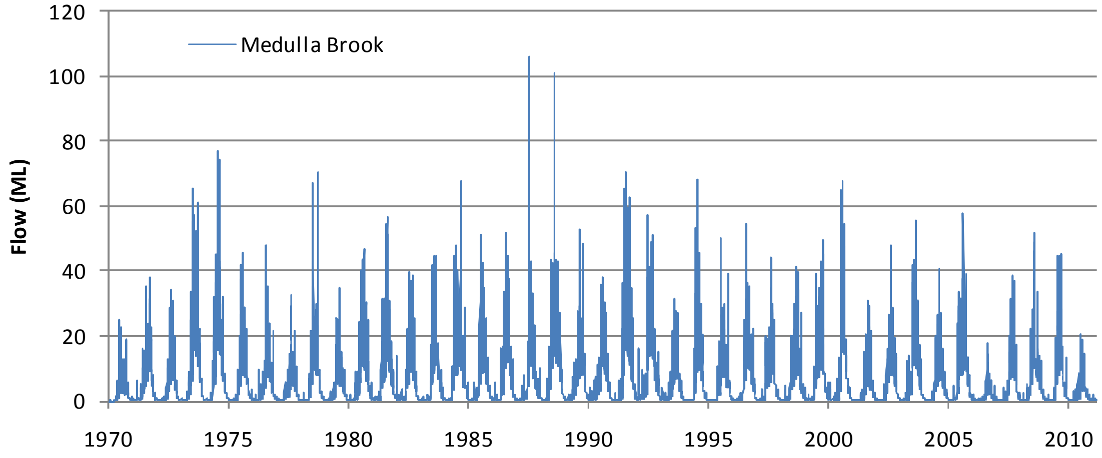


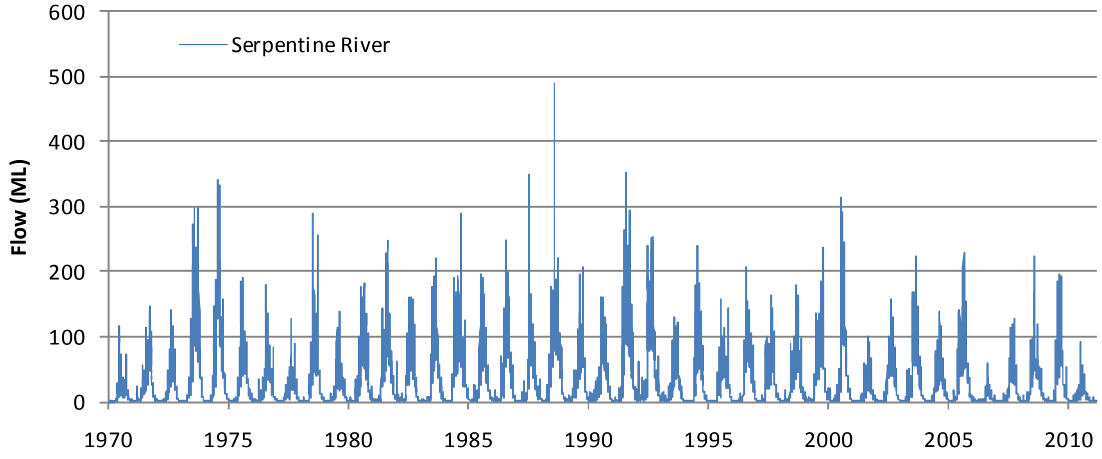
## Myara Brook

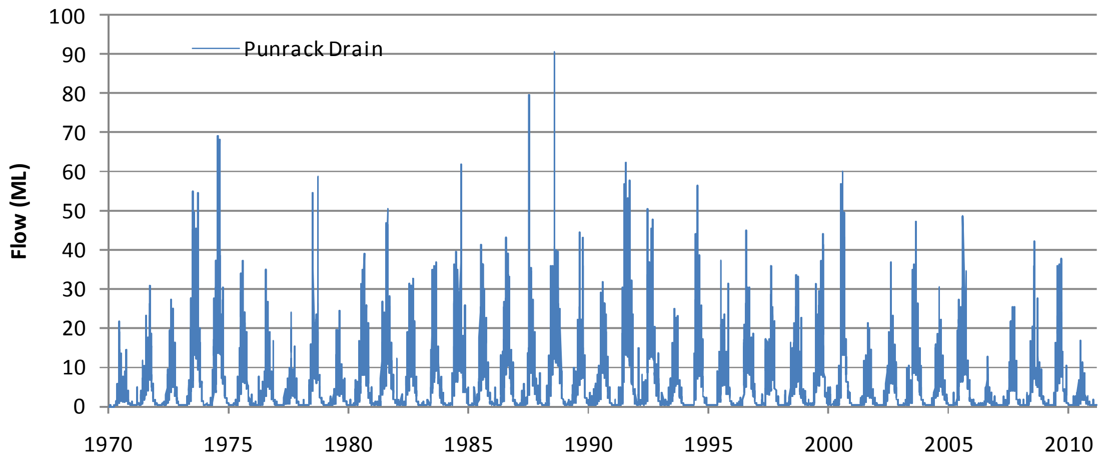

Elevation mAHD
Chainage m
Myara brook 0-2917
0
167
1155
1737
2297
2757
2917

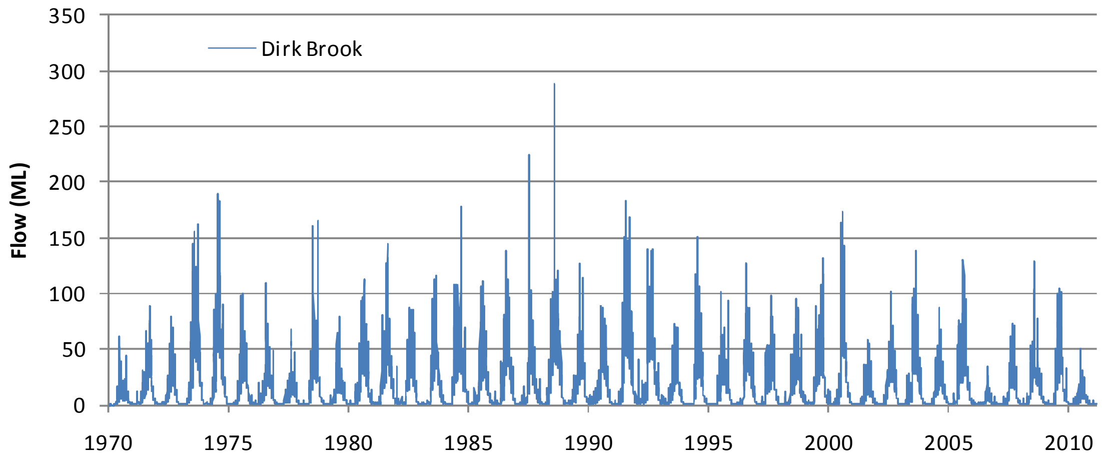
# Appendix B – Mike 11 inflow boundary conditions from SQUARE

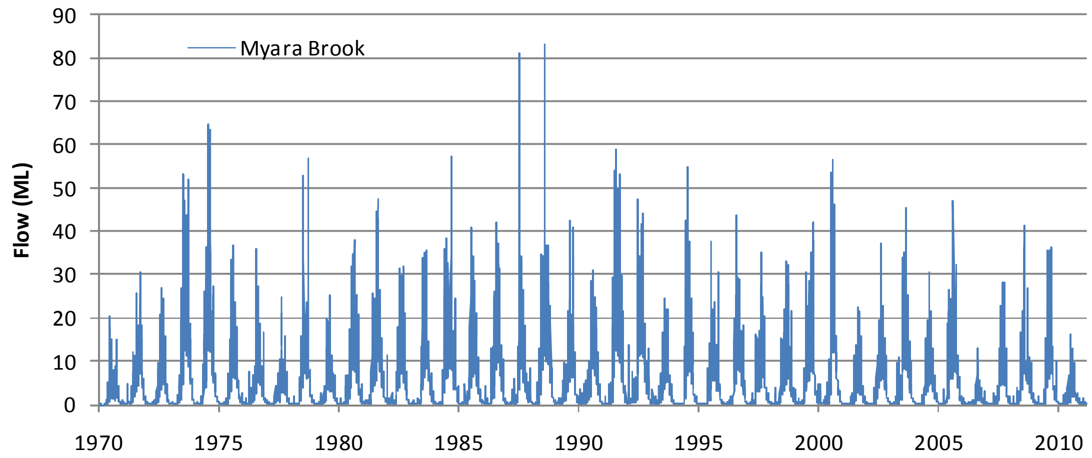


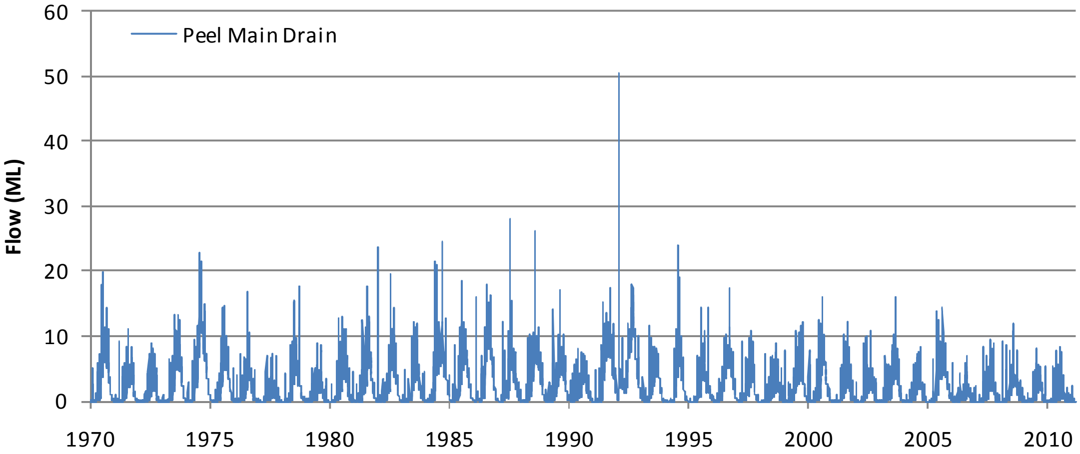




Punrack Drain
Flow (ML)
100
90
80
70
60
50
40
30
20
10
0
1970
1975
1980
1985
1990
1995
2000
2005
2010

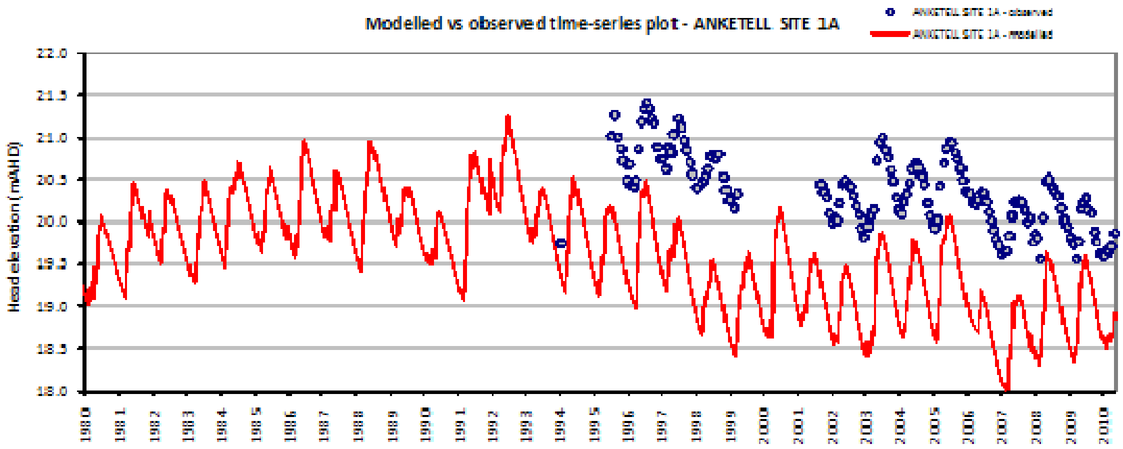

Dirk Brook
Flow (ML)
350
300
250
200
150
100
50
0
1970
1975
1980
1985
1990
1995
2000
2005
2010

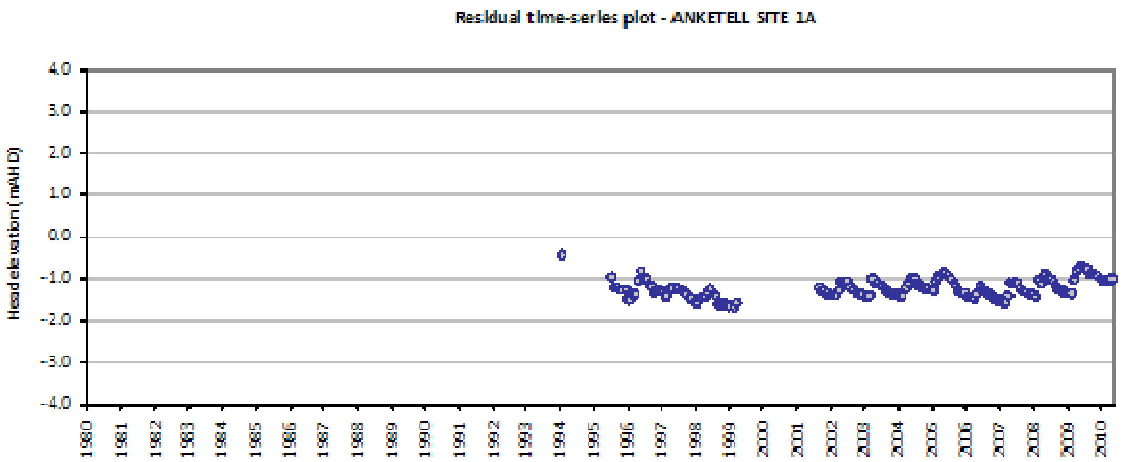

Myara Brook
Flow (ML)
90
80
70
60
50
40
30
20
10
0
1970
1975
1980
1985
1990
1995
2000
2005
2010


Peel Main Drain
Flow (ML)
60
50
40
30
20
10
0
1970
1975
1980
1985
1990
1995
2000
2005
2010

# Appendix C – Observed versus modelled heads for calibration and validation bores

## Superficial Aquifer – Anketell Site 1A

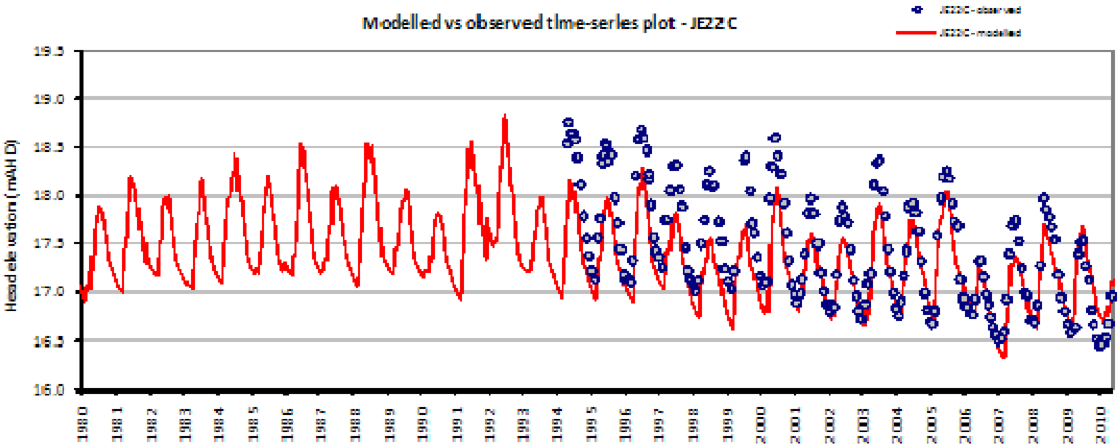


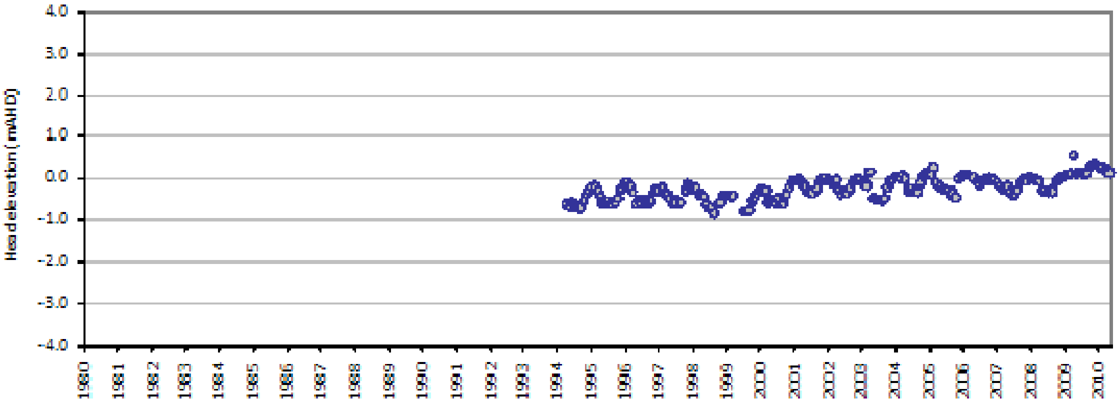




| Statistics | |
|---|---|
| Mean error (ME) | 1.29 |
| Mean absolute error (MAE) | 1.29 |
| Root mean square error (RMSE) | 1.31 |
| Standard deviation of residuals (STDres) | 0.20 |
| Correlation coefficient (R) | 0.92 |
| Nash Sutcliffe correlation coefficient (R2) | -11.08 |

Note: underestimation of modelled heads may be related to irrigation recharge from market gardens in this area.

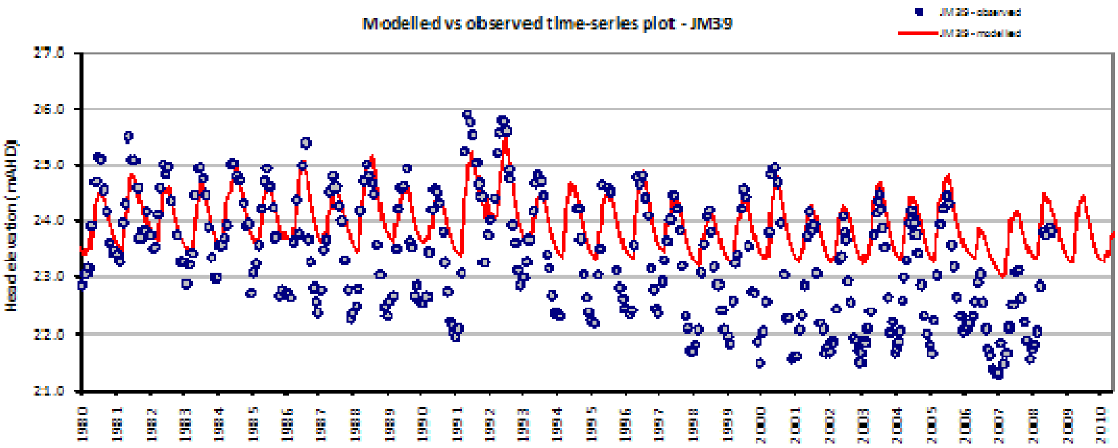
## Superficial Aquifer – JE22C

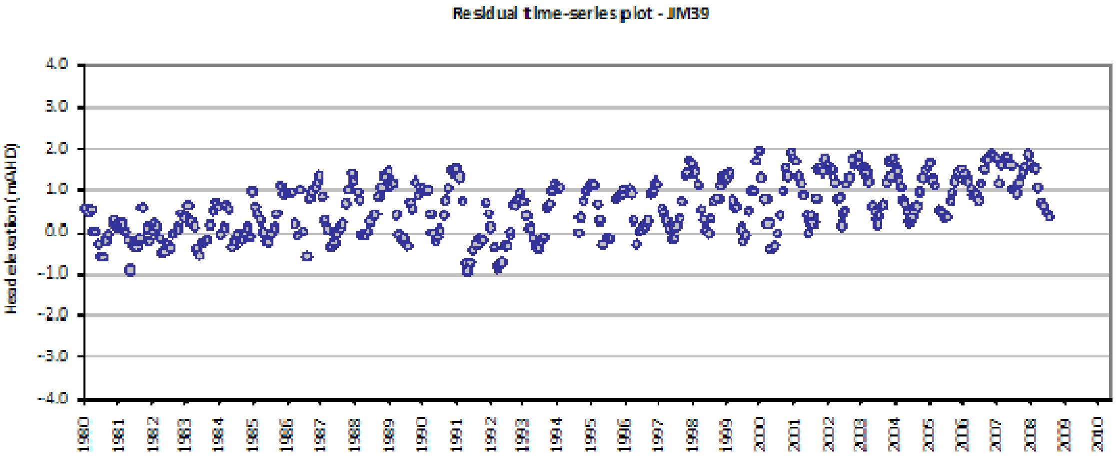



| Statistics | |
|---|---|
| Mean error (ME) | 0.36 |
| Mean absolute error (MAE) | 0.36 |
| Root mean square error (RMSE) | 0.42 |
| Standard deviation of residuals (STDres) | 0.22 |
| Correlation coefficient (R) | 0.96 |
| Nash Sutcliffe correlation coefficient (R2) | 0.43 |

## Superficial Aquifer – JM39

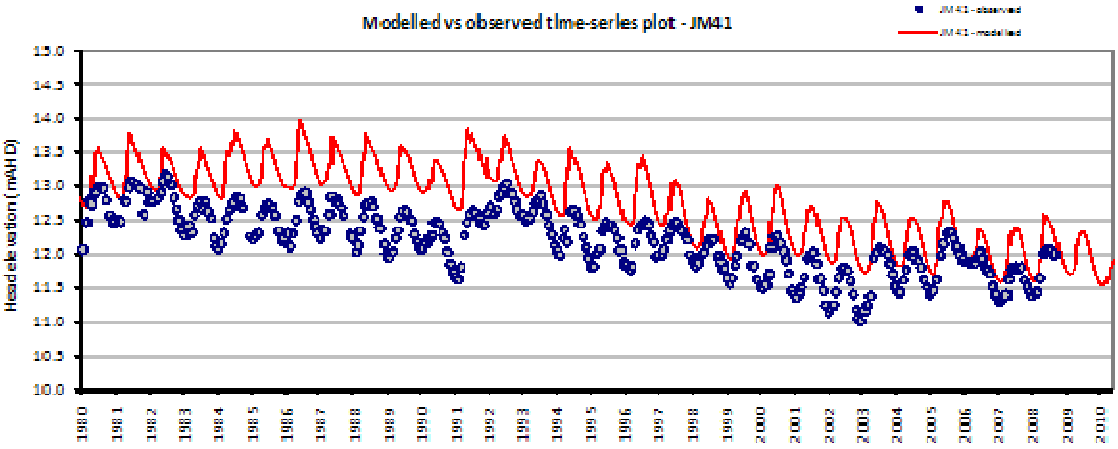


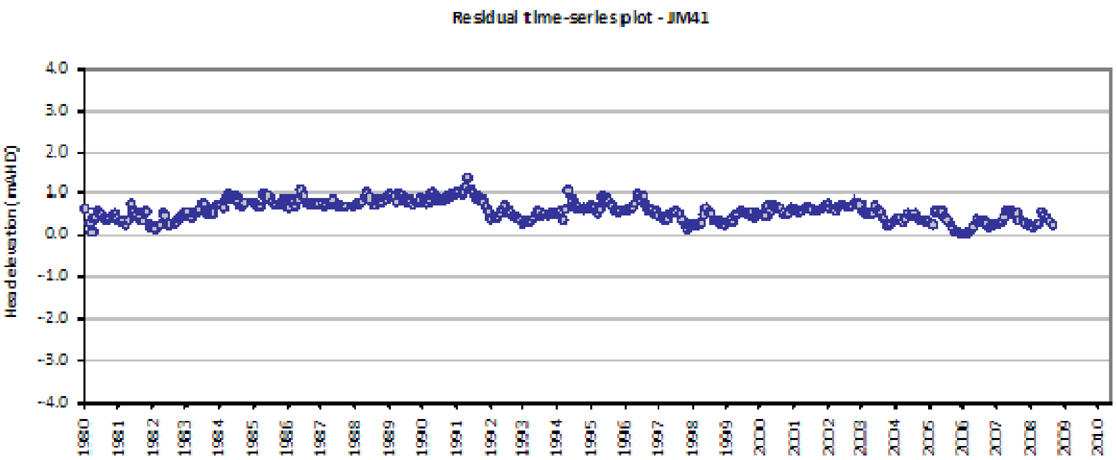




| Statistics | |
|---|---|
| Mean error (ME) | -0.53 |
| Mean absolute error (MAE) | 0.67 |
| Root mean square error (RMSE) | 0.84 |
| Standard deviation of residuals (STDres) | 0.65 |
| Correlation coefficient (R) | 0.91 |
| Nash Sutcliffe correlation coefficient (R2) | 0.36 |

Note: declining trend is likely from abstraction from the Jandakot Mound.

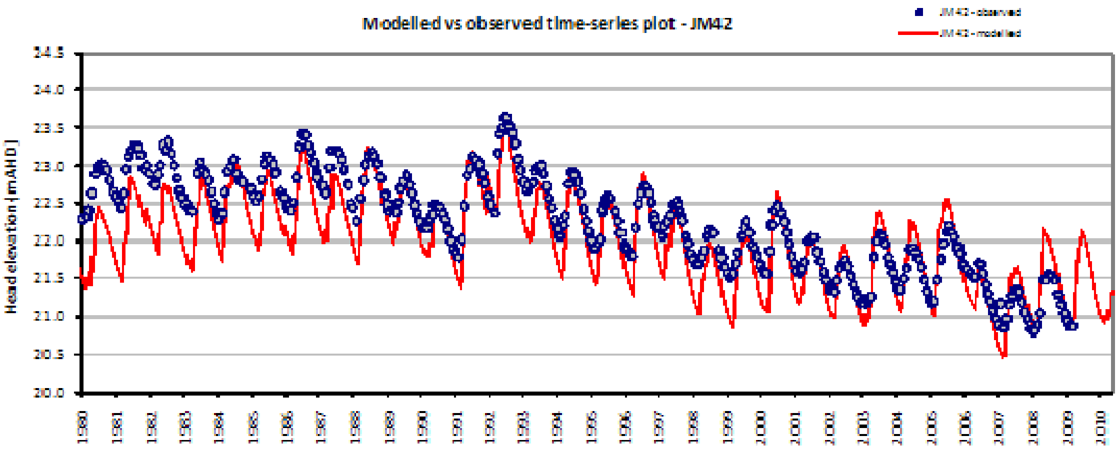
## Superficial Aquifer – JM41

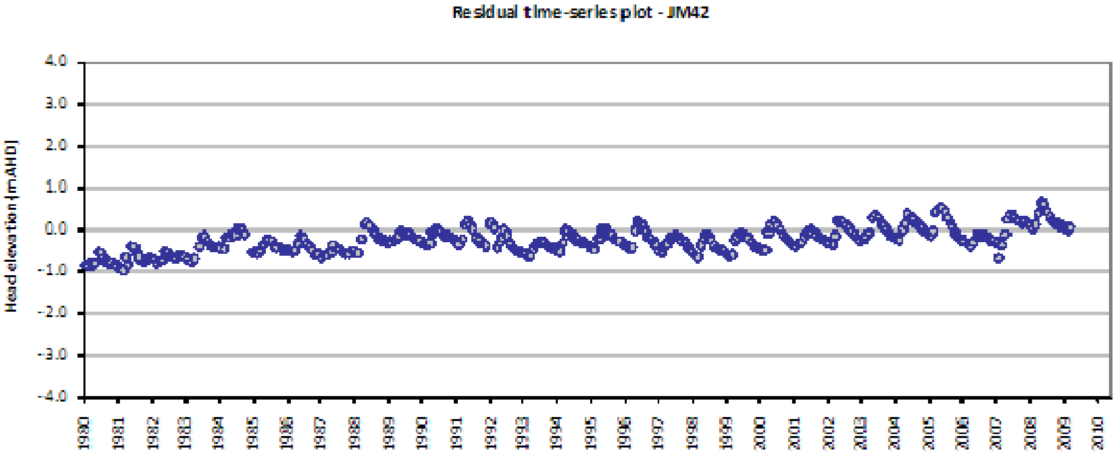



| Statistics | |
|---|---|
| Mean error (ME) | -0.64 |
| Mean absolute error (MAE) | 0.64 |
| Root mean square error (RMSE) | 0.67 |
| Standard deviation of residuals (STDres) | 0.21 |
| Correlation coefficient (R) | 0.90 |
| Nash Sutcliffe correlation coefficient (R2) | -1.26 |

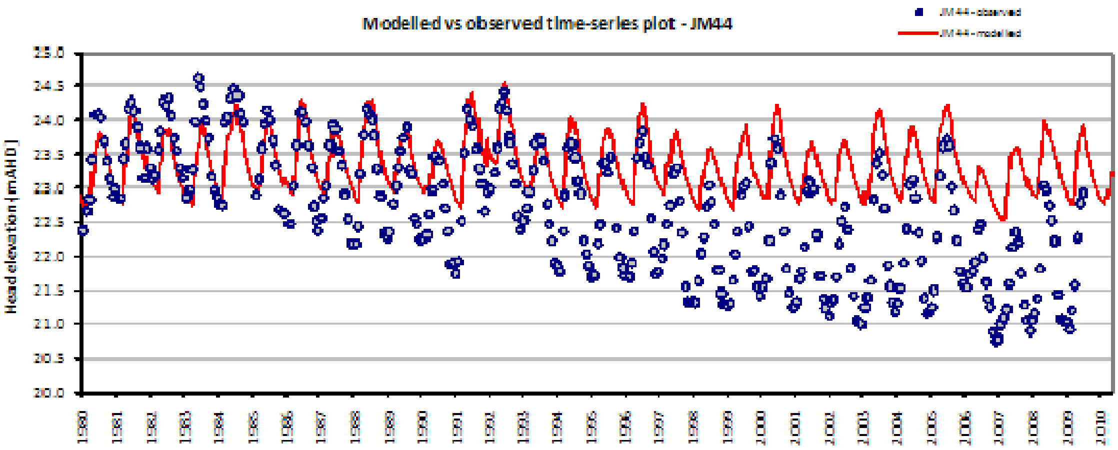
## Superficial Aquifer – JM42

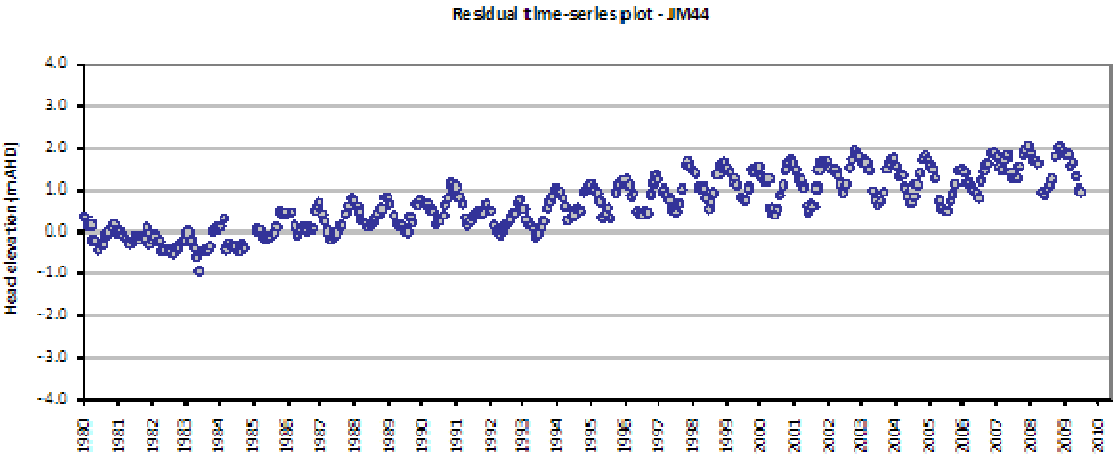



| Statistics | |
|---|---|
| Mean error (ME) | 0.29 |
| Mean absolute error (MAE) | 0.33 |
| Root mean square error (RMSE) | 0.40 |
| Standard deviation of residuals (STDres) | 0.26 |
| Correlation coefficient (R) | 0.88 |
| Nash Sutcliffe correlation coefficient (R2) | 0.47 |

## Superficial Aquifer – JM44

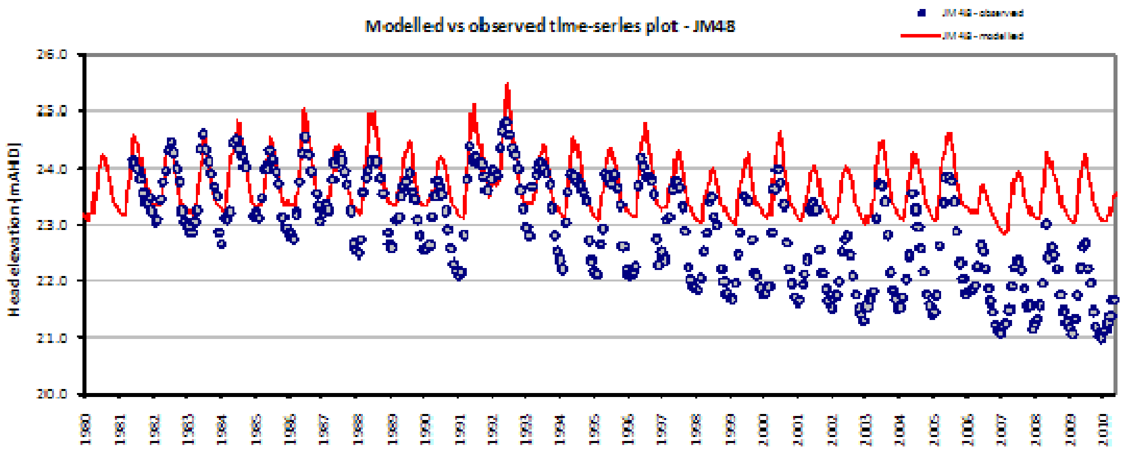


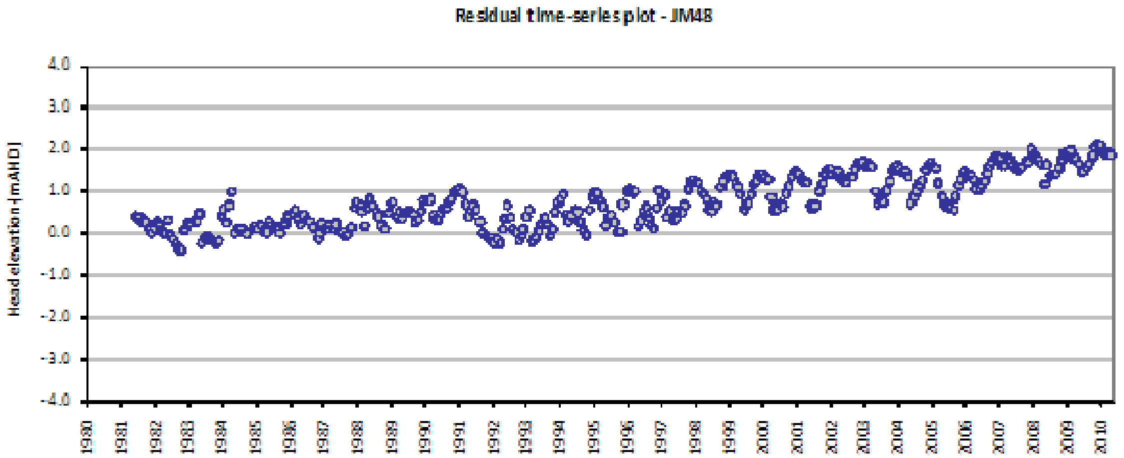




| Statistics | |
|---|---|
| Mean error (ME) | -0.57 |
| Mean absolute error (MAE) | 0.66 |
| Root mean square error (RMSE) | 0.83 |
| Standard deviation of residuals (STDres) | 0.61 |
| Correlation coefficient (R) | 0.79 |
| Nash Sutcliffe correlation coefficient (R2) | 0.11 |

Note: declining trend is likely from abstraction from the Jandakot Mound.

## Superficial Aquifer – JM48

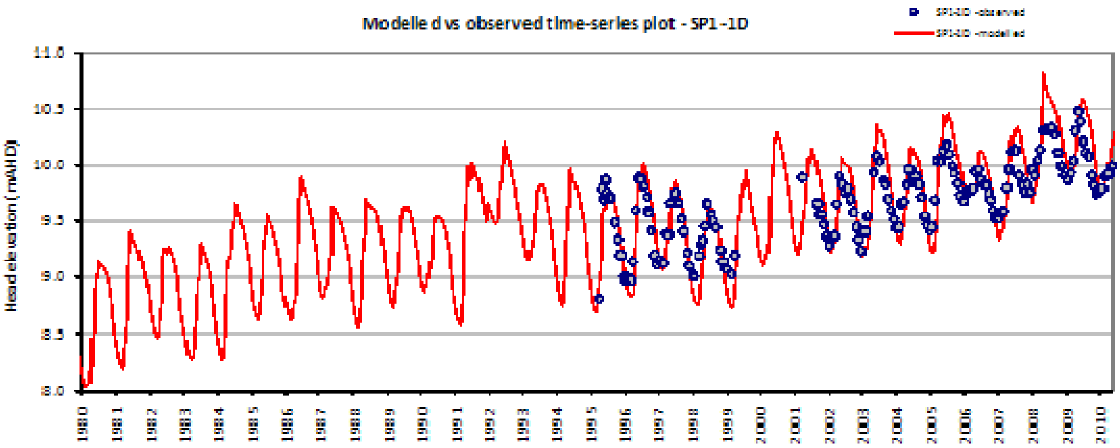


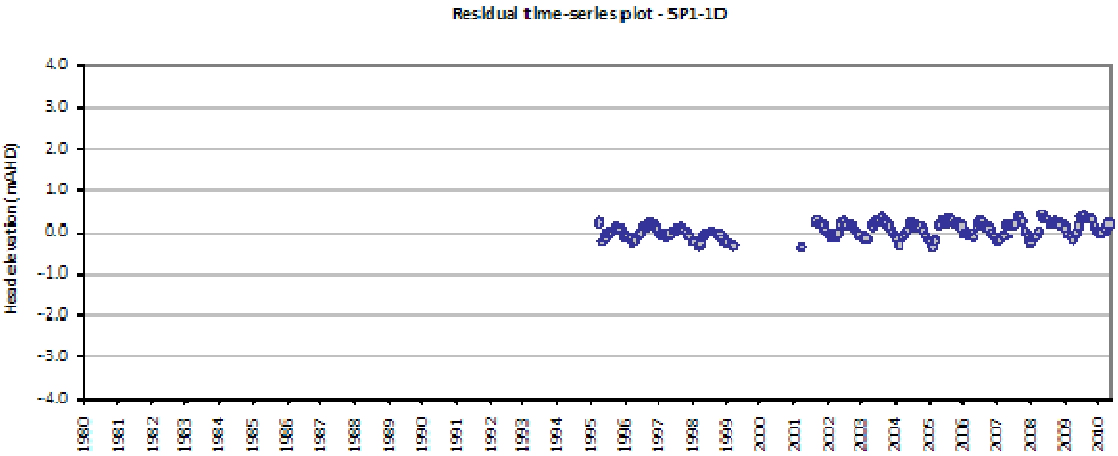




| Statistics | |
|---|---|
| Mean error (ME) | -0.59 |
| Mean absolute error (MAE) | 0.62 |
| Root mean square error (RMSE) | 0.77 |
| Standard deviation of residuals (STDres) | 0.50 |
| Correlation coefficient (R) | 0.83 |
| Nash Sutcliffe correlation coefficient (R2) | 0.14 |

Note: declining trend is likely from abstraction from the Jandakot Mound.

## Superficial Aquifer – SP1-1D

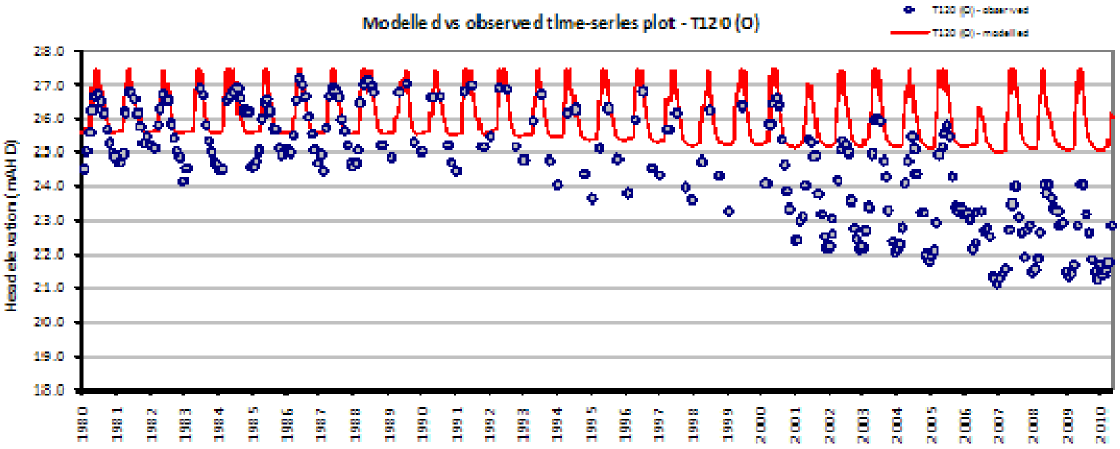


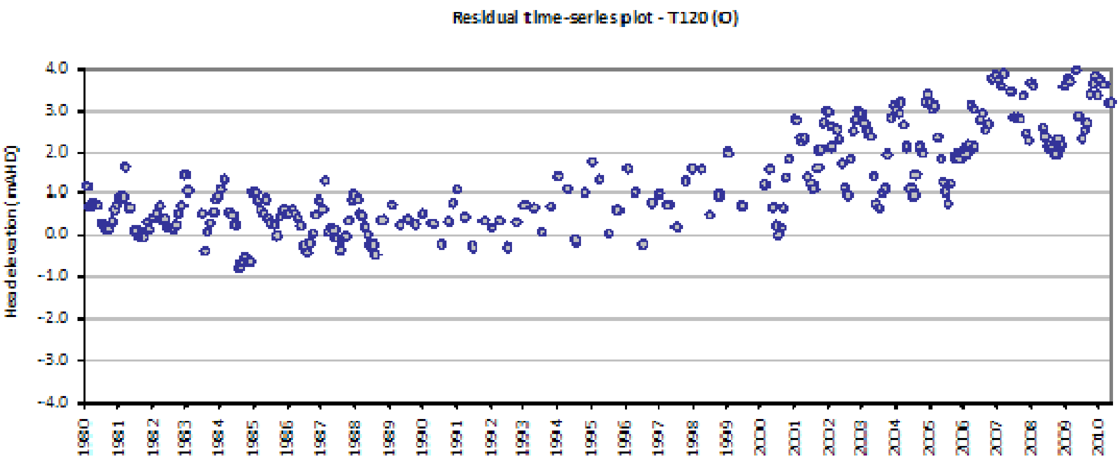




| Statistics | |
|---|---|
| Mean error (ME) | -0.01 |
| Mean absolute error (MAE) | 0.13 |
| Root mean square error (RMSE) | 0.16 |
| Standard deviation of residuals (STDres) | 0.16 |
| Correlation coefficient (R) | 0.93 |
| Nash Sutcliffe correlation coefficient (R2) | 0.70 |

Note: increasing trend results from infiltration of wastewater from the Kwinana waste water treatment plant. A localised groundwater mound is present in the model in this area.

## Superficial Aquifer – T120 (O)

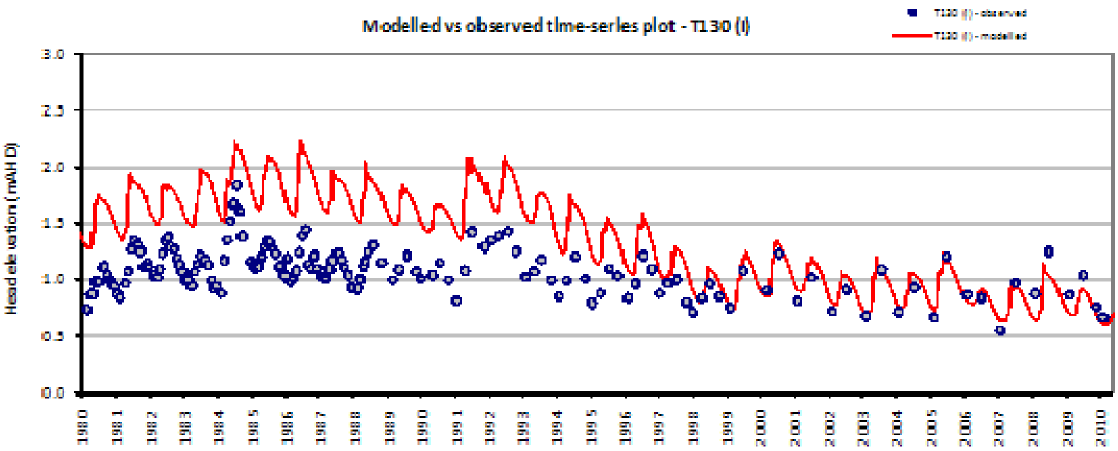


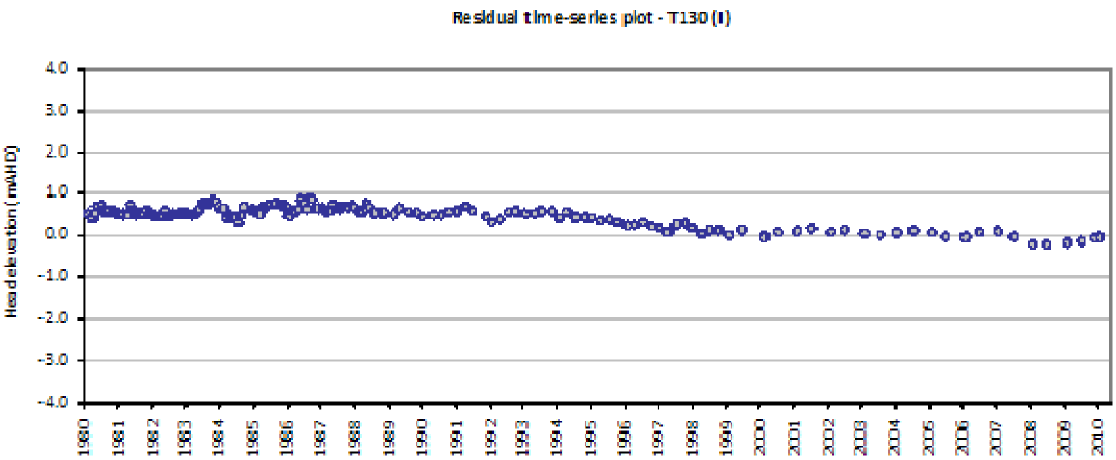




| Statistics | |
|---|---|
| Mean error (ME) | -0.87 |
| Mean absolute error (MAE) | 0.94 |
| Root mean square error (RMSE) | 1.25 |
| Standard deviation of residuals (STDres) | 0.89 |
| Correlation coefficient (R) | 0.76 |
| Nash Sutcliffe correlation coefficient (R2) | 0.07 |

Notes: the declining trend is probably related to abstraction in this area which is unaccounted for by the model.

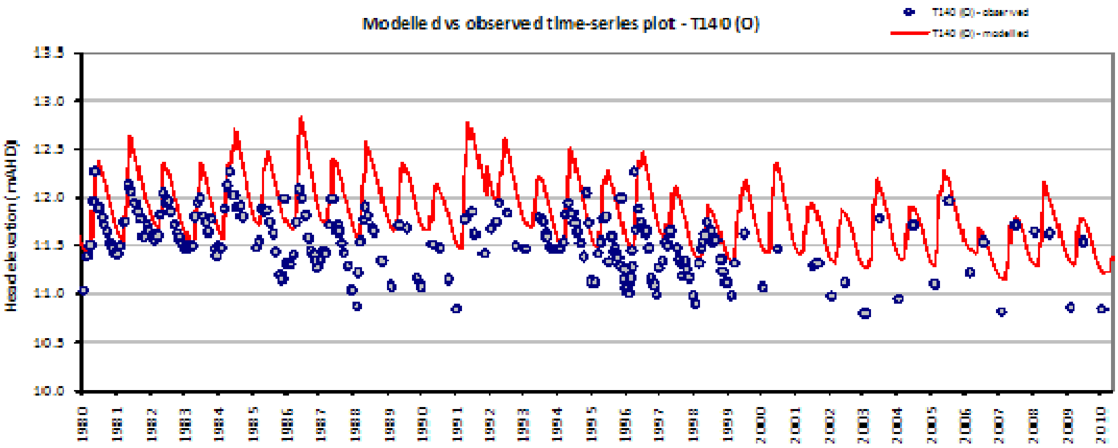
## Superficial Aquifer – T130 (I)

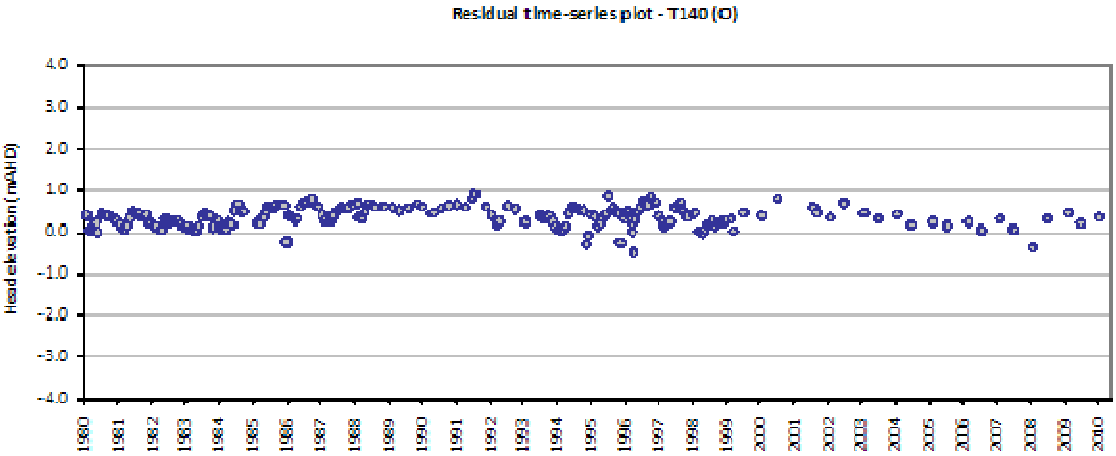



| Statistics | |
|---|---|
| Mean error (ME) | -0.52 |
| Mean absolute error (MAE) | 0.52 |
| Root mean square error (RMSE) | 0.56 |
| Standard deviation of residuals (STDres) | 0.20 |
| Correlation coefficient (R) | 0.79 |
| Nash Sutcliffe correlation coefficient (R2) | -7.13 |

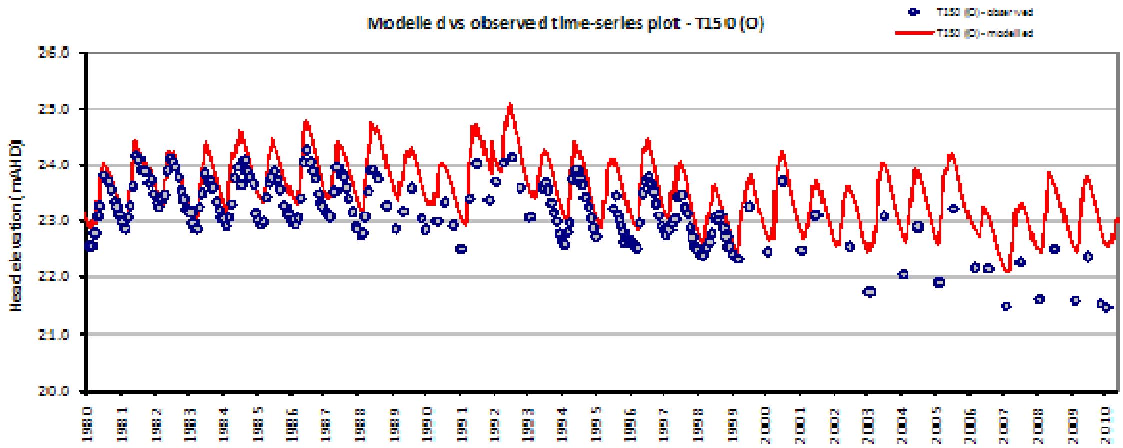
## Superficial Aquifer – T140 (O)

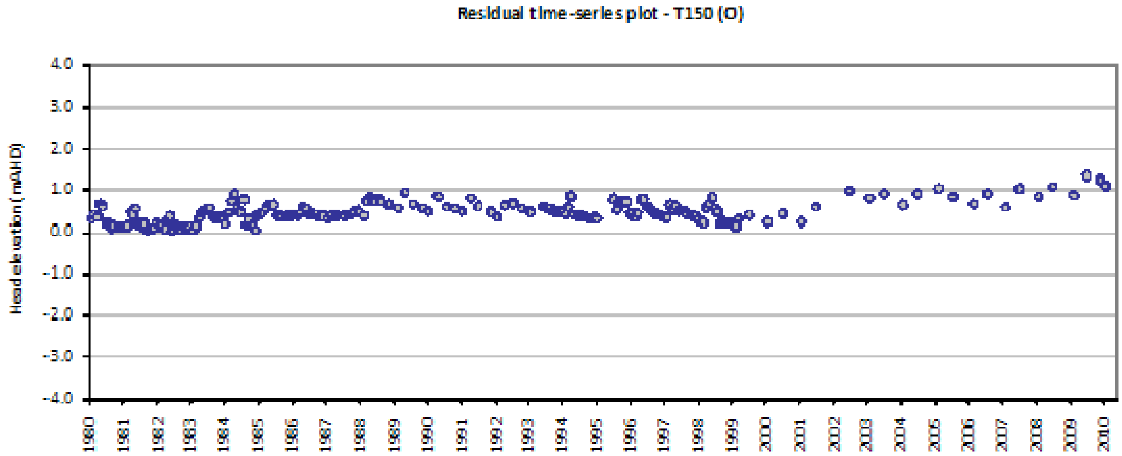



| Statistics | |
|---|---|
| Mean error (ME) | -0.38 |
| Mean absolute error (MAE) | 0.39 |
| Root mean square error (RMSE) | 0.45 |
| Standard deviation of residuals (STDres) | 0.23 |
| Correlation coefficient (R) | 0.73 |
| Nash Sutcliffe correlation coefficient (R2) | -1.25 |

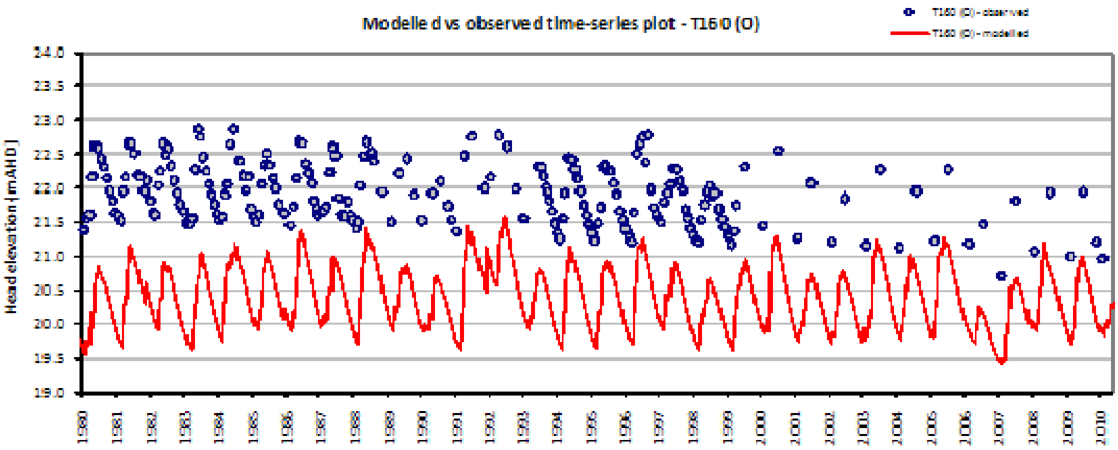
## Superficial Aquifer – T150 (O)

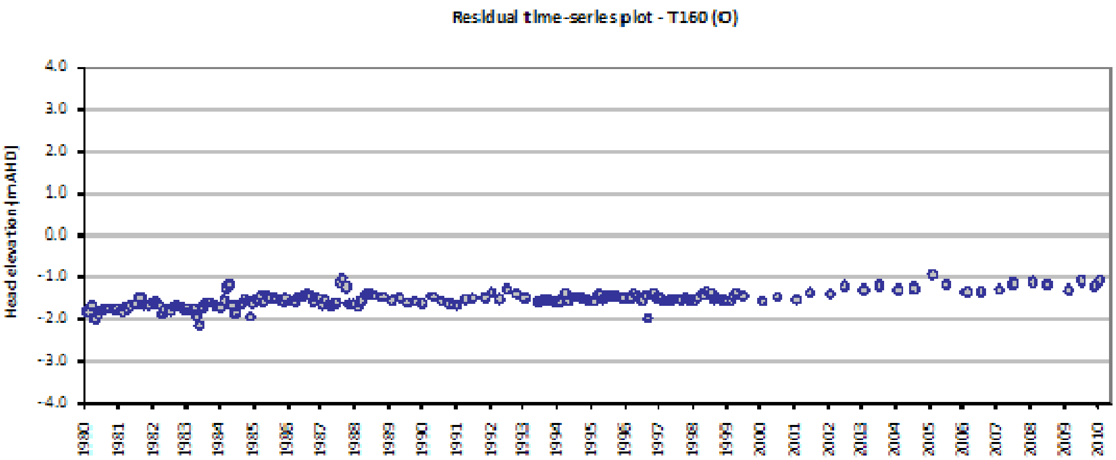



| Statistics | |
|---|---|
| Mean error (ME) | -0.44 |
| Mean absolute error (MAE) | 0.44 |
| Root mean square error (RMSE) | 0.49 |
| Standard deviation of residuals (STDres) | 0.21 |
| Correlation coefficient (R) | 0.91 |
| Nash Sutcliffe correlation coefficient (R2) | -0.06 |

## Superficial Aquifer – T160 (O)

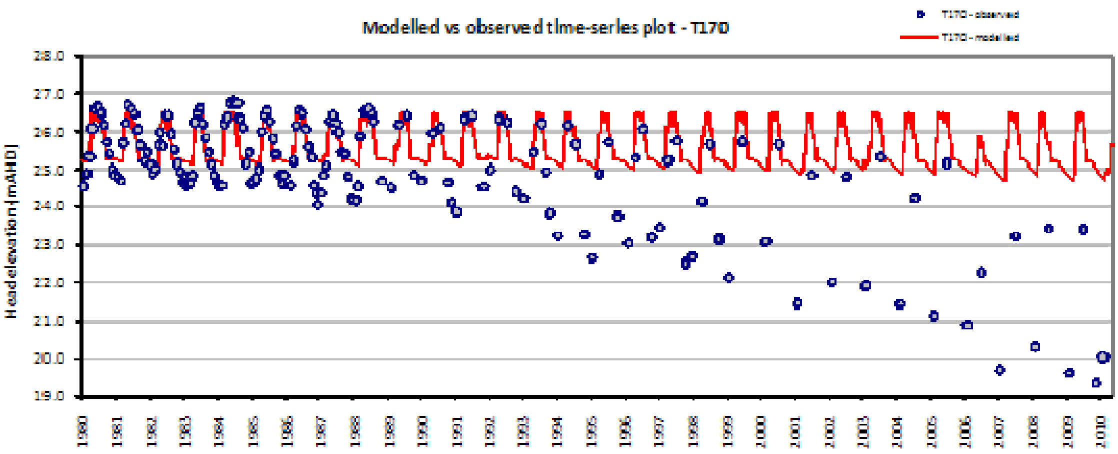


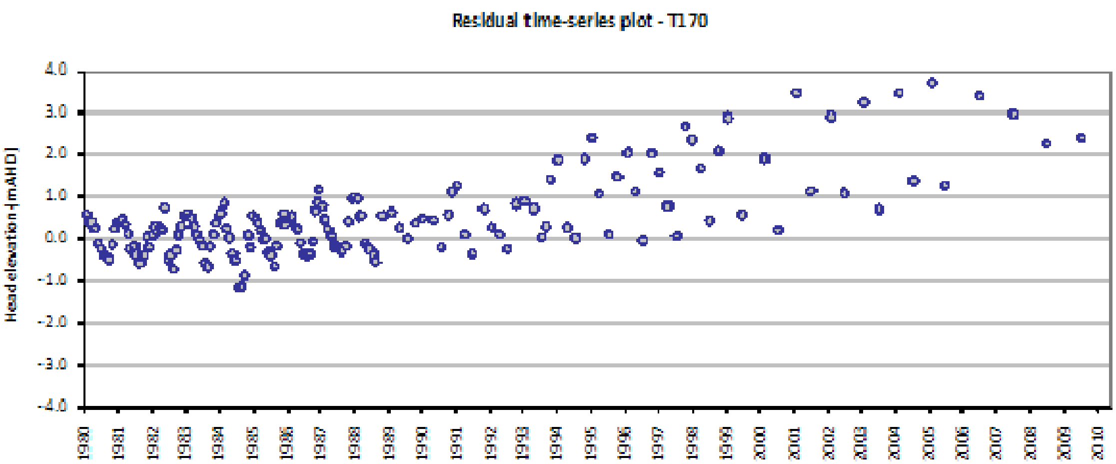




| Statistics | |
|---|---|
| Mean error (ME) | 1.55 |
| Mean absolute error (MAE) | 1.55 |
| Root mean square error (RMSE) | 1.56 |
| Standard deviation of residuals (STDres) | 0.16 |
| Correlation coefficient (R) | 0.93 |
| Nash Sutcliffe correlation coefficient (R2) | -12.32 |

Note: there is some evidence of a coffee rock layer at T160 (O) which may cause locally higher superficial groundwater levels. The single computational layer representing the Superficial Aquifer does not replicate this within the model.

## Superficial Aquifer – T170

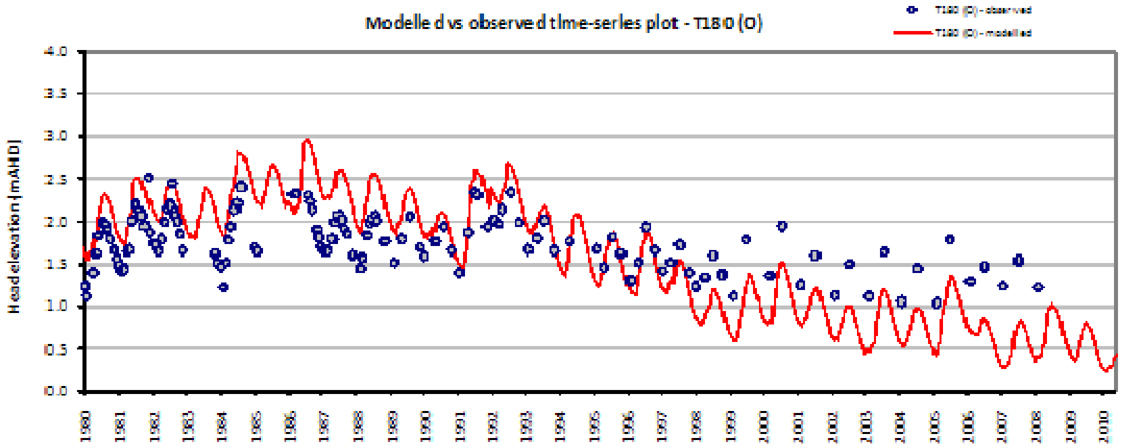


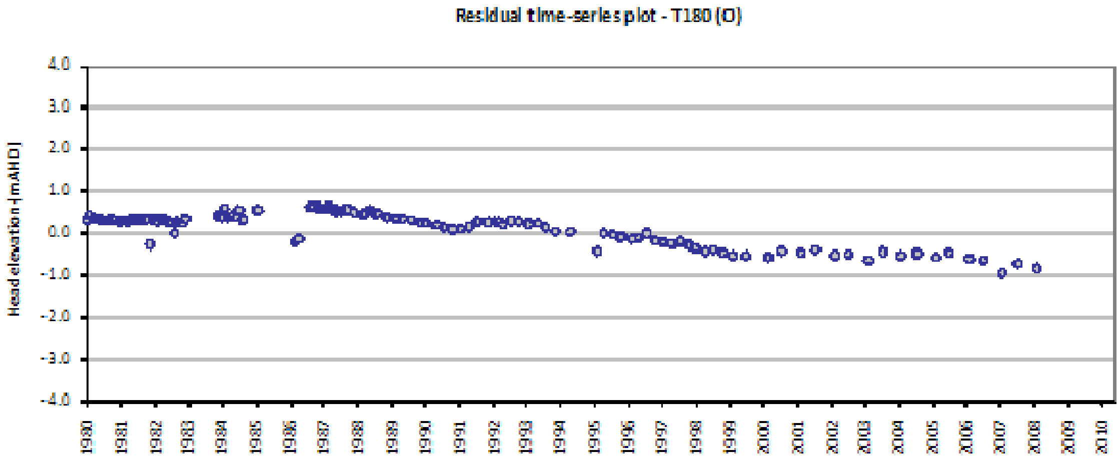




| Statistics | |
|---|---|
| Mean error (ME) | -0.42 |
| Mean absolute error (MAE) | 0.64 |
| Root mean square error (RMSE) | 0.94 |
| Standard deviation of residuals (STDres) | 0.84 |
| Correlation coefficient (R) | 0.73 |
| Nash Sutcliffe correlation coefficient (R2) | 0.31 |

Note: the declining trend is probably related to abstraction in this area which is unaccounted for by the model. The error is similar to T120 (O) nearby.

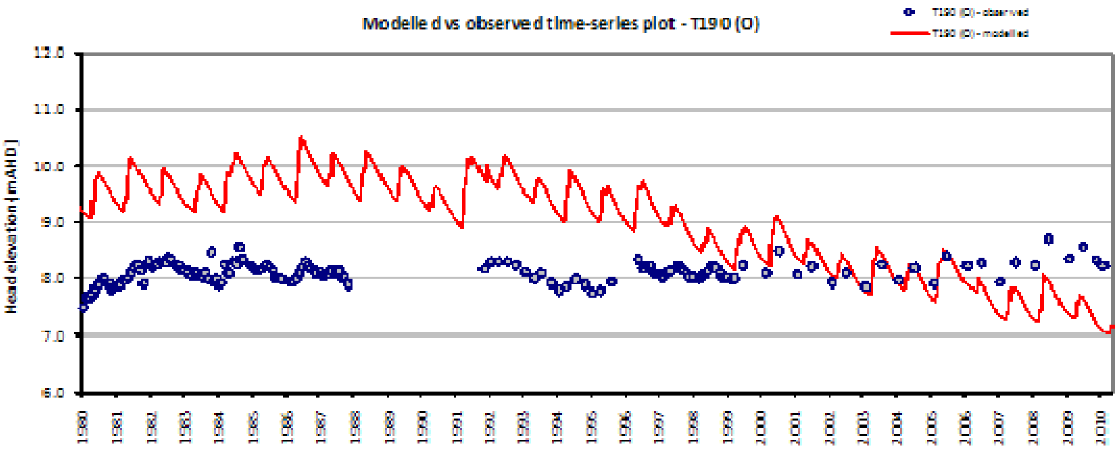
## Superficial Aquifer – T180 (O)

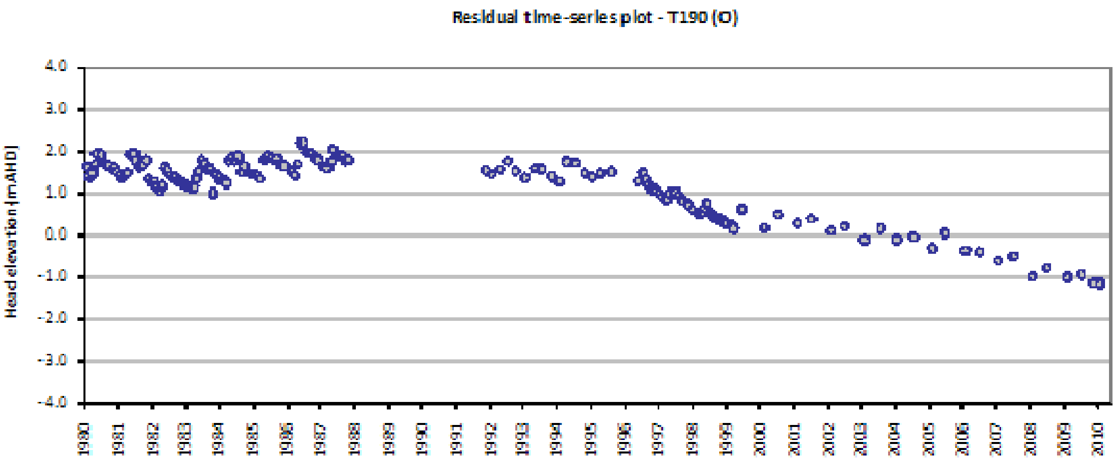



| Statistics | |
|---|---|
| Mean error (ME) | -0.20 |
| Mean absolute error (MAE) | 0.36 |
| Root mean square error (RMSE) | 0.39 |
| Standard deviation of residuals (STDres) | 0.34 |
| Correlation coefficient (R) | 0.81 |
| Nash Sutcliffe correlation coefficient (R2) | -0.56 |

## Superficial Aquifer – T190 (O)

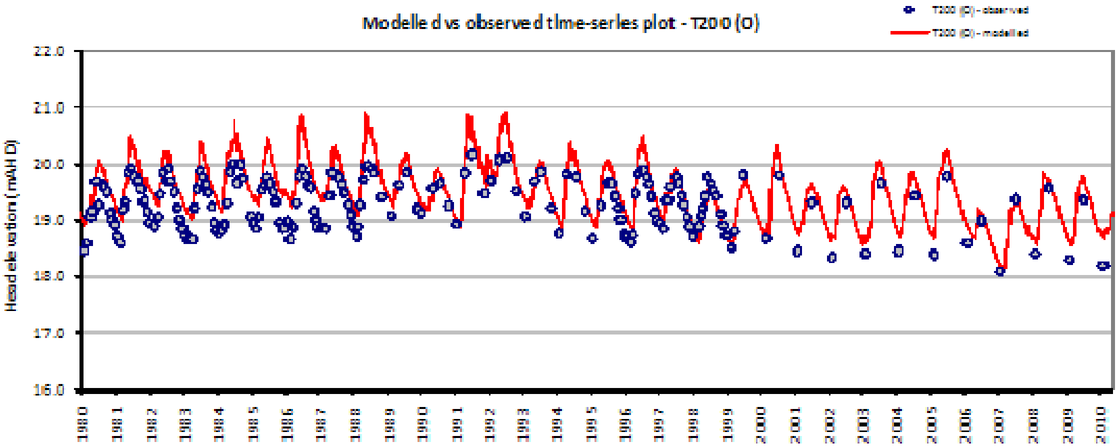


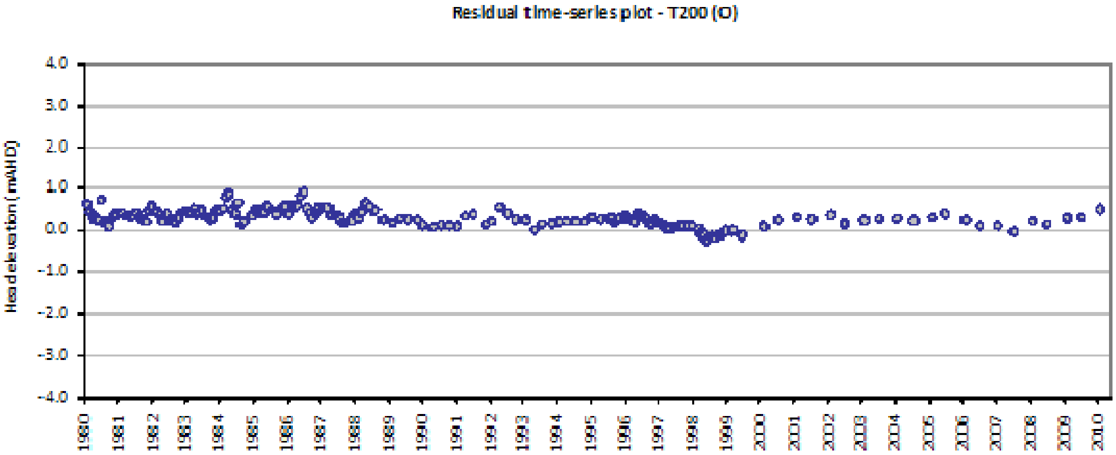




| Statistics | |
|---|---|
| Mean error (ME) | -1.32 |
| Mean absolute error (MAE) | 1.32 |
| Root mean square error (RMSE) | 1.42 |
| Standard deviation of residuals (STDres) | 0.53 |
| Correlation coefficient (R) | 0.25 |
| Nash Sutcliffe correlation coefficient (R2) | -62.21 |

Note: this error was introduced by inclusion of the Tamala Sand unit, which has increased water levels around T190 (O). The declining trend is probably a result of incorrect abstraction estimates within the model.

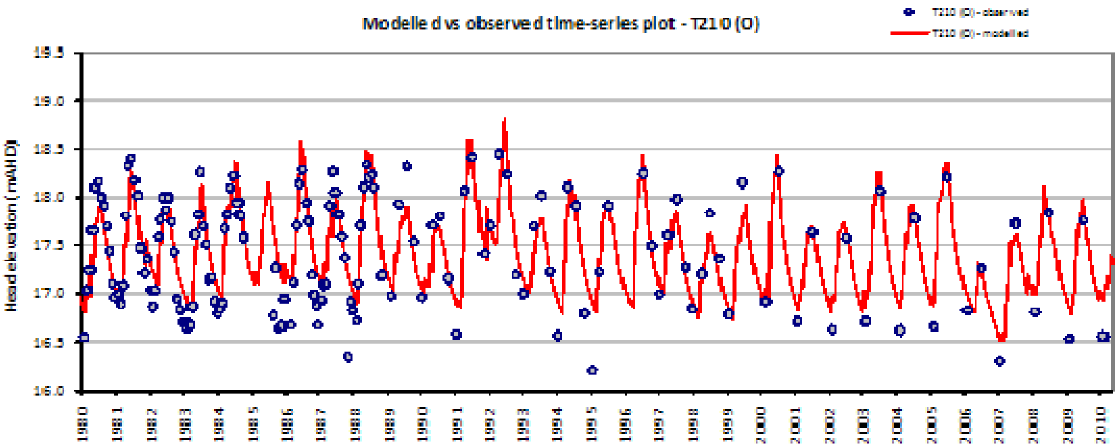
## Superficial Aquifer – T200 (O)

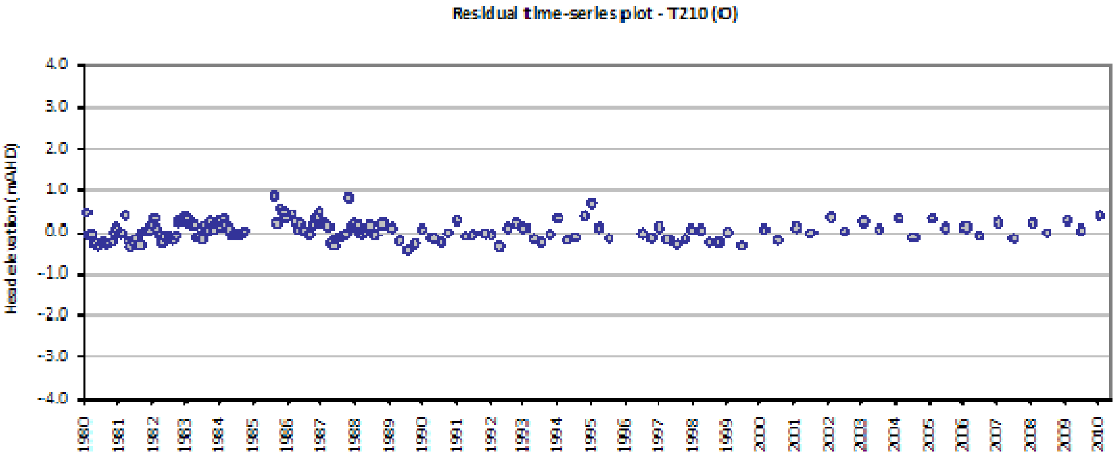



| Statistics | |
|---|---|
| Mean error (ME) | -0.32 |
| Mean absolute error (MAE) | 0.33 |
| Root mean square error (RMSE) | 0.38 |
| Standard deviation of residuals (STDres) | 0.21 |
| Correlation coefficient (R) | 0.90 |
| Nash Sutcliffe correlation coefficient (R2) | 0.26 |

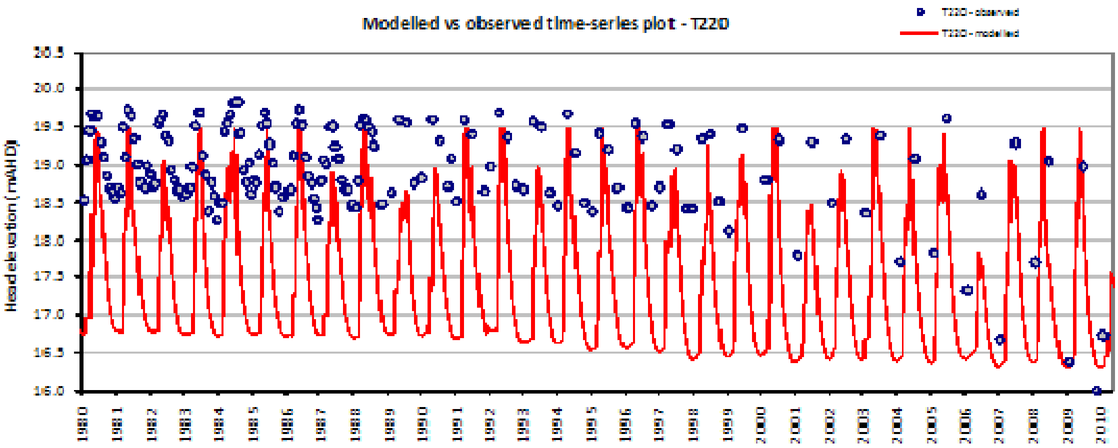
## Superficial Aquifer – T210 (O)

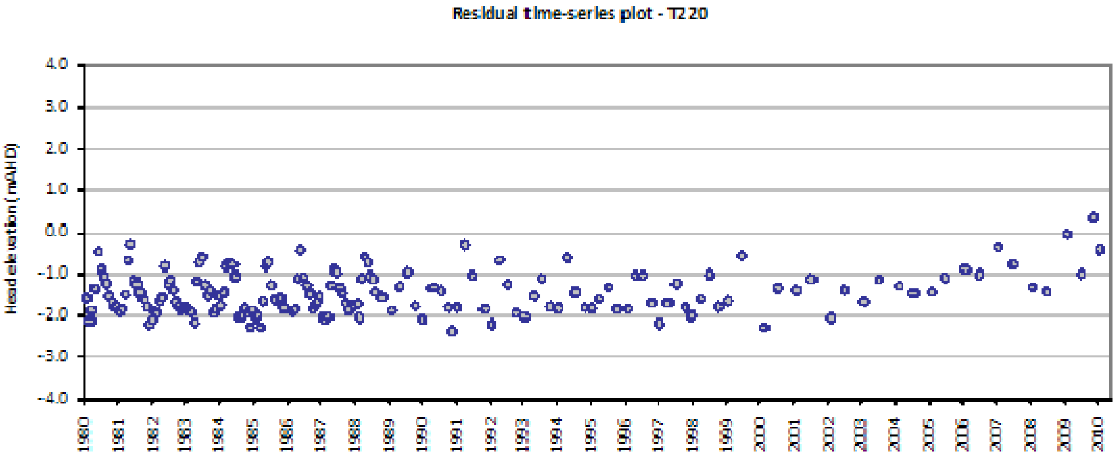



| Statistics | |
|---|---|
| Mean error (ME) | -0.04 |
| Mean absolute error (MAE) | 0.18 |
| Root mean square error (RMSE) | 0.23 |
| Standard deviation of residuals (STDres) | 0.23 |
| Correlation coefficient (R) | 0.93 |
| Nash Sutcliffe correlation coefficient (R2) | 0.82 |

## Superficial Aquifer – T220

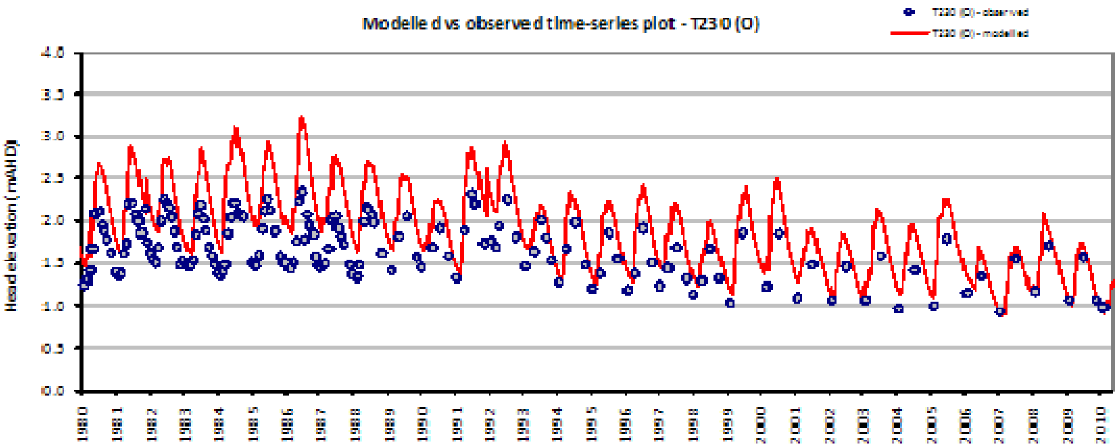


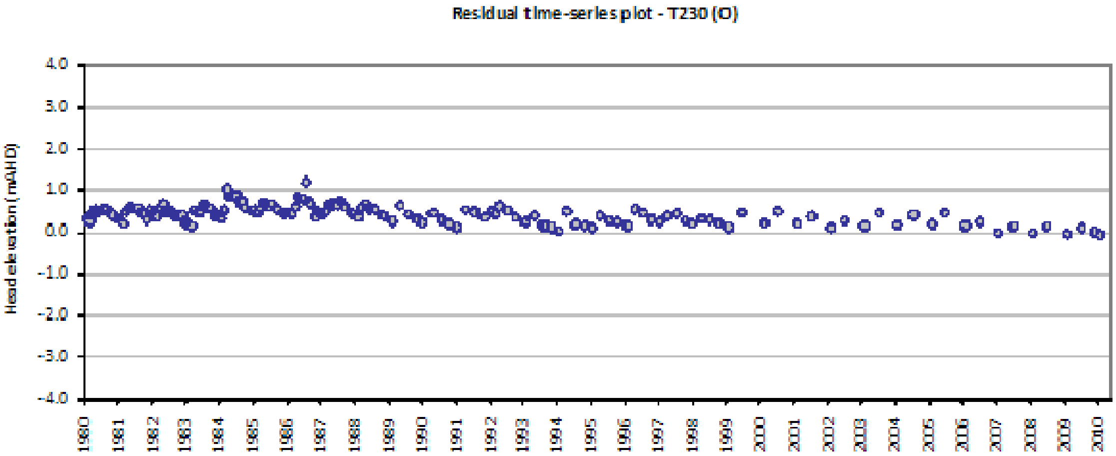




| Statistics | |
|---|---|
| Mean error (ME) | 1.51 |
| Mean absolute error (MAE) | 1.51 |
| Root mean square error (RMSE) | 1.57 |
| Standard deviation of residuals (STDres) | 0.46 |
| Correlation coefficient (R) | 0.90 |
| Nash Sutcliffe correlation coefficient (R2) | -10.71 |

Note: this error may be related to some local variation in geology which is unaccounted for. The amplitude of the groundwater signal is much too high, indicating either a problem with specific yield parameters, or abstraction time-series data.

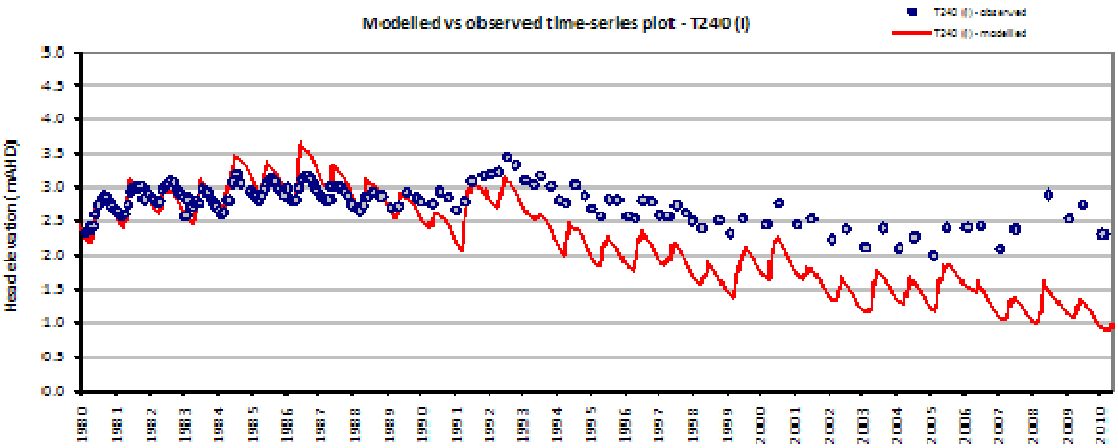
## Superficial Aquifer – T230 (O)

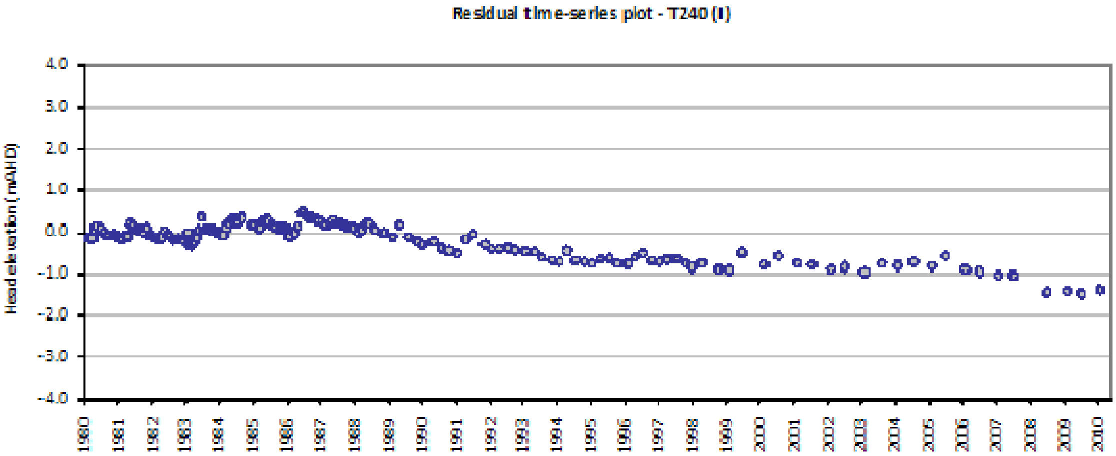



| Statistics | |
|---|---|
| Mean error (ME) | -0.45 |
| Mean absolute error (MAE) | 0.45 |
| Root mean square error (RMSE) | 0.49 |
| Standard deviation of residuals (STDres) | 0.19 |
| Correlation coefficient (R) | 0.94 |
| Nash Sutcliffe correlation coefficient (R2) | -1.36 |

## Superficial Aquifer – T240 (I)

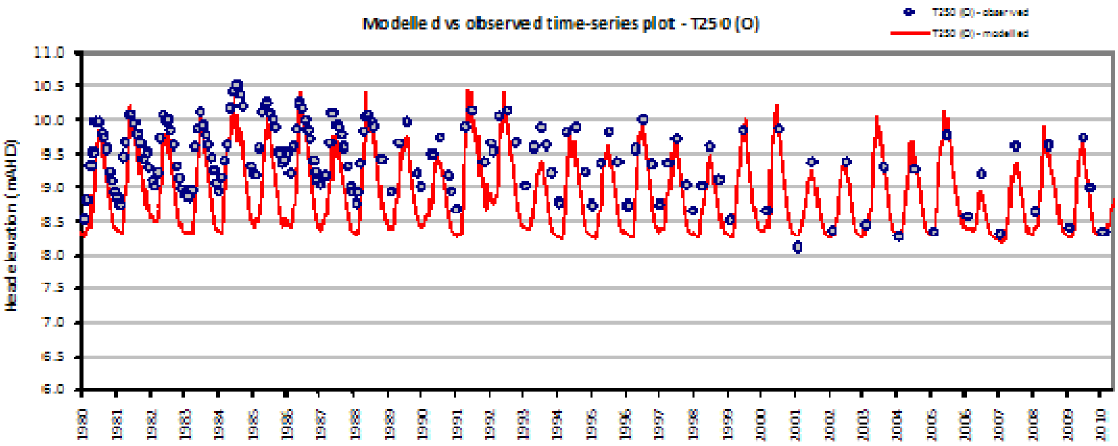


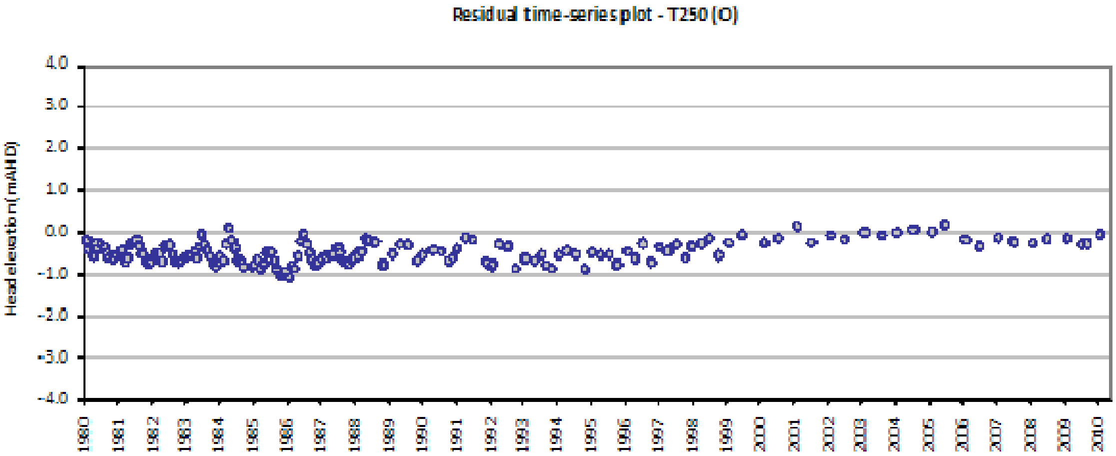




| Statistics | |
|---|---|
| Mean error (ME) | 0.13 |
| Mean absolute error (MAE) | 0.28 |
| Root mean square error (RMSE) | 0.38 |
| Standard deviation of residuals (STDres) | 0.36 |
| Correlation coefficient (R) | 0.79 |
| Nash Sutcliffe correlation coefficient (R2) | -1.65 |

Note: abstraction time-series used around the Kwinana area may be over-estimated, introducing the declining trend in the model from 1992 onward.

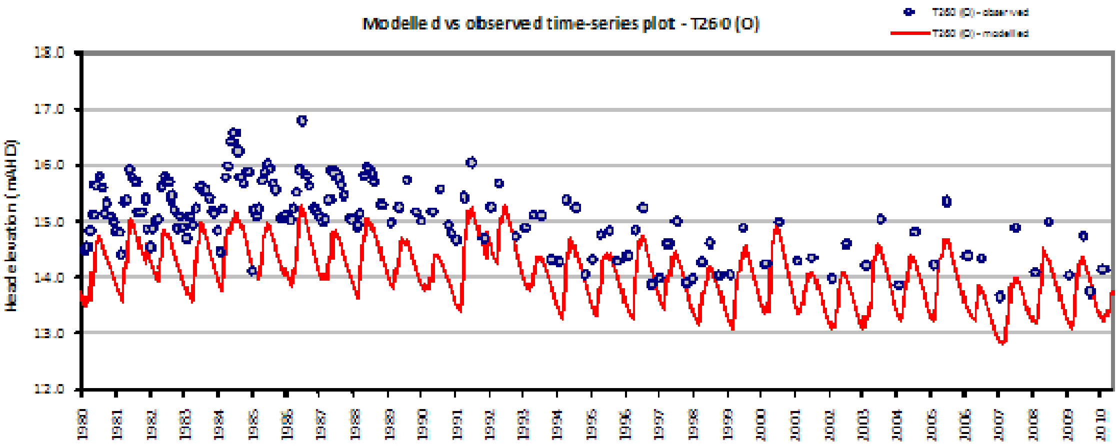
## Superficial Aquifer – T250 (O)

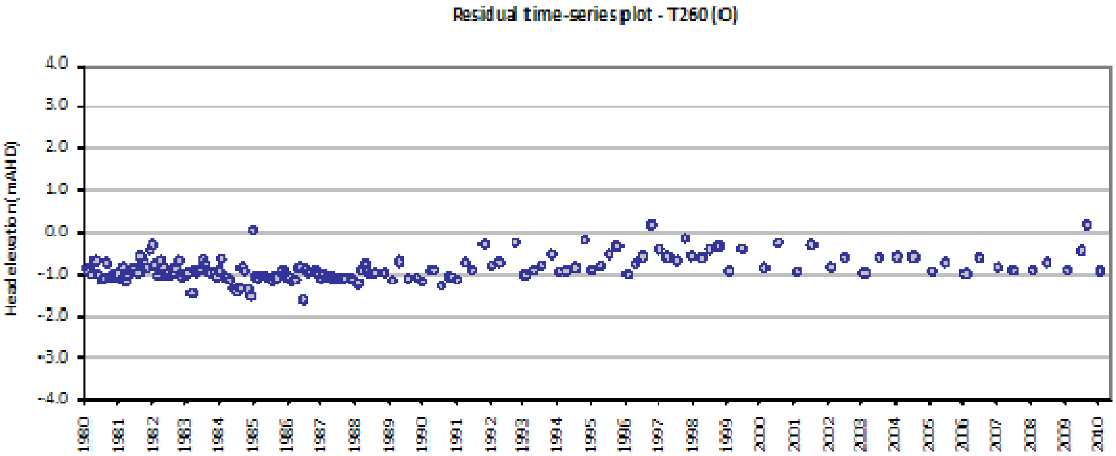



| Statistics | |
|---|---|
| Mean error (ME) | 0.49 |
| Mean absolute error (MAE) | 0.50 |
| Root mean square error (RMSE) | 0.55 |
| Standard deviation of residuals (STDres) | 0.24 |
| Correlation coefficient (R) | 0.90 |
| Nash Sutcliffe correlation coefficient (R2) | -0.26 |

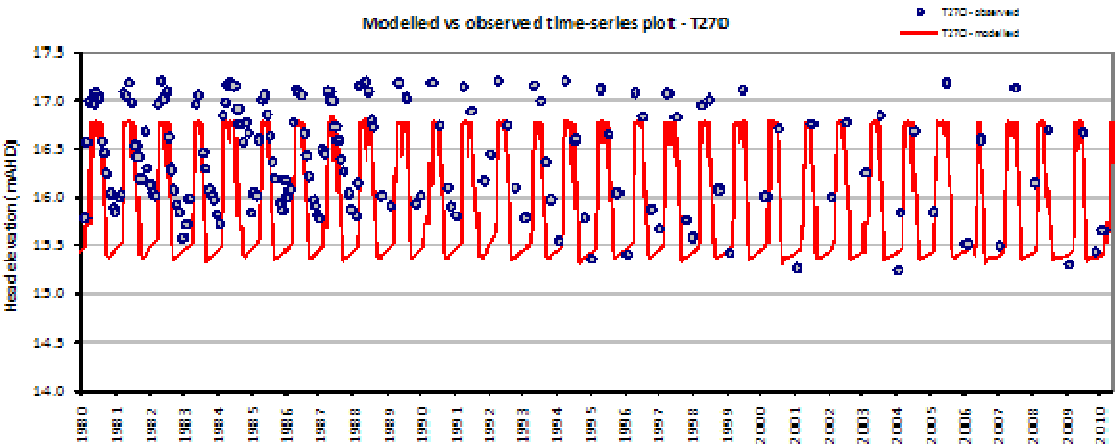
## Superficial Aquifer – T260 (O)

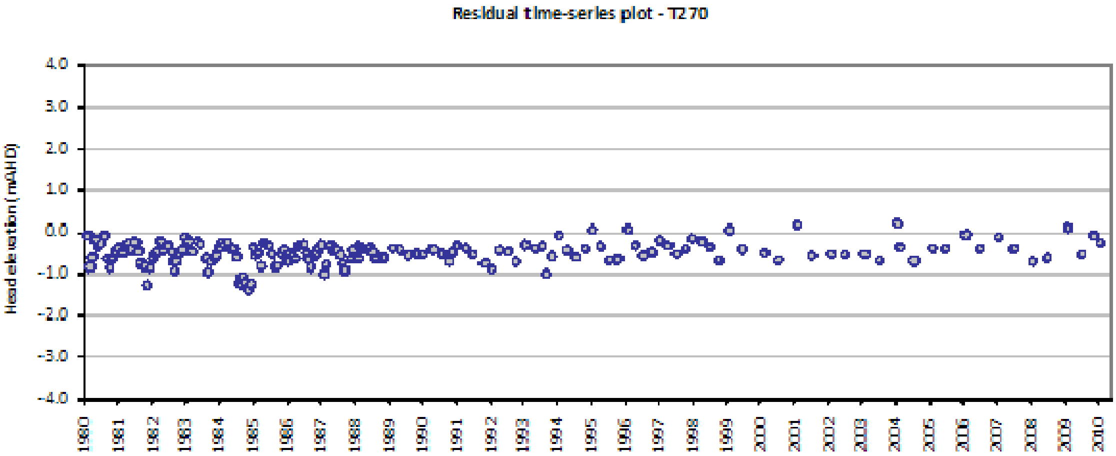



| Statistics | |
|---|---|
| Mean error (ME) | 0.88 |
| Mean absolute error (MAE) | 0.88 |
| Root mean square error (RMSE) | 0.92 |
| Standard deviation of residuals (STDres) | 0.29 |
| Correlation coefficient (R) | 0.87 |
| Nash Sutcliffe correlation coefficient (R2) | -1.54 |

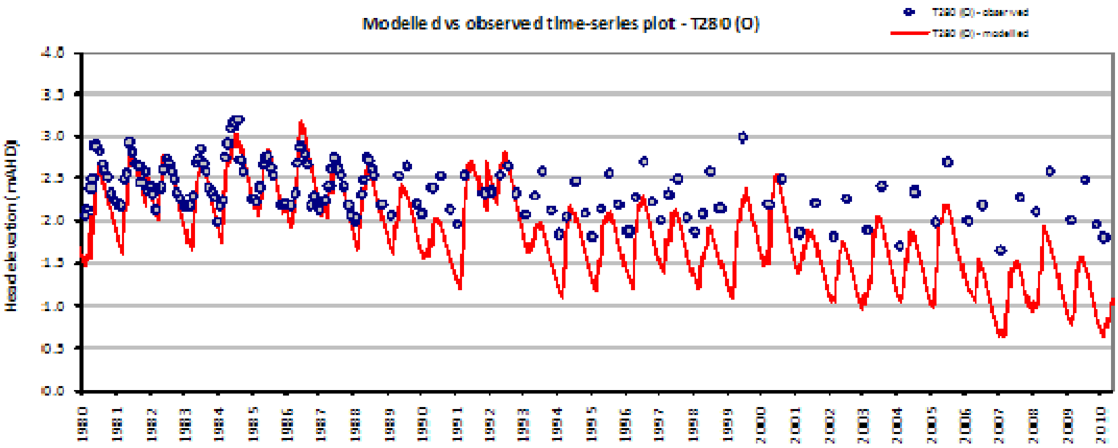
## Superficial Aquifer – T270

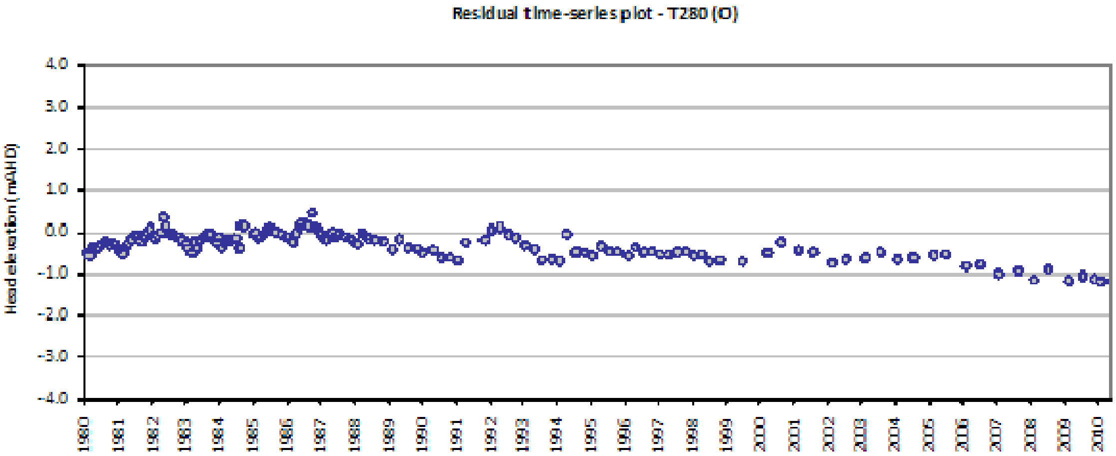



| Statistics | |
|---|---|
| Mean error (ME) | 0.50 |
| Mean absolute error (MAE) | 0.51 |
| Root mean square error (RMSE) | 0.56 |
| Standard deviation of residuals (STDres) | 0.26 |
| Correlation coefficient (R) | 0.89 |
| Nash Sutcliffe correlation coefficient (R2) | -0.14 |

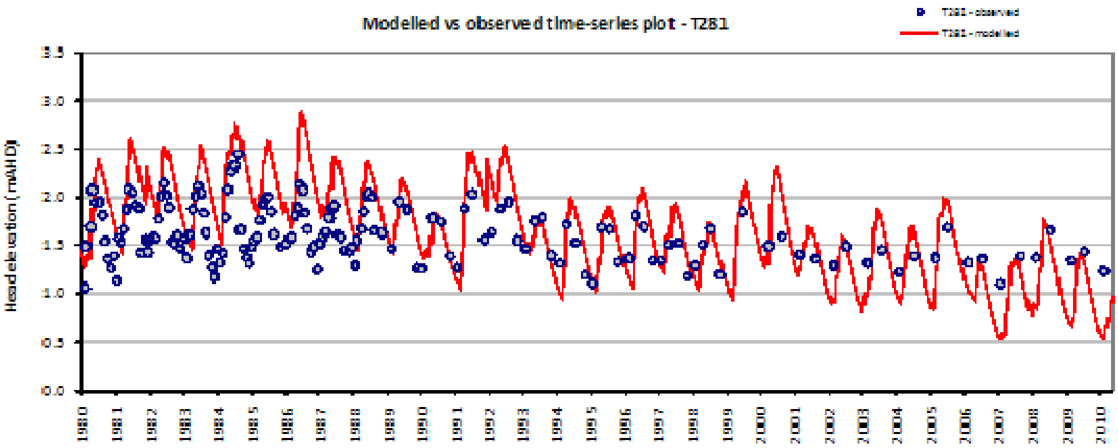
## Superficial Aquifer – T280 (O)

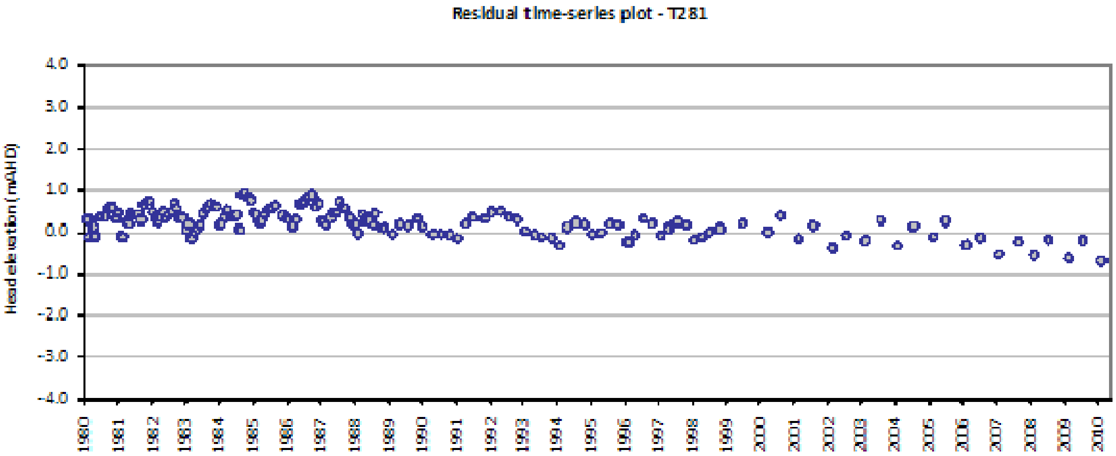



| Statistics | |
|---|---|
| Mean error (ME) | 0.24 |
| Mean absolute error (MAE) | 0.27 |
| Root mean square error (RMSE) | 0.34 |
| Standard deviation of residuals (STDres) | 0.24 |
| Correlation coefficient (R) | 0.87 |
| Nash Sutcliffe correlation coefficient (R2) | -0.40 |

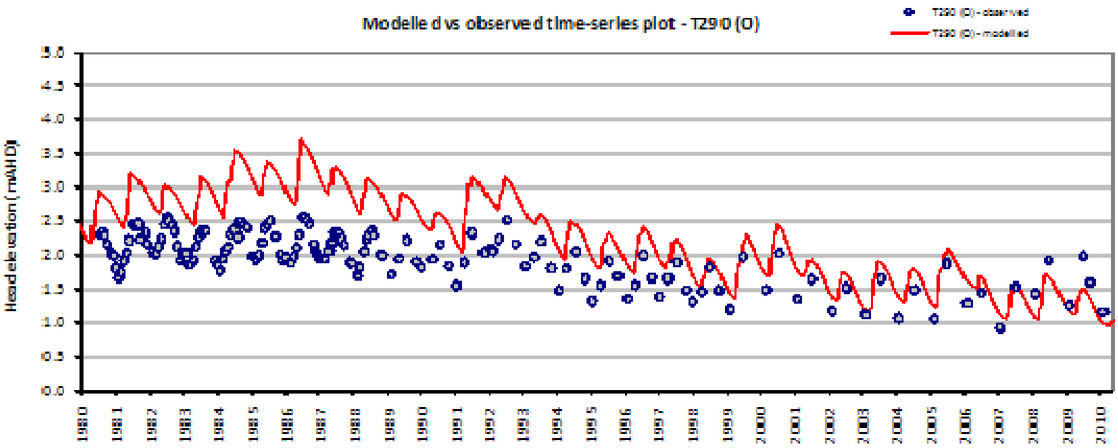
## Rockingham Aquifer – T281

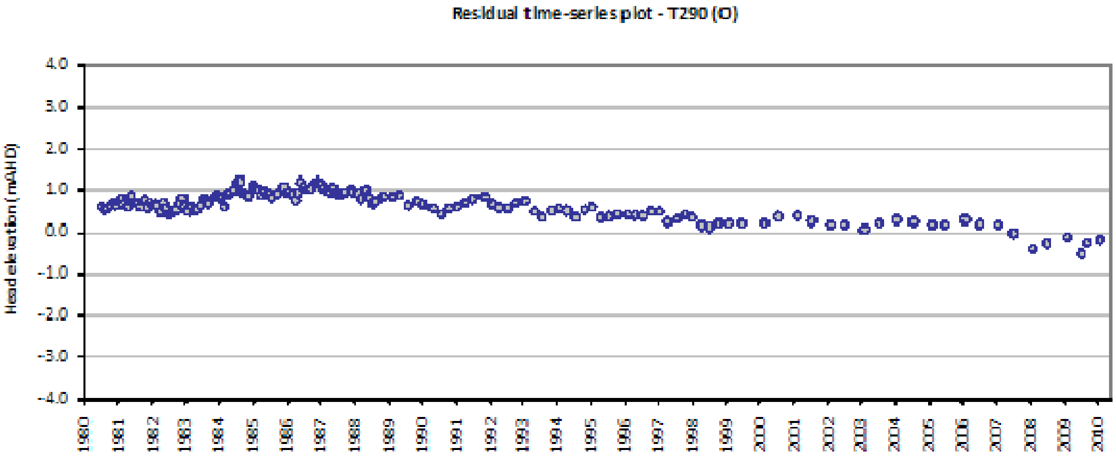



| Statistics | |
|---|---|
| Mean error (ME) | -0.30 |
| Mean absolute error (MAE) | 0.34 |
| Root mean square error (RMSE) | 0.41 |
| Standard deviation of residuals (STDres) | 0.28 |
| Correlation coefficient (R) | 0.76 |
| Nash Sutcliffe correlation coefficient (R2) | -1.09 |

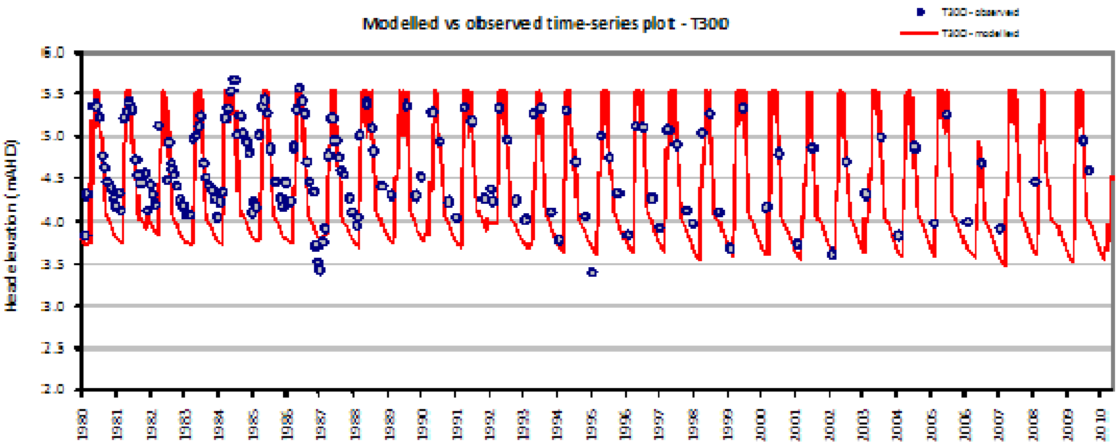
## Superficial Aquifer – T290 (O)

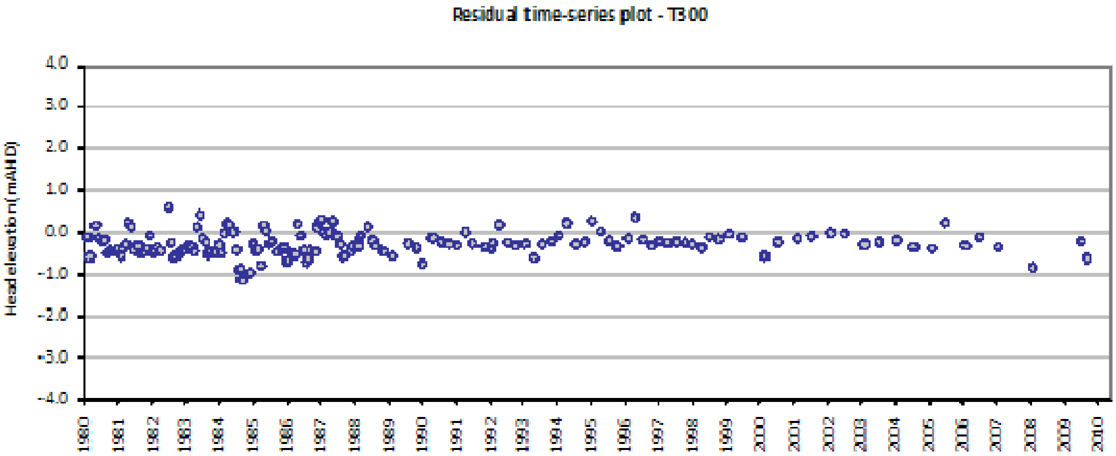



| Statistics | |
|---|---|
| Mean error (ME) | -0.70 |
| Mean absolute error (MAE) | 0.70 |
| Root mean square error (RMSE) | 0.75 |
| Standard deviation of residuals (STDres) | 0.27 |
| Correlation coefficient (R) | 0.89 |
| Nash Sutcliffe correlation coefficient (R2) | -4.01 |

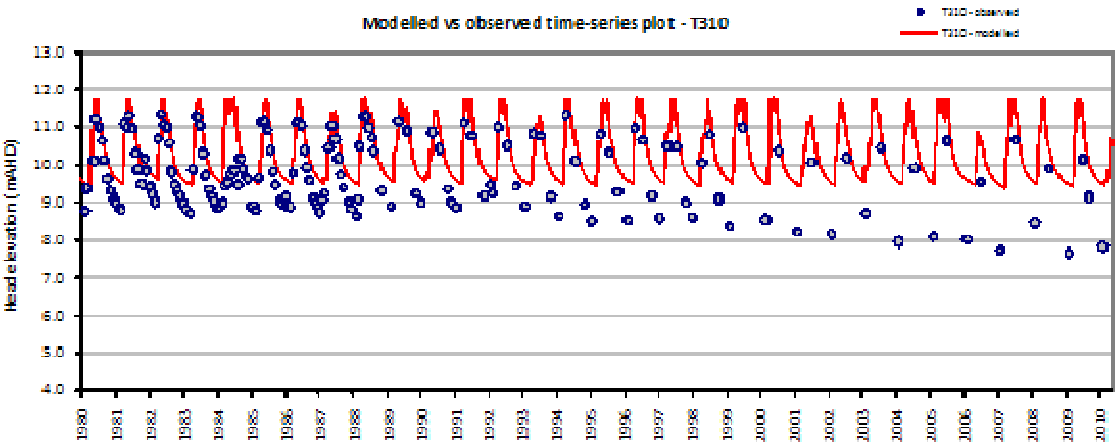
## Superficial Aquifer – T300

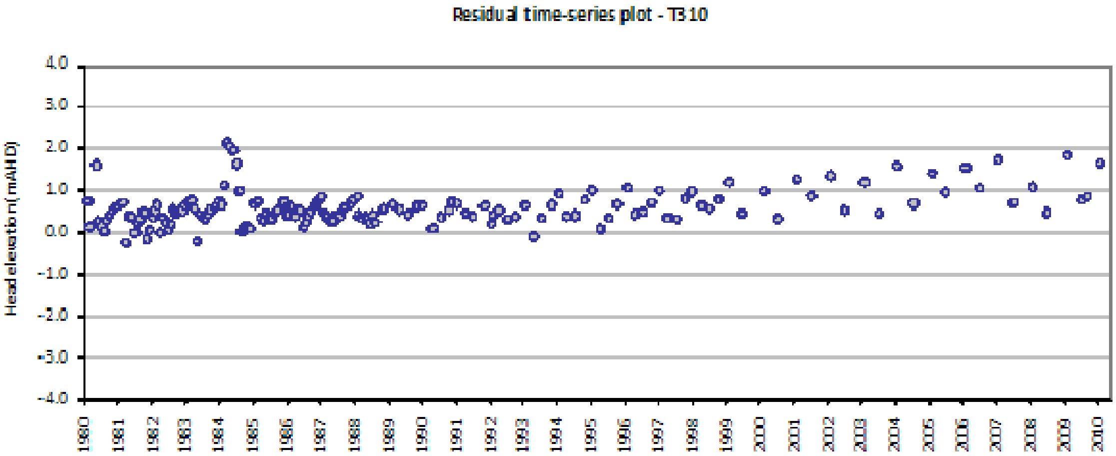



| Statistics | |
|---|---|
| Mean error (ME) | 0.27 |
| Mean absolute error (MAE) | 0.33 |
| Root mean square error (RMSE) | 0.39 |
| Standard deviation of residuals (STDres) | 0.28 |
| Correlation coefficient (R) | 0.89 |
| Nash Sutcliffe correlation coefficient (R2) | 0.46 |

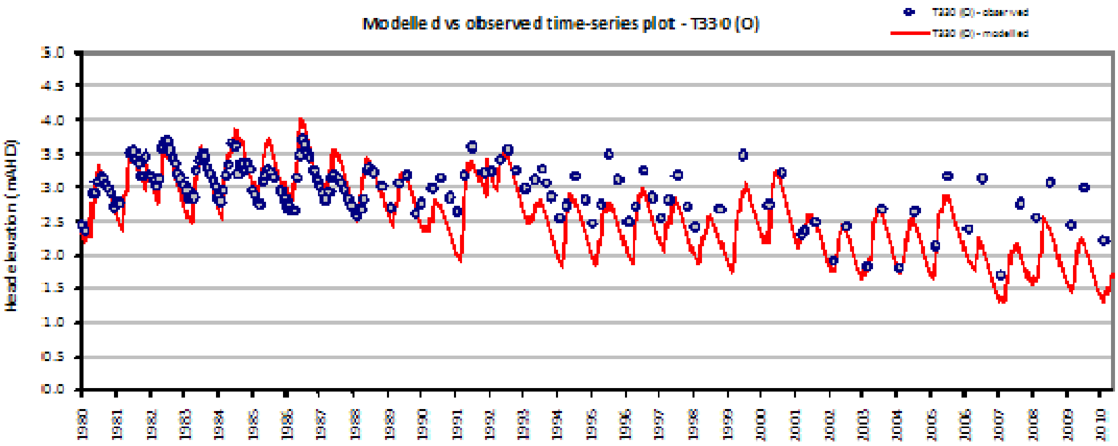
## Superficial Aquifer – T310

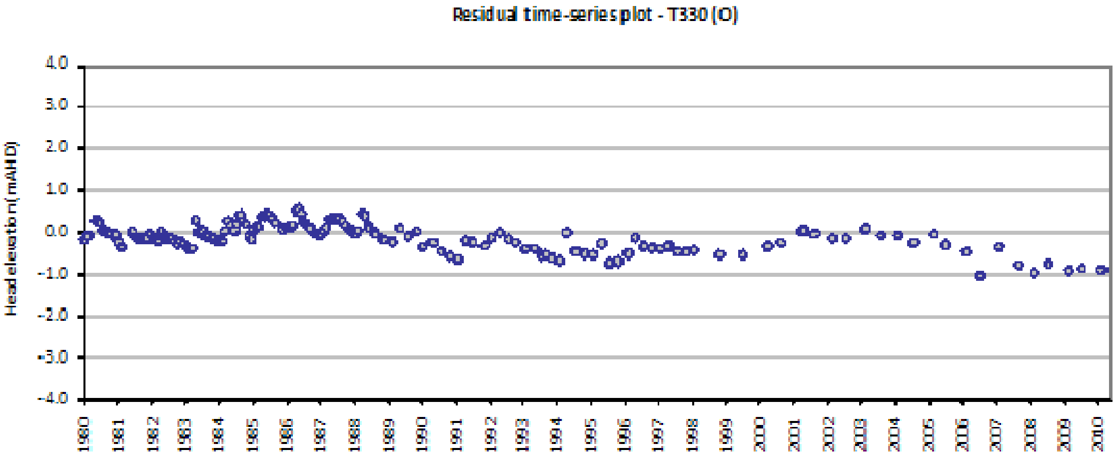



| Statistics | |
|---|---|
| Mean error (ME) | -0.56 |
| Mean absolute error (MAE) | 0.56 |
| Root mean square error (RMSE) | 0.67 |
| Standard deviation of residuals (STDres) | 0.37 |
| Correlation coefficient (R) | 0.91 |
| Nash Sutcliffe correlation coefficient (R2) | 0.42 |

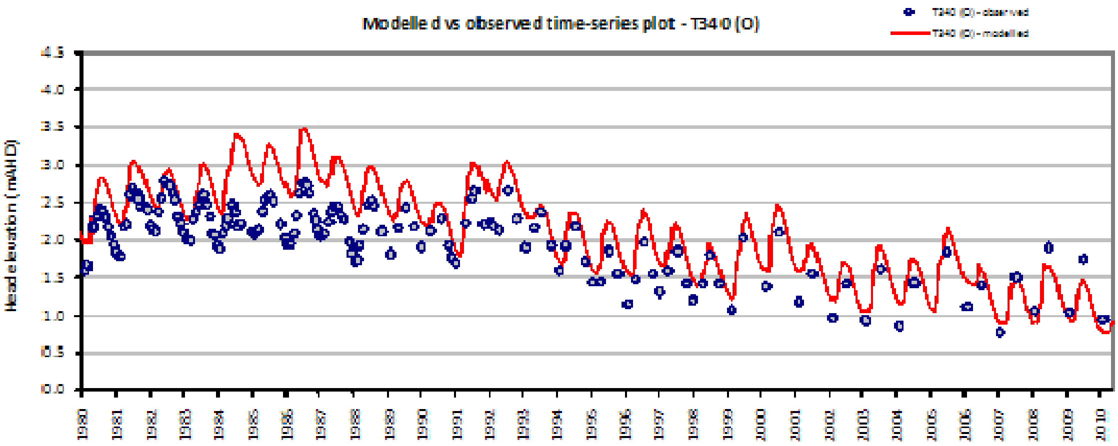
## Superficial Aquifer – T330 (O)

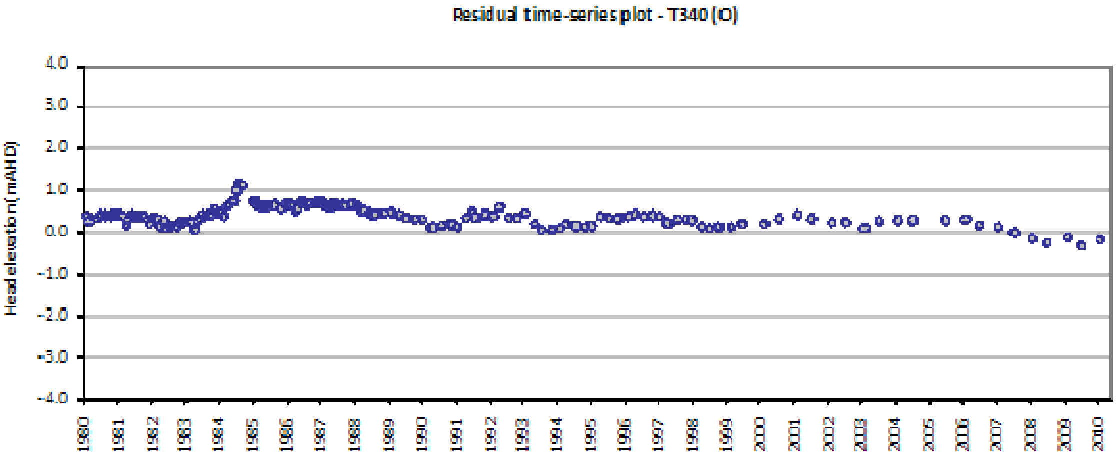



| Statistics | |
|---|---|
| Mean error (ME) | 0.08 |
| Mean absolute error (MAE) | 0.23 |
| Root mean square error (RMSE) | 0.28 |
| Standard deviation of residuals (STDres) | 0.27 |
| Correlation coefficient (R) | 0.82 |
| Nash Sutcliffe correlation coefficient (R2) | 0.38 |

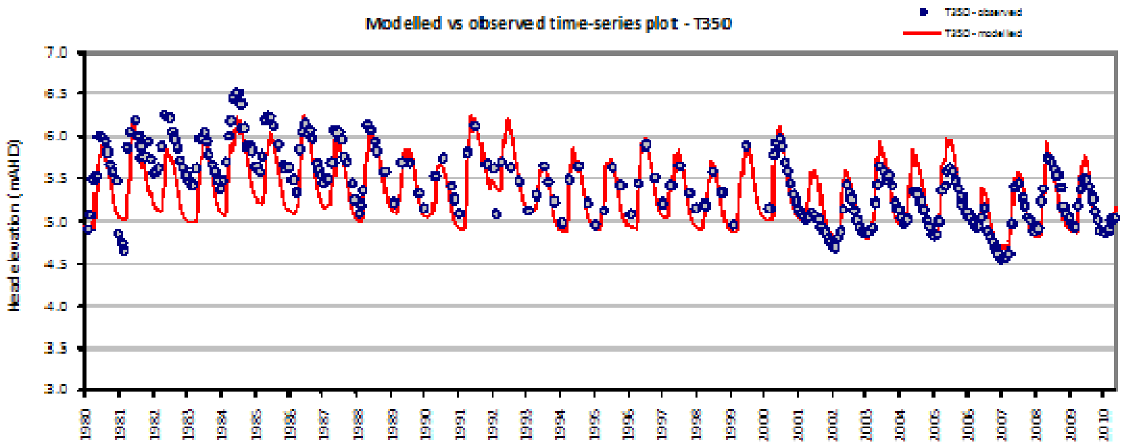
## Superficial Aquifer – T340 (O)

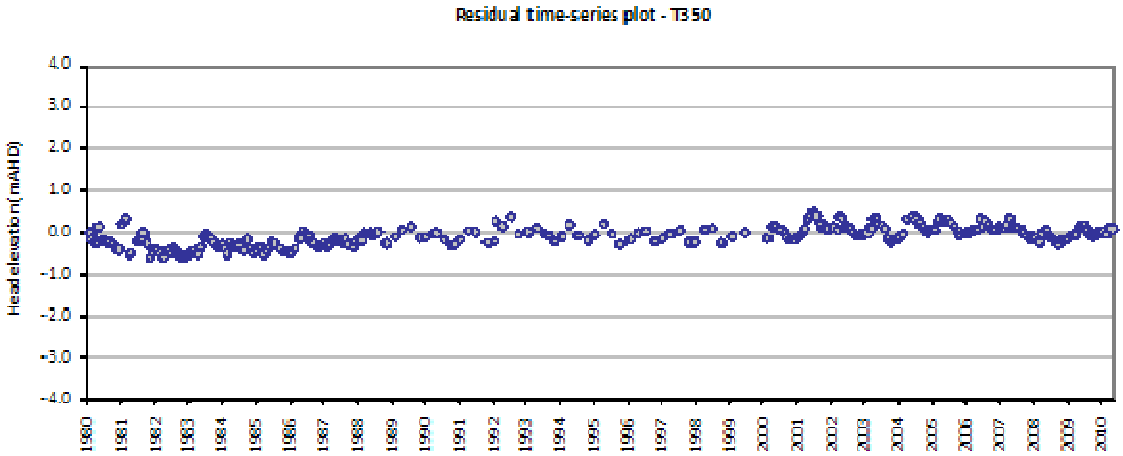



| Statistics | |
|---|---|
| Mean error (ME) | -0.42 |
| Mean absolute error (MAE) | 0.42 |
| Root mean square error (RMSE) | 0.47 |
| Standard deviation of residuals (STDres) | 0.20 |
| Correlation coefficient (R) | 0.92 |
| Nash Sutcliffe correlation coefficient (R2) | -0.26 |

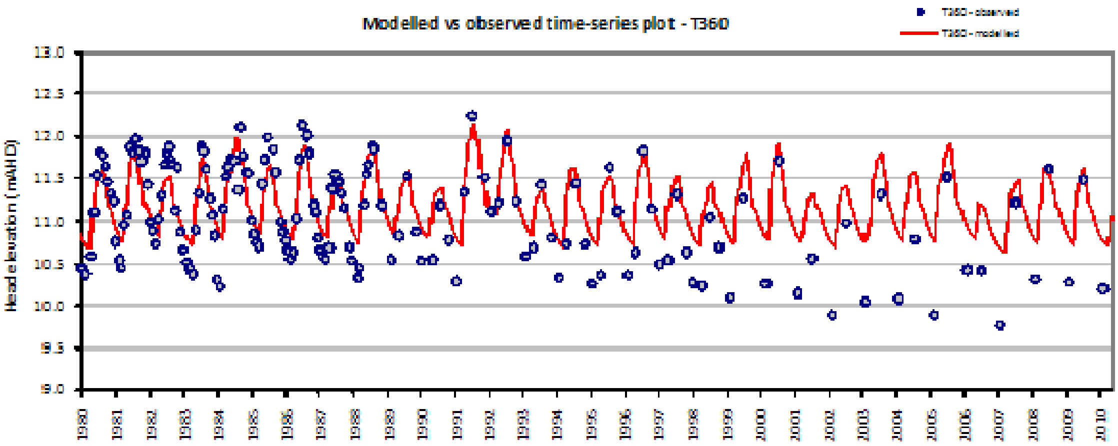
## Superficial Aquifer – T350

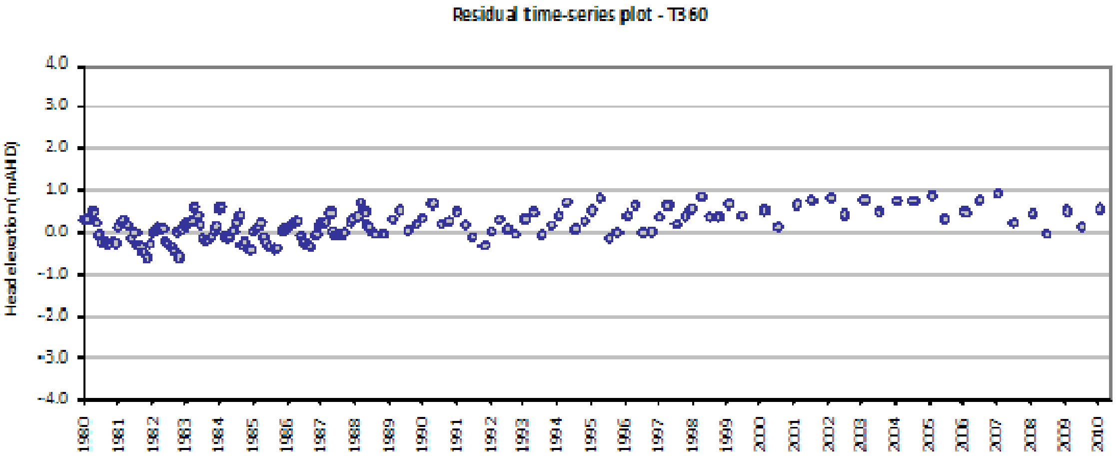



| Statistics | |
|---|---|
| Mean error (ME) | 0.13 |
| Mean absolute error (MAE) | 0.23 |
| Root mean square error (RMSE) | 0.27 |
| Standard deviation of residuals (STDres) | 0.24 |
| Correlation coefficient (R) | 0.81 |
| Nash Sutcliffe correlation coefficient (R2) | 0.55 |

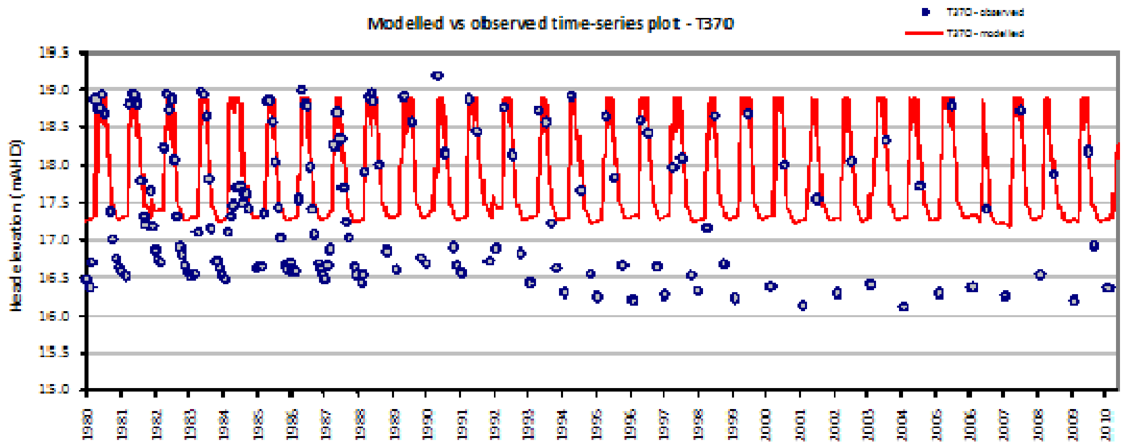
## Superficial Aquifer – T360

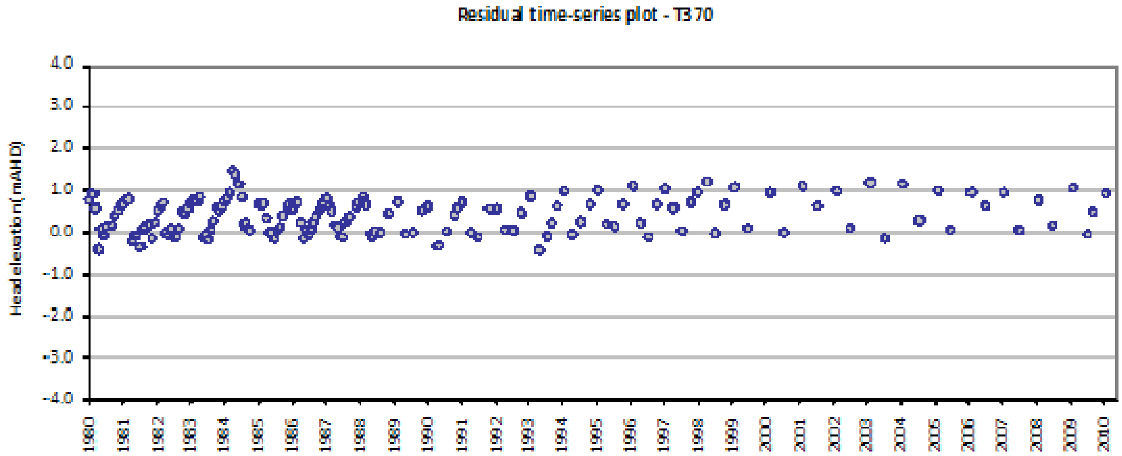



| Statistics | |
|---|---|
| Mean error (ME) | -0.13 |
| Mean absolute error (MAE) | 0.29 |
| Root mean square error (RMSE) | 0.35 |
| Standard deviation of residuals (STDres) | 0.33 |
| Correlation coefficient (R) | 0.84 |
| Nash Sutcliffe correlation coefficient (R2) | 0.60 |

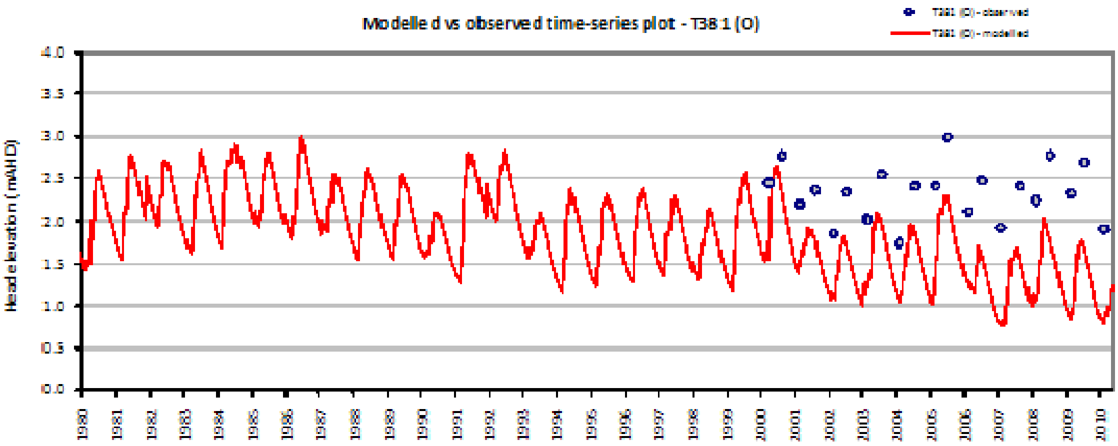
## Superficial Aquifer – T370

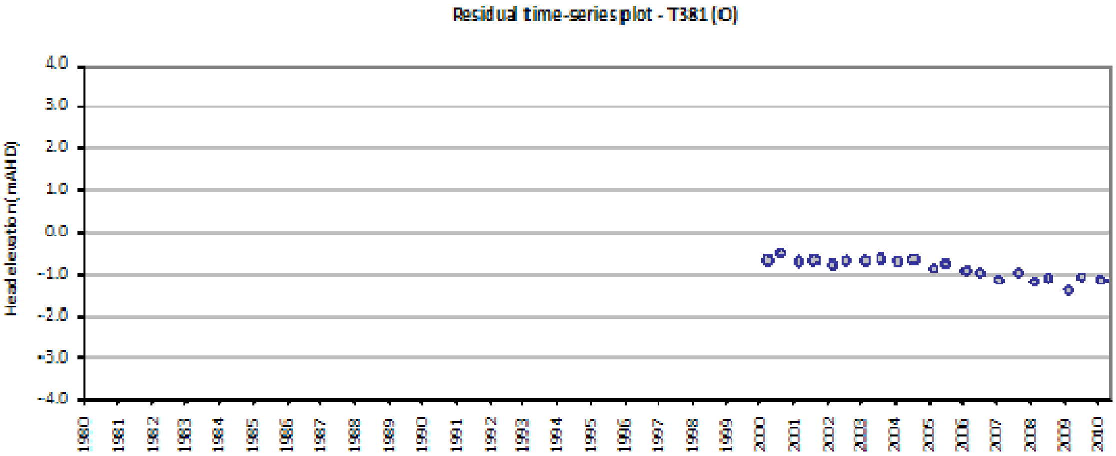



| Statistics | |
|---|---|
| Mean error (ME) | -0.40 |
| Mean absolute error (MAE) | 0.45 |
| Root mean square error (RMSE) | 0.57 |
| Standard deviation of residuals (STDres) | 0.40 |
| Correlation coefficient (R) | 0.94 |
| Nash Sutcliffe correlation coefficient (R2) | 0.61 |

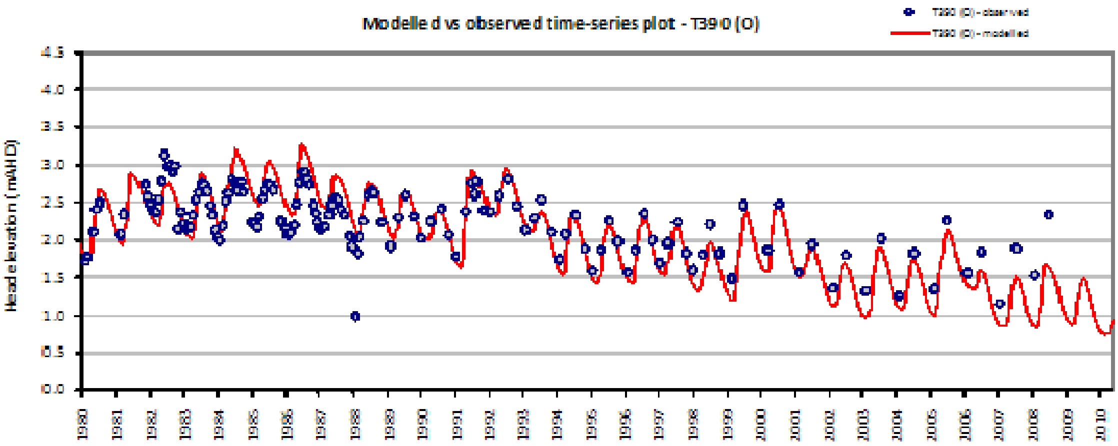
## Superficial Aquifer – T381 (O)

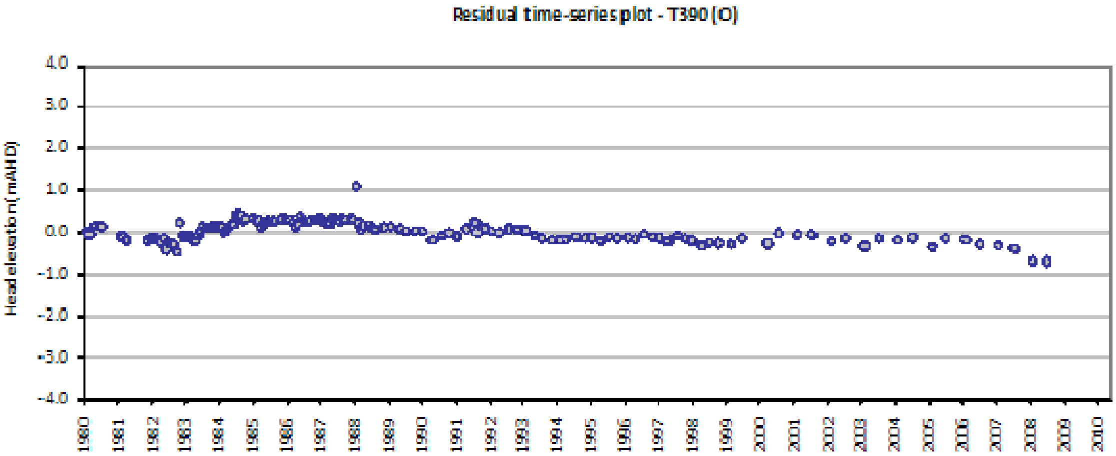



| Statistics | |
|---|---|
| Mean error (ME) | 0.66 |
| Mean absolute error (MAE) | 0.66 |
| Root mean square error (RMSE) | 0.66 |
| Standard deviation of residuals (STDres) | 0.07 |
| Correlation coefficient (R) | 0.99 |
| Nash Sutcliffe correlation coefficient (R2) | -3.68 |

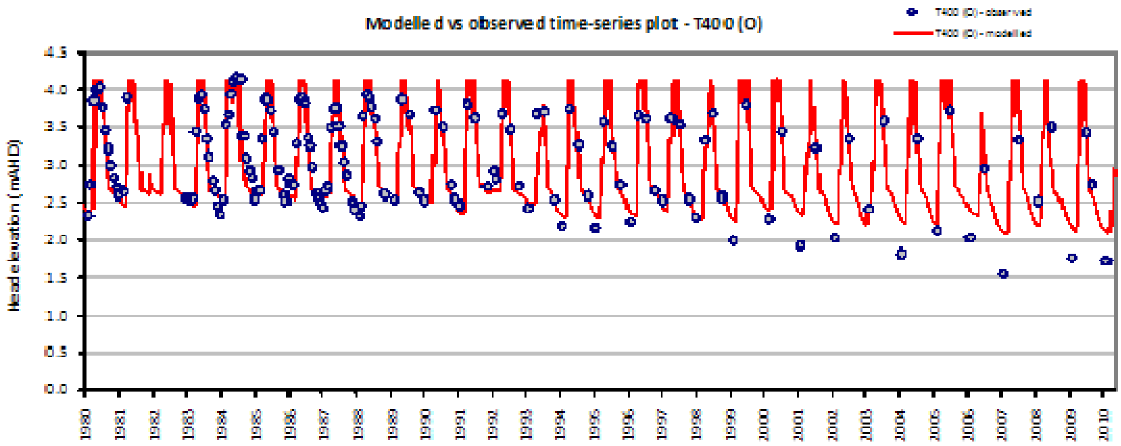
## Superficial Aquifer – T390 (O)

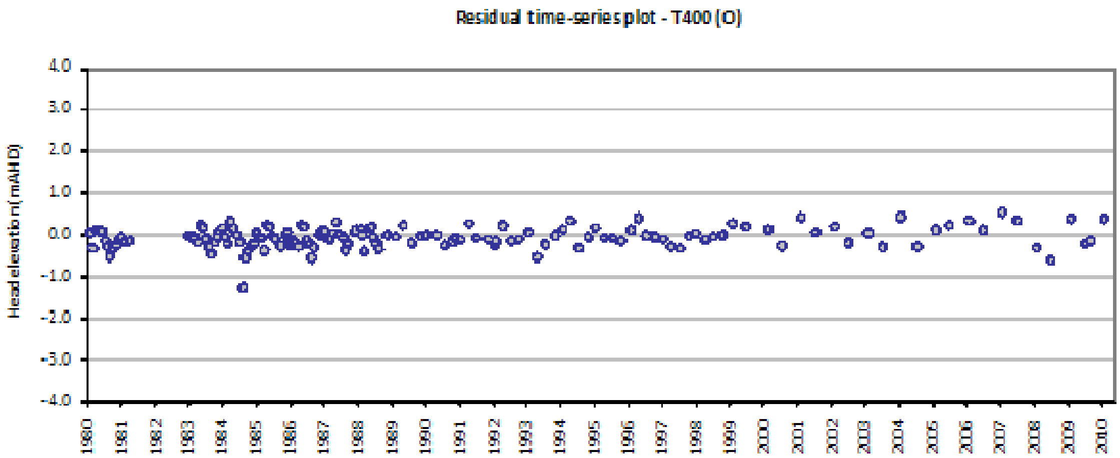



| Statistics | |
|---|---|
| Mean error (ME) | -0.05 |
| Mean absolute error (MAE) | 0.19 |
| Root mean square error (RMSE) | 0.23 |
| Standard deviation of residuals (STDres) | 0.22 |
| Correlation coefficient (R) | 0.89 |
| Nash Sutcliffe correlation coefficient (R2) | 0.67 |

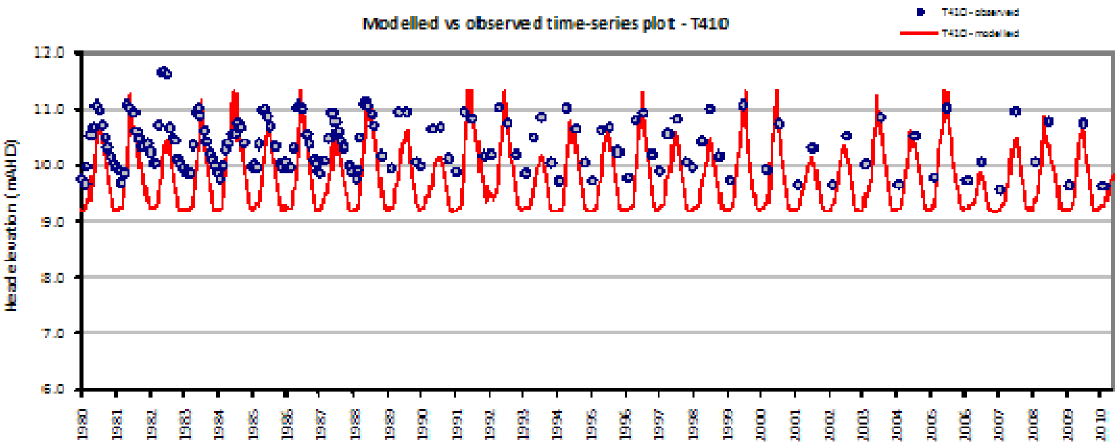
## Superficial Aquifer – T400 (O)

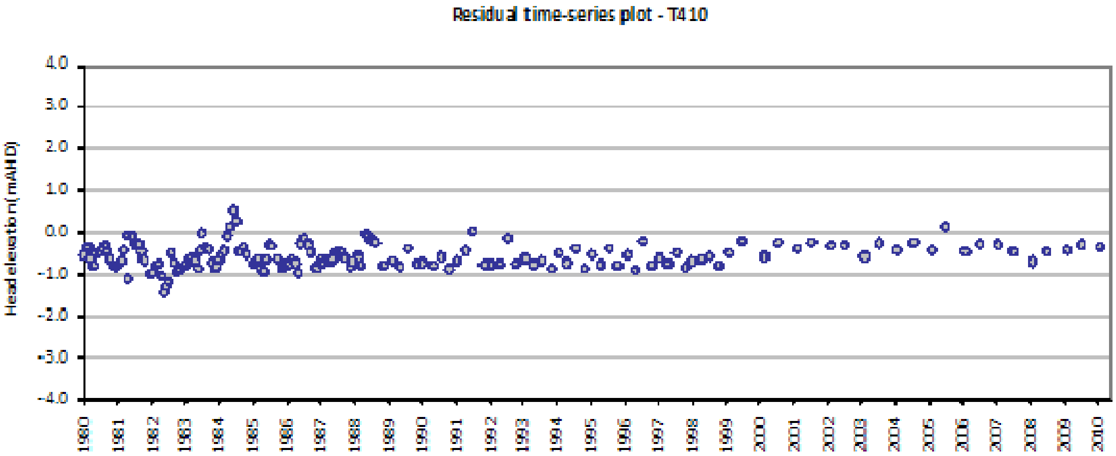



| Statistics | |
|---|---|
| Mean error (ME) | 0.07 |
| Mean absolute error (MAE) | 0.18 |
| Root mean square error (RMSE) | 0.24 |
| Standard deviation of residuals (STDres) | 0.23 |
| Correlation coefficient (R) | 0.93 |
| Nash Sutcliffe correlation coefficient (R2) | 0.84 |

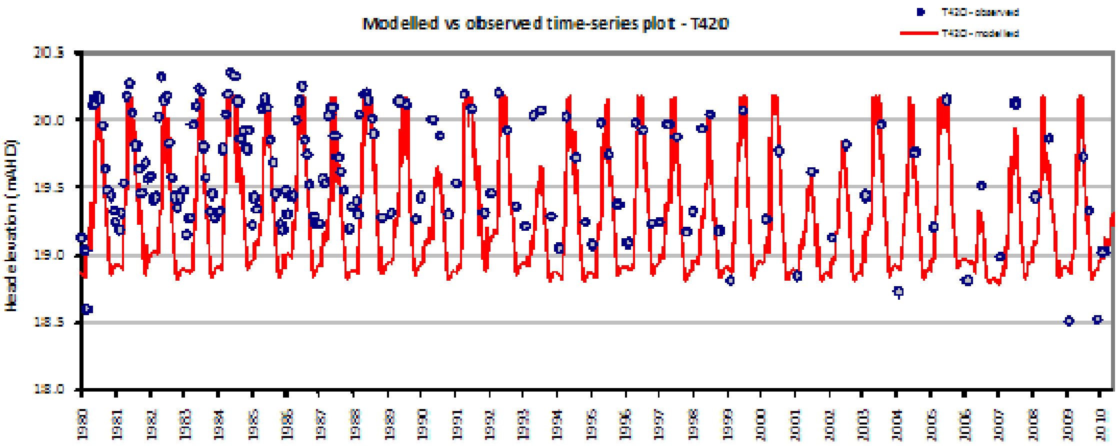
## Superficial Aquifer – T410

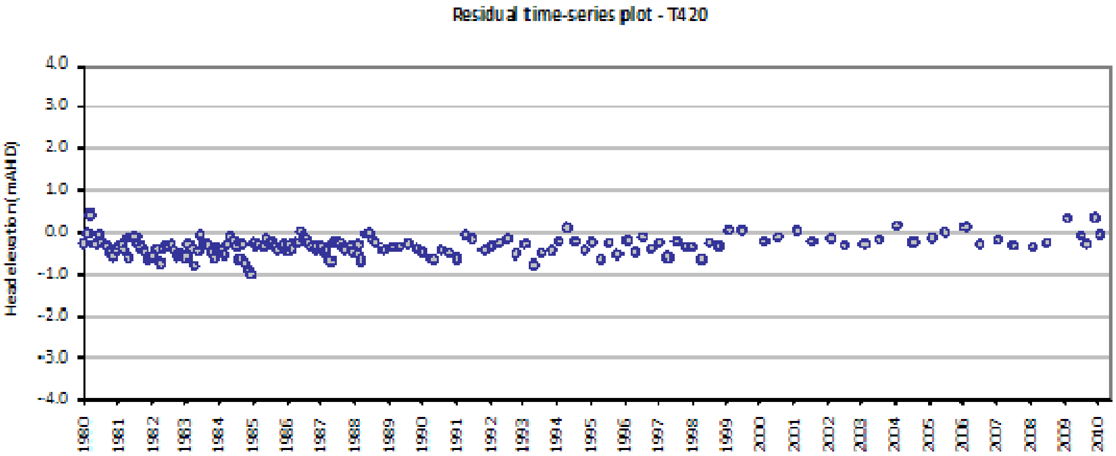



| Statistics | |
|---|---|
| Mean error (ME) | 0.58 |
| Mean absolute error (MAE) | 0.59 |
| Root mean square error (RMSE) | 0.64 |
| Standard deviation of residuals (STDres) | 0.28 |
| Correlation coefficient (R) | 0.86 |
| Nash Sutcliffe correlation coefficient (R2) | -1.02 |

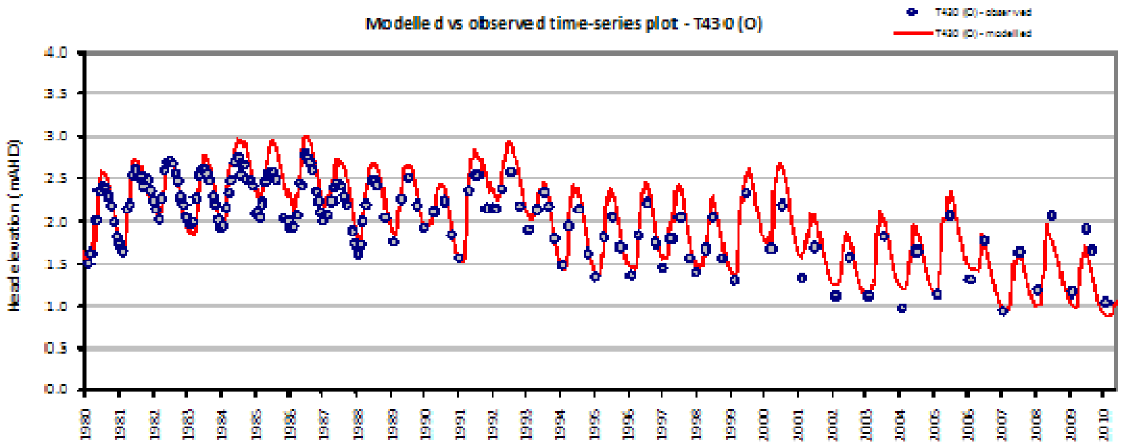
## Superficial Aquifer – T420

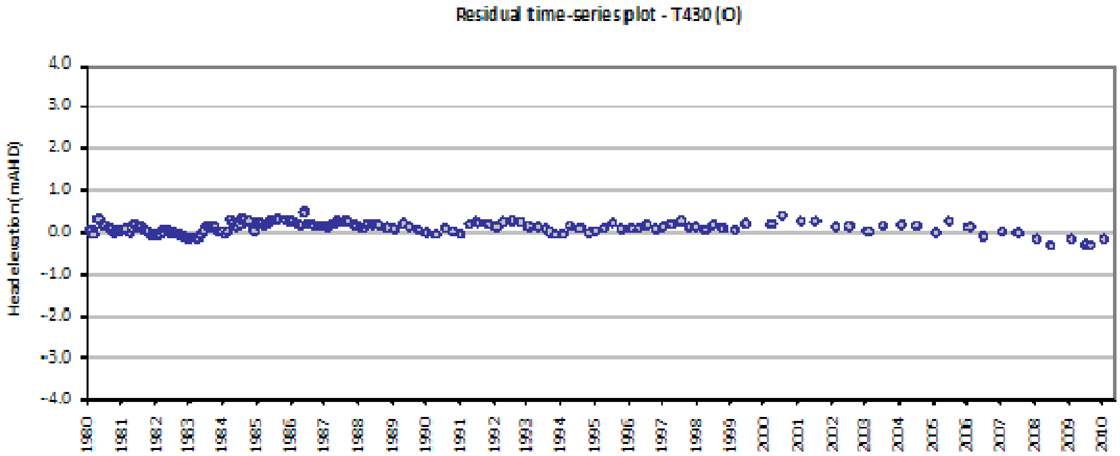



| Statistics | |
|---|---|
| Mean error (ME) | 0.34 |
| Mean absolute error (MAE) | 0.35 |
| Root mean square error (RMSE) | 0.39 |
| Standard deviation of residuals (STDres) | 0.21 |
| Correlation coefficient (R) | 0.88 |
| Nash Sutcliffe correlation coefficient (R2) | -0.02 |

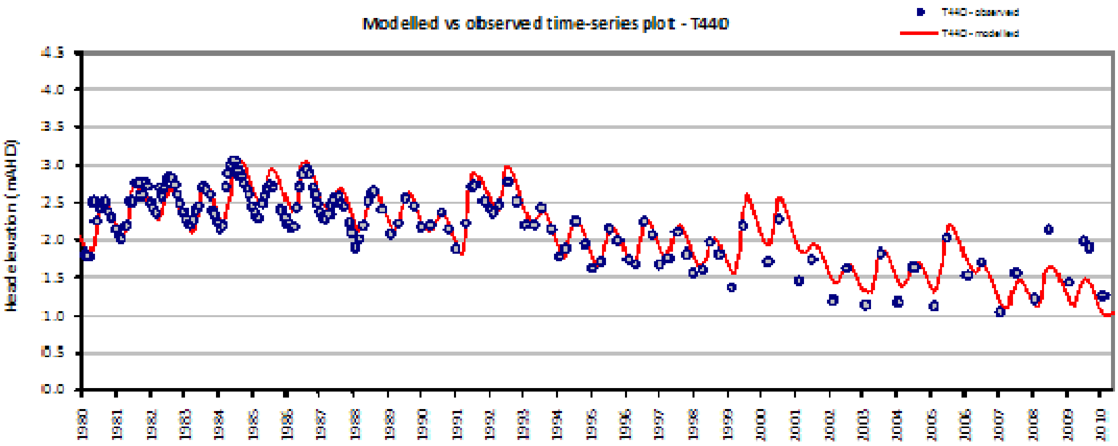
## Superficial Aquifer – T430 (O)

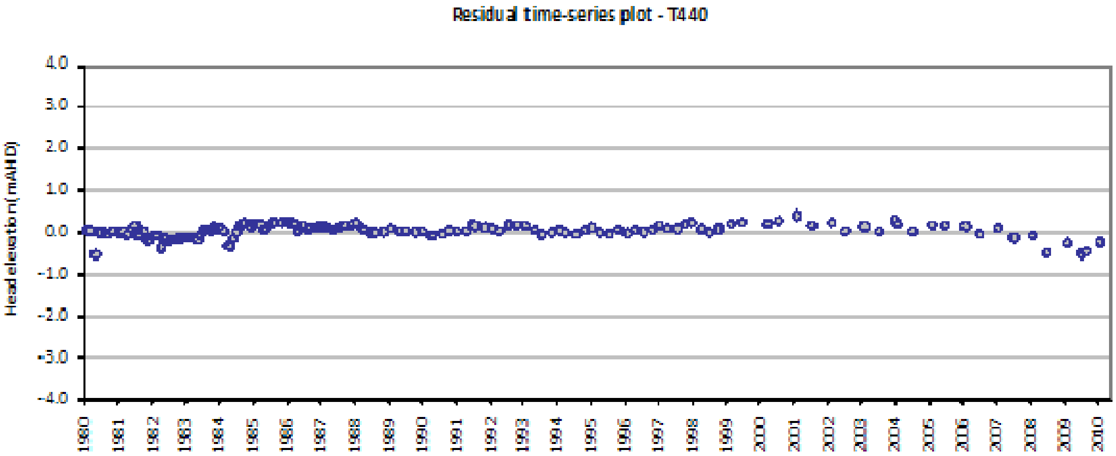



| Statistics | |
|---|---|
| Mean error (ME) | -0.14 |
| Mean absolute error (MAE) | 0.15 |
| Root mean square error (RMSE) | 0.18 |
| Standard deviation of residuals (STDres) | 0.12 |
| Correlation coefficient (R) | 0.96 |
| Nash Sutcliffe correlation coefficient (R2) | 0.78 |

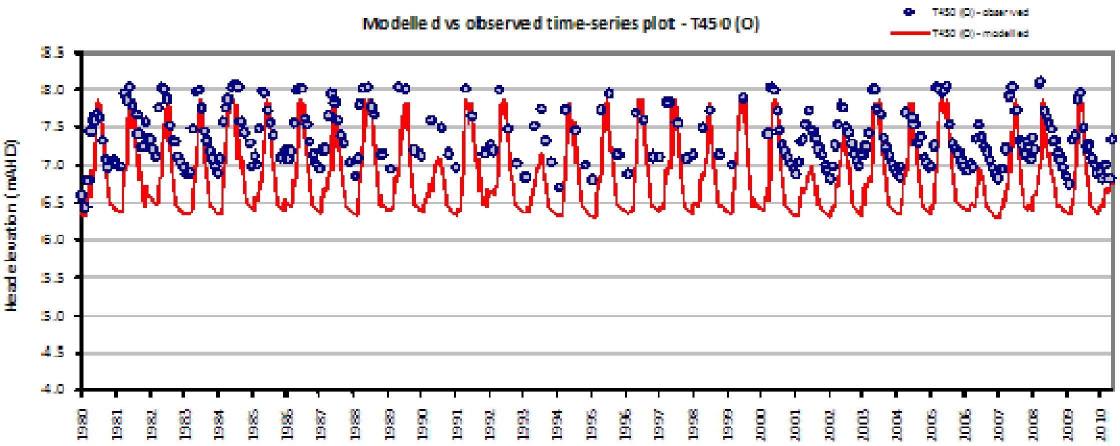
## Superficial Aquifer – T440 (O)

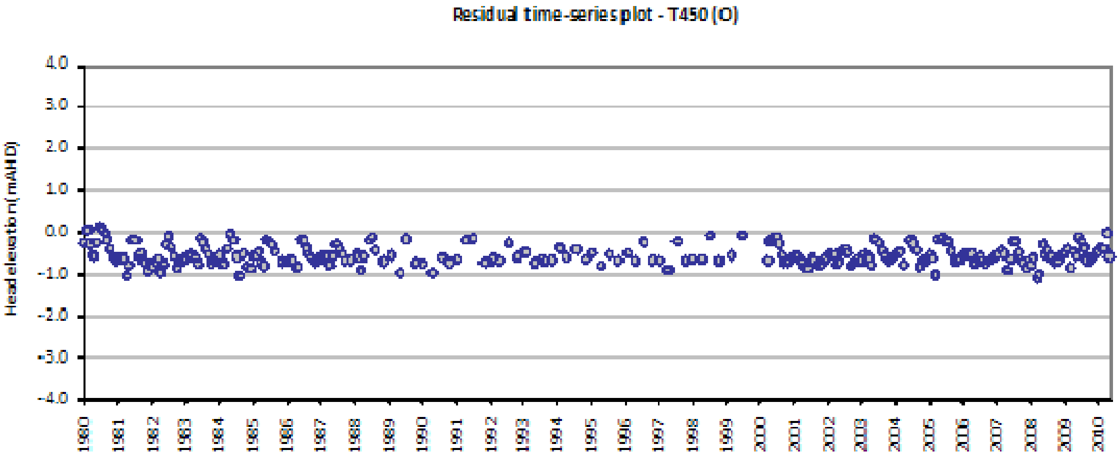



| Statistics | |
|---|---|
| Mean error (ME) | -0.06 |
| Mean absolute error (MAE) | 0.12 |
| Root mean square error (RMSE) | 0.15 |
| Standard deviation of residuals (STDres) | 0.14 |
| Correlation coefficient (R) | 0.93 |
| Nash Sutcliffe correlation coefficient (R2) | 0.85 |

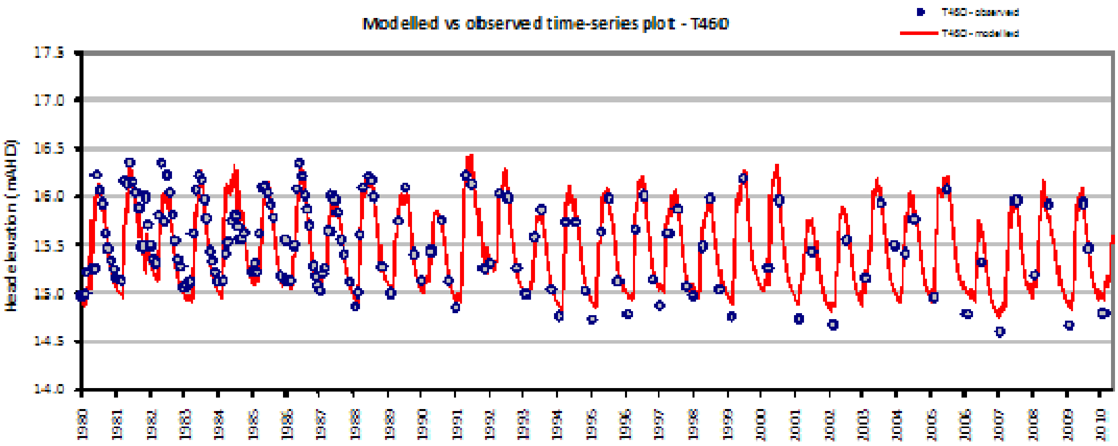
## Superficial Aquifer – T450 (O)

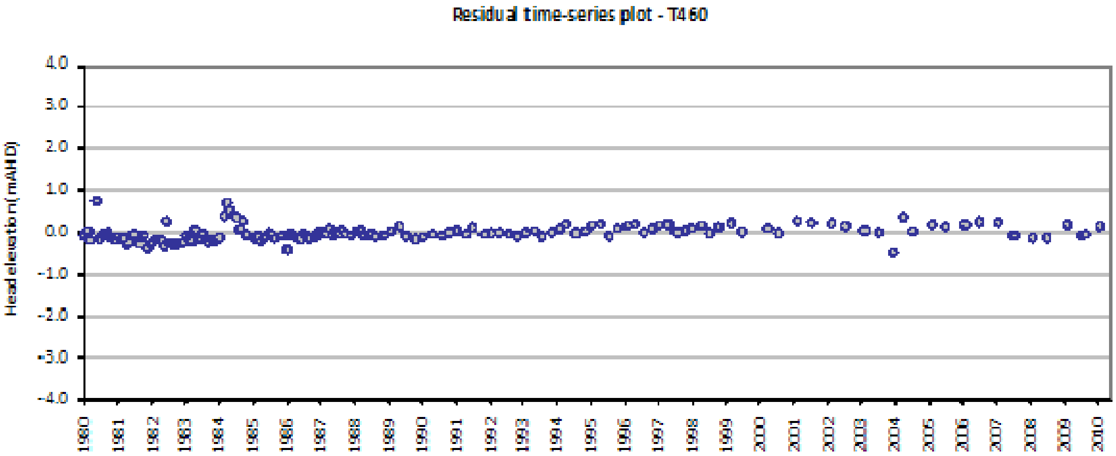



| Statistics | |
|---|---|
| Mean error (ME) | 0.54 |
| Mean absolute error (MAE) | 0.54 |
| Root mean square error (RMSE) | 0.59 |
| Standard deviation of residuals (STDres) | 0.23 |
| Correlation coefficient (R) | 0.88 |
| Nash Sutcliffe correlation coefficient (R2) | -1.44 |

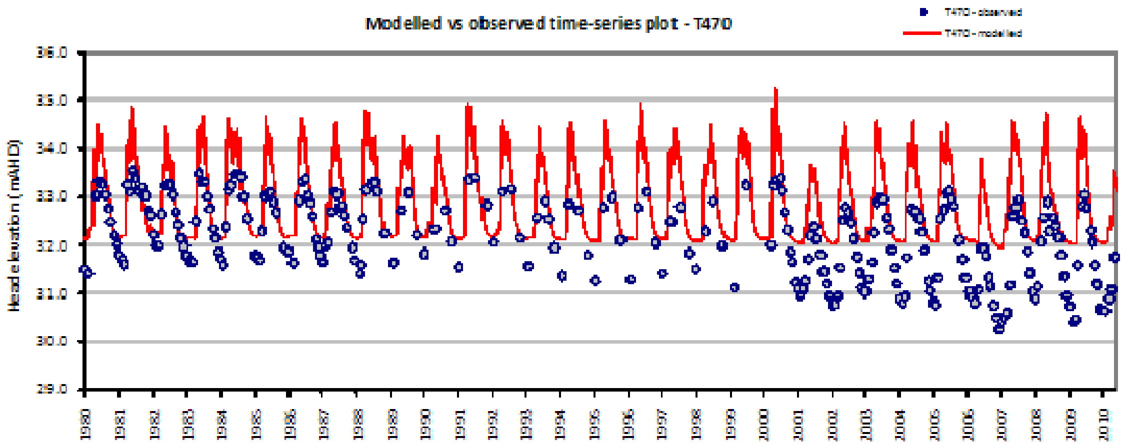
## Superficial Aquifer – T460

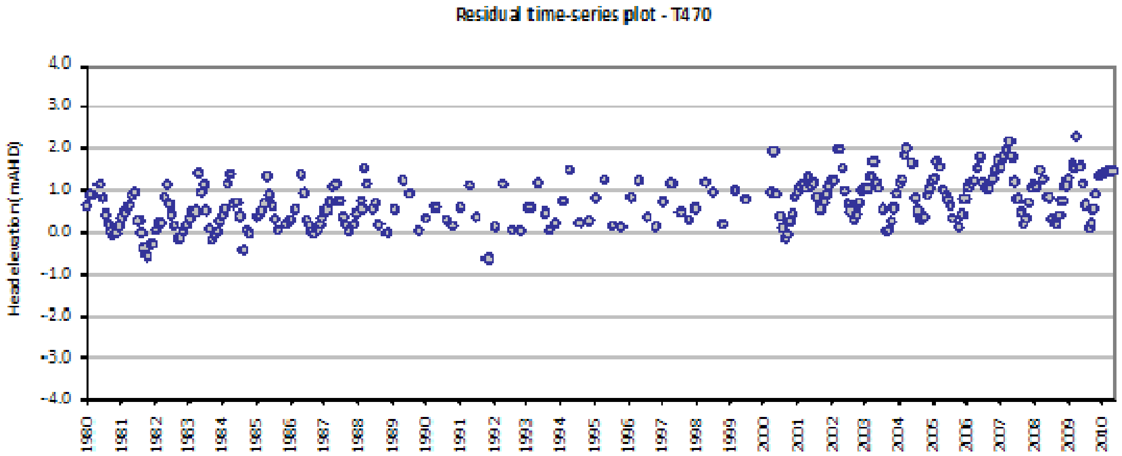



| Statistics | |
|---|---|
| Mean error (ME) | 0.03 |
| Mean absolute error (MAE) | 0.14 |
| Root mean square error (RMSE) | 0.19 |
| Standard deviation of residuals (STDres) | 0.18 |
| Correlation coefficient (R) | 0.91 |
| Nash Sutcliffe correlation coefficient (R2) | 0.81 |

## Superficial Aquifer – T470

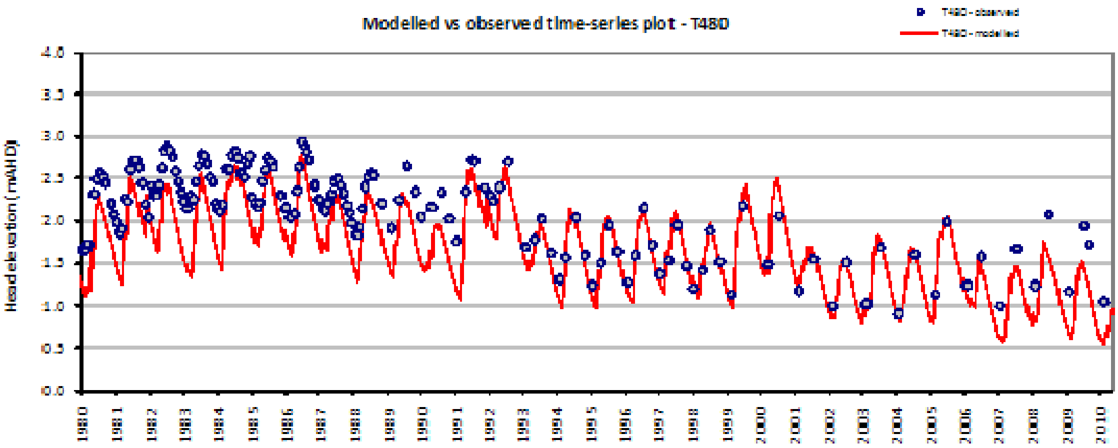


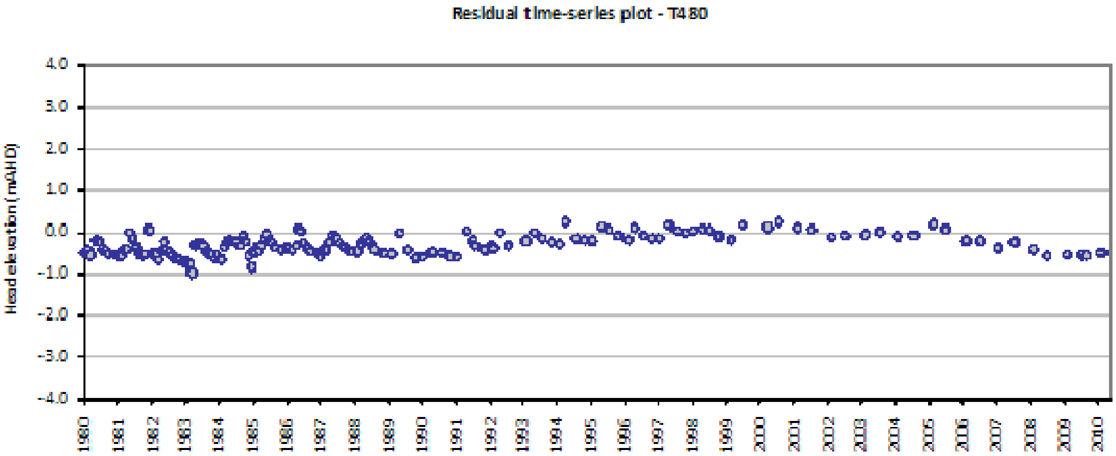




| Statistics | |
|---|---|
| Mean error (ME) | -0.61 |
| Mean absolute error (MAE) | 0.64 |
| Root mean square error (RMSE) | 0.79 |
| Standard deviation of residuals (STDres) | 0.51 |
| Correlation coefficient (R) | 0.78 |
| Nash Sutcliffe correlation coefficient (R2) | -0.22 |

Note: error may be related to the limitations of the 2-layer unsaturated zone model close to the Darling Scarp.

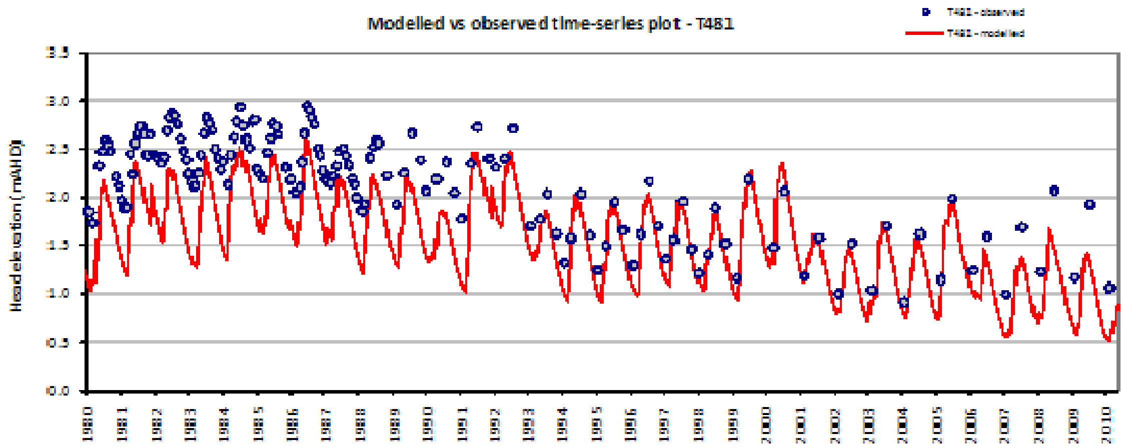
## Superficial Aquifer – T480

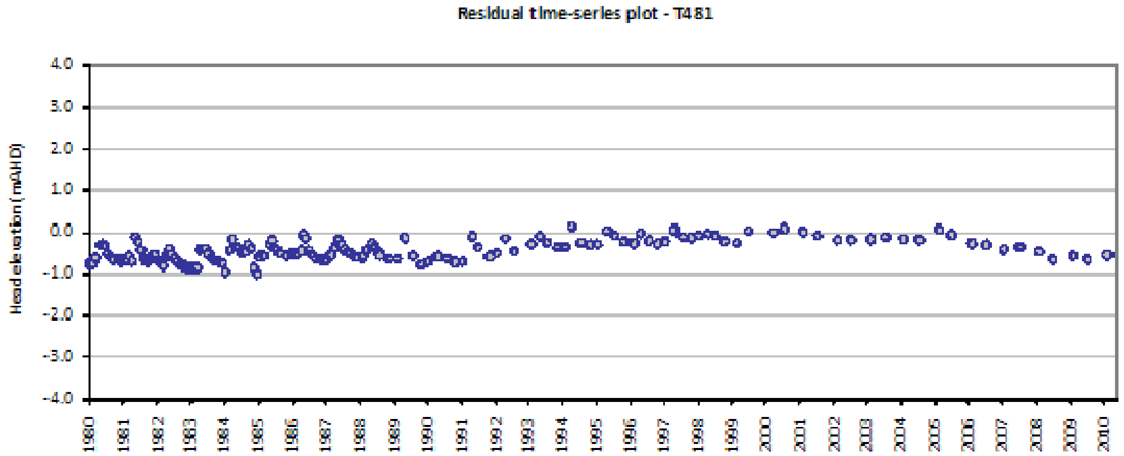



| Statistics | |
|---|---|
| Mean error (ME) | 0.31 |
| Mean absolute error (MAE) | 0.33 |
| Root mean square error (RMSE) | 0.39 |
| Standard deviation of residuals (STDres) | 0.24 |
| Correlation coefficient (R) | 0.85 |
| Nash Sutcliffe correlation coefficient (R2) | 0.26 |

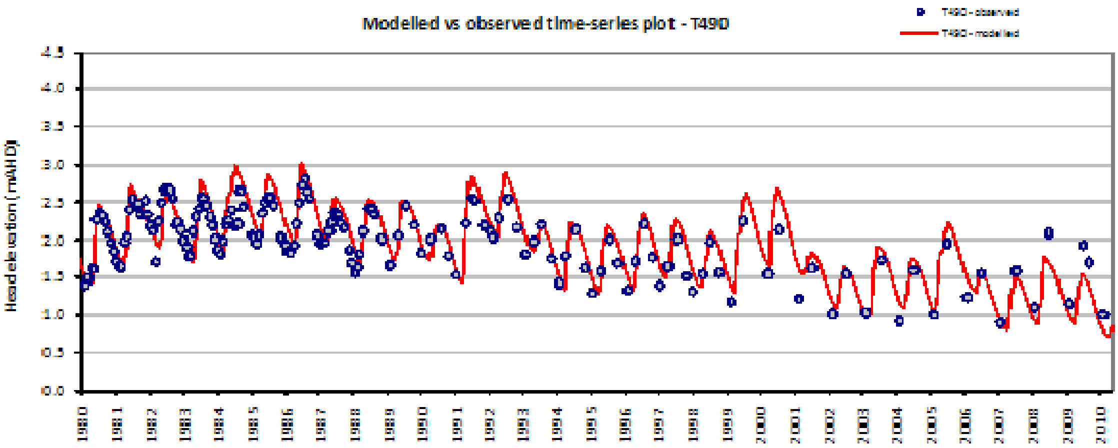
## Rockingham Aquifer – T481

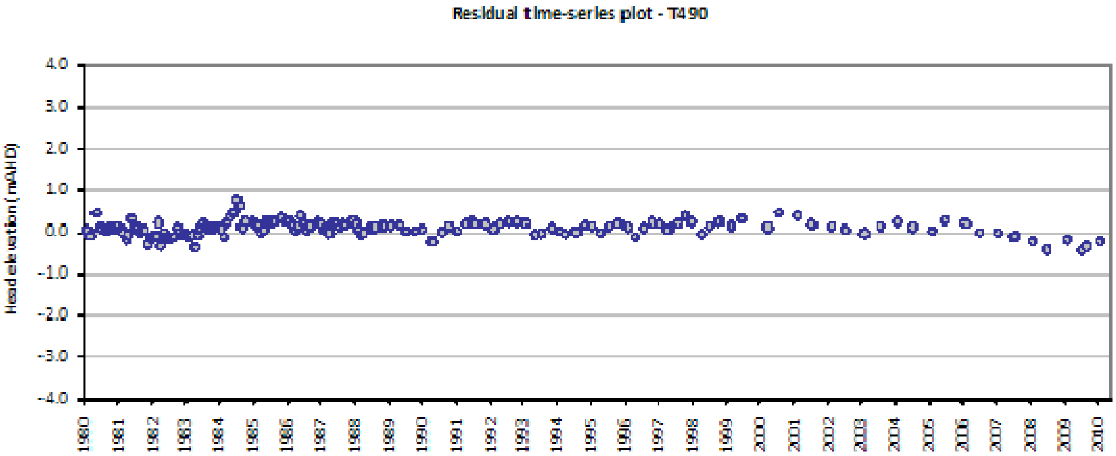



| Statistics | |
|---|---|
| Mean error (ME) | 0.44 |
| Mean absolute error (MAE) | 0.45 |
| Root mean square error (RMSE) | 0.51 |
| Standard deviation of residuals (STDres) | 0.25 |
| Correlation coefficient (R) | 0.84 |
| Nash Sutcliffe correlation coefficient (R2) | -0.23 |

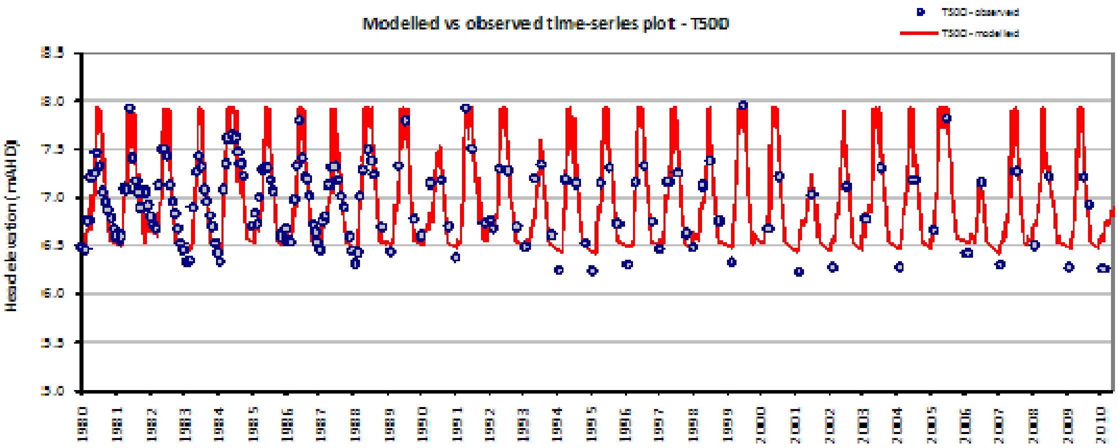
## Superficial Aquifer – T490

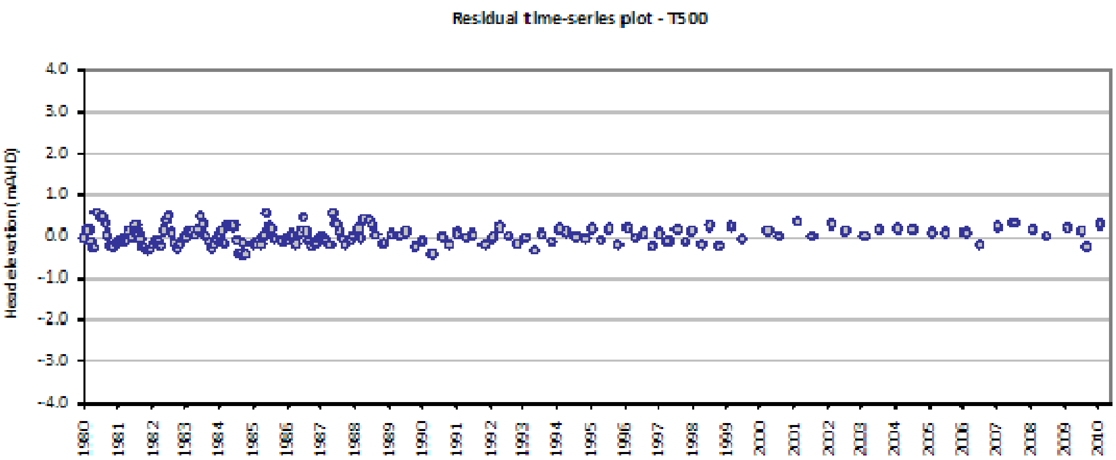



| Statistics | |
|---|---|
| Mean error (ME) | -0.12 |
| Mean absolute error (MAE) | 0.16 |
| Root mean square error (RMSE) | 0.20 |
| Standard deviation of residuals (STDres) | 0.16 |
| Correlation coefficient (R) | 0.93 |
| Nash Sutcliffe correlation coefficient (R2) | 0.74 |

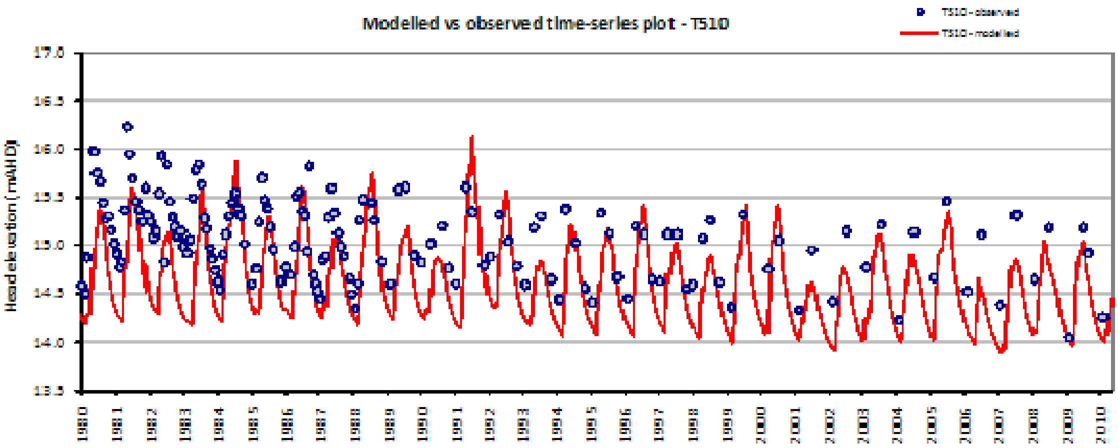
## Superficial Aquifer – T500

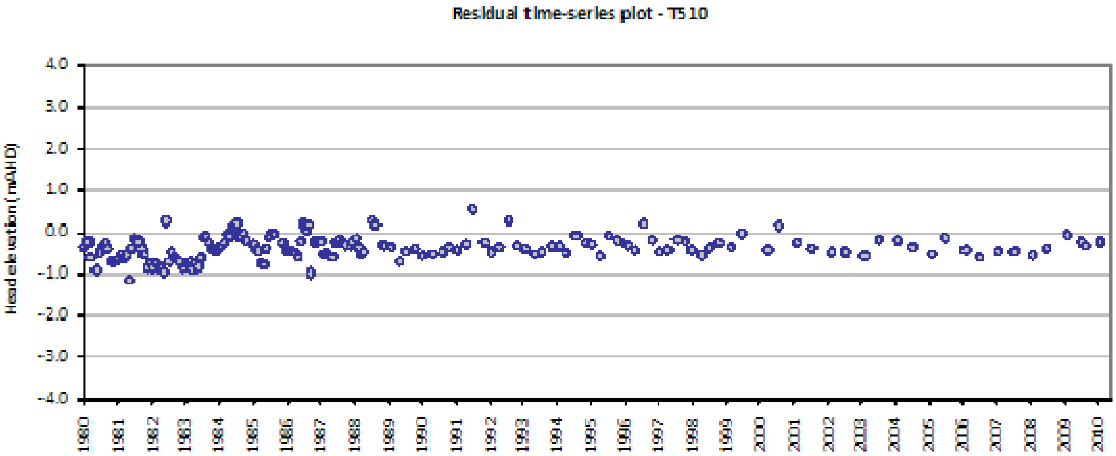



| Statistics | |
|---|---|
| Mean error (ME) | -0.03 |
| Mean absolute error (MAE) | 0.16 |
| Root mean square error (RMSE) | 0.20 |
| Standard deviation of residuals (STDres) | 0.20 |
| Correlation coefficient (R) | 0.91 |
| Nash Sutcliffe correlation coefficient (R2) | 0.74 |

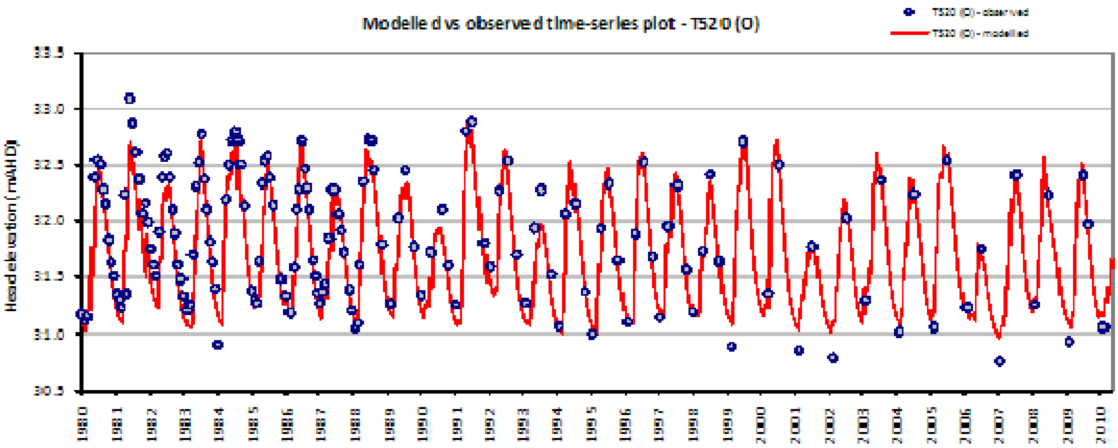
## Superficial Aquifer – T510

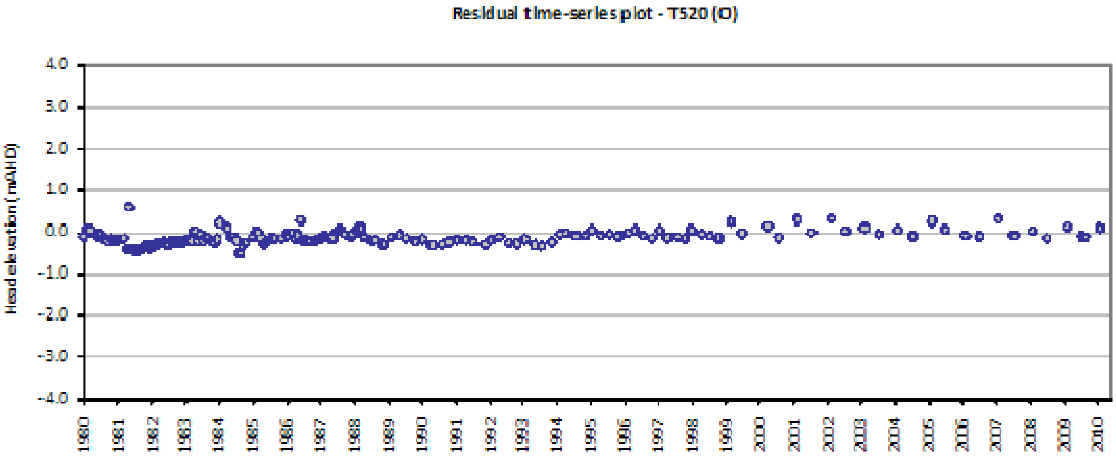



| Statistics | |
|---|---|
| Mean error (ME) | 0.38 |
| Mean absolute error (MAE) | 0.41 |
| Root mean square error (RMSE) | 0.47 |
| Standard deviation of residuals (STDres) | 0.29 |
| Correlation coefficient (R) | 0.77 |
| Nash Sutcliffe correlation coefficient (R2) | -0.38 |

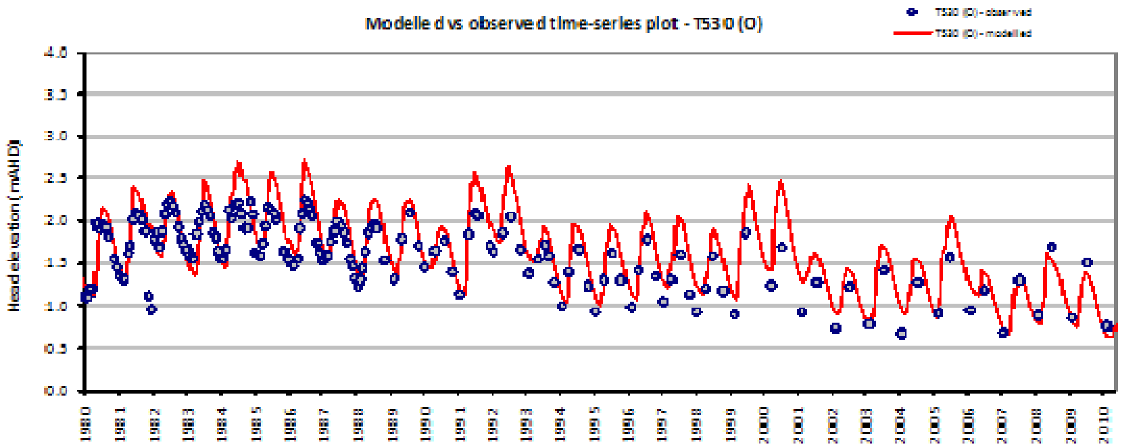
## Superficial Aquifer – T520 (O)

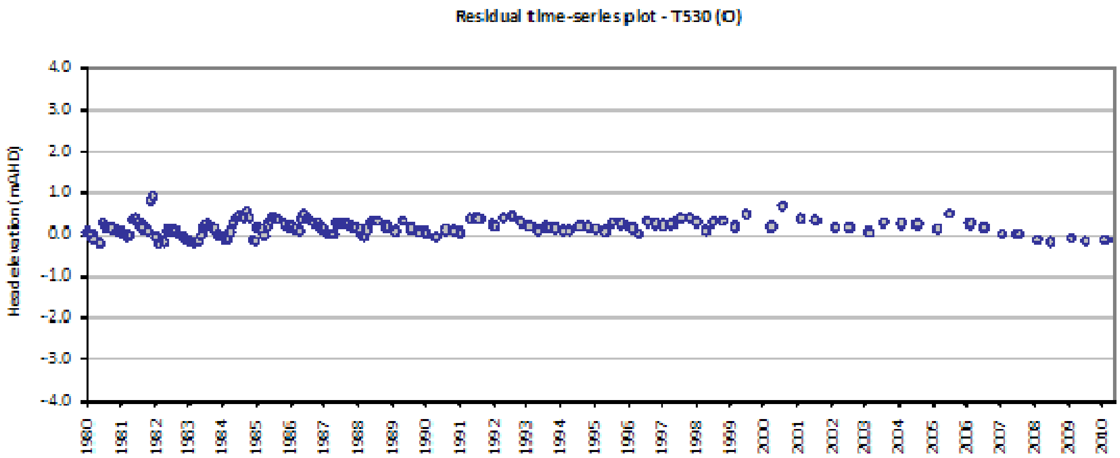



| Statistics | |
|---|---|
| Mean error (ME) | 0.12 |
| Mean absolute error (MAE) | 0.17 |
| Root mean square error (RMSE) | 0.20 |
| Standard deviation of residuals (STDres) | 0.15 |
| Correlation coefficient (R) | 0.96 |
| Nash Sutcliffe correlation coefficient (R2) | 0.87 |

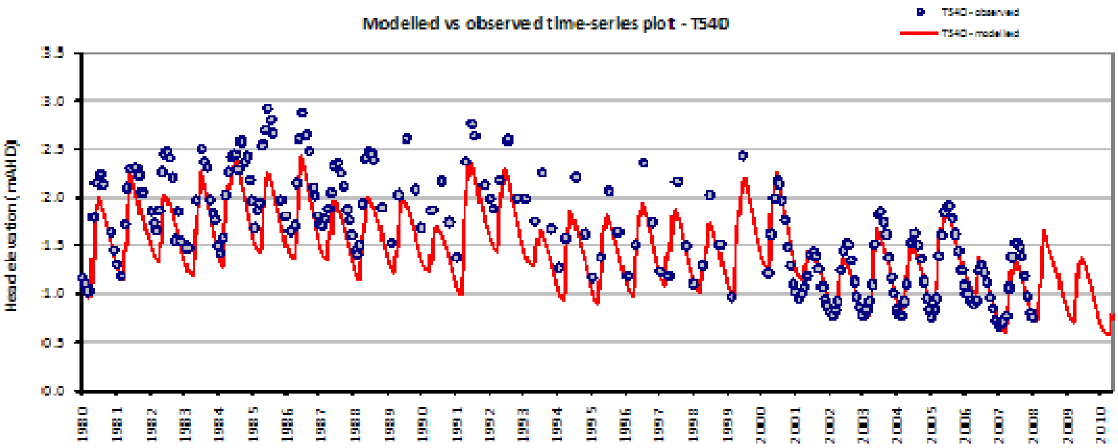
## Superficial Aquifer – T530 (O)

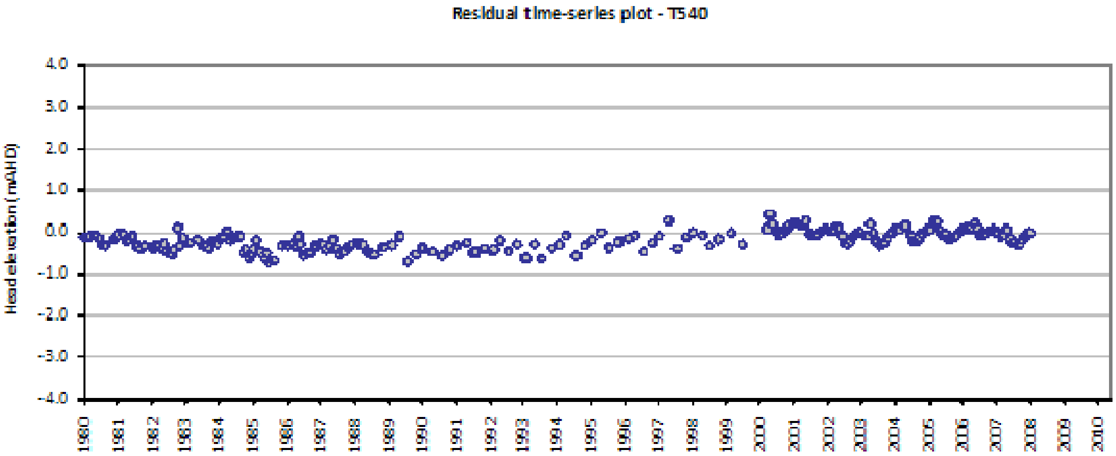



| Statistics | |
|---|---|
| Mean error (ME) | -0.18 |
| Mean absolute error (MAE) | 0.21 |
| Root mean square error (RMSE) | 0.26 |
| Standard deviation of residuals (STDres) | 0.18 |
| Correlation coefficient (R) | 0.90 |
| Nash Sutcliffe correlation coefficient (R2) | 0.51 |

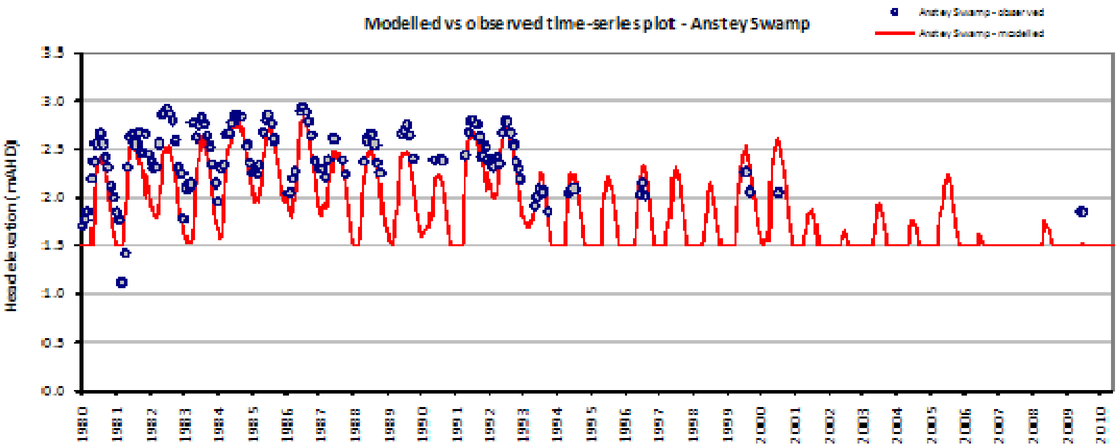
## Superficial Aquifer – T540

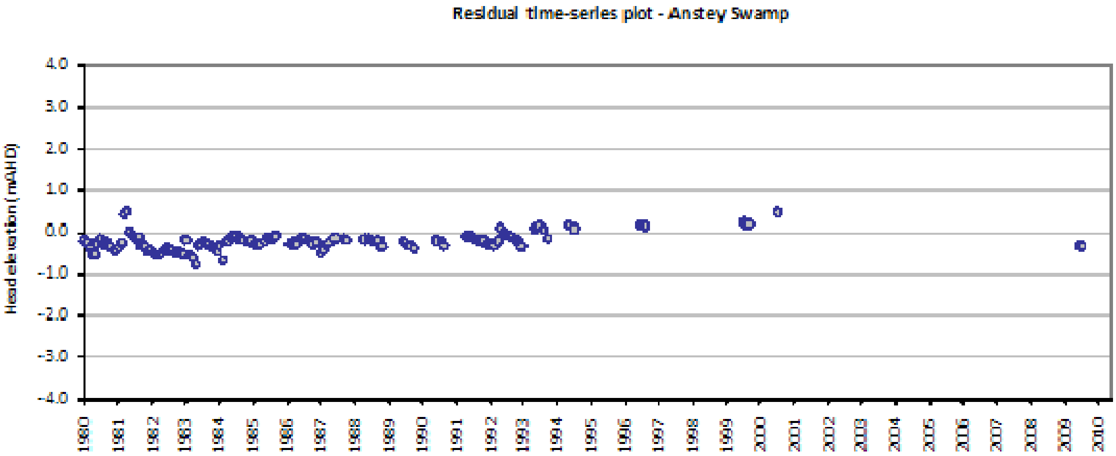



| Statistics | |
|---|---|
| Mean error (ME) | 0.22 |
| Mean absolute error (MAE) | 0.26 |
| Root mean square error (RMSE) | 0.31 |
| Standard deviation of residuals (STDres) | 0.22 |
| Correlation coefficient (R) | 0.92 |
| Nash Sutcliffe correlation coefficient (R2) | 0.65 |

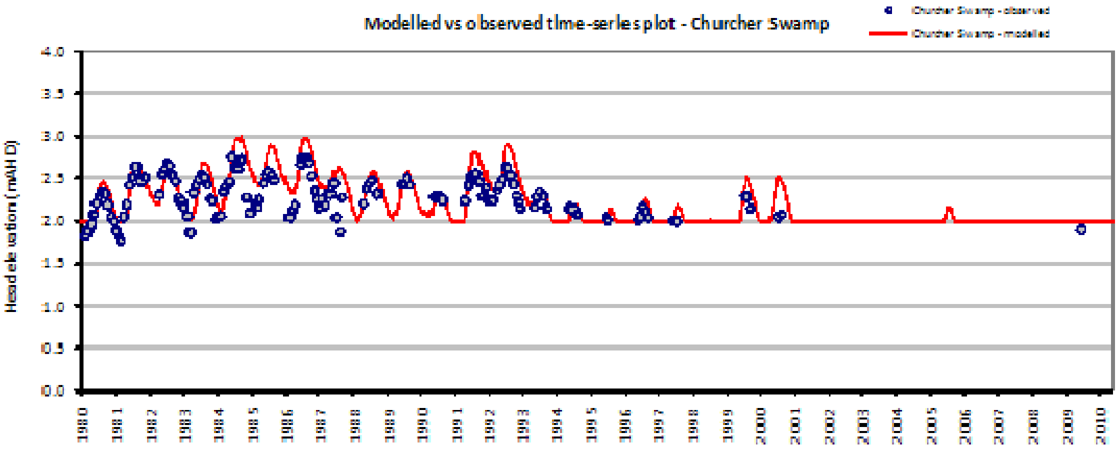
## Lake and wetland levels – Anstey Swamp

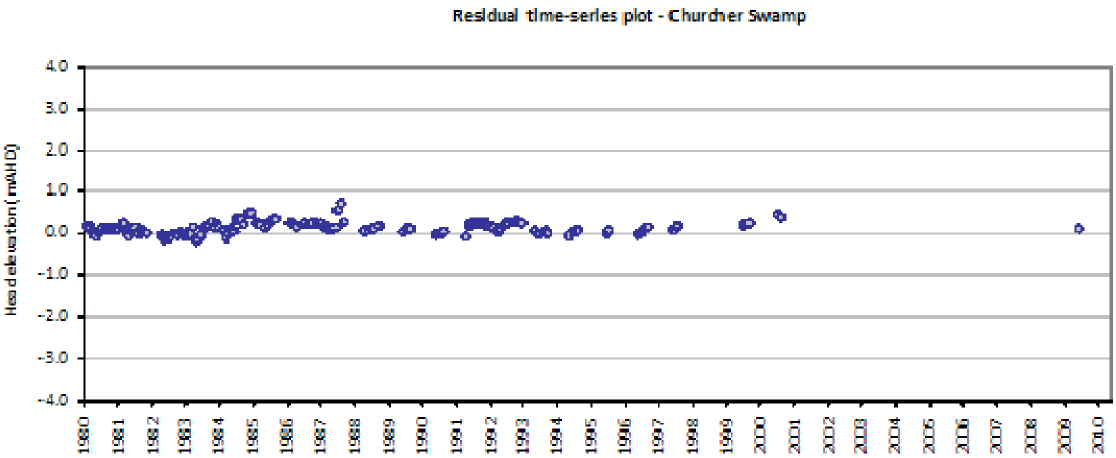



| Statistics | |
|---|---|
| Mean error (ME) | 0.30 |
| Mean absolute error (MAE) | 0.34 |
| Root mean square error (RMSE) | 0.39 |
| Standard deviation of residuals (STDres) | 0.25 |
| Correlation coefficient (R) | 0.77 |
| Nash Sutcliffe correlation coefficient (R2) | -0.63 |

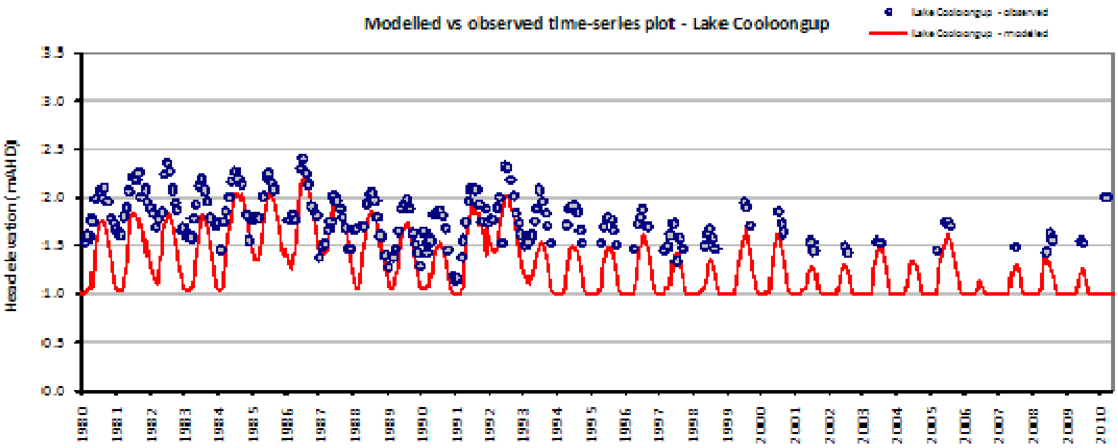
## Lake and wetland levels – Churcher Swamp

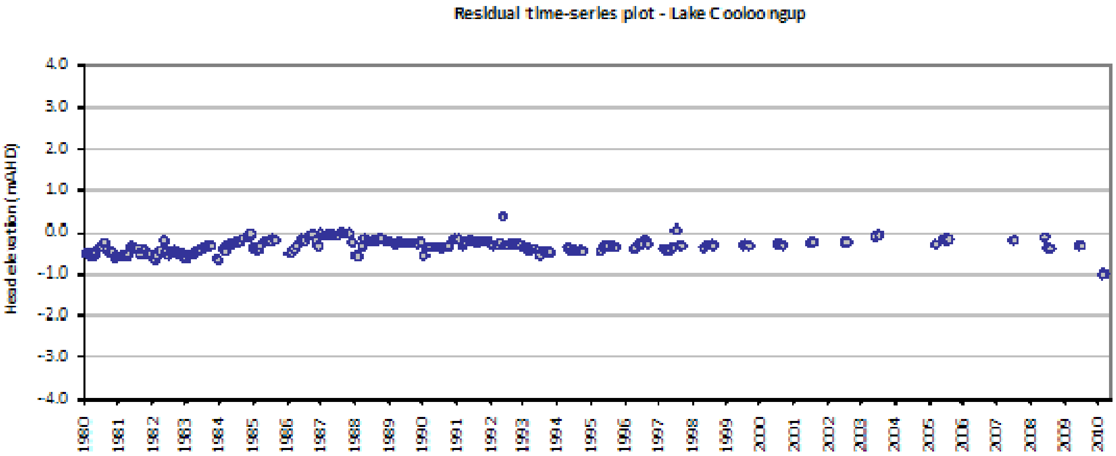



| Statistics | |
|---|---|
| Mean error (ME) | -0.08 |
| Mean absolute error (MAE) | 0.10 |
| Root mean square error (RMSE) | 0.16 |
| Standard deviation of residuals (STDres) | 0.13 |
| Correlation coefficient (R) | 0.88 |
| Nash Sutcliffe correlation coefficient (R2) | 0.49 |

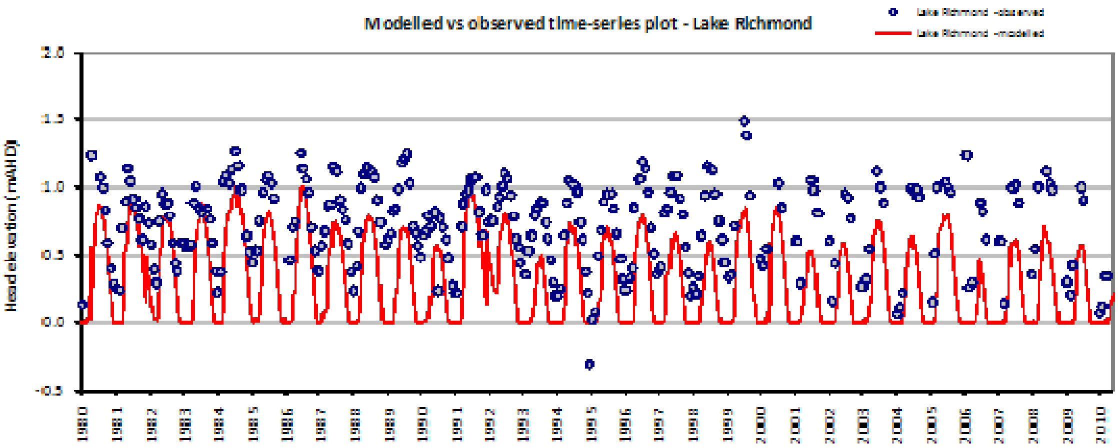
## Lake and wetland levels – Lake Cooloongup

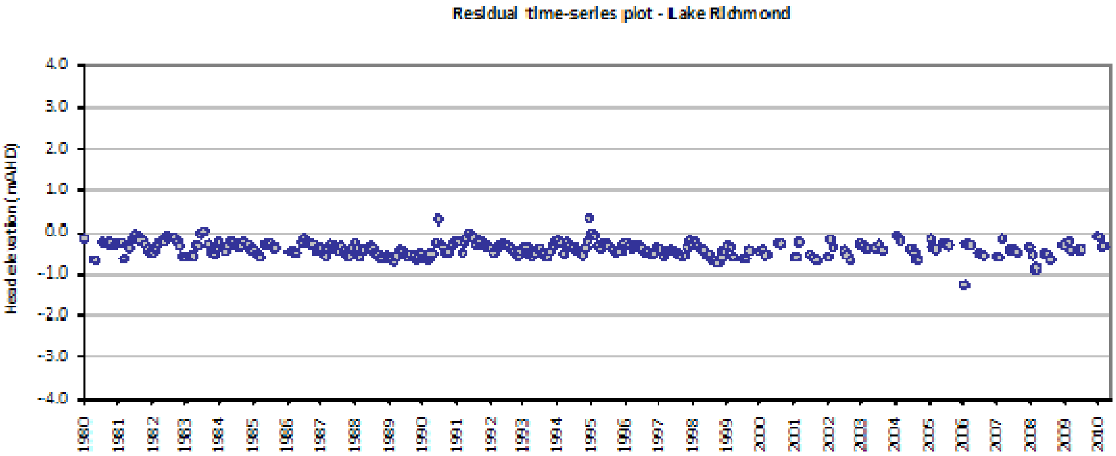



| Statistics | |
|---|---|
| Mean error (ME) | 0.34 |
| Mean absolute error (MAE) | 0.34 |
| Root mean square error (RMSE) | 0.37 |
| Standard deviation of residuals (STDres) | 0.15 |
| Correlation coefficient (R) | 0.88 |
| Nash Sutcliffe correlation coefficient (R2) | -0.92 |

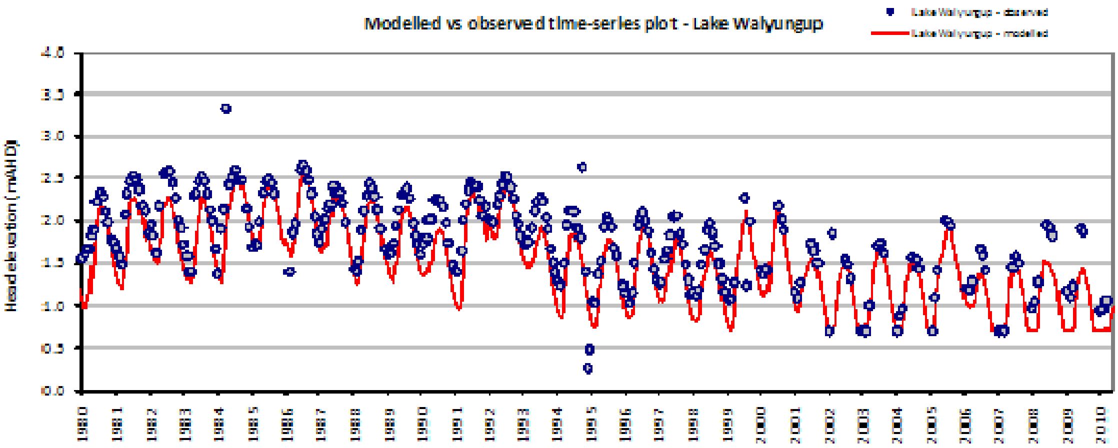
## Lake and wetland levels – Lake Richmond

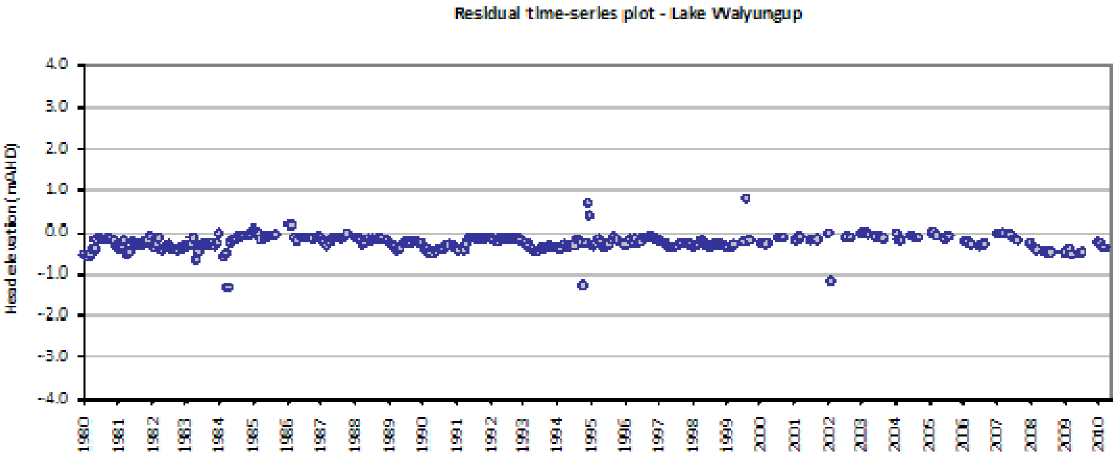



| Statistics | |
|---|---|
| Mean error (ME) | 0.38 |
| Mean absolute error (MAE) | 0.39 |
| Root mean square error (RMSE) | 0.42 |
| Standard deviation of residuals (STDres) | 0.17 |
| Correlation coefficient (R) | 0.85 |
| Nash Sutcliffe correlation coefficient (R2) | -0.88 |

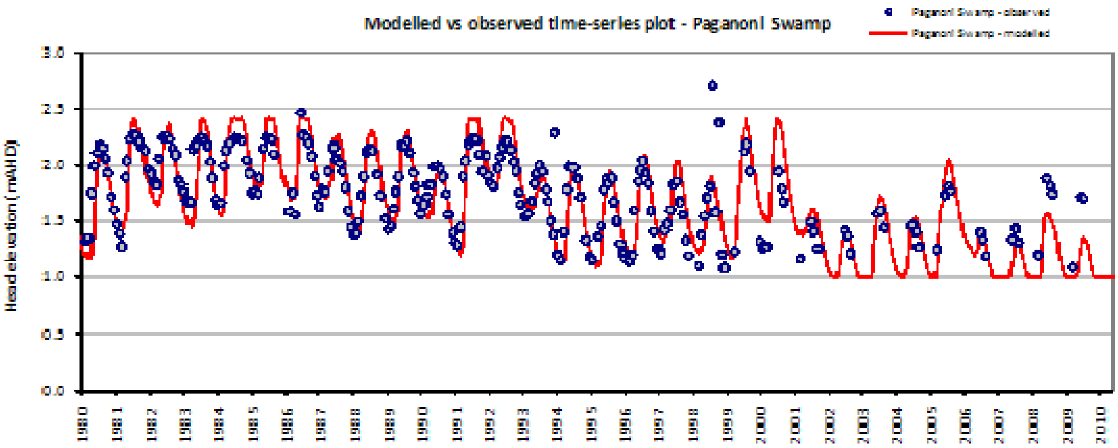
## Lake and wetland levels – Lake Walyungup

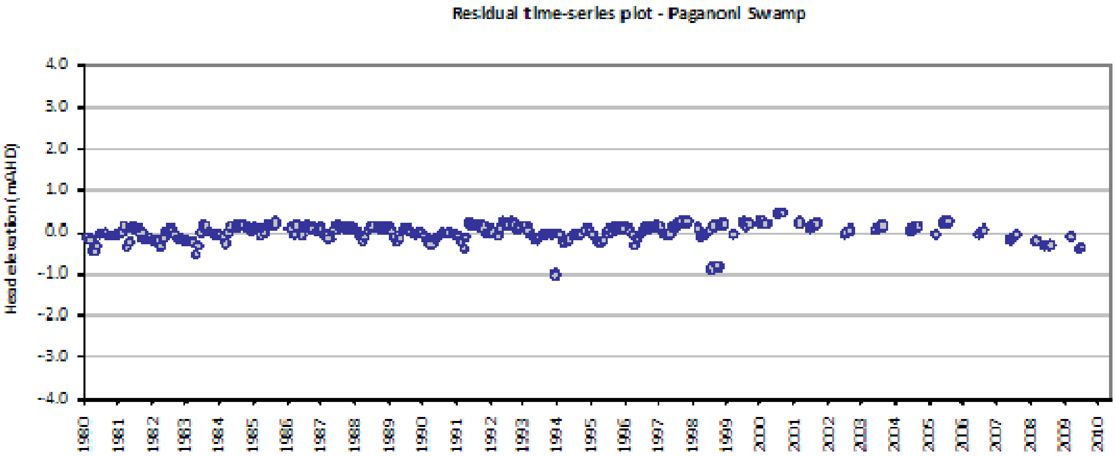



| Statistics | |
|---|---|
| Mean error (ME) | 0.23 |
| Mean absolute error (MAE) | 0.25 |
| Root mean square error (RMSE) | 0.30 |
| Standard deviation of residuals (STDres) | 0.20 |
| Correlation coefficient (R) | 0.91 |
| Nash Sutcliffe correlation coefficient (R2) | 0.58 |

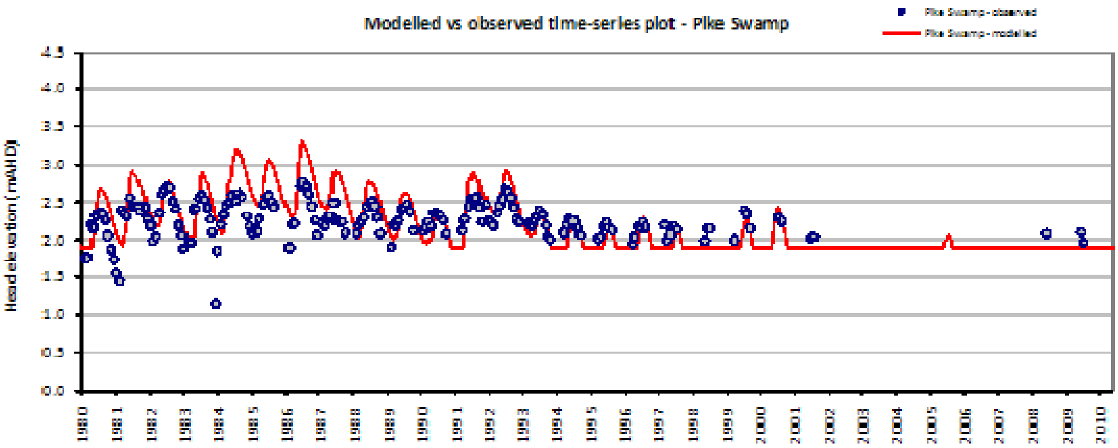
## Lake and wetland levels – Paganoni

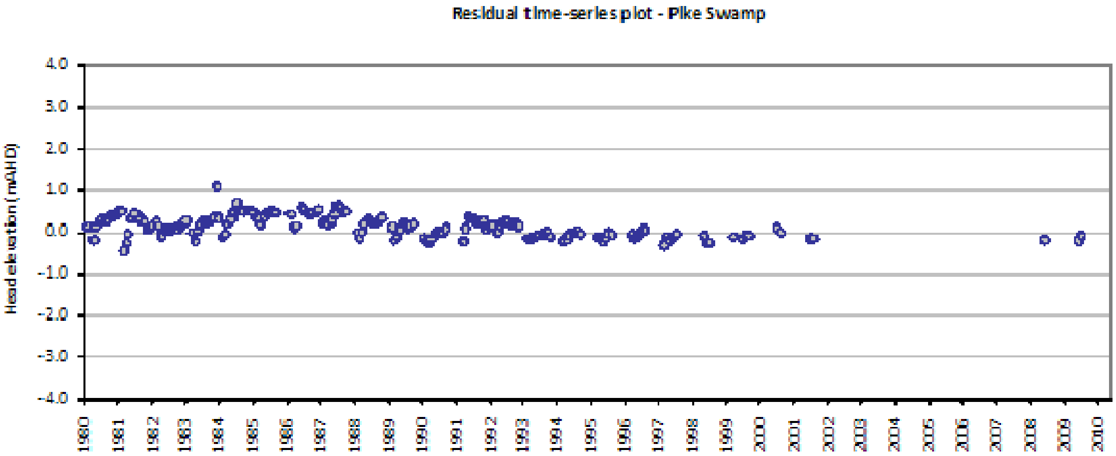



| Statistics | |
|---|---|
| Mean error (ME) | -0.02 |
| Mean absolute error (MAE) | 0.13 |
| Root mean square error (RMSE) | 0.19 |
| Standard deviation of residuals (STDres) | 0.19 |
| Correlation coefficient (R) | 0.88 |
| Nash Sutcliffe correlation coefficient (R2) | 0.76 |

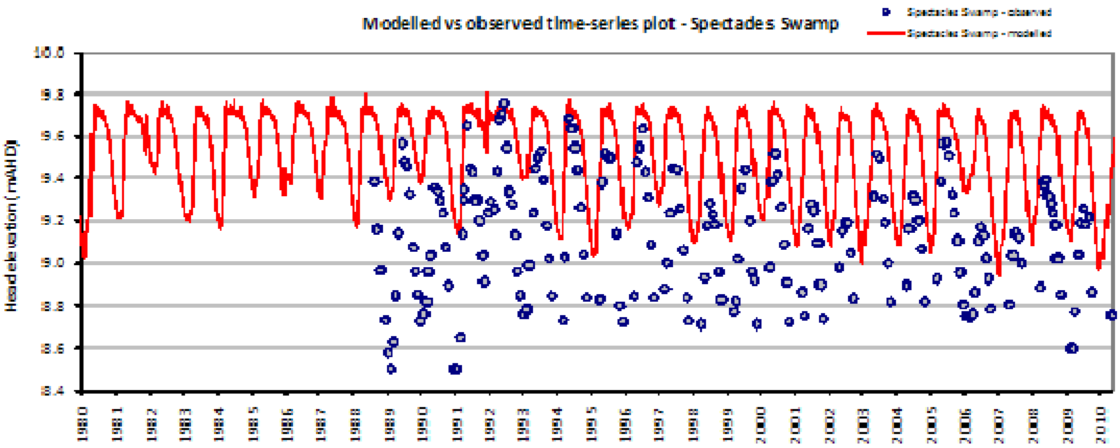
## Lake and wetland levels – Pike Swamp

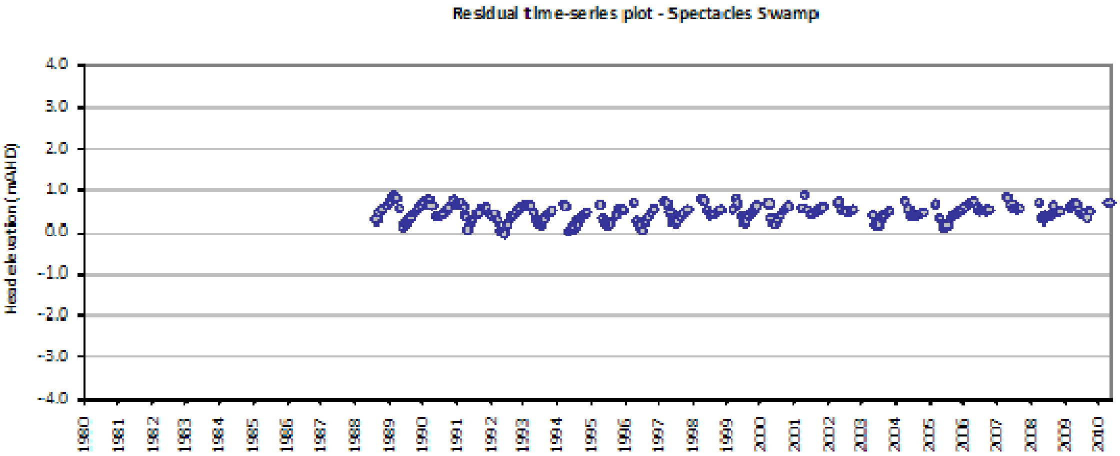



| Statistics | |
|---|---|
| Mean error (ME) | -0.12 |
| Mean absolute error (MAE) | 0.17 |
| Root mean square error (RMSE) | 0.24 |
| Standard deviation of residuals (STDres) | 0.21 |
| Correlation coefficient (R) | 0.81 |
| Nash Sutcliffe correlation coefficient (R2) | 0.15 |

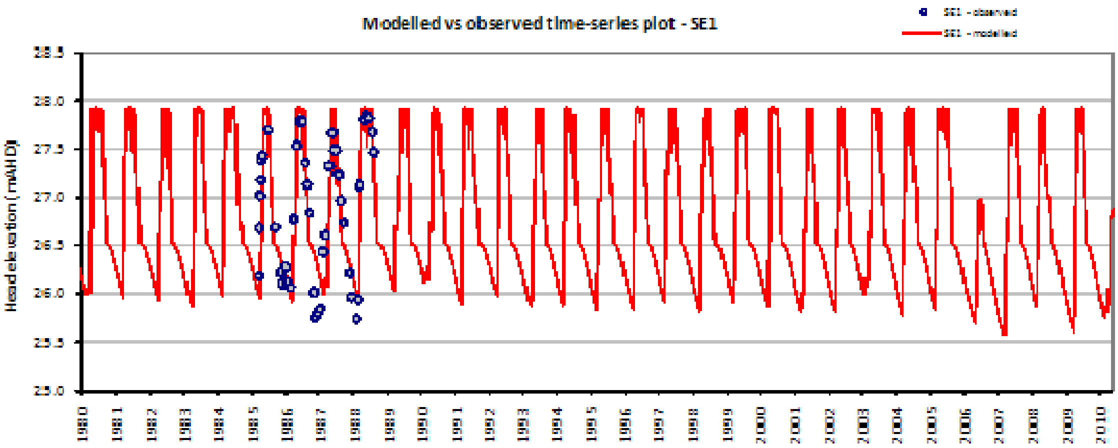
## Lake and wetland levels – Spectacles Wetlands

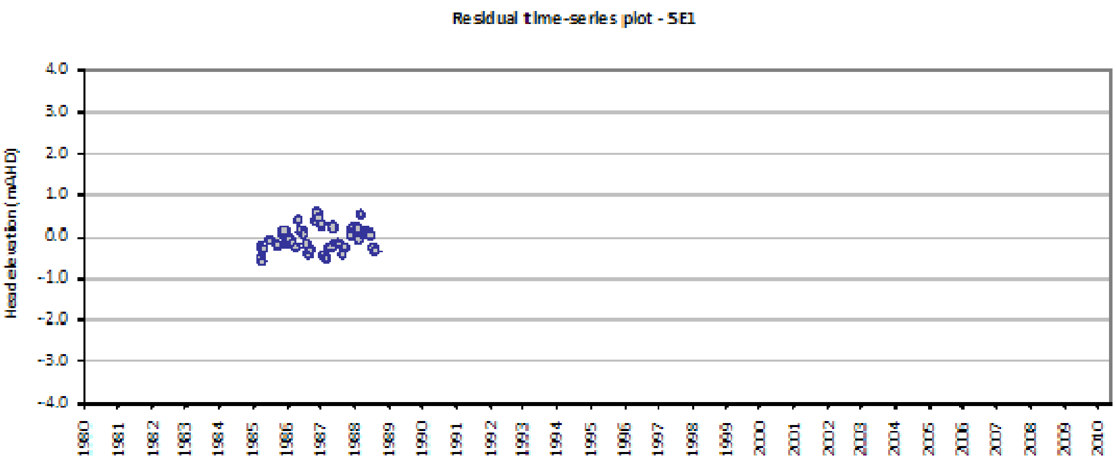



| Statistics | |
|---|---|
| Mean error (ME) | -0.47 |
| Mean absolute error (MAE) | 0.47 |
| Root mean square error (RMSE) | 0.50 |
| Standard deviation of residuals (STDres) | 0.18 |
| Correlation coefficient (R) | 0.85 |
| Nash Sutcliffe correlation coefficient (R2) | -1.50 |

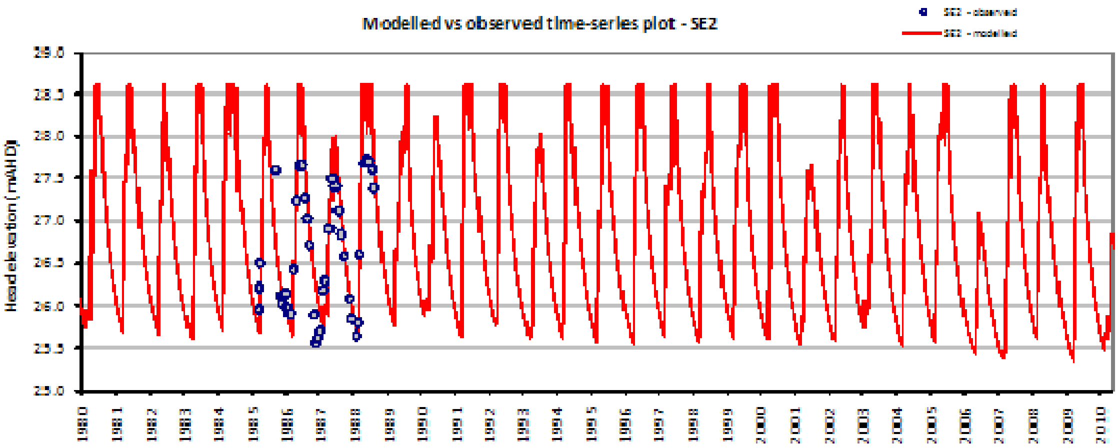
## Superficial Aquifer – SE1

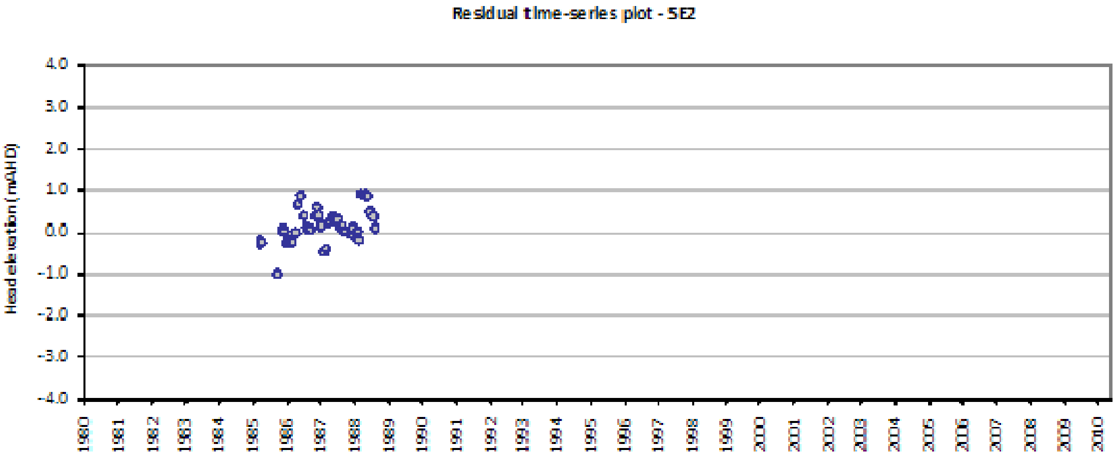



| Statistics | |
|---|---|
| Mean error (ME) | 0.08 |
| Mean absolute error (MAE) | 0.26 |
| Root mean square error (RMSE) | 0.31 |
| Standard deviation of residuals (STDres) | 0.30 |
| Correlation coefficient (R) | 0.91 |
| Nash Sutcliffe correlation coefficient (R2) | 0.80 |

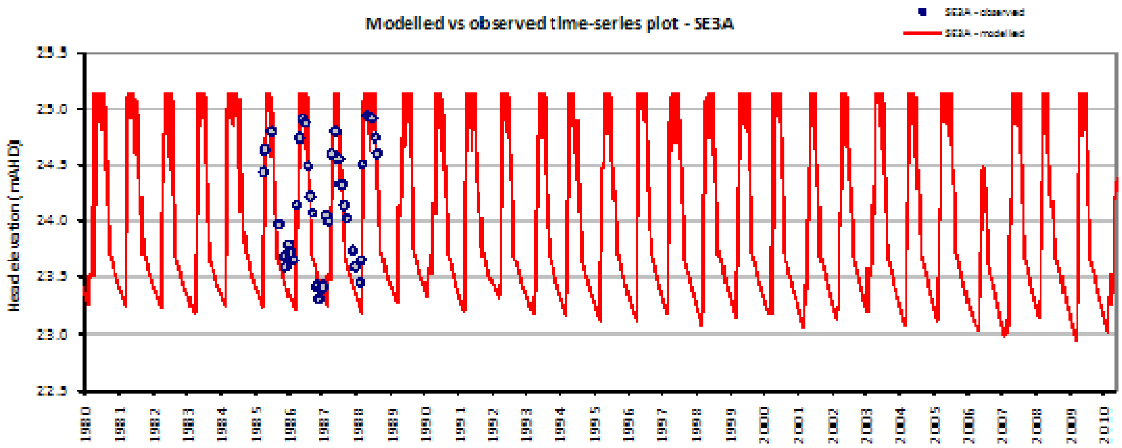
## Superficial Aquifer – SE2

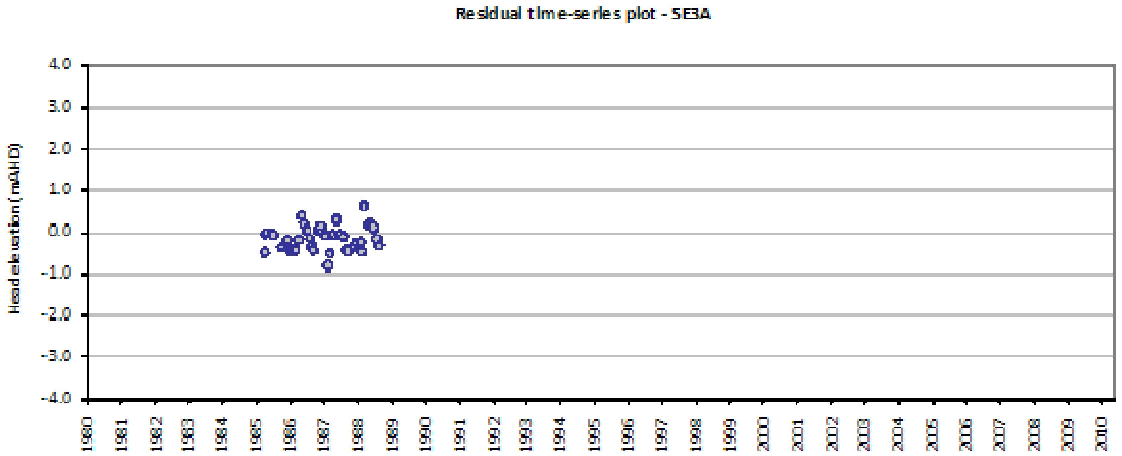



| Statistics | |
|---|---|
| Mean error (ME) | -0.14 |
| Mean absolute error (MAE) | 0.32 |
| Root mean square error (RMSE) | 0.42 |
| Standard deviation of residuals (STDres) | 0.39 |
| Correlation coefficient (R) | 0.92 |
| Nash Sutcliffe correlation coefficient (R2) | 0.66 |

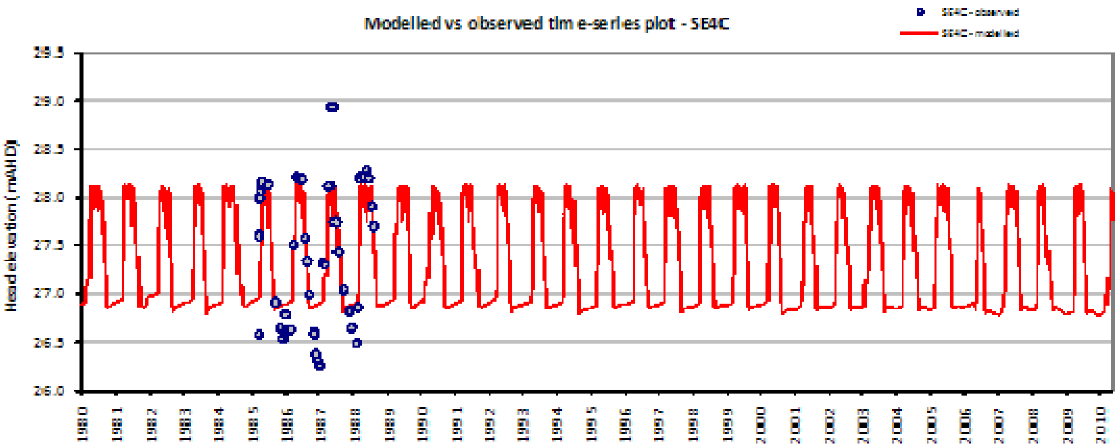
## Superficial Aquifer – SE3A

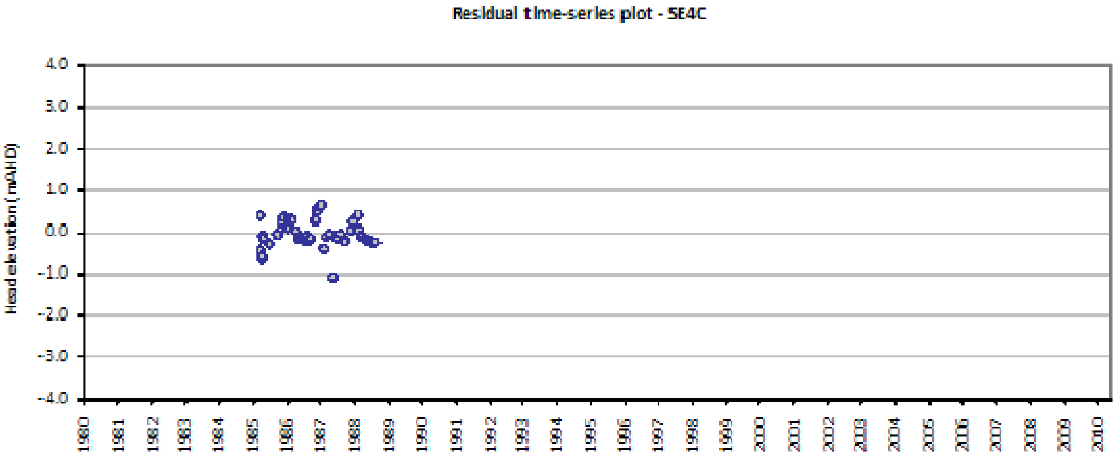



| Statistics | |
|---|---|
| Mean error (ME) | 0.15 |
| Mean absolute error (MAE) | 0.26 |
| Root mean square error (RMSE) | 0.32 |
| Standard deviation of residuals (STDres) | 0.28 |
| Correlation coefficient (R) | 0.93 |
| Nash Sutcliffe correlation coefficient (R2) | 0.62 |

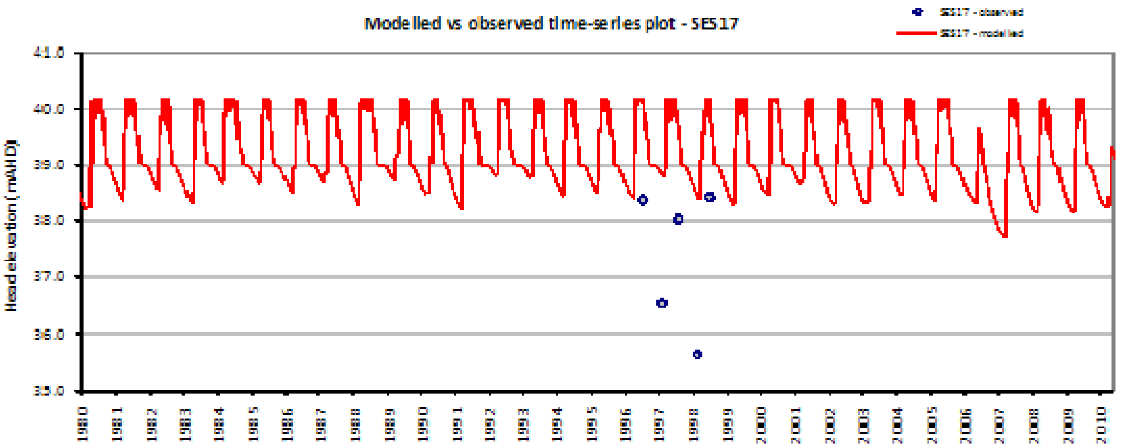
## Superficial Aquifer – SE4C

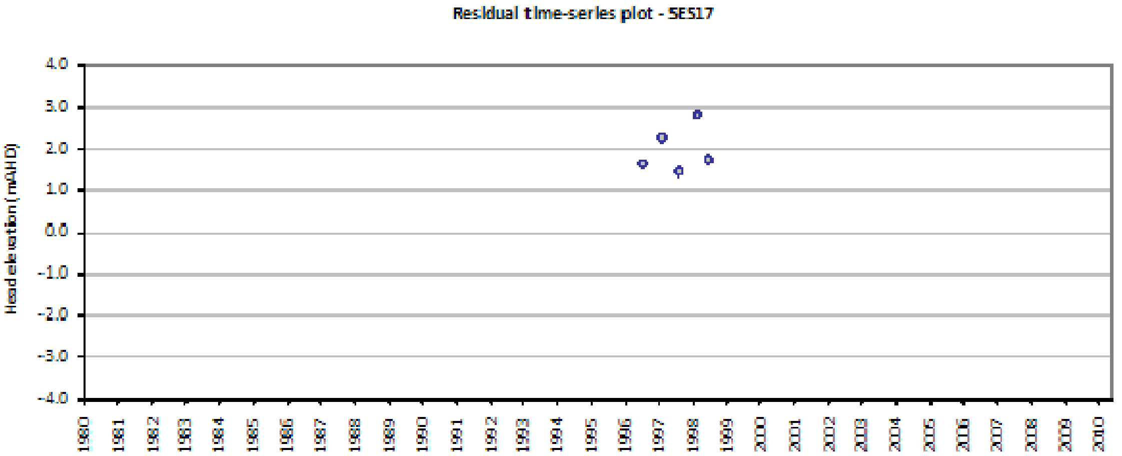



| Statistics | |
|---|---|
| Mean error (ME) | 0.04 |
| Mean absolute error (MAE) | 0.26 |
| Root mean square error (RMSE) | 0.34 |
| Standard deviation of residuals (STDres) | 0.33 |
| Correlation coefficient (R) | 0.92 |
| Nash Sutcliffe correlation coefficient (R2) | 0.78 |

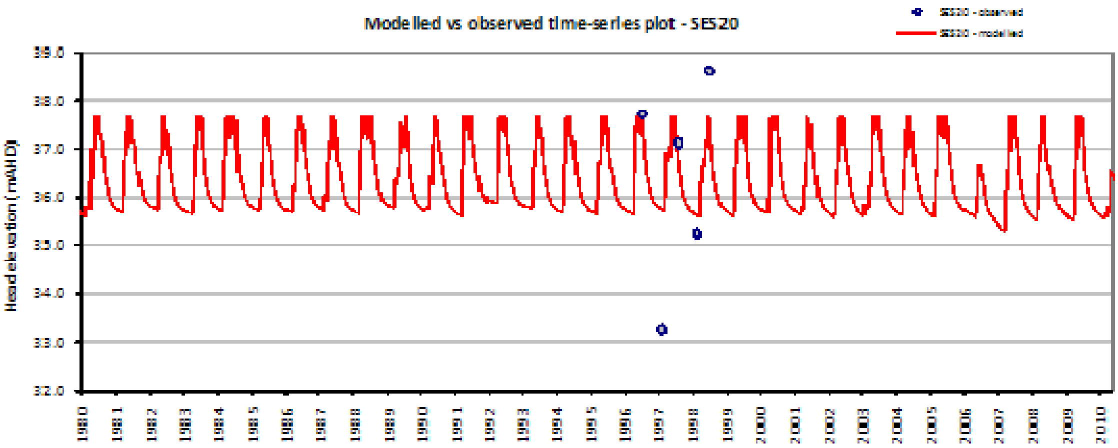
## Superficial Aquifer – SES17

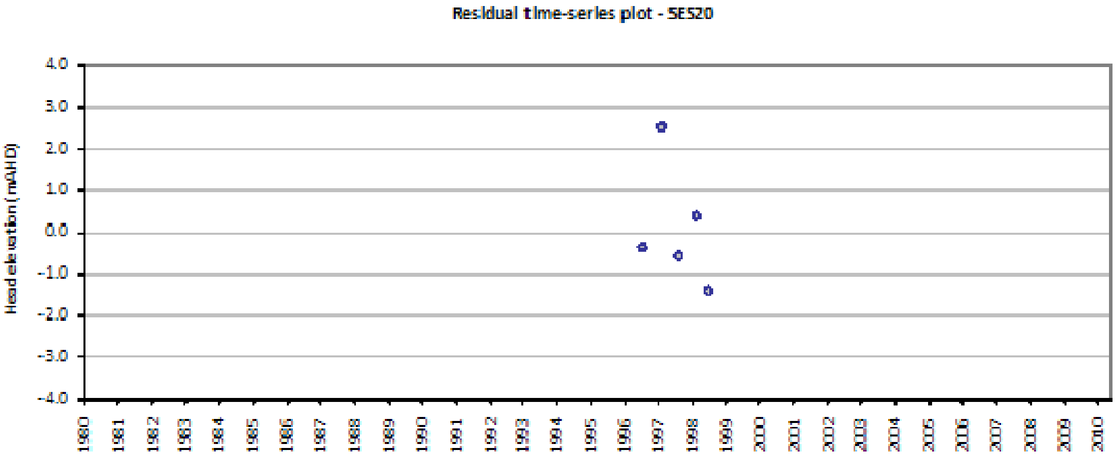



| Statistics | |
|---|---|
| Mean error (ME) | -1.99 |
| Mean absolute error (MAE) | 1.99 |
| Root mean square error (RMSE) | 2.05 |
| Standard deviation of residuals (STDres) | 0.48 |
| Correlation coefficient (R) | 0.98 |
| Nash Sutcliffe correlation coefficient (R2) | -2.34 |

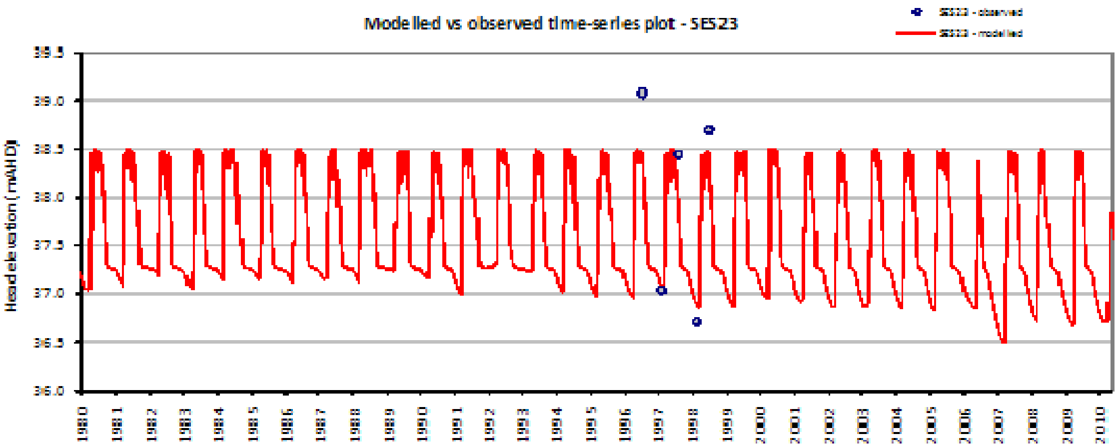
## Superficial Aquifer – SES20

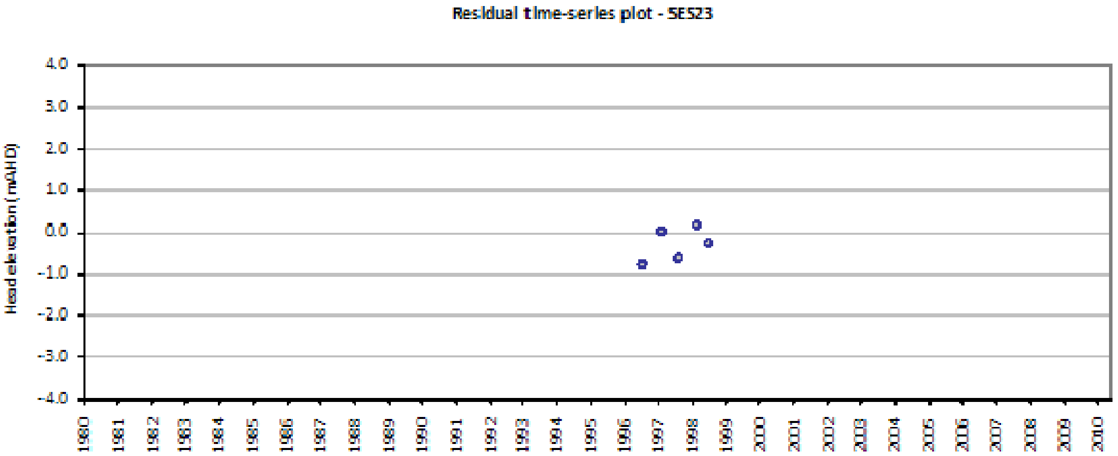



| Statistics | |
|---|---|
| Mean error (ME) | -0.13 |
| Mean absolute error (MAE) | 1.03 |
| Root mean square error (RMSE) | 1.33 |
| Standard deviation of residuals (STDres) | 1.32 |
| Correlation coefficient (R) | 0.89 |
| Nash Sutcliffe correlation coefficient (R2) | 0.52 |

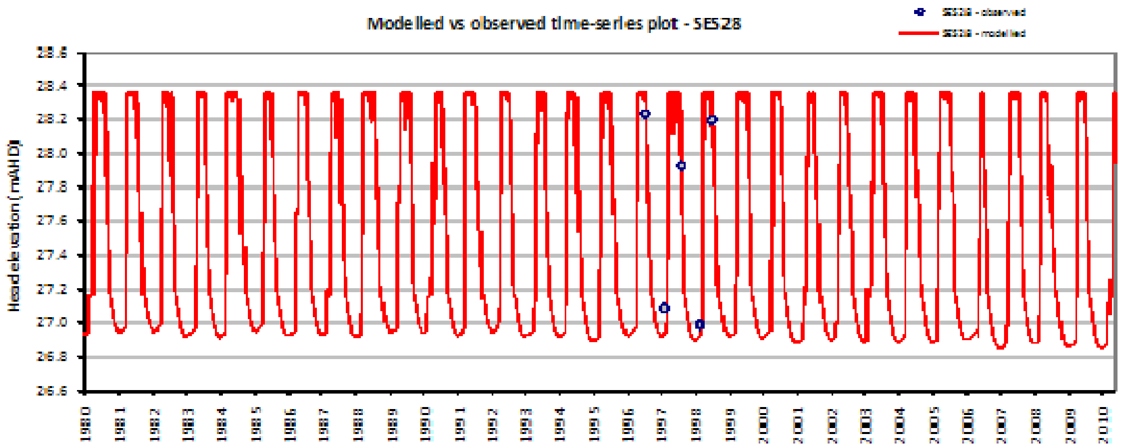
## Superficial Aquifer – SES23

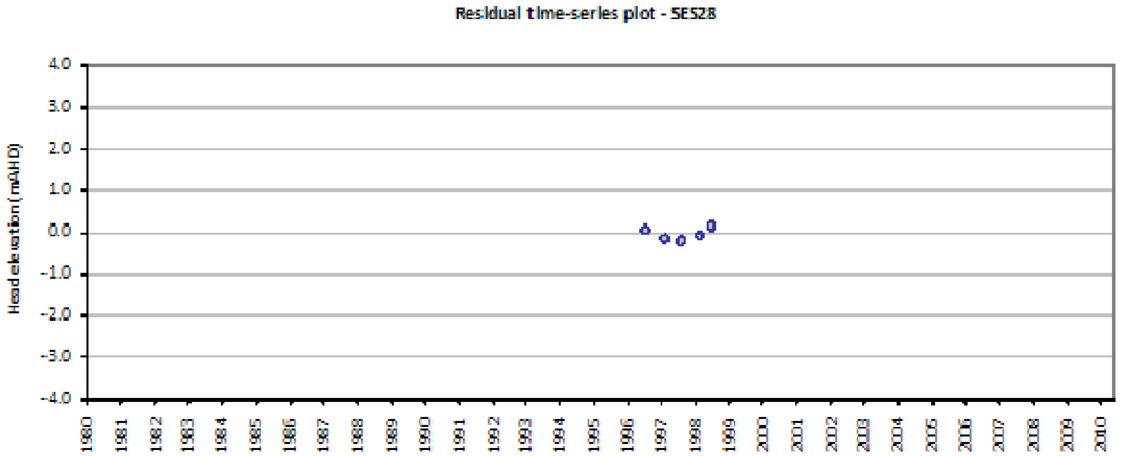



| Statistics | |
|---|---|
| Mean error (ME) | 0.28 |
| Mean absolute error (MAE) | 0.37 |
| Root mean square error (RMSE) | 0.46 |
| Standard deviation of residuals (STDres) | 0.36 |
| Correlation coefficient (R) | 0.97 |
| Nash Sutcliffe correlation coefficient (R2) | 0.76 |

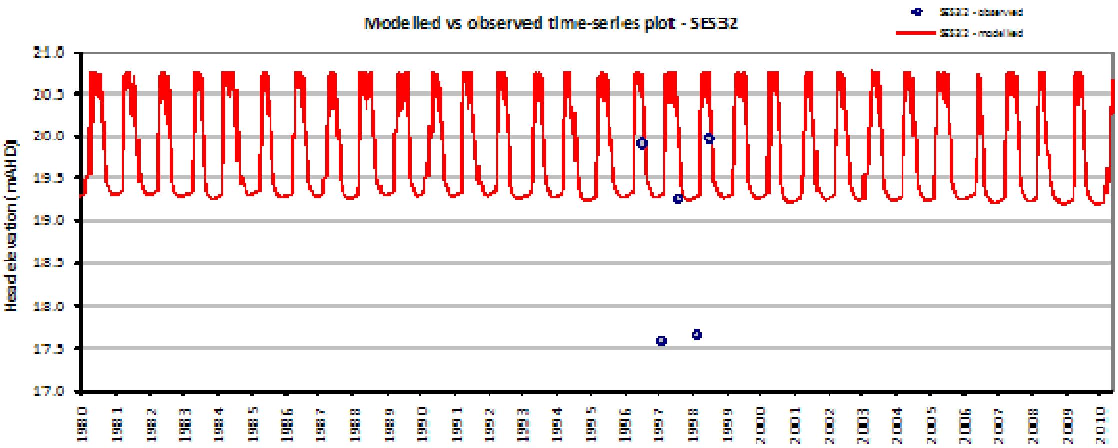
## Superficial Aquifer – SES28

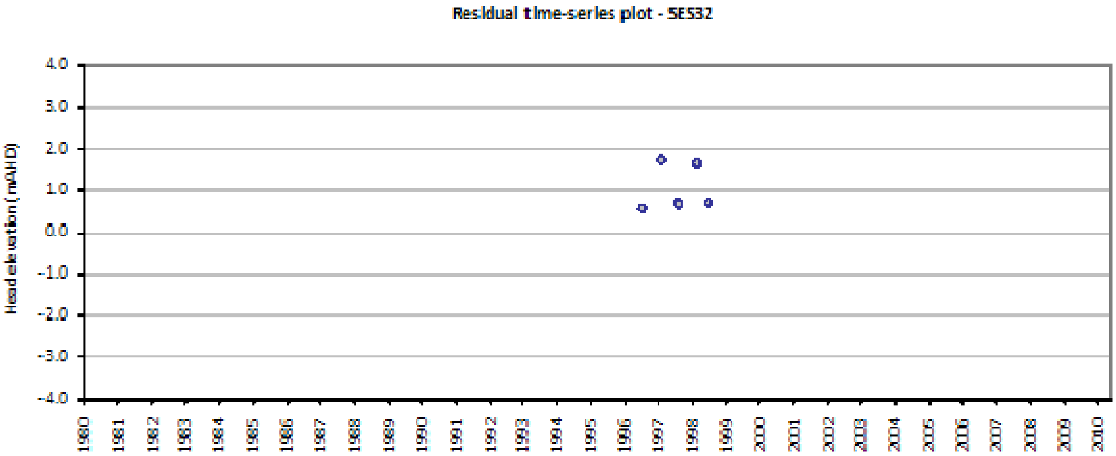



| Statistics | |
|---|---|
| Mean error (ME) | 0.03 |
| Mean absolute error (MAE) | 0.12 |
| Root mean square error (RMSE) | 0.13 |
| Standard deviation of residuals (STDres) | 0.13 |
| Correlation coefficient (R) | 0.99 |
| Nash Sutcliffe correlation coefficient (R2) | 0.94 |

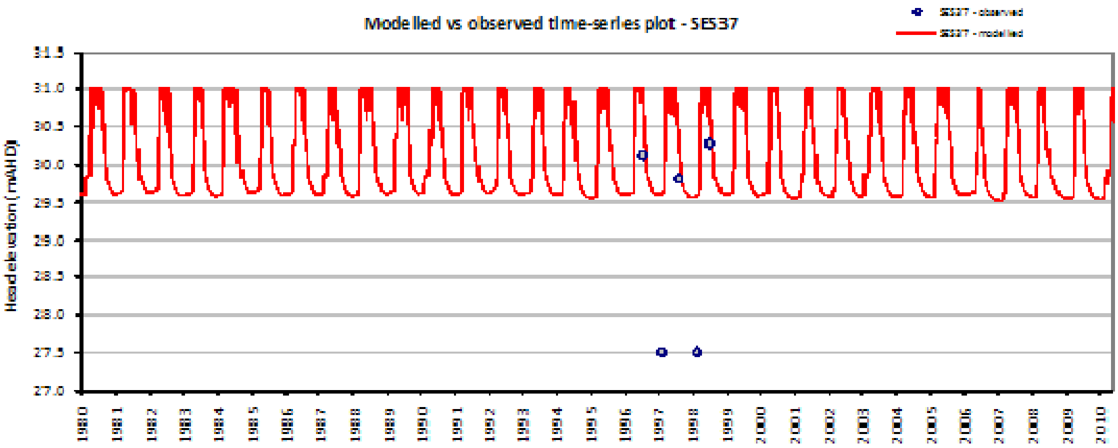
## Superficial Aquifer – SES32

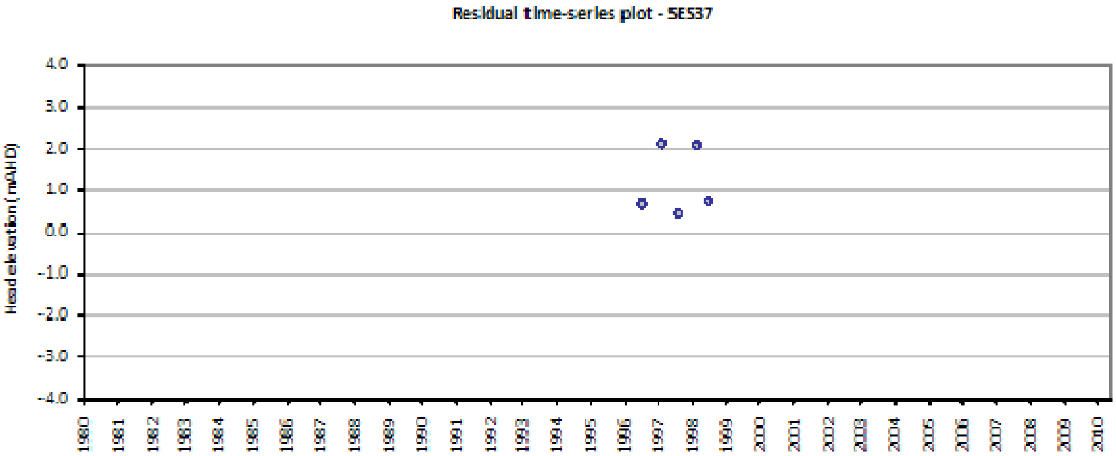



| Statistics | |
|---|---|
| Mean error (ME) | -1.08 |
| Mean absolute error (MAE) | 1.08 |
| Root mean square error (RMSE) | 1.19 |
| Standard deviation of residuals (STDres) | 0.50 |
| Correlation coefficient (R) | 0.98 |
| Nash Sutcliffe correlation coefficient (R2) | -0.27 |

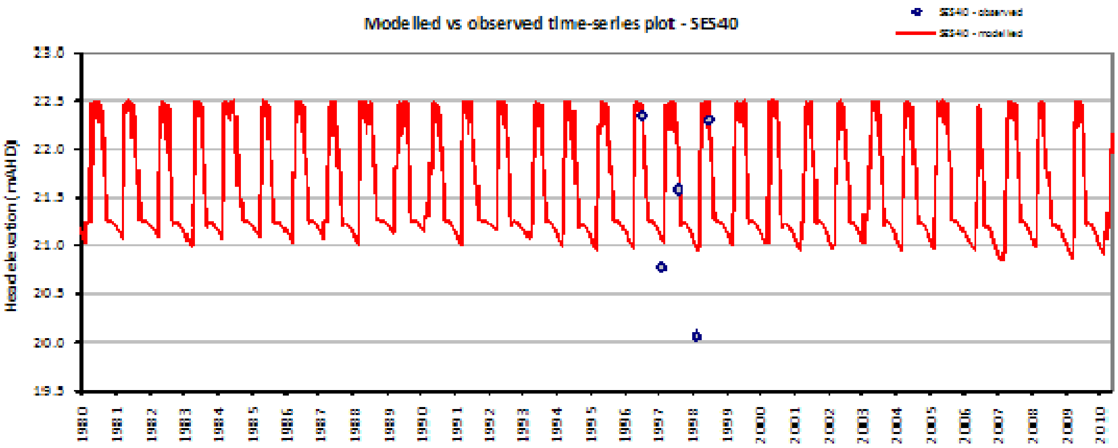
## Superficial Aquifer – SES37

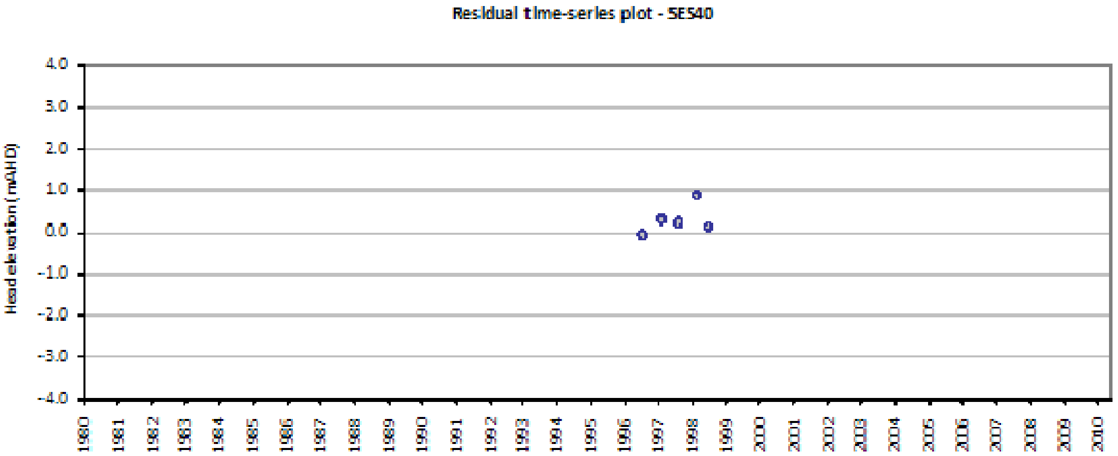



| Statistics | |
|---|---|
| Mean error (ME) | -1.22 |
| Mean absolute error (MAE) | 1.22 |
| Root mean square error (RMSE) | 1.42 |
| Standard deviation of residuals (STDres) | 0.72 |
| Correlation coefficient (R) | 0.95 |
| Nash Sutcliffe correlation coefficient (R2) | -0.26 |

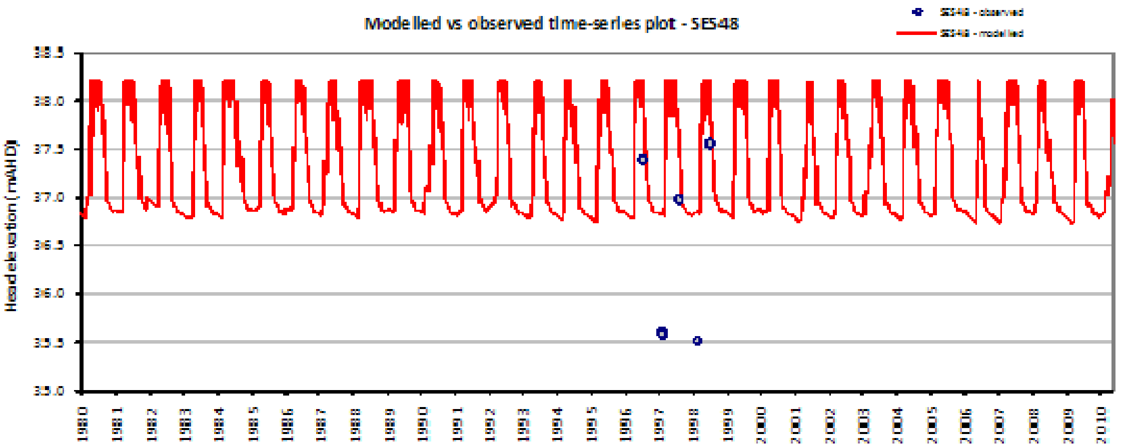
## Superficial Aquifer – SES40

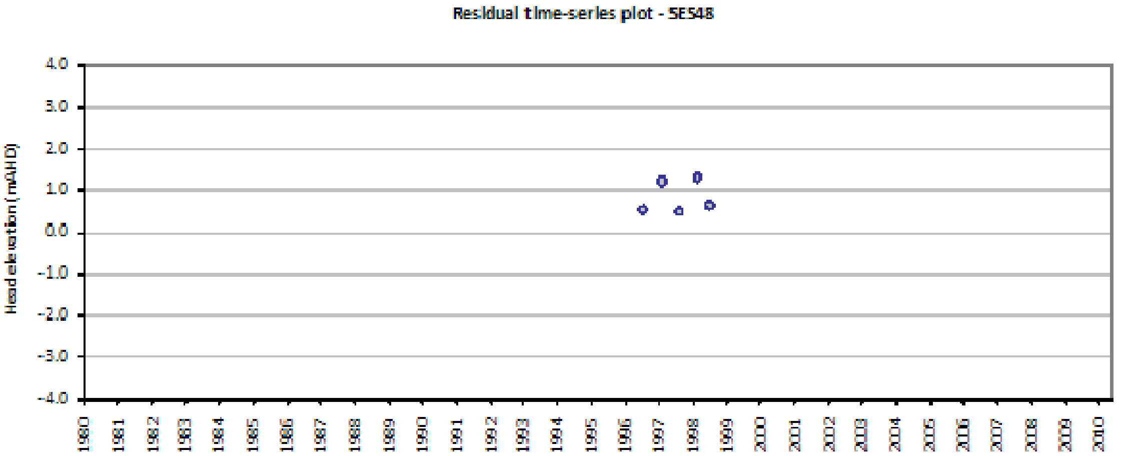



| Statistics | |
|---|---|
| Mean error (ME) | -0.31 |
| Mean absolute error (MAE) | 0.33 |
| Root mean square error (RMSE) | 0.44 |
| Standard deviation of residuals (STDres) | 0.31 |
| Correlation coefficient (R) | 0.98 |
| Nash Sutcliffe correlation coefficient (R2) | 0.75 |

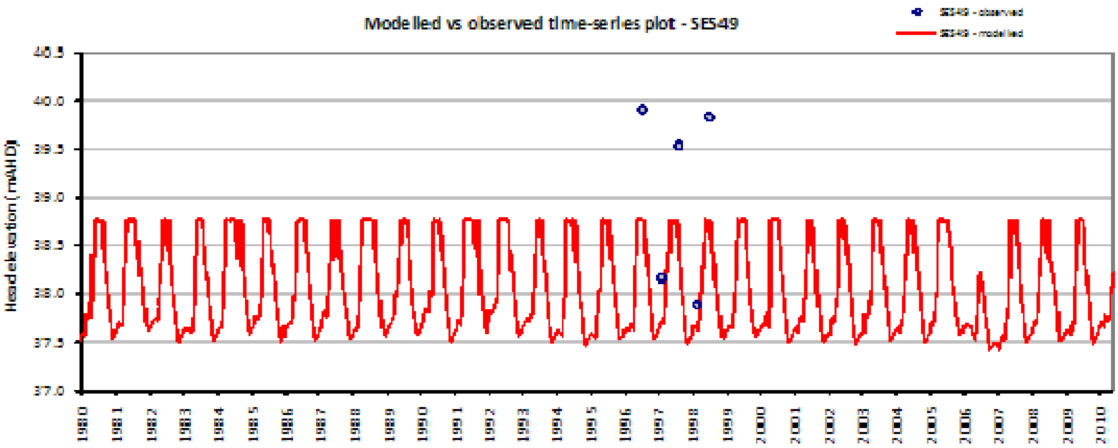
## Superficial Aquifer – SES48

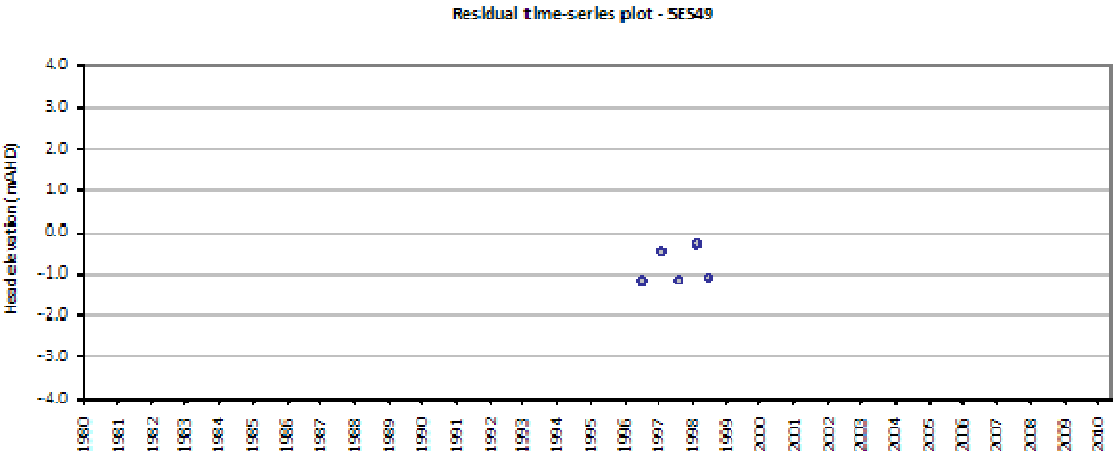



| Statistics | |
|---|---|
| Mean error (ME) | -0.84 |
| Mean absolute error (MAE) | 0.84 |
| Root mean square error (RMSE) | 0.91 |
| Standard deviation of residuals (STDres) | 0.35 |
| Correlation coefficient (R) | 0.98 |
| Nash Sutcliffe correlation coefficient (R2) | -0.08 |

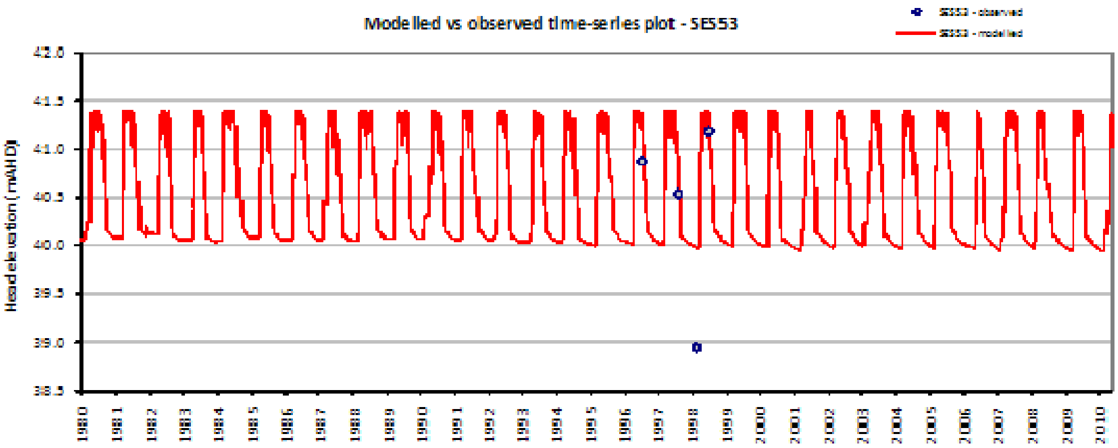
## Superficial Aquifer – SES49

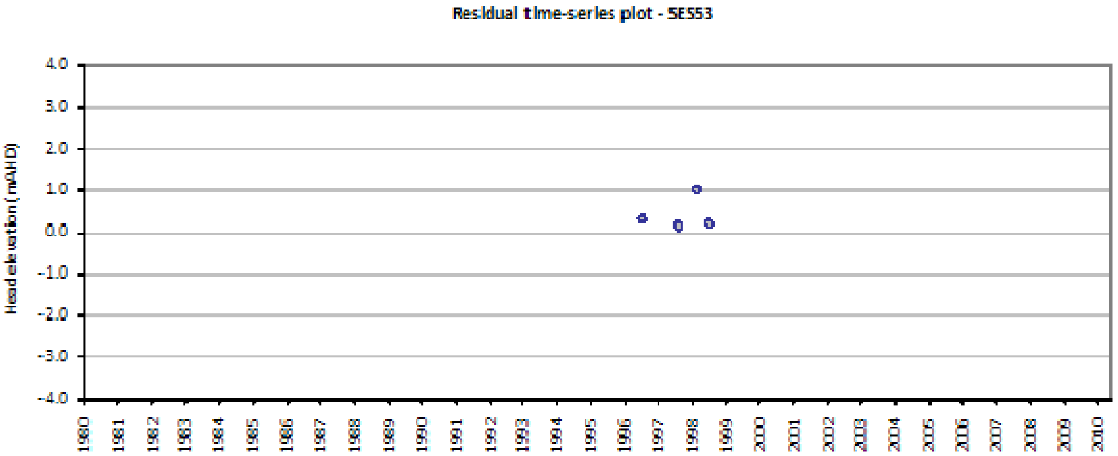



| Statistics | |
|---|---|
| Mean error (ME) | 0.81 |
| Mean absolute error (MAE) | 0.81 |
| Root mean square error (RMSE) | 0.89 |
| Standard deviation of residuals (STDres) | 0.37 |
| Correlation coefficient (R) | 0.99 |
| Nash Sutcliffe correlation coefficient (R2) | -0.07 |

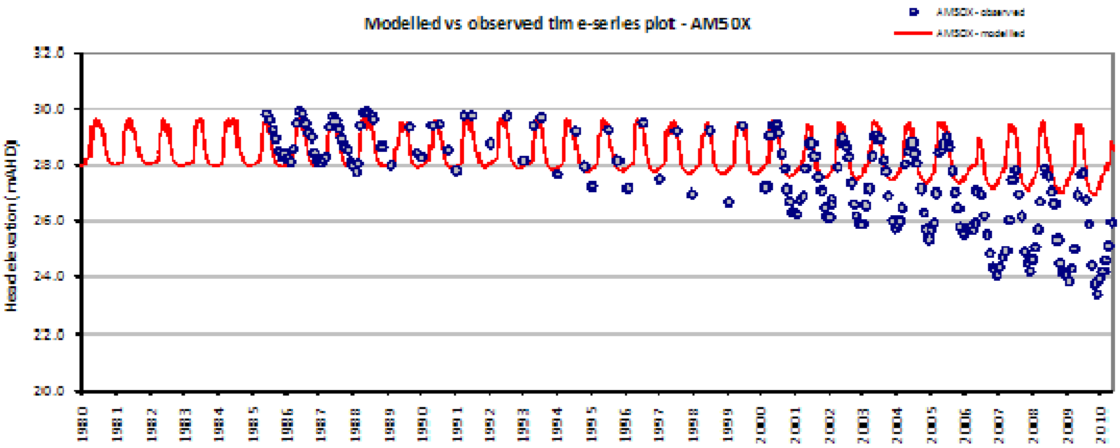
## Superficial Aquifer – SES53

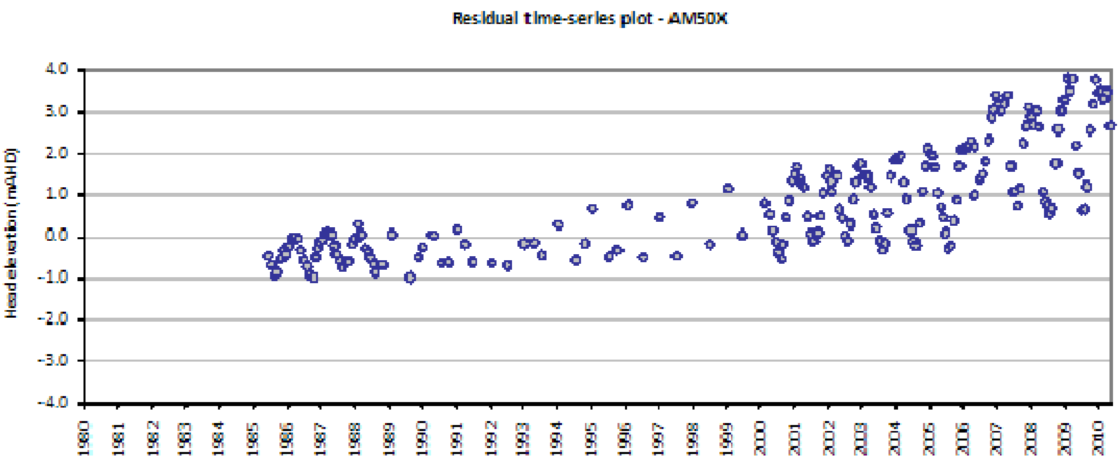



| Statistics | |
|---|---|
| Mean error (ME) | -0.43 |
| Mean absolute error (MAE) | 0.43 |
| Root mean square error (RMSE) | 0.56 |
| Standard deviation of residuals (STDres) | 0.35 |
| Correlation coefficient (R) | 0.98 |
| Nash Sutcliffe correlation coefficient (R2) | 0.58 |

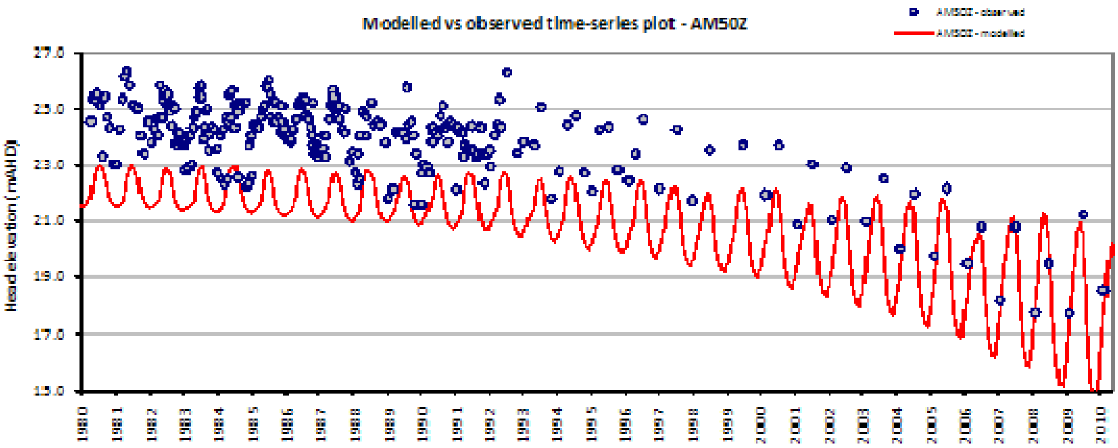
## Leederville Aquifer – AM50X

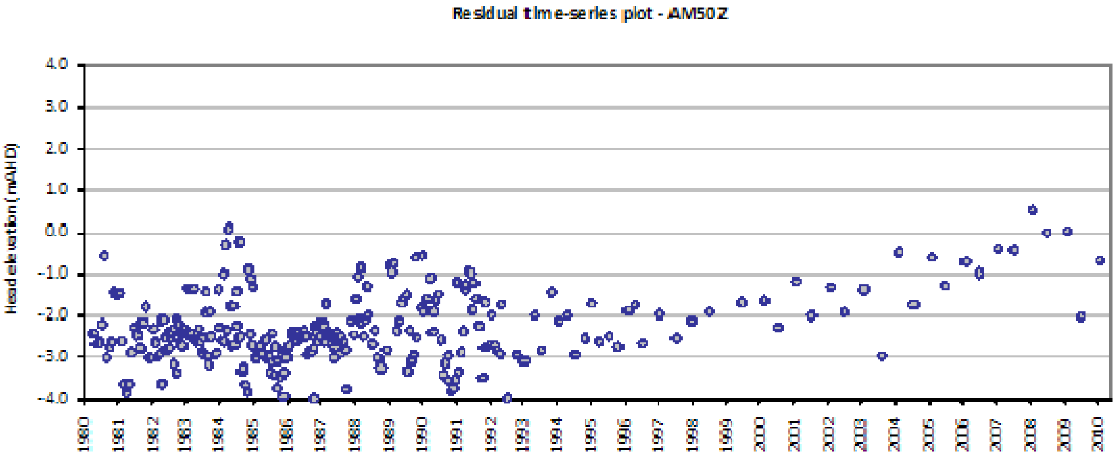



| Statistics | |
|---|---|
| Mean error (ME) | -0.19 |
| Mean absolute error (MAE) | 0.61 |
| Root mean square error (RMSE) | 0.79 |
| Standard deviation of residuals (STDres) | 0.77 |
| Correlation coefficient (R) | 0.76 |
| Nash Sutcliffe correlation coefficient (R2) | 0.52 |

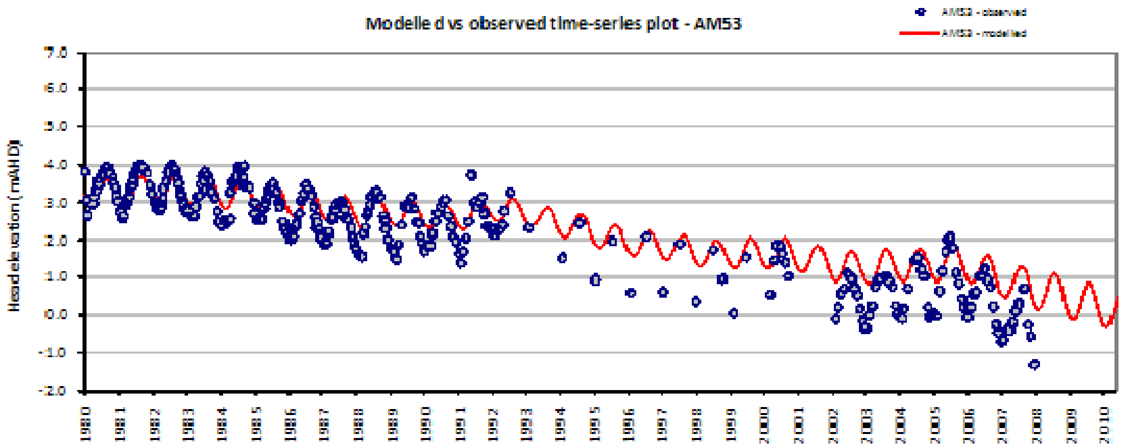
## Leederville Aquifer – AM50Z

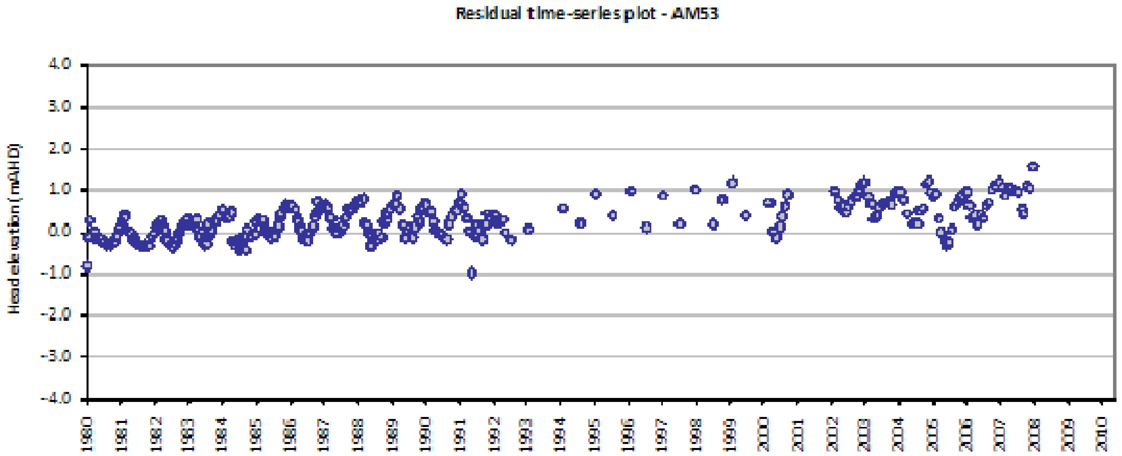



| Statistics | |
|---|---|
| Mean error (ME) | 2.37 |
| Mean absolute error (MAE) | 2.37 |
| Root mean square error (RMSE) | 2.49 |
| Standard deviation of residuals (STDres) | 0.75 |
| Correlation coefficient (R) | 0.71 |
| Nash Sutcliffe correlation coefficient (R2) | -4.40 |

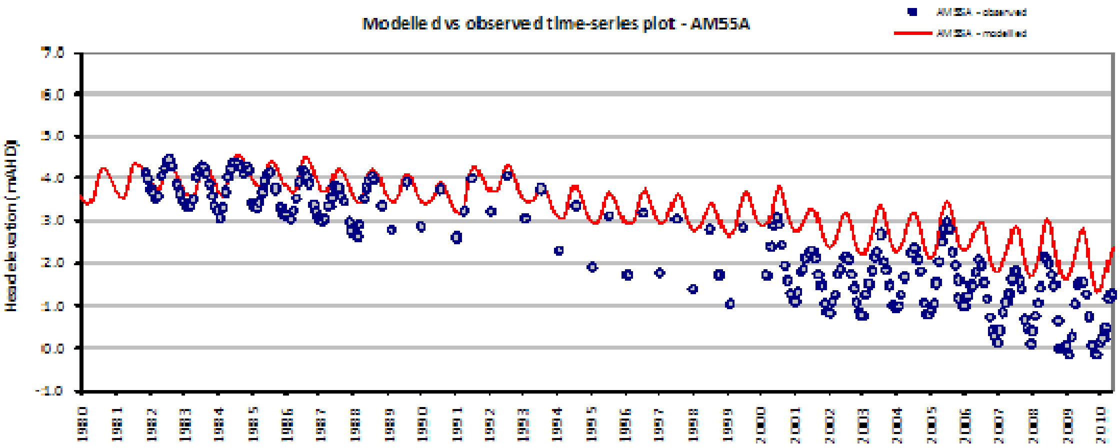
## Leederville Aquifer – AM53

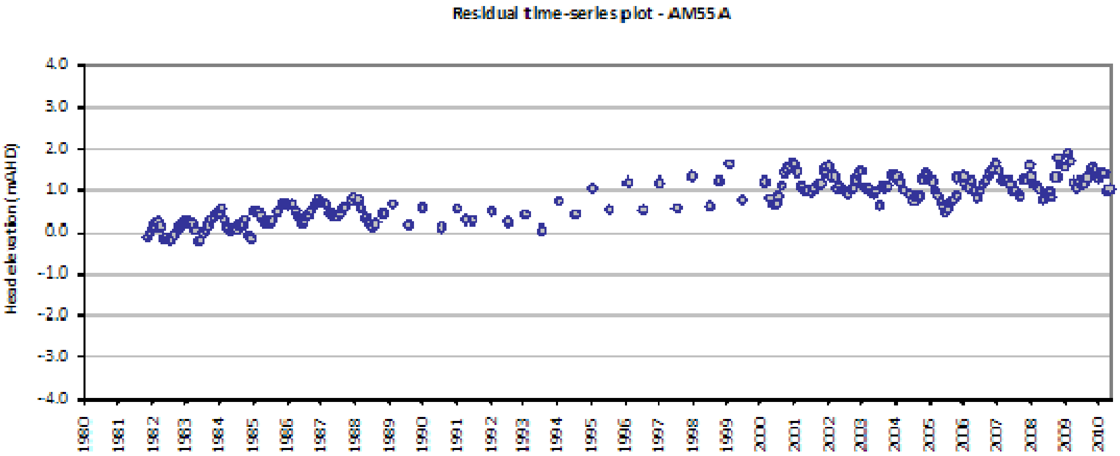



| Statistics | |
|---|---|
| Mean error (ME) | -0.21 |
| Mean absolute error (MAE) | 0.34 |
| Root mean square error (RMSE) | 0.43 |
| Standard deviation of residuals (STDres) | 0.38 |
| Correlation coefficient (R) | 0.97 |
| Nash Sutcliffe correlation coefficient (R2) | 0.81 |

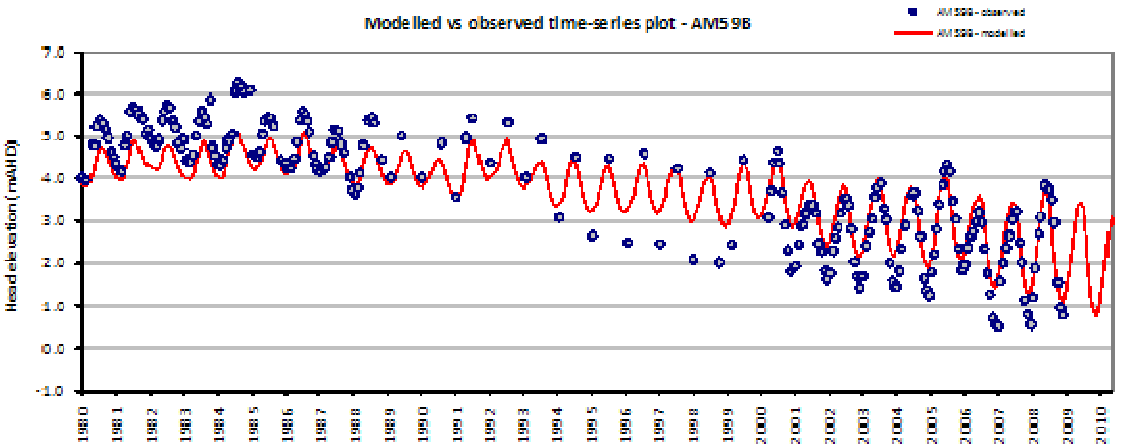
## Leederville Aquifer – AM55A

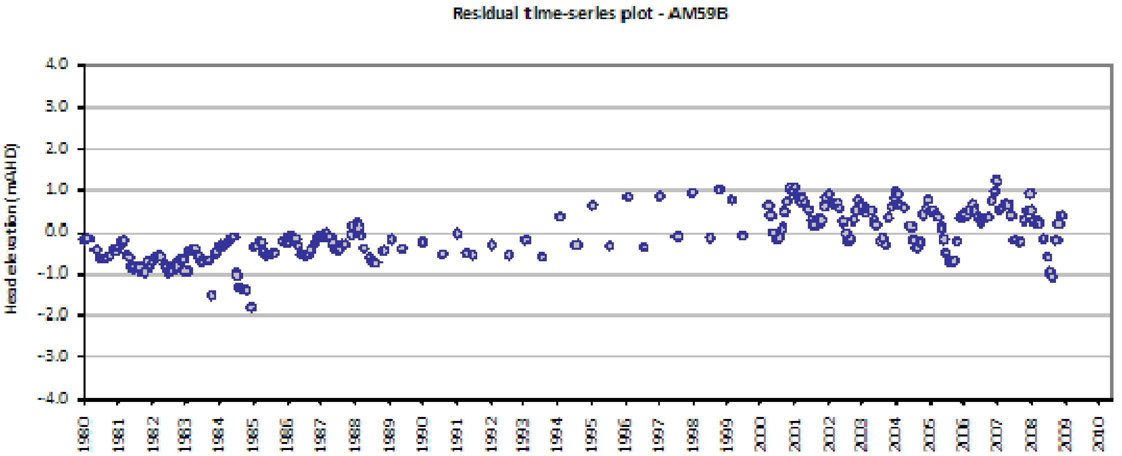



| Statistics | |
|---|---|
| Mean error (ME) | -0.65 |
| Mean absolute error (MAE) | 0.67 |
| Root mean square error (RMSE) | 0.81 |
| Standard deviation of residuals (STDres) | 0.48 |
| Correlation coefficient (R) | 0.97 |
| Nash Sutcliffe correlation coefficient (R2) | 0.42 |

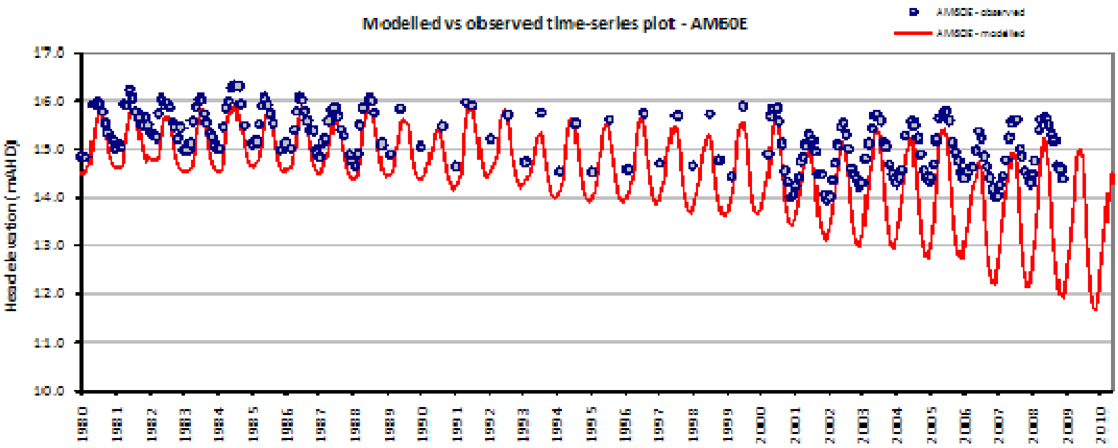
## Leederville Aquifer – AM59B

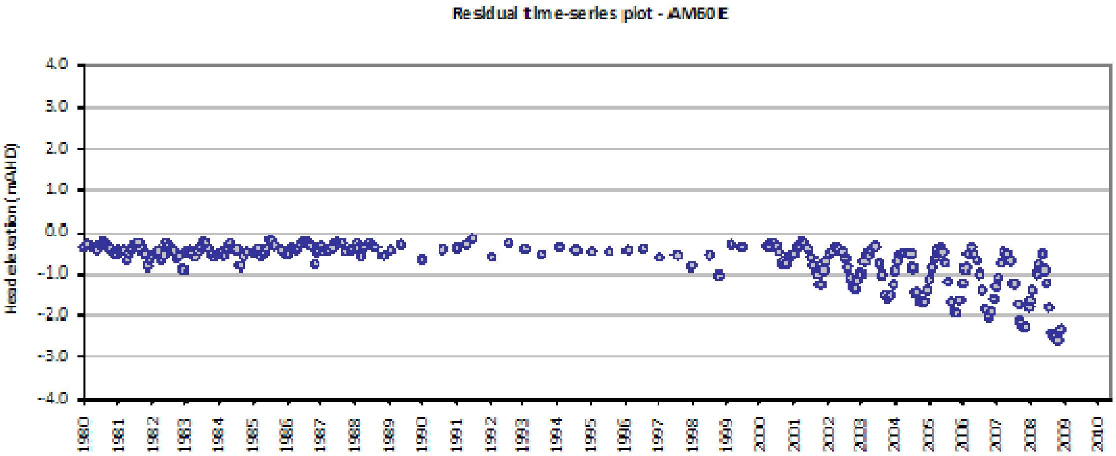



| Statistics | |
|---|---|
| Mean error (ME) | 0.16 |
| Mean absolute error (MAE) | 0.50 |
| Root mean square error (RMSE) | 0.59 |
| Standard deviation of residuals (STDres) | 0.57 |
| Correlation coefficient (R) | 0.95 |
| Nash Sutcliffe correlation coefficient (R2) | 0.76 |

## Leederville Aquifer – AM60E




| Statistics | |
|---|---|
| Mean error (ME) | 0.52 |
| Mean absolute error (MAE) | 0.52 |
| Root mean square error (RMSE) | 0.59 |
| Standard deviation of residuals (STDres) | 0.28 |
| Correlation coefficient (R) | 0.94 |
| Nash Sutcliffe correlation coefficient (R2) | -0.16 |

# Shortened forms

| | |
|---|---|
| ARI | average recurrence interval |
| DEC | Department of Environment and Conservation |
| DHI | Danish Hydrological Institute |
| DoW | Department of Water |
| DWMP | drainage and water management plan |
| ESRI | Earth Systems Research Institute |
| IPCC | Intergovernmental Panel on Climate Change |
| LAI | leaf area index |
| LiDAR | light detection and ranging |
| LS | locally sensitive |
| MDBC | Murray Darling Basin Commission |
| MGA | Map Grid of Australia |
| Mike SHE | System Hydrologic European |
| MSR | mean sum of residuals |
| NSE | Nash-Sutcliffe efficiency |
| PRAMS | Perth Regional Aquifer Modelling System |
| RD | root depth |
| RMS | root mean square |
| SOR | successive over-relaxation |
| SQUARE | Streamflow Quality for Rivers and Estuaries model |
| UTM | Universal Transverse Mercator |
| WAPC | Western Australian Planning Commission |

# Glossary

| | |
|---|---|
| **Abstraction** | pumping groundwater from an aquifer |
| **Australian height datum (AHD)** | height datum used within the study: where level (AHD) = mean seal level (MSL) + 0.026 m |
| **Alluvium** | detrital material transported by streams and rivers and deposited |
| **anticline** | sediments folded in an arch |
| **aquifer** | a geological formation or group of formations able to receive, store and transmit significant quantities of water |
| **unconfined aquifer** | a permeable bed only partly filled with water and overlying a relatively impermeable layer – its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure |
| **confined aquifer** | a permeable bed saturated with water and lying between an upper and a lower impermeable layer |
| **semi-confined** | a permeable bed saturated with water and lying between an upper and a lower impermeable layer |
| **artesian aquifer (bore)** | a confined aquifer with sufficient hydraulic head that the water in a bore would rise above the ground surface |
| **perched aquifer** | an unconfined aquifer separated from an underlying body of groundwater by an unsaturated zone (contains a perched watertable) |
| **baseflow** | that portion of a river and streamflow coming from groundwater discharge |
| **basin (geological)** | a depression of large size, which may be of structural or erosional origin (contains sediments) |
| **beds (geological)** | a subdivision of a formation: smaller than a member |
| **bore** | small-diameter well, usually drilled with machinery |
| **coffee rock** | colloquial term for iron oxide (limonite)-cemented sand grains |
| **colluvium (colluvial)** | material transported by gravity down hill slopes |

| | |
|---|---|
| **confining bed** | sedimentary bed of very low hydraulic conductivity |
| **conformably** | sediments deposited in a continuous sequence without a break |
| **unconformably** | time break in sequence of deposition |
| **discharge (groundwater)** | all water leaving the saturated part of an aquifer |
| **effective porosity** | drainable pore space, considered synonymous with specific yield of unconfined aquifer |
| **ephemeral stream** | stream or river that flows briefly in direct response to rainfall and whose channel is above the watertable |
| **estuary (estuarine)** | the seaward or tidal mouth of a river where fresh water comes into contact with seawater |
| **evapotranspiration** | a collective term for evaporation and transpiration |
| **fault** | a fracture in rocks or sediments along which there has been an observable displacement |
| **field capacity** | soil moisture retained by capillarity, not removable by gravity drainage |
| **fluvial** | pertaining to streams and rivers |
| **flux** | outflow or inflow |
| **formation (geological)** | a group of rocks or sediments which have certain characteristics in common and which were deposited in about the same geological period and constitute a convenient unit for description |
| **hydraulic** | pertaining to water motion |
| **conductivity (permeability)** | ease with which water is conducted through an aquifer |
| **gradient** | the rate of change of total head per unit of distance of flow at a given point and in a given direction |
| **head** | the height of the free surface of a body of water above a given subsurface point |
| **infiltration** | movement of water from the land surface to below ground level |
| **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 |
| **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 |
| **model (modelling system)** | a simplified version of the hydrological system that approximately simulates the excitation-response relations of the real system |
| **percolation** | movement of water from the land surface to the watertable after infiltration |
| **permeable** | ability to permit water movement |
| **plain** | tract of flat or level terrain |
| **pore space** | the open spaces in sediments, considered collectively |
| **potentiometric surface** | an imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a bore (The watertable is a particular potentiometric surface.) |
| **Quaternary** | the latest period in the Canozoic era |
| **recharge (groundwater)** | all water reaching the saturated part of an aquifer (artificial or natural) |
| **scarp** | a line of cliffs (steep slopes) produced by faulting or by erosion |
| **shelf** | shallow, marginal part of a sedimentary basin |
| **specific yield** | the volume of water that an unconfined aquifer releases from storage per unit surface area of the aquifer per unit decline in the watertable |
| **storage coefficient** | the volume of water that a confined aquifer releases from storage per unit surface area of aquifer per unite decline in the component of hydraulic head normal to the surface |
| **stratigraphy** | the science of rock strata: concerned with original succession and age relations of rock strata and their form, distribution, lithology, fossil |

| | |
|---|---|
| | content, geophysical and geochemical properties |
| **syncline** | a basin shaped fold in sedimentary strata |
| **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 |
| **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 |

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