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

Looking after all our water needs

Groundwater resource assessment of the Western Busselton-Capel groundwater area

Hydrogeological record series

Report no. HG38
November 2009

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By DB Schafer and SL Johnson

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Cover: Groundwater monitoring site CW4 near the corner of Osmington and Jindong Treeton Roads. Photograph by Geoff Sadgrove

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Summary

A three-dimensional groundwater flow model has been developed for the western Busselton-Capel Groundwater Area to assess groundwater resources and potential impacts of increasing allocation limits. The groundwater model is focused on the Leederville aquifer within the Cowaramup and Dunsborough-Vasse groundwater subareas.

Development of the groundwater model incorporated the conceptual understanding from the Cowaramup investigation undertaken in 2006. The model was constructed using the Visual MODFLOW graphical user interface and MODFLOW-SURFACT as the computational engine. The model has four layers that are considered to be hydrogeologically consistent and representative. Hydraulic conductivity zones within each layer were estimated following an analysis of sand percentage in the Leederville aquifer using PETREL software. Recharge and evapotranspiration zones were based on land use, topography and depth to watertable variables.

A complete hydrological cycle is represented in the groundwater model with groundwater recharge entering on the Blackwood Plateau area and flowing northward to Geographe Bay. There is shallow groundwater discharge into the Margaret, Carbunup and Vasse Rivers. The western and eastern boundaries of the model are marked by the Dunsborough and Busselton Faults respectively. The southern boundary coincides with a catchment divide to the south of Margaret River, while Geographe Bay marks the northern boundary.

The model has been calibrated under steady state and transient state conditions. Water level hydrographs from 55 monitoring bores were used as the calibration dataset. Final calibration was achieved within the recommended guideline values for scaled root mean square error and water balance error. The model was verified by comparing modelled hydraulic conductivity with pumping test data, as well as modelled particle track ages being consistent with carbon-14 groundwater age data.

Seven scenarios were run from 2005 to 2020 using the calibrated groundwater model representing different abstraction and climatic regimes. The scenarios assessed the potential for increasing allocation limits and identifying areas sensitive to water level drawdown. For each scenario, an annual water balance for 2005 to 2020 and water level drawdown figures were generated.

Scenario modelling indicated that winter residual drawdown occurs in parts of the Dunsborough–Vasse subarea associated with significant abstraction in the Jindong area, Quindalup borefield and lower Carbunup valley. This implies that there is local storage depletion in these areas.

No residual watertable impacts were observed in the scenarios suggesting that deeper abstraction from the Leederville aquifer will not impact the watertable. Most watertable fluctuations are believed to be related to recharge variability. It is also considered that any localised watertable decline is fully recharged by winter rainfall.

Groundwater resources in the Dunsborough–Vasse subarea are considered to be at full allocation. There is no scope for increasing groundwater allocations in this subarea. As part of good management practice, close monitoring and reviewing of water level impacts in the Jindong and Quindalup areas will be necessary. Scenario modelling has also suggested that sustained abstraction from the Quindalup borefield has potential for saltwater intrusion.

Scenario modelling indicates that an additional allocation of 1.5 GL/year is available from the Leederville aquifer in the Cowaramup subarea. Even though the subarea is sensitive to climate change, there is a high level of confidence that allocations can be increased with minimal impact on the groundwater resource. Model water balances suggest the additional allocation would only have a small impact on groundwater throughflow into the Dunsborough-Vasse subarea.

In the Cowaramup subarea, the lower reaches of Margaret River appear most sensitive to abstraction especially from shallow bores. This sensitivity has required the setting of licensing conditions / rules for protection of the groundwater resource. The application of the increased allocation requires different management approaches across the subarea.

In order to support the Department's groundwater licensing process, a number of management zones with specific conditions were developed. These management zones require minimum bore spacings, limits on individual bore licences, recommended bore depths, and an allocation exclusion zone around Margaret River.

Current groundwater monitoring is considered sufficient for observing maximum and minimum water levels. However, it is recommended that continuous water level data loggers be installed in all monitoring bores in the Cowaramup subarea to better monitor water level changes related to proposed allocation changes.

A groundwater review is recommended in five years (2013) to assess aquifer performance and response to the increased allocation limits. Prior to the review, there is a need for a thorough survey of all abstraction bores including the development of an improved abstraction database with surveyed bore levels and screen intervals, actual abstraction data for bores greater than 50 ML/year, as well as resting and pumping water levels from all abstraction bores.

1 Introduction

1.1 Background

Since 1999, the Leederville aquifer in the Cowaramup subarea has been fully allocated with licensed allocations exceeding the existing allocation limits. A groundwater resource assessment indicated that substantial groundwater resources may be available from the Leederville aquifer for use by the local viticultural industry (Johnson, 2000). It was recommended that a groundwater investigation would be required, prior to recommending modifications to the allocation limit.

Most groundwater allocation and use in the region is related to horticultural and viticultural activities. The expansion of the Margaret River wine-growing region, to the east of the town, and development of broad-acre irrigation on the sandy soils overlying the Perth Basin has led to an increased demand for groundwater.

Groundwater investigations in the Cowaramup groundwater subarea, funded under the State Groundwater Investigation Program, were completed in 2006. The investigation involved the installation of 14 groundwater monitoring bores to improve understanding of the hydrogeology and groundwater resources. A number of complementary studies on groundwater age dating, hydrochemistry and permanency of pools along Margaret River were also undertaken. The results of the drilling investigation and subsequent studies are detailed in Schafer et al. (2008).

The new hydrogeological interpretations formed the basis and conceptual understanding of this groundwater resource assessment in both the Cowaramup and Dunsborough–Vasse subareas. The development of a numerical groundwater model was recommended, as a means of determining new allocation limits in the western part of the Busselton–Capel Groundwater Area. In order to gain a thorough appreciation of the hydrogeology, it is recommended that this document is read in conjunction with Schafer et al. (2008).

This report details the development of the numerical groundwater model, its calibration, predictive simulations, sensitivities and limitations. The model outputs will be discussed in a groundwater resource management context including recommendations for modifying allocation limits, buffer zones around sensitive areas, licensing considerations and monitoring requirements.

1.2 Scope and purpose

A subregional, numerical groundwater flow model has been developed to represent the groundwater system and assess potential impacts of modifying allocation on groundwater dependent ecosystems and neighbouring subareas. It was critical for the model to incorporate surface water–groundwater interaction features that could provide quantified predictions of groundwater levels in aquifers and water levels in pools along Margaret River, based on different abstraction and climate change scenarios.

The model covers the western portion of the Busselton–Capel Groundwater Area including the Cowaramup and Dunsborough–Vasse subareas (Fig. 1). This was recommended by Johnson (2000) who indicated that the Cowaramup subarea is considered the recharge area for the Dunsborough–Vasse subarea. Consequently, any reassessment of the allocation limits in the Cowaramup subarea needs to consider potential effects on the more northerly subarea.

The modelling was undertaken in-house by the Groundwater Investigation Section. The development of the model was required to conform to the Murray Darling Basin groundwater flow modelling guidelines (MDBC, 2001). The model was constructed to be independent of the South West Aquifer Modelling System (Sun, 2005), known as SWAMS, but some model parameters / constraints were based on SWAMS.

The primary objective of the groundwater model was to simulate the groundwater system of the study area requiring (1) the model domain and boundary conditions to be a reasonable representation of the physical entity; (2) parameters and zonations to be a reasonable representation of the hydrogeology; and (3) a good calibration between the observed and calibrated water levels. The model was designed to:

- simulate groundwater flow within and between all hydrogeological units in the superficial and Leederville aquifers within the model area;
- under a range of scenarios, including abstraction and climate variations, predict the scale of changes in recharge and water levels;
- evaluate changes in groundwater discharge to Geographe Bay;
- predict the general drawdown in water levels near other groundwater users, wetlands, and rivers and streams, and provide seasonal variations of such reductions; and
- provide results that will support the determinations of new allocation limits.

1.3 Previous studies

Since the early 1960s, there have been a variety of geological and hydrogeological studies throughout the area. This has included structural and stratigraphical interpretations of the southern Perth Basin, coal and petroleum exploration by various mining companies, as well as regional groundwater exploration and groundwater resource assessments by the Geological Survey of Western Australia. These studies are summarised in Schafer et al. (2008).

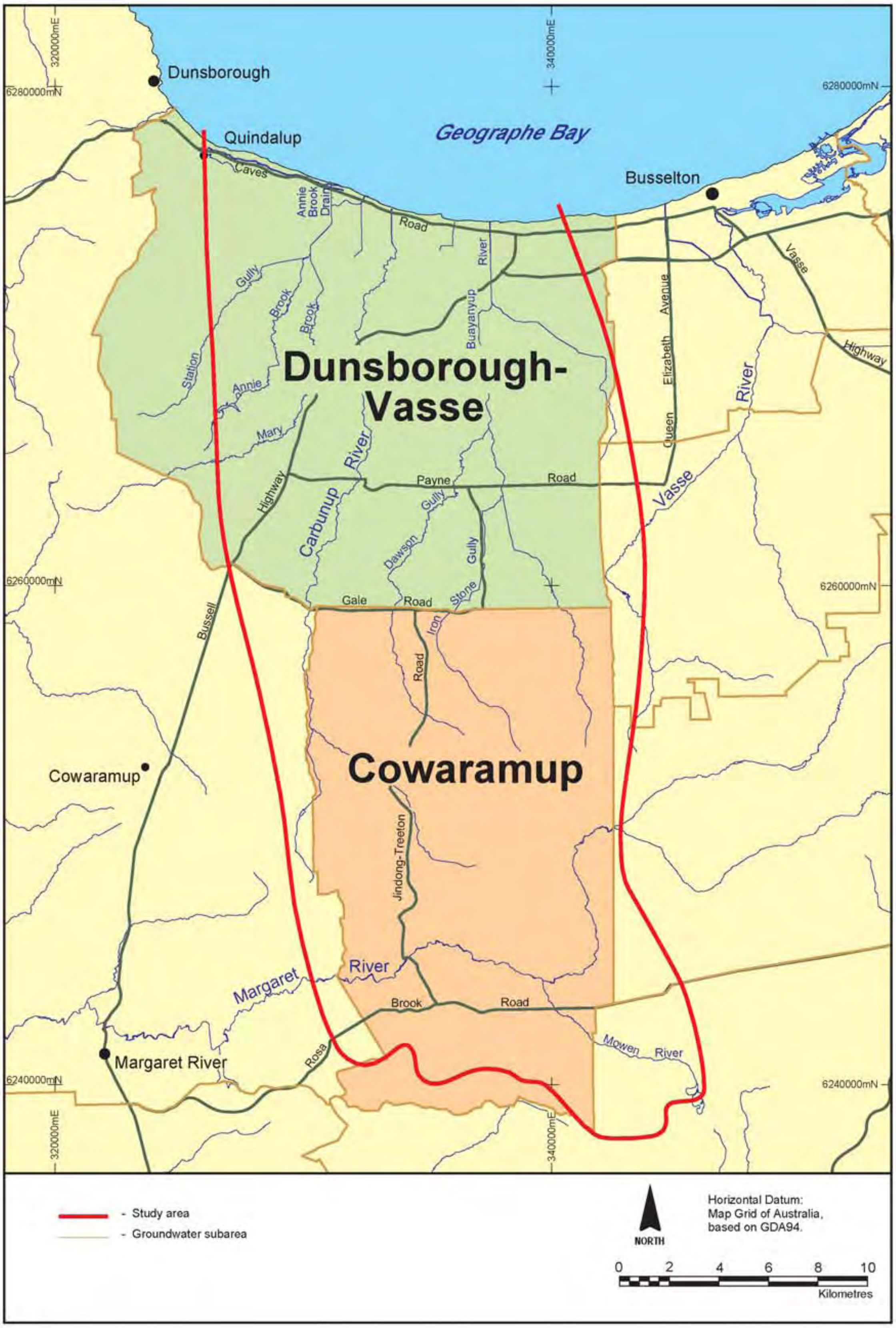


Figure 1 Location

A groundwater model to simulate the aquifers in the Southern Perth Basin was developed by the Water Corporation (2005). The SWAMS model, based on extensive groundwater investigations, is a regional representation of the groundwater system and covers more than 8500 km^2. The SWAMS model is considered too regional in extent and lacks sufficient hydrogeological interpretation on the Vasse Shelf, which is the focus of this groundwater resource assessment.

An analysis of hydrographs for the entire South West groundwater area was undertaken by Golder Associates (2008). Cumulative rainfall departure methods of HARTT (Hydrograph Analysis: Rainfall and Time Trends) and CDFM (Cumulative Departure from Mean) were used to analyse water level trends in hydrographs.

2 Geological and hydrogeological review

2.1 Regional geology

The regional geology is dominated by a Cretaceous sedimentary sequence which was deposited within the southern Perth Basin. The southern Perth Basin is situated between the Yilgarn Craton in the east and the Leeuwin Complex to the west. A major north-south trending Busselton Fault subdivides the southern Perth Basin into two major structural units: the deep Bunbury Trough to the east and a relatively shallow fault block, known as the Vasse Shelf, to the west. The model area is situated entirely within the Vasse Shelf (Fig. 2).

The Busselton Fault delineates the eastern edge of the Vasse Shelf and the model area. The Cretaceous sequence extends across and is not affected by the Busselton Fault. The western edge of the Vasse Shelf is bound by the Dunsborough Fault, which separates the sedimentary deposits of the Vasse Shelf from the gneissic rocks of the Leeuwin Complex. The Dunsborough Fault also marks the western boundary of the model area.

There has been extensive faulting of the Permian rocks on the Vasse Shelf, though the overlying Cretaceous and Quaternary sediments are believed to be largely unfaulted. Faulting and weathering processes have created an undulating surface at the top of the Permian sequence upon which the Cretaceous sediments were deposited. The top of the Permian sequence forms the base of the groundwater flow model.

2.2 Stratigraphy

Stratigraphic units in the study area are described in order of deposition and summarised in Table 1. The Cretaceous Leederville Formation unconformably overlies Permian deposits and comprises a sequence of onshore fluviatile (river) and paludal (swamp) deposits. The sediments are essentially flat-lying with a gentle slope to the north and have a thick weathering profile, up to about 25 m thick, where they outcrop on the Blackwood Plateau.

2.3 Hydrostratigraphy

There are two regional aquifer systems in the study area: the superficial aquifer and the Leederville aquifer. The superficial aquifer is a thin unconfined aquifer that only occurs on the Swan Coastal Plain. The Leederville aquifer is a major multi-layered sedimentary aquifer that extends throughout the model area. For the most part, the Leederville aquifer is a confined aquifer system.

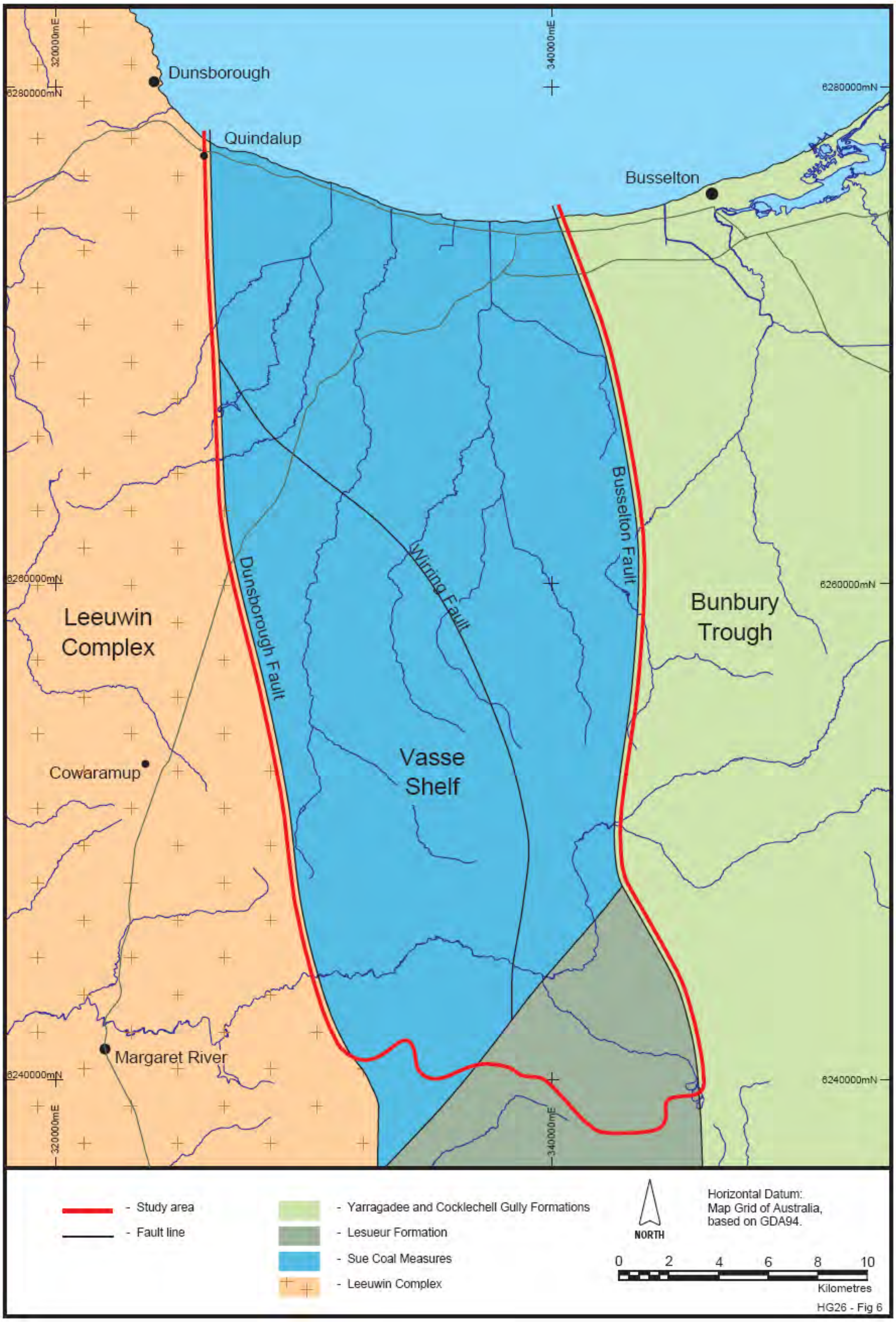


Figure 2 Pre-Cretaceous geology

Table 1 Stratigraphic sequence

Age	Stratigraphy	Thickness (m)	Lithology	Hydrogeological characteristics
Quaternary – Late Tertiary	Superficial formations	3–9		
	Tamala Limestone		Calcarenite, sand with shell debris	Superficial aquifer
	Bassendean Sand		Fine to medium sub-rounded quartz sand	Superficial aquifer
	Guildford Formation		Sandy silt and clay, ferruginised horizons	Local aquitard
	Yoganup Formation		White coarse sand, locally heavy minerals	Superficial aquifer
Cretaceous	Leederville Formation			
	Quindalup	0–33	Glauconitic silty clay, associated with sand and organic clay. Often has basal bed of coarse sand with minor clay	Leederville aquifer (local aquifer)
	Upper Mowen	0–7	Lignite seams and black carbonaceous clay, minor sand	Leederville aquifer (confining bed)
	Lower Mowen	8–43	Interbedded organic clay and sand, thin lignite seam, very clayey with minor sand	Leederville aquifer (minor aquifer)
	Upper Vasse	12–25	Interbedded sand and clay with minor lignite, common sandy beds (5 m+)	Leederville aquifer
	Lower Vasse	20–75	Consolidated grey clay and sand with common cemented bands	Leederville aquifer
	Yelverton	10–85	Well-consolidated grey / olive clay and sand, rare thin lignite seams	Leederville aquifer (minor aquifer)
Permian	Sue Group Sue Coal Measures	200+	Sandstone, minor shale and coal seams	Sue aquifer (local, minor aquifer)

There is limited interconnection between the superficial and Leederville aquifers beneath the Swan Coastal Plain due to the presence of confining beds. The

Leederville aquifer is underlain by the Sue aquifer, which has minor groundwater resources within localised fracture systems.

2.3.1 Superficial aquifer

The superficial aquifer forms an unconfined aquifer beneath the Swan Coastal Plain. It is thin with a saturated thickness of generally less than 5 m, and collectively includes the Tamala Limestone, Bassendean Sand, Guildford Formation and Yoganup Formation. The hydrogeology of the superficial aquifer is discussed in detail by Hirschberg (1989) and summarised by Schafer et al. (2008).

2.3.2 Leederville aquifer

The Leederville aquifer is a multi-layered aquifer system comprising discontinuous interbedded sequences of sand and clay. It extensively outcrops throughout the Blackwood Plateau and has been subdivided into six distinct members – Quindalup, Upper Mowen, Lower Mowen, Upper Vasse, Lower Vasse and Yelverton.

Quindalup Member

The Quindalup Member, the uppermost member, consists mostly of marine and estuarine clays that are generally laterally continuous. Beneath the Swan Coastal Plain, the Quindalup Member is generally thin (less than 10 m thick) except near Quindalup where it may be up to 40 m thick. It is completely absent at the base of the Whicher Scarp in the vicinity of the Carbunup River, and in the north-east corner of the model area where the Sue Coal Measures subcrop.

In the northern part of the Blackwood Plateau, the Quindalup Member is 30 to 50 m thick but becomes sandier and thins significantly towards Margaret River. It is completely absent from the lower parts of Margaret River. South of Margaret River, there is a change in lithology with more carbonaceous (organic) clay.

As a whole, the Quindalup Member is generally considered an aquitard. It is believed that the sandier parts of the Quindalup Member may be an important near-surface localised aquifer.

Upper Mowen and Lower Mowen Members

The Upper Mowen and Lower Mowen Members comprise lignitic and organic clay beds of the Upper Mowen Member and the dominant clay interbeds of the Lower Mowen Member. They typically range in thickness from 20 to 40 m, but thin significantly in the lower reaches of the Margaret River valley and at the base of the Whicher Scarp.

The Upper Mowen and Lower Mowen Members are interpreted to form a leaky aquitard. The discontinuous nature of individual clay and sand interbeds may provide localised flow paths and may contribute significantly to vertical leakage. The continuity of individual beds is considered highly variable but continuous beds of 500 to 1000 m may be common. The position and permanency of the riverine pools in

Margaret River is believed to be related to lithological variation in the Upper Mowen and Lower Mowen Members.

Upper Vasse Member

The Upper Vasse Member is considered the most significant aquifer within the Leederville aquifer, due to its high percentage (typically 65 to 75%) of sand beds. Individually sand beds are relatively thick, often up to 5 m.

The member extends throughout the study area and is up to 25 m thick. It is less consolidated than the underlying Lower Vasse and Yelverton Members, and consequently is believed to have high horizontal hydraulic conductivities in comparison. The discontinuous clay interbeds will reduce the vertical hydraulic conductivity throughout this member.

Lower Vasse and Yelverton Members

The Lower Vasse and Yelverton Members form the deepest aquifer system in the Leederville aquifer. They have a combined thickness of up to 125 m, and consist of thinly interbedded clays and sands with individual sand beds less than 3 m thick. The members are well consolidated. Cemented bands at the top of the Lower Vasse Member are believed to impede vertical groundwater flow. Despite the high proportion of clay and cement bands, the Lower Vasse and Yelverton Members have localised sand beds that are important aquifer horizons.

Vertical recharge from the overlying Upper Vasse aquifer is probably limited due to cemented bands and clay interbeds. However, Water Corporation (2005) suggested that there may be significant horizontal conductivity in these members.

2.3.3 Sue aquifer

The Sue aquifer consists of well-consolidated sandstone, siltstone and coal of the Sue Group, which has been locally fractured. Groundwater movement in the Sue aquifer is restricted to localised, open fractures in the sandstone and coal seams. Groundwater flow and interconnectivity between the Leederville and Sue aquifers is considered negligible.

2.4 Hydrogeological processes – Leederville aquifer

2.4.1 Recharge

The Leederville aquifer is recharged directly by rainfall infiltration on the Blackwood Plateau. Most recharge occurs in the area of topographic high coinciding with an east-west groundwater flow divide and in the vicinity of bores CW2 and CW4. In areas away from the divide, the hydraulic gradient is sufficiently steep to enable the recharge water to be transmitted as horizontal groundwater flow. The amount of recharge will vary considerably depending on land use, vegetation cover and surface geology.

On the Blackwood Plateau, the amount of recharge is controlled by downwards increasing hydraulic gradients. Areas of higher recharge are associated with cleared areas and where the sandy facies of the Quindalup Member outcrops. Colluvial slopes are likely to have higher recharge than hill tops that may have a thick weathering profile. Ferruginised hardpan and areas of discharge along watercourses will also inhibit recharge. On the Swan Coastal Plain, recharge of the Leederville aquifer from the thin overlying superficial aquifer is limited owing to low downwards hydraulic gradients and predominantly horizontal groundwater flow.

2.4.2 Groundwater flow

Groundwater flow in the Leederville aquifer is dominated by the regional groundwater flow divide located to the north of Margaret River (Fig. 3 and 4). The flow divide extends east-west across the model area and separates groundwater flow into northerly and southerly-trending flow.

Groundwater isopotential configuration throughout the model domain (Fig. 3 and 4) was generated by interpolating synoptic water level measurements by point kriging using SURFER (Golden Software, 2004). Some isopotentials were corrected manually to be consistent with surface features such as drainage lines where detailed localised data was unavailable.

There is a large loss of potentiometric head in the Leederville aquifer down the Whicher Scarp. The potentiometric head decreases from about 85 m AHD on the Blackwood Plateau to about 35 m AHD on the Swan Coastal Plain. Groundwater is believed to discharge into watercourses and wetlands across the Whicher Scarp, as well as through evapotranspiration loss.

There is shallow groundwater flow within the Quindalup and Upper Mowen Members, which is strongly influenced by topography with groundwater flowing from areas of high topography. This shallow system is strongly influenced by Margaret River, where it supports more than 20 permanent pools. There is also groundwater discharge along the Yelverton Shelf and Whicher Scarp, which act as a broad seepage face with high evapotranspiration and the presence of swampy areas.

In the deeper Leederville aquifer, there is a more regional groundwater flow within the Upper Vasse, Lower Vasse and Yelverton Members. Groundwater moves northward discharging in Geographe Bay and southward toward the Blackwood River catchment. Most groundwater flow in the deep Leederville aquifer is predominantly horizontal, especially in areas away from the groundwater flow divide.

The rate of flow and interconnection between the Leederville and superficial aquifers is considered not significant. Beneath the Swan Coastal Plain, the Leederville and superficial aquifers are largely separated by the clayey Quindalup and Lower Mowen Members, which act as semi-confining layers.

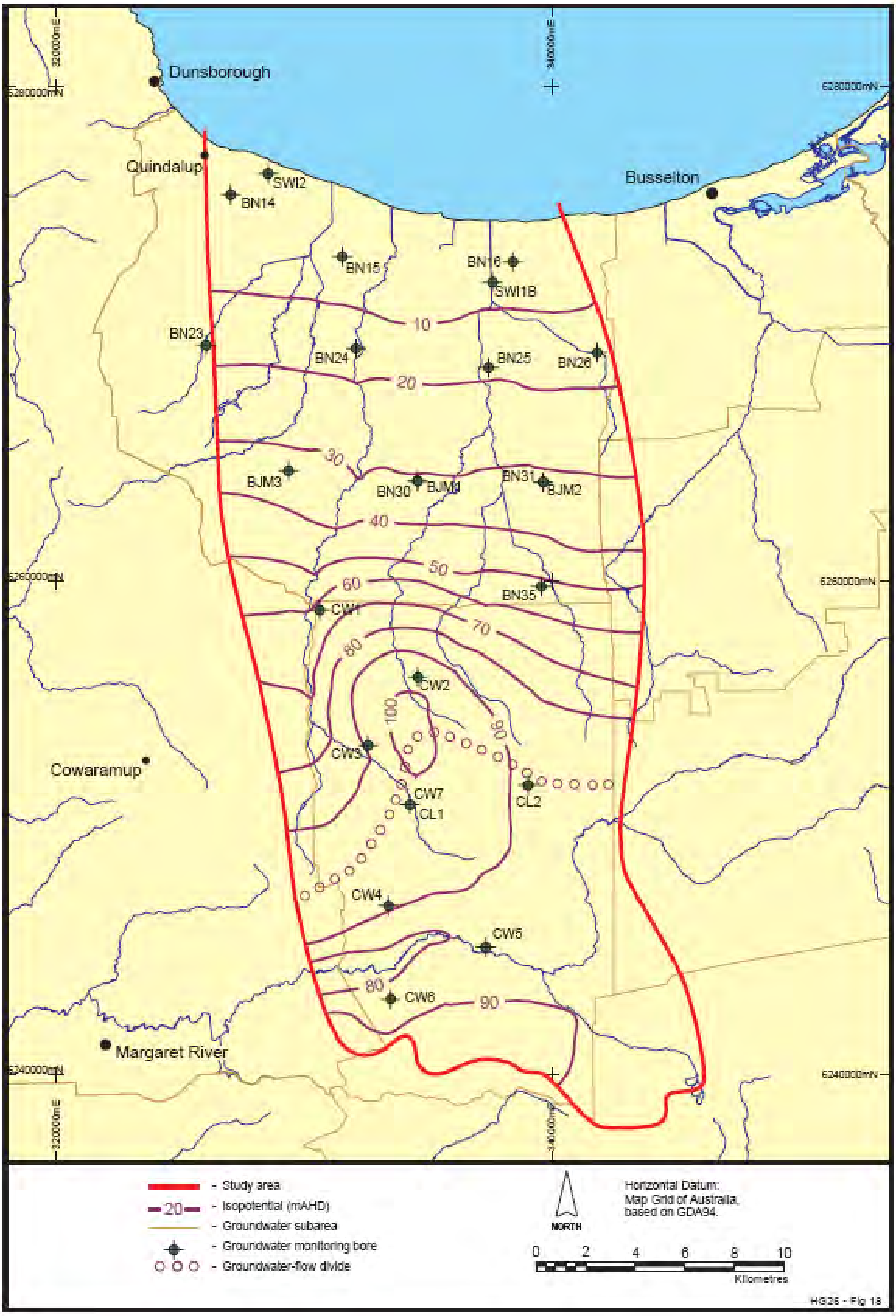


Figure 3 Isopotentials for intermediate bores (screened 17 m to 65 m bgl)

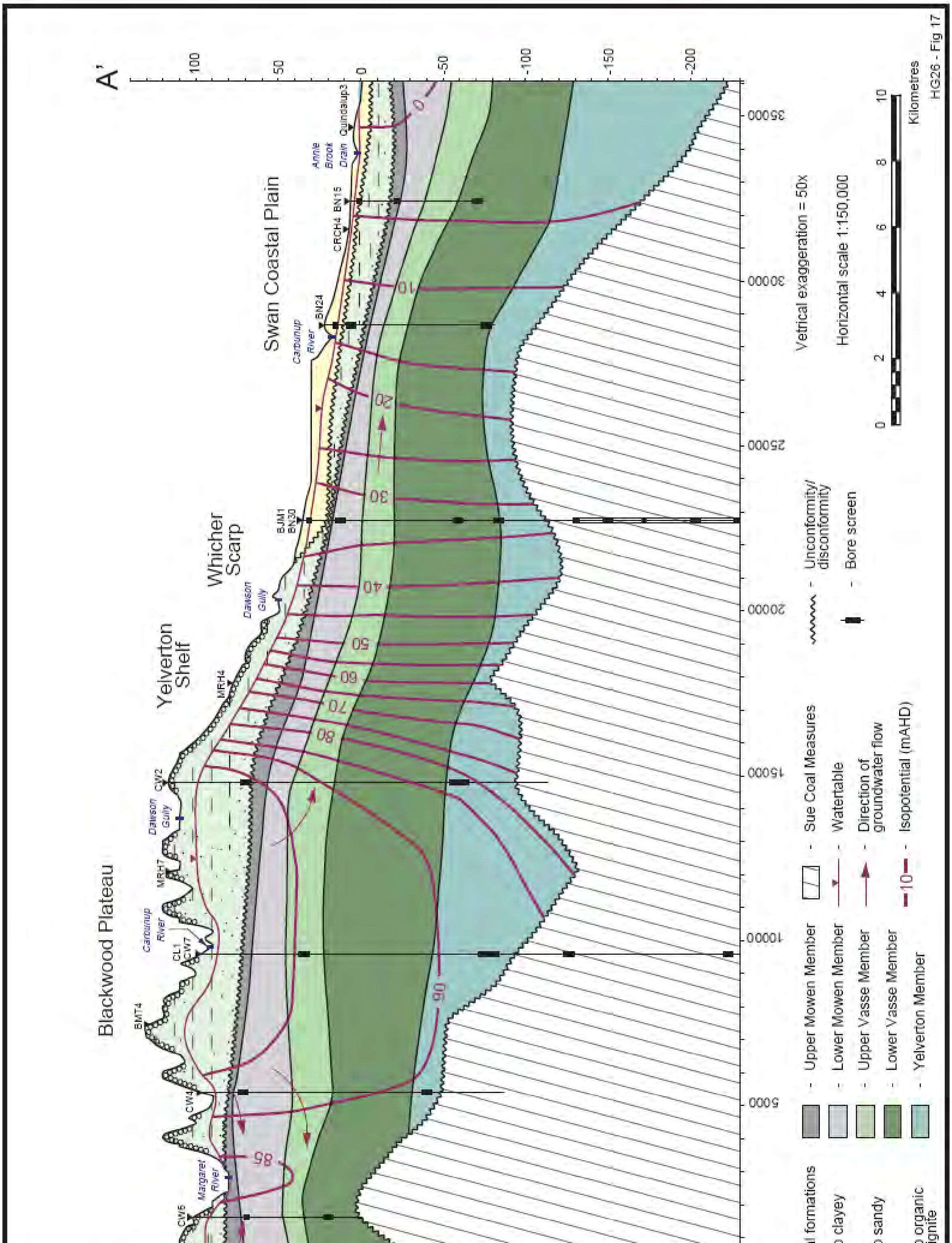


Figure 4 Hydrogeological south-north cross-section

Groundwater flow between the Leederville aquifer and the underlying Sue aquifer is considered very small due to the low permeability of the Sue aquifer. In addition, there is no appreciable westward flow or interconnection with the basement rocks of the Leeuwin Complex.

2.4.3 Discharge

Most groundwater discharge from the Leederville aquifer is associated with shallow groundwater flow. The main discharge occurs within the Margaret River valley in the south and at the base of the Whicher Scarp seepage face in the north.

The Margaret River valley is an area of upward potentiometric head and an important discharge area. Under the current lower rainfall conditions, there is no measurable baseflow but there are many riverine pools that remain permanent throughout summer. The permanency of these pools is dependent on groundwater discharge from the upper members of the Leederville aquifer.

Along the Yelverton Shelf and Whicher Scarp, there is a broad seepage face with most discharge from evaporation losses from wetlands and high rates of evapotranspiration. The base of valleys of north-trending drainage systems, including the Carbunup River, Dawson Gully and Ironstone Gully, are possible discharge areas with seasonal seepage.

3 Development of the numerical model

3.1 Model area

The Cowaramup groundwater model area is geologically and hydrogeologically complex, as it contains numerous alternating aquifer and aquitard layers that are heterogeneous. The conceptual model has simplified this complexity, whilst retaining sufficient features to allow a realistic representation (Fig. 5).

The groundwater model is subregional in scale and focused on the Leederville aquifer within the western portion of the Busselton-Capel Groundwater Area. The model includes the Cowaramup and Dunsborough-Vasse groundwater subareas. The western and eastern boundaries of the model are marked by the Dunsborough and Busselton Faults respectively. The southern boundary coincides with a catchment divide to the south of Margaret River, while Geographe Bay marks the northern boundary.

A complete hydrological cycle is represented in the model with groundwater recharge entering on the Blackwood Plateau area and flowing northward discharging at Geographe Bay. There is also some shallow groundwater discharge into the Margaret, Carbunup and Vasse Rivers.

3.2 Level of model complexity

The model is sufficiently complex to be regarded as an impact assessment model that can be used for evaluating aquifer response to changes in abstraction and climate over a sub-regional extent. The model is not considered a detailed aquifer simulator that is capable of accurately assessing local scale impacts. Model complexity is between moderately and highly complex, in accordance with the Murray-Darling Basin Commission groundwater modelling guidelines (MDBC, 2001).

3.3 Data collection

3.3.1 Surface topography

The surface topography has been taken from a Digital Elevation Model (DEM) dataset by the Department of Land Administration (DOLA). This dataset has a grid interval of 10 m x 10 m with a vertical accuracy for most points (about 95%) within +/-1.5 m. Some errors are likely in areas of dense vegetation, as the data was derived from digital photogrammetry techniques.

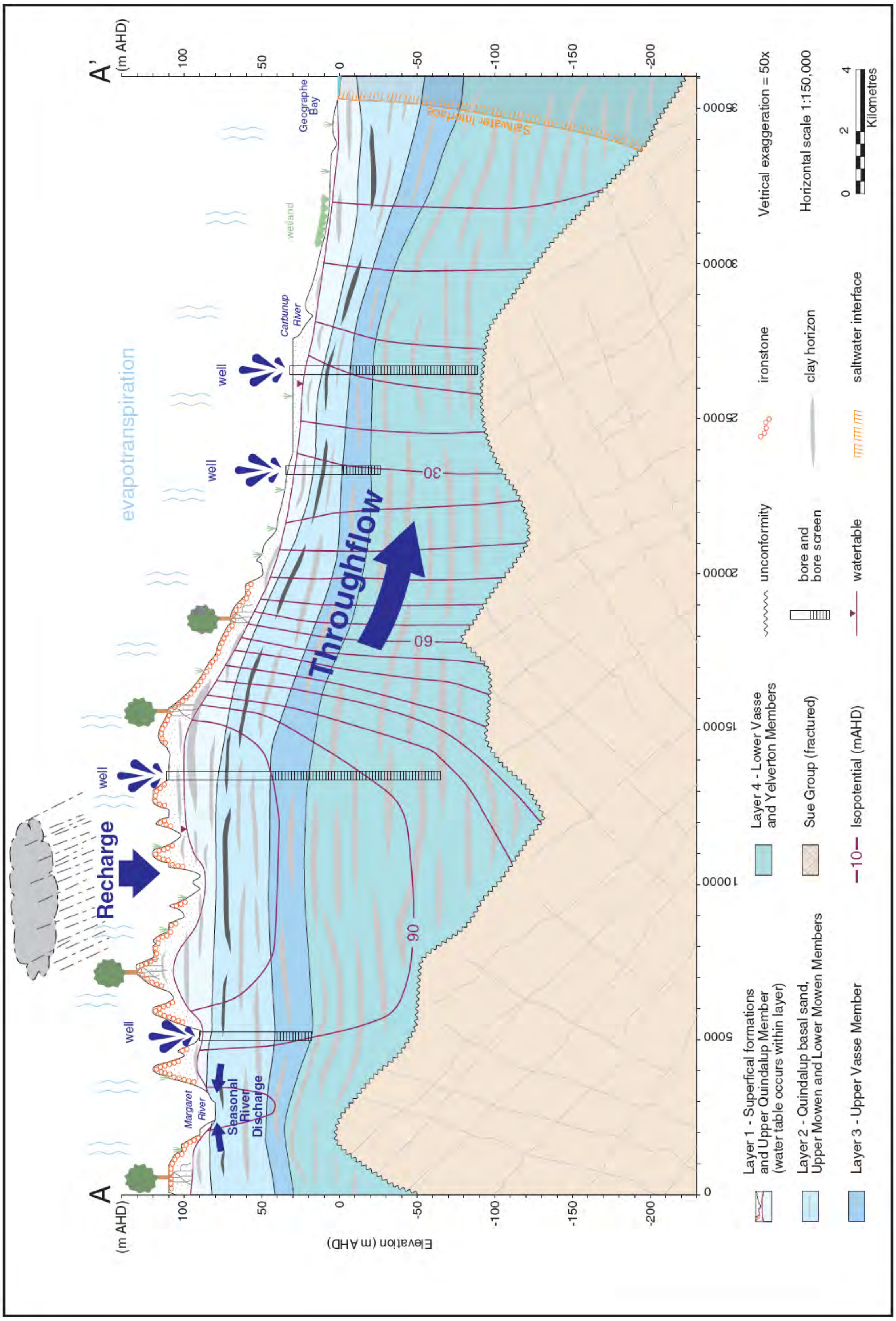


Figure 5 Conceptual model diagram

3.3.2 Rivers and drains

The location of rivers and surface water features was obtained from the Department of Water hydrography-linear GIS dataset. Reduced levels along major rivers were estimated using the DEM and the state 5 m contour layer (DOLA, 2002). A dataset for the agricultural drains on the Swan Coastal Plain was provided by the Water Corporation.

3.3.3 Stratigraphy

Stratigraphy within the model is based on interpretations of the Leederville Formation by Schafer et al. (2008). Structural contour surfaces of each member within the Leederville Formation were created based on lithological and geophysical data from 20 groundwater bores and 107 coal exploration bores. The surfaces were generated by point kriging using SURFER (Golden Software, 2004) with some manual correction. The representation of stratigraphic members as discrete model layers is detailed in Section 3.6.

3.3.4 Faults

The position of the Busselton and Dunsborough Faults was sourced from the Geological Survey of Western Australia (DME, 1999). It is important to note that these fault locations are considered approximate, as they have been interpreted from various geophysical and geological datasets.

3.3.5 Groundwater levels

Groundwater levels were obtained from a number of sources, primarily Department of Water databases. Additional data was acquired from licensing files held by the Department's South West regional office. Most construction data on groundwater bores was collected from the water information (or WIN) database. Time-variant water level data was also collected from the Department of Water's HYDSTRA database. All groundwater monitoring data from the new Cowaramup bores was included.

3.3.6 Groundwater abstraction

Groundwater abstraction data for the period 1990 to 2004 was obtained from the SWAMS model database, licensing files held by the Department's South West regional office, and Water Corporation for the Quindalup borefield. Abstraction data from 2004 to present was considered too inconsistent. This is not considered an issue as abstraction has not significantly changed in the last four years due to the Leederville aquifer being fully allocated. Details on processing and incorporating abstraction data into the model are discussed in Sections 3.11 and 4.3.

3.3.7 Rainfall and evaporation data

Daily rainfall and evaporation records for the Jarrahwood station near Nannup were obtained from the Commonwealth Bureau of Meteorology's database. Rainfall records from Department of Water Site 509062 (Margaret River - George Road) were also considered. These sites were selected due to their location within the model domain and length of record.

3.3.8 Streamflow data

Streamflow data was sourced from the Department of Water's HYDSTRA database in daily and monthly format. Gauged sites on the Margaret River and Carbunup River were selected.

3.4 Selection of a suitable modelling package

The MODFLOW-SURFACT groundwater modelling package was selected for the Cowaramup groundwater model, as it allows modelling of unsaturated conditions, seepage faces and drying/re-wetting processes. It is based on MODFLOW developed by the United States Geological Survey, which is the most widely used groundwater modelling package.

MODFLOW-SURFACT has a number of additional computational modules and distinct advantages, when compared with the standard MODFLOW modelling package. These were considered critical in the development of the groundwater model and include:

- prescribed ponding where watertable build-up beyond a specified ponding elevation (such as land surface) is prevented. This is important in addressing seasonal saturation of the land surface at the end of the winter;
- automatic apportioning of well flow rate to correct layers where wells are screened across multiple layers, even when the upper cells are pumped dry. This is important as many production bores are screened across different members of the Leederville aquifer;
- accurate watertable modelling that accounts for unsaturated zone flow, delayed yield and vertical flow components.

The model was constructed using the Visual MODFLOW 4.3 graphical user interface. This interface to the MODFLOW-SURFACT 3.0 computational engine allows ease of data input, and is also practical as other users can be trained in its use.

A finite element package was not considered appropriate or necessary, as the model geometry is essentially layered and rivers largely act as discharging drains with no permanent baseflow. The seepage face along the Yelverton Shelf / Whicher Scarp is easily handled by the prescribed ponding module within MODFLOW-SURFACT. A finite element package would only be required for more detailed modelling of groundwater-surface water interactions, but this was not considered necessary for this model.

3.5 Model grid

The model grid is aligned in a north–south orientation. This aligns the model grid with the general groundwater flow direction and broadly parallels the strike direction of the Busselton and Dunsborough Faults.

The selection of cell size is an important consideration and is often a compromise between accuracy and computational run time. As the groundwater model is subregional in scale, a grid cell size of 200 m x 200 m was considered appropriate. The total number of cells in each layer is 28 380 (215 rows x 132 columns); hence, there are 113 520 cells across the whole model domain. Previous modelling studies, such as Zhang (2007), demonstrated that the most efficient groundwater models have less than 200 000 cells in total.

3.6 Model layers

3.6.1 General

The Leederville aquifer is heterogenous consisting of interbedded clays and sands. This heterogeneity ensures it is not possible to represent all individual clay and sand horizons due to the complexity of the task, insufficient data and the large computation time required. As such, a number of assumptions were made to simplify the model.

The stratigraphic subdivision of the Leederville aquifer into six distinct members (Schafer et al., 2008) was simplified for the model. In determining the number of layers, the aquifer characteristics of each member were compared before combining stratigraphic members into four model layers.

Consequently, the groundwater model has been constructed as a four-layer model with each layer considered to be hydrogeologically consistent and representative (Fig. 5). The layered model approach is considered appropriate due to the relatively flat-lying nature of the Leederville aquifer. The top and base contoured surfaces of each model layer are shown in Appendix A, and model layer thicknesses are shown in Appendix B. Each model layer is discussed in more detail below.

Layer 1 - Superficial aquifer and Upper Quindalup Member: The superficial aquifer and Upper Quindalup Member together broadly form an unconfined aquifer covering the entire model area. The superficial aquifer occurs beneath the Swan Coastal Plain but is too thin (less than 5 m in thickness) to model as an individual layer. The Upper Quindalup Member occurs across the Blackwood Plateau, south of the Swan Coastal Plain. Layer 1 is strongly influenced by recharge, discharge and evapotranspiration processes.

There is a small area in the lower reaches of the Margaret River where Layer 1 is absent. Layer 1 has been extended across this area as a ‘dummy layer’ with the same properties as Layer 2, as MODFLOW requires layers to extend across the whole model domain. The thickness of dummy layer in this area was set at approximately half the thickness of Layer 2 to prevent cells drying.

Layer 2 - Quindalup basal sand, Upper Mowen and Lower Mowen Members: These members generally consist of sandy horizons interbedded with organic clay and lignite beds. This combined layer is generally considered confining to semi-confining with low vertical hydraulic conductivity and variable horizontal hydraulic permeability.

Layer 3 - Upper Vasse Member: The Upper Vasse Member is considered the most prospective aquifer horizon in the Leederville aquifer with consistently thick sand beds. This layer has the highest horizontal and vertical hydraulic conductivity, when compared with all other model layers.

Layer 4 - Lower Vasse and Yelverton Members: These members consist of relatively well-consolidated interbedded clay and sand. This lowest layer is characterised by moderate horizontal conductivity, but vertical hydraulic conductivity is restricted by the discontinuous clay interbeds and cementation. The model is inactive below Layer 4 with no groundwater interaction with the underlying, impermeable Sue Group.

3.6.2 Layer type

All model layers have been defined as confined/unconfined aquifers with variable transmissivity (Layer Type ‘3’ in MODFLOW). This layer type is appropriate since the watertable occurs in several model layers in their respective areas of outcrop. Another advantage is that the model layer can be unconfined in some areas and confined in other areas. Vertical leakage is limited when the overlying aquifer layer becomes unsaturated, which is most applicable to Layer 2 with the overlying Layer 1 varying between unconfined to confined conditions.

3.6.3 Layer properties

Input parameters for each layer include horizontal conductivity (Kh), vertical hydraulic conductivity (Kz), specific storage (Ss) and specific yield (Sy). The initial hydraulic parameters for model calibration were taken from SWAMS, but were further refined through zonation of hydraulic conductivity and during model calibration.

Hydraulic conductivities for the model layers were divided into several zones based on sand percentage within each member of the Leederville aquifer. This zonation approach has been adopted to address the often large, lateral variation in lithology and determine more accurate hydraulic conductivity parameters within model layers.

The sand percentage within each model layer was determined through the analysis of gamma logs and lithological logs (Fig. 6) using Petrel software. Lithological logs were compared with the gamma logs to determine gamma values that related to the presence of sand horizons. The percentage of sand along each gamma trace was estimated, as a measure of hydraulic conductivity, using the functionality of the Petrel software. This analysis was performed on 81 bore logs from bores drilled for coal exploration, groundwater investigation and water supply in the model domain.

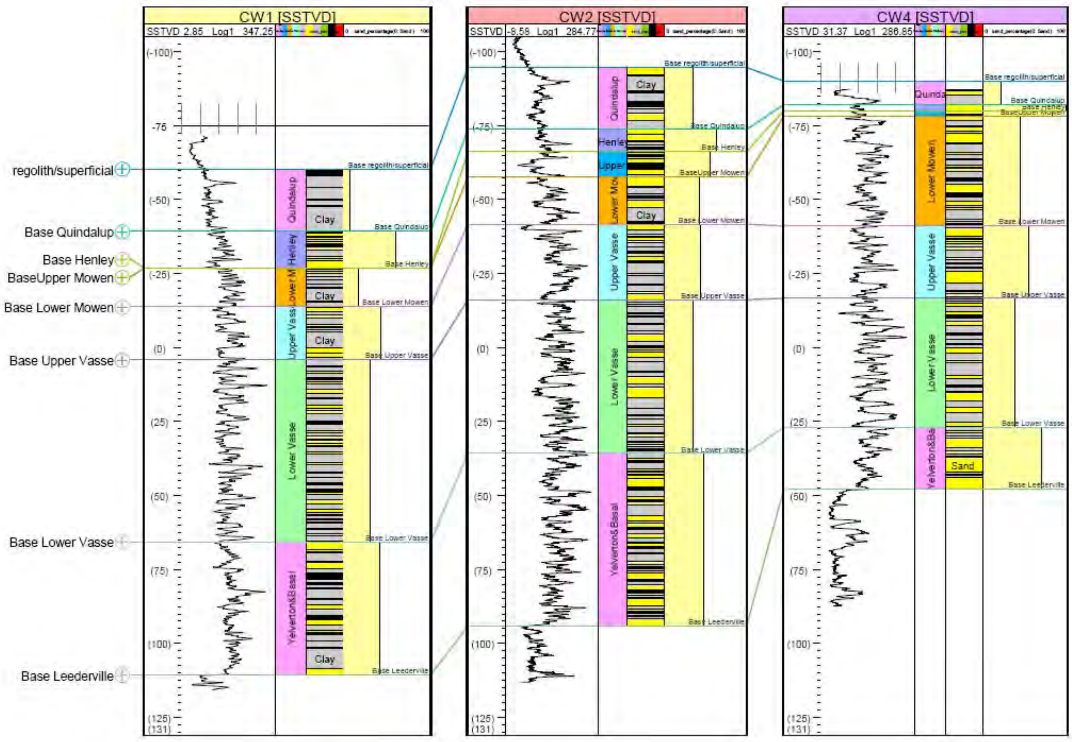


Figure 6 Example of Petrel analysis of gamma log for sand percentage

Sand percentage distribution maps for each member within the Leederville aquifer were generated (Appendix C). The initial sand percentage zonation was based on 25th percentile contours showing four different zones for each member. As the calibration progressed, zones were amalgamated and modified to better reflect the hydrogeological environment. Final hydraulic conductivity zones for each model layer are presented in Appendix D.

3.7 Model boundaries

3.7.1 Western boundary

The western boundary of the Cowaramup groundwater model represents the Dunsborough Fault, which separates the impermeable Leeuwin Complex from the Leederville aquifer (Fig. 7). The boundary is considered a no-flow boundary with all cells to the west of the boundary being inactive. There is a small veneer of sediments that overlie the Leeuwin Complex to the west of the Dunsborough Fault; however, groundwater inflow from these sediments was considered small and was not factored into the model.

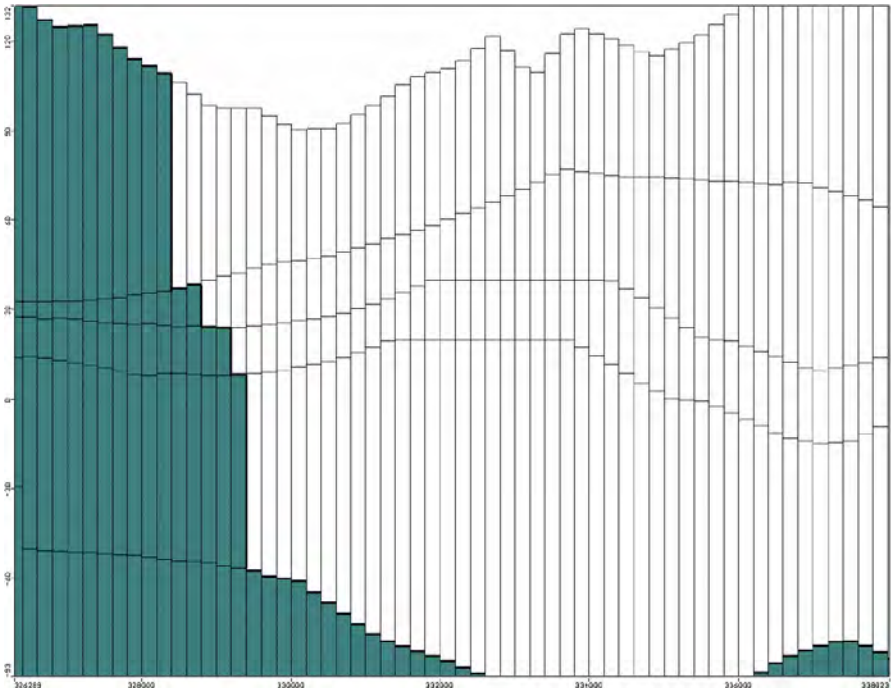


Figure 7 Western model boundary representing Dunsborough Fault (Row 134)

3.7.2 Eastern boundary

The eastern boundary coincides with the position of the Busselton Fault. This fault has not offset stratigraphy within the Leederville aquifer; but it does separate the Sue Group and Yarragadee Formation beneath the Leederville aquifer. In determining boundary conditions, it was considered necessary in the lower part of the model to reflect a component of hydraulic connection between the Leederville and Yarragadee aquifers.

In the upper three model layers (Layers 1 to 3), the eastern boundary is represented as a no-flow boundary. This is considered appropriate as the majority of groundwater flow is in a north–south direction with limited east–west groundwater movement.

Water levels in the lower part of the Leederville aquifer, east of the Busselton Fault, suggest that the more permeable Yarragadee aquifer is interacting with the Leederville aquifer. A general head boundary was used in Layer 4 to represent this interaction (Fig. 9) and reflect known water levels with a linear gradient from 58 m AHD at the groundwater flow divide through to 0 m AHD near the coast (Fig. 8). The effect of the general head boundary was to remove water from the model, when water levels in the Leederville aquifer are higher to the west of the Busselton Fault than in the east.

There is little groundwater information along the Busselton Fault to the south of the groundwater divide. As a result, it was decided to place a no-flow boundary in Layer 4 from the groundwater divide to the southern boundary rather than extending the general head boundary.

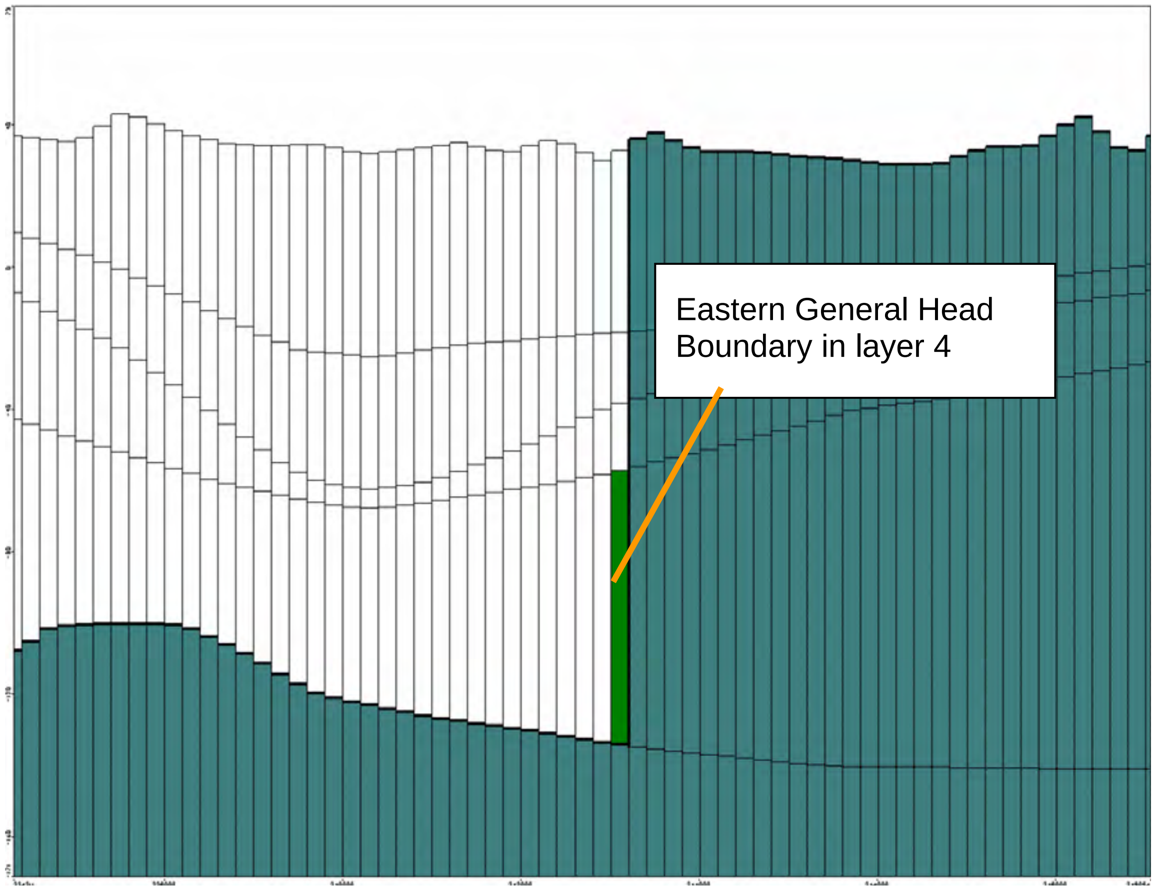


Figure 8 Eastern model boundary (Row 91)

3.7.3 Southern boundary

The southern boundary coincides with the topographic divide between the Margaret River and Upper Chapman Brook, which has been assumed to coincide with a groundwater divide. Though the position of the groundwater divide may move slightly due to seasonal water level fluctuation, it is assumed that the high groundwater potentials along the divide are sufficient to permit groundwater flow to the south. As such, the southern boundary is considered a no-flow boundary.

3.7.4 Northern boundary

The northern boundary along the coast represents the interface between the freshwater of the Leederville aquifer and seawater of Geographe Bay. The effect of the ocean has been modelled as a constant head of 0 m AHD in Layer 1 (Fig. 10), which has been extended northward to the edge of the model domain. A general head boundary has been placed in Layers 2, 3 and 4 at this northern extremity of the model (about 3 to 6 km offshore) to represent groundwater discharge into Geographe Bay and possible landward migration of seawater (Fig. 11).

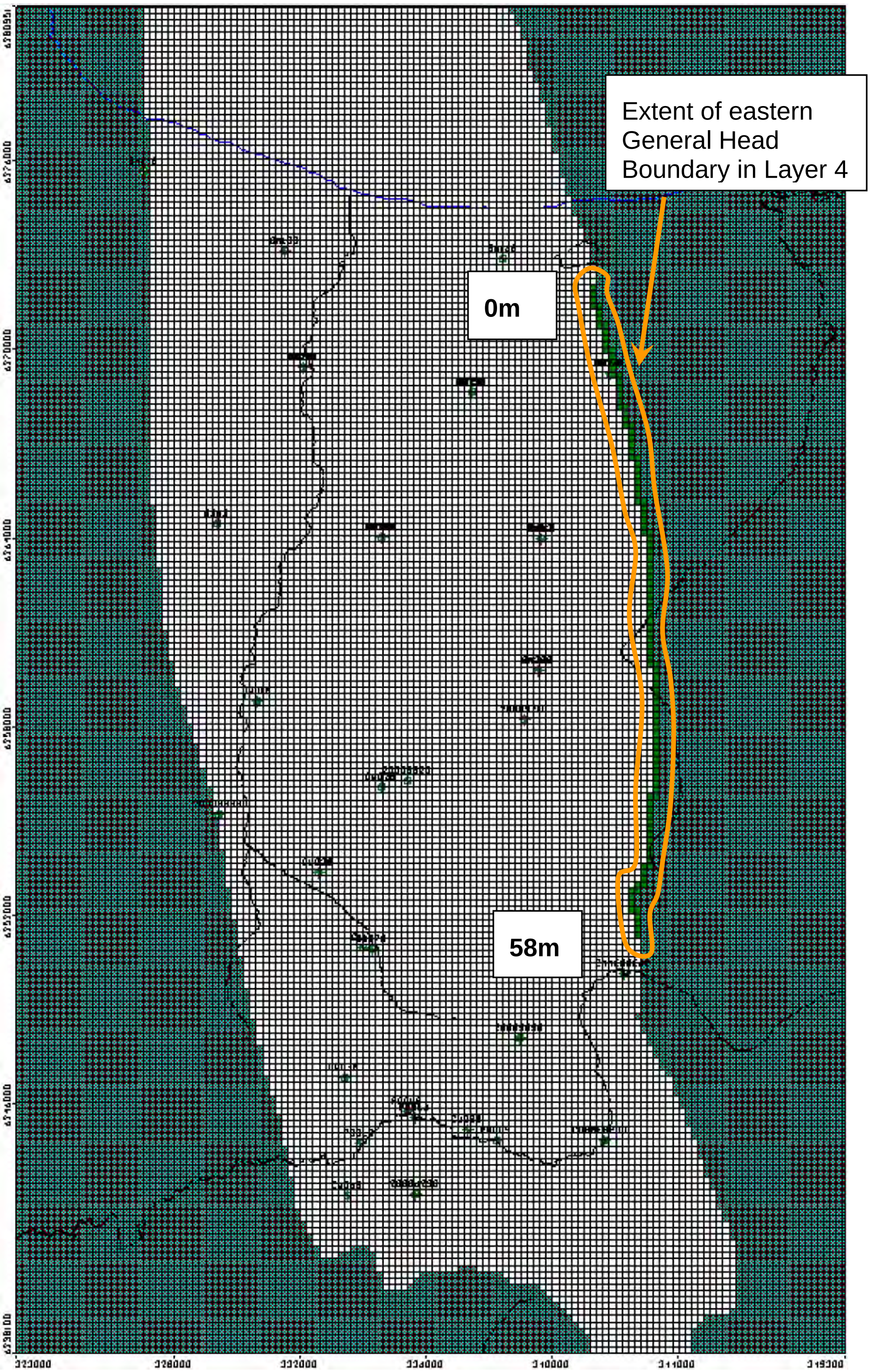


Figure 9 Extent of eastern general head boundary in Layer 4

The general head boundary is sufficiently offshore to allow the potentiometric head under the ocean to reach equilibrium with minimal impact on water levels along the coastline. The general head varies from +2 m in Layer 4 to +0.5 m in Layer 2 to simulate the additional buoyant head that freshwater needs to overcome when discharging due to the higher density of seawater.

3.7.5 Base of the model

The model area is underlain by the Sue Group, which is considered to be essentially impermeable. There is likely to be some interaction between the Leederville aquifer and Sue Group, but it is not considered significant for this model. As such, the base of the model (or Layer 4) has been set as a no-flow boundary with all cells beneath being inactive.

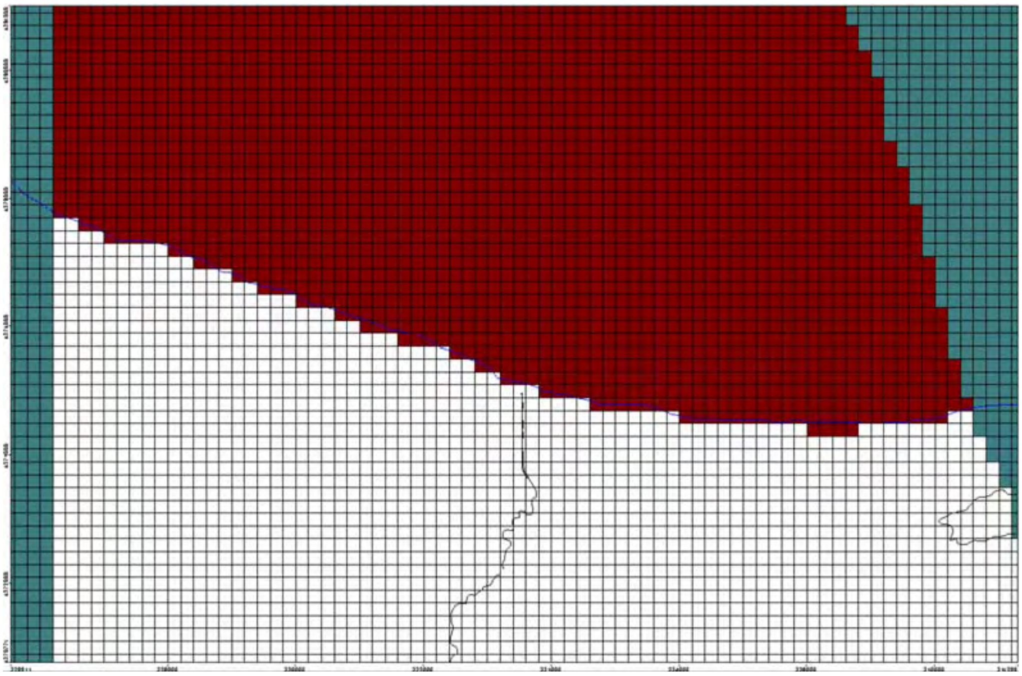


Figure 10 Constant head boundary of 0 m in Layer 1 at Geographe Bay

3.8 Rainfall recharge and discharge

3.8.1 General

The major source of groundwater recharge across the model domain is considered to be rainfall infiltration. High volumes of low intensity rainfall during the winter wet season, when evaporation rates are low, are believed to result in groundwater recharge. Most groundwater recharge occurs on the Blackwood Plateau within the Cowaramup subarea.

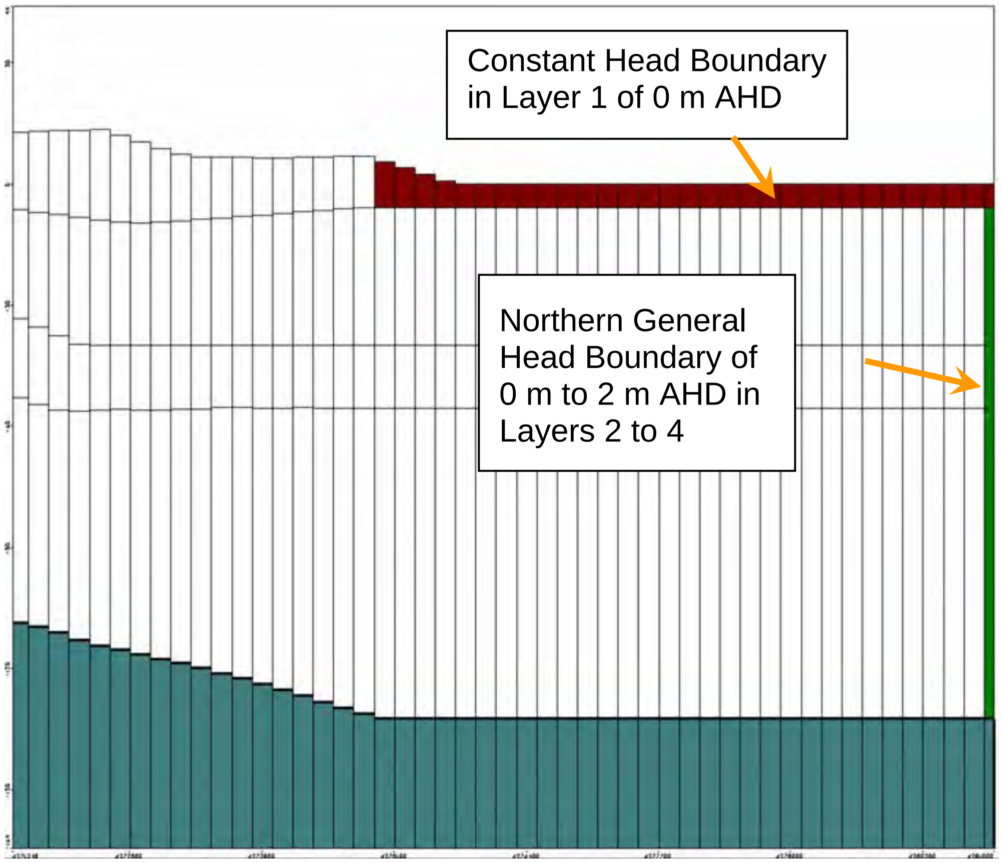


Figure 11 Coastal constant head and general head boundaries

Groundwater flows northward and southward from the groundwater divide on the Blackwood Plateau. The north-flowing groundwater moves towards and discharges at the coast, and also discharges from the Yelverton Shelf / Whicher Scarp area that acts as a broad seepage face. Groundwater that flows southward from the groundwater divide discharges into Margaret River.

The main drainages represented in the model are Margaret River, Carbunup River and a small section of the Vasse River. These rivers typically act as groundwater discharge features. They have been modelled as drains where groundwater is discharged from the model, when the watertable rises above the base of the river. Some groundwater recharge as leakage from the Carbunup River may occur, where the river dissects the Yelverton Shelf / Whicher Scarp.

3.8.2 Representation of recharge and discharge in the model

Rainfall that infiltrates the ground surface and reaches the watertable is termed net recharge. There is no net recharge into the model from its boundaries and river leakage as the rivers act as groundwater discharge features. Net recharge in the model is represented in terms of mm/year for the steady state calibration and mm/day for the transient (time series) calibration.

Groundwater discharge via evapotranspiration will occur when the watertable rises above a specified depth below the land surface known as the ‘extinction depth’. This approach to modelling evapotranspiration allows the amount of net recharge to vary dependent on the depth to watertable. Some groundwater related to seepage flow along the Yelverton Shelf and Whicher Scarp will be removed from the model by evapotranspiration.

Groundwater discharge also occurs as flow into drains (rivers) when the watertable rises above the specified elevation of the base of streams. There is also groundwater discharge at the general head (eastern) boundary, when groundwater levels are above the specified head. Discharge to the ocean from Layer 1 is controlled by the constant head boundary near the ocean.

During winter when recharge rates are high and evaporation rates are low, the watertable is prevented from building up beyond the land surface by the 'ponding' functionality of MODFLOW-SURFACT. In the model, the ponding depth has been set to the land surface. This way when the watertable rises above the ponding depth, water is removed from the model as surface flow.

3.8.3 Recharge zones

The spatial distribution of recharge depends upon many factors such as land clearing, vegetation type (rooting depth), surface geology, topography, depth to watertable, and groundwater flow configuration. Seven recharge zones from the SWAMS model were initially considered, which were predominantly based on river catchments and physiographic units. Further refinement and partitioning of the model domain into recharge zones was undertaken during the calibration process.

Seventeen recharge zones were finally selected for the model domain. The extent of the recharge zones is shown in Figure 12 and their characteristics are discussed below. Final calibrated recharge for each zone is discussed in Section 4.4.

1. Default zone (ocean)
2. Lower Swan Coastal Plain in the lower Carbunup River catchment - cleared, low downwards hydraulic gradient and shallow watertable.
3. Coastal Tamala Limestone - mostly cleared, low downwards hydraulic gradient, high permeability surface geology and shallow watertable.
4. Whicher Scarp - mostly cleared, low downwards hydraulic gradients, shallow to moderate watertable depth and swampy areas.
5. Yelverton Shelf - cleared in most parts, large seasonal fluctuations in watertable, and has a lateritic weathering profile.
6. Upper Swan Coastal Plain - mostly cleared, low downwards hydraulic gradients, shallow to moderate watertable depth and consists of sandy clay.
7. Carbunup River on the Swan Coastal Plain - partially vegetated, downward hydraulic gradients, high seasonal watertable fluctuation, river leakage where the river crosses the Yelverton Shelf, and has a lateritic weathering profile.

8. Broadwater swamp - watertable at surface.
9. Cleared northern edge of the Blackwood Plateau - cleared of vegetation, deep watertable and has a lateritic weathering profile.
10. Carbunup River valley on the Blackwood Plateau - partially vegetated, variable depth to watertable and has a lateritic weathering profile.
11. Margaret River valley on the Blackwood Plateau - cleared, generally shallow to moderate watertable depth, upward hydraulic gradients near Margaret River and has a lateritic weathering profile.
12. Forested area on Blackwood Plateau - entirely forested (mostly Jarrah- Marri), deep watertable, high topography, downward hydraulic gradients and has a lateritic weathering profile.
13. Small cleared area east of forested area on Blackwood Plateau - cleared of vegetation, probably deep watertable and has a lateritic weathering profile.
14. Vasse River valley - partially vegetated, shallow watertable and likely groundwater discharge area.
15. Cleared area central Blackwood Plateau - cleared, deep watertable, large downward hydraulic gradients, lateritic weathering profile, high topography, and presence of subcropping sandy facies of the Quindalup Member.
16. Cleared elevated area to south of Margaret River on Blackwood Plateau - cleared, moderate depth to watertable and has a lateritic weathering profile.
17. Lower Swan Coastal Plain (Buayanyup catchment) - cleared, shallow to moderate watertable depth, sandy clay geology, and influenced by groundwater abstraction and agricultural drains.

3.8.4 Evapotranspiration

Evapotranspiration (EVT) is a very large component of the water balance. This process returns water to the atmosphere by direct evaporation or transpiration by vegetation. Evapotranspiration processes are largely dependent on the root depth of vegetation, extent of capillary rise and depth to watertable.

As with net recharge, evapotranspiration is represented in terms of mm/year for the steady state calibration and mm/day for the transient calibration. Extinction depths are represented in terms of metres below ground surface. Evapotranspiration rates and extinction depths were assigned to each recharge zone.

3.8.5 Adjustment of recharge during calibration

Modelled groundwater recharge is controlled by the ponding depth (set to ground surface), evapotranspiration rates and extinction depth. If excess recharge is input in the model, it is largely removed by evapotranspiration, ponding or the drains. Recharge and EVT rates were adjusted during model calibration so that the following conditions were satisfied:

- The modelled steady state watertable matched the hydrographs for shallow bores (including estimates for the Blackwood Plateau where watertable monitoring bores are absent).
- Recharge rates on the Blackwood Plateau were consistent with the rates determined by the chloride method.

3.9 Surface water features

3.9.1 Rivers

Modelling of the interaction between rivers and the groundwater system was considered critical to model success. All rivers in the model domain are considered to be groundwater discharge features. The rivers have all been modelled as drains where, once the watertable reaches the river bed level, groundwater is discharged as surface flow and is removed from the model (Figure 13).

The Margaret, Carbunup, Vasse and the lower Buayanyup Rivers are all represented in the model. Other drainage such as the Dawson and Ironstone Gullies, tributaries of the Buayanyup River, were included in early calibration but were not found to impact groundwater levels. The small section of the Vasse River within the model domain is an important local control on groundwater levels.

Drainage levels were estimated from the state 5 m contour layer (DOLA, 2002). Conductance values were automatically calculated by Visual MODFLOW based on a conductivity of the bed material of 5 m/day and a thickness of streambed material of 5 m and average stream width of 10 m. These values were left constant during the entire model calibration.

It is considered that river bed level is the most critical factor when modelling the influence of rivers on groundwater levels. Once the watertable reached the river bed level, groundwater was allowed to enter the drains and leave the model as surface water runoff.

3.9.2 Agricultural drains

An extensive system of agricultural drains occurs across the Swan Coastal Plain. These drains are generally shallow (less than 3 m) but are important for removing surface water during the wet season. They may also locally influence the watertable in the superficial aquifer, but are not considered to influence water levels in the Leederville aquifer beneath the Swan Coastal Plain.

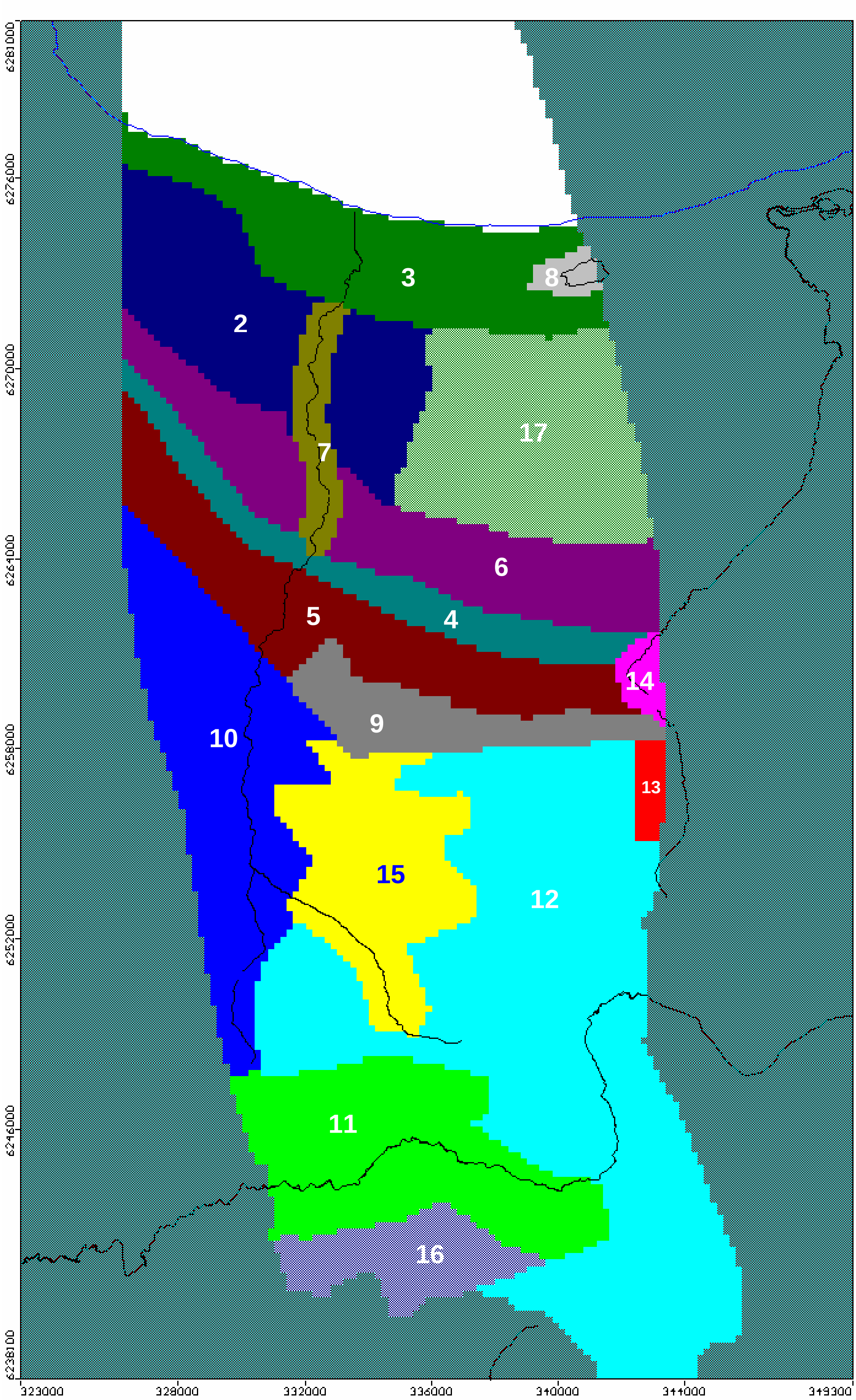


Figure 12 Modelled recharge zones

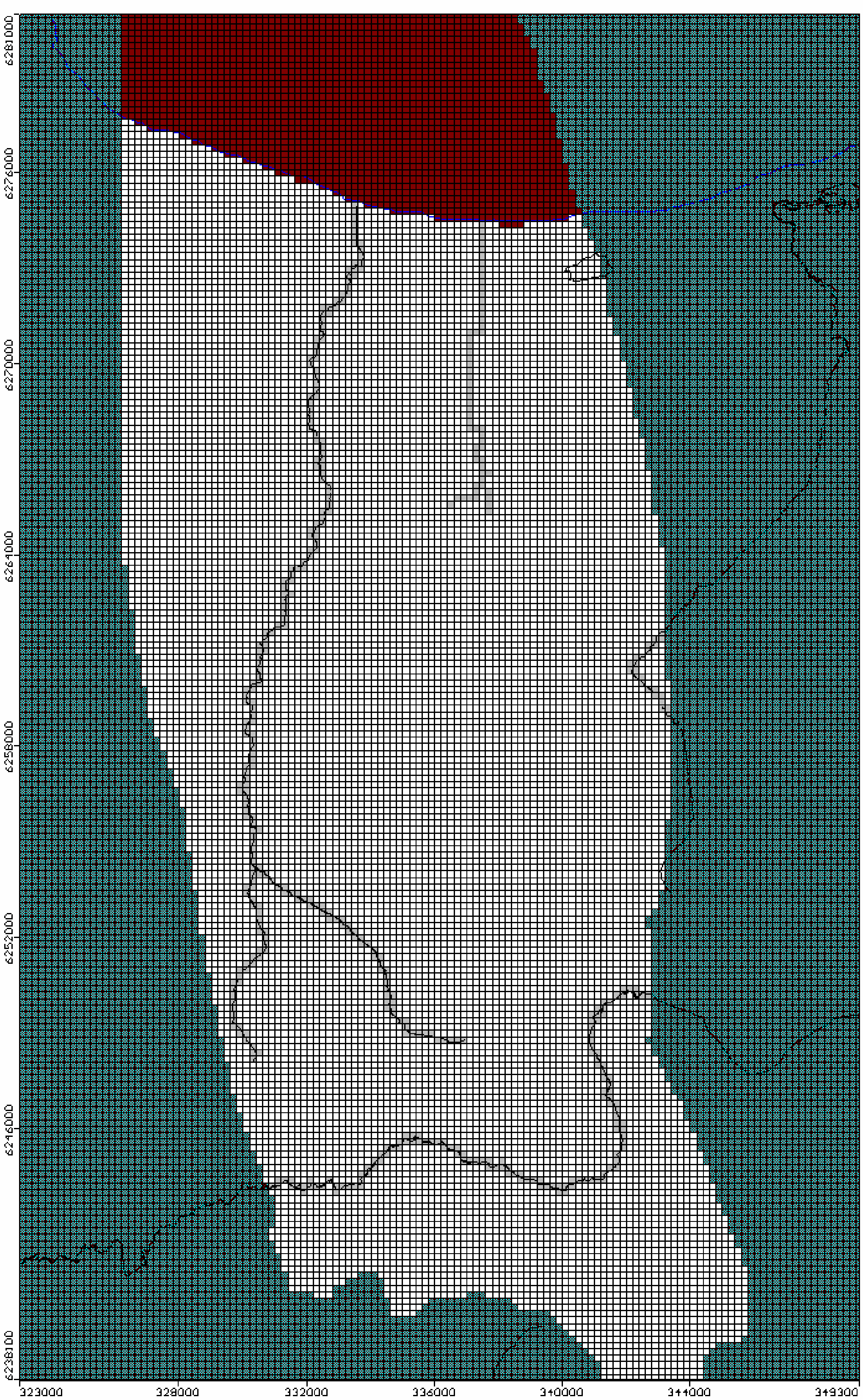


Figure 13 Rivers (modelled as drains)

The whole network of drains has not been modelled specifically. However, the net effect of the drains has been factored into the evapotranspiration extinction depths on the Swan Coastal Plain. Buayanyup River, also known as Buayanyup Drain, has been individually modelled as it is a significant drainage feature.

3.9.3 Wetlands

The coastal wetlands are generally considered to be surface water features, although shallow groundwater levels and some groundwater discharge may play a role in maintaining these wetlands. These wetlands have not been modelled specifically apart from matching the calibration of water levels in the shallow coastal bores.

3.9.4 River pools

There are more than 20 riverine pools along Margaret River within the model domain, which are considered to be ‘window’ pools that represent the watertable. The pools have not been modelled individually in this subregional model. However, data logger results from four pools and estimated steady state water levels for two other pools were used in the calibration process.

3.10 Monitoring bores

A total of 55 sites were used for model calibration, including 45 monitoring bores and four river pools with surveyed levels and data logger results (Fig. 14). Estimates of steady state water levels were also determined based on historic water level measurements for four farm bores, and two other river pools on the Margaret River were based on river bed levels. These additional estimated water levels were critical to ensure that the model was calibrated to the steady state watertable. Sites used for model calibration are listed in Appendix E.

Most monitoring bores on the Swan Coastal Plain have hydrographs starting in the 1980s, and as such 1990 was selected as the start year for the transient model calibration. Synthetic results were generated to assist with transient model calibration, in areas with limited hydrograph records on the Blackwood Plateau. These were based on river baseflow records and the long-term hydrograph for the monitoring bores at site CL1.

3.11 Groundwater abstraction

The abstraction database created for the SWAMS model was used as the basis for groundwater abstraction data for the period from 1990 to 2004. Current production bores in the Leederville aquifer and shallow superficial aquifer on the Swan Coastal Plain have been included in this model.

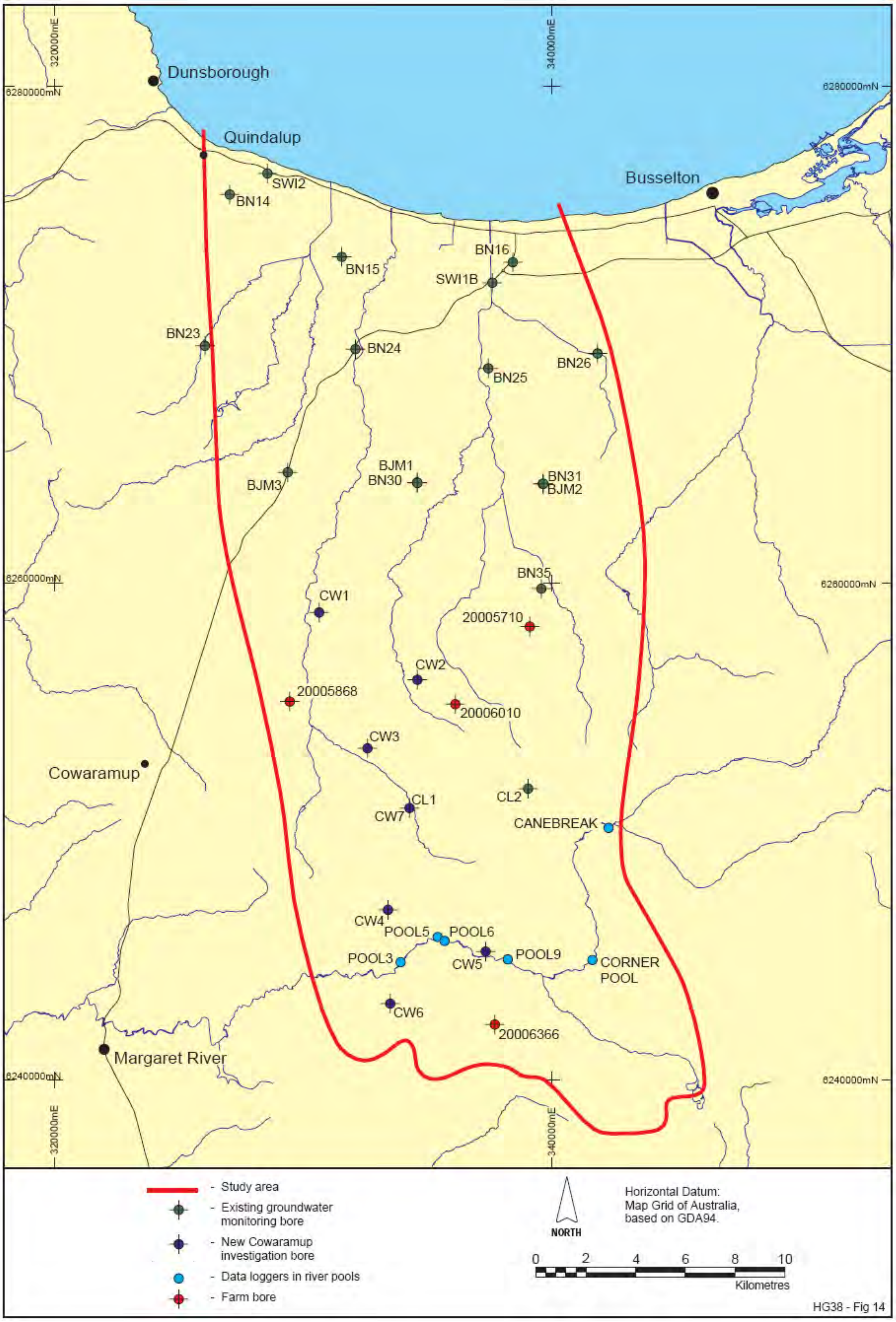


Figure 14 Monitoring bores and river pool sites

Detailed abstraction records (weekly production data) provided by the Water Corporation for six Leederville aquifer bores in Quindalup borefield were included. Licence information for 17 ‘pump in stream’ surface water licences from the Margaret River considered as shallow groundwater abstraction were also added to the database. A total of 224 groundwater and surface water allocation licences were included in the transient calibration (Fig. 15).

Total modelled abstraction for the period 1990 to 2004 increases from 2.4 GL in 1990 to a maximum of 7.4 GL in 2000 (Fig. 16). Groundwater usage of 6.6 GL in 2004 was considered indicative of current usage. During scenario model predictions, the level of abstraction was increased up to an additional 5 GL from 41 scenario bores. The abstraction dataset for the transient model is discussed in Section 4.3.

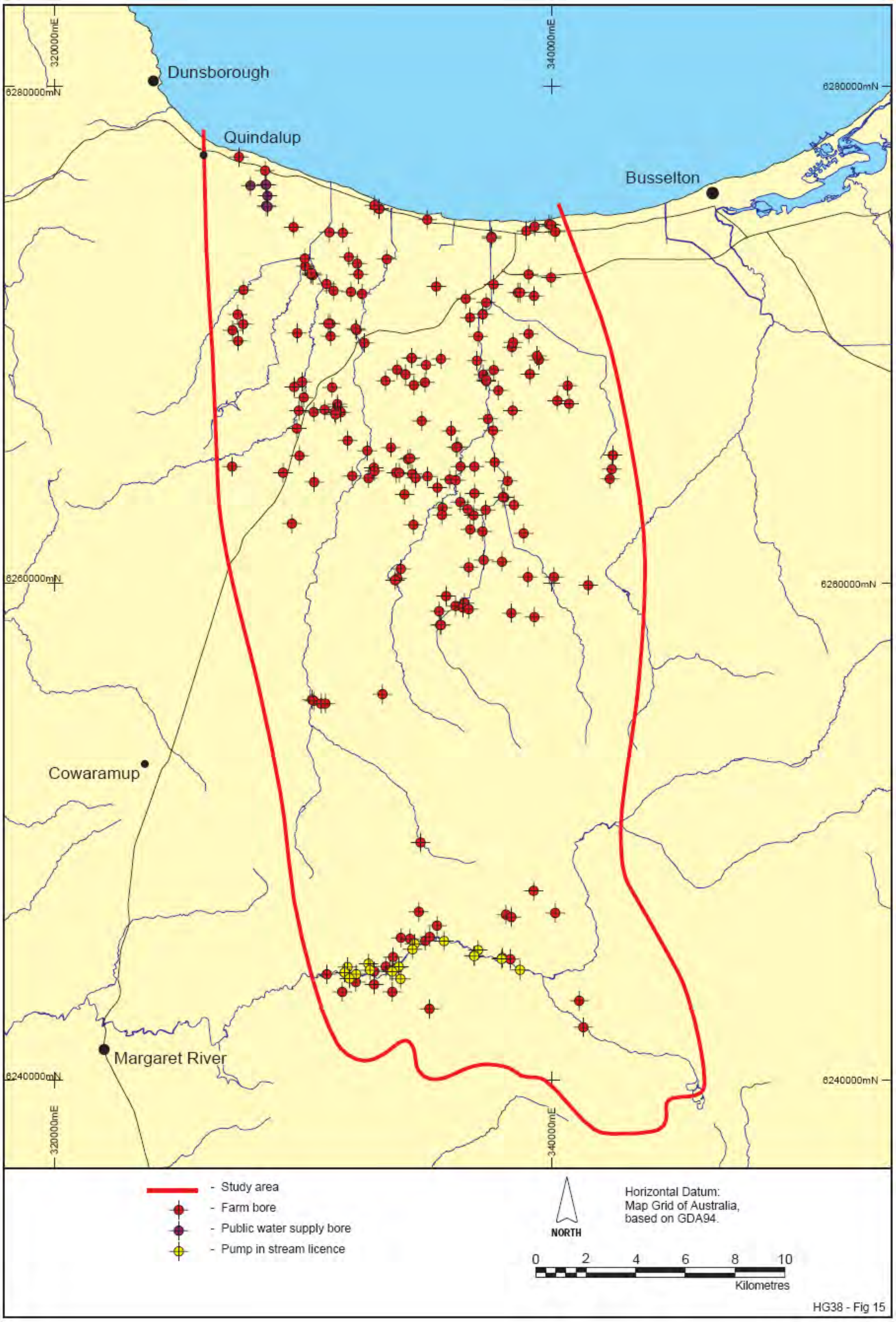


Figure 15 Abstraction bores and 'pump in stream' licences

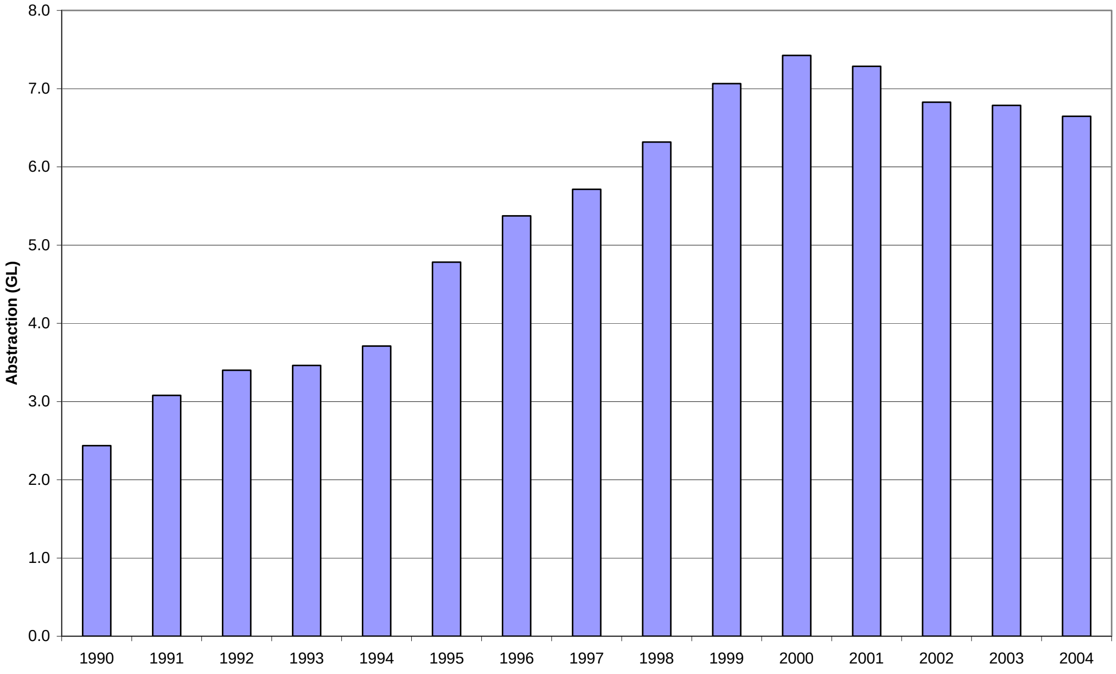


Figure 16 Modelled groundwater abstraction

4 Model calibration

4.1 Overview

Model calibration involves the iterative adjustment of model parameters to minimise the error between modelled and observed groundwater levels. The Cowaramup groundwater model has been calibrated under both steady state and transient conditions.

Steady state calibration was undertaken prior to transient calibration as a test of the components of the water balance. The steady state condition is where the input stresses (such as recharge and evapotranspiration) do not vary with time. During steady state calibration, hydraulic conductivity and recharge parameters were adjusted. Calibration was performed until there was a good match for resting water levels at the end of the winter/spring wet season, as they were considered representative of land use conditions in the absence of abstraction. No abstraction stresses were applied to the initial steady state model.

Water levels generated from the steady state model were the starting heads in the subsequent transient calibration. Under transient conditions, input stresses vary with time. During the transient calibration, aquifer storage parameters were estimated, while hydraulic conductivity and recharge parameters were further refined.

4.2 Steady state calibration

4.2.1 Assumed steady state conditions

Calibration year

Water levels for spring 1990 (after winter and the irrigation off season) were selected for steady state calibration. The year 1990 was selected as it corresponds with the start of the dataset used to calibrate the SWAMS model, and groundwater abstraction was comparatively low at this time.

Calibration water levels

Resting water levels at the start of spring were selected, as there is limited abstraction during winter and levels are only minimally impacted. As seasonal fluctuations are small (generally less than 2 m) in areas not impacted by abstraction, the spring water levels provide a reasonable indication of the long-term watertable configuration for the steady state calibration.

The steady state calibration attempted to match measured and estimated water levels for 54 monitoring sites throughout the model domain. These monitoring sites had a range of screen interval depths within the Leederville aquifer.

Spring water level measurements for 1990 were available for the Busselton shallow (BN series) bores on the Swan Coastal Plain. For monitoring bores constructed after spring 1990 water levels (such as the new Cowaramup investigation CW series of bores and the BJM series of bores), resting water levels were estimated. Bore SWI2, located near the Water Corporation production borefield at Quindalup which is heavily impacted by abstraction was excluded from the steady state calibration.

Calibration of steady state watertable configuration

There are sufficient shallow monitoring bores on the Swan Coastal Plain to provide an adequate representation of the watertable configuration. On the Blackwood Plateau, there are fewer shallow bores at or near the watertable, but there are a number of deeper bores in the Leederville aquifer. As a result, it was considered necessary to estimate water levels for four shallow farm bores (based on historic watertable measurements) and six groundwater window pools along Margaret River (based on river bed levels and data logger observations). These additional shallow calibration sites were critical in ensuring a reasonable representation of the watertable under steady state conditions.

4.2.2 Model parameters

Hydraulic conductivity

The initial parameters for horizontal and vertical conductivity were based on the SWAMS regional model. All conductivity zones within each layer were initially assigned the same value. Zones of hydraulic conductivity within layers were further refined during the calibration process.

Recharge

Groundwater recharge rates were initially based on the SWAMS model (Sun, 2005), with the exception of zone 15. Recharge zone 15 is located on the groundwater divide and is considered the main groundwater recharge area within the model domain. Recharge in zone 15 was constrained to recharge estimates based on the chloride method, estimated at 138 mm/year, which allowed hydraulic conductivity estimates to be determined independently of recharge during the calibration process. Table 2 shows that chloride concentrations were available from three of the new Cowaramup bores screened at intermediate levels (CW2B, CW3B and CW7B).

Evapotranspiration

Evapotranspiration was initially considered only for the Swan Coastal Plain, as represented within the SWAMS model. During calibration, evapotranspiration was extended to the Blackwood Plateau, which was a recommended improvement to the SWAMS model by Sun (2005).

Table 2 Estimation of recharge for zone 15

Bore	Distance from coastline (km)	Estimated chloride content in rainfall* (mg/L) **C_P**	Measured chloride in groundwater# (mg/L) **C_G**	Precipitation (mm/year) **P**	Estimated recharge (mm/year) **$R = (C_P/C_G)xP$**
CW3B	18.1	10.3	62	1050	174
CW7B	20	10	86	1050	122
CW2B	18.7	10.1	90	1050	118
				Average	138

* reference (Hingston and Gailitis, 1976) Figure 3
# reference (Schafer et al., 2008) Table 5

The maximum evapotranspiration rate throughout the model domain was based on the average (1975 to 2008) annual pan evaporation of 1214 mm/year from the Bureau of Meteorology Jarrahwood station. Modelled evapotranspiration from groundwater occurs at a maximum rate when the watertable is at or above the ground surface. When the watertable is below the 'extinction depth', evapotranspiration is considered negligible. Between these two extents, modelled evapotranspiration varies linearly depending on watertable elevation.

Extinction depths, based on previous values by Sun (2005), have been estimated considering effective rooting depth of vegetation and depth to watertable. Different extinction depths were evaluated to determine the effect of varying extinction depths on model calibration. The following extinction depths were assigned:

- 2 m extinction depth near the coast where the watertable is very shallow (recharge zone 3);
- 3 m extinction depth in the cleared agricultural areas of the lower Swan Coastal Plain, Margaret River, Carbunup River and Vasse River valleys where the watertable is relatively shallow (recharge zones 2, 11, 14 and 17);
- 4 m extinction depth in the cleared agricultural areas of the upper Swan Coastal Plain, Whicher Scarp, Yelverton Shelf, and areas of cleared, high topography on the Blackwood Plateau where the watertable is generally greater than 5 m bgl (recharge zones 4, 5, 6, 7, 9, 10, 13, 15 and 16); and
- 5 m extinction depth for forested (predominantly Jarrah and Marri vegetation) areas on the Blackwood Plateau (recharge zone 12).

Ponding

Ponding depth was set to land surface (0 m) throughout the model domain. This was not varied during model calibration.

Initial water levels

Initial water levels for the steady state model were set to a nominal value of 200 m in all model cells, which ensured that cells were fully saturated at the start of the steady state runs.

4.2.3 Calibration refinement

After the initial parameters were entered and the model run, plots were made showing the distribution and magnitude of errors between the observed and modelled water levels. Model parameters were adjusted based on error distribution plots. There were many conceptual refinements during steady state calibration including confirmation of recharge and hydraulic conductivity zones, position of general head boundaries, determining those rivers and streams to be modelled as 'drains', and extinction depths for evapotranspiration zones.

Final calibration refinement was performed using PEST (Parameter Estimation) software, which allowed all parameters to be varied for a more accurate calibration. Parameters were constrained within acceptable ranges during calibration.

4.2.4 Calibration measures

Observed versus simulated heads

A comparison of observed and simulated heads was undertaken for 54 watertable bores (Fig. 17). Calibration statistics confirmed a good, even calibration with no concentration of error within any particular model layer. The mean absolute error (where all errors are converted to positive values so that positives and negatives do not cancel each other out) is 1.37 m and the normalised (or scaled) root mean square error is 1.61%. The groundwater flow modelling guideline (MDBC, 2001) recommends a scaled root mean square error of less than 5%. As such, the calibration errors are small and are more than acceptable for a subregional model.

Twenty-eight bores have calibration errors of less than 1 m; while 11 bores have calibration errors greater than 2 m. Bore BN24 near the Carbunup River on the Swan Coastal Plain has the largest error in observed versus measured water levels under steady state conditions. At this site, bore BN24S has a modelled water level 4.26 m below the observed water level while BN24I has a modelled water level of 2.87 m above the observed water level. These two bores occur in the same layer (Layer 1), suggesting that additional layers would be required to resolve these head differences.

Factors such as heterogeneity, localised recharge effects and difficulty in estimating steady state water levels may be factors contributing to errors. Overall, there was an excellent steady state calibration at the subregional scale, and this is the scale at which the model should be applied.

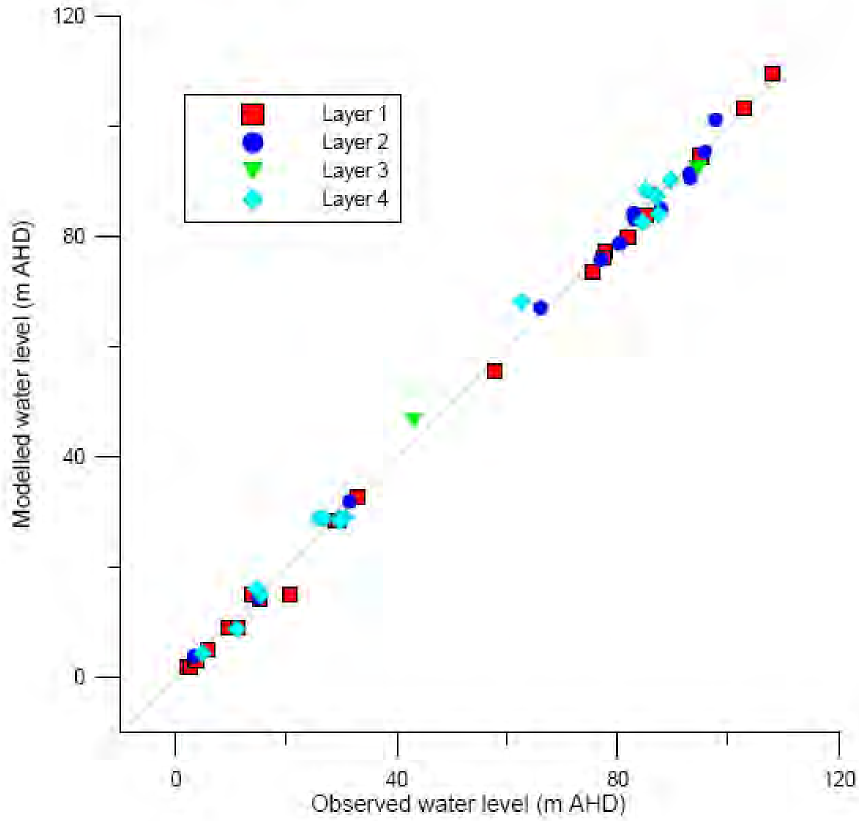


Figure 17 Observed versus modelled water levels in steady state calibration

Representation of watertable and groundwater flow

The modelled watertable configuration satisfactorily matches the shallow monitoring points, including the estimated farm bore and river pool water levels. The contours of modelled watertable show a close correlation with the watertable contours by Schafer et al. (2008). The general configuration of the watertable is synchronous with the topography.

There is good correlation between the groundwater flow represented in the model and the conceptual understanding by Schafer et al. (2008). Figure 18 shows this good correlation with groundwater recharge occurring in the vicinity of the groundwater divide on the Blackwood Plateau in Layer 2, and groundwater flow in both northern and southerly directions. The vertical flow patterns, shown in Figure 19, demonstrate water exchange and vertical leakage between model layers, and more horizontal groundwater flow in deeper parts of the Leederville aquifer.

The magnitude of flow vectors within the model layers, shown in Figure 19, confirms that most groundwater moves in the upper layers (especially Layer 1). This is consistent with the conceptual understanding obtained from the groundwater age dating and groundwater salinity studies (Schafer et al., 2008), where groundwater flow was interpreted as being most significant in the upper Leederville aquifer.

Water balance error

The total water balance error for the error between the total water entering the model minus the total water leaving the model was less than 0.07%, which confirms that numerical error is minimal.

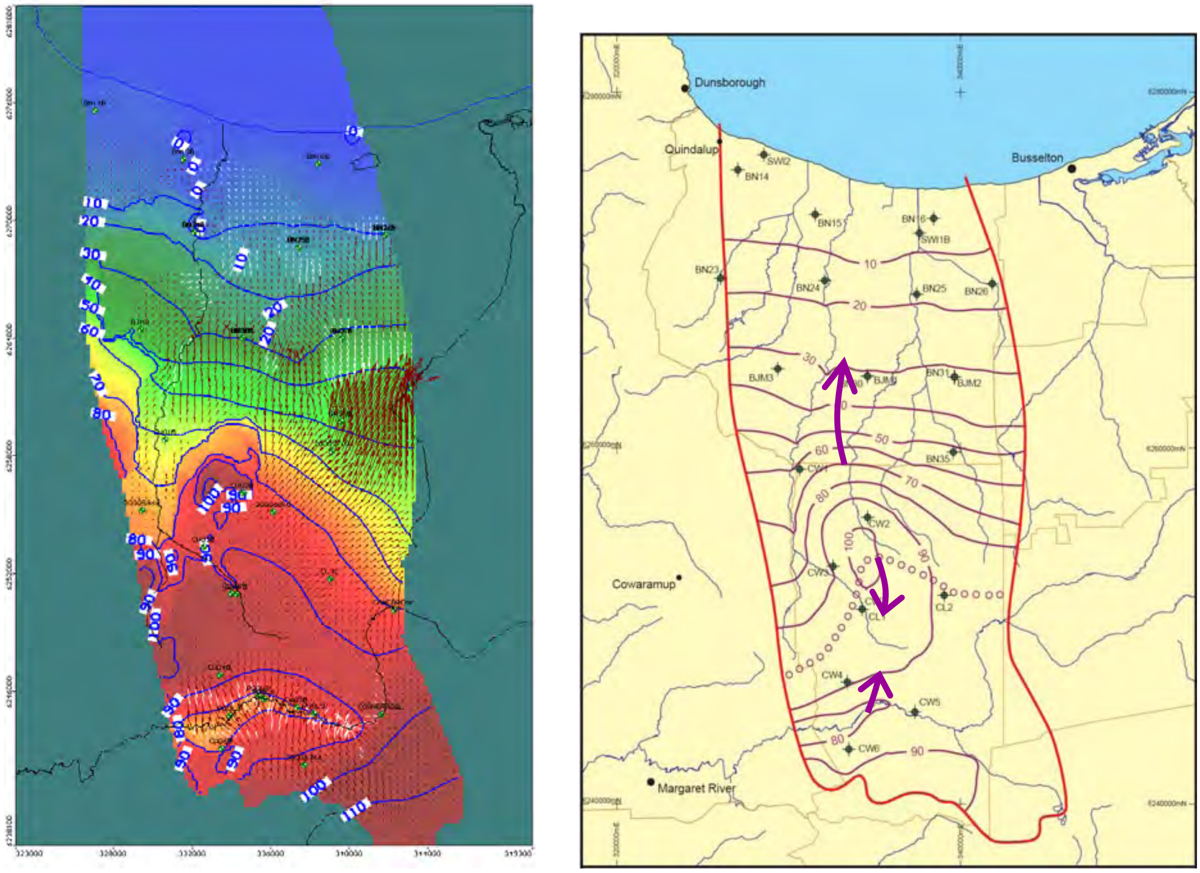


Figure 18 Modelled and measured isopotentials in Layer 2

4.3 Transient calibration

4.3.1 Calibration period and initial conditions

Calibration period

The calibration period was set as a 15 year period between 1990 and 2004. This is the same period for which abstraction data was available from the SWAMS model abstraction database. Hydrograph data is largely available for this period, especially on the Swan Coastal Plain.

Initial aquifer parameters

Initial hydraulic and vertical conductivity parameters were determined in the steady state model. Storage parameters of specific yield and specific storage were initially based on those used in the SWAMS model.

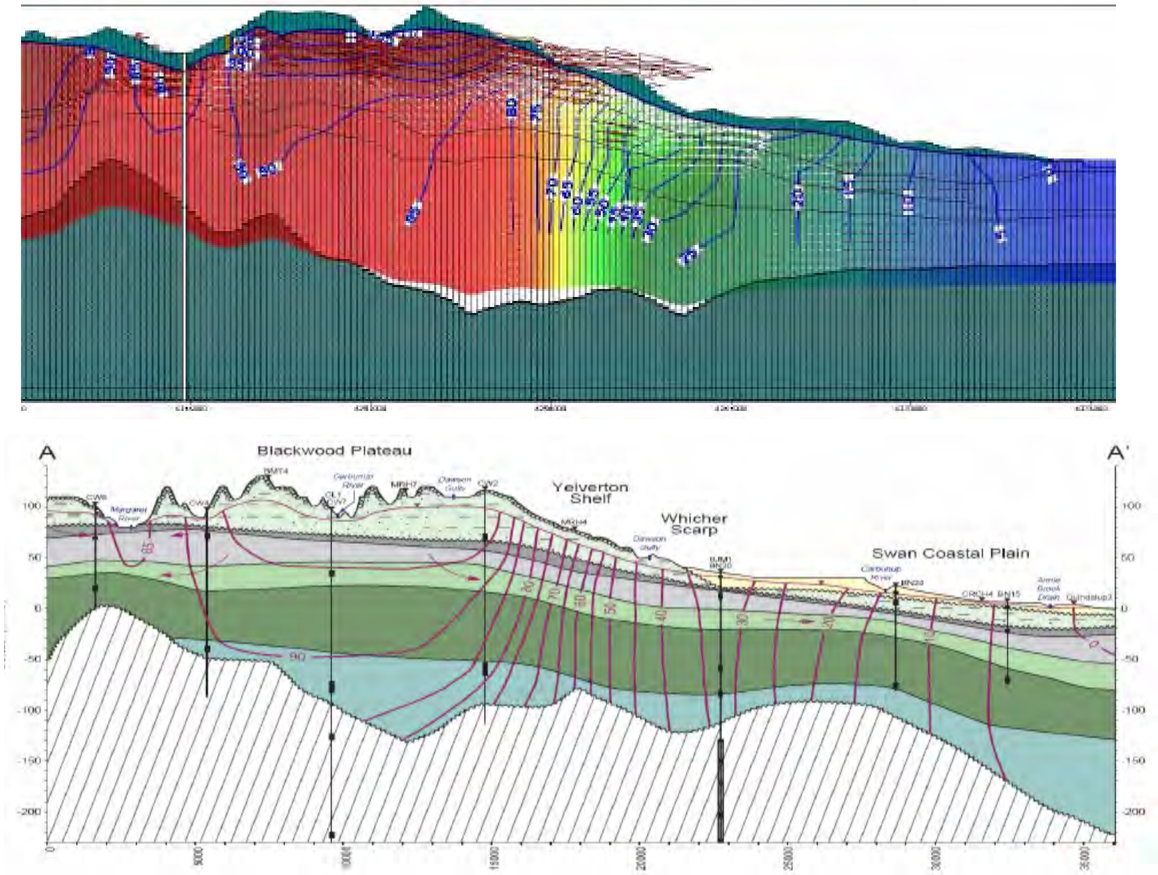


Figure 19 Cross-section showing modelled and measured isopotentials

4.3.2 Abstraction

Groundwater abstraction data for 1990 to 2004 is largely from the SWAMS abstraction database. Abstraction records from the Water Corporation for the Quindalup borefield and 17 ‘pump in stream’ licences in Margaret River were also included. The abstraction dataset was made more manageable by removing bore licences of less than 2000 kL/year, which allowed 42% of bore licences to be removed with only a 2.6% reduction in total allocation.

Actual abstraction usage was estimated for the SWAMS model to be 80% of the licensed allocation (Sun, 2005). During the calibration process, it become apparent that for the deeper bores in Layers 3 and 4 using 100% of licensed allocation produced a better calibration. This was considered more representative of abstraction from deeper large bores for irrigation, where most water use occurs during the summer growing season.

For the transient model, monthly groundwater usage factors were used to generate a monthly abstraction series from the annual allocation volumes (Table 3). These groundwater usage factors were estimated from irrigation metering data for the SWAMS model. Groundwater usage is greatest during summer months when evaporation rates are highest.

Table 3 Monthly water use factors

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.1846	0.2167	0.1331	0.0760	0.0273	0.0078	0.0010	0.0018	0.0109	0.0553	0.1207	0.1648

Data from 224 bore and 'pump in stream' licences were used for the transient calibration. As discussed in Section 3.11, modelled abstraction increases from 2.4 GL in 1990 to a maximum of 7.4 GL in 2000.

The largest individual licence is for the Quindalup borefield operated by the Water Corporation, which is in the north-west corner of the model domain. There are a number of large, private groundwater licences near BN35 (280 ML/yr), BN30 (176 ML/yr) and BN24 (118 ML/yr). Information on the screen diameters and bore diameters was not available for the majority of the abstraction bores. A nominal screen diameter of 150 mm and a nominal well diameter of 200 mm were assumed for the model.

4.3.3 Temporal recharge

Temporal variation in recharge was correlated to the baseflow component of river flow. This approach, similar to that of the SWAMS model (Sun, 2005), is based on the observation that shallow groundwater is discharged as temporary baseflow in rivers during recharge events. All rivers in the model domain are considered to have a high proportion of groundwater baseflow. Studies suggest that Margaret River for 1985 to 2007 has a baseflow component of about 62% of total river flow (*Richard Pickett pers. comm.*).

The character of the temporary baseflow component of river flow in comparison to rainfall is shown in Figure 20. Temporary baseflow is more variable than rainfall, as it is more responsive to antecedent catchment conditions such as sub-soil moisture content.

A strong correlation between groundwater recharge and river flow is demonstrated when bore hydrographs are compared to river flow hydrographs. Figure 21 shows the bore hydrograph for CW2B (positioned at the groundwater divide), flow in the Margaret River and rainfall at Jarrahwood station. The rise in water level (period of maximum groundwater recharge) is closely related to the period of river flow.

River flow in Margaret River was selected as representative of temporal variation in recharge across the model domain. It was assumed that the groundwater baseflow proportion of river flow remains relatively constant from year to year. This enabled the recharge time series for the transient calibration to be scaled directly to the monthly river flow in Margaret River for 1990 (steady state calibration year). As a result, steady state recharge for each zone was scaled as a monthly time series from 1990 to 2004, based on measured river flow in Margaret River.

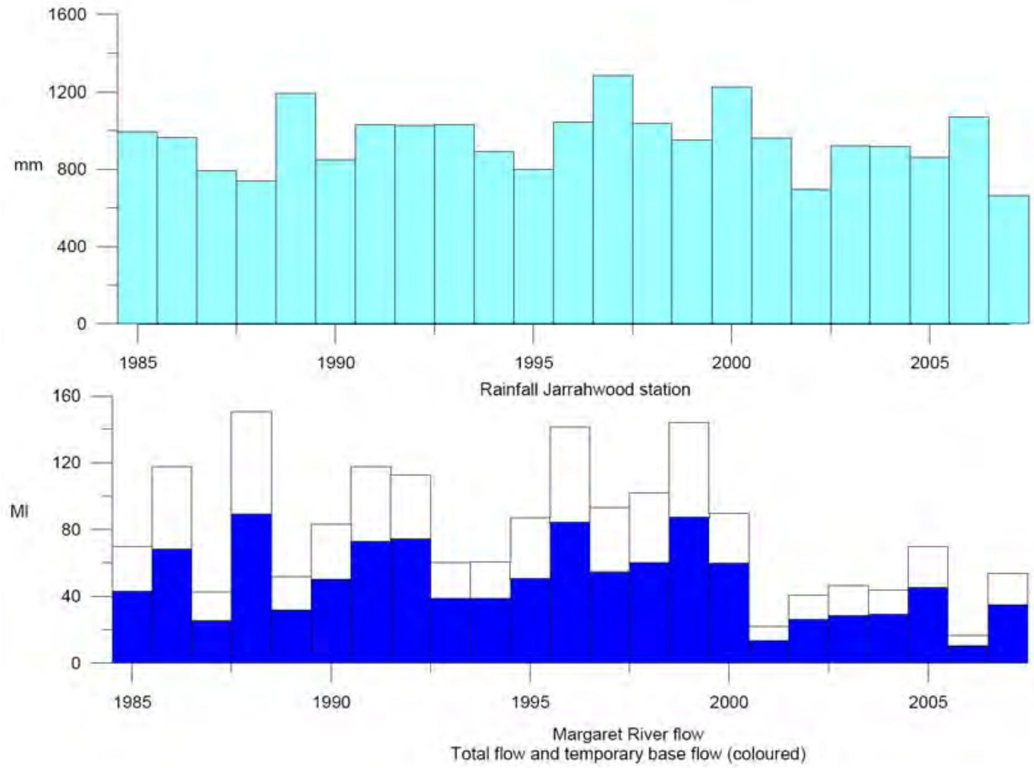


Figure 20 Rainfall and river flow

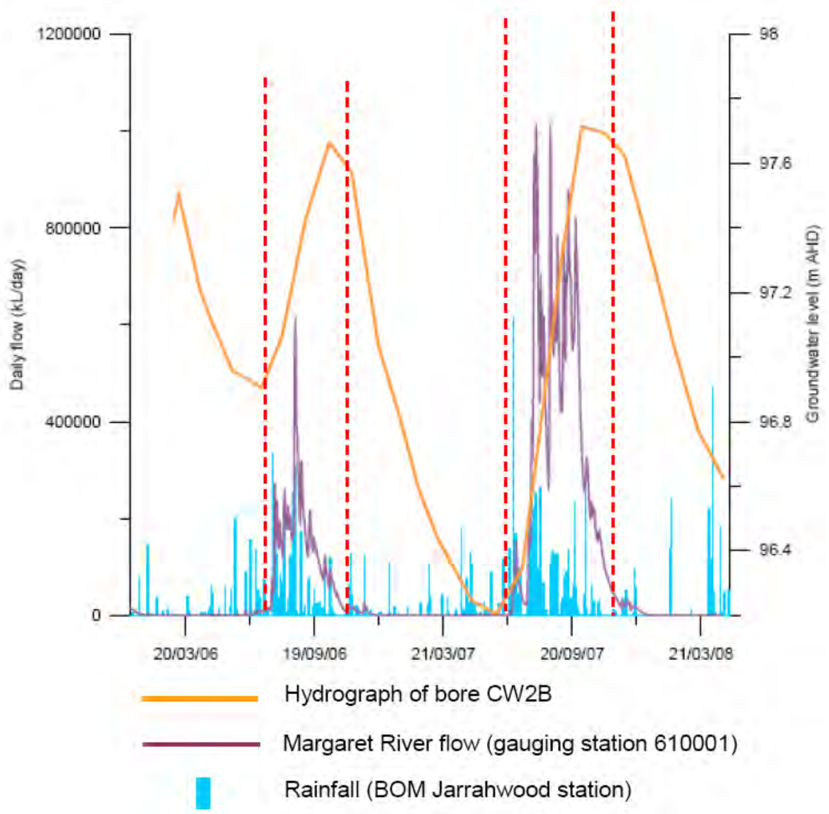


Figure 21 Hydrograph showing Margaret River flow and water levels in bore CW2B

4.3.4 Temporal variation of evapotranspiration

Maximum evapotranspiration (EVT) was entered into the model as a monthly time series. This series was calculated based on the daily pan evaporation reading from the Bureau of Meteorology Jarrahwood station, which was summed for each month.

4.3.5 Initial heads

Initial heads for the transient model were taken from the steady state model. It was important to have a good representation of water level distribution at the start of the transient calibration. This ensured that the modelled outputs were a product of the model parameters and configuration, rather than an artefact of initial heads.

4.3.6 Discretisation of time

Time is discretised in MODFLOW-SURFACT into stress periods (between which model stresses can change) and time steps (a number of time steps make up each stress period). Calculations are made after each time step, but model stresses do not change for the time steps. Monthly time steps have been used with the length of each time step corresponding to the days in the month, resulting in 180 stress periods over the 15 year period from 1990 to the end of 2004. Each stress period was subsequently divided into ten time steps, which was sufficiently small to produce an accurate solution with minimal water balance error.

4.3.7 Adjustment of parameters

The transient model was calibrated, using PEST, to establish storage parameters. The storage parameters were constrained within defined limits of a maximum specific storage of 0.026 (representative of plastic clay) and a minimum specific storage of $8x10^{-7}$ (representing the compressibility of water).

Hydraulic conductivity values were refined but were constrained to a minimum hydraulic conductivity of 10^{-6} m/day. Maximum hydraulic conductivity values of 12 m/day were set for conductivity zone 13 near the general head boundary. This prevented artificial lowering of heads by draining unrealistic amounts of water through the general head boundary and to calibrate the water levels in bore BN35.

After storage and hydraulic conductivity parameters were established, calibration runs were performed to adjust annual recharge multipliers. During calibration of recharge, the ratio of recharge values between zones was the same as those obtained from the steady state calibration.

4.3.8 Refinement of conductivity zones

Three local conductivity zones in Layers 2, 3 and 4 were established in the north-west of the model domain to address the significant abstraction from the Water Corporation's Quindalup borefield. Horizontal conductivity values were constrained in these new zones to a minimum of 0.3 m/day to prevent abstraction cells drying.

There was some difficulty with model calibration near bore BN24, which is in an area of high abstraction and high seasonal drawdown fluctuation. An additional conductivity zone (zone 18) was created in Layer 4, in the vicinity of BN24, to improve model calibration.

4.3.9 Adjustment of recharge on the Swan Coastal Plain

The model was initially calibrated with the distribution of recharge based on the steady state calibration. Under steady state calibration, net recharge under the Swan Coastal Plain was determined as being minimal. This produced a good calibration in the transient model except that there was no water level response in modelled hydrographs.

Nominal recharge values varying from 25 mm/year to 300 mm/year were applied to the recharge zones on the Swan Coastal Plain to better model and represent observed, seasonal water level fluctuations in shallow bores. Evapotranspiration extinction depths were also increased. In combination, this produced a better calibration in the transient model; however, there was no water level response in modelled hydrographs.

The large thickness of Layer 1 is seen as a limitation in the modelling of water level response on the Swan Coastal Plain, as hydraulic conductivity and specific storage parameters could not be adjusted without impacting other aspects of the calibration. In the future, the Swan Coastal Plain should be divided into two layers with a thin upper layer representing the superficial aquifer. It was decided in this model to not have an upper layer to prevent issues with drying cells.

4.3.10 Observed versus simulated heads

Hydrographs for 54 bores and groundwater window pools in the Margaret River were used for transient model calibration. Extrapolated hydrographs were generated for farm bores, Margaret River pools and the new Cowaramup bores (CW series) by analysing rainfall and evaporation data from available short-term records. These sites were selected as they are largely unaffected by pumping and have small annual water level fluctuations. Bore SWI2, omitted from the steady state calibration, was used in the transient calibration. The hydrograph for bore BN24I was omitted from the calibration, as bores BN24S and BN24I occur in the same layer.

Comparisons of modelled and observed hydrographs for individual calibration sites are shown in Appendix F. There is a very good match between observed and modelled hydrographs, as well as water level trends. Matching water level trends is important, as it indicates whether the overall water balance is correct. The modelling of downward trends in bores BN15D and BN24D in areas of high groundwater abstraction are well matched and confirm that the transient model is well calibrated.

There are often difficulties in matching water levels, particularly where the magnitude of seasonal fluctuation is impacted by abstraction. There have been good matches of seasonal water level fluctuation in areas of large abstraction, such as near BN30, BN31D, BN35D and BJM1B. In contrast, some bores such as BN24 show a lack of response highlighting that actual abstraction is greater than modelled abstraction. These inaccuracies are largely the result of abstraction database limitations with abstractions being estimated from annual allocations, the coarseness of the model grid (200 m x 200 m) and local variations in geology.

Figure 22 shows the comparison of observed versus modelled heads for the 54 calibration sites. The calibration statistics show that the root mean square error for 2004 (the end of the transient model run) is 2.72 %. This meets the groundwater flow modelling guideline (MDBC, 2001), which recommends a root mean square error of less than 5%. It is considered that the calibration errors are acceptable for a subregional model.

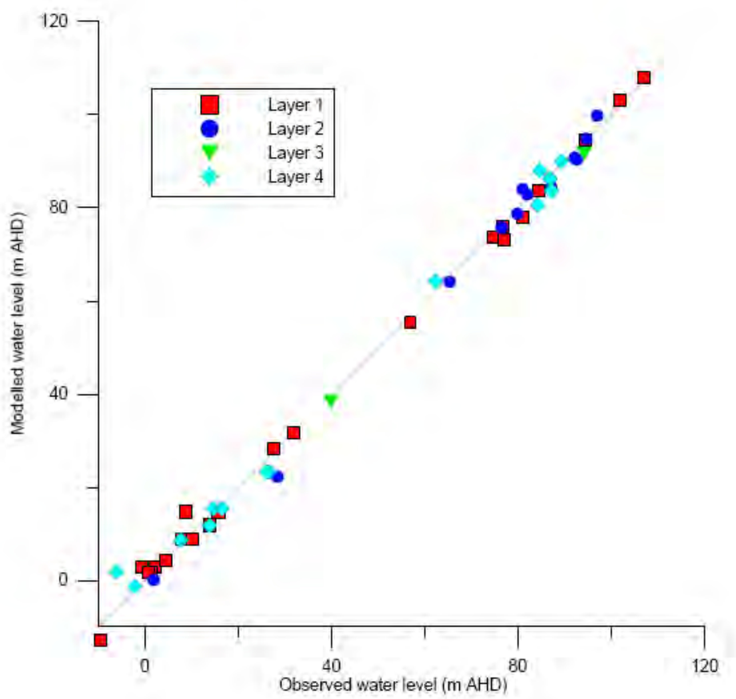


Figure 22 Observed versus modelled heads in transient calibration

4.3.11 Water balance error

Total water balance error at the end of the 15 year calibration run was 0.09%. This is considered acceptable and suggests that numerical error is not significant.

4.4 Final model parameters

4.4.1 Hydraulic conductivity

Final calibrated parameters for vertical and horizontal conductivity are presented in Table 4. Horizontal conductivity (K_x and K_y) values range from 0.01 to 10 m/day with typical values being between 0.2 to 2.1 m/day. Vertical conductivity values (K_z) are typically 2 to 5 orders of magnitude less than horizontal conductivity. This distribution of conductivity values reflects lithological variation and the interbedded nature of the Leederville aquifer.

Mean and standard deviation of horizontal hydraulic conductivity distributions for each model layer is shown in Table 5. Horizontal hydraulic conductivity shows a broad trend of decreasing with depth related to increased consolidation. In contrast, there is no noticeable trend with vertical hydraulic conductivity. The variability in vertical hydraulic conductivity is more controlled by the continuity of clay layers.

4.4.2 Storage parameters

Specific storage, specific yield and storage parameters at the end of transient calibration are presented in Table 6. Specific storage parameters increase with depth and are very low (around 1×10^{-6}) in the lower layers related to the consolidated nature and presence of cemented bands in these layers. The model is not sensitive to specific storage; as such the final calibrated parameters are not well constrained and can be considered as estimates.

Mean and standard deviation of storage parameter values in each model layer are shown in Table 7. There is no discernible trend in specific storage or specific yield, which is a product of the heterogeneous nature of the Leederville aquifer with its interbedded sand and clay layers. Varying proportions of sand and clay layers will only mask any trends in storage parameters that may occur with depth.

4.4.3 Recharge

Final recharge parameters at the end of the transient calibration are presented in Table 8. These recharge values represent net recharge into the Leederville aquifer and do not account for water that may infiltrate and subsequently be removed by seasonal evapotranspiration processes. It is important to recognise that the recharge values estimated by the model (being all recharge zones except zone 15) are dependent on the model hydraulic conductivity values and boundary conditions.

Model calibration has demonstrated that net recharge occurs primarily on the Blackwood Plateau. Net recharge has been estimated at between 63 and 225 mm/year. This finding is consistent with the conceptual understanding, as this area has large downward hydraulic gradients.

There is significantly less net recharge across the Swan Coastal Plain, as well as the Yelverton Shelf and Whicher Scarp areas. In these areas, groundwater flow is predominantly horizontal and downward hydraulic gradients are small. The highest recharge rate on the Swan Coastal Plain occurs in the Carbunup River valley (11.7 mm/yr) and the Buayanyup catchment (7.1 mm/yr), where recharge is enhanced by the presence of agricultural drains.

There is also an annual flooding effect on the Swan Coastal Plain with full saturation at the end of the winter. The watertable declines over summer due to discharge into the agricultural drains and evapotranspiration loss, which produces seasonal water level fluctuations in the shallow bores. Recharge into the Leederville aquifer beneath the Swan Coastal Plain is considered negligible due to the low downwards hydraulic gradients.

Table 4 Hydraulic conductivity parameters

Zone	Layer	K_x (m/day)	K_y (m/day)	K_z (m/day)
1 (default)	not used			
2	Layer 4	4.2×10^{-2}	4.2×10^{-2}	1.4×10^{-6}
3	Layer 3	0.30	0.30	1.2×10^{-4}
4	Layer 2	0.30	0.30	3.2×10^{-3}
5	Layer 4	0.93	0.93	1.5×10^{-3}
6	Layer 1	0.50	0.50	6.5×10^{-5}
7	Layer 1	1.64	1.64	2.4×10^{-4}
8	Layer 1	0.28	0.28	7.7×10^{-4}
9	Layer 2	2.06	2.06	8.0×10^{-4}
10	Layer 2	0.15	0.15	9.0×10^{-4}
11	Layer 3	1.26	1.26	8.7×10^{-3}
12	Layer 4	1.4×10^{-3}	1.4×10^{-3}	5.0×10^{-4}
13	Layer 2	10.0	10.0	7.8×10^{-4}
14 (Quindalup)	Layer 2	2.06	2.06	8.0×10^{-4}
15 (Quindalup)	Layer 3	0.25	0.25	5.0×10^{-2}
16 (Quindalup)	Layer 4	1.20	1.20	5.0×10^{-4}
17	Layer 4	0.67	0.67	3.1×10^{-5}
18	Layer 4	0.03	0.03	5.0×10^{-4}

Table 5 Horizontal hydraulic conductivity statistics for model layers

	K_x , K_y (m/day)	K_z (m/day)
Layer 1	$\mu = 1.21$ $\sigma = 0.62$	$\mu = 5.16 \times 10^{-4}$ $\sigma = 1.74 \times 10^{-3}$
Layer 2	$\mu = 0.99$ $\sigma = 1.92$	$\mu = 2.29 \times 10^{-3}$ $\sigma = 1.15 \times 10^{-3}$
Layer 3	$\mu = 0.83$ $\sigma = 0.48$	$\mu = 4.88 \times 10^{-3}$ $\sigma = 4.26 \times 10^{-3}$
Layer 4	$\mu = 0.54$ $\sigma = 0.46$	$\mu = 1.10 \times 10^{-3}$ $\sigma = 6.27 \times 10^{-4}$

Table 6 Storage parameters

Zone	Layer	Specific storage (m^{-1})	Specific yield
1 (default)	not used		
2	Layer 4	8.5×10^{-7}	0.12
3	Layer 3	3.3×10^{-6}	0.19
4	Layer 2	8.0×10^{-7}	0.11
5	Layer 4	3.9×10^{-6}	0.15
6	Layer 1	5.0×10^{-4}	0.18
7	Layer 1	1.4×10^{-6}	0.08
8	Layer 1	1.3×10^{-5}	0.25
9	Layer 2	3.1×10^{-3}	0.19
10	Layer 2	8.0×10^{-7}	0.20
11	Layer 3	2.0×10^{-6}	0.15
12	Layer 4	8.4×10^{-5}	0.18
13	Layer 2	1.5×10^{-6}	0.15
14 (Quindalup)	Layer 3	2.4×10^{-4}	0.15
15 (Quindalup)	Layer 1	2.0×10^{-6}	0.15
16 (Quindalup)	Layer 4	3.9×10^{-6}	0.12
17	Layer 4	1.2×10^{-6}	0.12
18	Layer 4	1.2×10^{-6}	0.12

Table 7 Vertical hydraulic conductivity statistics for model layers

	Specific storage (m^{-1})	Specific yield
Layer 1	$\mu = 2.93 \times 10^{-5}$ $\sigma = 1.09 \times 10^{-4}$	$\mu = 0.13$ $\sigma = 0.07$
Layer 2	$\mu = 5.69 \times 10^{-4}$ $\sigma = 1.20 \times 10^{-3}$	$\mu = 0.14$ $\sigma = 0.04$
Layer 3	$\mu = 2.68 \times 10^{-6}$ $\sigma = 4.43 \times 10^{-6}$	$\mu = 0.17$ $\sigma = 0.02$
Layer 4	$\mu = 2.08 \times 10^{-5}$ $\sigma = 3.37 \times 10^{-5}$	$\mu = 0.15$ $\sigma = 0.02$

Recharge is also inhibited in the Margaret River valley (recharge zone 11 – 0.14 mm/year), as it is an important groundwater discharge area. There is some recharge in the higher slopes of Margaret River valley that eventually discharges into the river.

The high recharge estimate in the Carbunup River valley (recharge zone 10) of 225 mm/year predominantly represents rainfall that infiltrates the slopes of this incised valley and discharges as shallow groundwater baseflow. A limited amount of recharge may enter the deeper groundwater flow systems where downwards hydraulic heads are present.

Table 8 Calibrated recharge parameters

Zone	Description	Net recharge (mm/year)
1	Default zone (ocean)	0
2	Lower Swan Coastal Plain – Carbunup catchment	0
3	Coastal limestone	0.58
4	Whicher Scarp	0
5	Yelverton Shelf	12
6	Upper Swan Coastal Plain	0
7	Carbunup River – Swan Coastal Plain	11.7
8	Broadwater swamp	0.09
9	Cleared northern edge of Blackwood Plateau	151
10	Carbunup River valley on Blackwood Plateau	225
11	Margaret River valley (cleared) on Blackwood Plateau	9.7
12	Forested area on Blackwood Plateau	97
13	Small cleared area, east of forested area on Blackwood Plateau	63
14	Vasse River valley	0
15	Cleared area Blackwood Plateau	138
16	Cleared elevated area to south of Margaret River	21.4
17	Lower Swan Coastal Plain – Buayanyup catchment	7.1

5 Sensitivity analysis

In order to assess uncertainty in the numerical groundwater model, it is necessary to determine the sensitivity of model parameters. Sensitive parameters are those that when varied cause significant change to model outputs, while insensitive parameters are those that can be varied without causing minimal change in model outputs.

Relative sensitivities were determined by PEST. Figure 23 shows the relative sensitivities of all the model parameters. The general trends in sensitivities from most sensitive to least sensitive are as follows:

- vertical conductivity (upper layers more sensitive than lower layers);
- recharge on the Blackwood Plateau;
- horizontal conductivity (lower layers more sensitive than upper layers);
- specific storage (confined aquifer storage); and
- specific yield (unconfined aquifer storage).

The most sensitive parameters are the vertical conductivities for zone 7 and zone 8 in Layer 1. As such, it is believed that vertical conductivity in Layer 1 has the greatest influence on water levels in the model domain. High sensitivities for recharge parameters on the Blackwood Plateau and horizontal conductivity for upper layers is consistent with the conceptual understanding.

There are eight parameters that have no influence on the model observations and essentially are not used by the model. These include recharge zone 14, a small zone in the Vasse River valley at the eastern edge of the model, where any recharge is removed by drain cells. Confined storage in upper layers (zones 6 and 8) and specific yield in lower layers (zones 2, 3, 5, 12 and 13) are considered to have minimal impact on the model. Notably the recharge parameters for the Swan Coastal Plain have low sensitivity.

Although Figure 23 indicates the relative sensitivity of individual parameters, it is only when parameters are varied concurrently that maximum sensitivities become apparent, such as parameters in adjacent zones. It is too complex to display which combinations of parameters are highly sensitive; however, PEST does concurrently vary the parameters during the automatic parameter estimation process.

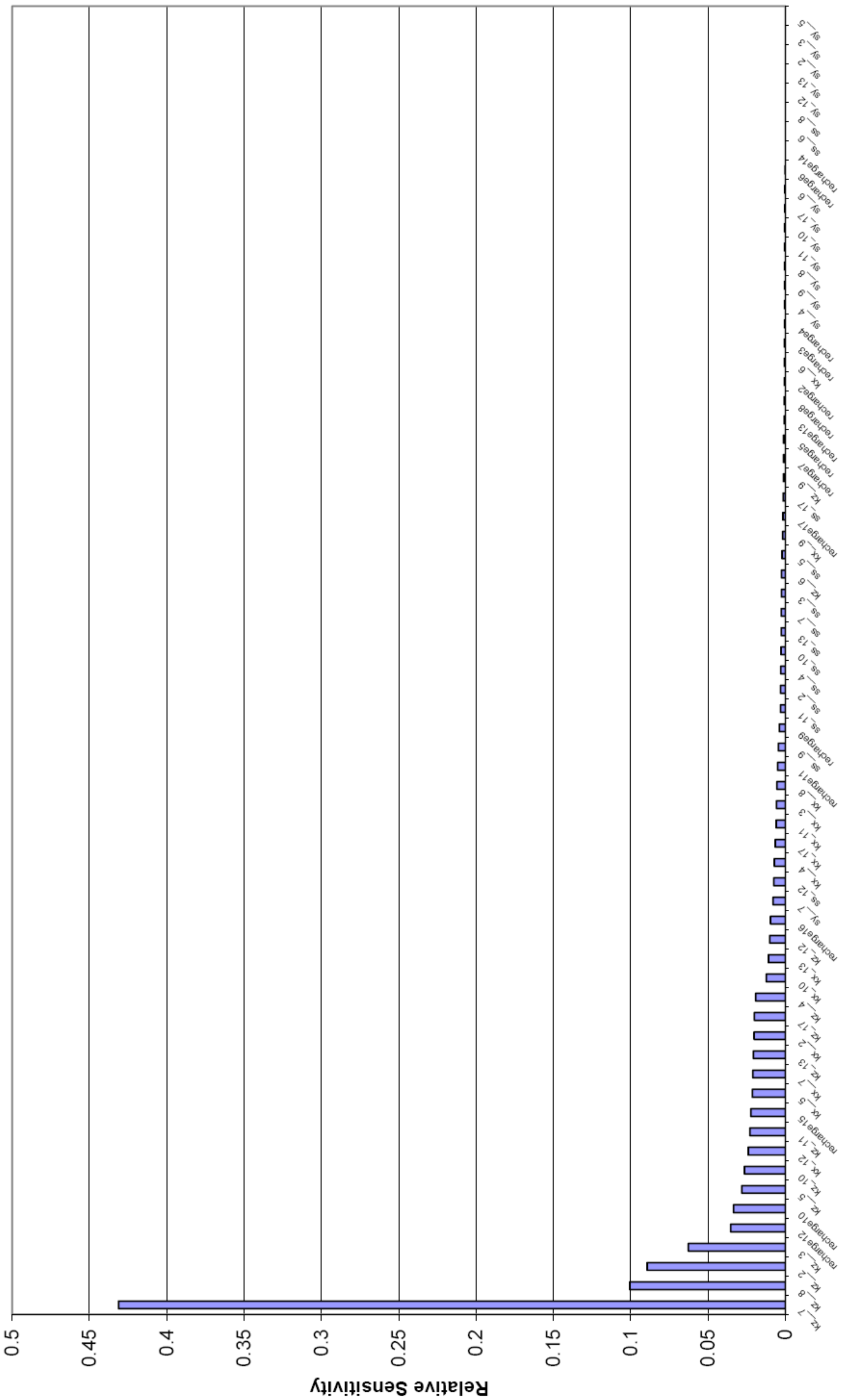


Figure 23 Plot of relative sensitivity of parameters

6 Validation of the model

The validation of the calibrated groundwater model involved testing model predictions against measured hydrograph data for the period 2005 to 2007. Comparisons were also made with available pump test data and carbon-14 data. Model verification with pump test data and carbon-14 results was undertaken by Sun (2005) for the SWAMS model. It provides a meaningful measure of model accuracy and an independent verification of simulated groundwater flow.

6.1 Validation period from 2005 to 2007

The three years from 2005 to 2007 were used as the validation period for the model. Modelled results were compared with the measured hydrographs for this period. Where hydrographs were unavailable synthetic hydrographs such as for farm bores and Margaret River pools were extended using the daily rainfall, stream flow and evaporation from 2005 to 2007.

Abstraction for the 2005 to 2007 validation period was set to be the same as for 2004. This was considered a reasonable assumption as allocation limits had been reached by this time and abstraction could be considered to be constant during this period.

The model achieved a good match with measured water levels for the period from 2005 to 2007. Normalised root mean square error was an average of 2.4% for the thirty-six monthly time steps from 2005 to 2007 (Figure 24). As well the mean absolute error was 2.4 m through the model domain for the validation period. This was considered a good match considering the large seasonal fluctuation (greater than 20 m) in many of the deeper monitoring bores on the Swan Coastal Plain and assumptions regarding abstraction which was largely estimated from allocation limits.

Consequently because the model successfully reproduces the measured water levels for the period from 2005 to 2007, which were not used as part of the calibration data set, the model can be considered validated. Ideally a longer validation period would have been preferable, but given that the calibration data set was only 15 years (1990 to 2004) a three year validation period was considered reasonable given the available data.

6.2 Comparison with pumping test data

Although no large-scale pumping tests were completed in the Cowaramup groundwater investigation, there is some data available from private production bores. Estimates of horizontal hydraulic conductivity from pumping tests can be used to compare hydraulic conductivity values determined during model calibration (Table 9). There appears to be a very good match between the modelled values for horizontal conductivity (ranging between 0.28 and 2.06 m/day from four individual layers) and those determined from the pumping tests (ranging between 0.6 and 1.55 m/day for screen intervals which cross up to four layers).

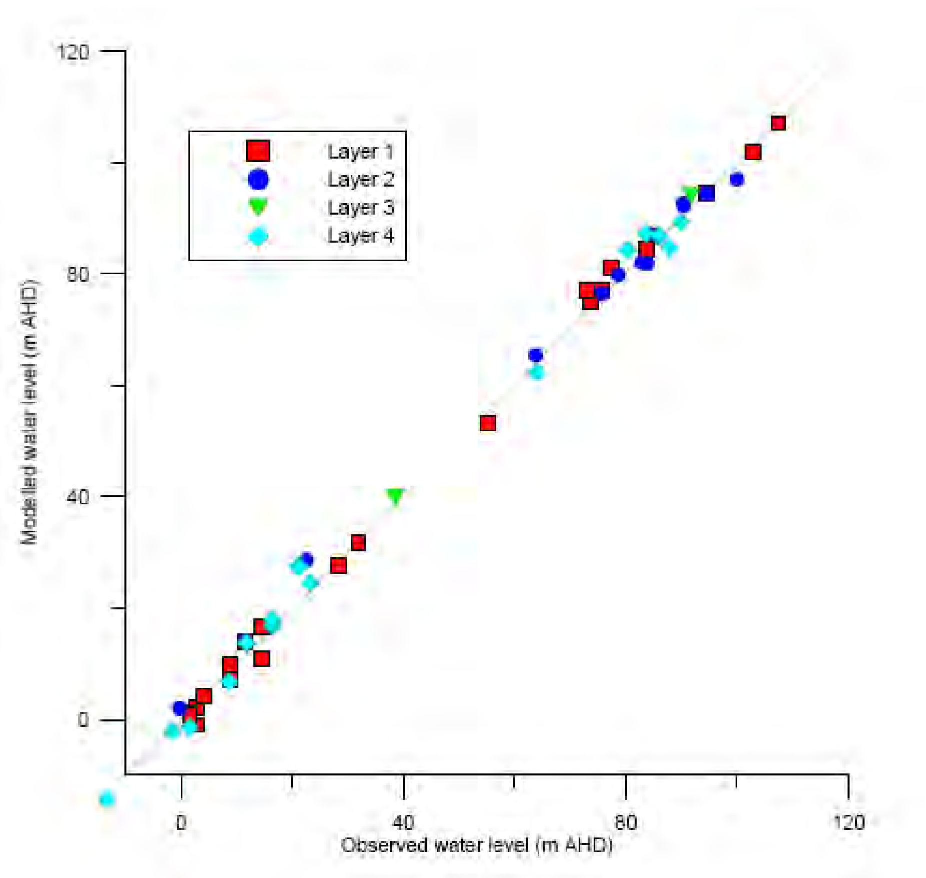


Figure 24 Observed Vs modelled heads for 2005 to 2007

Table 9 Pumping test data for Leederville aquifer (from Water Corporation, 2005)

Bore	Location	Screen interval (m bgl)	Hydraulic conductivity (m/day)	Modelled hydraulic conductivity (m/day)
GB2/82	Near BN16 (337338E, 6272048N)	9.5 - 99.4	1.55	Layer 1 / zone 8: 0.28 Layer 2 / zone 9: 2.06 Layer 3 / zone 3: 0.30 Layer 4 / zone 5: 0.93
VER1	Jindong near BN30 (near 334592E, 6264038N)	51.3 - 95	0.6	Layer 3 / zone 3: 0.30 Layer 4 / zone 5: 0.93
ET2	Evans & Tate (near 333700E, 6263300N)	75 - 137	1	Layer 4 / zone 5: 0.93

The values of hydraulic conductivity determined from the model represent the calibrated average over a much larger areal extent than the values determined from pumping tests. The good correlation independently verifies the model.

6.3 Comparison with carbon-14 (C-14) data

Modelled travel times for particles travelling from the top of Layer 1 to the monitoring bore screens were determined using the MODPATH module of VISUAL MODFLOW. In the steady state model, ‘backward’ particles were placed at the centre of the screen in those monitoring bores with C-14 data. MODPATH calculated the time for the particle to reach the screen by stepping back in time.

Figures 25 and 26 show simulated flow lines and typical particle flow paths in the Leederville aquifer with each tick mark denoting 1000 years of travel time. The simulated flow lines and C-14 age data produce spatial patterns of groundwater flow and age similar to observed data, which suggests a good representation of flow in the aquifers. Particle flow paths move north and south away from the groundwater divide on the Blackwood Plateau discharging in Geographe Bay and the Margaret River, which is consistent with the conceptual hydrogeological model.

Direct comparisons between C-14 and modelled particle track ages are misleading, and it is necessary to consider stagnant zone diffusion. Stagnant zone diffusion is a physical correction to the C-14 ages, which accounts for diffusion of water in stagnant zones (clay layers) mixing with water in sand layers (or aquifers) where groundwater predominantly occurs (Appelo and Postma, 2005).

Modelled particle track flow times are the same order of magnitude as the corrected C-14 ages, though tending to be slightly lower (Table 10). The sensitivity of changing model parameters, especially hydraulic conductivity in Layer 4, demonstrated that particle track age can increase significantly (become older than the uncorrected C-14 ages) with only a small change to the model calibration. Since the model remains broadly calibrated within the range of the C-14 ages, the water balance at the subregional scale can be considered to be verified.

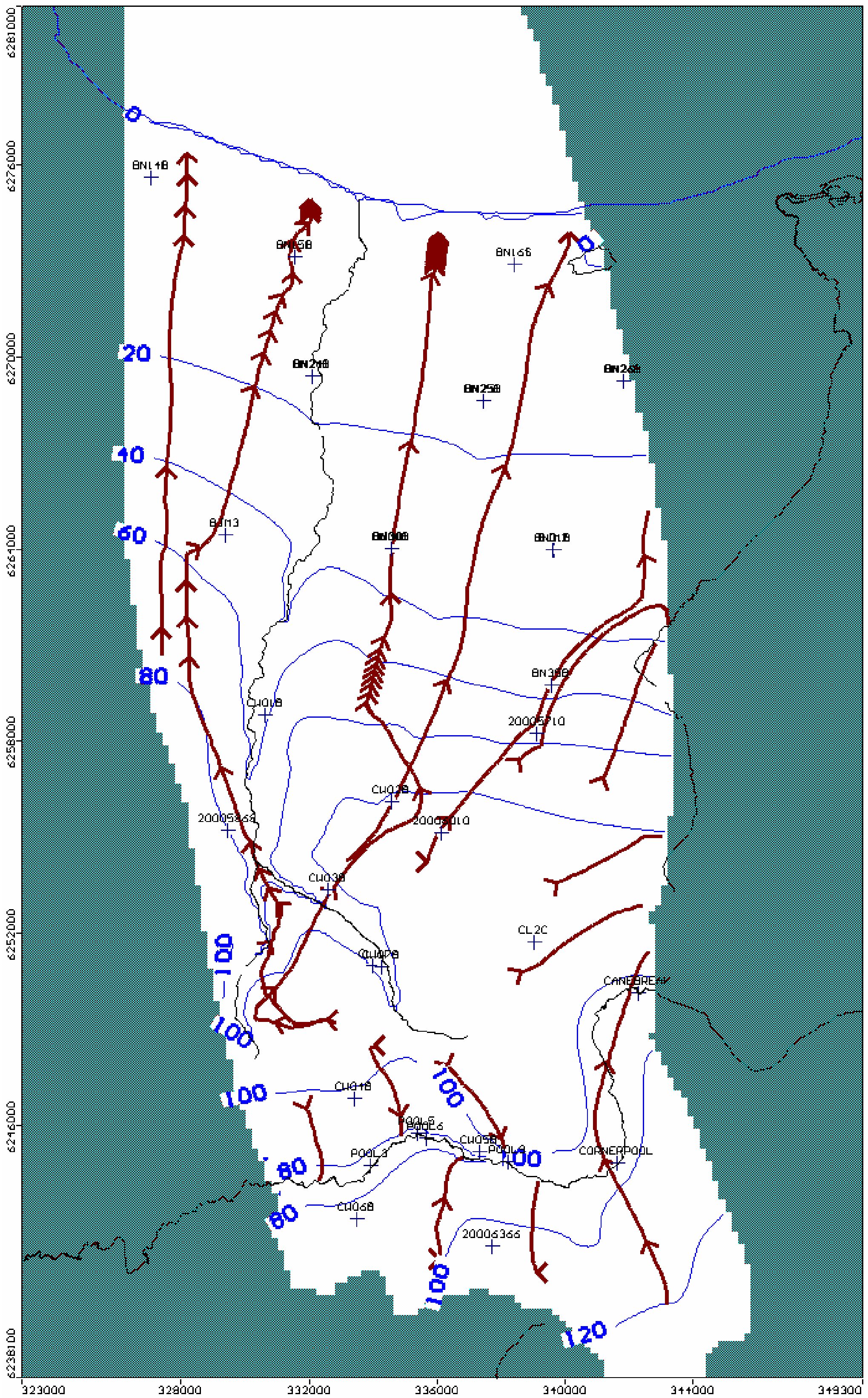


Figure 25 Typical particle flow paths (tick marks occur every 1000 years)

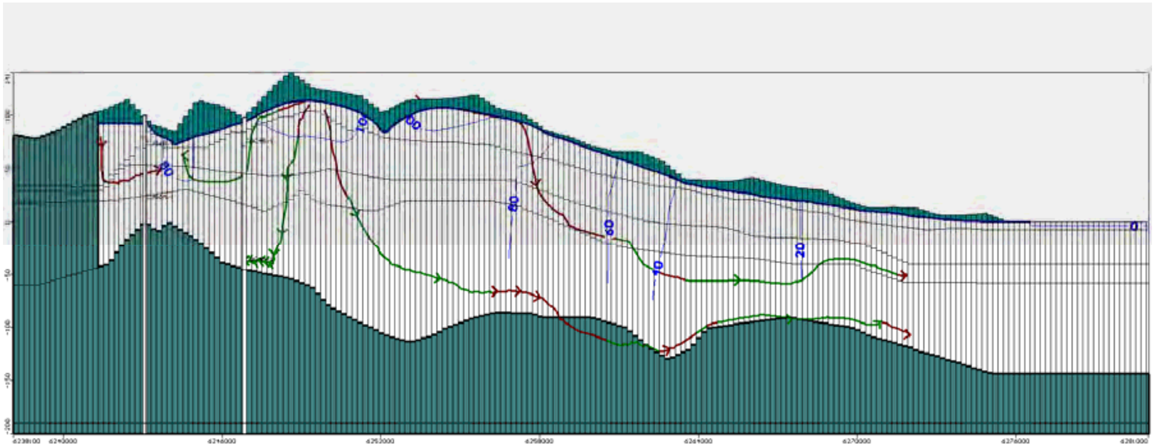


Figure 26 Cross-section showing typical particle flow paths

Table 10 Comparison of carbon-14 and modelled particle track ages

	Fraction of sand beds	Uncorrected C-14 age# (years)	C-14 ages corrected for stagnant zone diffusion (years) (assuming total porosity of clay layers 0.2 and effective porosity of sand layers 0.15)	Modelled particle track ages (years)
CW1A	0.32	28000	7300	6400
CW1B	0.18	1710	240	1200
CW2A	0.42	11430	4020	2500
CW2B	0.43	1280	460	300
CW3A	0.46	15560	6070	1400
CW3B	0.60	3300	1750	600
CW4A	0.47	23250	9290	9100
CW4B	0.59	5320	2760	300
CW5A	0.46	21560	8400	13800
CW5B	0.43	5020	1810	300
CW6A	0.35	26670	7670	>2200*
CW6B	0.25	2790	560	>1100*
CW7A	0.46	11460	4470	4200
CW7B	0.58	3800	1930	200

from Turner and Dighton (2007)

* particle starts outside model domain

7 Application of the model

7.1 Water balance

The quantitative volumes for each component of the water balance were generated from the 'zone budget' functionality of Visual MODFLOW. Figure 27 shows the water balance components estimated for 1990, 1994, 1999 and 2004 in the Cowaramup and Dunsborough–Vasse groundwater subareas. Annualised water balances for 1990 to 2004 showing changes in storage for the Cowaramup and Dunsborough–Vasse groundwater subareas are shown in Figures 28 and 29 respectively.

The water budget appears consistent with the conceptual model. The major source of groundwater is rainfall recharge. Groundwater discharges mainly through baseflow into rivers, by evapotranspiration and limited discharge to the ocean. There is relatively consistent groundwater throughflow from the Cowaramup subarea to the Dunsborough-Vasse subarea. There is also a small component of groundwater throughflow leaving the model domain, eastward across the Busselton Fault.

The Cowaramup subarea is the dominant recharge area, while recharge to the Dunsborough-Vasse groundwater subarea is small. The Cowaramup subarea is considered more sensitive to rainfall and climate variability than the Dunsborough-Vasse subarea.

Groundwater throughflow, mainly from the Cowaramup subarea, is a very important component of the water balance for the Dunsborough–Vasse subarea. The amount of throughflow remains relatively constant with only a slight decrease in drier years.

Storage change is represented as a blue line on Figures 28 and 29. In the Cowaramup subarea, storage changes track around zero suggesting no substantial change in storage. There was an increase in storage for the Cowaramup subarea in the late 1990s during wetter years and a slight storage decrease as a result of drier years from 2000. In contrast, the Dunsborough-Vasse subarea shows a storage change that is largely below zero indicating slight depletion of storage.

By comparing storage change for the Cowaramup and Dunsborough–Vasse subareas, it is apparent that the Cowaramup subarea is more responsive to wetter years than the Dunsborough–Vasse subarea. Consequently, it can be inferred that the Cowaramup groundwater subarea will be replenished faster than the Dunsborough-Vasse subarea during wetter years.

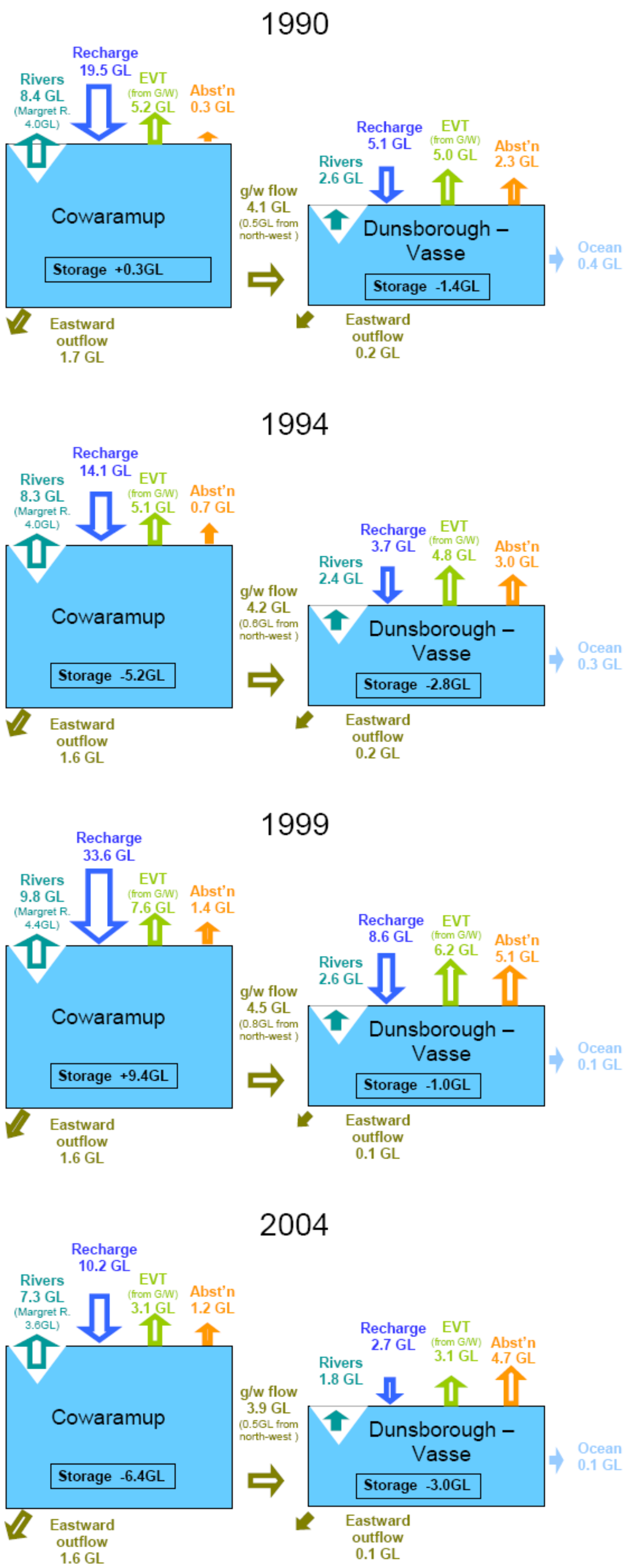


Figure 27 Schematic water balances 1990, 1994, 1999 and 2004

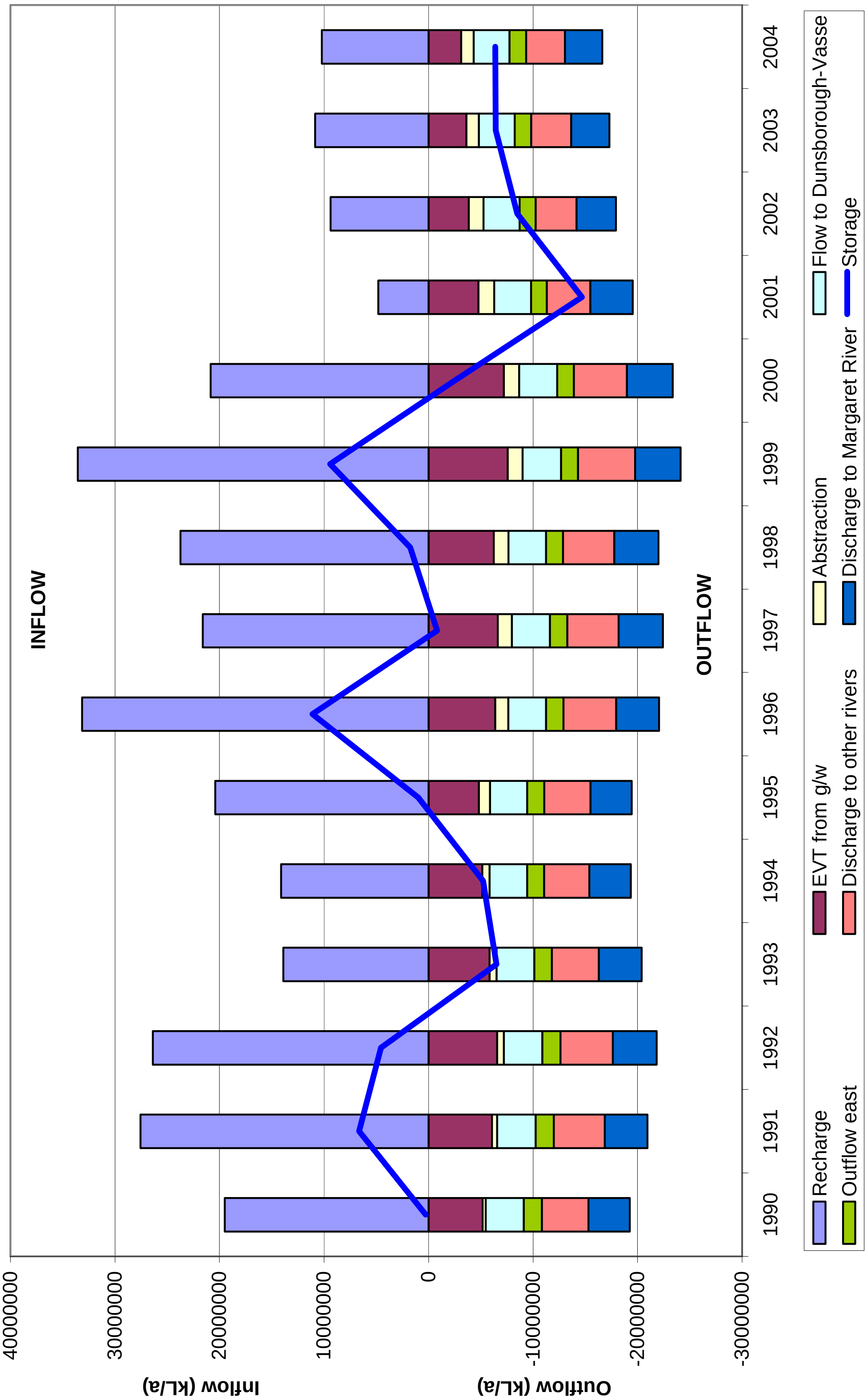


Figure 28 Annual water balance series 1990 — 2004 for Cowaramup subarea

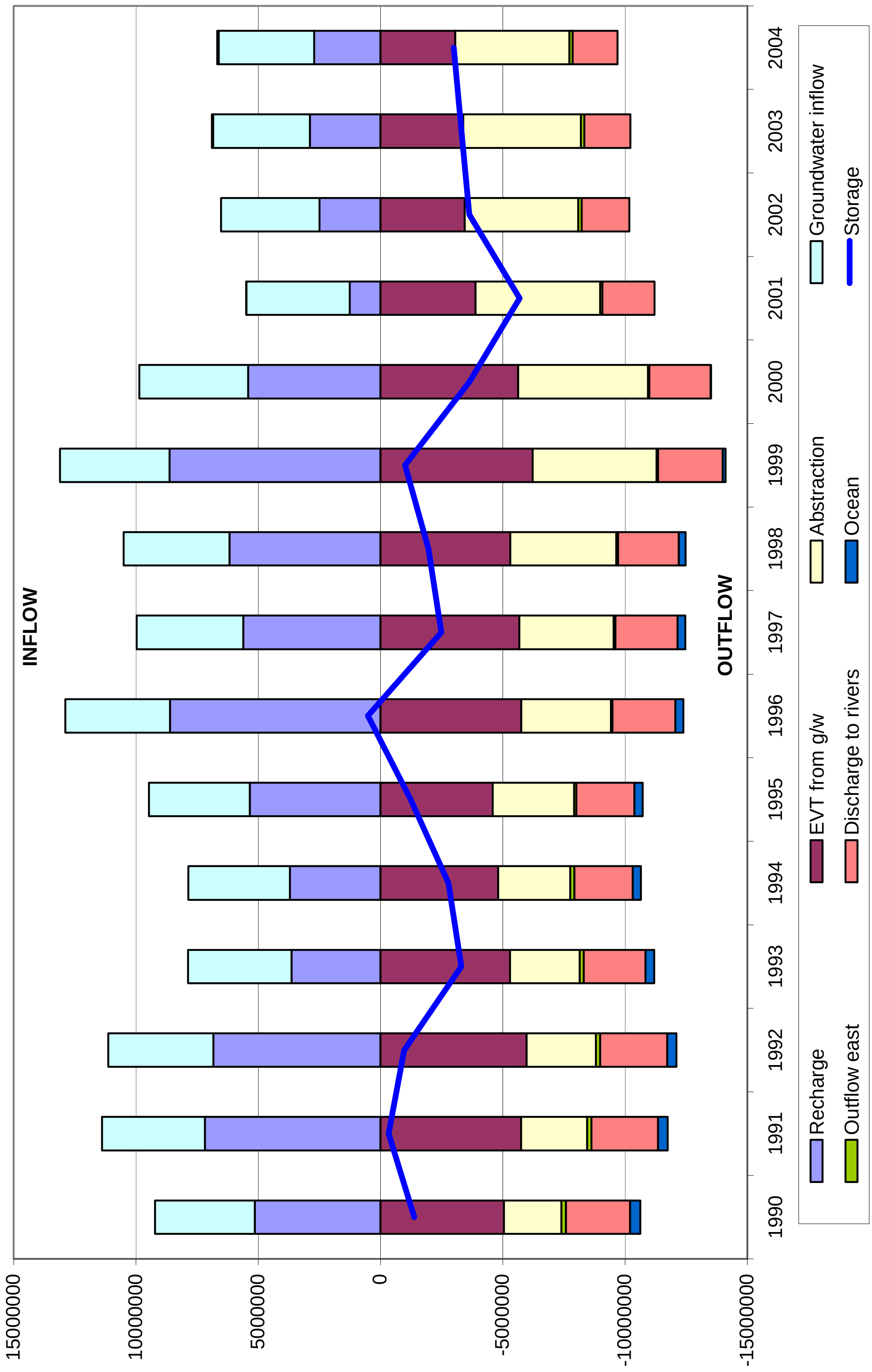


Figure 29 Annual water balance series 1990 — 2004

7.2 Impact of previous abstraction

The calibrated model has been used to assess the impact of previous groundwater abstraction. Figures 30 to 35 show water level drawdown in Layer 4 for the years 1994, 1999 and 2004. This series of figures shows the relative change in water level (or drawdown) compared with modelled water levels in winter 1990. Layer 4 was selected as it is the most susceptible to impact from groundwater abstraction.

There was a noticeable increase in the water level drawdown throughout the 1990s as a result of the increased utilisation of groundwater resources. The main areas experiencing water level drawdown include the Water Corporation's Quindalup borefield; the Jindong area in the vicinity of bores BN30 and BN31 with large groundwater abstraction for irrigation; and smaller localised areas related to large individual licences in the vicinity of bores BN24 and BN35.

There are localised areas on the Swan Coastal Plain with a watertable drawdown of around 2 m (Figure 35), which do not necessarily correspond to the major abstraction areas. This is probably a modelling effect in Layer 1 related to evapotranspiration loss over summer and localised abstraction from shallow bores. It is believed that seasonal inundation, which has not been well modelled, maintains water levels in the superficial aquifer.

Most importantly, water level drawdown in all layers generally recovers by the end of winter. There is still some residual water level drawdown in the deeper layers due to the combination of sustained high abstraction and low rainfall recharge in the early 2000s. Figure 33 shows a residual drawdown, up to 5 m, within the main abstraction areas.

There is large residual drawdown, greater than 10 m, occurring as a result of major production bores near BN35 and BN24. The large residual drawdown is probably due to relatively low hydraulic conductivity and low hydraulic gradients in these areas. In contrast, there is smaller residual drawdown (less than 6 m) in the Jindong area near BN 30 and BN31.

The Water Corporation bores in the Quindalup area (five bores with average annual abstraction of 156 ML/year) also show residual water level drawdown of around 6 m. The modelled water level drawdown is consistent with the measured water levels in monitoring bore SWI2. Some modelled residual drawdown has also propagated under the coastline, which indicates that there is potential for saltwater intrusion.

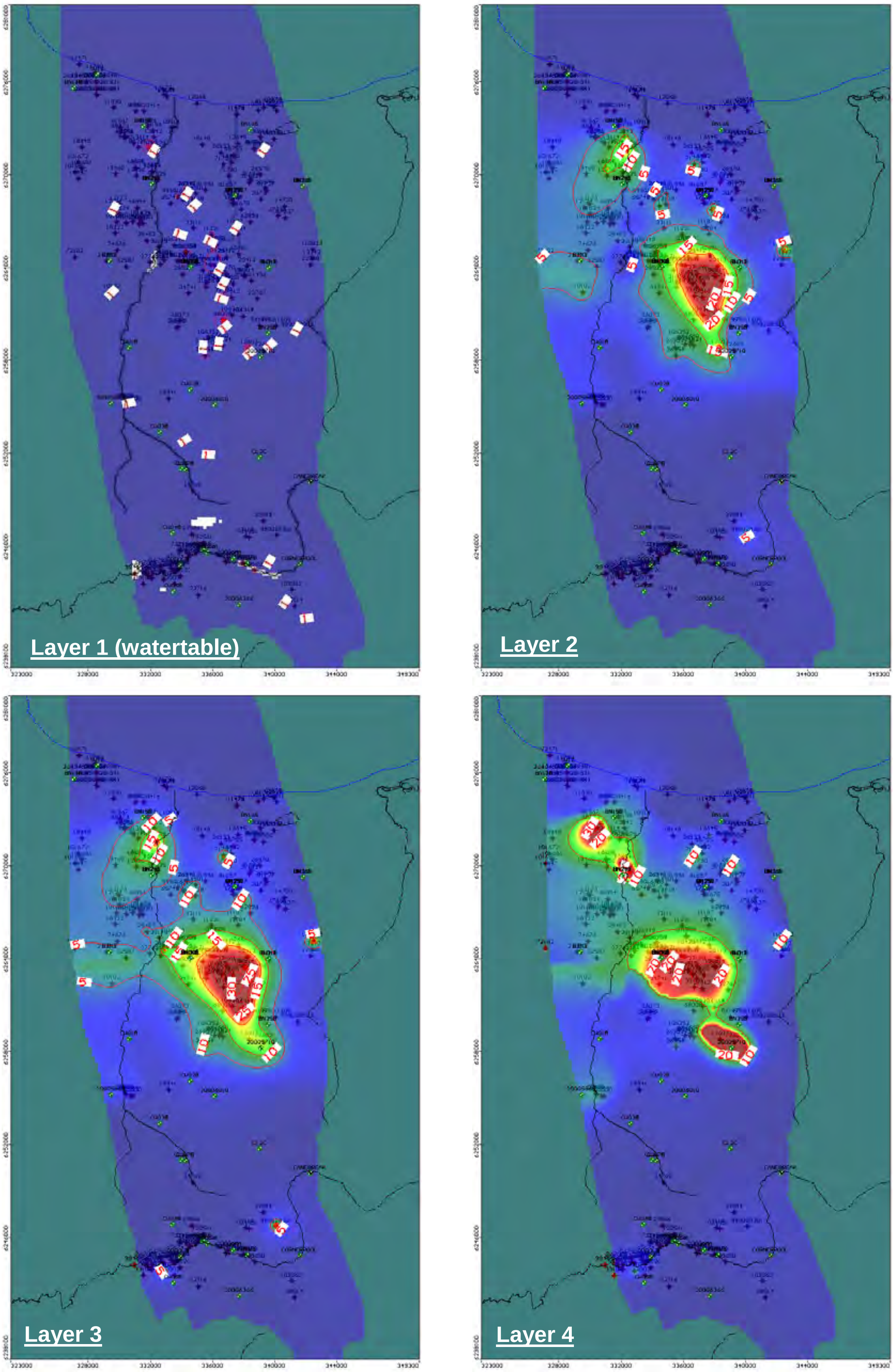


Figure 30 Modelled summer drawdown in 1994

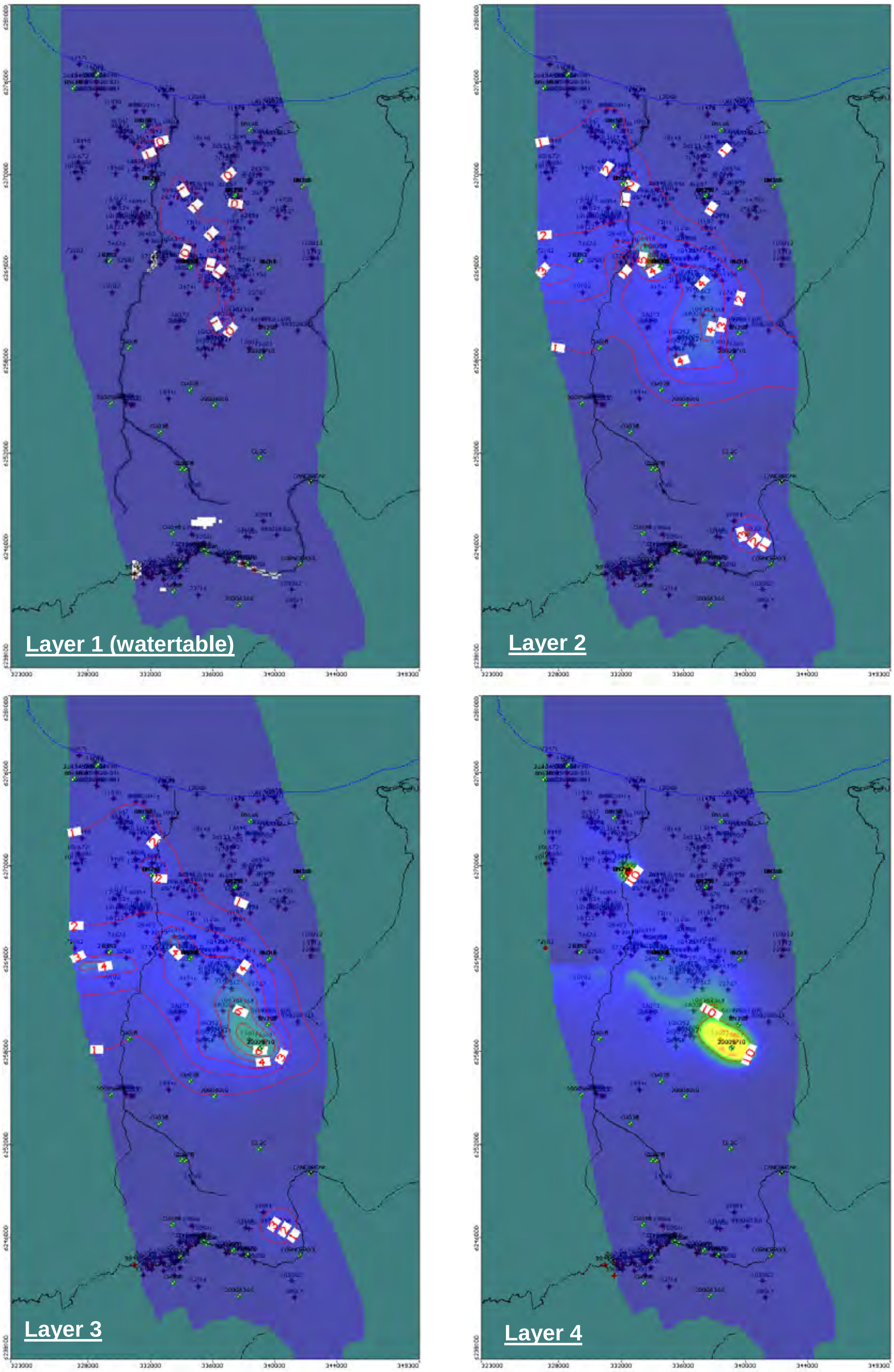


Figure 31 Modelled residual winter drawdown in 1994

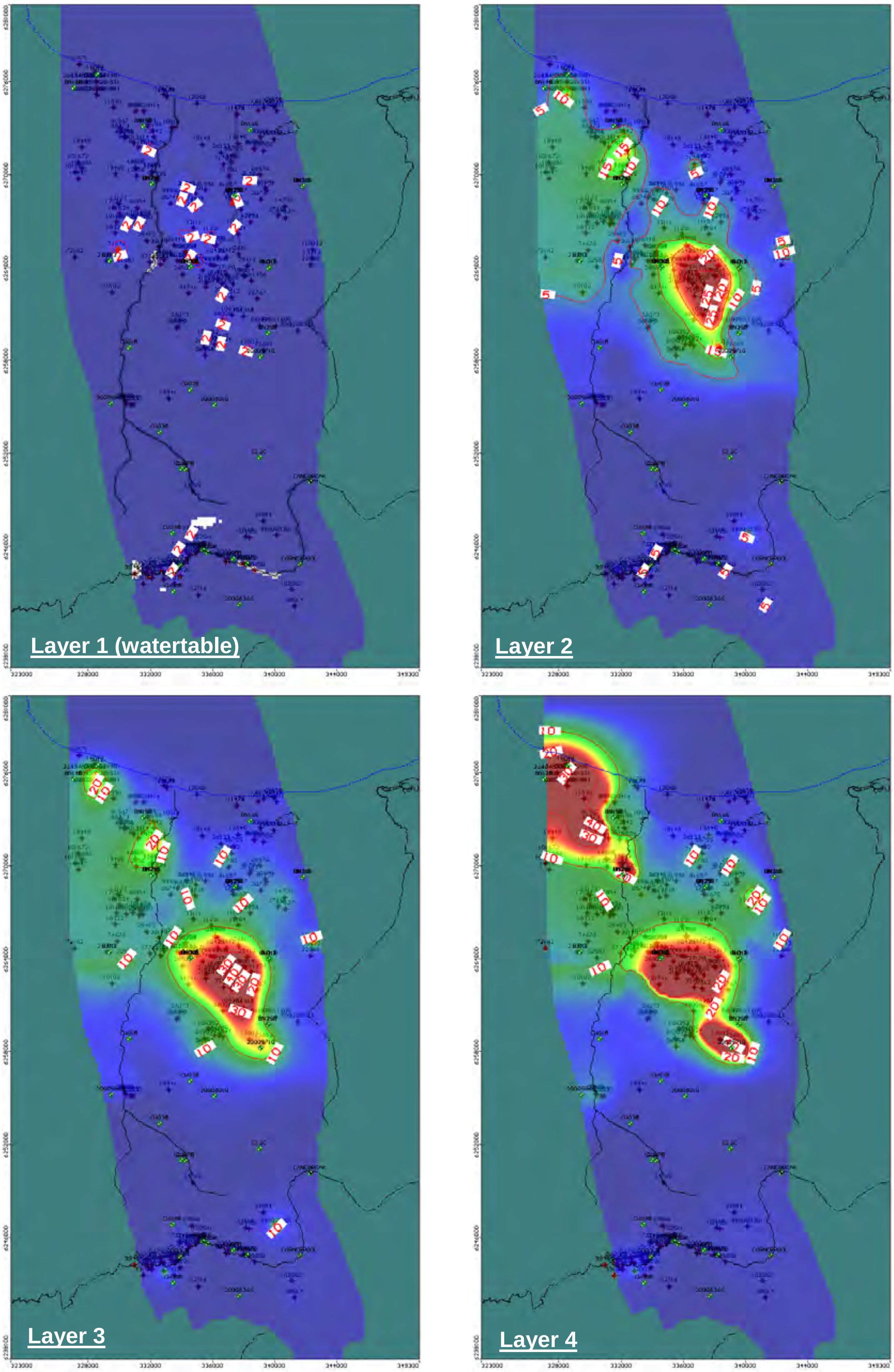


Figure 32 Modelled summer drawdown in 1999

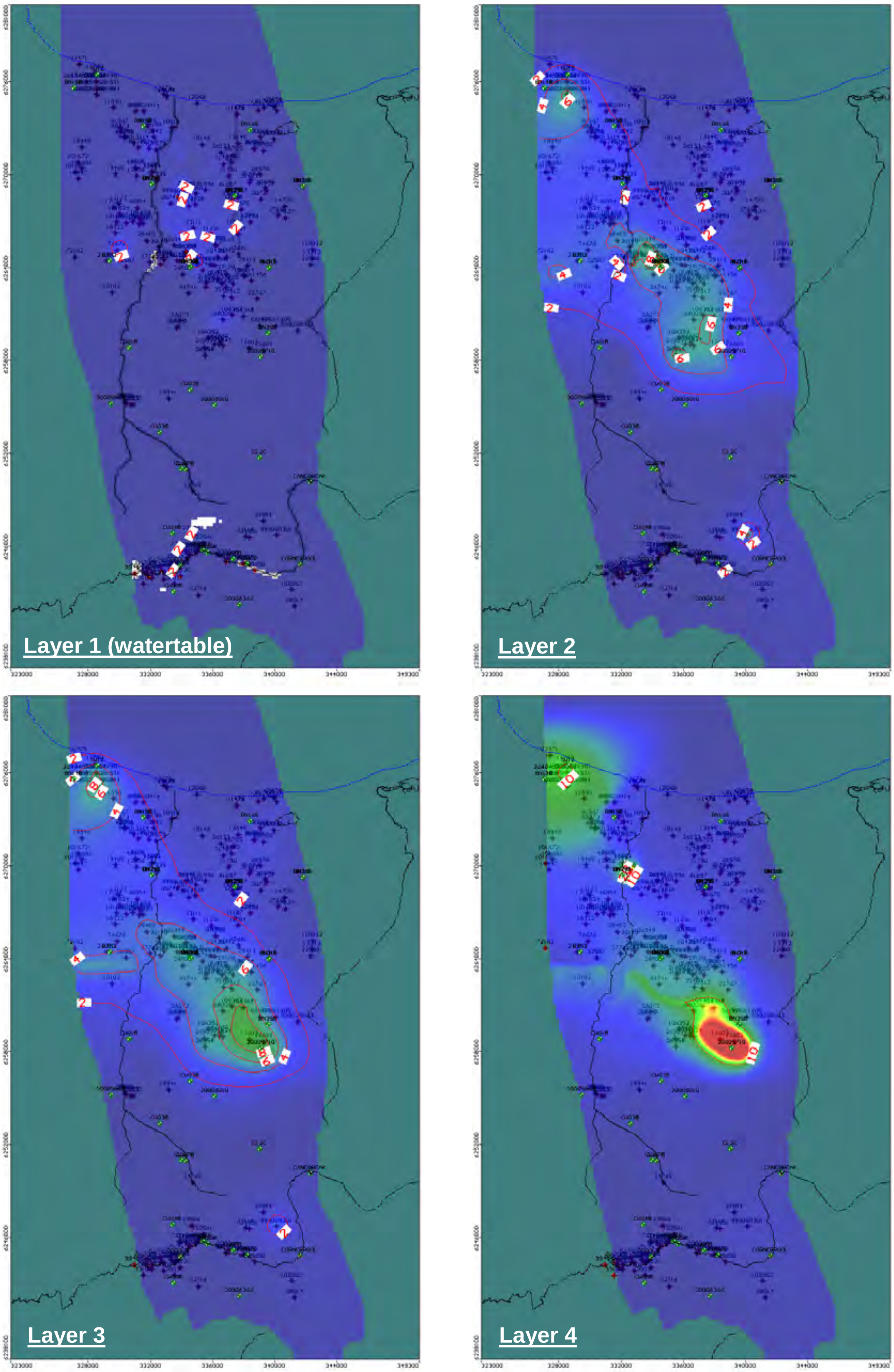


Figure 33 Modelled residual winter drawdown in 1999

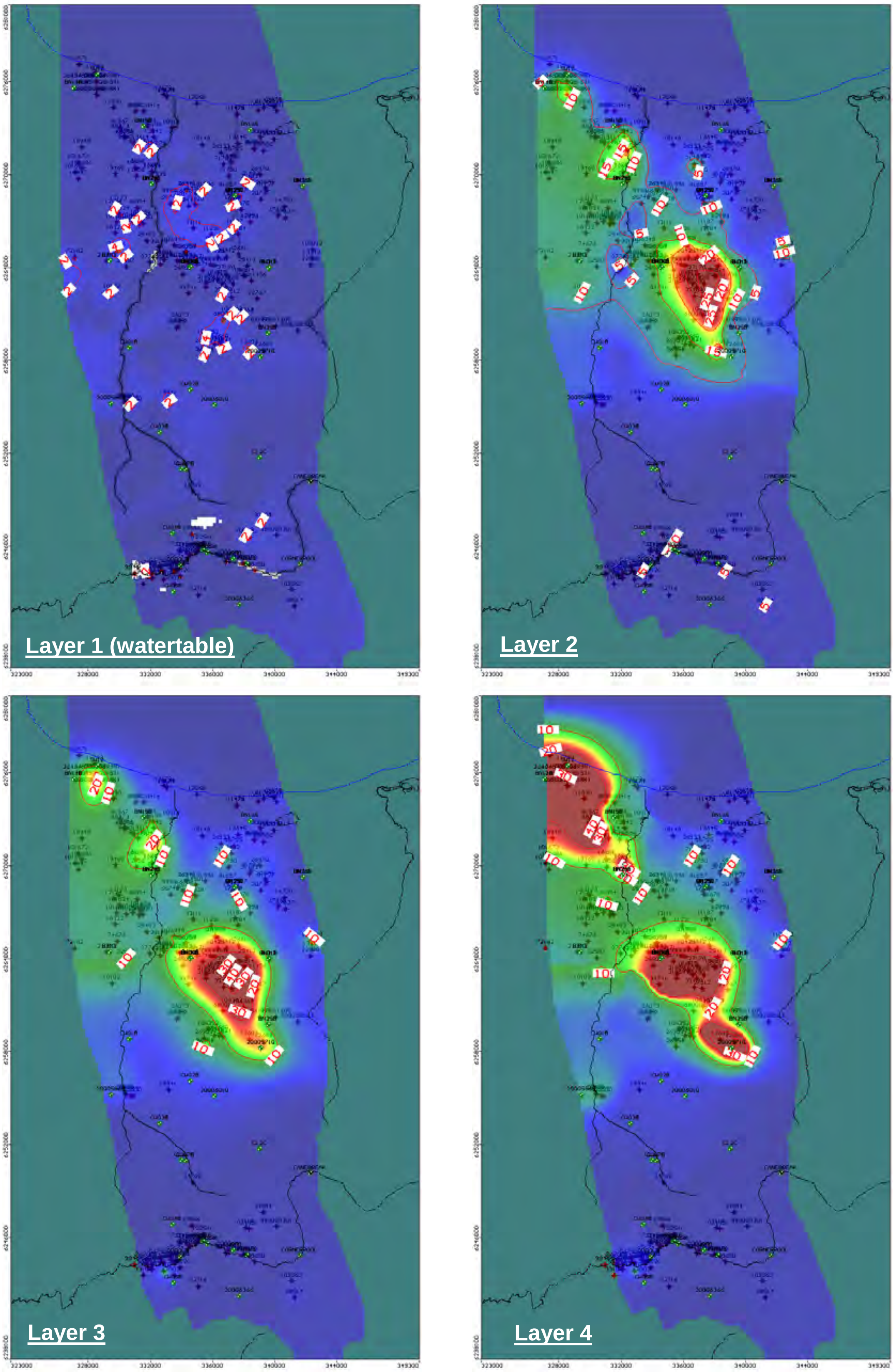


Figure 34 Modelled summer drawdown in 2004

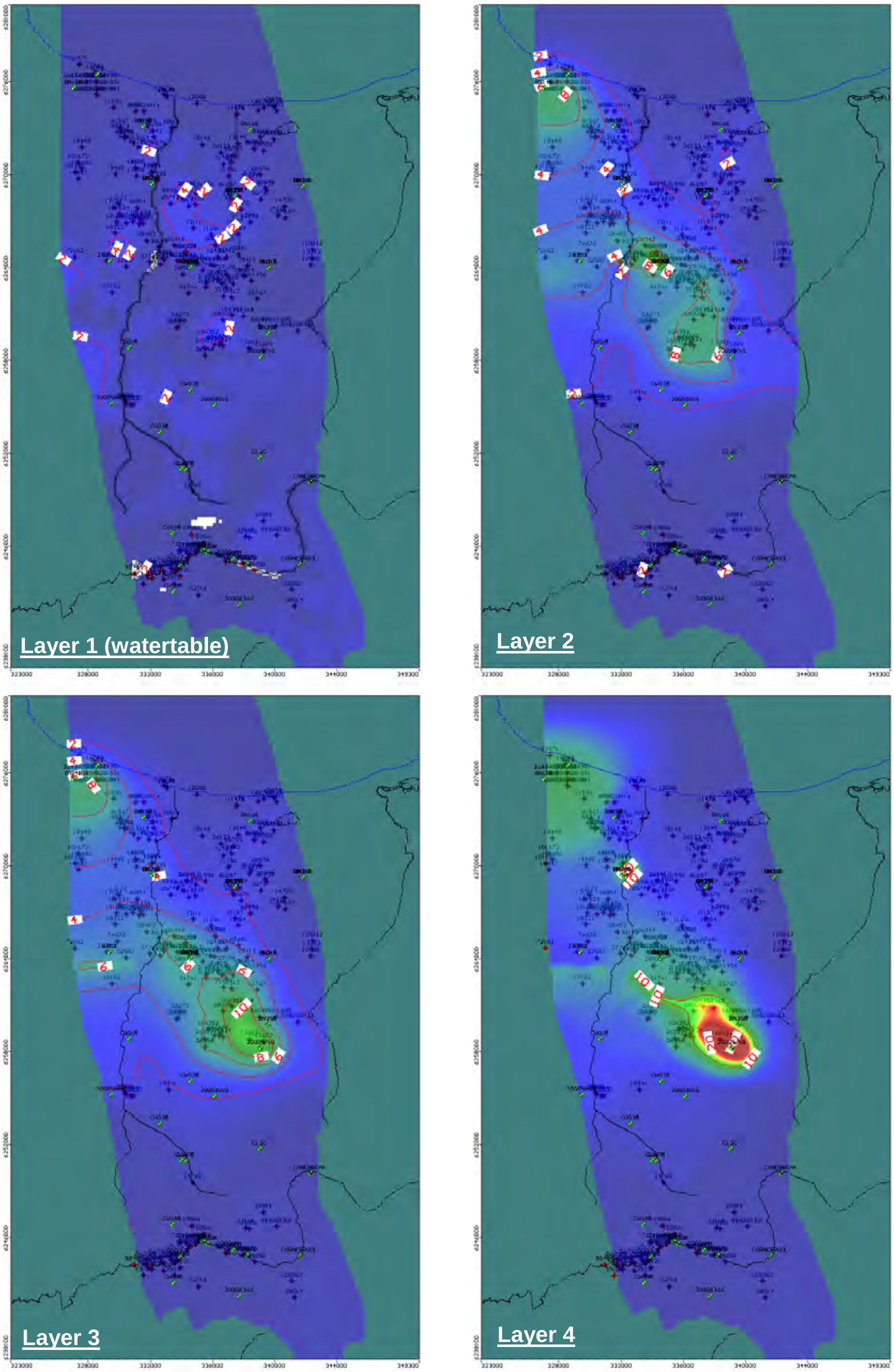


Figure 35 Modelled residual winter drawdown in 2004

7.3 Predictive scenarios

The main benefit of a calibrated groundwater model is the ability to evaluate water level and water balance response to various applied stresses including abstraction and climate change. A number of scenarios with varying abstraction and climatic regimes can be applied to the model to provide a predictive indication of impact from a water level and flux perspective.

Seven scenarios were developed for this assessment to evaluate proposed changes in allocation, as well as considering changes in rainfall recharge related to a drying climate. The changes in abstraction reflect proposed changes in allocation limits for the Cowaramup subarea. The predictive scenarios were run from 2005 to 2020 using the calibrated model with different abstraction and climatic variables.

The final scenarios selected for evaluation were:

1) base case **-** current abstraction with 95% of average 1990 – 2003 recharge (as per the SWAMS base case);
2) northern **-** increase abstraction in the northern Cowaramup subarea by 3 GL/year with 95% of average 1990 – 2003 recharge (as per the SWAMS base case);
3) southern **-** increase abstraction in the southern Cowaramup subarea by 2 GL/year with 95% of average 1990 – 2003 recharge (as per the SWAMS base case);
4) combined **-** increase abstraction across Cowaramup subarea by 5 GL/year being a combined northern and southern scenario with 95% of average 1990 – 2003 recharge (as per the SWAMS base case);
5) climate 1 **-** increase abstraction across Cowaramup subarea by 1.5 GL/year and 95% of average 1990 – 2003 recharge (as per the SWAMS base case);
6) climate 2 **-** increase abstraction across Cowaramup subarea by 1.5 GL/year with average recharge for 1997 – 2006 (recent dry period); and
7) climate 3 **-** increase abstraction across Cowaramup subarea by 1.5 GL/year with 95% average recharge for 1997 – 2006.

Each scenario was developed, in consultation with Water Allocation Branch, to assess the sustainable yield of the Cowaramup groundwater subarea and identify areas susceptible to water level decline by altering groundwater allocations. For each scenario, an annual water balance for 2005 to 2020 was produced to show change in aquifer storage. In addition, maps showing maximum water level drawdown in summer and residual drawdown remaining in winter for each of the four model layers were also generated. Drawdown was measured relative to water levels in winter 1990.

7.3.1 Scenario variables

Starting heads

The calibrated head data at the end of December 2004 were used as the starting head for the scenario runs, starting from January 2005.

Recharge

Recharge in scenarios 1 to 5 was set at 95% of the average recharge during 1990 to 2003. This average recharge represents a reduced recharge under the current drying regime, when compared with longer-term climate condition. This approach is similar to that used in general scenario runs of SWAMS, which was the average recharge from 1971 to 2003.

In order to evaluate the sensitivities and potential impacts of a drying climate, the final two scenarios (6 and 7) used different recharge regimes to better represent the reduced rainfall conditions since 1997. These two scenarios were to provide useful information on the long-term impact of climate change and sustainability of groundwater resources.

Recharge in scenario 6 was set at average recharge during 1997 to 2006. This reflects the step change reduction in rainfall experienced in the south-west of the State. Rainfall for this period including two of the driest years on record, 2001 and 2006, is considered equivalent to the average climate expected by the 1ºC increase predicted for climate warming by 2038 (CSIRO, 2006). It is considered to be a more representative estimate of future recharge.

Recharge for scenario 7 was set at a 5% reduction of the scenario 6 recharge. This is considered a more extreme or conservative estimate for future rainfall reduction in the south-west of the State. This scenario will demonstrate the longer-term impacts of drying climate on the groundwater resource.

Average recharge was applied in the scenarios from 2007 onwards. Recharge and evapotranspiration for 2005 and 2006 were estimated based on measured river flow and pan evaporation.

Abstraction

The scenario runs used cumulated abstraction data with each scenario inputted into the model and run individually. Scenario 1 represents the base case scenario with abstraction set at 2004 levels, which is considered indicative of current abstraction. Weekly production data from Water Corporation bores and surface water 'pump in stream' licences for the Margaret River pools were added to the SWAMS abstraction data set. The average abstraction for 2004 was applied from 2005 onwards during the scenario runs.

Scenarios 2, 3 and 4 were developed to evaluate the sensitivities and potential impacts of abstraction across the Cowaramup subarea. These scenarios included the base abstraction from scenario 1, as well as additional abstraction in selected areas and model layers. The scenario abstraction points (or simulated bores) were positioned in prospective horticultural areas, and areas that were susceptible to water level change related to abstraction.

In scenario 2, an additional 18 scenario bores were added in the northern portion of the subarea to increase abstraction by 3 GL/year (Figure 36a). In scenario 3, an additional 21 scenario bores were added in the southern portion of the subarea to increase abstraction by 2 GL/year (Figure 36b). Scenario 4 was a combined scenario developed to evaluate the cumulative impact of scenarios 2 and 3 (Fig 36c).

Results from the first four scenarios suggested that groundwater allocations (abstraction) could be potentially increased by 1.5 GL/year. As a result, abstraction for scenarios 5 to 7 included base case and an additional 1.5 GL/year from 18 scenario bores positioned in both the northern and southern portion of the subarea (Figure 36d). The final three scenarios were developed to evaluate the impact of drying climate on a fixed abstraction regime.

7.3.2 Drawdown from scenario runs

Water level drawdown to 2020 for each of the seven scenarios is expressed as summer maximum (Appendix G) and spring residual drawdown (Appendix H). The summer maximum drawdown reflects the maximum extent of water level decline, which reflects higher abstraction rates in the summer months. In contrast, the spring residual drawdown represents the resting water level drawdown after winter, when abstraction rates are minimal. The spring residual drawdown is considered more important when assessing the long-term impact of water level decline.

Scenario 1 – base case

Modelled summer maximum (Appendix G1) and spring residual drawdown (Appendix H1) at 2020 for the base case scenario are similar to those water levels in 2004 (Figures 34 and 35). This further verifies the model and its predictive ability, as water levels will only change with substantial variation in abstraction and/or climate.

The watertable in Layer 1 for the base case scenario also shows a subtle increase in drawdown compared to the 2004 drawdown. This drawdown is localised and is not residual, suggesting it is related to modelled recharge rather than impacts propagating from deeper abstraction.

Summer drawdown in the Jindong area (near bores BN30 and BN31) in Layers 3 and 4 does slightly increase and appears to merge with an area of drawdown near BN35.

There is also a small increase in the area of spring residual drawdown greater than 10 m in Layers 3 and 4. In addition, there is a slight increase in depth of winter residual drawdown in the Quindalup borefield.

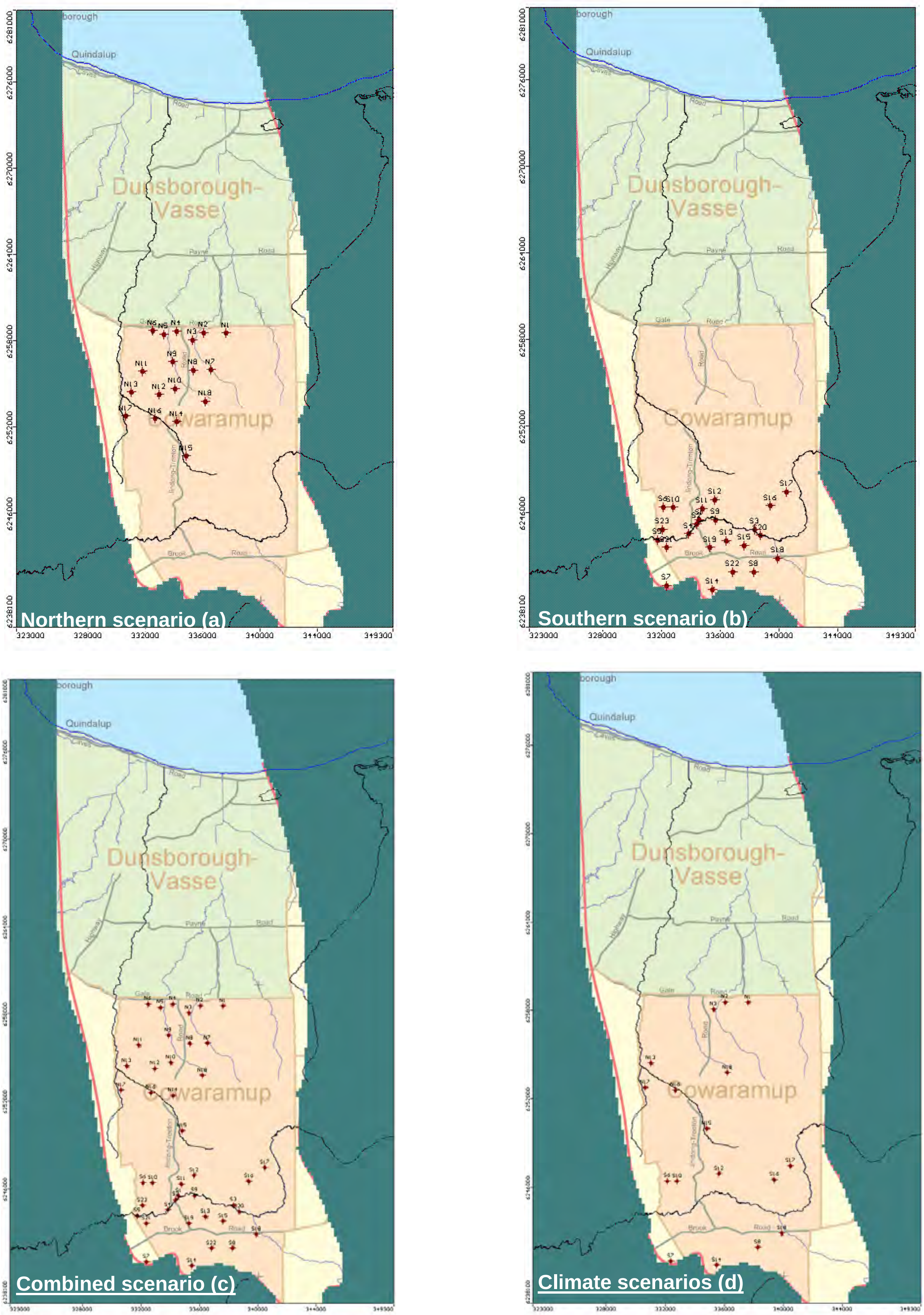


Figure 36 Position of scenario bores

Scenario 2 - northern

Modelled summer maximum (Appendix G2) and spring residual drawdown (Appendix H2) for the northern scenario is most significant in the vicinity of the added scenario bores. The watertable (Layer 1) for scenario 2 is not impacted by abstraction from the scenario bores and is basically to the base case scenario. The main reason is that scenario bores are simulating abstraction from deeper layers, and watertable drawdown is more related to recharge variations and shallow abstraction.

All Layers 2, 3 and 4 show an increase in both summer maximum and spring residual drawdown in the northern part of the Cowaramup subarea. The scenario bores along the Cowaramup and Dunsborough-Vasse subarea boundary have a significant impact, as they merge with the cone of depression related to abstraction in the Jindong area.

In conclusion, there are no residual impacts on the watertable but water level drawdown is increased in the deeper layers. The Jindong area appears to be most sensitive to water level drawdown related to increased abstraction; as such, additional abstraction in the northern portion of the Cowaramup subarea requires careful consideration.

Scenario 3 – southern

Modelled summer maximum (Appendix G3) and spring residual drawdown (Appendix H3) for the southern scenario is most noticeable in the vicinity of Margaret River. Watertable drawdown in Layer 1 (and Layer 2 at Margaret River) is considered significant in the lower reaches of Margaret River near the western model boundary. This drawdown is also exacerbated in the western portion of Margaret River, as the Leederville aquifer abuts the Leeuwin Complex.

Layers 2, 3 and 4 show increases in both summer maximum and winter residual drawdown along the Margaret River valley. Residual drawdown near the southern model boundary is considered an overestimation. Despite the boundary representing a groundwater divide, there may be some groundwater flow across this boundary.

This scenario has demonstrated that the downstream portion of Margaret River is highly sensitive to abstraction. No increase in abstraction is recommended in the western portion of Margaret River, and upstream areas are also considered sensitive to drawdown.

Scenario 4 - combined

Modelled summer maximum (Appendix G4) and spring residual drawdown (Appendix H4) for the combined scenario is very similar to the individual responses for scenarios 2 and 3. Consequently, water level drawdown impacts are most noticeable in the western portion of Margaret River (as observed in scenario 3), and along the Cowaramup and Dunsborough-Vasse boundary in the deeper aquifer.

Scenario 5 – climate 1

Modelled summer maximum (Appendix G5) and spring residual drawdown (Appendix H5) for the climate 1 scenario shows localised impacts in Layers 2, 3 and 4. The most significant water level decline is in the north-eastern part of the Cowaramup subarea related to abstraction in the Jindong area and near BN35. Watertable drawdown in Layer 1 is minimal with only localised impacts.

There appear to be no residual impacts on the watertable; however, water level drawdown is slightly increased in the deep Leederville aquifer. The Jindong area appears to be most sensitive to water level drawdown related to increased abstraction.

Scenario 6 – climate 2

Modelled summer maximum (Appendix G6) and spring residual drawdown (Appendix H6) for climate 2 is very similar to the climate 1 scenario. There is no apparent difference in the drawdown for Layers 2, 3 and 4, which demonstrates that a drying climate will have no noticeable short-term impact on the deeper aquifer. In contrast, there is a slight increase in watertable drawdown in Layer 1, which is most likely related to the reduction in recharge rather than impacts from deeper abstraction. As there are no apparent spring residual impacts, this confirms that winter rainfall in most years is sufficient to fully recharge the watertable.

Scenario 7 – climate 3

Modelled summer maximum (Appendix G6) and spring residual drawdown (Appendix H6) for climate 3 is very similar to climate 1 and 2 scenarios. There is no apparent difference in the drawdown for Layers 2, 3 and 4, which again demonstrates that a drying climate will have no noticeable short-term impact on the deeper aquifer. The increased watertable drawdown in Layer 1 demonstrates that water level decline is a product of recharge reduction rather than deeper abstraction. There is no apparent spring residual impact, suggesting that winter rainfall in most years is sufficient to fully recharge the watertable.

7.3.3 Water balance of scenario run

Annual water balances for the Cowaramup and Dunsborough-Vasse groundwater subareas are presented graphically in Appendix I and Appendix J respectively. This graphical representation of each component in the water balance is an innovative approach, and shows the annual change of each component. It is most useful in understanding relative change in aquifer storage and groundwater throughflow.

Aquifer storage

Aquifer storage, represented as a blue line on the annual water balance diagrams in Appendices I and J, can be used as a relative measure of aquifer sustainability. There is no storage change when aquifer storage tracks around zero, but either positive or negative values indicate increasing storage or storage depletion.

In all scenarios, except scenario 3 (combined), there was no appreciable change in aquifer storage for the Cowaramup subarea. The large combined abstraction of 5 GL/year in scenario 3 was considered unsustainable in the long term, which was confirmed in the water level drawdowns. It can be suggested that groundwater allocation can increase in the Cowaramup subarea, up to 1.5 GL/year, without depleting aquifer storage.

In all scenarios, there are negative values of storage change for the Dunsborough-Vasse subarea indicating that this subarea is fully allocated and there may be some ongoing depletion of aquifer storage. Despite increasing allocations in the Cowaramup subarea, there was no associated impact on aquifer storage in the Dunsborough-Vasse subarea. It is therefore suggested that there should be no increase in groundwater allocations for the Dunsborough-Vasse subarea, and that there is more thorough groundwater review of the Jindong and Quindalup area in the future.

Groundwater throughflow

Groundwater throughflow from the Cowaramup subarea into the Dunsborough-Vasse subarea remained fairly constant for all scenarios. This indicates that abstraction and drying climate had only a small impact on the hydraulic gradient between subareas. The only noticeable difference occurred when scenario bores were positioned in the immediate vicinity of the subarea boundary.

In addition to aquifer storage and throughflow, annual water balances for all scenarios highlighted that there is a small amount of seawater inflow toward the Dunsborough-Vasse subarea. This would suggest that there is potential for saltwater intrusion, primarily related to groundwater abstraction from the Water Corporation’s Quindalup borefield.

8 Model results and findings

The development, calibration and scenario runs of the Cowaramup groundwater model has revealed a number of key findings about the groundwater resources and functioning of the Leederville aquifer. This new understanding has ramifications for groundwater resource allocation and future management of the western Busselton-Capel Groundwater Area. This section highlights model results and management considerations required for future development of the groundwater resource.

8.1 Hydraulic properties

The Leederville aquifer in the western Busselton-Capel Groundwater Area is a moderate-yielding aquifer. Model calibration suggests that horizontal conductivity (K_x and K_y) ranges from 0.01 to 10 m/day with most values being between 0.2 to 2 m/day. Low vertical conductivities between 10^{-3} and 10^{-4} restrict rainfall recharge entering the deep Leederville aquifer, which has been confirmed in the groundwater age dating.

The aquifer is highly anisotropic with horizontal conductivity being two to five orders of magnitude greater than vertical conductivity, which is a related to the high percentage of clay interbeds. Water level changes from groundwater abstraction are likely to propagate horizontally rather than vertically. This suggests that groundwater abstraction from the deep Leederville aquifer will not impact the watertable.

Low hydraulic conductivities and anisotropy dictate that groundwater abstraction should be evenly spread. Large production bores are to be spaced to prevent overlapping cones of depression that propagate horizontally.

8.2 Groundwater recharge

Most groundwater recharge occurs on the Blackwood Plateau with modelled recharge being between 63 to 225 mm/year. This is predominantly due to the downwards hydraulic gradients and areas of modest vertical conductivity related to the sandy Quindalup Member.

There is minimal recharge (0 to 12 mm) of the deep Leederville aquifer beneath the Swan Coastal Plain, as well as groundwater discharge areas such as Margaret River valley and the base of the Whicher Scarp. This is a result of small downwards heads or localised upward hydraulic gradients in these areas.

The groundwater model is sensitive to recharge. Modelled recharge has been estimated using a relatively simple approach based on river baseflow. Recharge is a more complex process with a number of factors affecting whether groundwater reaches the watertable and is able to infiltrate the aquifer; however, the modelled recharge predictions are still considered meaningful.

Modelling has confirmed that the Cowaramup subarea is highly dependent on rainfall recharge. As a result, this area is most sensitive to any reduction in recharge related to a drying climate. In contrast, the Dunsborough-Vasse subarea is more dependent on groundwater throughflow.

8.3 Groundwater throughflow

Groundwater throughflow from the Cowaramup subarea into the Dunsborough-Vasse subarea remains fairly constant between 3.87 and 4.24 GL/year for a range of recharge and abstraction conditions (Table 11). This indicates that abstraction and drying climate had only a small impact on the hydraulic gradient between subareas. The only noticeable impact occurred when scenario bores were positioned in the immediate vicinity of the subarea boundary, which produced a 0.4 GL/year reduction in throughflow.

Table 11 Groundwater throughflow entering the Dunsborough-Vasse subarea

Scenario	Throughflow from Cowaramup to Dunsborough-Vasse in 2020 (GL)
1. Base case (no increase)	3.56
2. Northern (3 GL increase)	3.16
3. Southern (2 GL increase)	3.56
4. Combined (5 GL increase)	3.16
5. Climate 1 (1.5 GL increase)	3.46
6. Climate 2 (1.5 GL increase)	3.35
7. Climate 3 (1.5 GL increase)	3.32

Modelling has demonstrated that allocation limits in the Cowaramup subarea can be increased without significant impact on the water balance of the Dunsborough-Vasse subarea. The scenarios have demonstrated that no new production bores be installed along the northern edge of the Cowaramup subarea, especially near areas of current high abstraction, as this has potential to impact groundwater throughflow.

8.4 Groundwater dependent ecosystems

Areas of shallow watertable and groundwater discharge such as springs, wetlands and rivers may potentially support groundwater dependent ecosystems (GDEs). It is likely that groundwater contribution to surface water features also plays an important function in maintaining streamflow and/or wetland features.

8.4.1 Depth to watertable and GDEs

A useful product from the groundwater model is a representation of depth to watertable (Figure 37), which was generated using high recharge on the Swan Coastal Plain. Most GDEs are likely to occur in areas of shallow watertable being

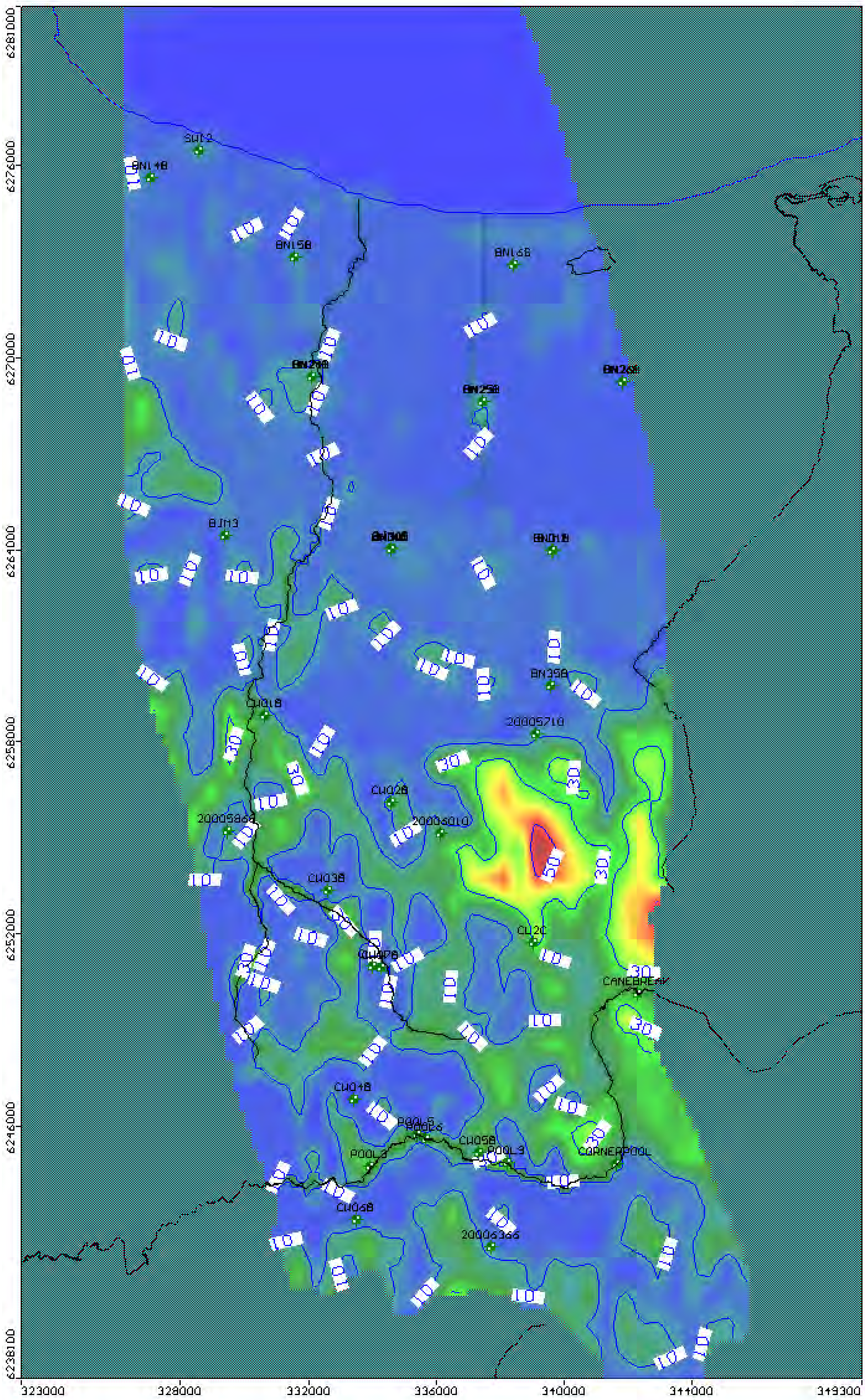


Figure 37 Modelled depth to watertable

less than 10 m. This would include most of the Swan Coastal Plain, parts of the Yelverton Shelf, as well as the Carbunup River and Margaret River valleys. The deep watertable, greater than 10 m, across most of the Blackwood Plateau indicates that there are fewer areas of potential GDEs in the Cowaramup subarea.

8.4.2 Margaret River pools

The permanent, riverine pools along Margaret River are recognised as an important potential GDE. They have been identified as management zone 6 in the South West groundwater areas water management plan (Department of Water, 2008). A focus of the modelling was to assess the sensitivity of these pools in Margaret River to increased groundwater abstraction. The model scenarios have demonstrated that the lower reaches of Margaret River, near the western model boundary, are highly sensitive to additional groundwater abstraction especially from shallow bores.

In addition to groundwater abstraction, it is highlighted that existing surface water abstraction (estimated at 300 ML/year) is considered the most significant risk to pool levels compared with groundwater abstraction. As most surface water is abstracted during the summer, it is suggested that this abstraction should be considered as groundwater abstraction.

In order to prevent impacts on Margaret River, a buffer zone is recommended with no new production bores to be installed within a 1 km distance of Margaret River. In addition, no shallow bores that are screened less than 40 m bgl are recommended for the remaining Margaret River valley. It is also recommended that surface water licences that abstract during summer months should be reviewed as groundwater licences.

8.4.3 Ironstone communities

The ironstone communities on the Yelverton Shelf are stands of remnant vegetation that have been identified as a ‘threatened ecological community’ (Figure 38). They have been identified for their protection in the water allocation management plan for the South West (Department of Water, 2008).

It is apparent that the ironstone communities have adapted to changing hydraulic regimes including large seasonal watertable fluctuation (up to 5 m) related to evapotranspiration and large groundwater abstraction from the deep Leederville bores. It is considered that these communities are quite robust, providing that the watertable is fully recharged during winter and there continues to be a lack of connection with the deeper Leederville aquifer. From a management perspective, these communities can be considered as perched systems.

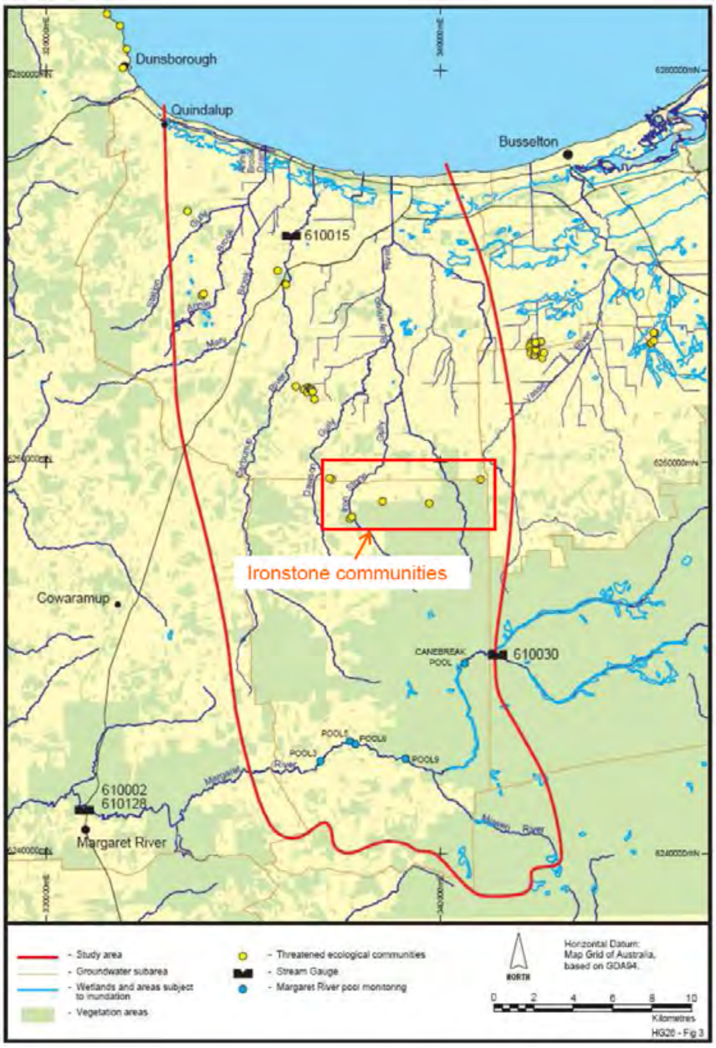


Figure 38 Location of ironstone communities

8.5 Aquifer development

The most prospective horizon in the Leederville aquifer is considered to be the Upper Vasse Member. However, the heterogeneity of the Leederville aquifer requires large production bores to be screened in the Upper Vasse, Lower Vasse and sometimes Yelverton Members to intersect sufficient sand beds.

The deep Leederville aquifer is confined with large water level fluctuations, greater than 20 m/year, related to aquifer depressurisation. These impacts are most noticeable in the vicinity of large production bores in the Dunsborough-Vasse subarea near Jindong.

A small number of large production bores, greater than 100 ML/year, are also showing residual drawdowns of more than 10 m remaining after the winter recharge period. This indicates that aquifer recovery is slow and not keeping pace with the rates of abstraction and that there is some storage depletion.

It is recommended that all large abstraction bores be screened in the deeper aquifer. For the new allocations, maximum licence limits should be set at 100 ML/yr, unless it can be demonstrated that sustained abstraction will not result in residual drawdown over winter. An even distribution of small to moderate size licences between 10 and 50 ML/year is considered most appropriate to ensure more sustainable groundwater abstraction.

9 Model review

9.1 External peer review

NTEC Environmental Technology provided a peer review of the Cowaramup groundwater model (NTEC, 2009). The review was carried out in accordance with guidelines prepared by the Murray-Darling Basin Commission (MDBC, 2001).

Using the terminology suggested by the MDBC guidelines, the model is an impact assessment model, rather than an aquifer simulator. The level of detail needed in some areas of model development is therefore less than for more complex models.

NTEC (2009) noted that a significant effort has been made to understand and describe the hydrostratigraphy of the study area. A good attempt has been made to demonstrate that the calibration of the model remains reasonable for a 3 year period that extends the 15 year calibration period. Useful efforts were also made to verify the model by comparing the results with other models, and using carbon-14 dating.

It was commented that uncertainty in model parameters is acknowledged, along with the fact that uncertain parameters lead to uncertain predictions; however, no formal uncertainty analysis has been carried out. In the opinion of the reviewer, this is acceptable for an impact assessment model. The amount of effort made to calibrate and verify the model is in many respects far greater than would often be made for a model of this kind.

The water balance summaries are useful for understanding the tradeoffs, and perhaps more use could be made of water balance analysis to explain the way the hydrogeological system works. In addition, the lumped water balances in Sections 7.1 and 8 are a good way to summarise the behaviour of the system.

NTEC (2009) concluded that the hydrogeological report has very few weaknesses, is well structured and complete. The groundwater model is technically sound and a good representation of the hydrogeology. When considered in the context of the MDBC guidelines, it is suggest that nearly all efforts that could be made to produce a high-quality, well-calibrated model have been made.

9.2 Reliability of model outputs

As part of the model review, it was considered important to independently assess the reliability of the groundwater model outputs. This was achieved by comparing water balance components with those from the SWAMS regional model, as well as matching the modelled hydrograph outputs for bore CL2C with the future hydrograph trend obtained independently from HARRT analysis.

9.2.1 Comparison with SWAMS model

The SWAMS model was initially constructed to support the South West Yarragadee proposal by the Water Corporation (Sun, 2005). The model was considered too regional for this groundwater assessment; as such a new groundwater model was developed to incorporate the new understanding.

The SWAMS model poorly represents the geological conditions on the Vasse Shelf, as only the original Cowaramup bores (CL1 and CL2) were included in the interpretation. In order to address this situation, the conceptual geological model has been significantly improved in the groundwater model for this assessment.

The latest version of SWAMS (SWAMS 2.1) adopts the methodology of Vertical Flux Model (VFM) developed for the PRAMS model (Perth Regional Aquifer Modelling System) to estimate recharge. The recharge VFM in SWAMS uses daily rainfall and physical properties of soil and vegetation to estimate rooting depth and net recharge (Silberstein et al., 2004). This is conceptually different from this groundwater model approach as recharge constrained by chloride method estimations, assumed rooting depths, and temporal fluctuation of recharge is scaled to fluctuations in the baseflow component of river flow.

The annual water balance in 2004 (the final year of transient calibration) is shown schematically in Figure 39. For both models, the magnitudes of the water balance components are of the same order and, more importantly, throughflow between the Cowaramup and Dunsborough-Vasse subareas is similar. The main difference between the models is that the VFM model used in SWAMS is applying higher recharge, which is resulting in the SWAMS model having higher fluxes especially in the shallow system.

9.2.2 Modelled hydrograph comparison using HARTT analysis

The HARTT (Hydrograph Analysis: Rainfall and Time Trends) technique estimates a regression fit to hydrographs based on CDFM rainfall (DAF, 2009). This technique can also be applied to provide regression fit to hydrographs based on CDFM river baseflow.

The technique is only applicable where rainfall or the temporary baseflow component of river flow is related to the variation in groundwater hydrographs, such as monitoring bores in recharge areas. In contrast, it is not applicable in areas where lateral throughflow is large, abstraction is occurring or land use change has taken place.

Bore CL2C, located in the recharge area on the Blackwood Plateau (Figure 14), was assessed by Golder Associates (2008) to be highly suitable for HARRT analysis. This bore also has the longest reliable hydrograph available in the Cowaramup groundwater subarea.

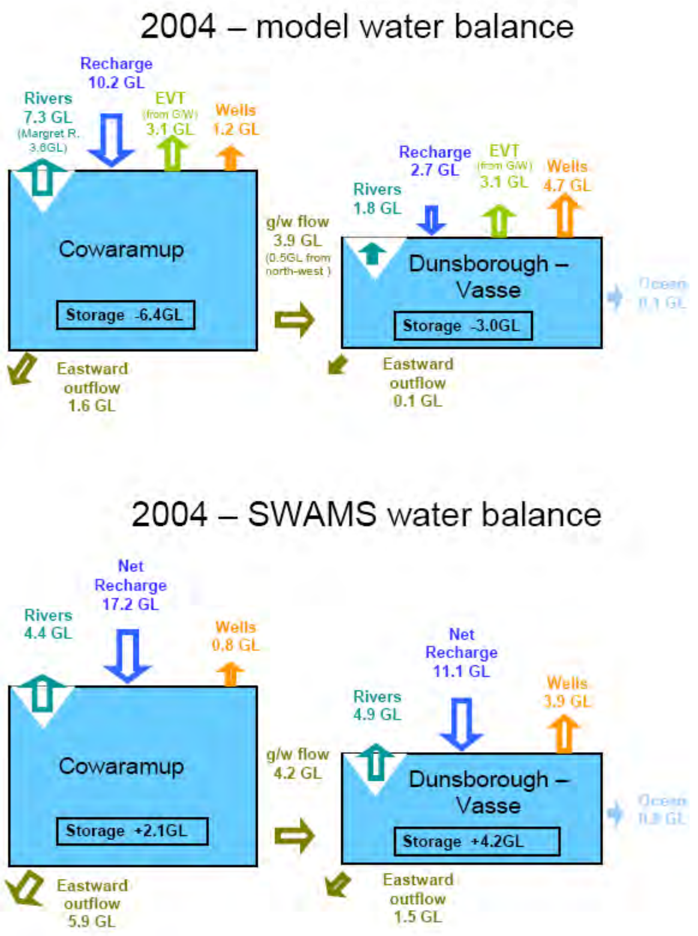


Figure 39 2004 water balance comparison with SWAMS model

The HARTT technique was applied to the hydrograph for CL2C with regression fits being obtained for both CDFM rainfall and CDFM river flow (Figure 40). The regression fits were extended to 2020 with the base case climate (95% of the average 1990 to 2003 climate as per the SWAMS base case). There is an excellent correlation to the hydrograph data in terms of trend for both CDFM rainfall and CDFM river flow.

There is an excellent correlation between the future trend obtained from the HARTT analysis (especially the CDFM river flow trend) and the groundwater model for the base case climate scenario for bore CL2C (Figure 40. The matching trend from the HARTT analysis provides independent verification that the magnitude of recharge, calibrated aquifer parameters and model layer configuration allows the expected hydrograph response to be represented in the recharge area on the Blackwood Plateau.

The best regression fit to the historical data using CDFM rainfall has a time lag of 2-3 months between CDFM rainfall and the hydrograph response; whereas, there is no time lag between the best regression fit to the CDFM river flow (baseflow) and the hydrograph response.

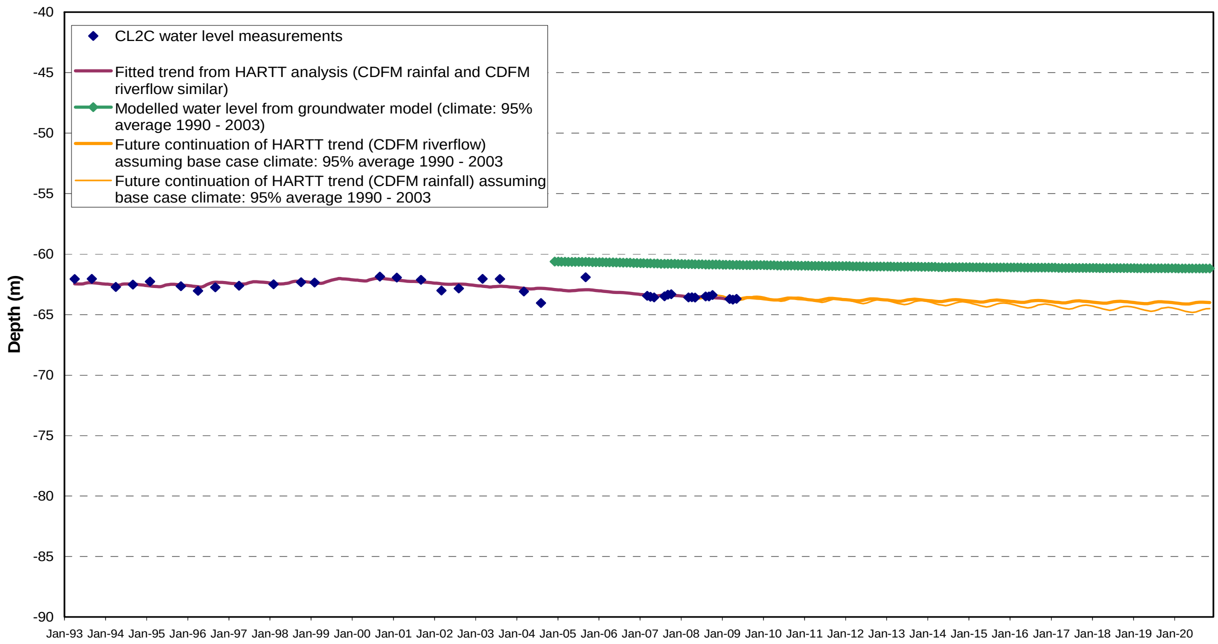


Figure 40 CL2C Hydrograph with HARTT regression fits and modelled hydrograph

This is also consistent with the hydrograph response for bore CW2B with water levels increasing, when river flow was occurring without any noticeable lag (Fig. 21). The fact that a strong correlation between river (base) flow and recharge is also found by hydrograph analysis further gives confidence to the recharge methodology used in this groundwater assessment.

9.3 Assumptions and limitations

Despite the Cowaramup groundwater model being a good representation of hydrogeological processes related to the Leederville aquifer, there have been many assumptions and limitations that have affected the development and accuracy of the groundwater model including:

- The groundwater model was developed at a subregional scale and as such any conclusions or results should be considered at this scale. The model is best suited to estimating water balance components and regional changes in water level. Local area models are required to be constructed for assessing localised impacts on individual GDEs.
- There is an incomplete understanding of the hydraulic characteristics of the Leederville aquifer. There have been extensive interpretations in developing the conceptual stratigraphy and hydraulic zonation; however, it is still considered a broad representation of aquifer and aquitard distribution.

- Model layers comprise heterogeneous stratigraphic units of sand and clay, but the properties of these individual units have been homogenised by combining them into single model layers. This ‘bulking up’ of stratigraphy is required for model efficiency; however, it does misrepresent formation heterogeneity.

- The thin superficial aquifer on the Swan Coastal Plain was combined with the upper Quindalup Member of the Leederville aquifer into Layer 1. Ideally, the superficial aquifer should be modelled as a separate layer to better represent hydraulic variability and water level changes in shallow bores.

- The Sue Group at the base of the Leederville Formation was considered as a no-flow boundary. This is a reasonable assumption considering the low hydraulic conductivity of the Sue Group.

- Modelled recharge was estimated as net recharge from the steady state model and has been applied to the transient model using a relatively simple approach based on a correlation to river baseflow. In reality, recharge is a very complex process with a number of variables. The spatial distribution of rainfall recharge across the model domain is considered coarse, but the overall water budget is consistent with the conceptual understanding.

- Modelled abstraction data was largely estimated from allocation limits. A percentage of allocation was used (100% for deep bores and 80% for shallow bores) including a monthly usage factor. The abstraction database is considered the most significant limitation in the accuracy of the groundwater model. The preferred approach would be to use metered or actual abstraction data, such as that provided by the Water Corporation for the Quindalup borefield.

- A detailed uncertainty analysis has not been undertaken for aquifer properties, stress datasets (abstraction, recharge and evapotranspiration) and observation hydrograph data. This was considered too detailed for the complexity level of this model.

In order to produce a more accurate groundwater model, a number of model improvements could be made and considered in the future upgrading of SWAMS or local area models. These include:

- calibration using an updated / improved abstraction database incorporating metered abstraction volumes;

- re-calibration of the model using the C-14 age dating results (corrected for stagnant zone diffusion) as a direct calibration dataset rather than water levels;

- calibration of the recharge model to the measured river flows for the Margaret and Carbunup Rivers;

- the introduction of a separate layer for the superficial aquifer on the Swan Coastal Plain;
- incorporating recharge estimations based on results from data logger monitoring of shallow bores;
- recalibration of the transient model with longer and more detailed hydrographs obtained from data loggers;
- using CDFM techniques to model hydrographs of suitable bores as a calibration dataset for future scenarios; and
- undertaking a detailed uncertainty analysis to identify the areas of the model targeted for improvement during future investigations.

10 Management considerations

The prime objective of the Cowaramup groundwater investigation and subsequent assessment was to modify groundwater allocation limits in the western Busselton-Capel Groundwater Area. The groundwater model has focused on determining sensitivities within the Leederville aquifer to changing abstraction regimes, as well as factoring in climate change. The resultant allocation limits and management considerations are to be incorporated into the water allocation management plan for the South West (Department of Water, 2008).

10.1 Modifications to allocation limits

10.1.1 Dunsborough-Vasse groundwater subarea

Scenario modelling has indicated that there is winter residual drawdown and potential storage depletion in parts of the Dunsborough-Vasse subarea. The two areas that require more intensive review and ongoing monitoring are: (1) the Jindong area monitored by bores BN30, BN31 and BN35; and (2) the Water Corporation's Quindalup borefield including the lower Carbunup valley monitored by bores BN15, BN24 and SWI2.

In the water allocation management plan for the South West (Department of Water, 2008), the Jindong irrigation area is a designated management zone that stipulates that abstraction be reduced to allow aquifer recovery, and any additional abstraction to be spread laterally and in depth. This assessment supports this approach and suggests that there is a need for more frequent reviewing of groundwater abstraction in the Quindalup area.

There are many data gaps that have prevented a more comprehensive and definitive review of the Dunsborough-Vasse subarea. The main limitation has been a poor regional understanding of actual groundwater usage with no digital capture of metering data outside the Quindalup borefield. There is much uncertainty and lack of data about bore positions, screen intervals, as well as resting and pumping water levels in abstraction bores. It is recommended that continuous water level data loggers should be placed on monitoring bores in support of future reviews.

The main conclusion of this assessment is that groundwater resources in the Dunsborough-Vasse subarea are at full allocation. There is no scope for increasing groundwater allocations in this subarea. As part of good management practice, it is necessary for the Department of Water to closely monitor and review water level impacts in the Jindong and Quindalup areas.

10.1.2 Cowaramup groundwater subarea

Scenario modelling indicates that an additional allocation of 1.5 GL/year is available in the Cowaramup subarea. Even though the subarea is highly sensitive to climate change, there is a high level of confidence that allocations can be increased with minimal impact on the groundwater resource.

Model water balances for the Cowaramup subarea demonstrated that the additional 1.5 GL/year has only a small impact on groundwater throughflow, up to 0.24 GL/year, into the Dunsborough-Vasse subarea. It is also believed that this impact could be further minimised if no abstraction is allowed along the northern edge of the Cowaramup subarea. There is no impact to groundwater throughflow into the Dunsborough-Vasse subarea from any abstraction to the south of the groundwater divide.

In conclusion, groundwater allocation limits for the Leederville aquifer in the Cowaramup subarea can be increased by an additional 1.5 GL/yr. As the current allocation limit in the Leederville aquifer is 0.3 GL/year, this will increase allocation to 1.8 GL/year. The increase in allocation is conditional on the setting of strict management rules (to be discussed in Section 10.2) including buffer zones, enhanced groundwater monitoring and follow-up groundwater reviews.

10.2 Application of new allocations

The sensitivity of the Leederville aquifer in the Cowaramup subarea has required the setting of licensing conditions / rules for protection of the groundwater resource. The application of the increased allocation requires different management approaches for different parts of the subarea. In order to support the Department's South West regional office with groundwater licensing, a number of management zones have been developed. These management zones for the Leederville aquifer in the Cowaramup subarea are shown in Figure 41 and described below.

10.2.1 Zone A - Allocation available

This zone in the north-western portion of the Cowaramup subarea is considered the least sensitive to groundwater abstraction and is preferred for allocating new groundwater licences. The primary management objective of this zone is to spread groundwater abstraction as much as practicable.

Individual groundwater licences are to be less than 100 ML/year. For all licences greater than 50 ML/year, production intervals are to be greater than 60 m bgl; aquifer testing is required to determine potential for storage depletion and impact on other users; and minimum bore spacing is about 3 km for 100 ML/year allocations. Smaller licences, less than 50 ML/year, may be screened at shallower intervals and be closer together.

10.2.2 Zone B - Strict allocation rules

This zone covers the flanks of the Margaret River valley and southern flowing groundwater system. It is considered sensitive to shallow groundwater abstraction; however, deep abstraction is encouraged for new groundwater licences. There are the same conditions as for Zone A, except that no shallow bores less than 40 m are permitted.

10.2.3 Zone C - No new licences

This zone covers the Margaret River valley and forms a 2 km wide corridor across the subarea. It is considered highly sensitive and susceptible to impact by groundwater abstraction. In addition, the riverine pools along Margaret River are important ecological and social features that require protection. Current allocations in this zone appear to be sustainable; however, no new surface (summer abstraction) or groundwater licences are to be allocated. Surface water usage in summer months has the greatest potential to impact the riverine pools; as such the exisiting 'pump in stream' allocations should be reviewed.

10.2.4 Zone D – Protection of throughflow and ironstone communities

This zone covers the northern boundary of the Cowaramup subarea. It is required to maintain groundwater throughflow and water levels under ironstone communities on the Yelverton Shelf. There are the same conditions as for Zone B with no shallow bores less than 40 m being permitted. As the deeper Leederville aquifer is experiencing significant residual drawdown in this area, new groundwater licences should be discouraged unless existing licences are relinquished.

10.3 Other allocation considerations

10.3.1 Surface water 'pump in stream' licences

There are currently approximately 300 ML/a of surface water 'pump in stream' licences. This surface water abstraction must be considered as groundwater abstraction where pumping occurs during summer months. Due to potential impact on the permanent pools in Margaret River, no increases in these licences are recommended. It is also suggested that there be closer monitoring and review of these surface water licences in future.

10.3.2 Shallow allocations from surficial aquifer

Currently excavated soaks, dams and bores with screens less than 10 m bgl into the Leederville aquifer are assigned to the 'surficial' aquifer. There is no recommendation to modify the current allocation of 900 ML/year from this assessment.

10.3.3 Change to subarea boundary

As mentioned previously by Johnson (2000), there is a significant thickness of Leederville aquifer that is currently outside the Cowaramup subarea. It is recommended to extend the western boundary of the model to the Dunsborough Fault, as shown in Figure 42.

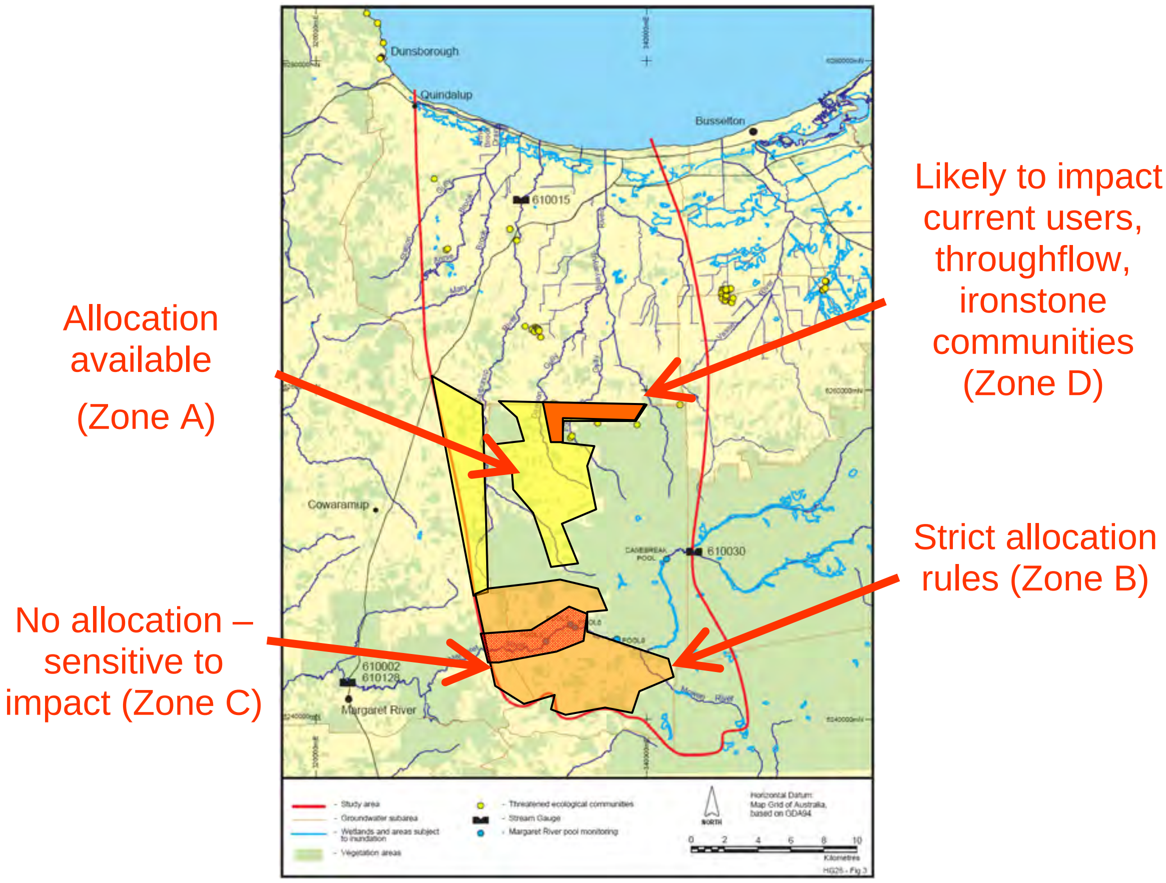


Figure 41 Recommended management zones

10.4 Future monitoring and review

Despite the high level of confidence in the groundwater model, it is important that results can be only be considered as a guide to the extent and potential for water level change related to groundwater abstraction and climate change. As part of good resource management practice, ongoing groundwater monitoring and review are crucial for future assessments of aquifer performance.

Current groundwater monitoring is considered the minimum requirement to observe the peak and low water level fluctuations; measurements are taken in March, April, May, September, October and November.

This frequency of monitoring is not considered ideal for gaining a true measure of aquifer performance or response to groundwater abstraction and recharge. It is recommended that continuous water level data loggers be installed in all monitoring bores in the Cowaramup subarea to better monitor water level changes related to the increased allocation limits. Data loggers should be installed in two riverine pools in Margaret River that already have surveyed bench marks used in the Cowaramup groundwater investigation (Schafer et al., 2008).

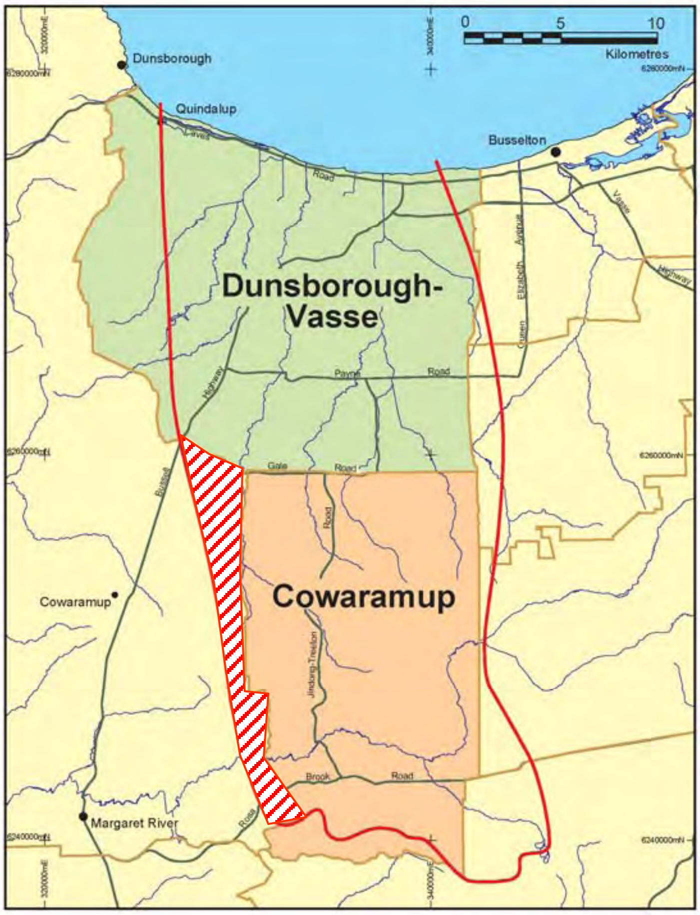


Figure 42 Proposed boundary change (shaded area)

A groundwater review is recommended in five years (2013) to assess aquifer performance and response to the increased allocation limits. Prior to the review, there is a need for a thorough survey of all abstraction bores including the development of an improved abstraction database with surveyed bore levels and screen intervals, actual abstraction data for bores greater than 50 ML/year, as well as resting and pumping water levels from all abstraction bores.

Local area models may need to be considered in those areas experiencing significant water level impact. The initial focus should be the Quindalup borefield to assess the potential for saltwater intrusion, and Jindong area to assess interference effects and residual drawdown.

11 Conclusions

A three-dimensional groundwater flow model has been developed for the western Busselton-Capel Groundwater Area to assess groundwater resources and potential impacts related to increasing allocation limits. The groundwater model is focused on the Leederville aquifer within the Cowaramup and Dunsborough-Vasse groundwater subareas.

Development of the groundwater model incorporated the conceptual understanding from the Cowaramup investigation undertaken in 2006. This investigation involved the installation of 14 groundwater monitoring bores, as well as complementary studies on hydrochemistry, groundwater age dating and permanency of pools along Margaret River.

The model was constructed using the Visual MODFLOW graphical user interface. This interface to the MODFLOW-SURFACT computational engine allows ease of data input. The model has four layers that are considered to be hydrogeologically consistent and representative. Hydraulic conductivity zones within each layer were based on an analysis of sand percentage in the Leederville aquifer using Petrel software. Recharge and evapotranspiration zones were based on land use, topography and depth to watertable.

A complete hydrological cycle is represented in the groundwater model with groundwater recharge entering on the Blackwood Plateau area and flowing northward to Geographe Bay. There is also shallow groundwater discharge into the Margaret, Carbunup and Vasse Rivers. The western and eastern boundaries of the model are marked by the Dunsborough and Busselton Faults respectively. The southern boundary coincides with a catchment divide to the south of Margaret River, while Geographe Bay marks the northern boundary.

The model has been calibrated under steady state and transient state conditions. Water level hydrographs from 55 monitoring bores were used as the calibration dataset. Recharge was estimated during the calibration process as net recharge during the steady state calibration, with recharge on the central Blackwood Plateau constrained to the estimate based on the chloride method. Steady state recharge estimates were applied to the transient model based on a correlation to river baseflow. Hydraulic conductivity and storage parameters were refined during the transient calibration.

Final calibration was achieved within the recommended guideline values for scaled root mean square error and water balance error. The model was verified by comparing hydraulic conductivity values with those obtained from pumping tests, and modelled particle track ages against carbon-14 groundwater age data.

Final model parameters were consistent with the SWAMS regional model. Horizontal conductivity (K_x and K_y) values in the Leederville aquifer range from 0.01 to 10 m/day with values largely between 0.2 to 2 m/day. The Leederville aquifer is considered highly anisotropic with horizontal conductivity being two to five orders of magnitude higher than vertical conductivity (K_z). Consequently, water level impacts from groundwater abstraction tend to propagate horizontally rather than vertically.

Modelled recharge occurs primarily on the Blackwood Plateau, typically between 63 to 225 mm/year, which is consistent with the conceptual understanding. Net recharge of deeper groundwater is considered minimal beneath the Swan Coastal Plain and in groundwater discharge areas such as Margaret River valley and the base of the Whicher Scarp.

Seven scenarios were run from 2005 to 2020 using the calibrated groundwater model representing different abstraction and climatic regimes. The scenarios were undertaken to assess the potential for increasing allocation limits and identifying areas of sensitivity to water level drawdown. For each scenario, an annual water balance for 2005 to 2020 and water level drawdown figures were generated.

Scenario modelling indicated that there is winter residual drawdown occurring in parts of the Dunsborough-Vasse subarea associated with significant abstraction in the Jindong area, Quindalup borefield and lower Carbunup valley. This implies that there is local storage depletion in these areas.

No residual watertable impacts were observed in the scenarios suggesting that deeper abstraction from the Leederville aquifer will not impact the watertable. Most watertable fluctuations are believed related to recharge variability rather than upward propagation of abstraction impacts from deeper layers. It is also suggested that any localised decline in watertable is fully recharged by winter rainfall.

Groundwater throughflow between the Cowaramup and Dunsborough-Vasse subareas remained constant, ranging from 3.87 to 4.24 GL/year, during scenario modelling. There was a reduction in groundwater throughflow when there was abstraction from scenario bores along the common subarea boundary.

Groundwater resources in the Dunsborough-Vasse subarea are considered to be at full allocation. There is no scope for increasing groundwater allocations in this subarea. As part of good management practice, close monitoring and reviewing of water level impacts in the Jindong and Quindalup areas will be necessary. Scenario modelling has also suggested that sustained abstraction from the Quindalup borefield has potential for saltwater intrusion.

Scenario modelling indicates that an additional 1.5 GL/year abstraction is possible in the Cowaramup subarea. Even though the subarea is highly sensitive to climate change, there is a high level of confidence that allocations can be increased with minimal impact on the groundwater resource. Model water balances suggest the additional allocation would only have a small impact on groundwater throughflow into the Dunsborough-Vasse subarea.

In the Cowaramup subarea, the lower reaches of Margaret River are the most sensitive to additional abstraction especially from shallow bores. This sensitivity requires the setting of licensing conditions / rules for protection of the groundwater resource. The application of the increased allocation requires different management approaches for different parts of the subarea. In order to support the Department's groundwater licensing process, a number of management zones with different conditions were developed. These management zones require minimum bore spacing, limits on individual bore licences, recommended bore depths, and even no allocation zones around Margaret River.

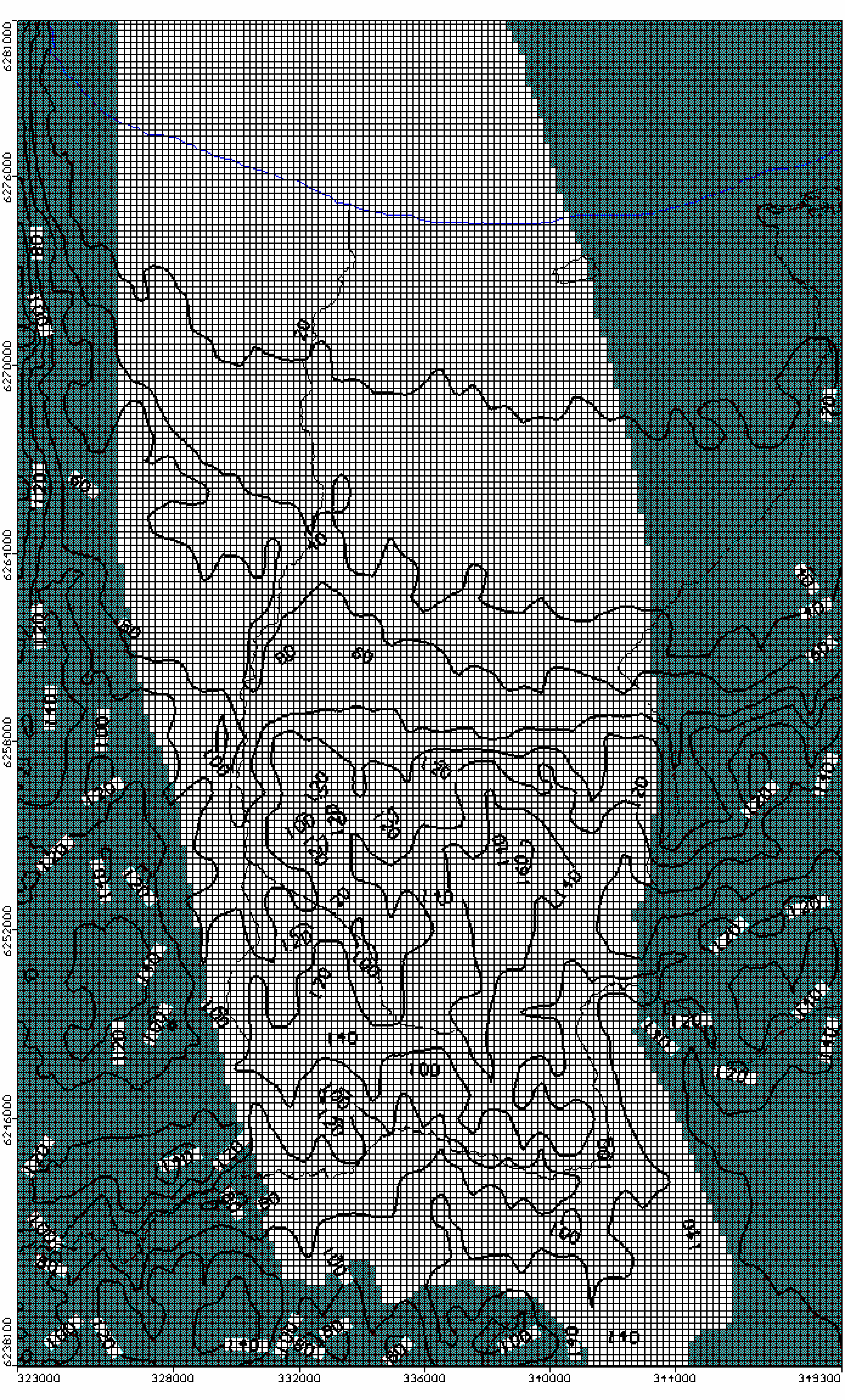
Despite the high level of confidence in the groundwater model, ongoing groundwater monitoring and review are crucial for the future management of the resource. Current groundwater monitoring is considered the minimum requirement to observe the peak and low water level fluctuations. It is recommended that continuous water level data loggers be installed in all monitoring bores in the Cowaramup subarea to better monitor water level changes related to the increased allocation limits.

A groundwater review is recommended in five years (2013) to assess aquifer performance and response to the increased allocation limits. Prior to the review, there is a need for a thorough survey of all abstraction bores including the development of an improved abstraction database with surveyed bore levels and screen intervals, actual abstraction data for bores greater than 50 M/year, as well as resting and pumping water levels from all abstraction bores.

In conclusion, the groundwater model is a good representation of hydrogeological processes related to the Leederville aquifer in the western Busselton-Capel Groundwater Area. The comprehensive investigation and subsequent assessment has demonstrated that groundwater allocations in the Cowaramup subarea can be increased by 1.5 GL/year. There is a high level confidence in the groundwater model; however, ongoing monitoring and reviews will be critical for future management of the groundwater resource.

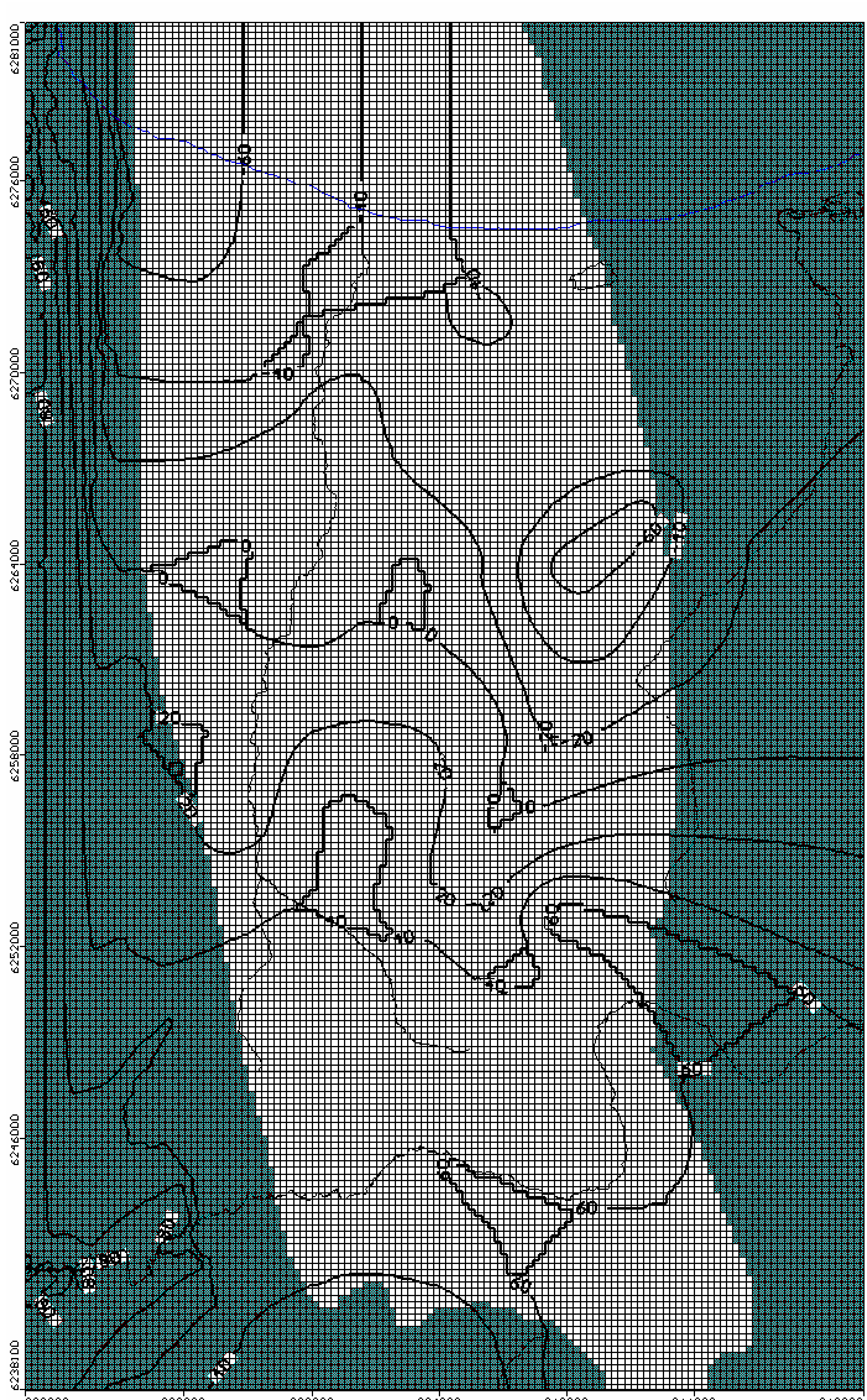
Appendices

Appendix A — Surface contours of model layers



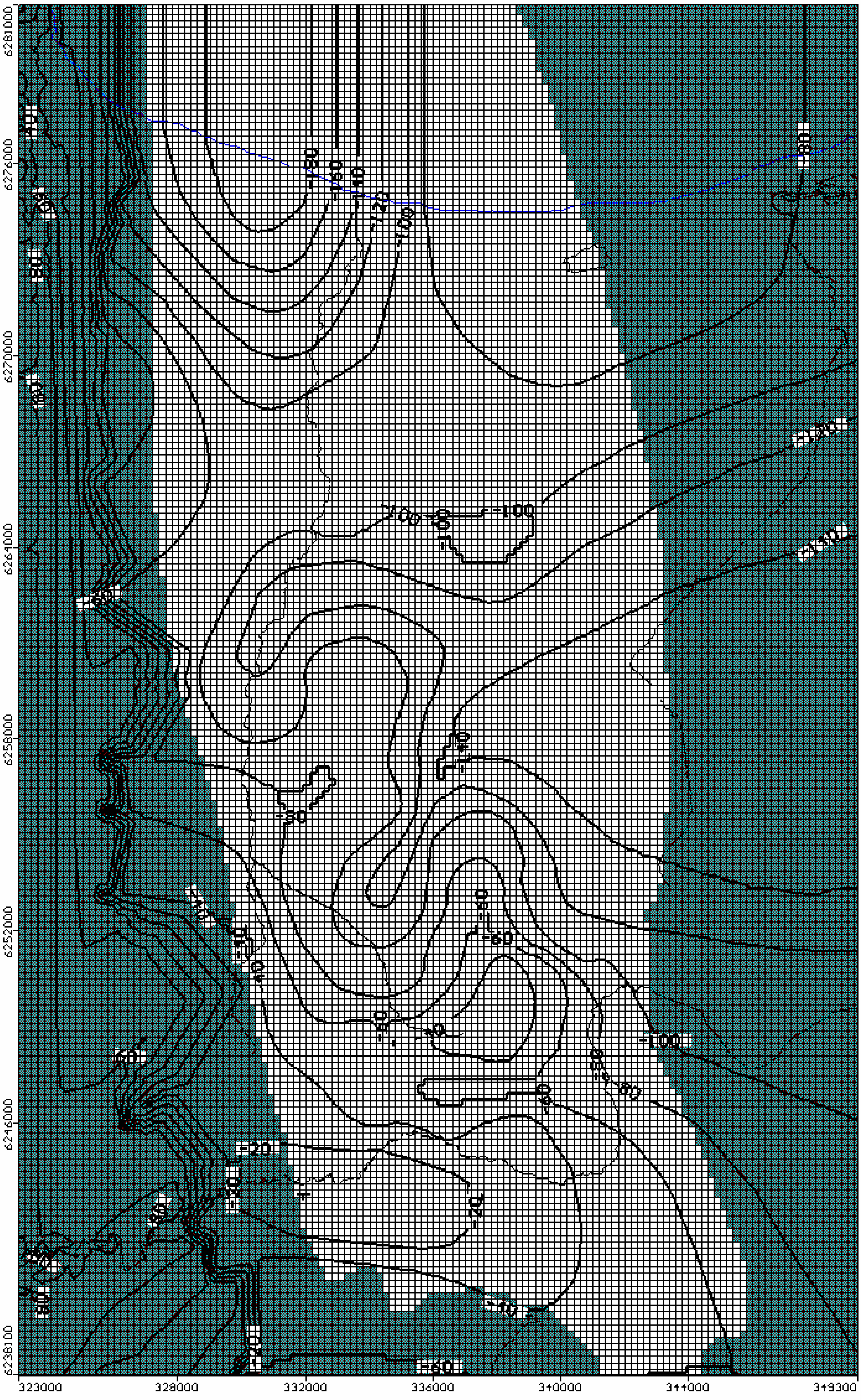
Appendix A1 - Contours top of Layer 1 (surface topography)

Appendix A2 - Contours base of Layer 1



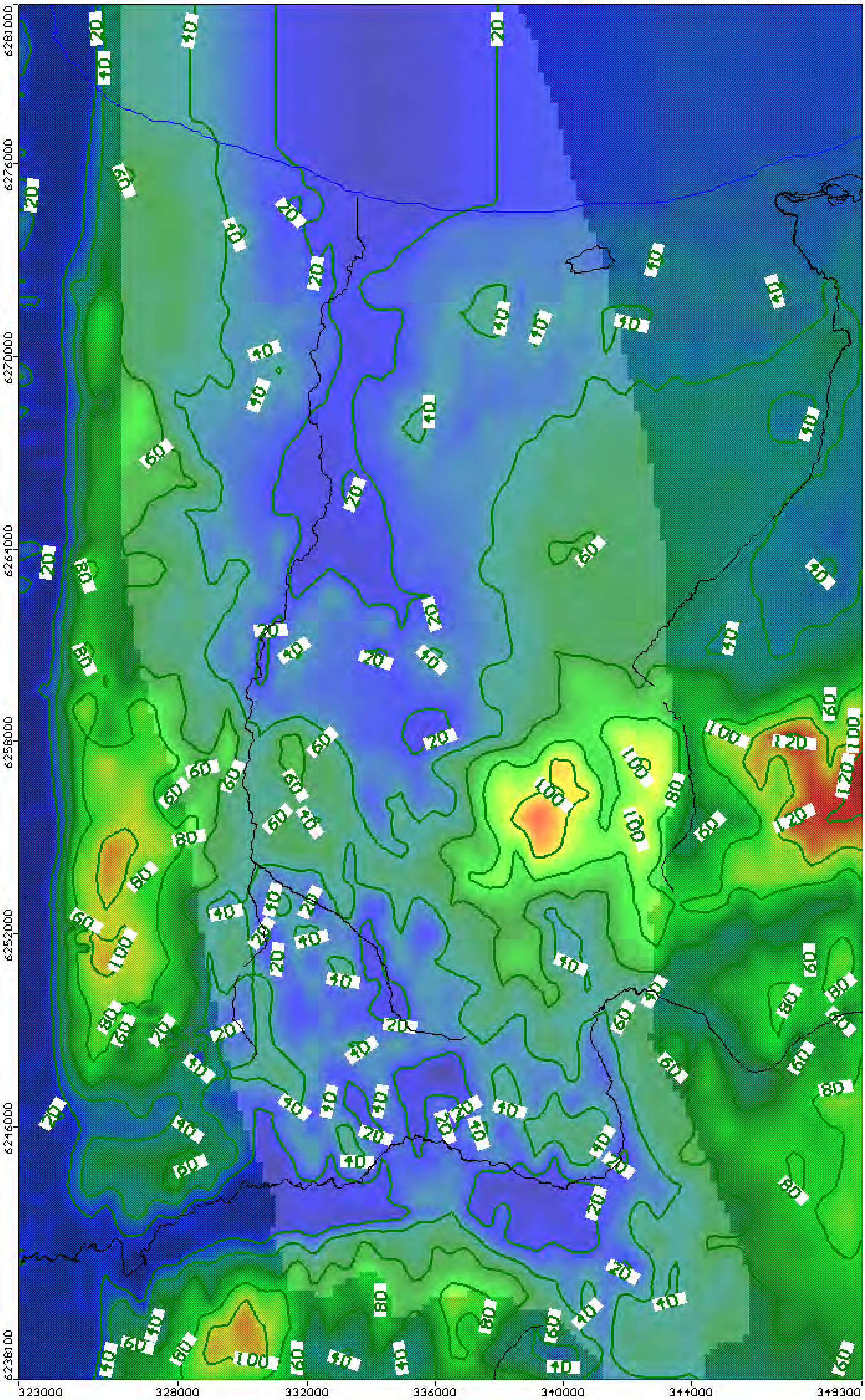
Appendix A3 - Contours base of Layer 2

Appendix A4 - Contours base of Layer 3

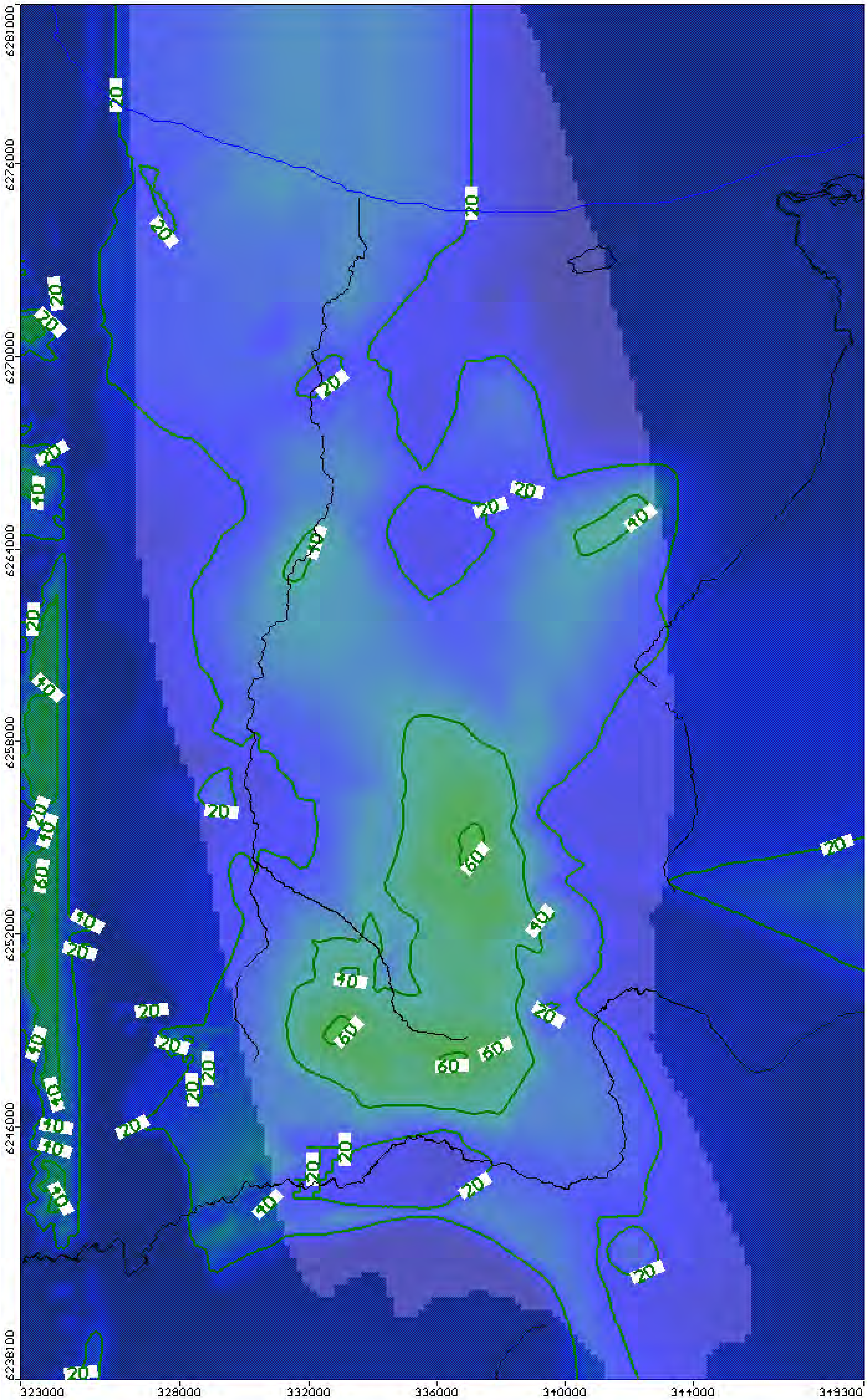


Appendix A5 - Contours base of Layer 4

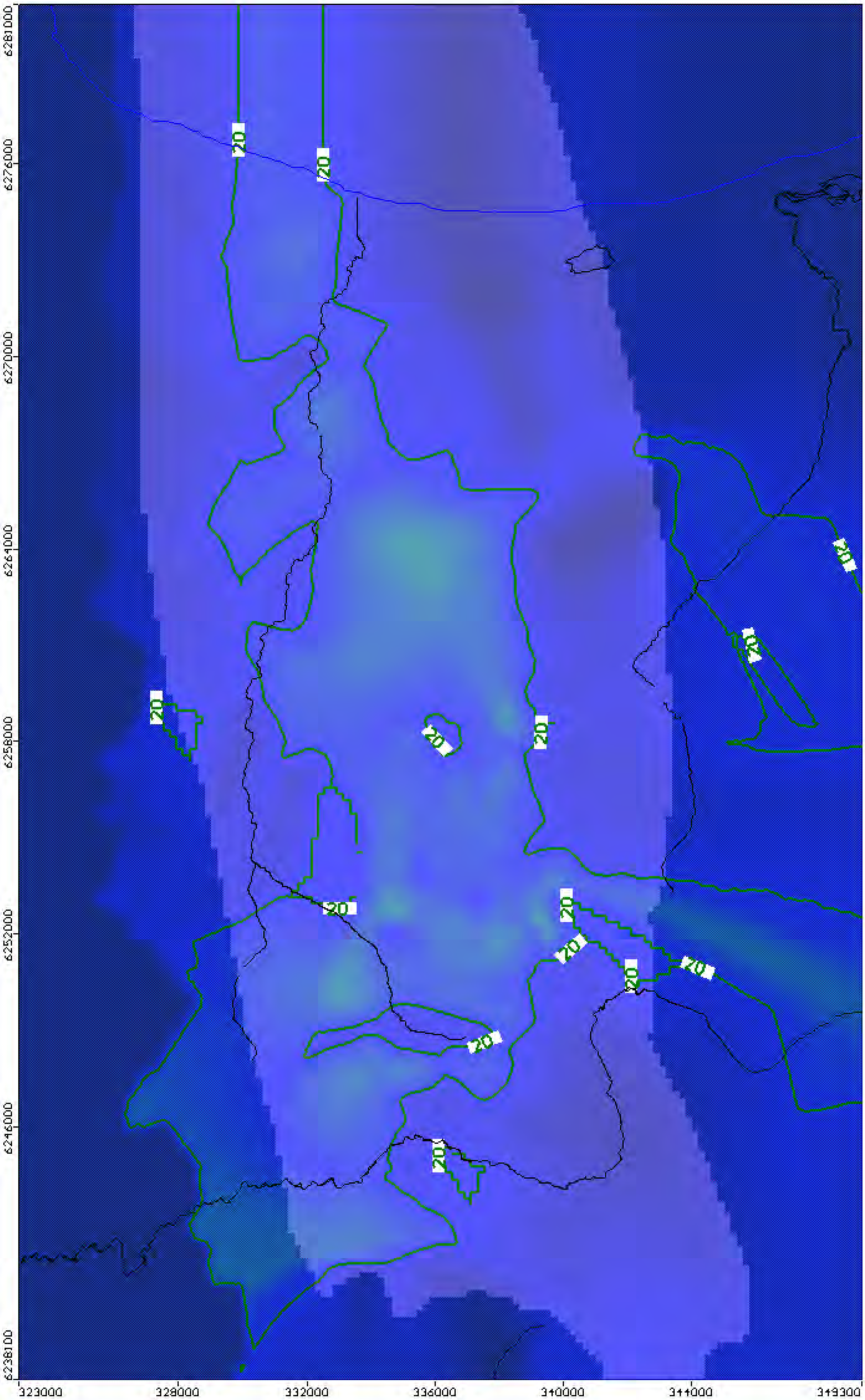
Appendix B — Isopach maps of model layers



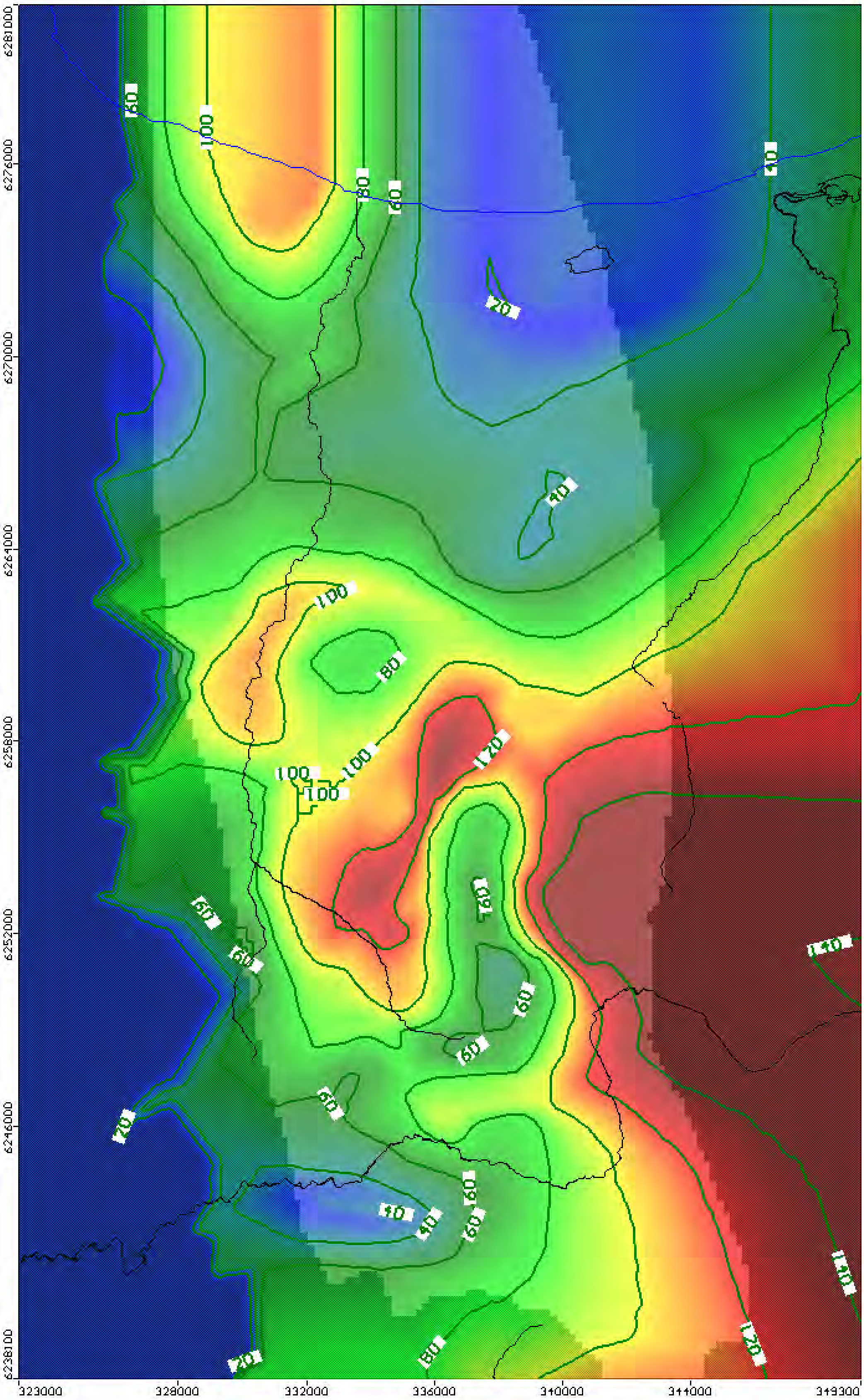
Appendix B1 - Isopach map of Layer 1



Appendix B2 - Isopach map of Layer 2



Appendix B3 - Isopach map of Layer 3



Appendix B4 - Isopach map of Layer 4

Appendix C — Sand percentage in each aquifer

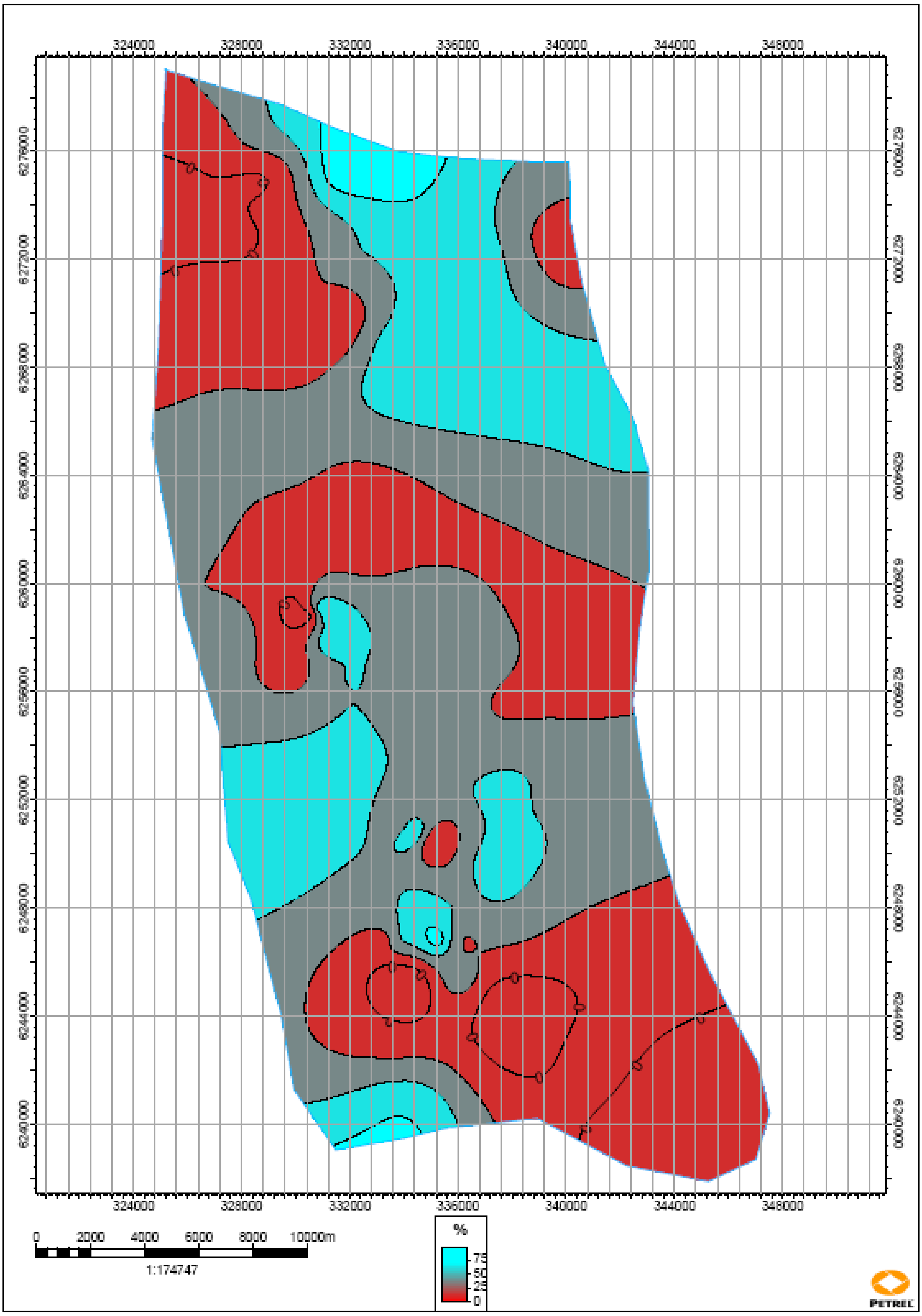


Figure C1 – Upper Quindalup sand percentage map

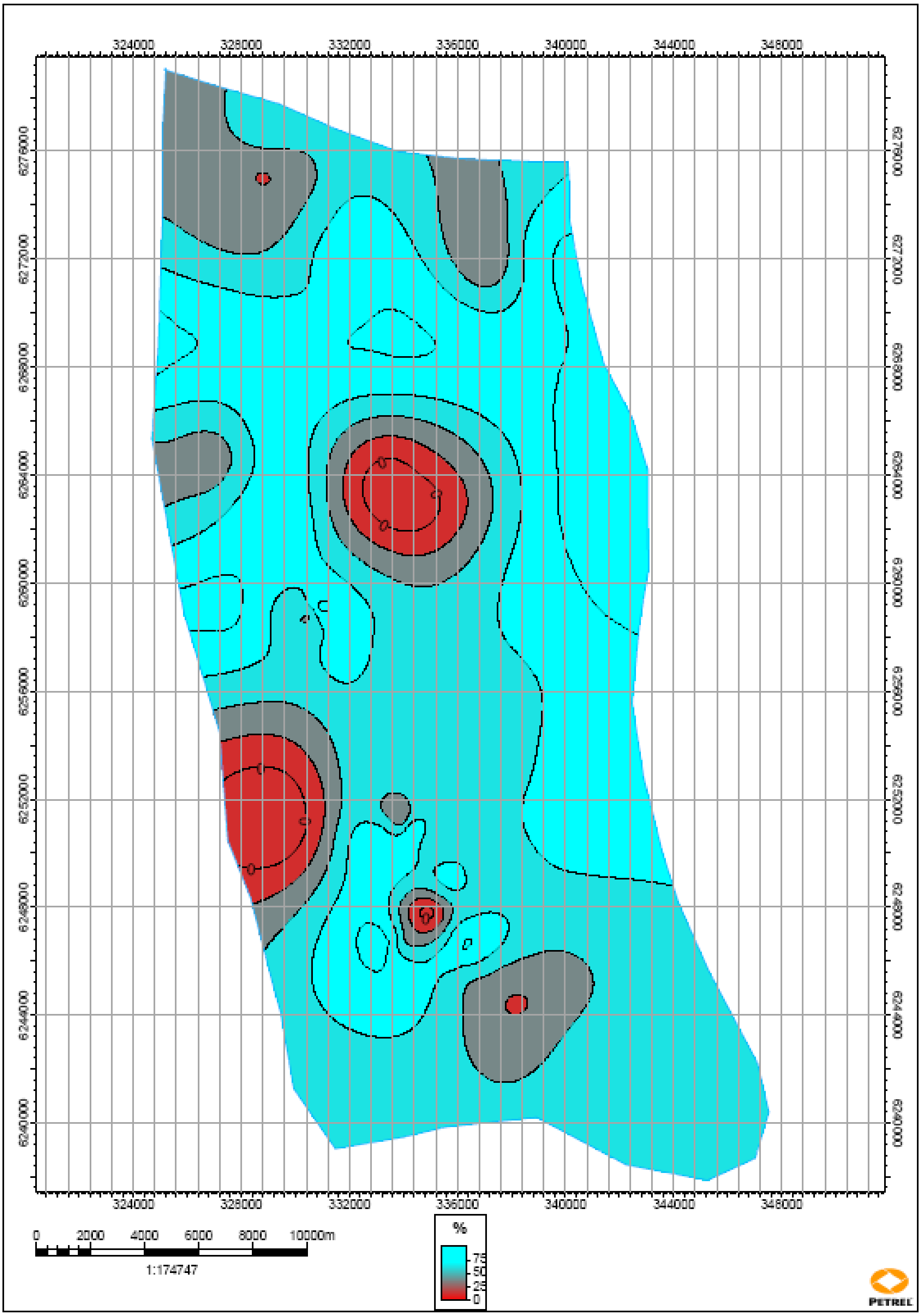


Figure C2 – sandy base of Quindalup sand percentage map

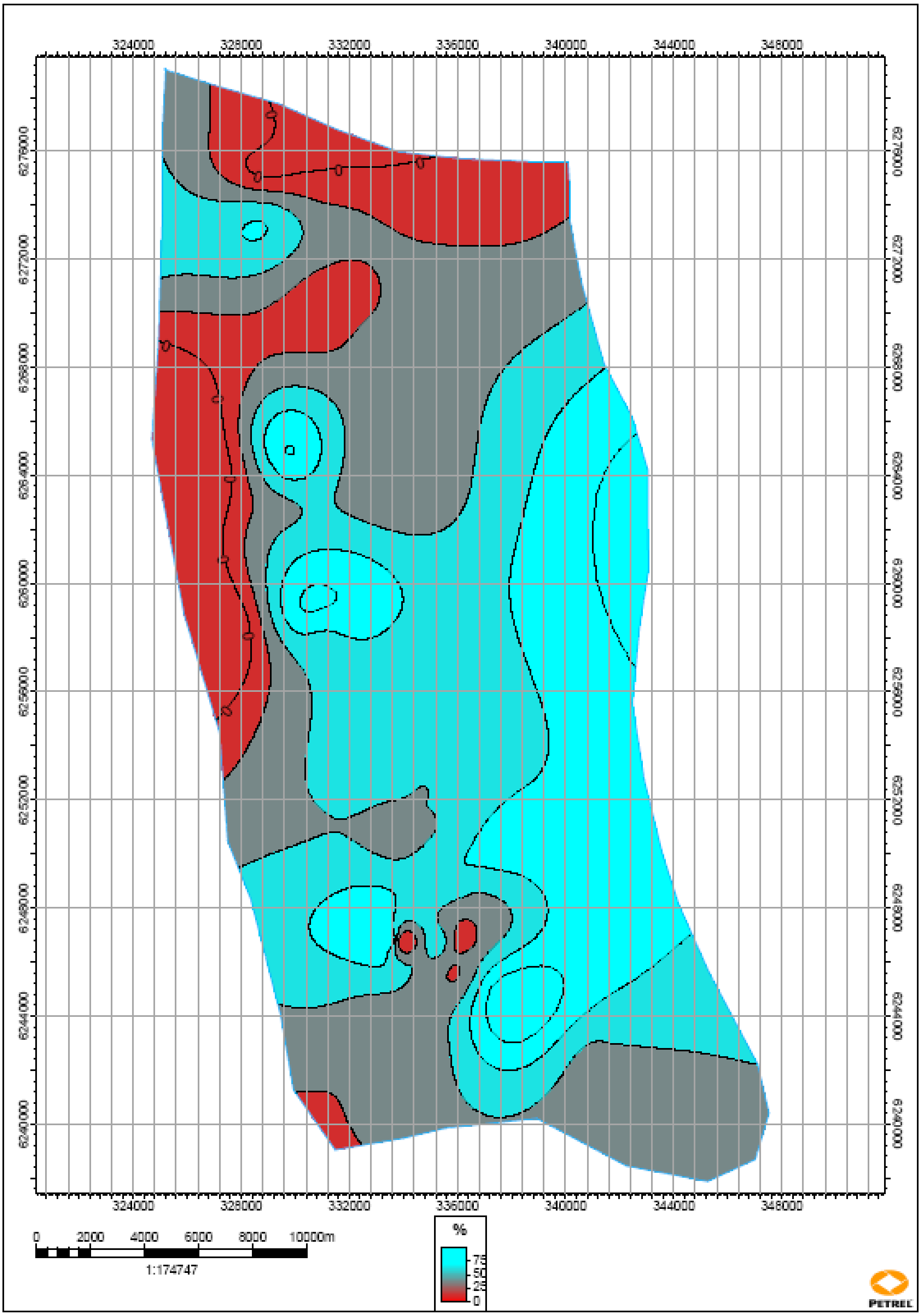


Figure C3 – Upper Mowen sand percentage map

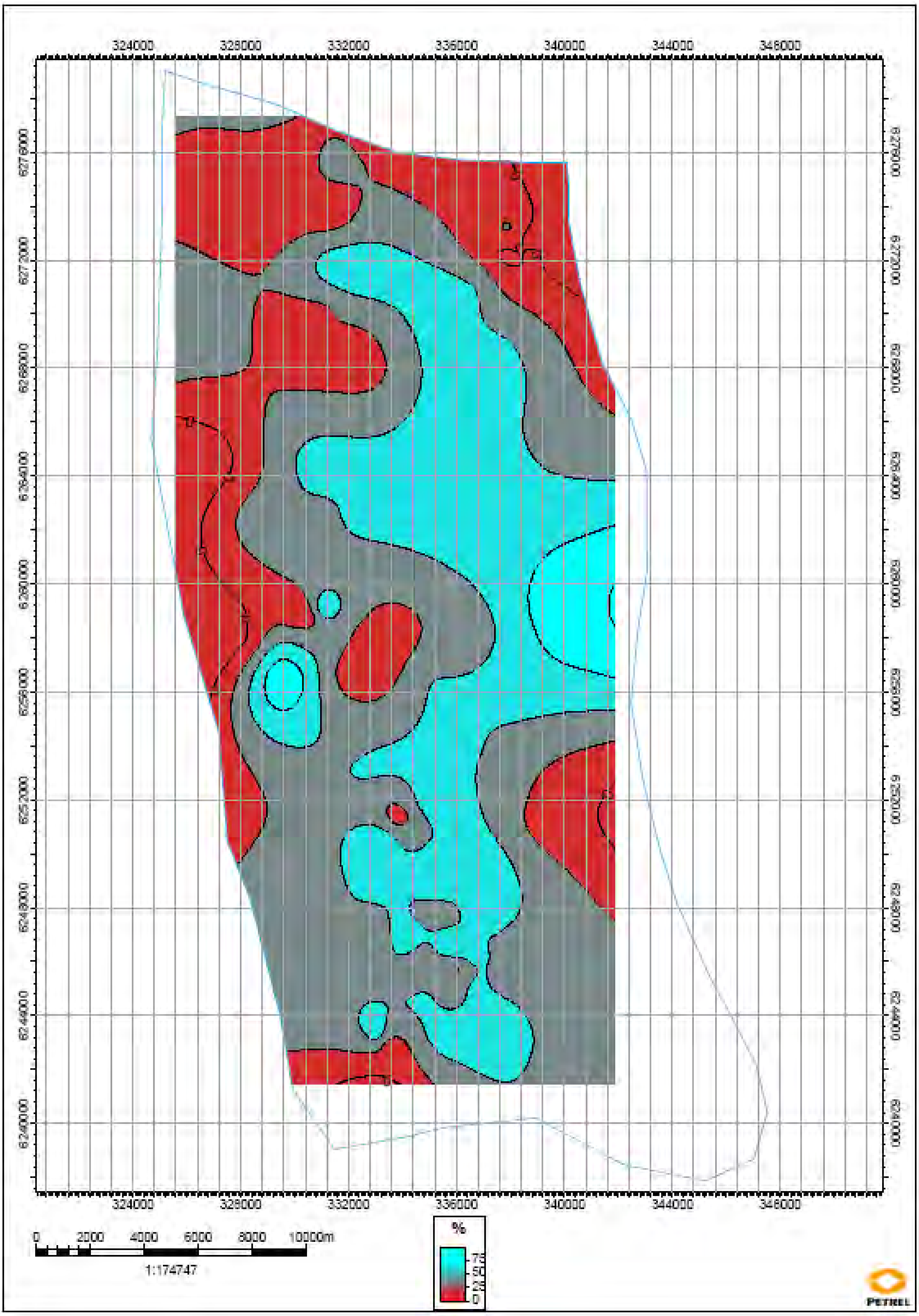


Figure C4 – Lower Mowen sand percentage map

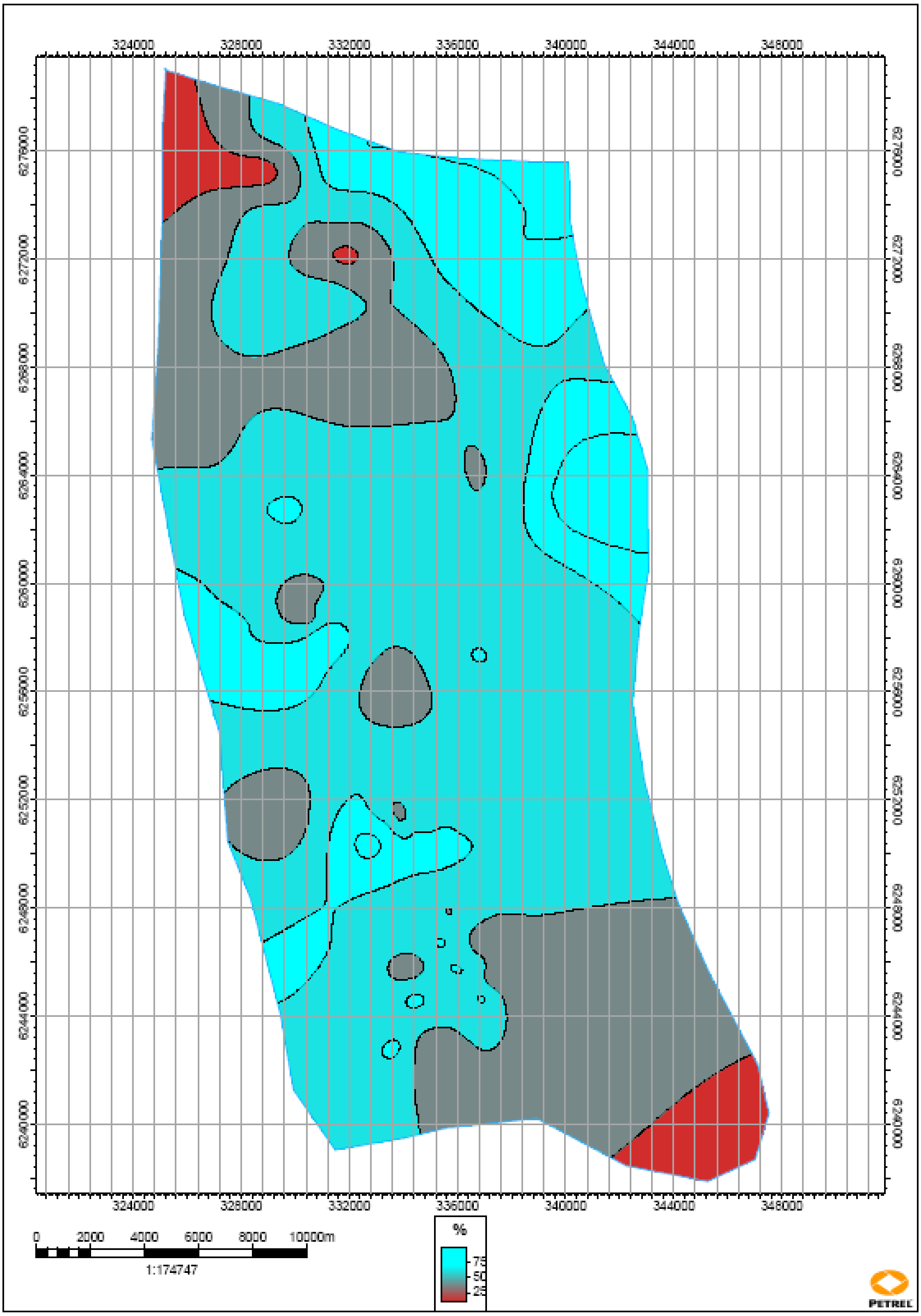


Figure C5 – Upper Vasse sand percentage map

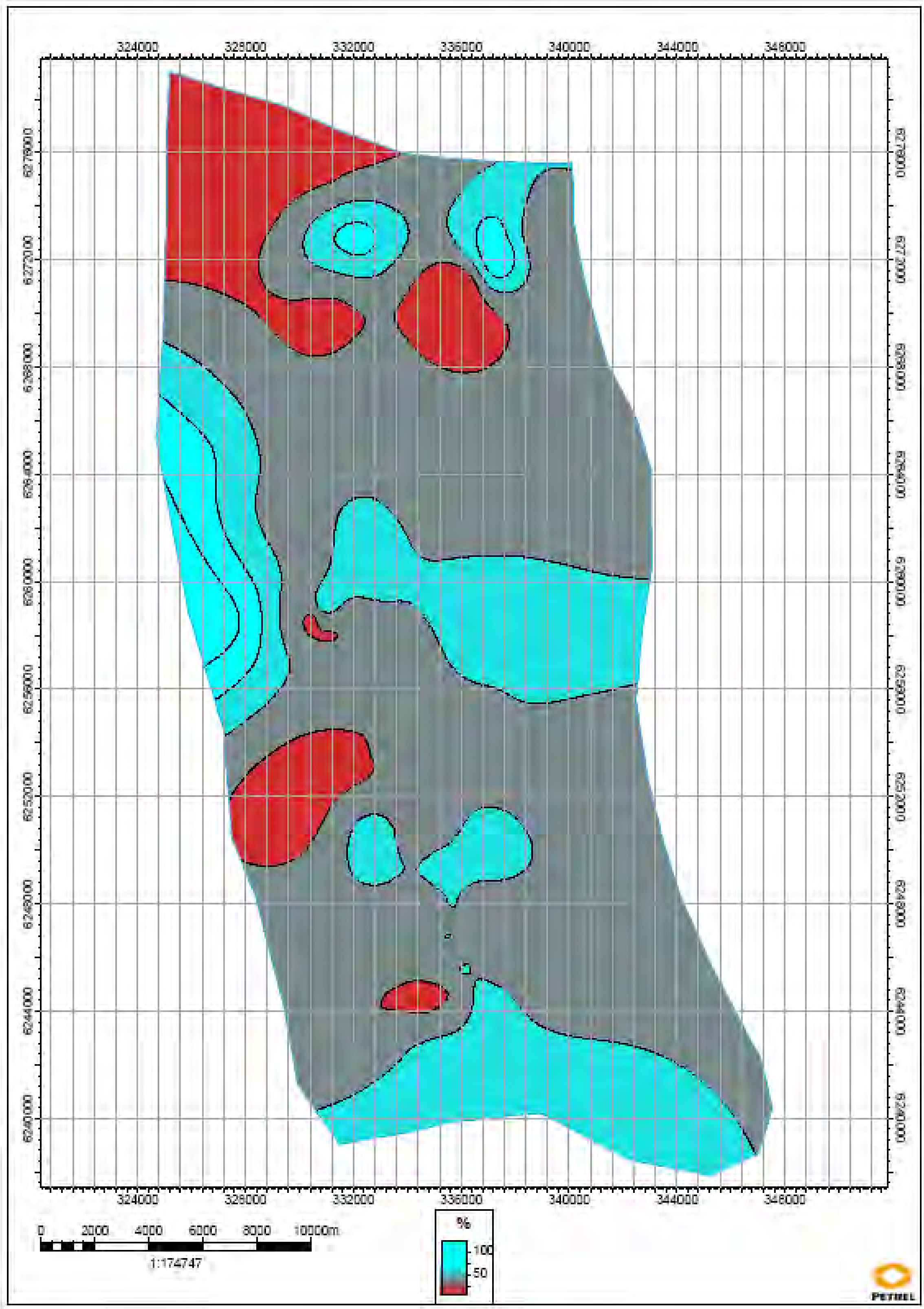


Figure C6 – Lower Vasse sand percentage map

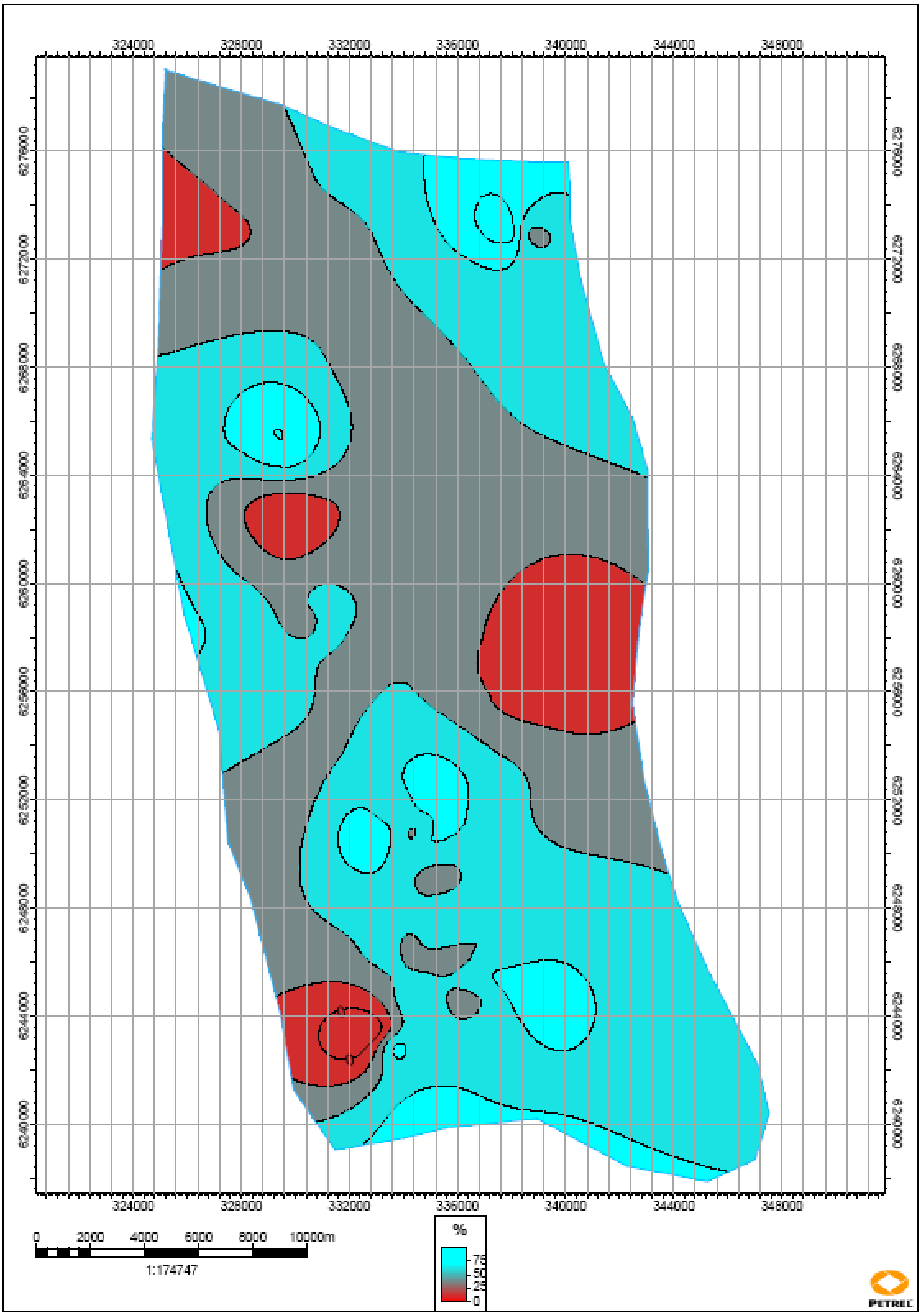


Figure C7 – Yelverton sand percentage map

Appendix D — Hydraulic conductivity zones for each model layer

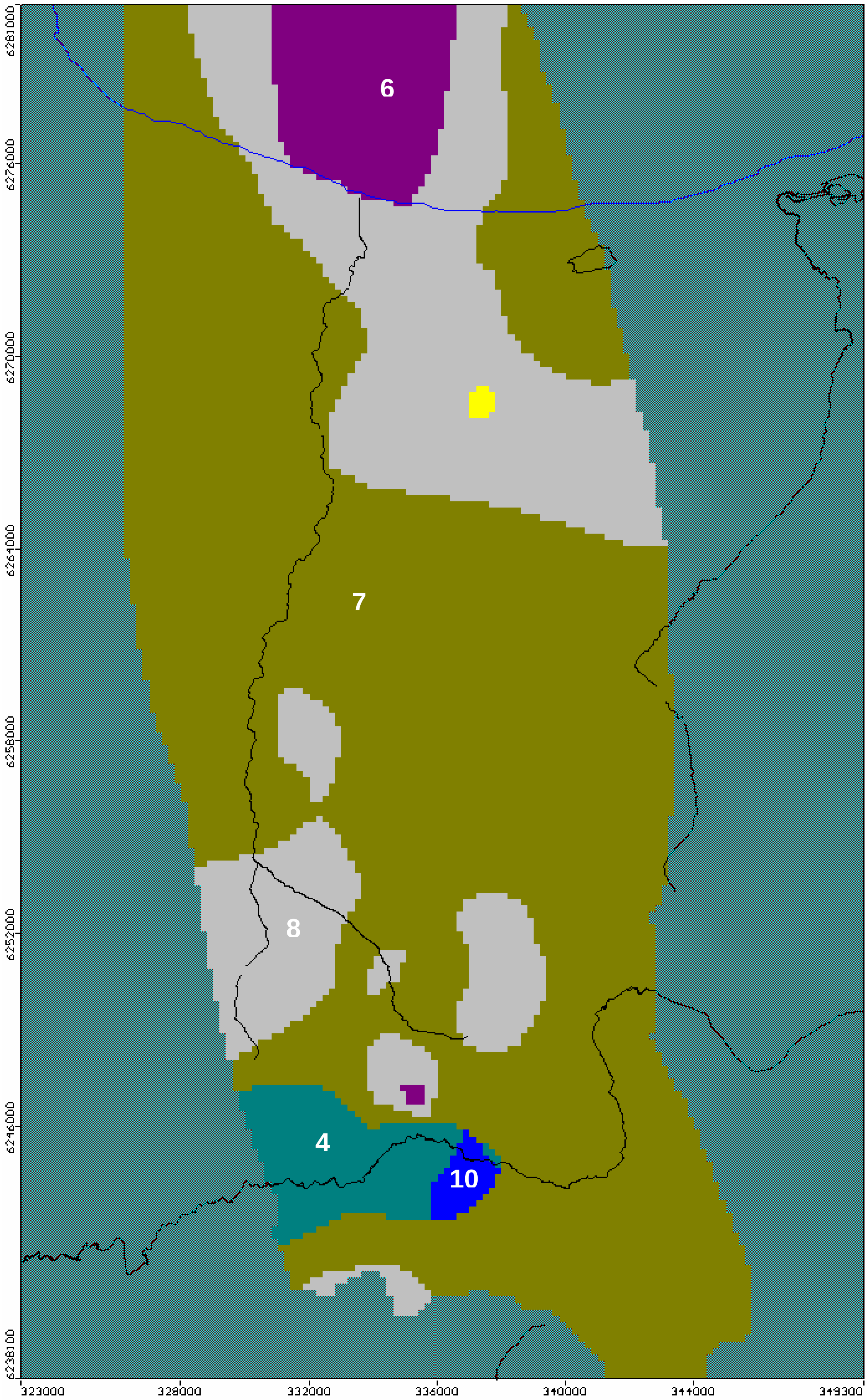


Figure D1 - Hydraulic conductivity zones in Layer 1

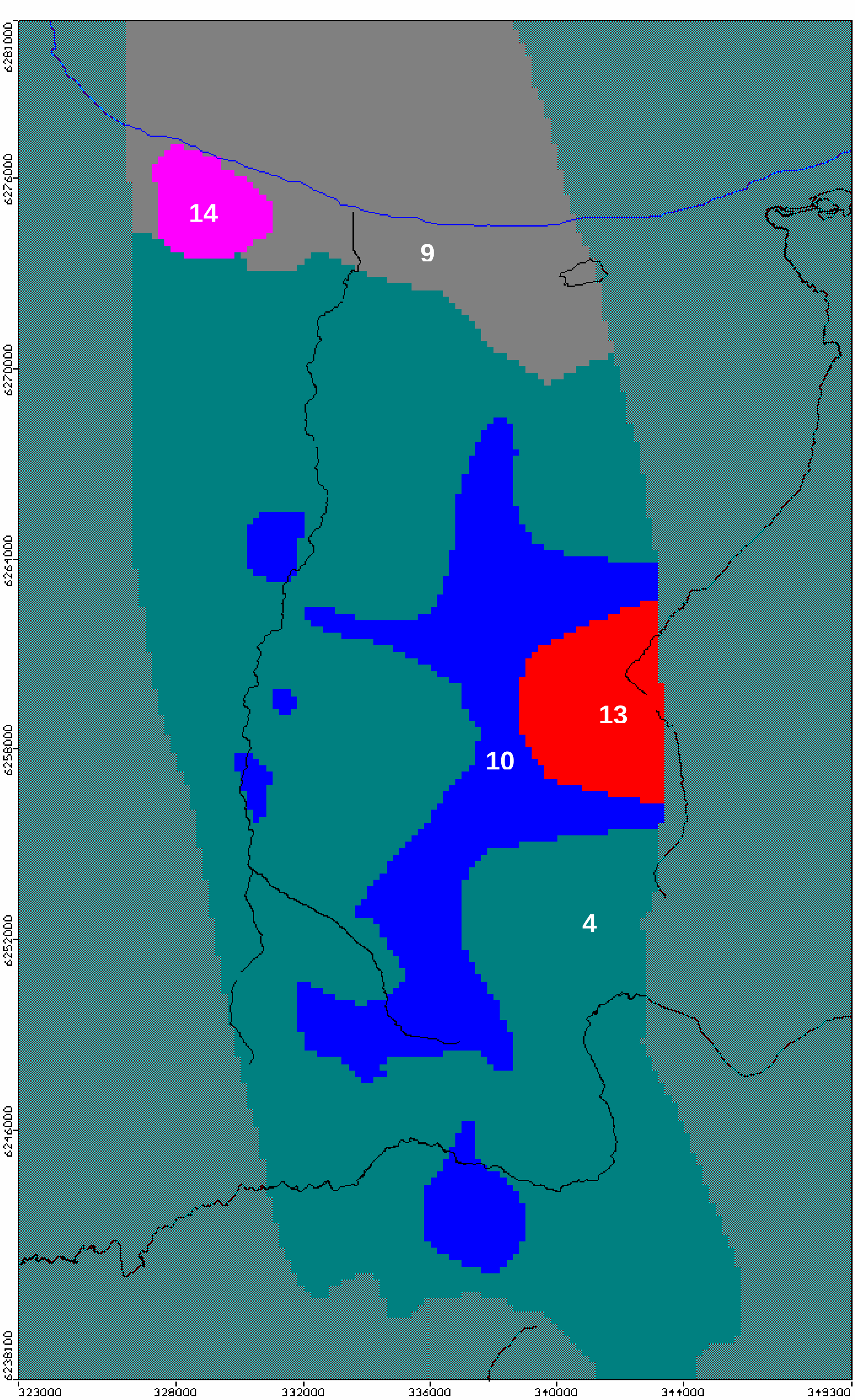


Figure D2 – Hydraulic conductivity zones in Layer 2

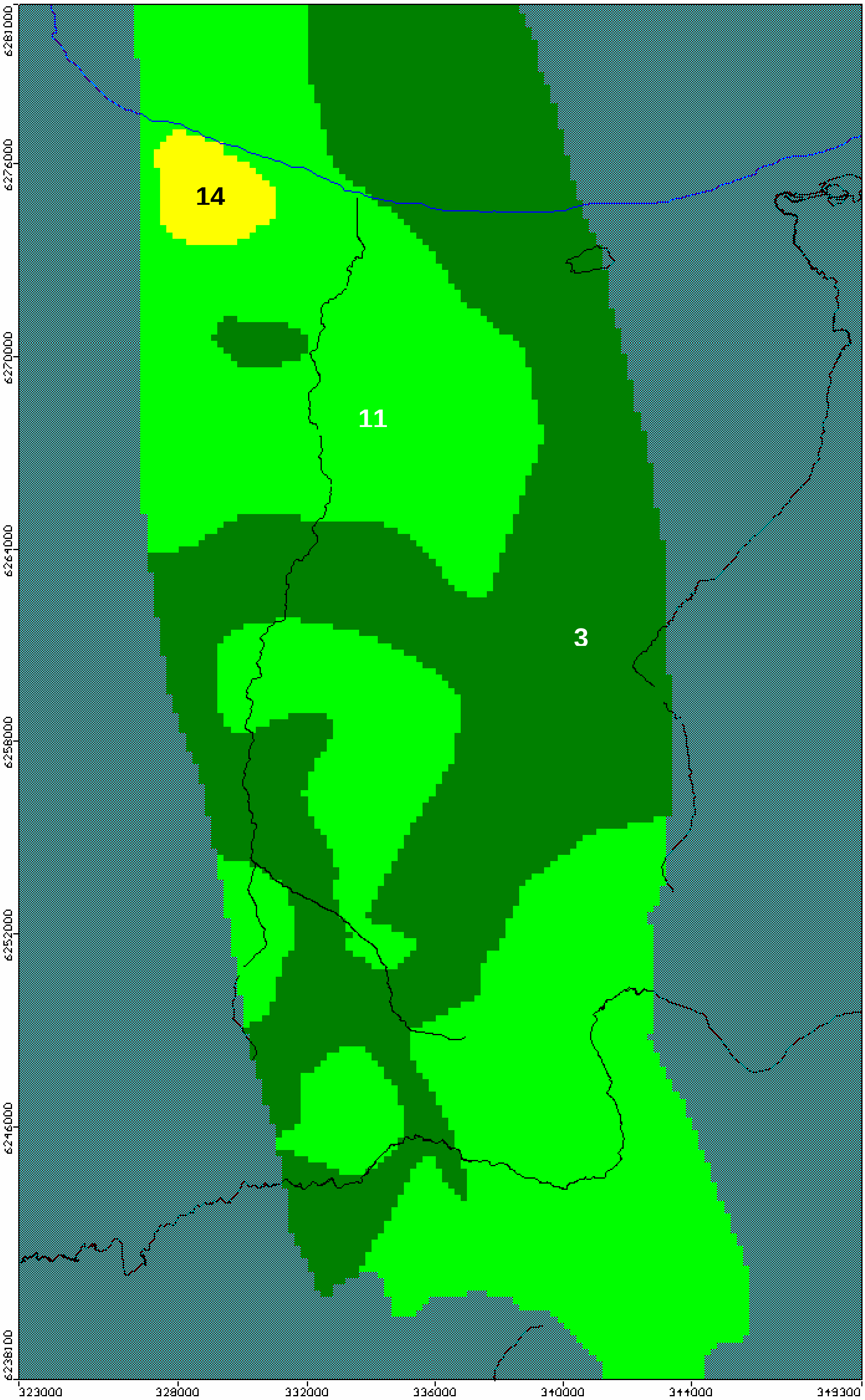


Figure D3 – Hydraulic conductivity zones in Layer 3

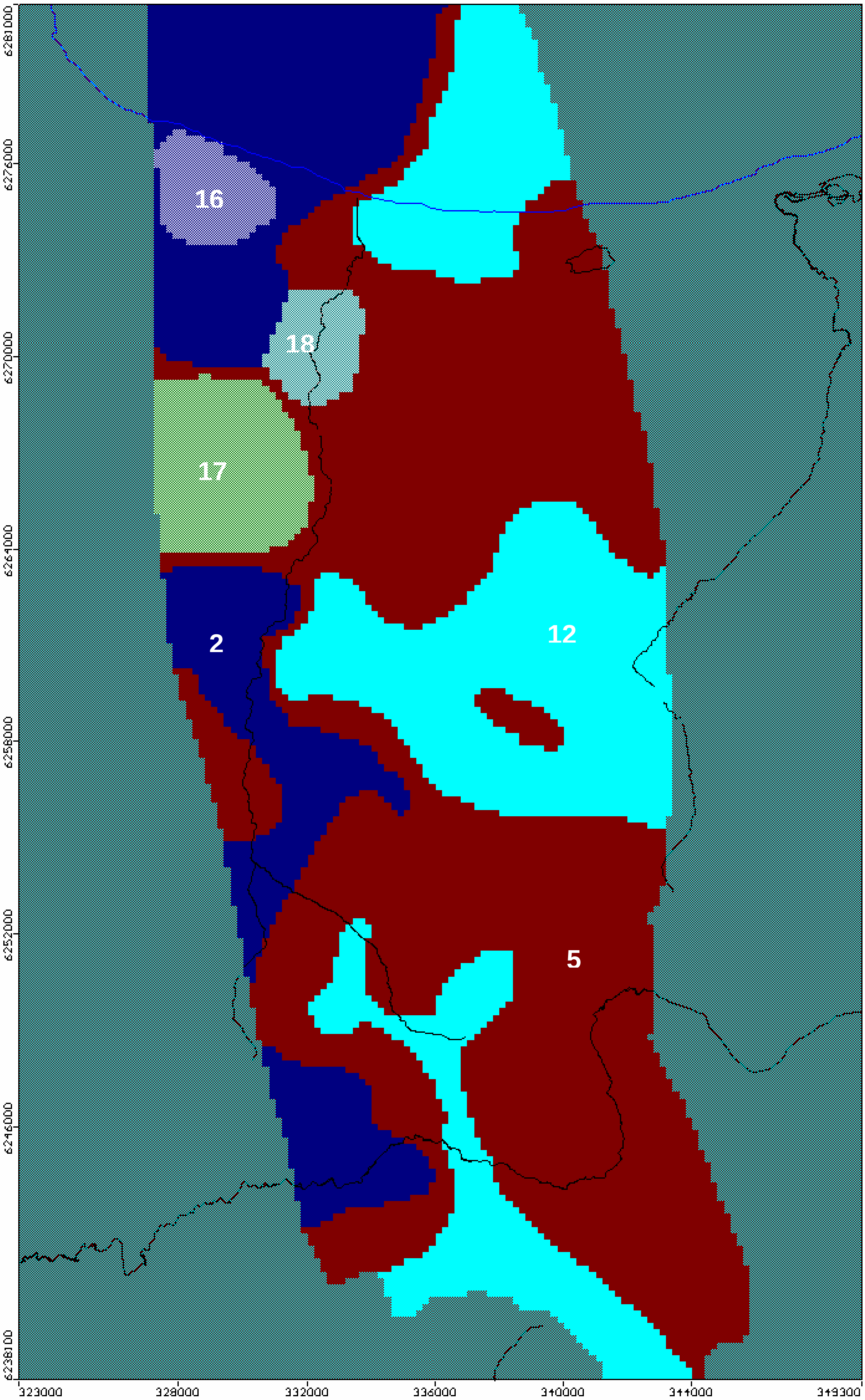


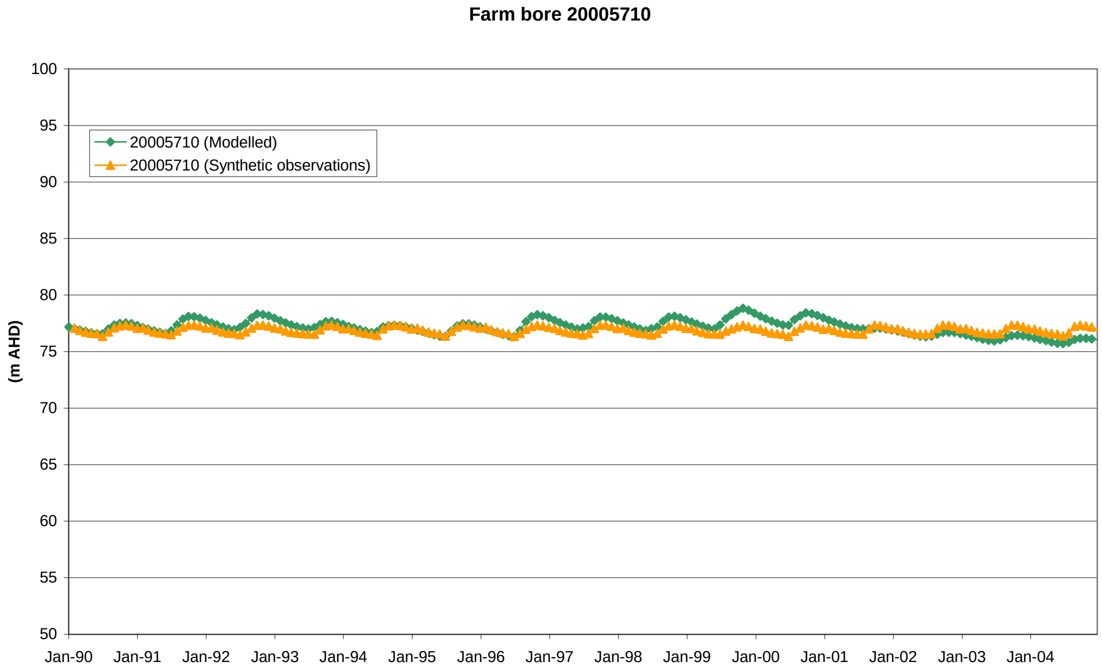
Figure D4 – Hydraulic conductivity zones in Layer 4

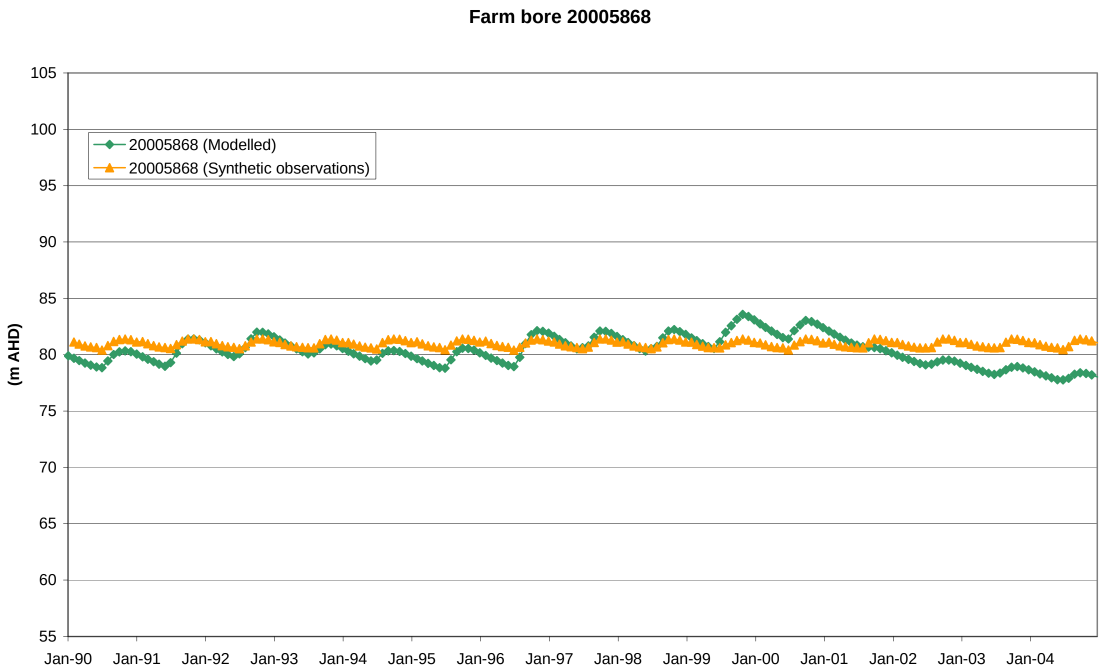
Appendix E — Sites used for model calibration

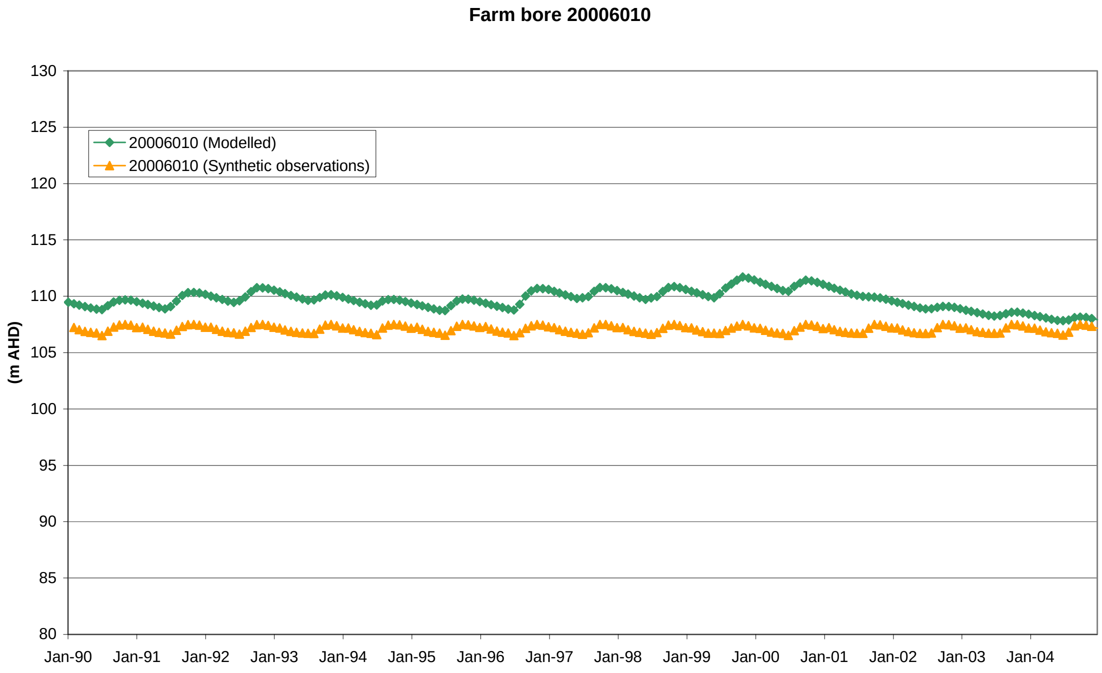
Site name	Easting (MGA coordinates)	Northing (MGA coordinates)	Screen elevation (m AHD)	Date start hydrograph	1990 steady state water level (m AHD)
BJM1B	334592	6264038	-84.145	Feb 1998	20.23
BJM2	339662	6264000	-101.615	Sep 1996	28.25
BJM3	329374	6264461	-64.37	Sep 1996	28.06
BN14D	327046	6275645	-49.554	Oct 1987	-0.504
BN14I	327046	6275645	-14.554	Oct 2000	1.775
BN14S	327046	6275645	-0.554	Oct 1987	2.681
BN15D	331549	6273137	-71.3	Oct 1987	2.036
BN15I	331549	6273137	-22.8	Apr 2001	2.037
BN15S	331549	6273137	0.2	Oct 1987	4.448
BN16I	338431	6272916	-26.238	Jul 2001	1.237
BN16S	338431	6272916	-2.338	Oct 1987	0.47
BN24D	332104	6269418	-76	Oct 1987	4.444
BN24I	332104	6269418	5.75	Oct 2000	11.341
BN24S	332104	6269418	15.5	Oct 1987	18.467
BN25D	337448	6268647	-77.91	Feb 1984	12.425
BN25I	337448	6268647	-7.81	Mar 1984	14.628
BN25S	337448	6268647	9.59	Mar 1984	14.119
BN26D	341838	6269248	-78.7	Oct 1987	9.538
BN26I	341838	6269248	-14.7	Oct 2000	7.851
BN26S	341838	6269248	4.3	Oct 1987	10.099
BN30D	334592	6264038	-59.145	Mar 1984	19.155
BN30I	334592	6264038	11.855	Mar 1984	27.528
BN30S	334592	6264038	30.855	Mar 1984	32.146
BN31D	339637	6264001	-67.615	Oct 1987	27.04
BN31I	339637	6264001	9.385	Mar 1984	27.04
BN31S	339637	6264001	25.385	Mar 1984	27.783
BN35D	339580	6259779	-36.003	Oct 1987	40.952
BN35S	339580	6259779	53.997	Mar 1984	54.898
CL1W	333996	6250994	80.85	Apr 1988	94.754
CL2C	339047	6251728	47.5	Apr 1988	82.729
CW1A	330639	6258819	-78.4755	May 2006	62.37683
CW1B	330639	6258819	35.647	May 2006	65.28983
CW2A	334594	6256112	-59.802	May 2006	84.28117

CW2B	334594	6256112	70.163	May 2006	96.93983
CW3A	332587	6253354	-60.214	May 2006	86.82658
CW3B	332587	6253354	54.836	May 2006	92.1355
CW4A	333410	6246847	-39.9095	May 2006	89.39
CW4B	333410	6246847	71.55	May 2006	92.63533
CW5A	337340	6245171	-5.882	May 2006	87.24133
CW5B	337340	6245171	66.854	May 2006	81.97417
CW6A	333503	6243073	19.4865	May 2006	84.75
CW6B	333503	6243073	69.51	May 2006	87.11183
CW7A	334279	6250947	-77.2215	May 2006	86.8975
CW7B	334279	6250947	34.9	May 2006	94.19433
SWI2	328564	6276494	-82.168	Mar 2003	Not used in steady state calibration
Pool 3	333917	6244739	71.815	Dec 2006	74.835
Pool 5	335408	6245758	73.487	Dec 2006	76.489
Pool 6	335684	6245597	74.023	Dec 2006	77.02
Pool 9	338227	6244855	76.831	Dec 2006	79.841
Canebreak Pool (Margaret river)	342287	6250149	89.5	estimate only	94.5
Corner Pool (Margaret River)	341636	6244827	80.5	estimate only	84.5
Farm bore: 20005710	339120	6258254	73.5	measured on 22-9-1977	76.84
Farm bore: 20006010	336116	6255127	83	measured on 18-1-1998	99.78
Farm bore: 20006366	337710	6242233	89	*measurement date not recorded*	95.5428
Farm bore: 20005868	329457	6255236	78.5	measured on 23-1-1979	85.4

Appendix F — Calibration hydrographs






Farm bore 20006010
20006010 (Modelled)
20006010 (Synthetic observations)
(m AHD)
130
125
120
115
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105
100
95
90
85
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Jan-90
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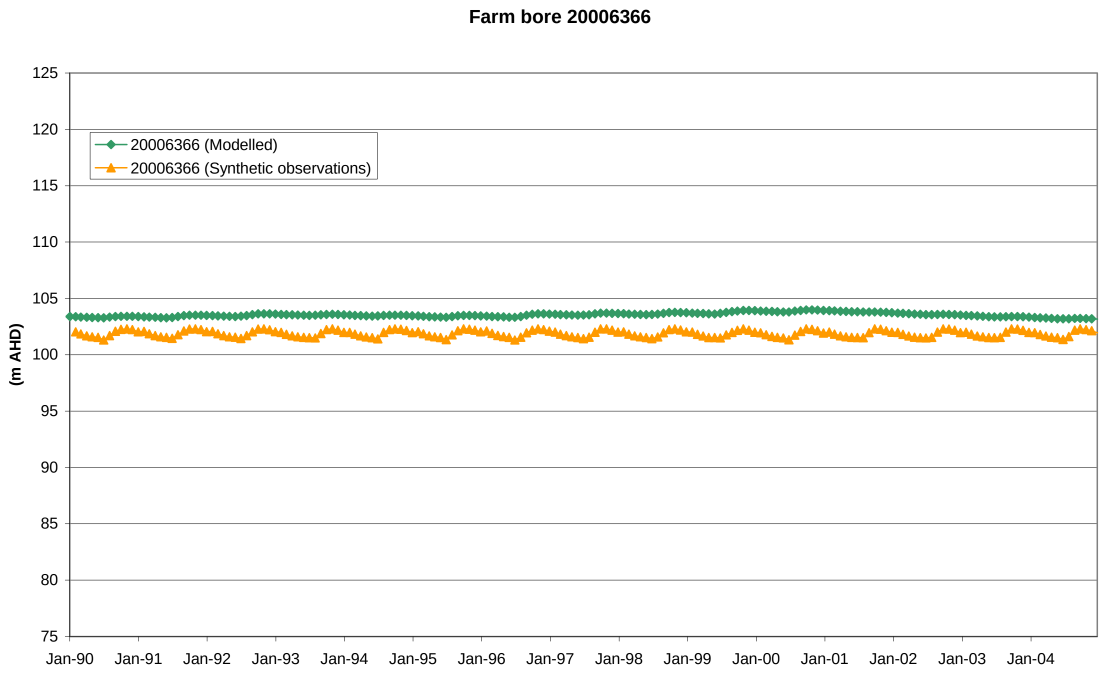
Farm bore 20006366
20006366 (Modelled)
20006366 (Synthetic observations)
(m AHD)
125
120
115
110
105
100
95
90
85
80
75
Jan-90
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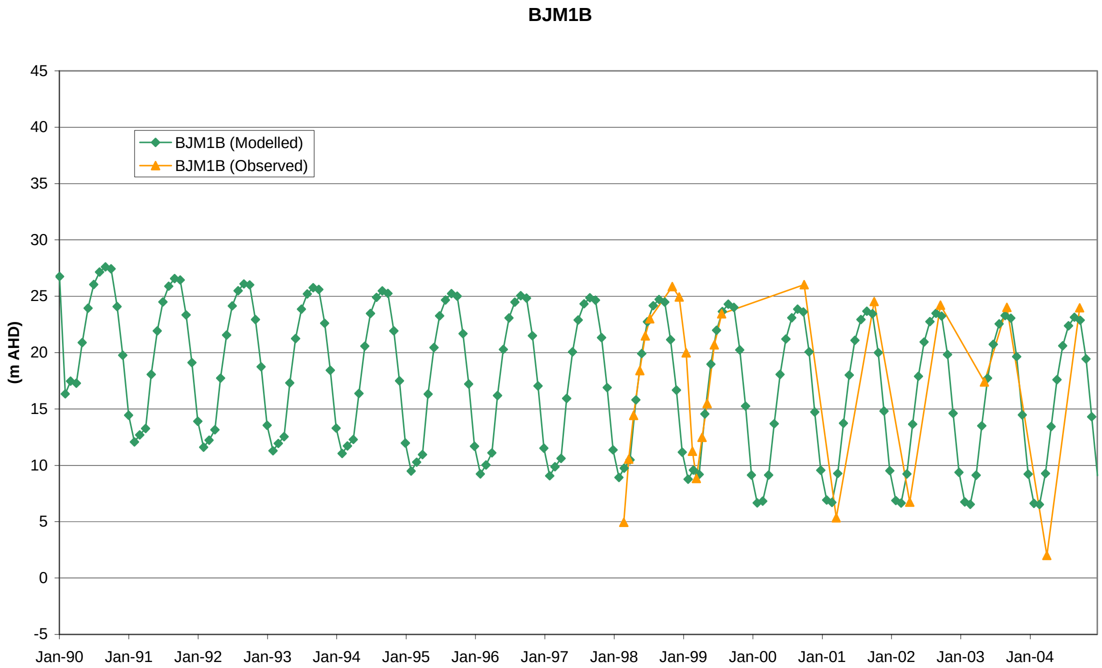
BJM1B
BJM1B (Modelled)
BJM1B (Observed)
(m AHD)
45
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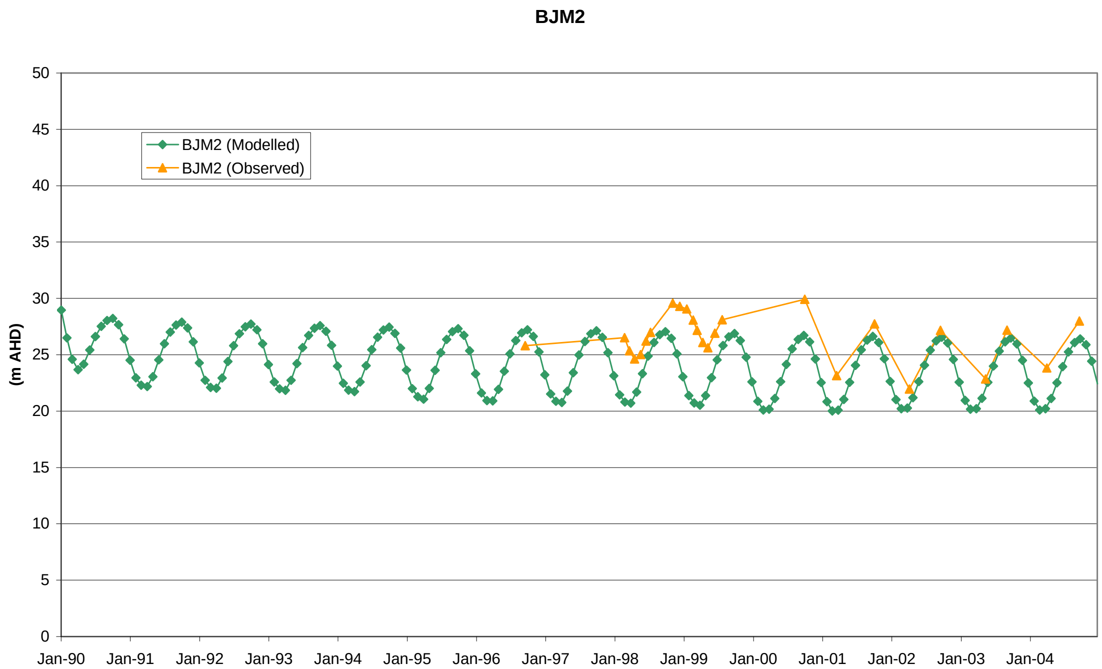
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BJM2 (Modelled)
BJM2 (Observed)
(m AHD)
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Jan-90
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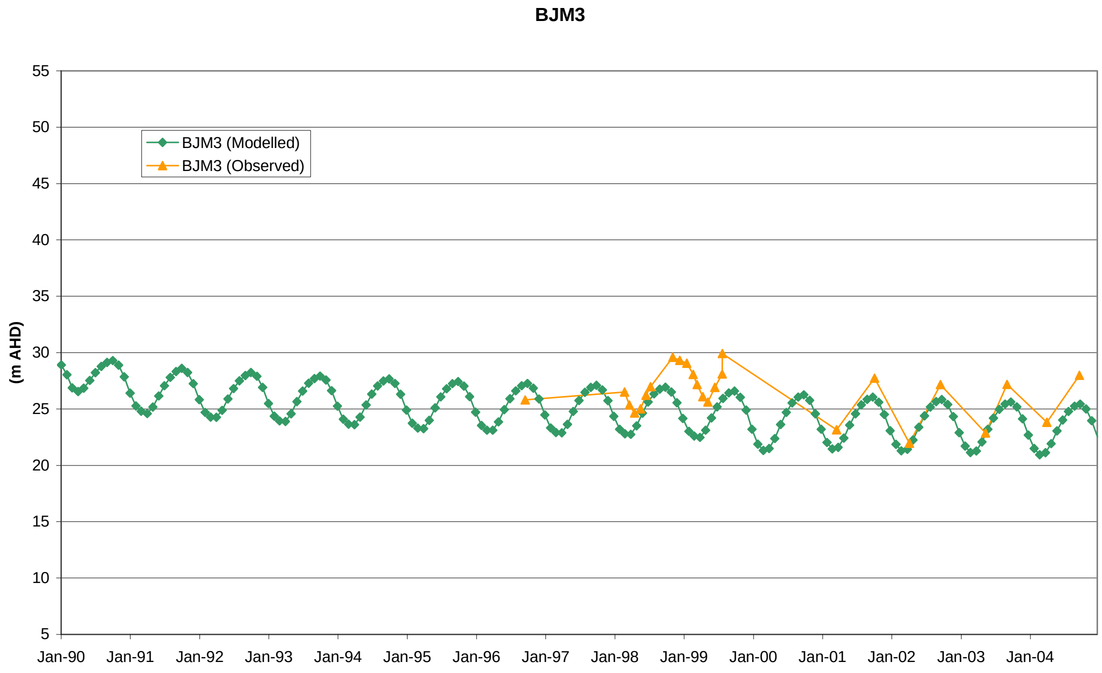
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BJM3 (Modelled)
BJM3 (Observed)
(m AHD)
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Jan-90
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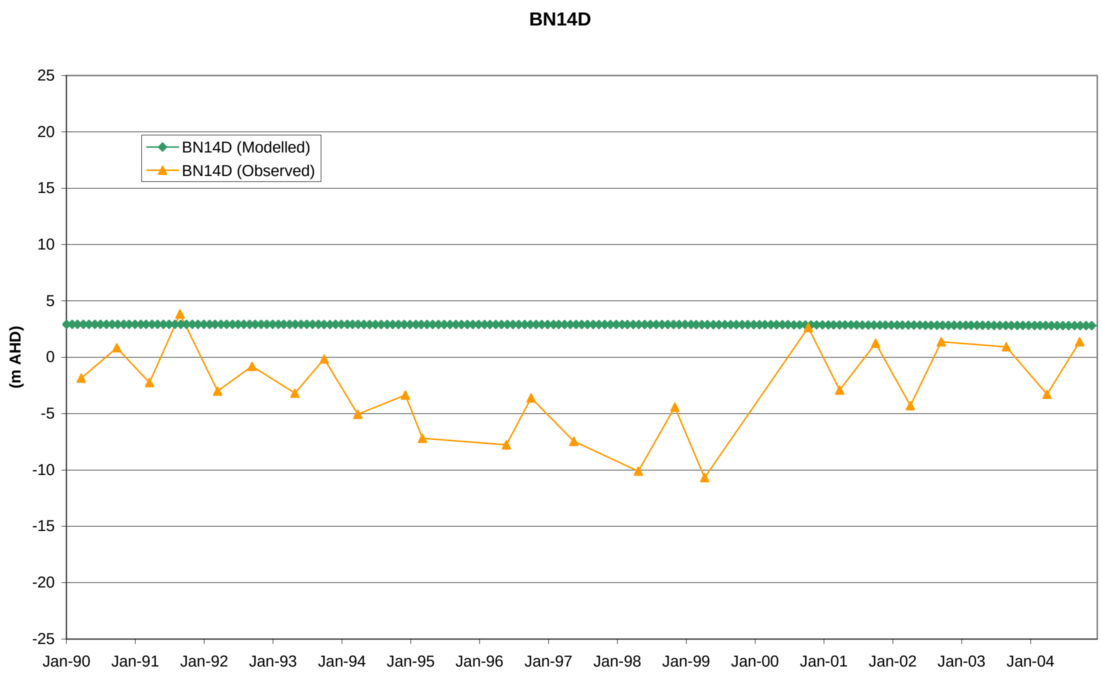
BN14D
BN14D (Modelled)
BN14D (Observed)
(m AHD)
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-20
-25
Jan-90
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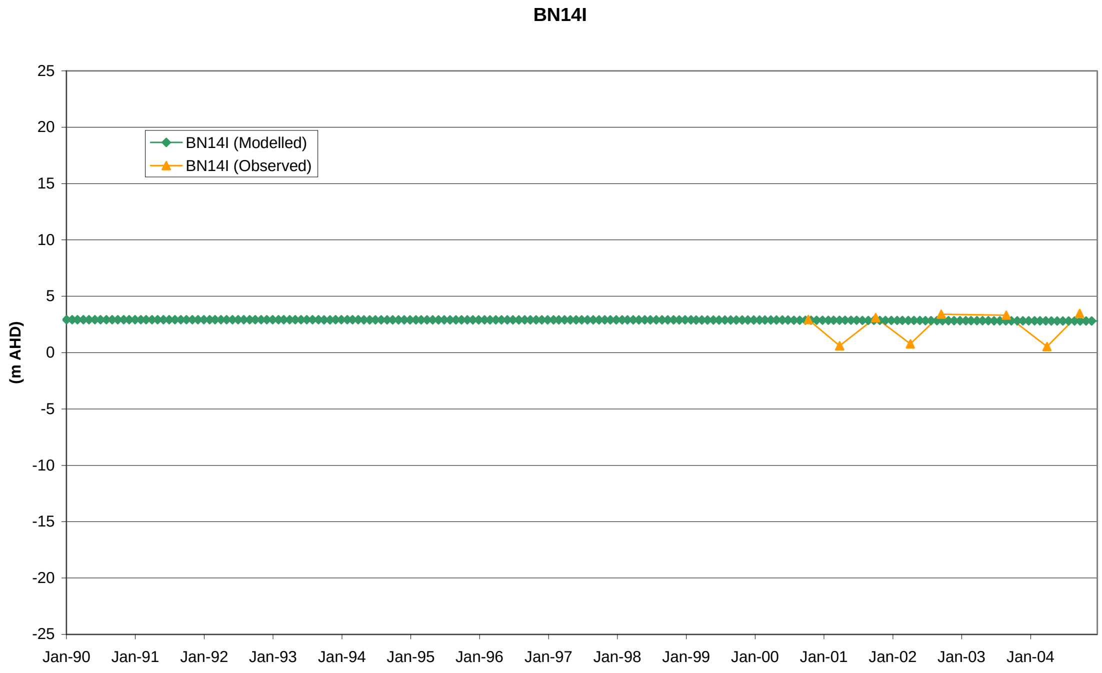
BN14I
BN14I (Modelled)
BN14I (Observed)
(m AHD)
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Jan-90
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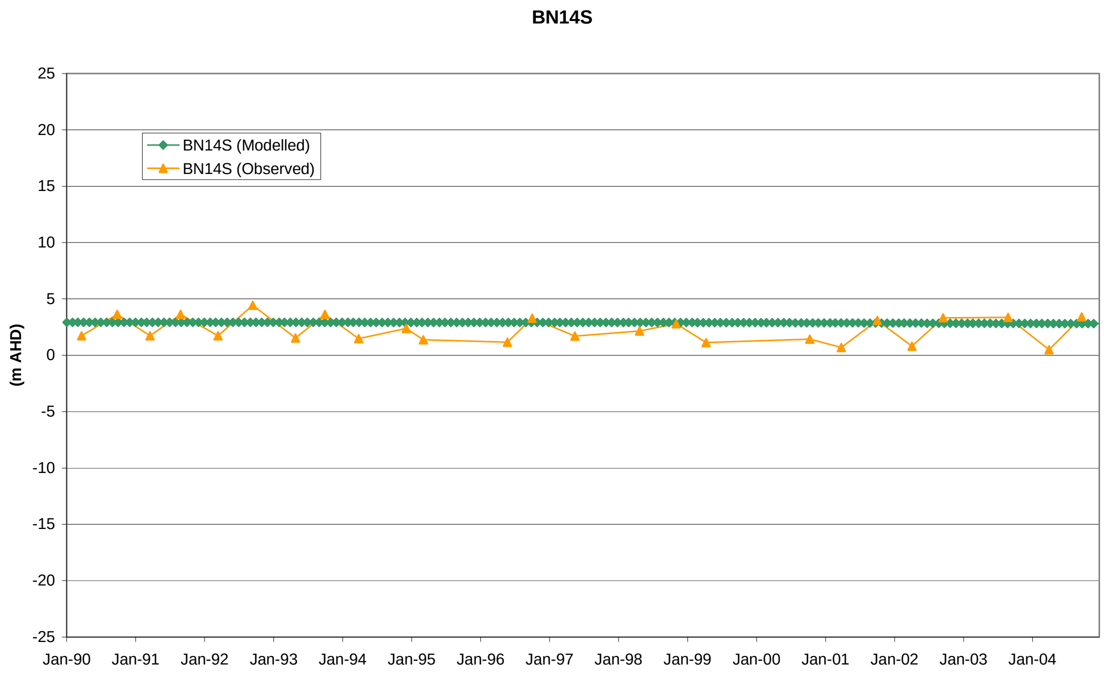
BN14S
BN14S (Modelled)
BN14S (Observed)
(m AHD)
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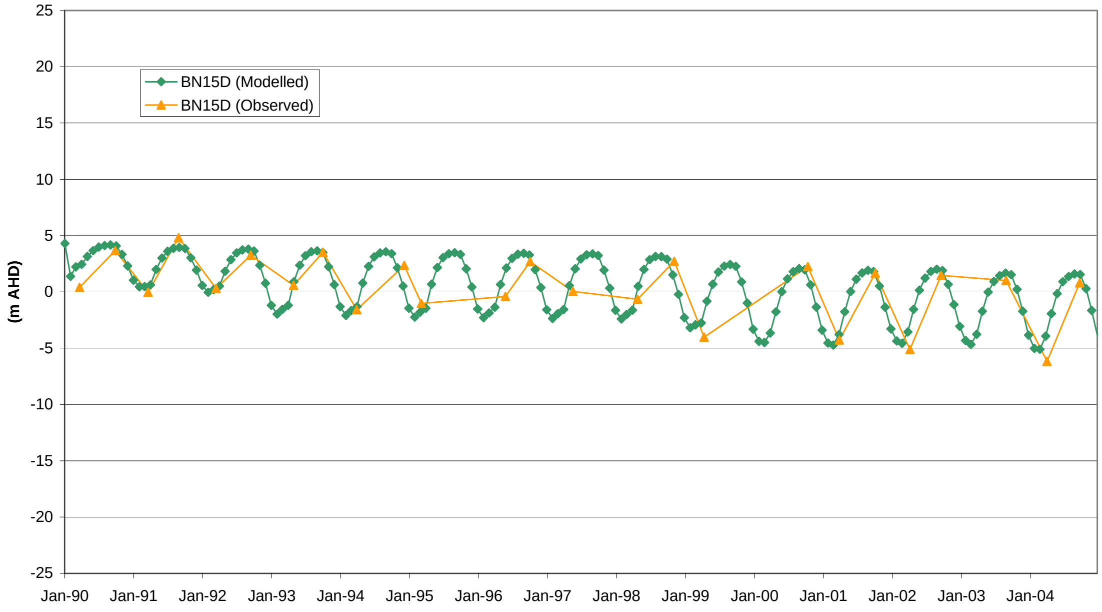
BN15D


BN15D (Modelled)
BN15D (Observed)
(m AHD)
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Jan-90
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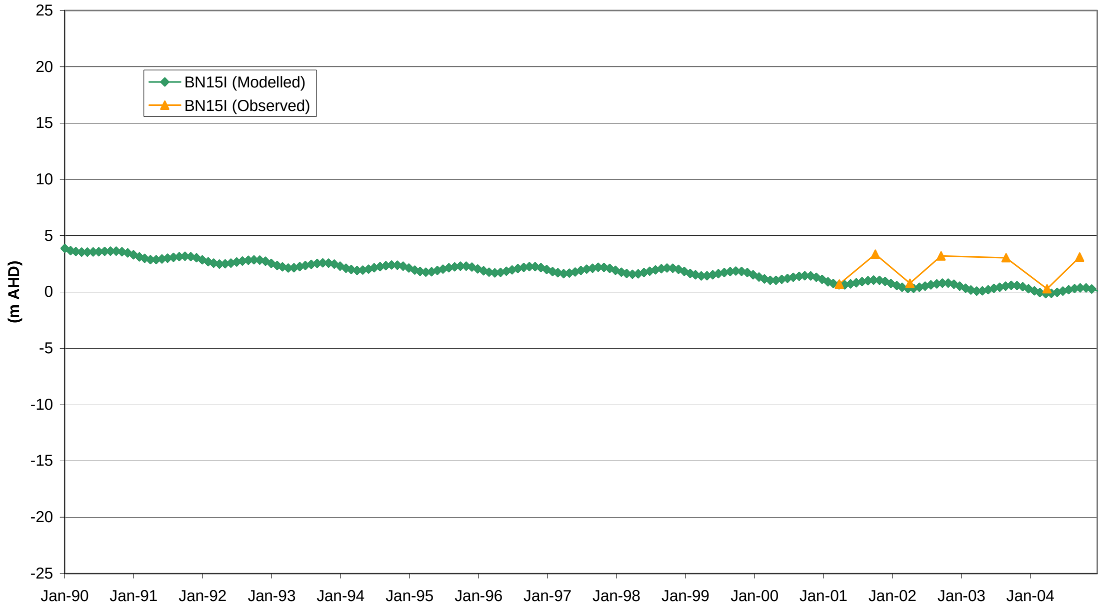
BN15I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BN15I (Observed)
(m AHD)
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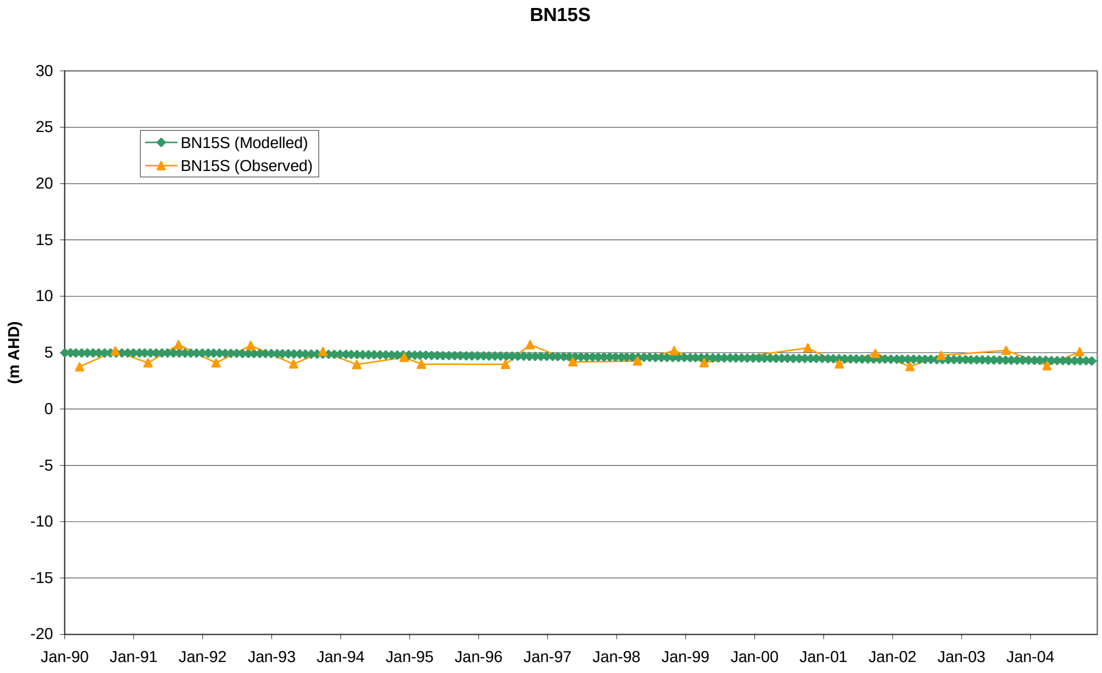
BN15S
BN15S (Modelled)
BN15S (Observed)
(m AHD)
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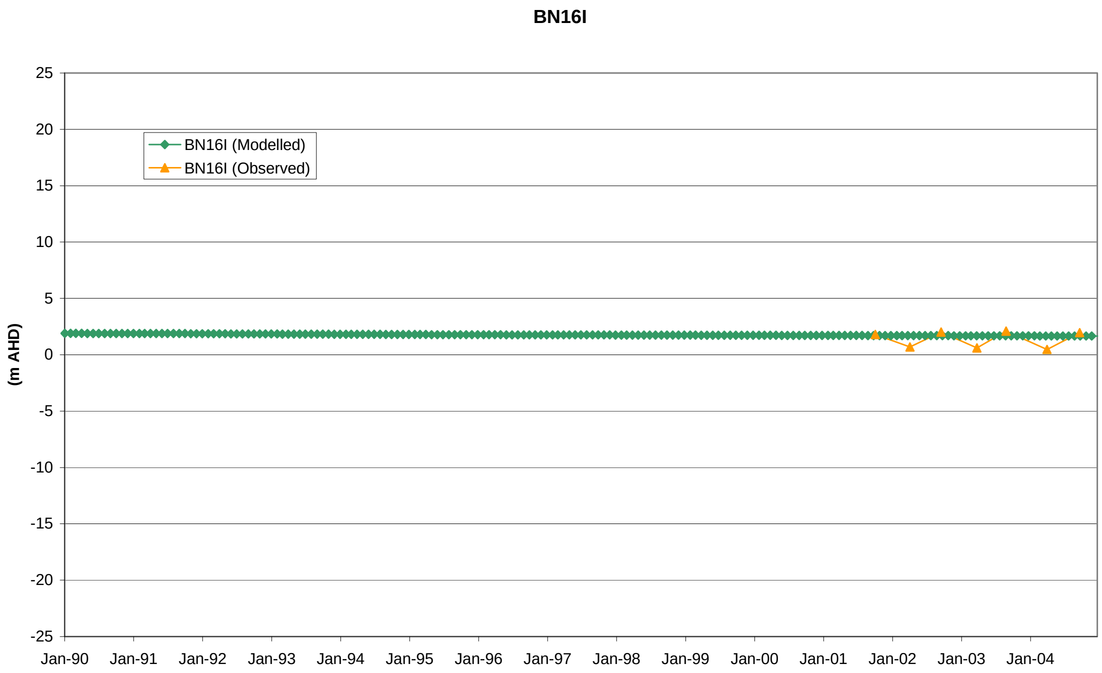
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BN16I (Modelled)
BN16I (Observed)
(m AHD)
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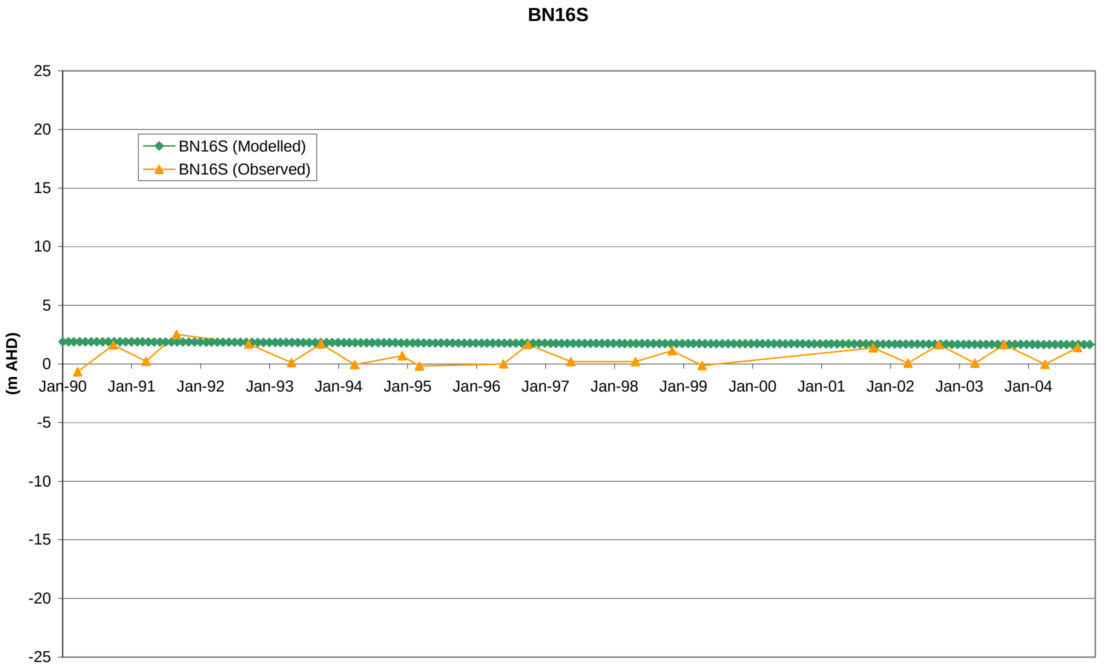
BN16S
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BN16S (Observed)
(m AHD)
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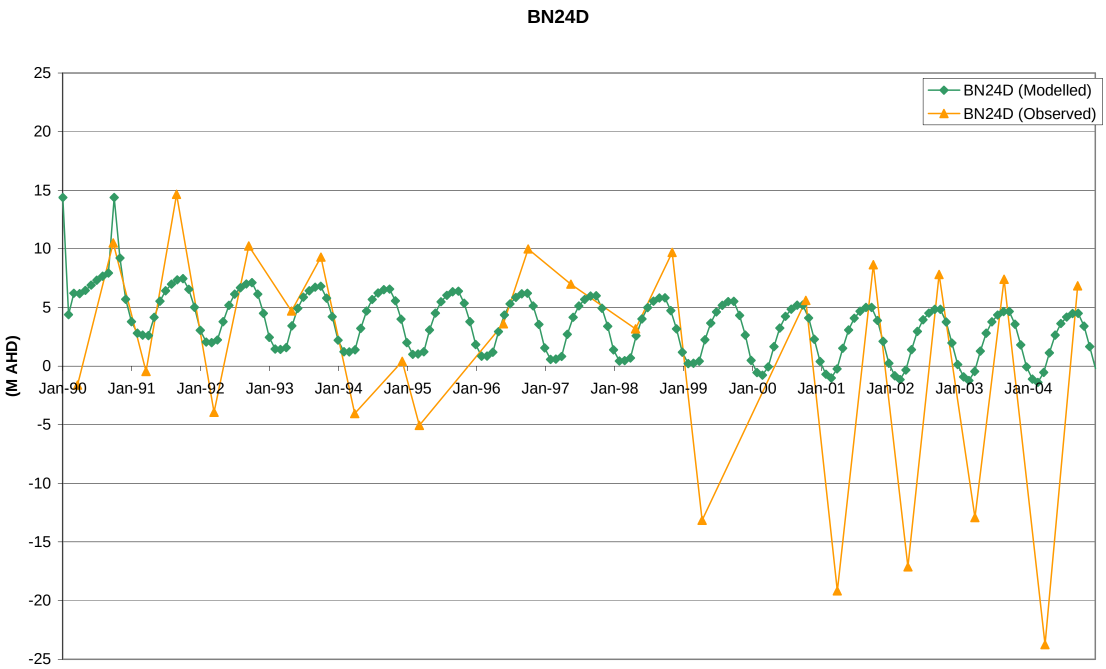
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BN24D (Observed)
(M AHD)
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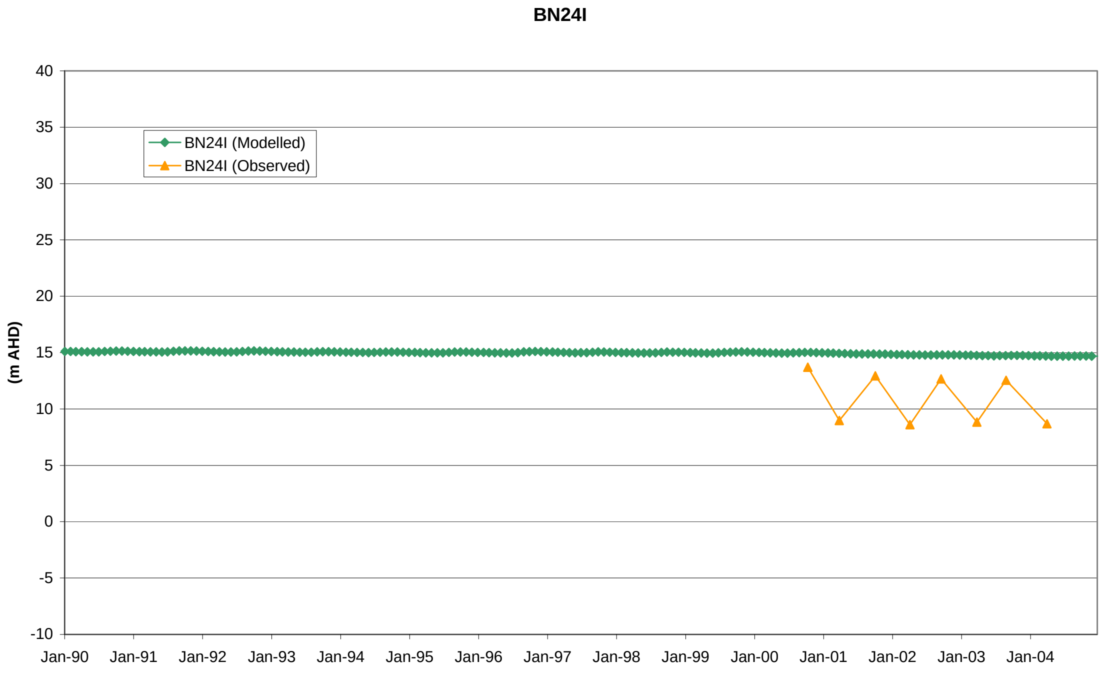

BN24I
BN24I (Modelled)
BN24I (Observed)
(m AHD)
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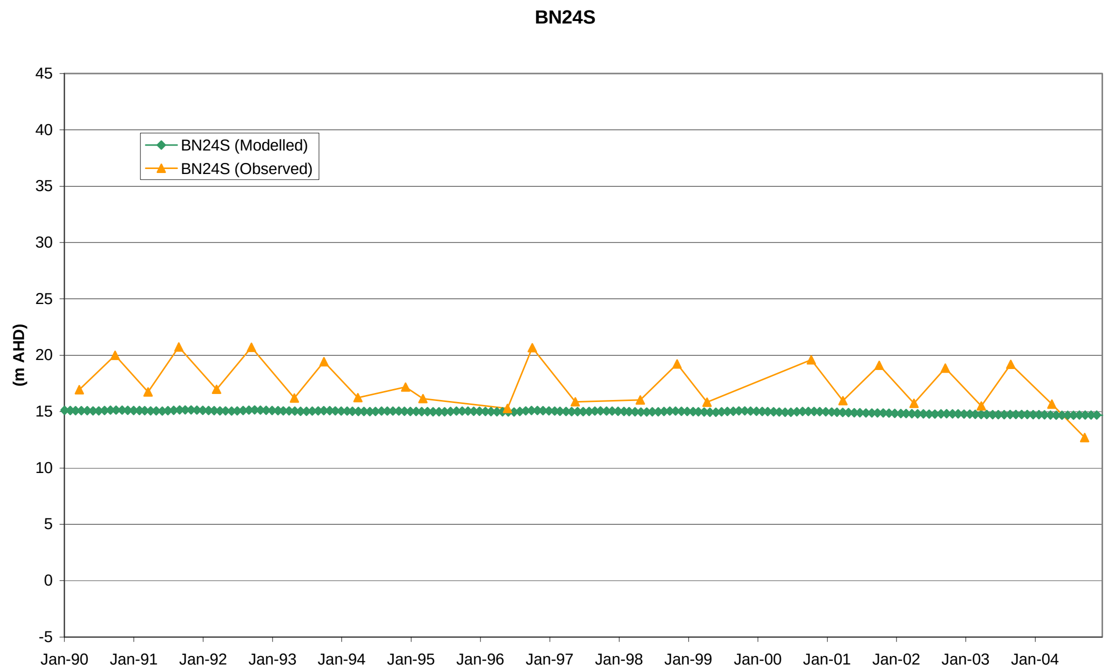

BN24S
BN24S (Modelled)
BN24S (Observed)
(m AHD)
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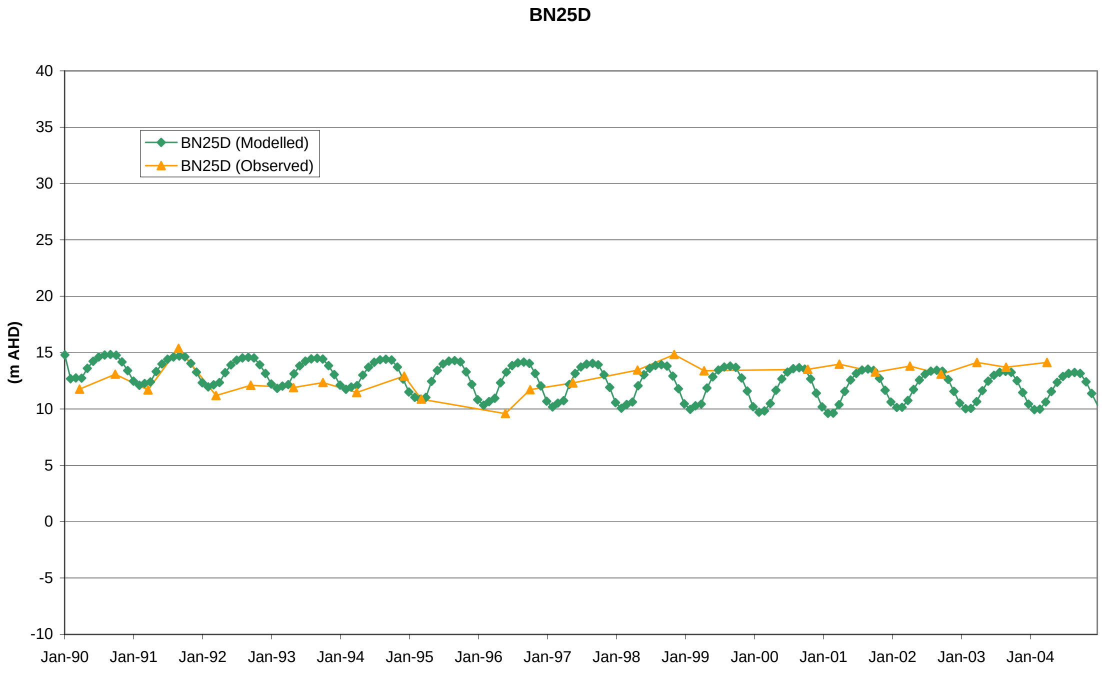
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BN25D (Observed)
(m AHD)
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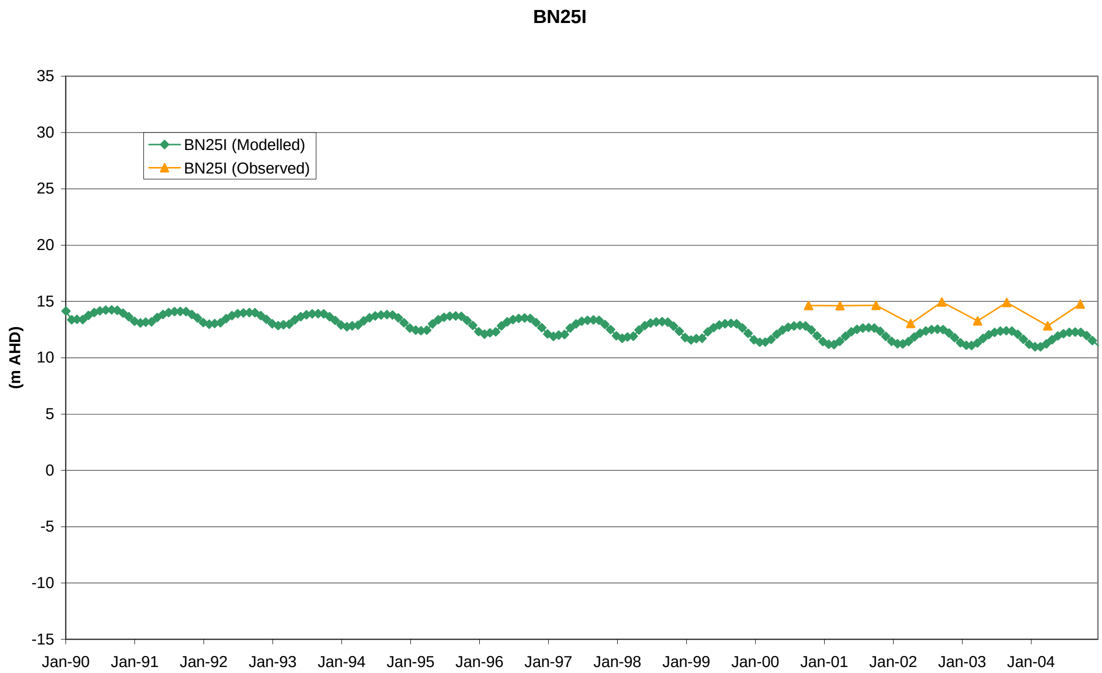
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BN25I (Modelled)
BN25I (Observed)
(m AHD)
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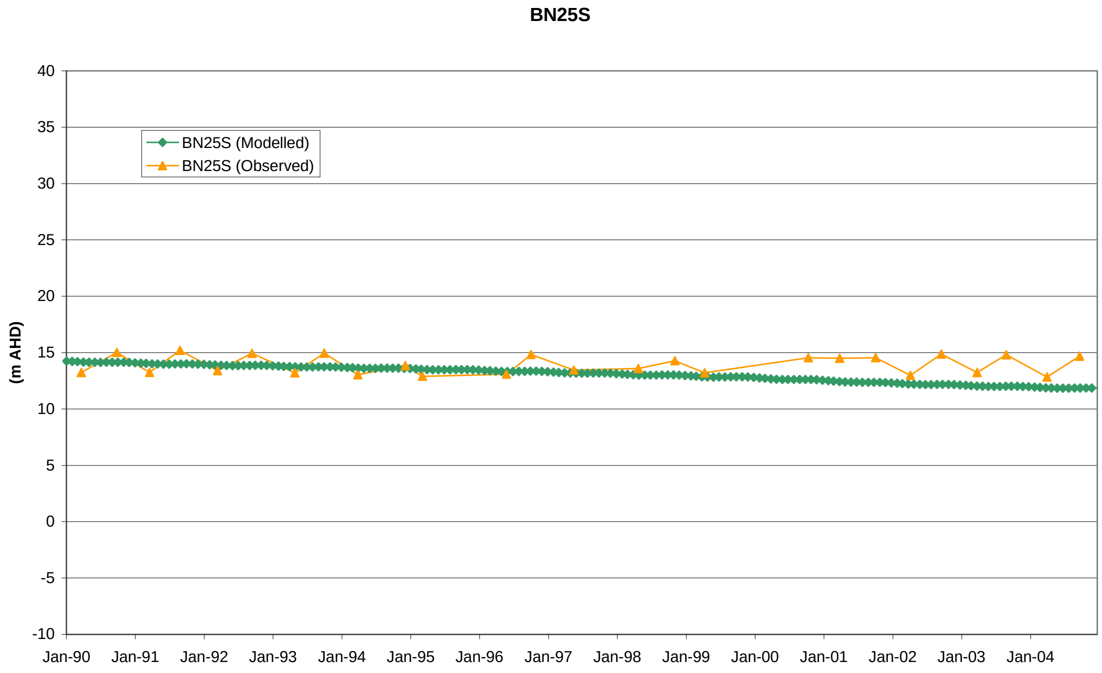
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BN25S (Observed)
(m AHD)
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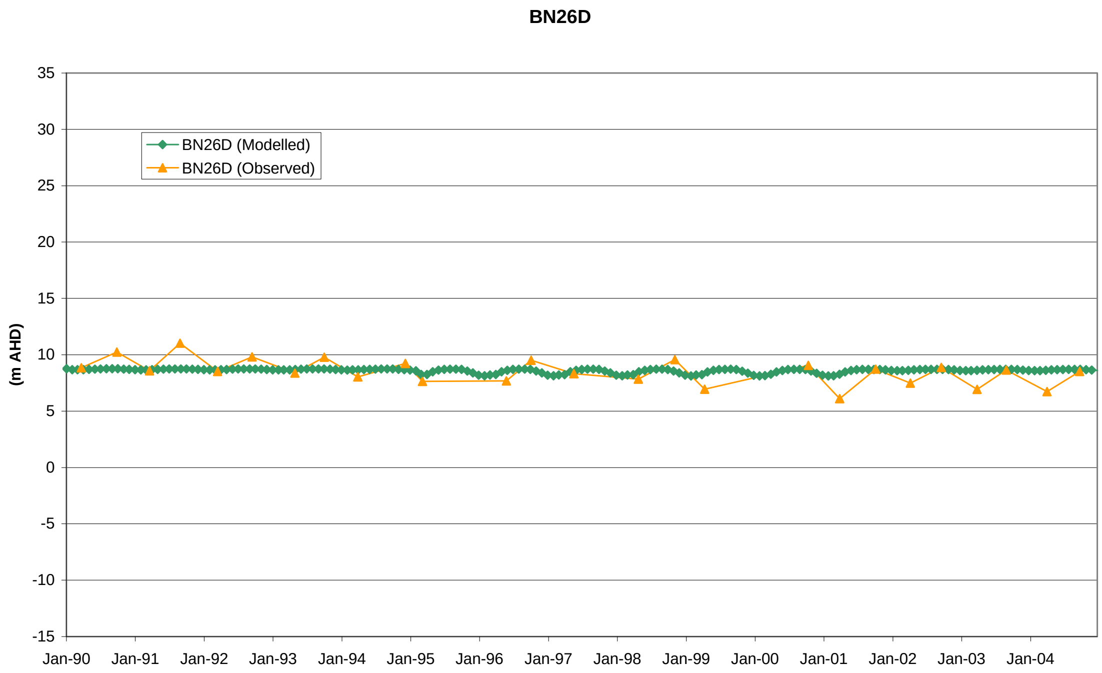
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BN26D (Observed)
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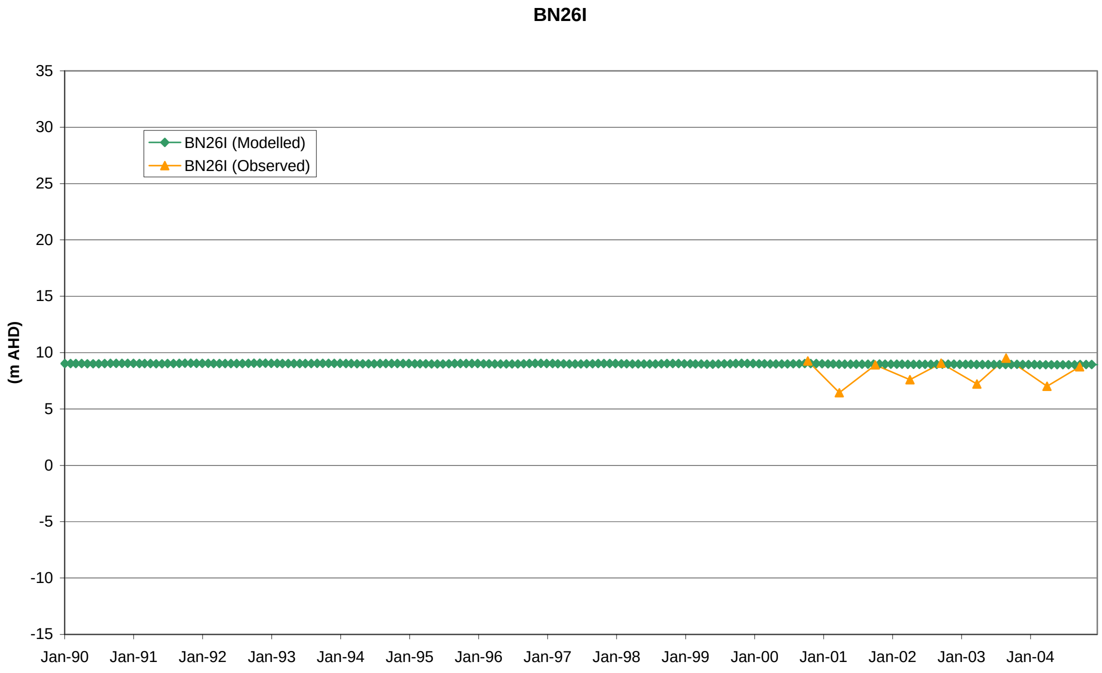
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BN26I (Observed)
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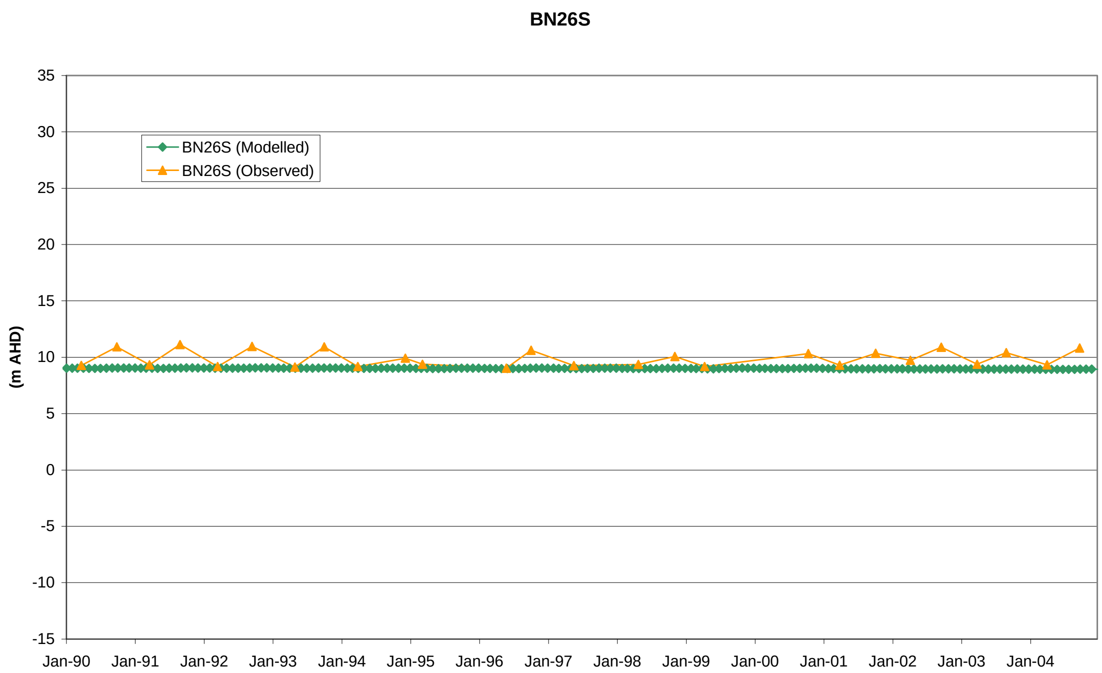
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BN26S (Observed)
(m AHD)
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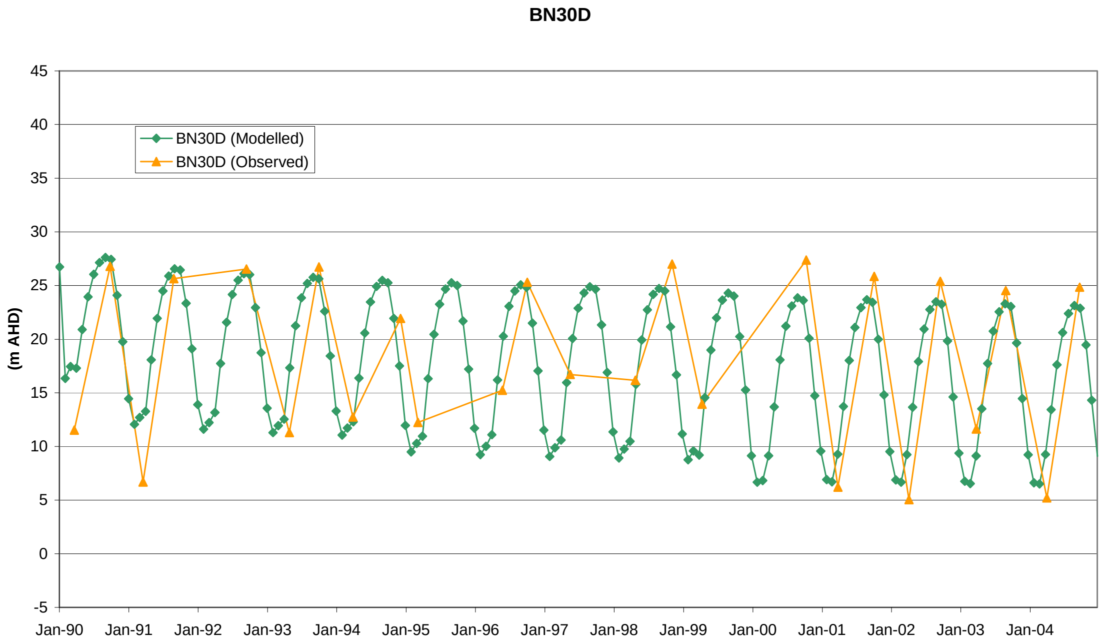
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BN30D (Modelled)
BN30D (Observed)
(m AHD)
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Jan-90
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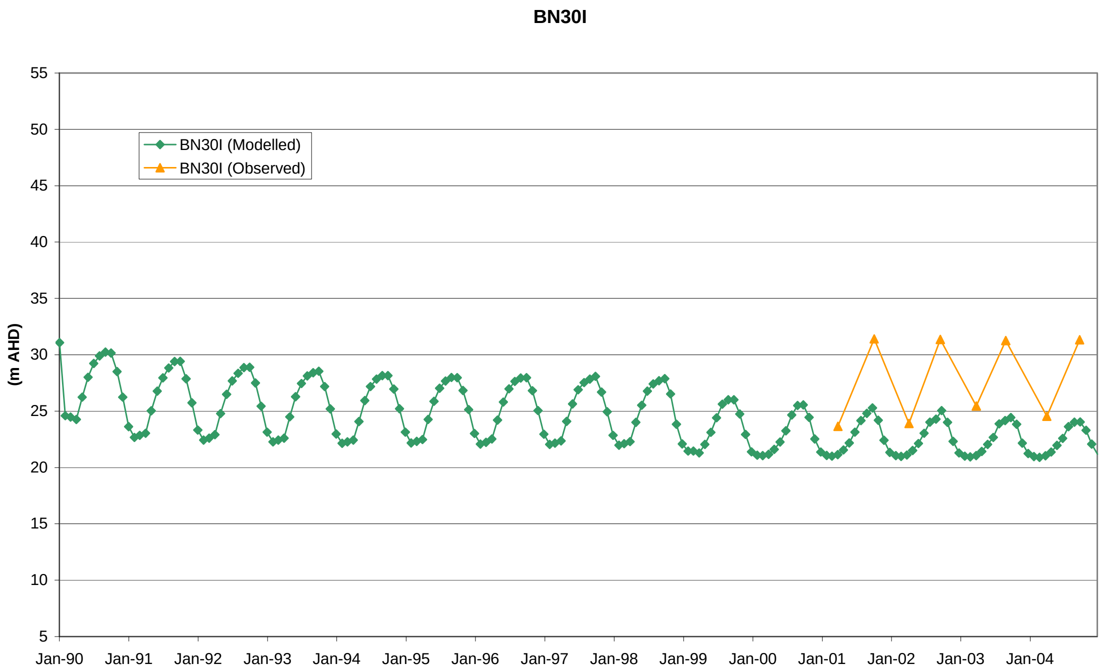
BN30I
BN30I (Modelled)
BN30I (Observed)
(m AHD)
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Jan-90
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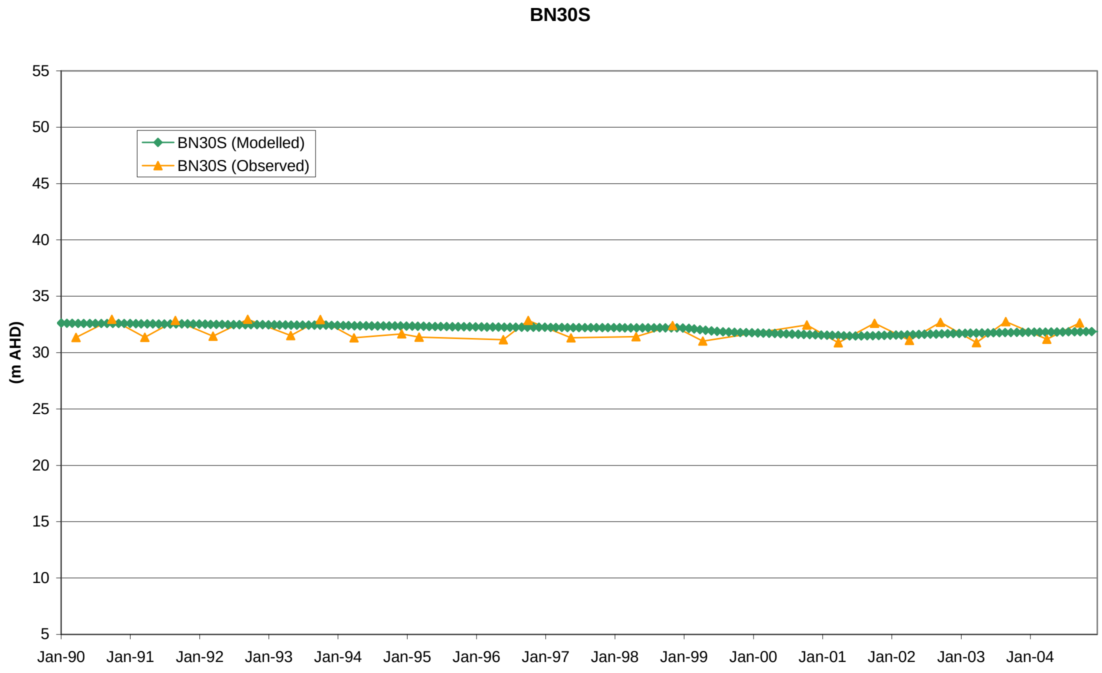
BN30S
BN30S (Modelled)
BN30S (Observed)
(m AHD)
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Jan-90
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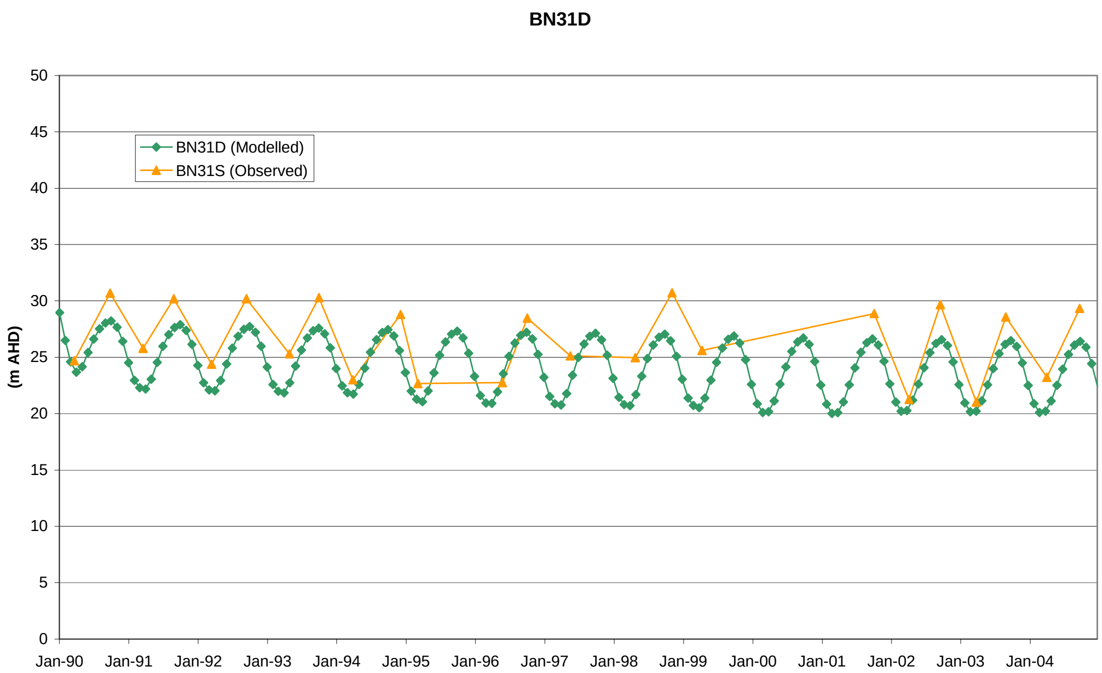
BN31D
BN31D (Modelled)
BN31S (Observed)
(m AHD)
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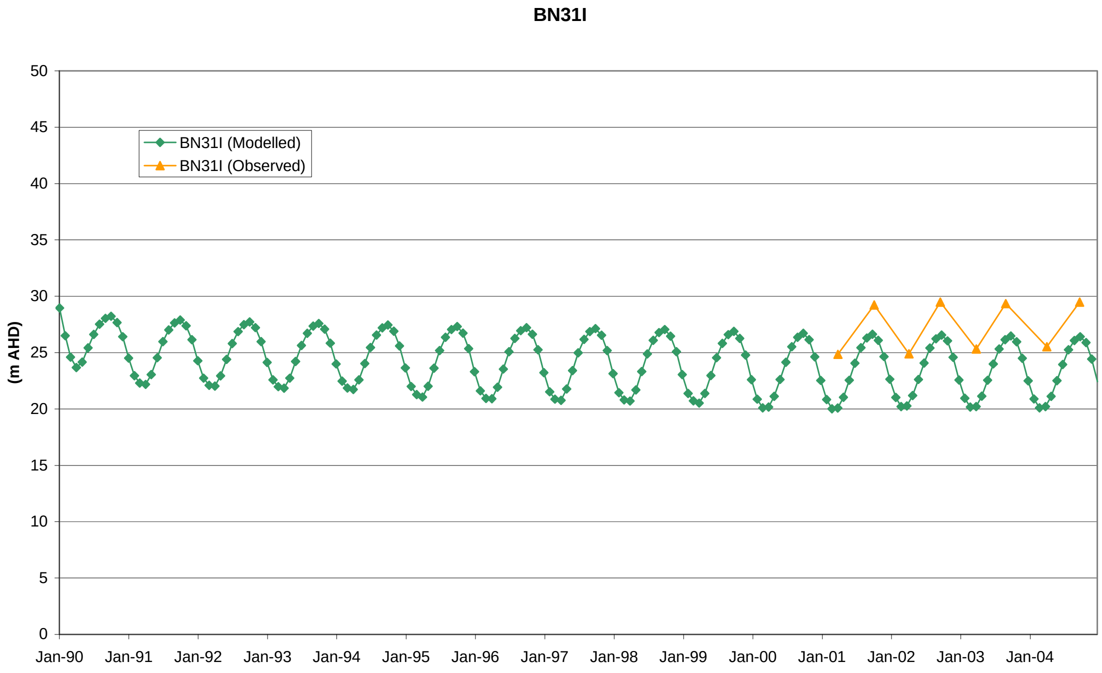
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BN31I (Modelled)
BN31I (Observed)
(m AHD)
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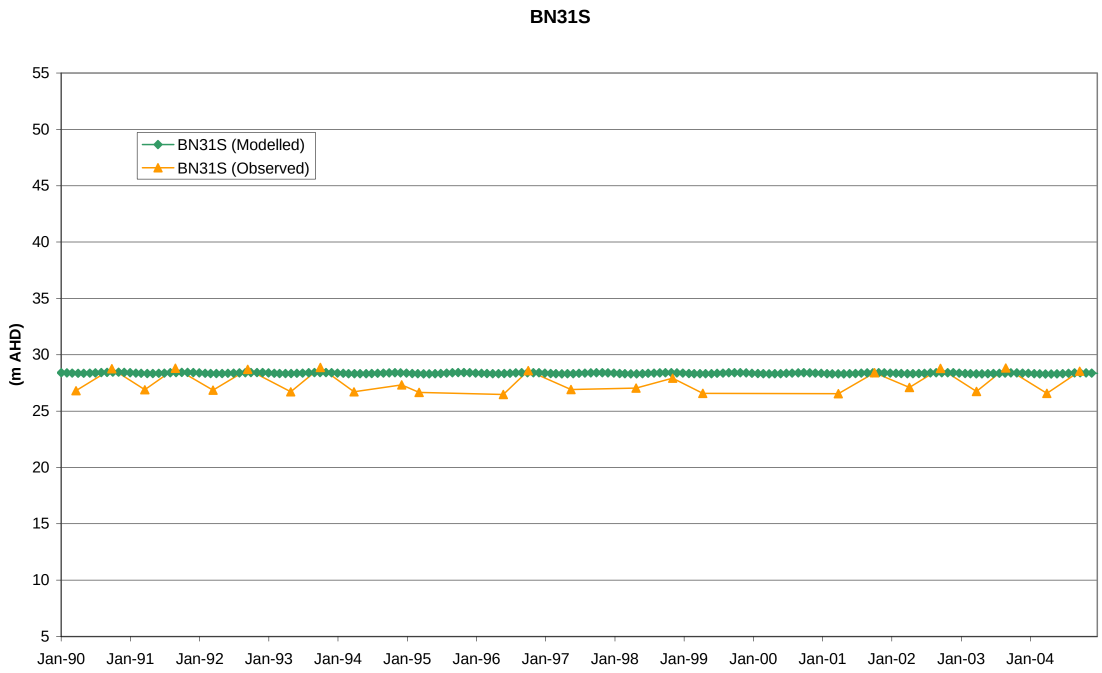
BN31S
BN31S (Modelled)
BN31S (Observed)
(m AHD)
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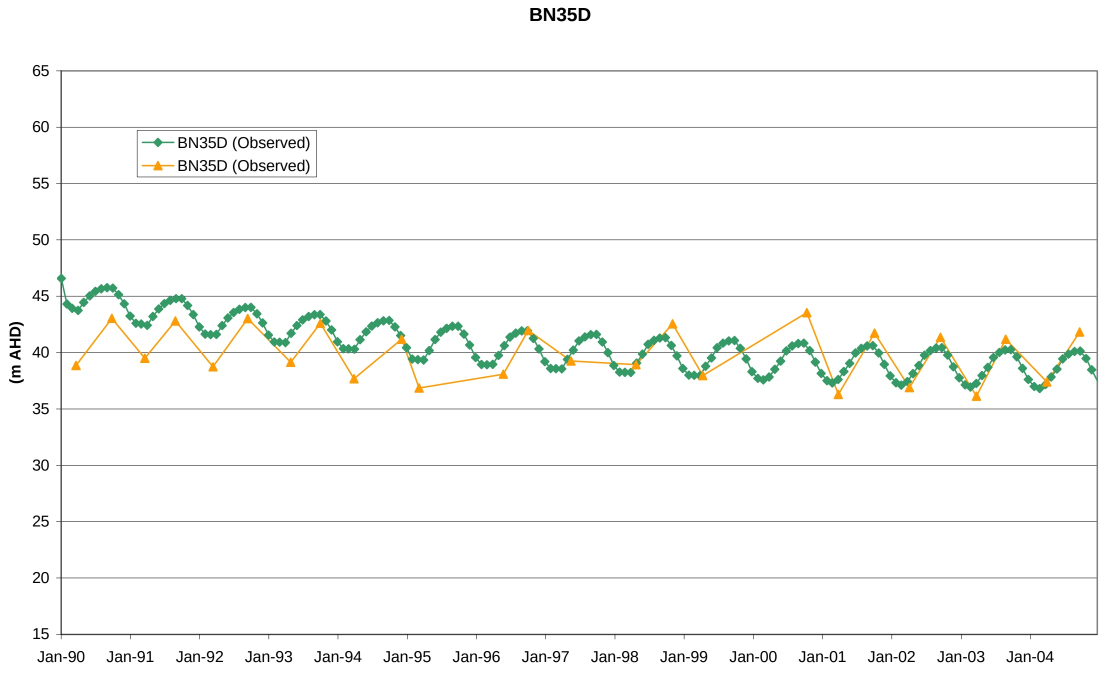
BN35D
BN35D (Observed)
BN35D (Observed)
(m AHD)
65
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Jan-90
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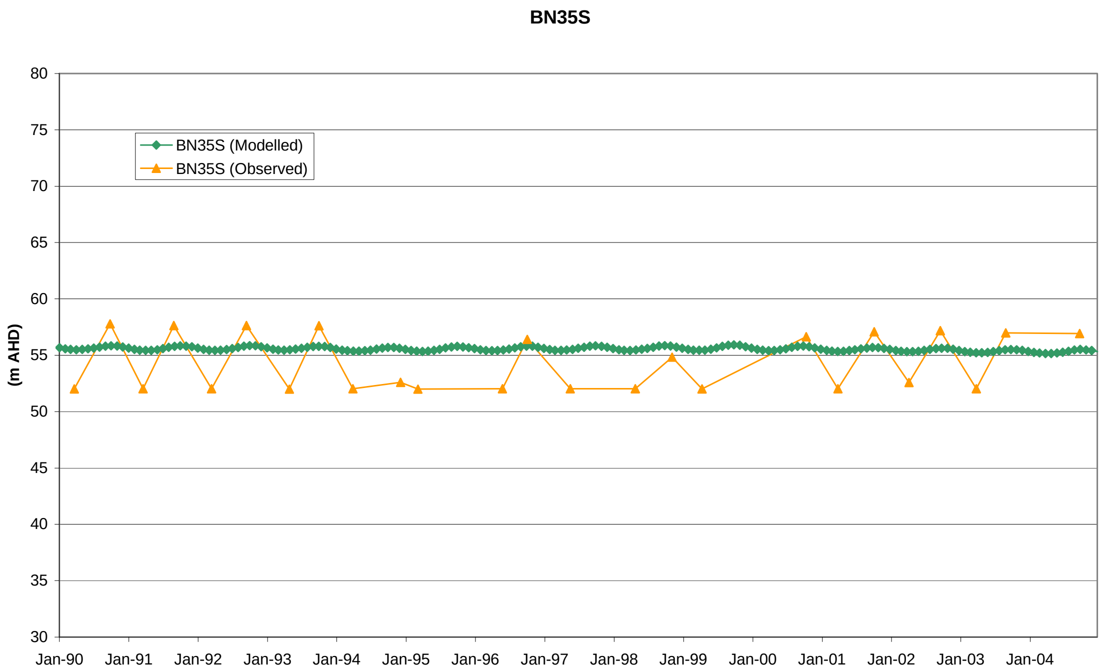
BN35S
BN35S (Modelled)
BN35S (Observed)
(m AHD)
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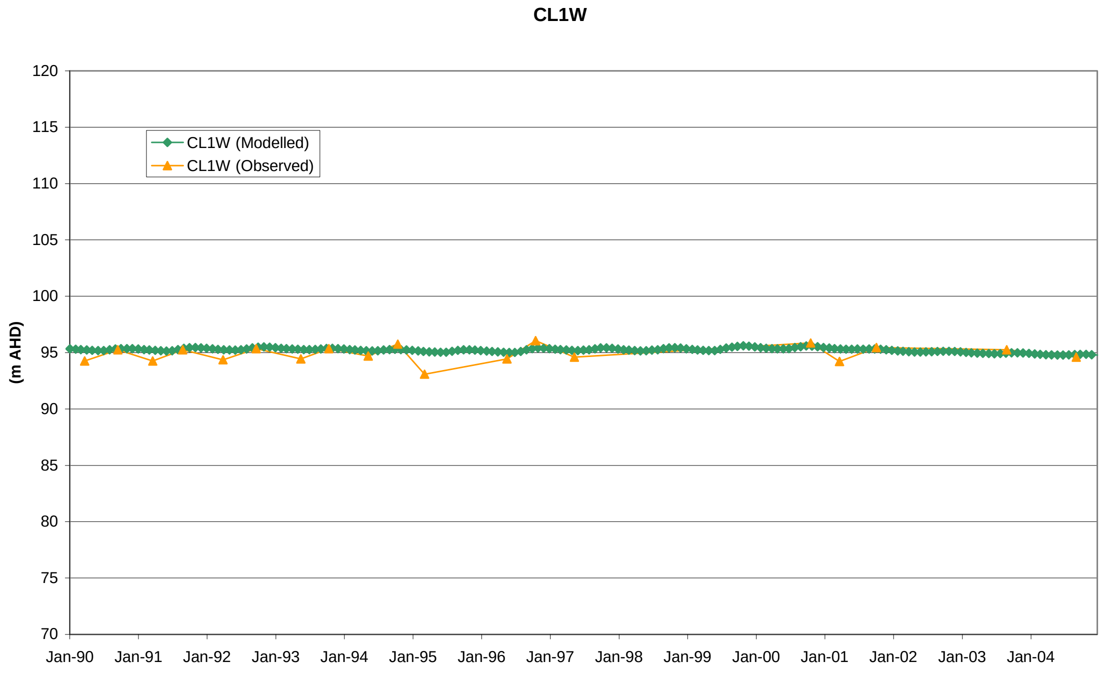
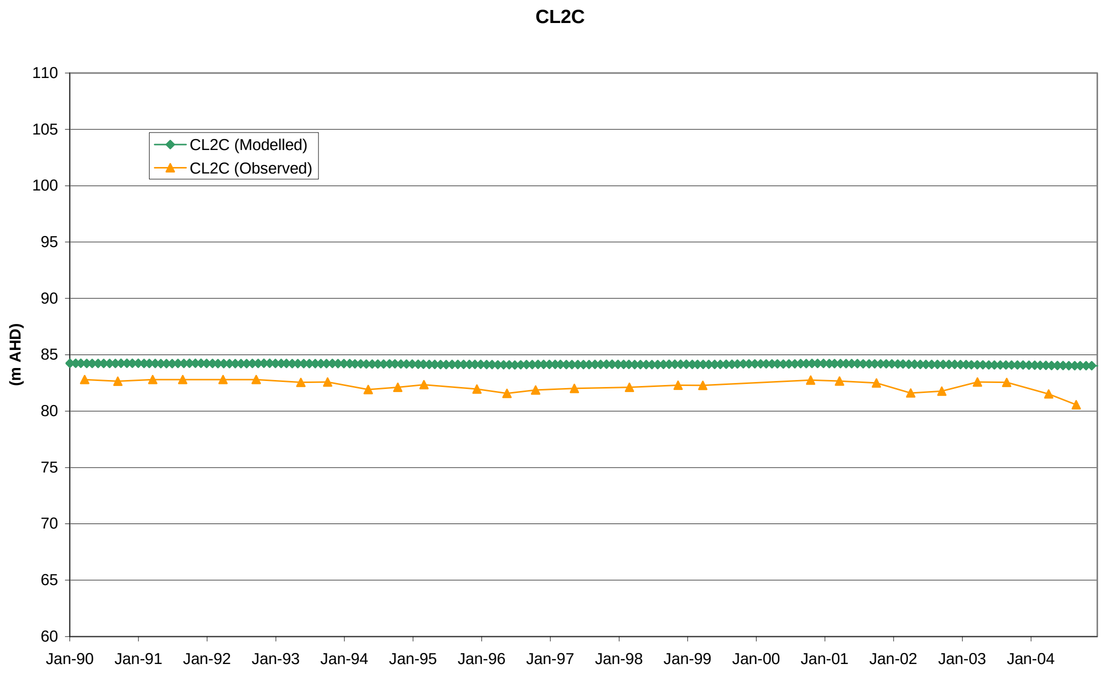
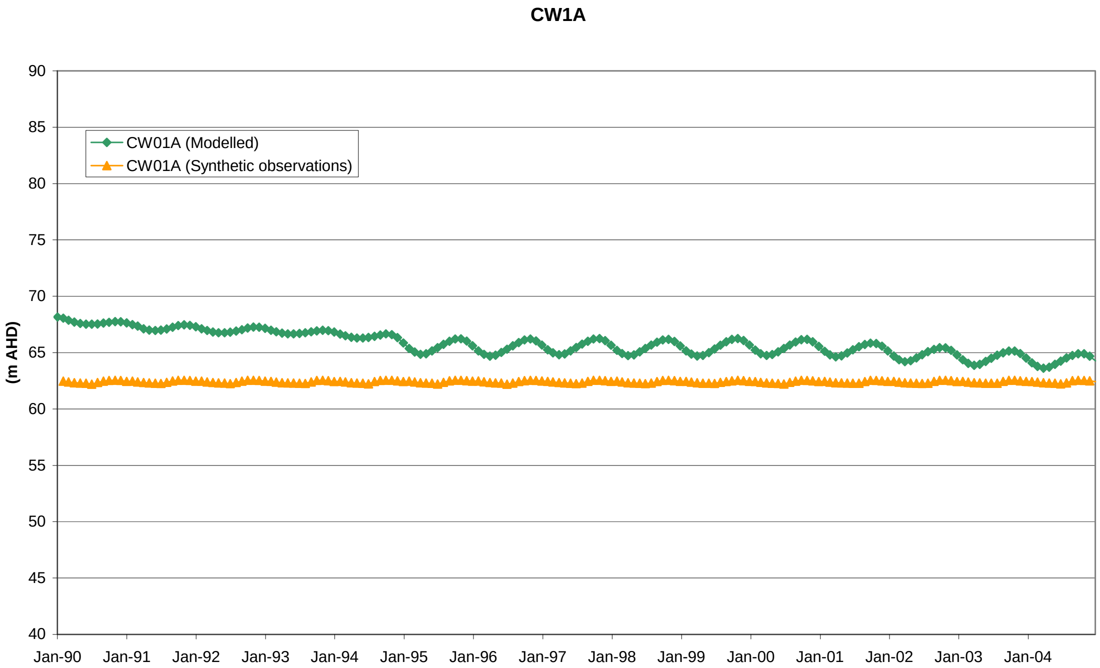
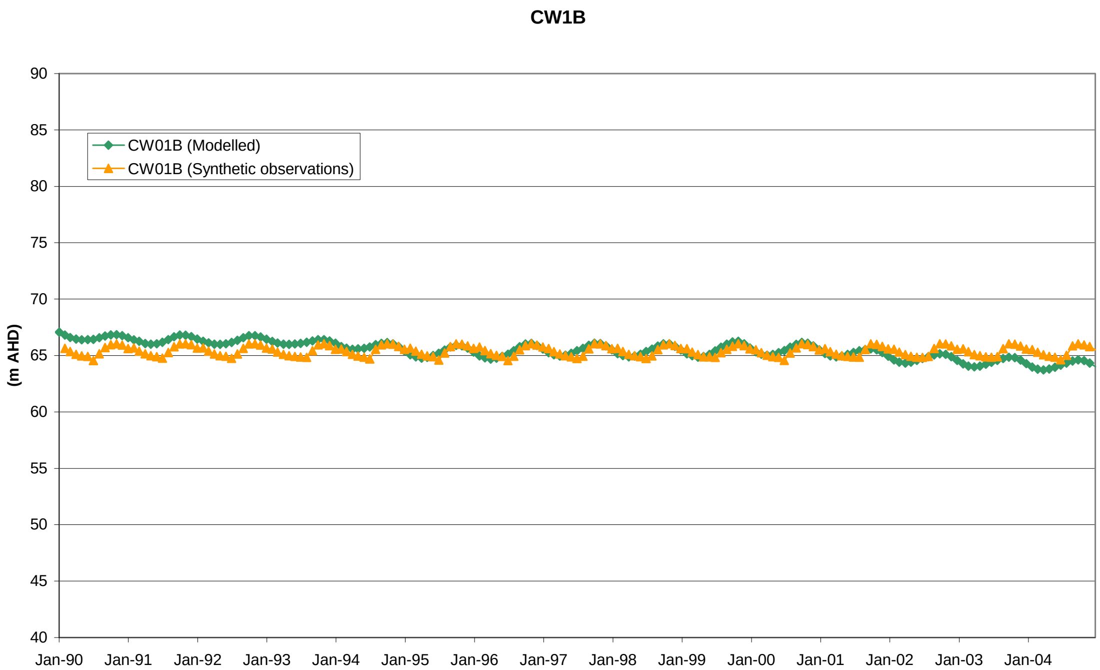
Jan-03
Jan-04

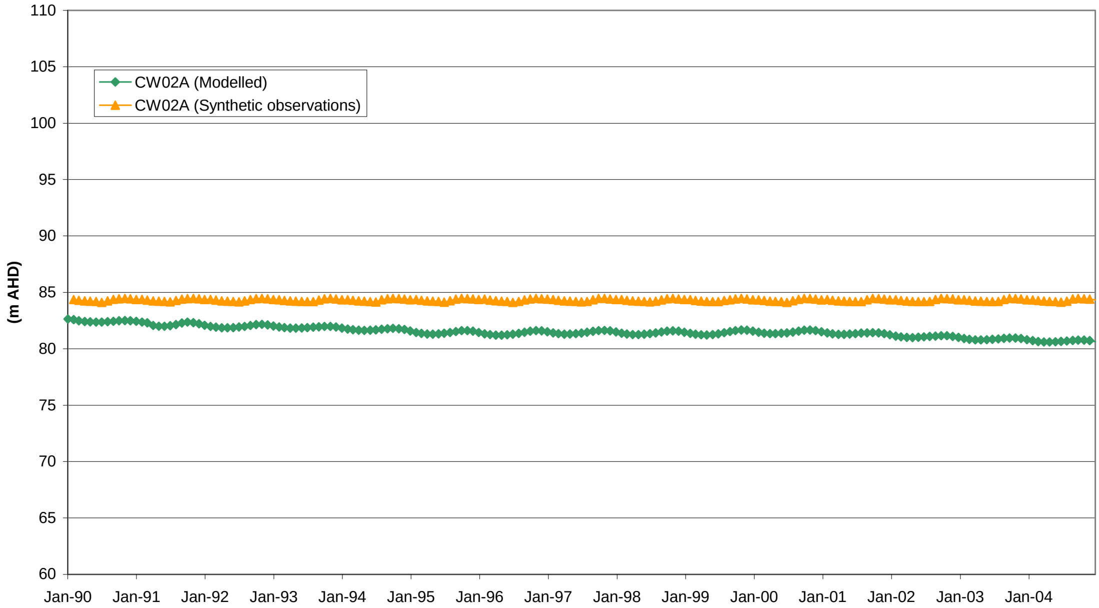

CL1W
120
115
110
105
100
95
90
85
80
75
70
(m AHD)
CL1W (Modelled)
CL1W (Observed)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


CL2C
110
105
100
95
90
85
80
75
70
65
60
(m AHD)
CL2C (Modelled)
CL2C (Observed)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

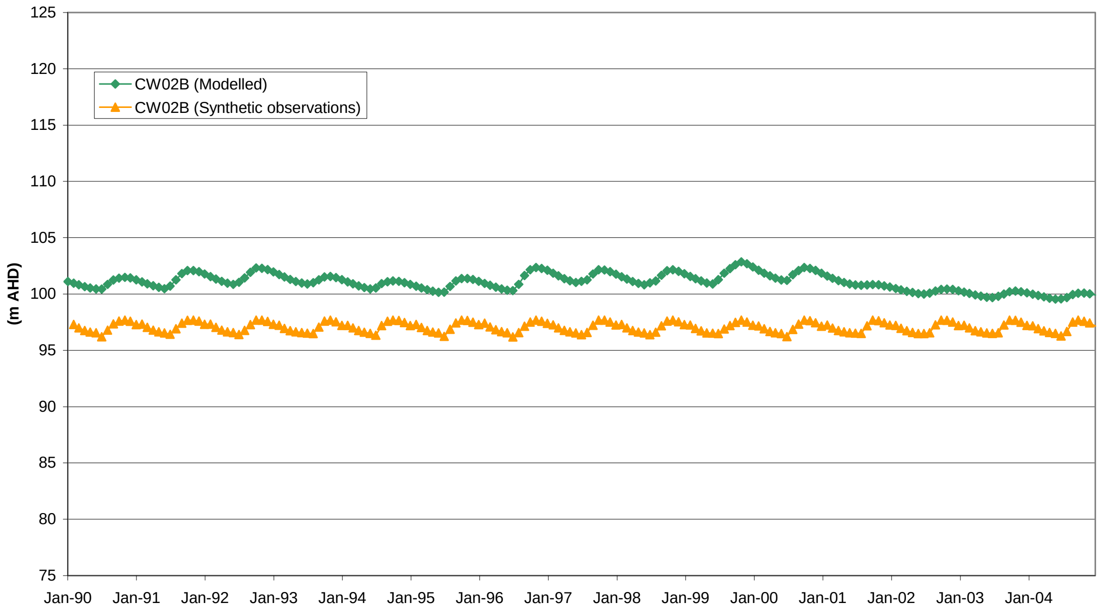

CW1A
90
85
80
75
70
65
60
55
50
45
40
(m AHD)
CW01A (Modelled)
CW01A (Synthetic observations)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

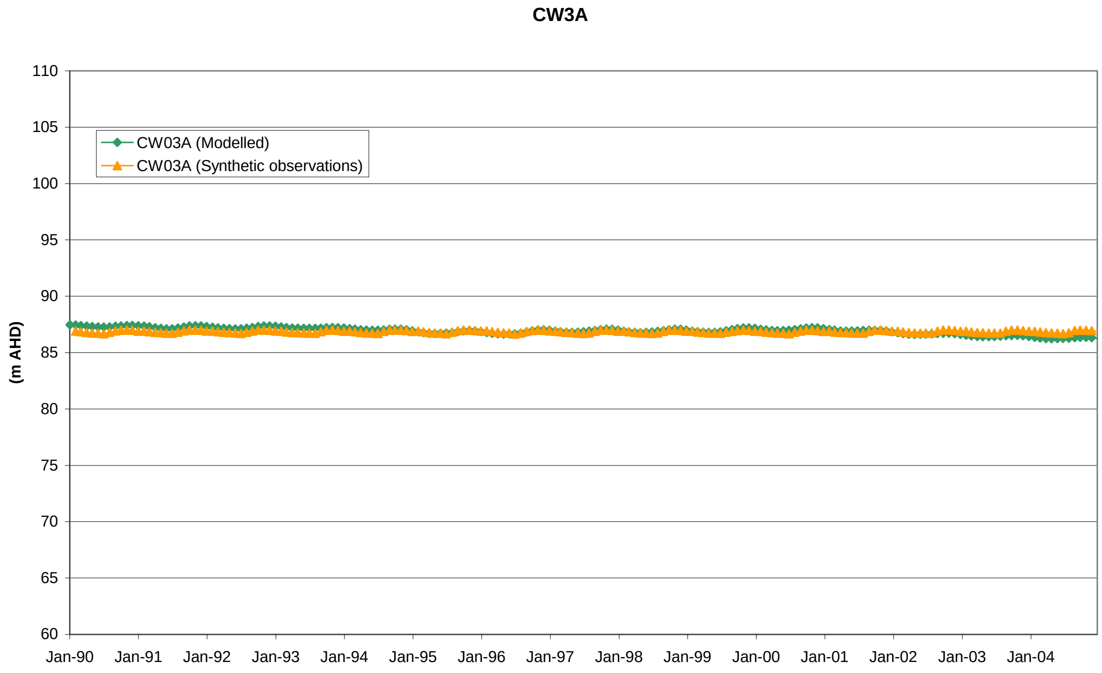

CW1B
90
85
80
75
70
65
60
55
50
45
40
(m AHD)
CW01B (Modelled)
CW01B (Synthetic observations)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

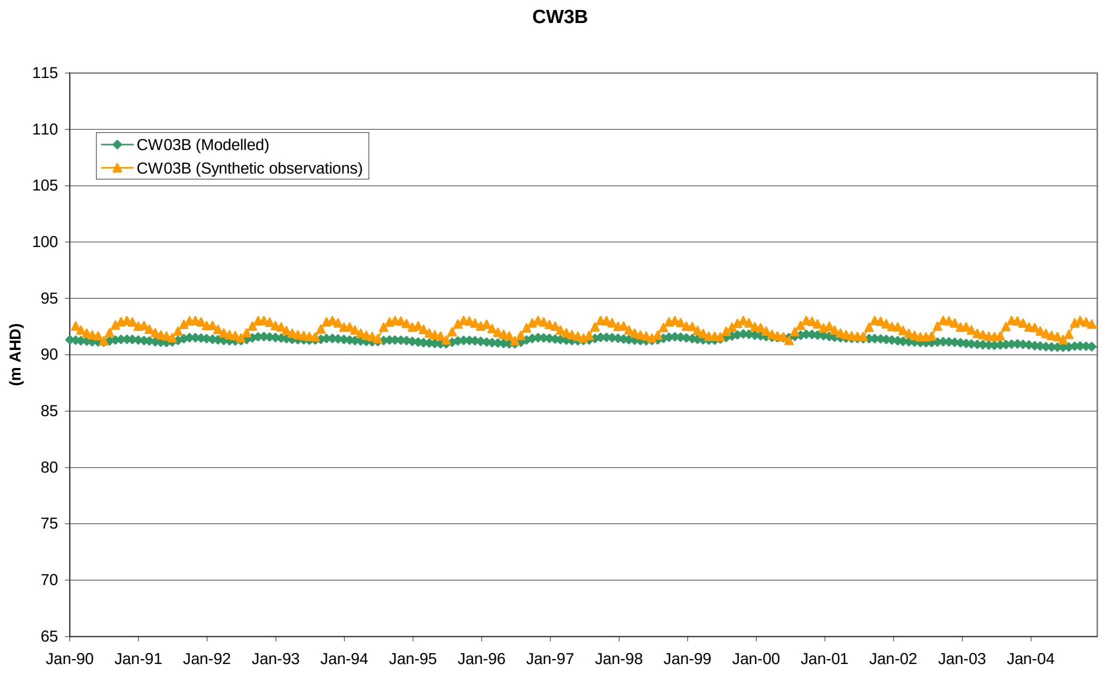
CW2A

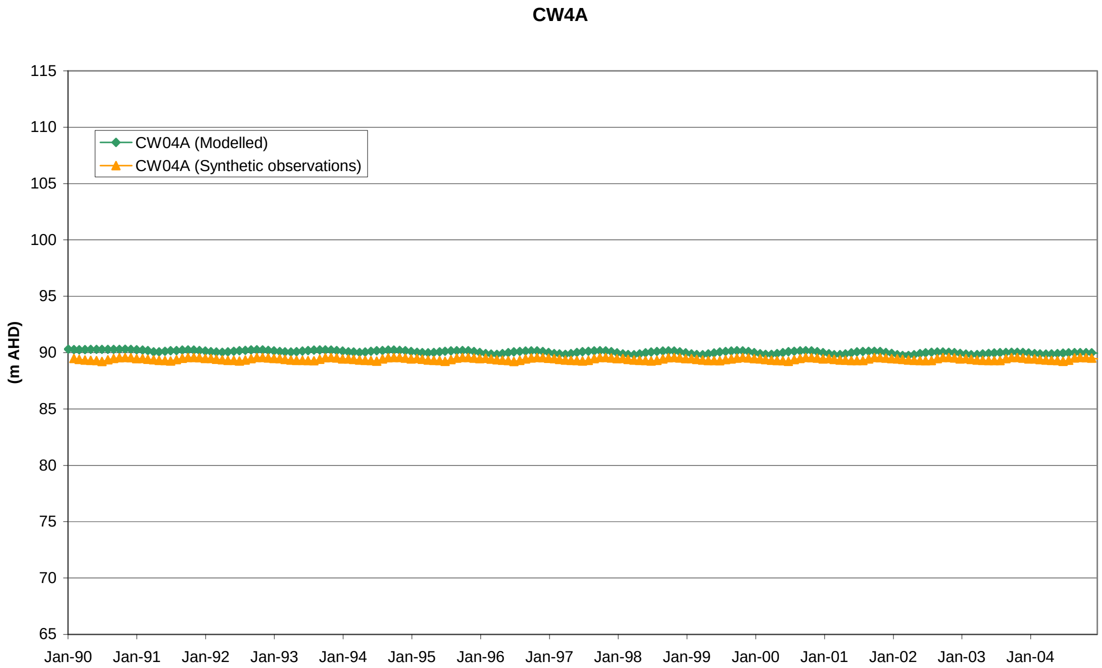

110
105
100
95
90
85
80
75
70
65
60
(m AHD)
CW02A (Modelled)
CW02A (Synthetic observations)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

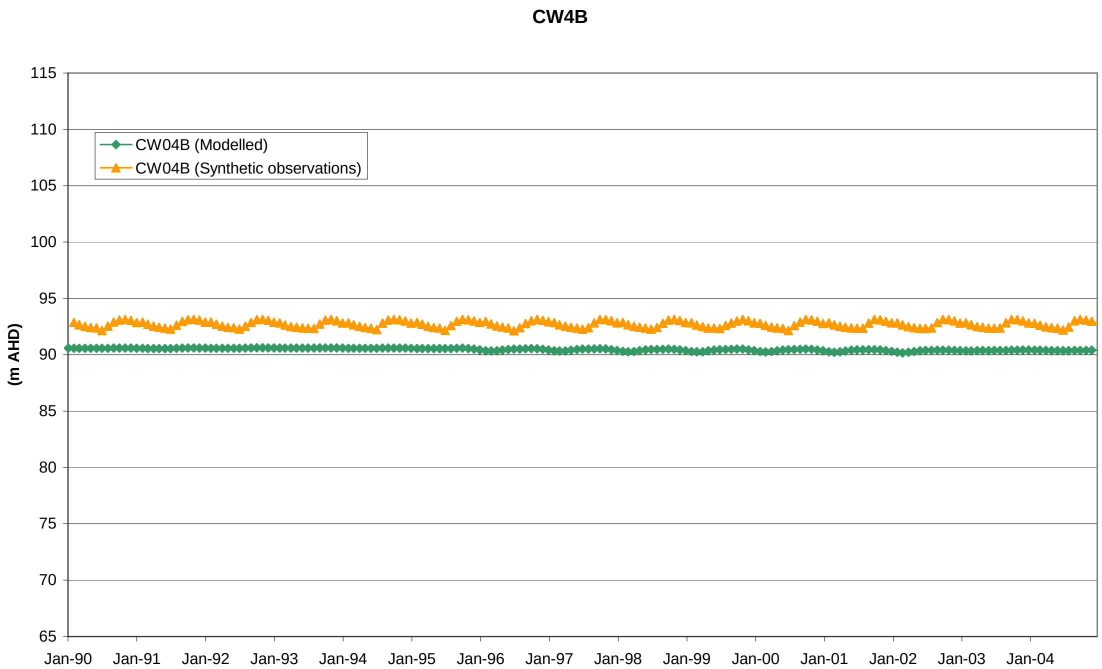
CW2B


125
120
115
110
105
100
95
90
85
80
75
(m AHD)
CW02B (Modelled)
CW02B (Synthetic observations)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


CW3A
CW03A (Modelled)
CW03A (Synthetic observations)
(m AHD)
110
105
100
95
90
85
80
75
70
65
60
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


CW3B
CW03B (Modelled)
CW03B (Synthetic observations)
(m AHD)
115
110
105
100
95
90
85
80
75
70
65
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


CW4A
(m AHD)
115
110
105
100
95
90
85
80
75
70
65
CW04A (Modelled)
CW04A (Synthetic observations)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


CW4B
(m AHD)
115
110
105
100
95
90
85
80
75
70
65
CW04B (Modelled)
CW04B (Synthetic observations)
Jan-90
Jan-91
Jan-92
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Jan-96
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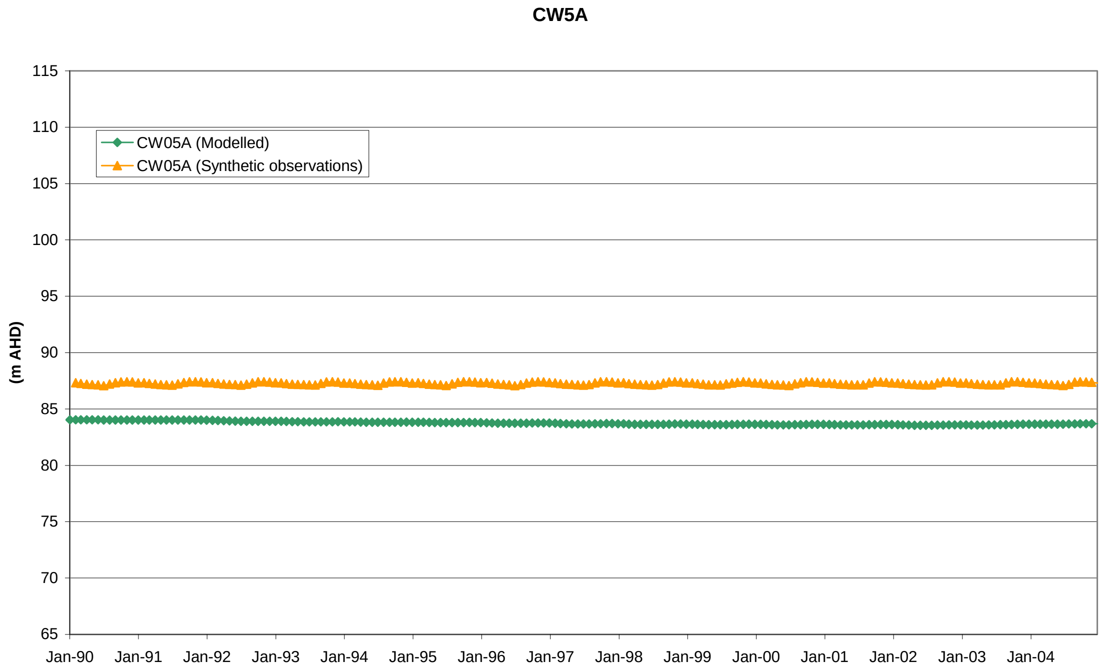
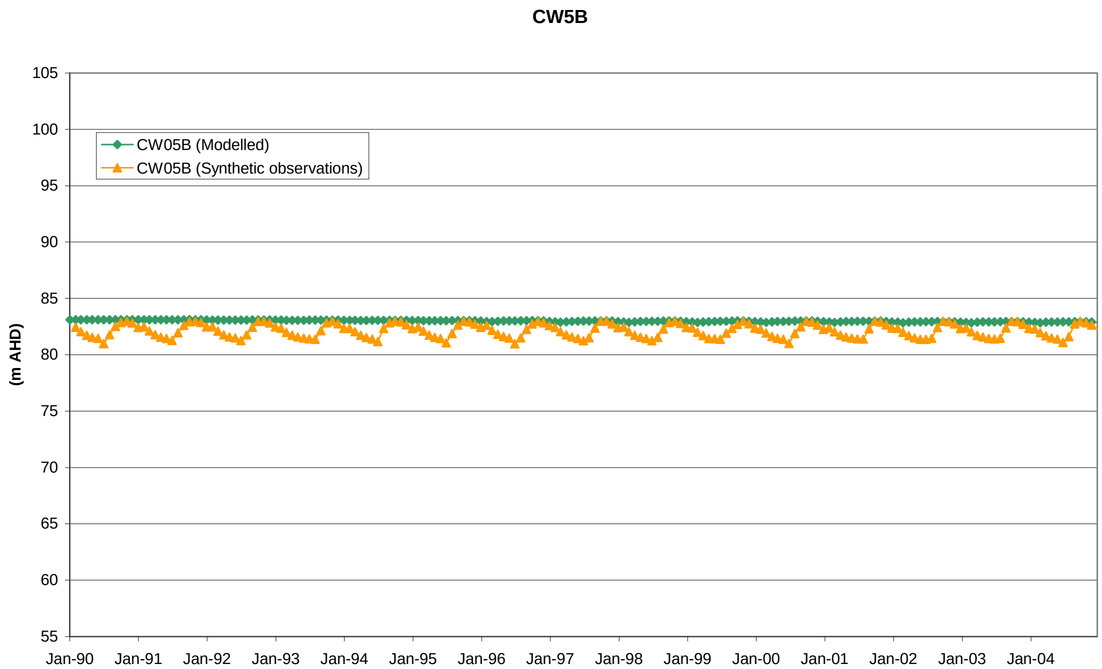
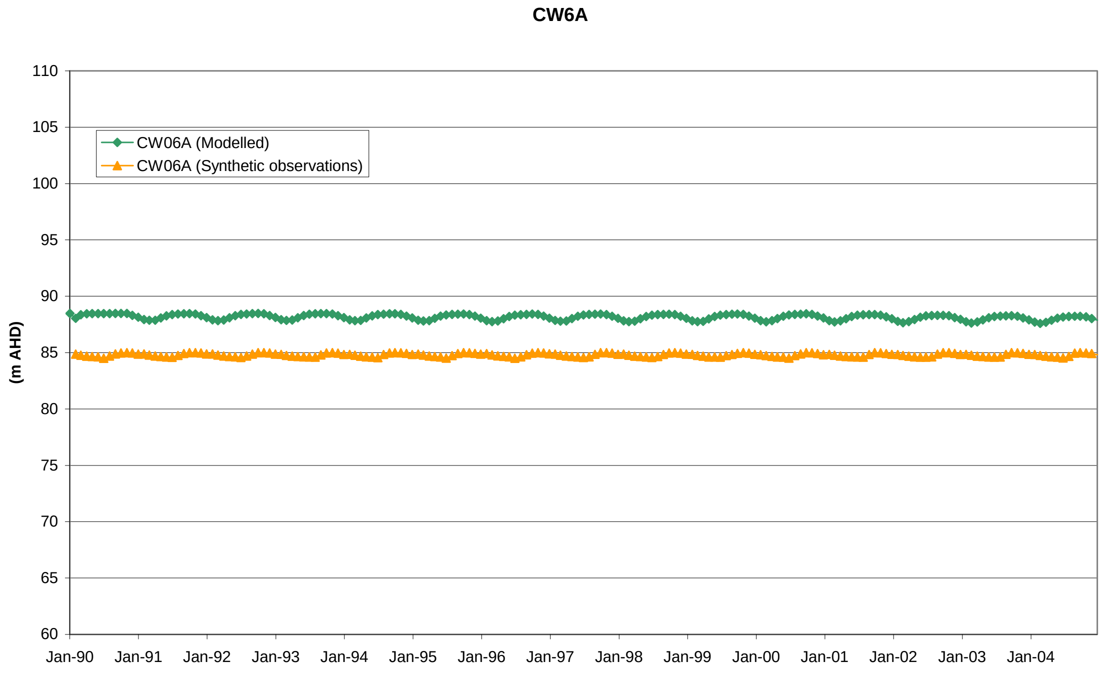
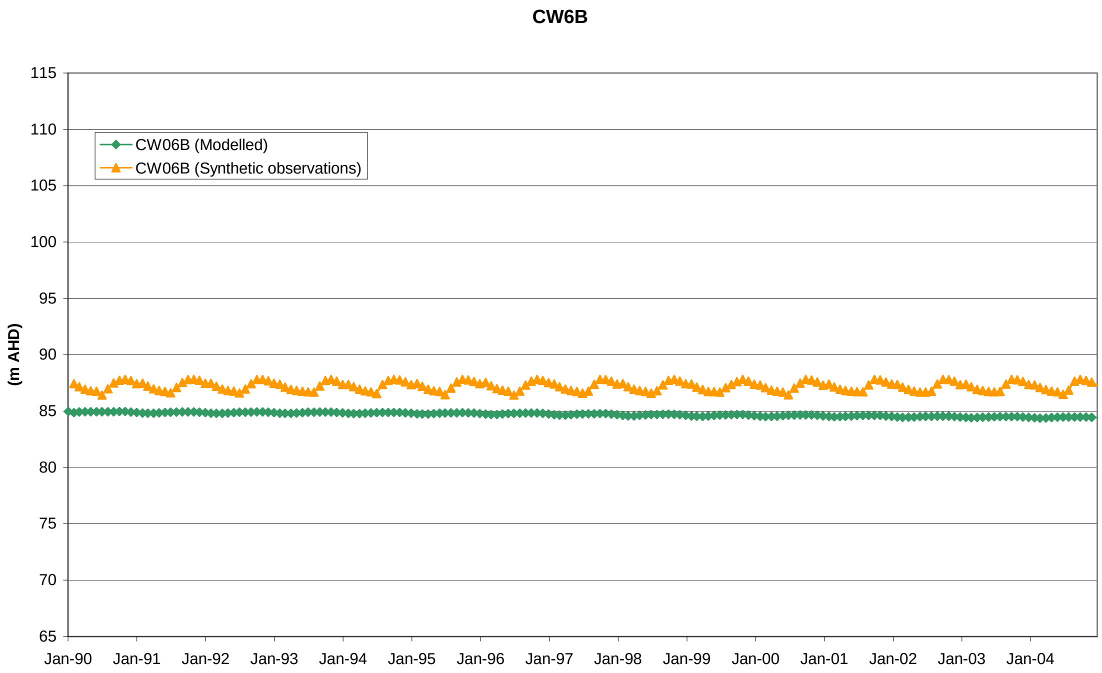
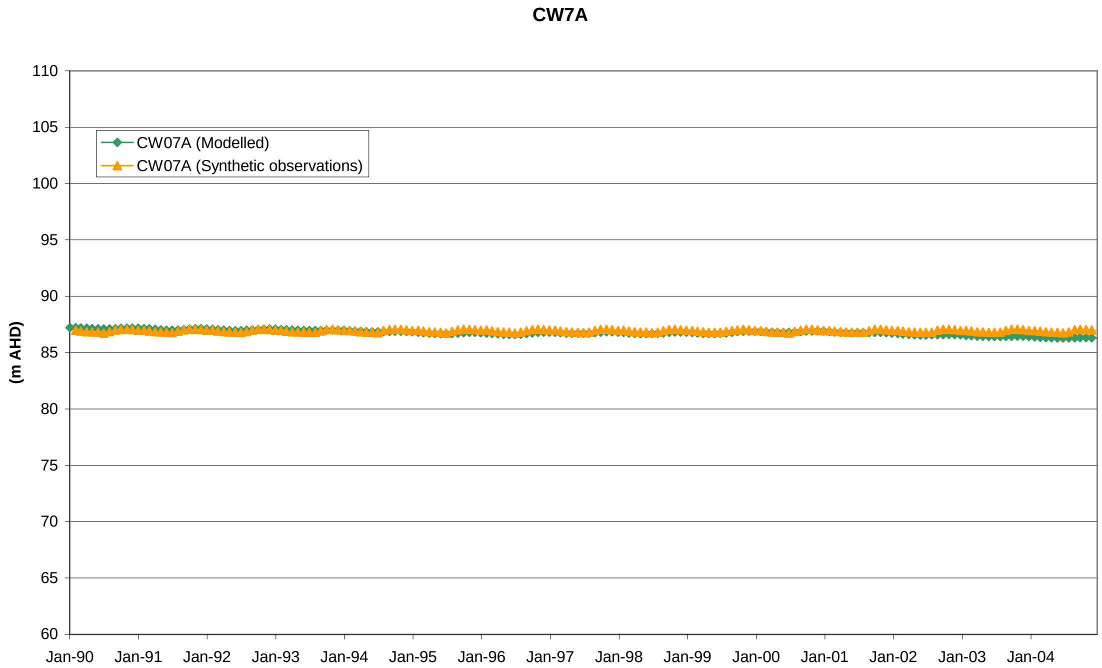
Jan-02
Jan-03
Jan-04

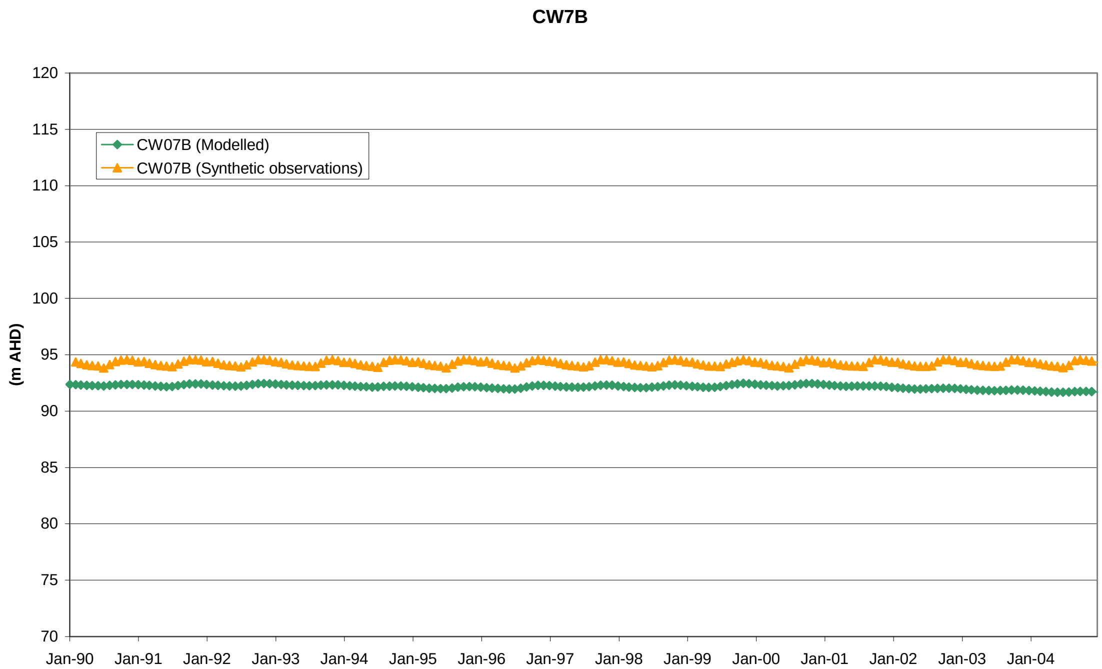

CW5A
CW05A (Modelled)
CW05A (Synthetic observations)
(m AHD)
115
110
105
100
95
90
85
80
75
70
65
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

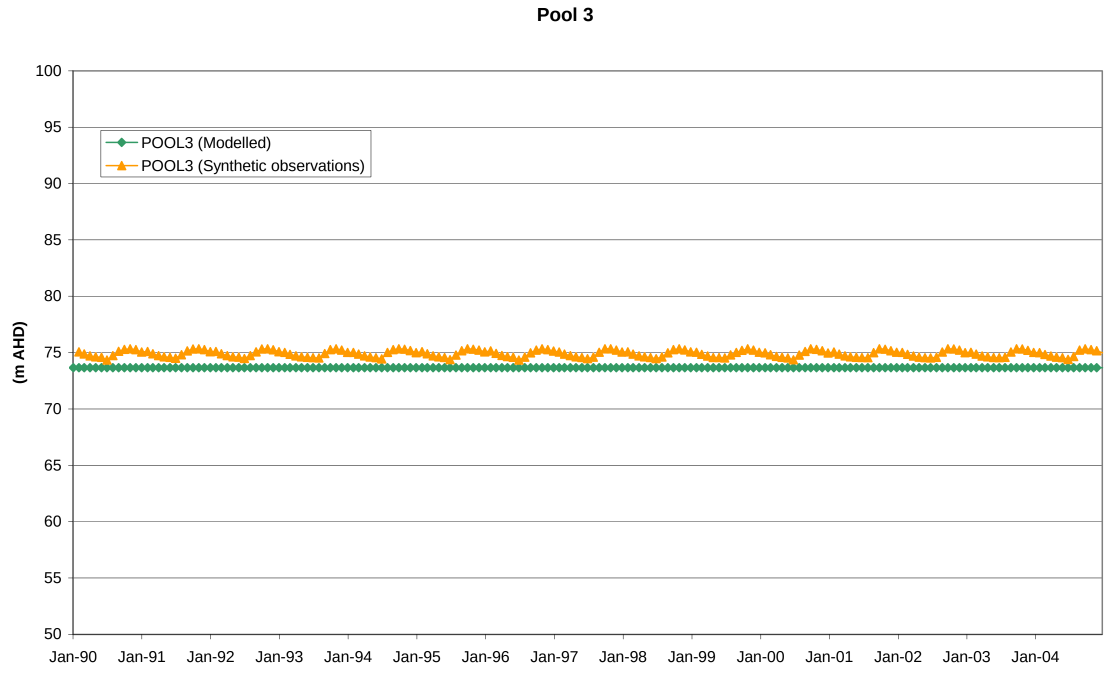

CW5B
CW05B (Modelled)
CW05B (Synthetic observations)
(m AHD)
105
100
95
90
85
80
75
70
65
60
55
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

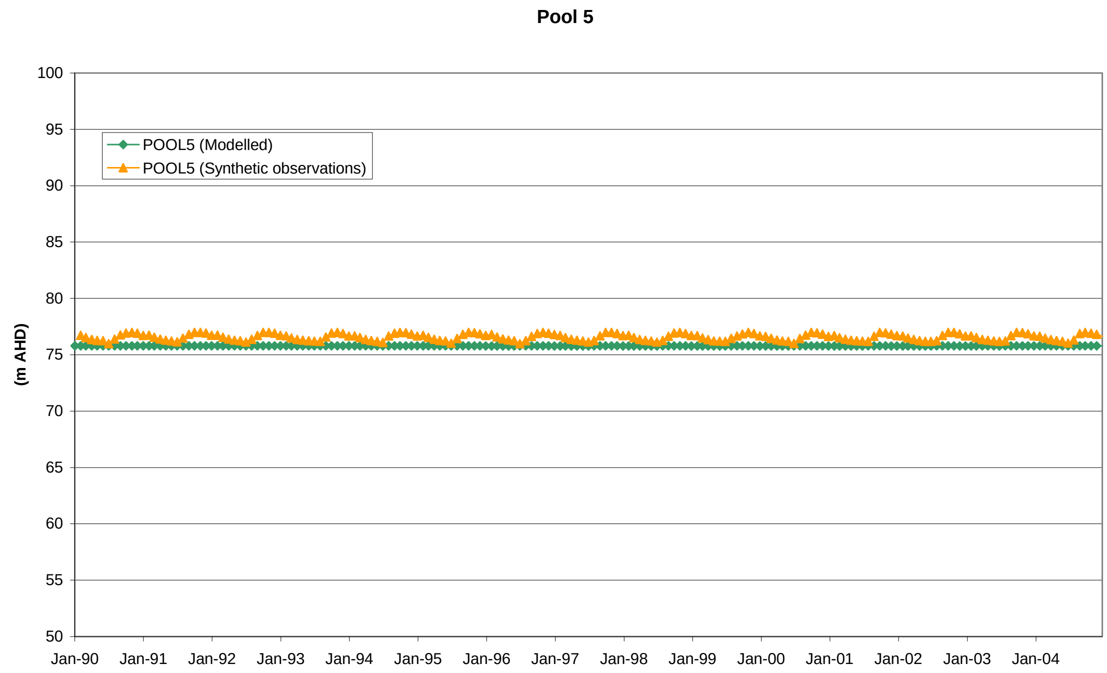

CW6A
(m AHD)
CW06A (Modelled)
CW06A (Synthetic observations)
110
105
100
95
90
85
80
75
70
65
60
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

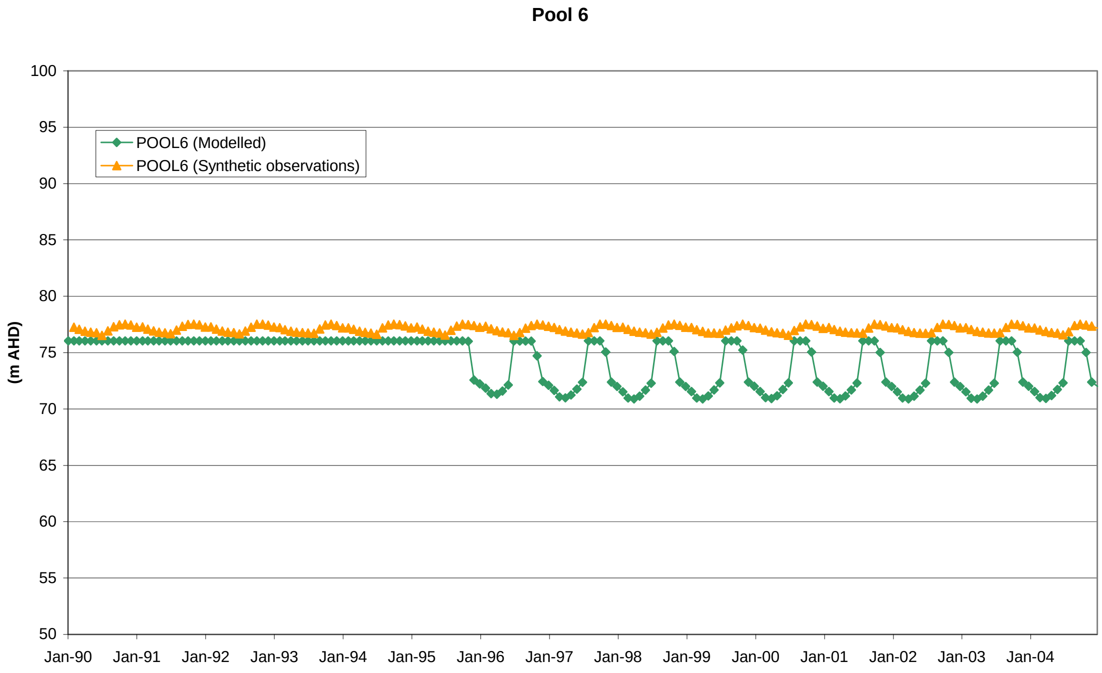

CW6B
(m AHD)
CW06B (Modelled)
CW06B (Synthetic observations)
115
110
105
100
95
90
85
80
75
70
65
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

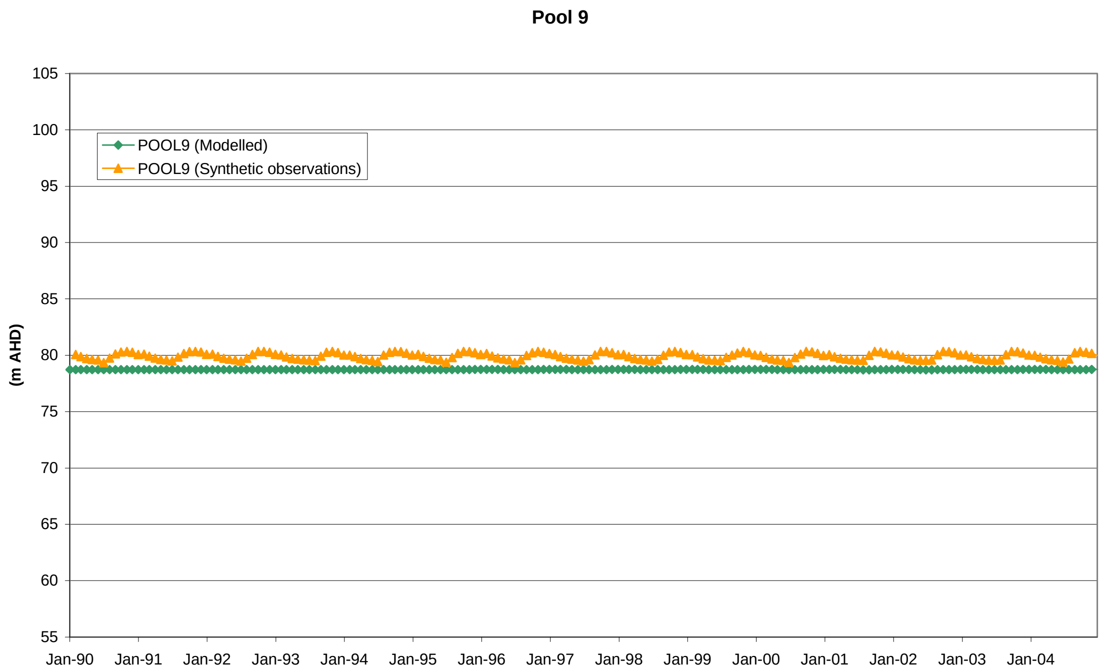

CW7A
(m AHD)
CW07A (Modelled)
CW07A (Synthetic observations)
110
105
100
95
90
85
80
75
70
65
60
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

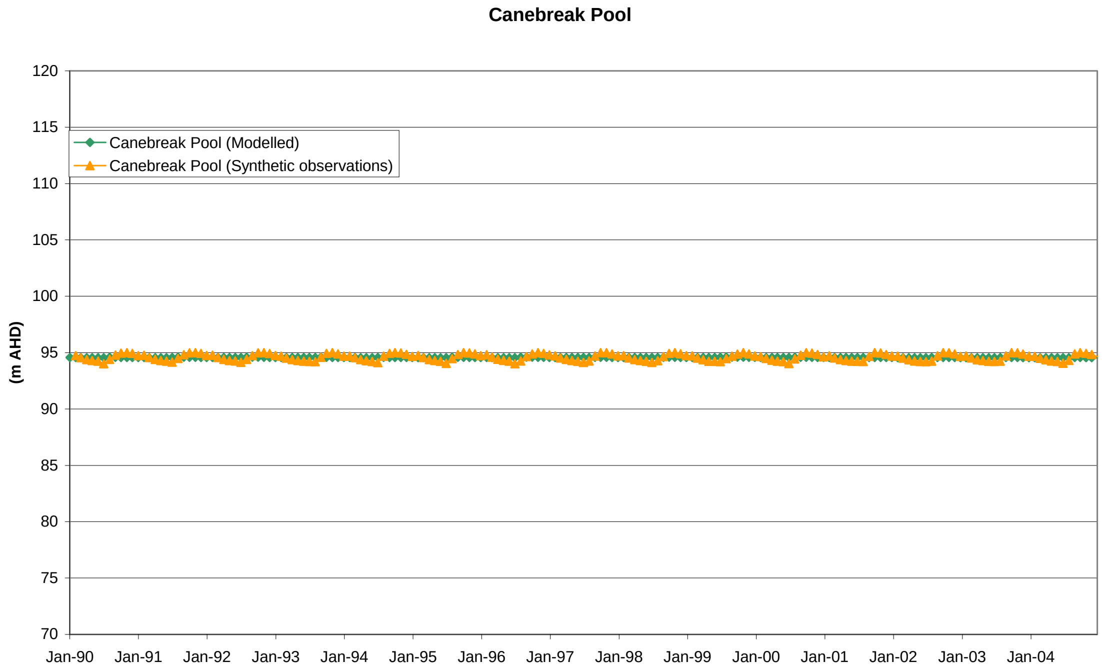

CW7B
(m AHD)
CW07B (Modelled)
CW07B (Synthetic observations)
120
115
110
105
100
95
90
85
80
75
70
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

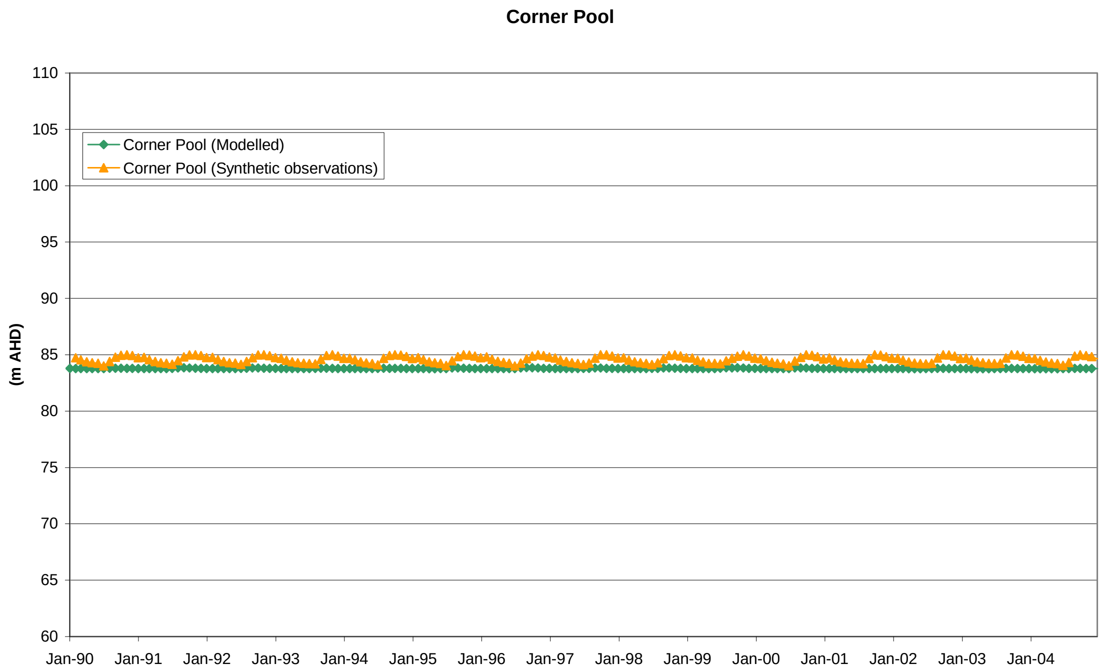

Pool 3
100
95
90
85
80
75
70
65
60
55
50
(m AHD)
POOL3 (Modelled)
POOL3 (Synthetic observations)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

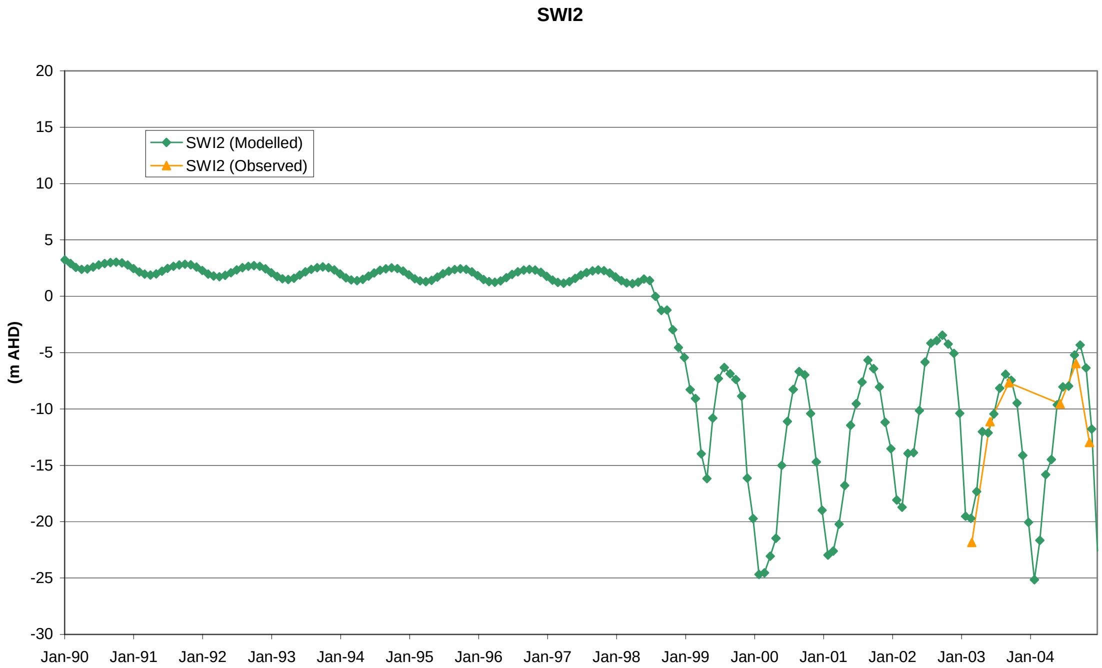

Pool 5
100
95
90
85
80
75
70
65
60
55
50
(m AHD)
POOL5 (Modelled)
POOL5 (Synthetic observations)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


Pool 6
(m AHD)
100
95
90
85
80
75
70
65
60
55
50
POOL6 (Modelled)
POOL6 (Synthetic observations)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


Pool 9
(m AHD)
105
100
95
90
85
80
75
70
65
60
55
POOL9 (Modelled)
POOL9 (Synthetic observations)
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


Canebreak Pool
Canebreak Pool (Modelled)
Canebreak Pool (Synthetic observations)
(m AHD)
120
115
110
105
100
95
90
85
80
75
70
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


Corner Pool
Corner Pool (Modelled)
Corner Pool (Synthetic observations)
(m AHD)
110
105
100
95
90
85
80
75
70
65
60
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04


SWI2
SWI2 (Modelled)
SWI2 (Observed)
(m AHD)
20
15
10
5
0
-5
-10
-15
-20
-25
-30
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
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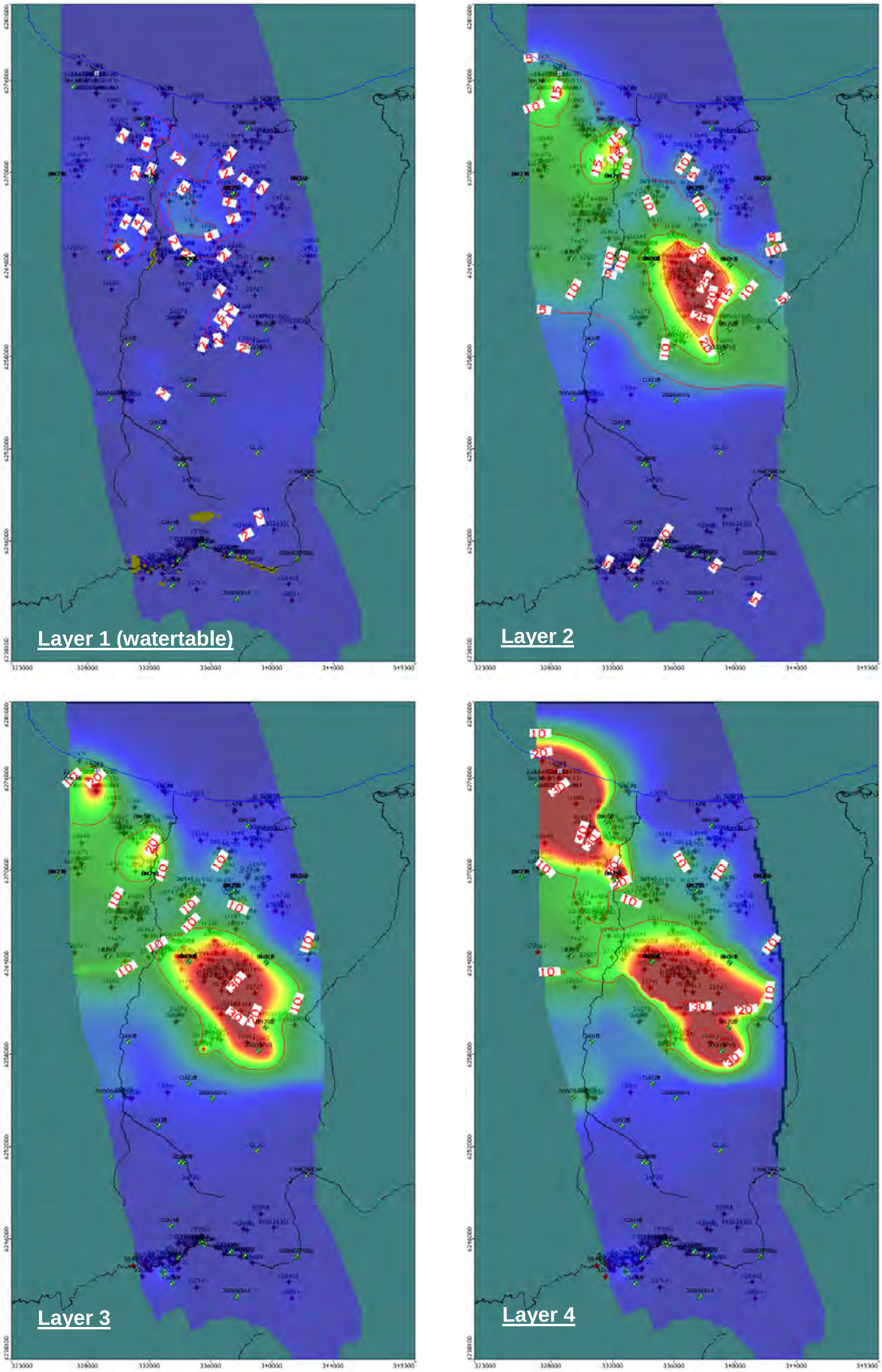
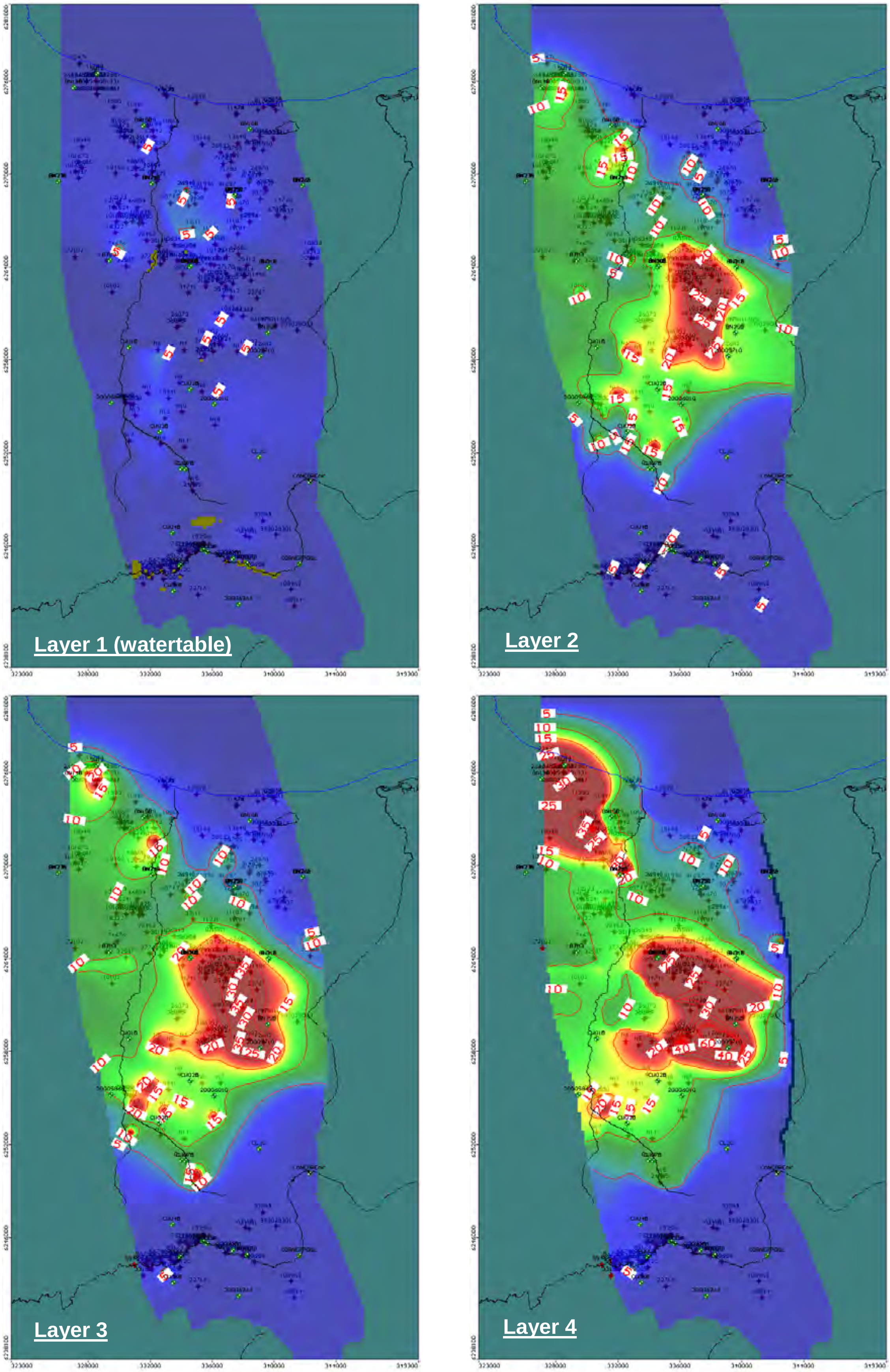
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

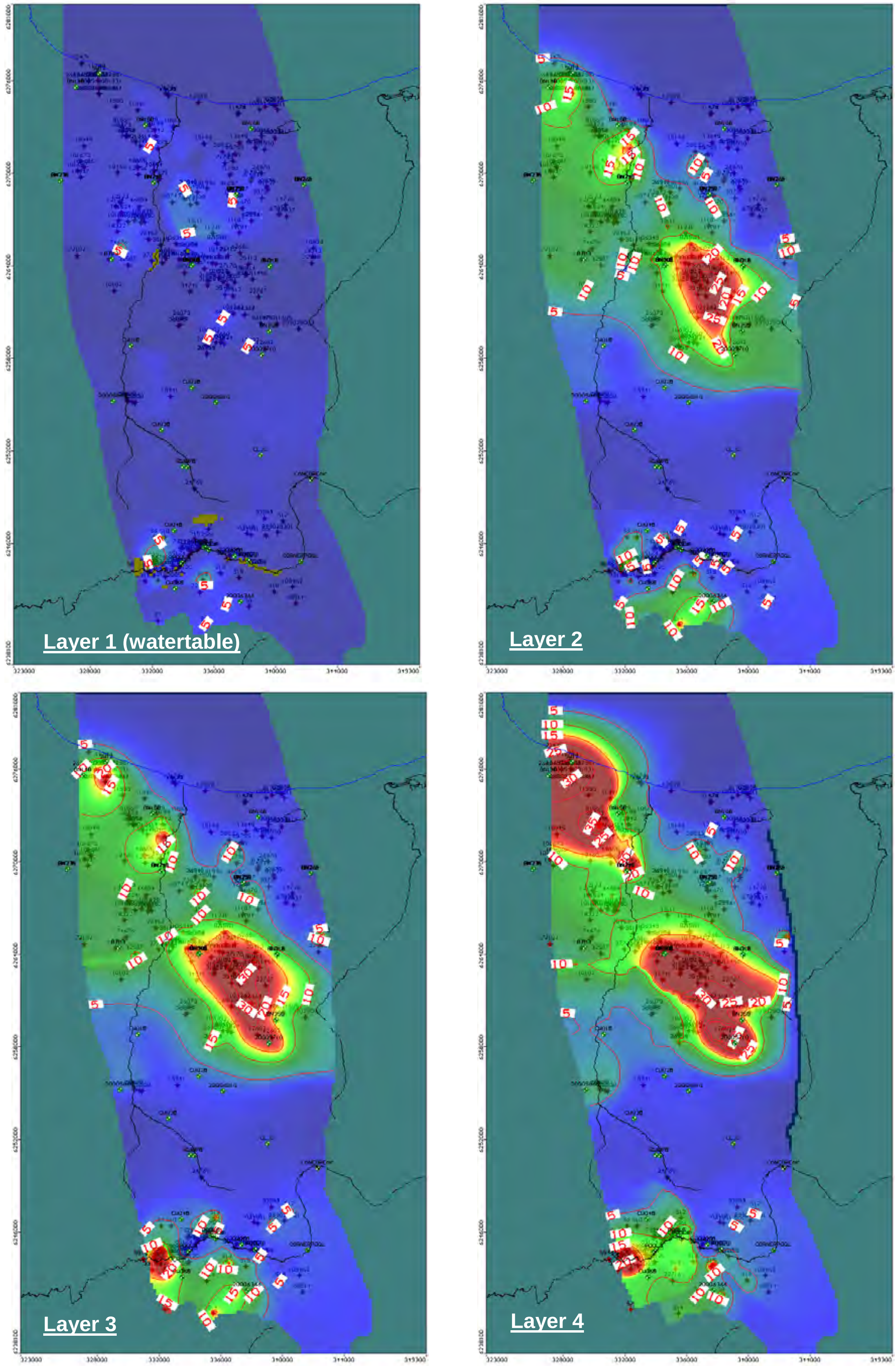
Appendix G — Summer drawdown to 2020 for each scenario



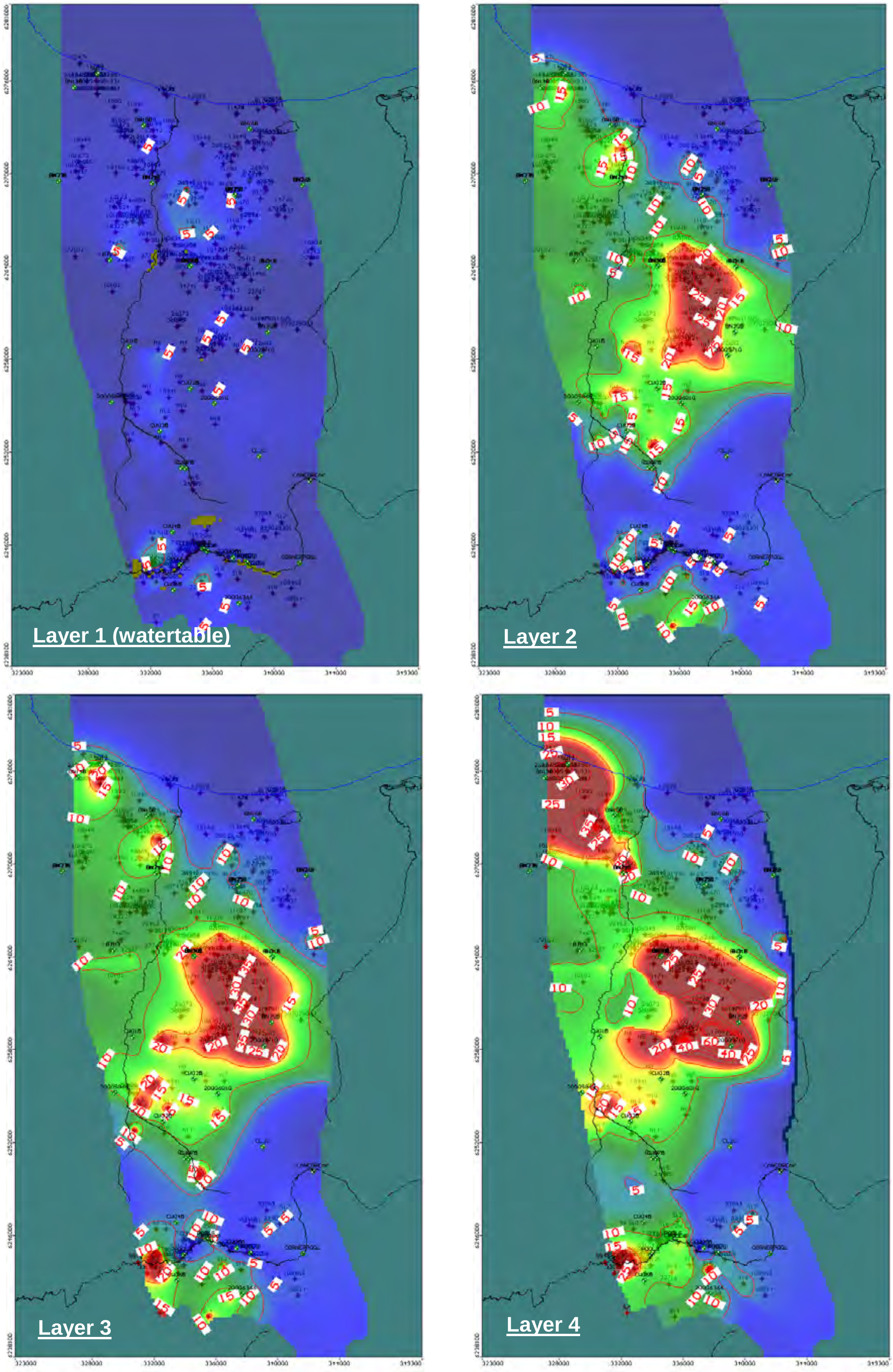
Appendix G1 Scenario 1 (base case)



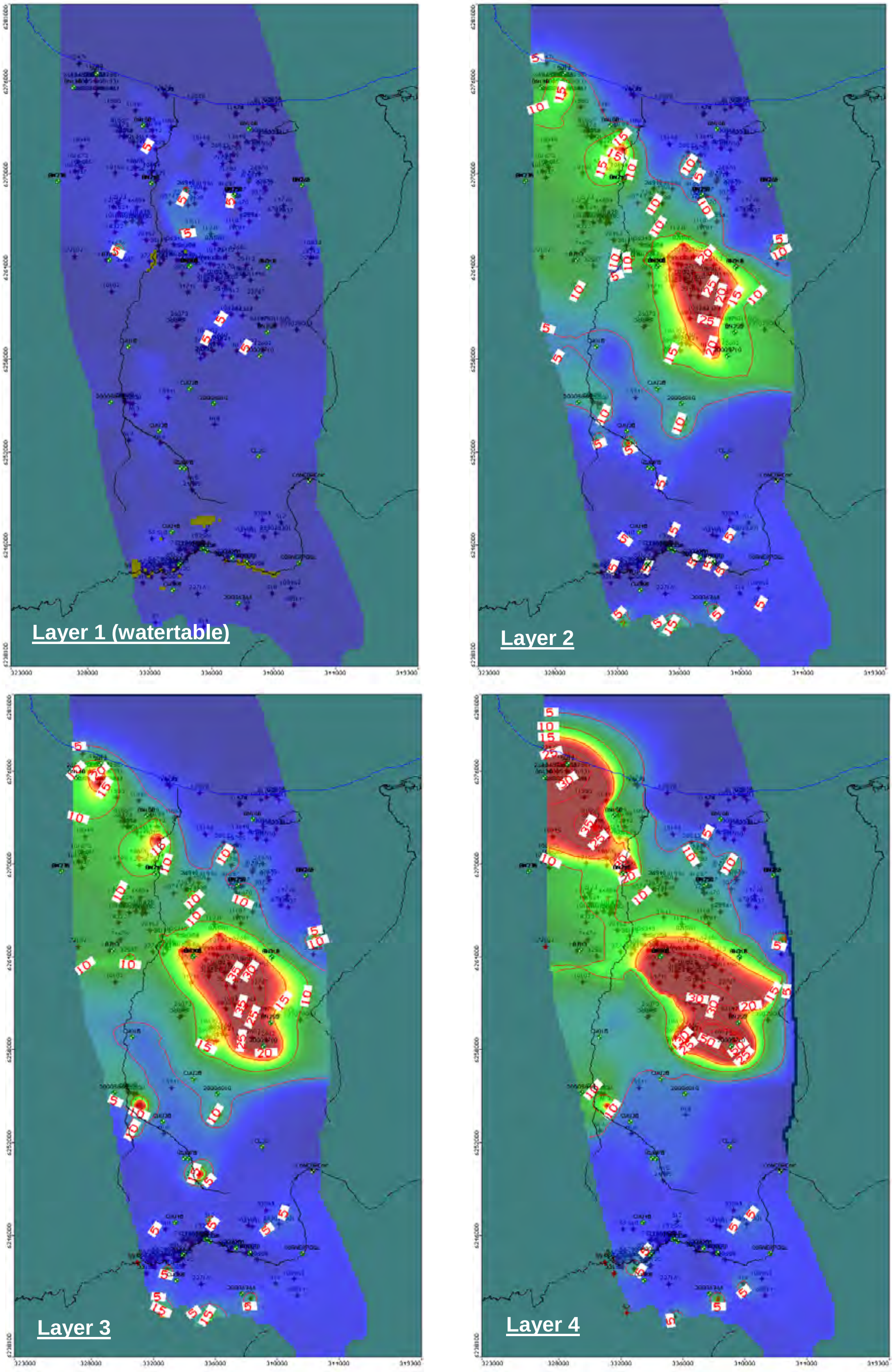
Appendix G2 Scenario 2 (northern case)



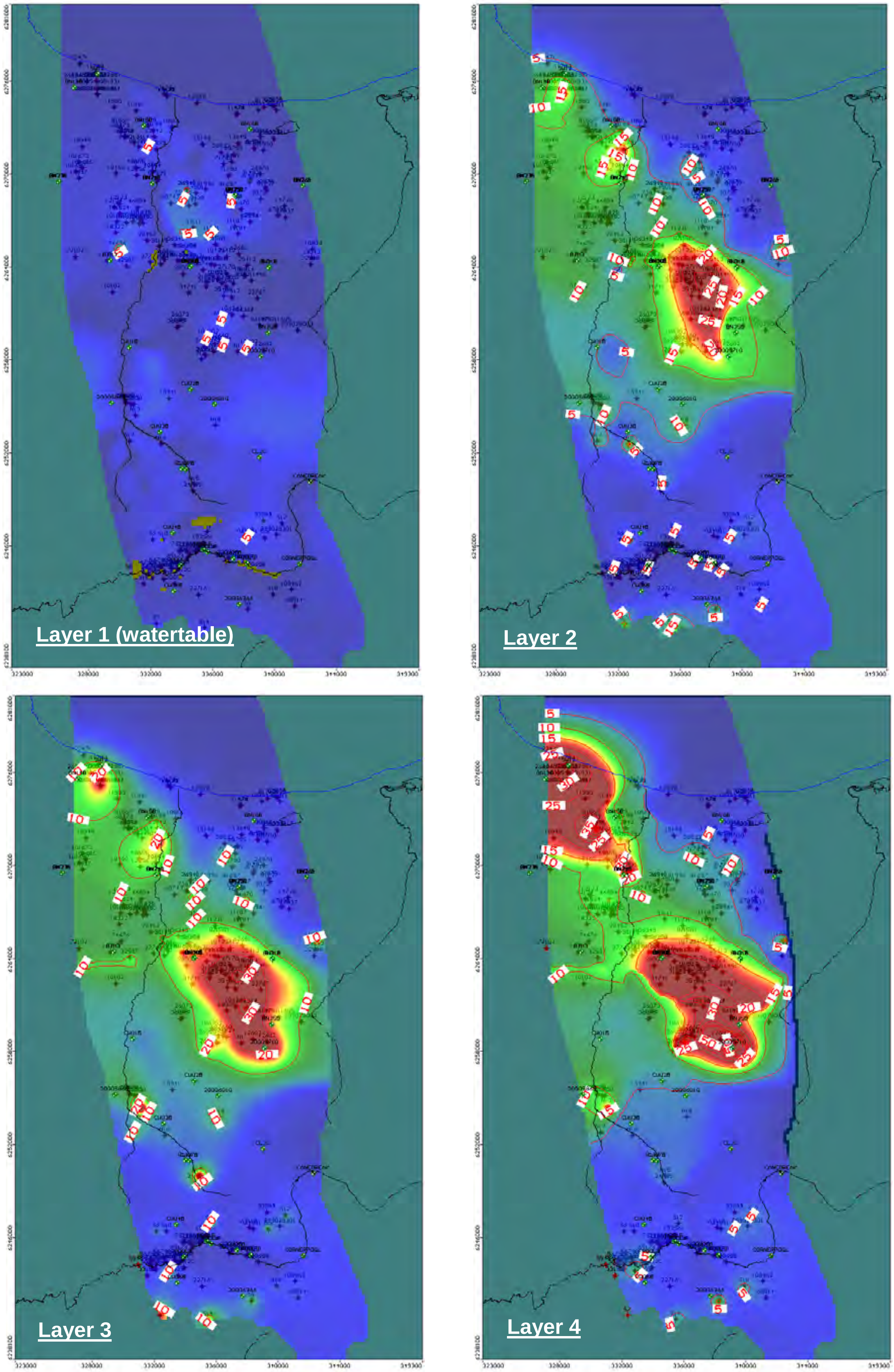
Appendix G3 Scenario 3 (southern case)



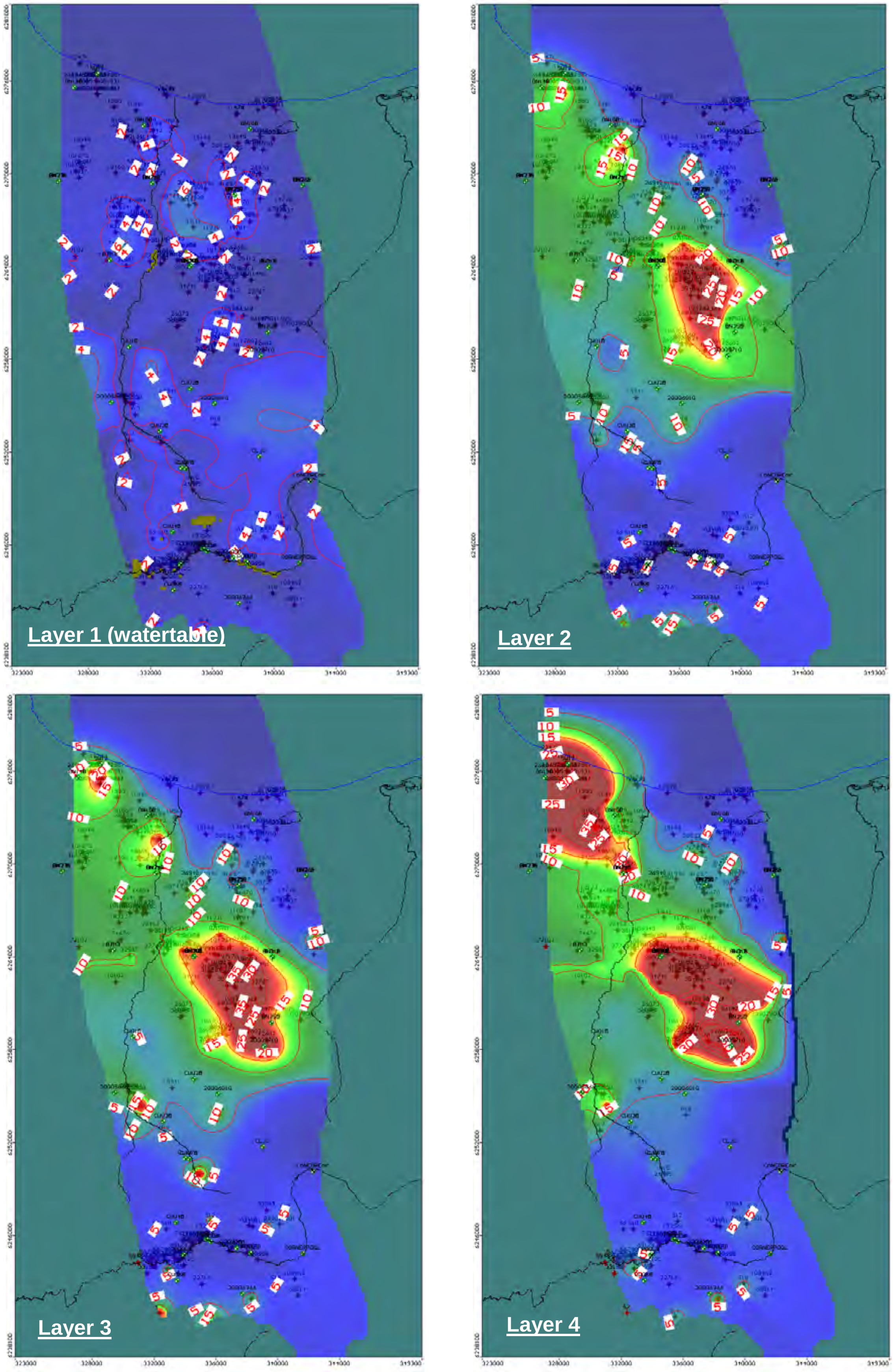
Appendix G4 Scenario 4 (combined case)



Appendix G5 Scenario 5 (climate 1 case)

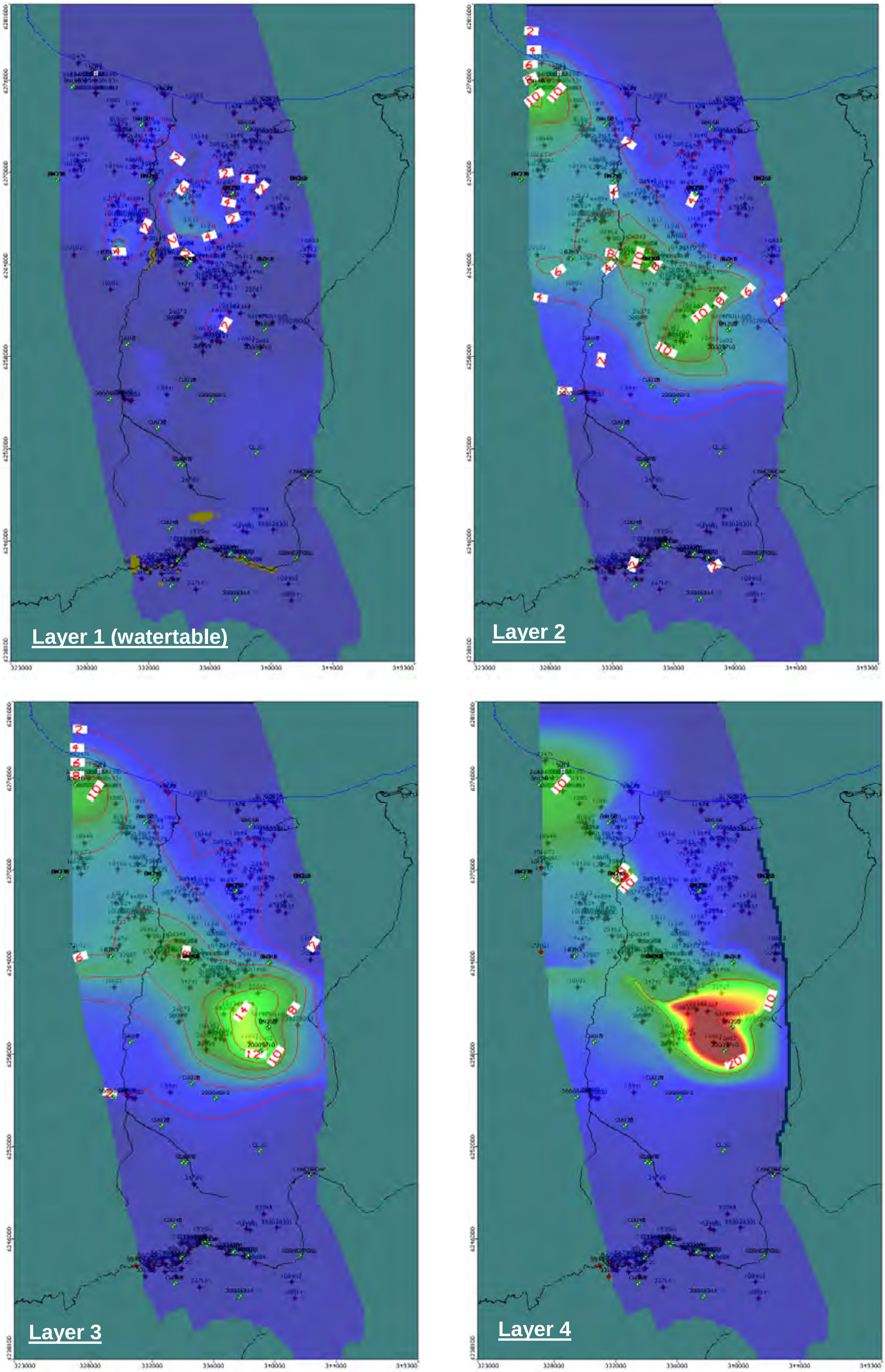


Appendix G6 Scenario 6 (climate 2 case)

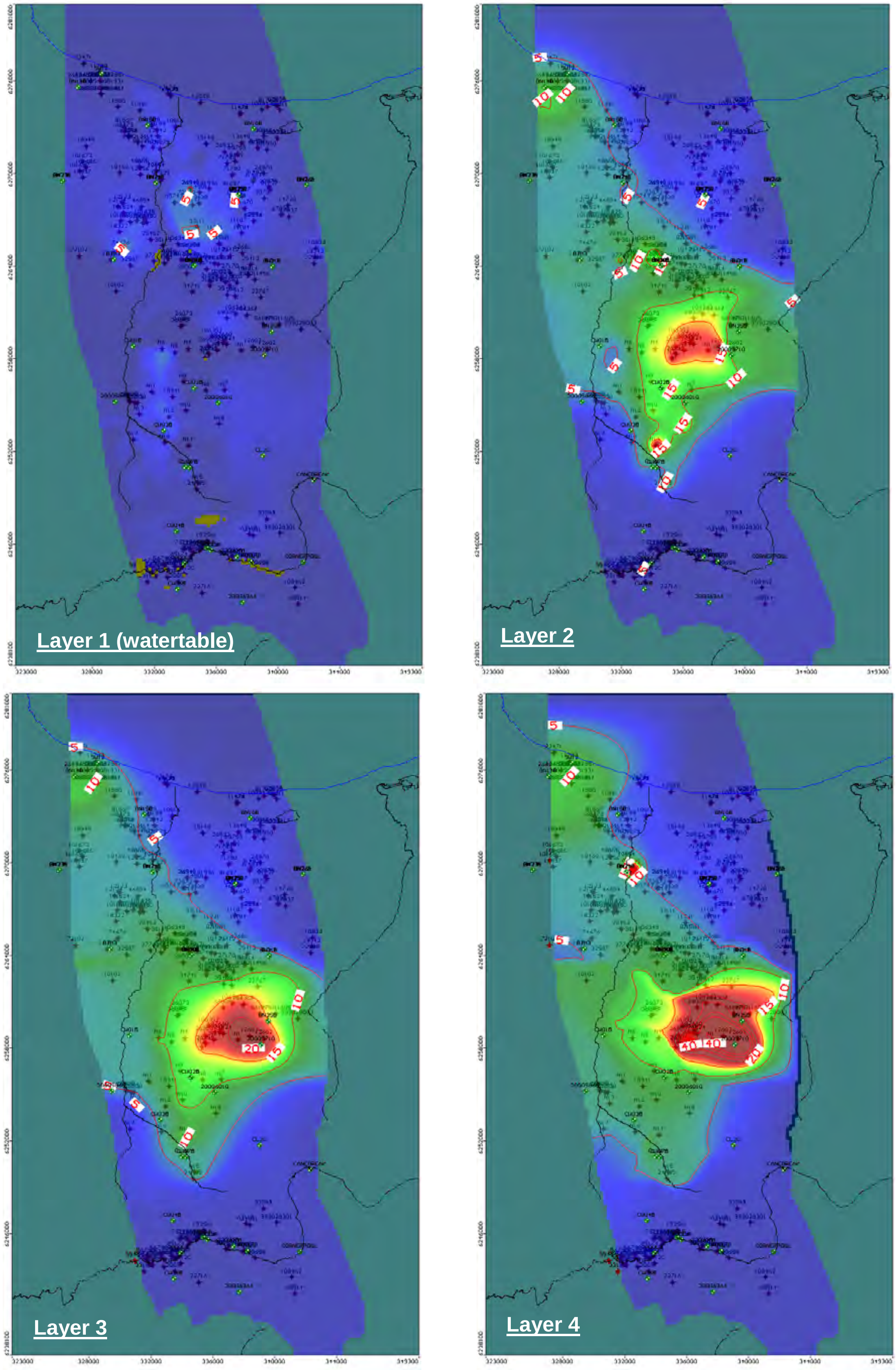


Appendix G7 Scenario 7 (climate 3 case)

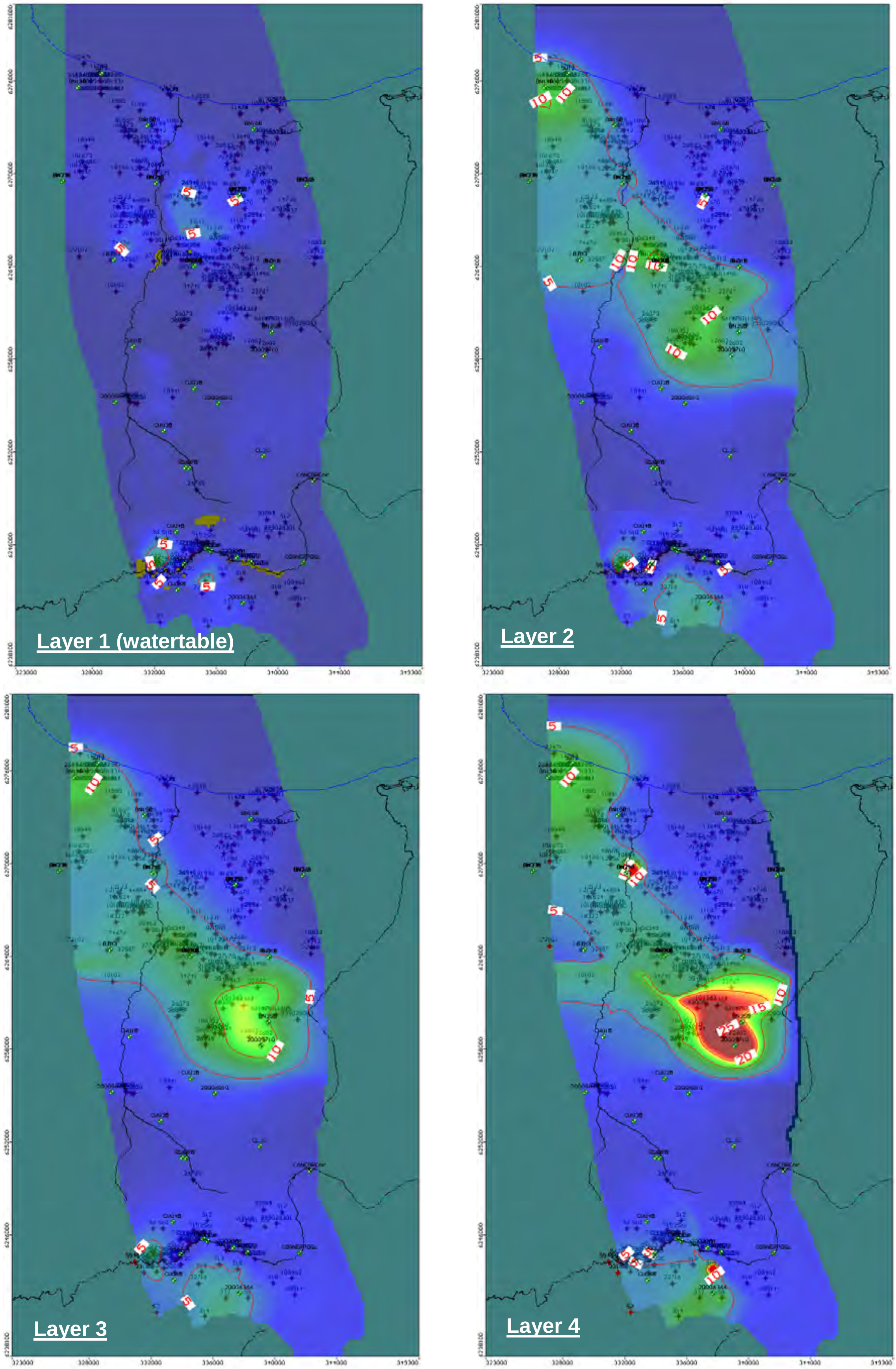
Appendix H — Residual winter drawdown to 2020 for each scenario



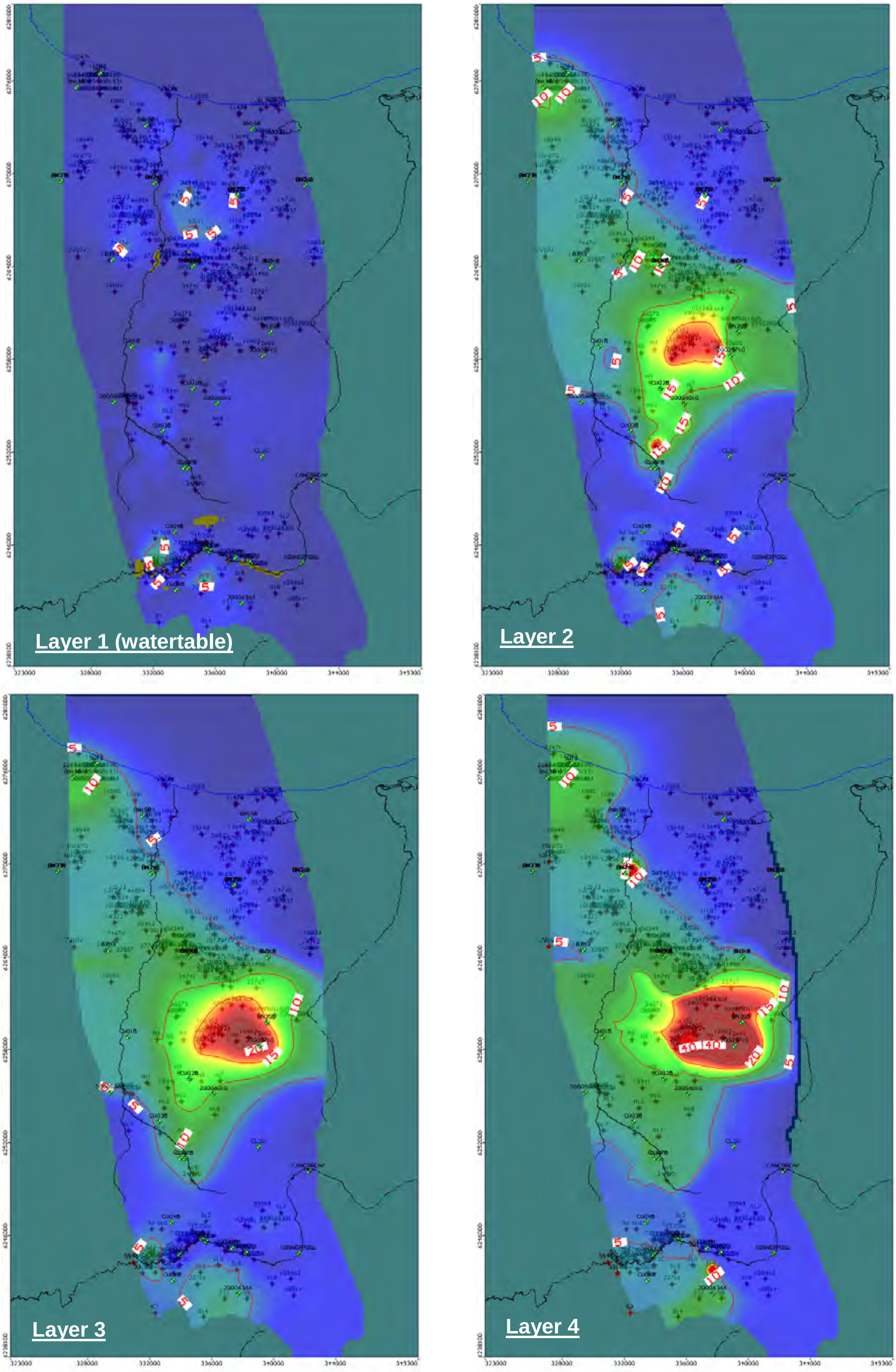
Appendix H1 Scenario 1 (base case)



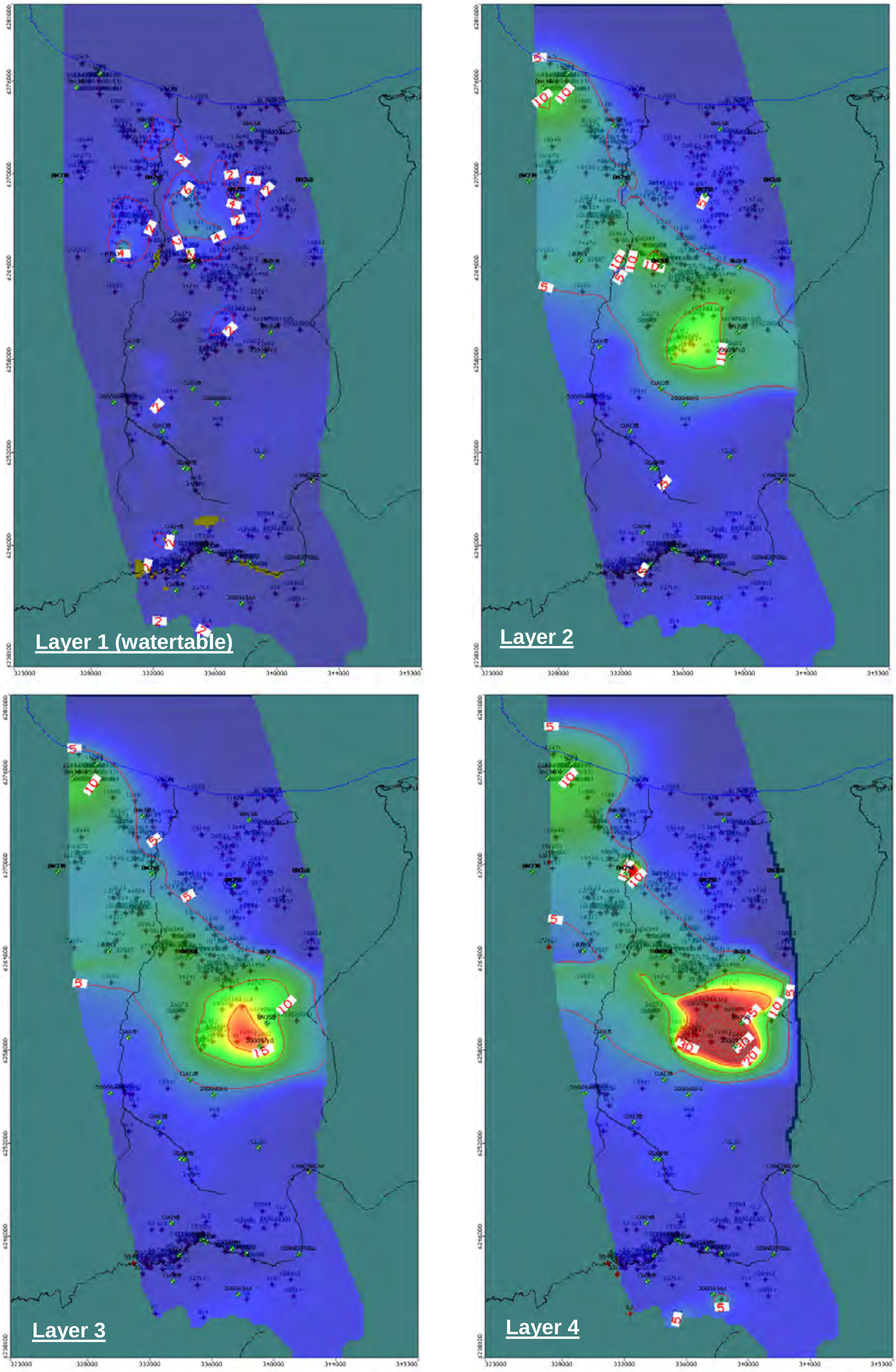
Appendix H2 Scenario 2 (northern case)



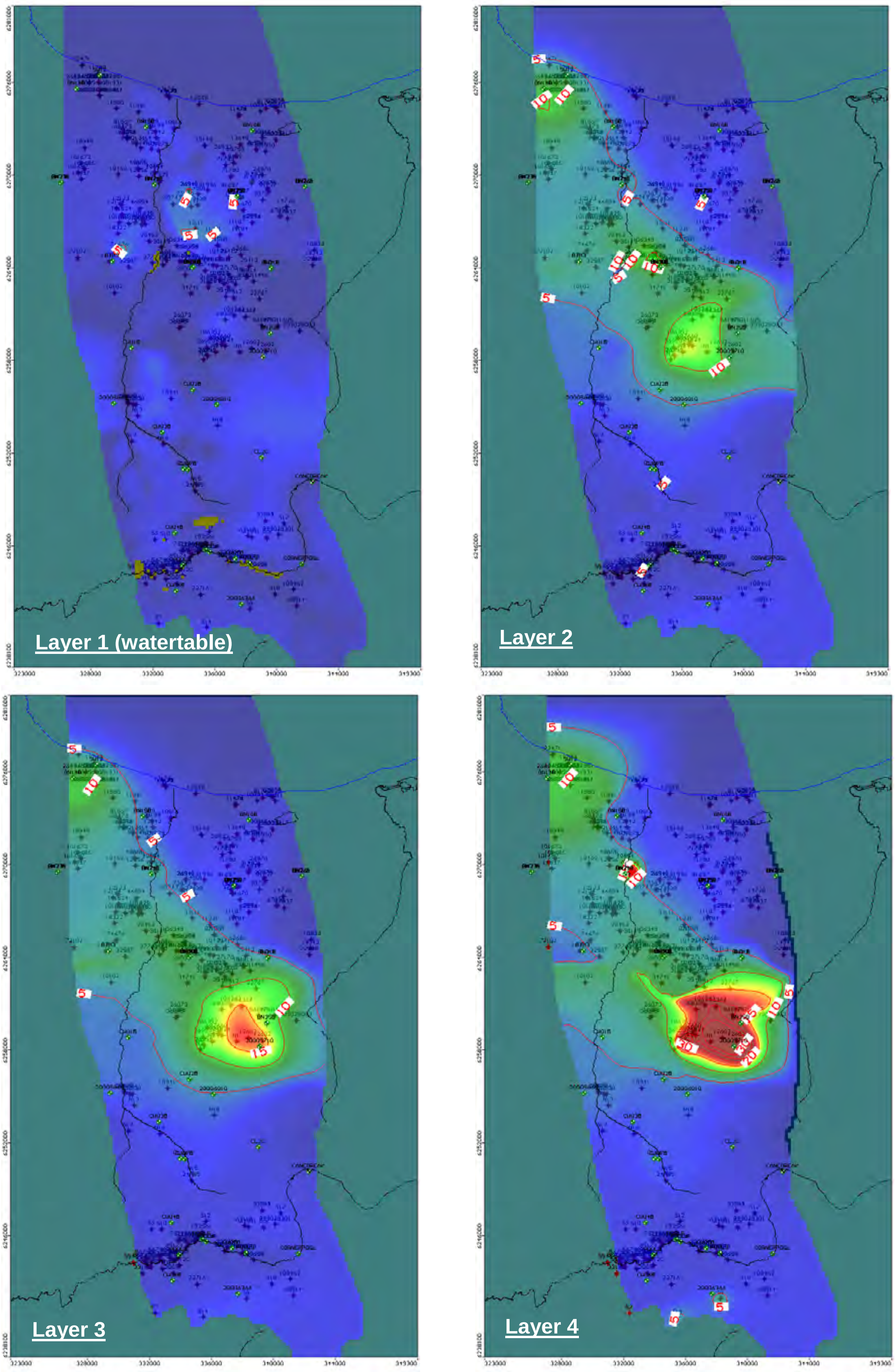
Appendix H3 Scenario 3 (southern case)



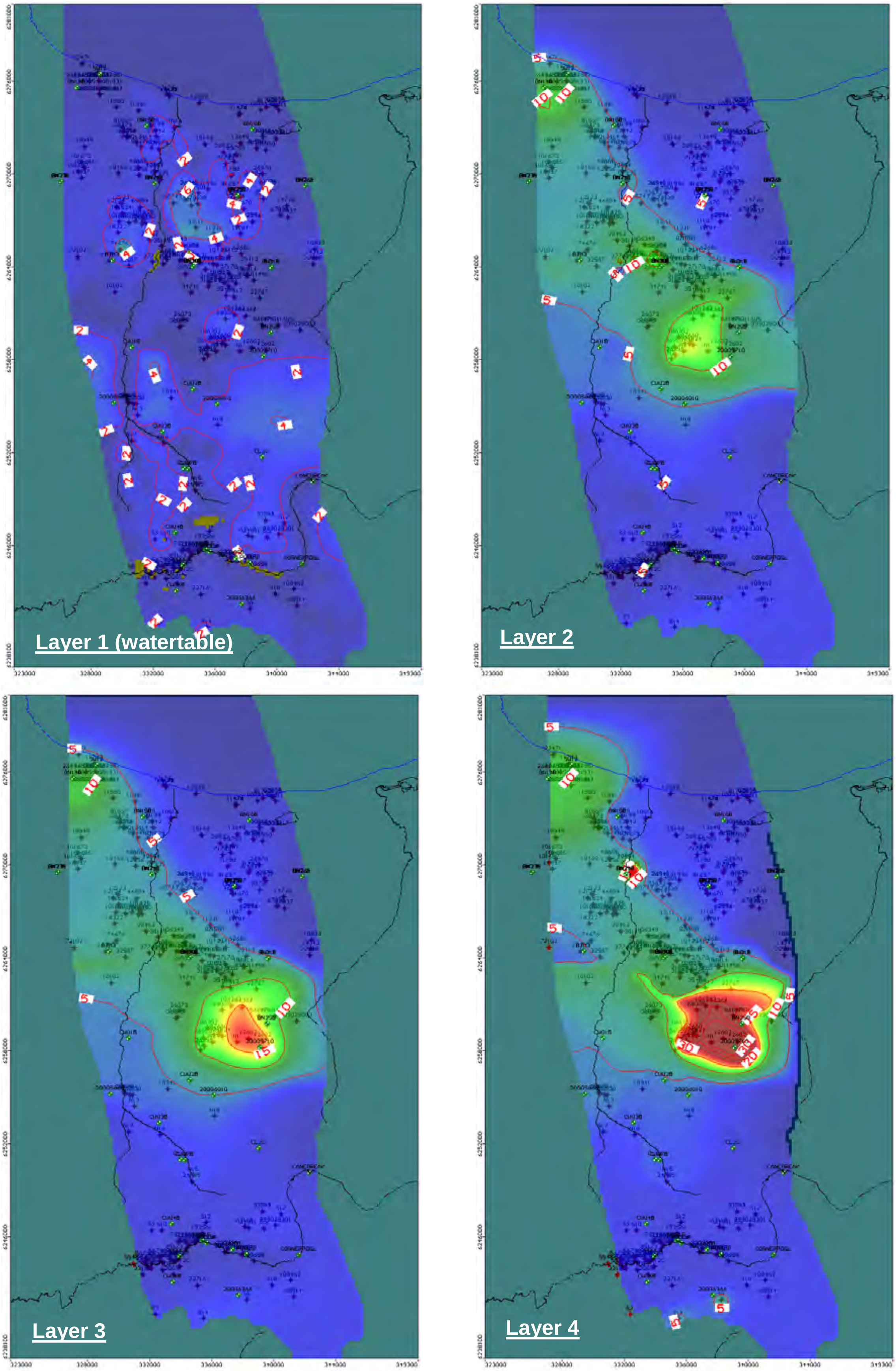
Appendix H4 Scenario 4 (combined case)



Appendix H5 Scenario 5 (climate 1 case)

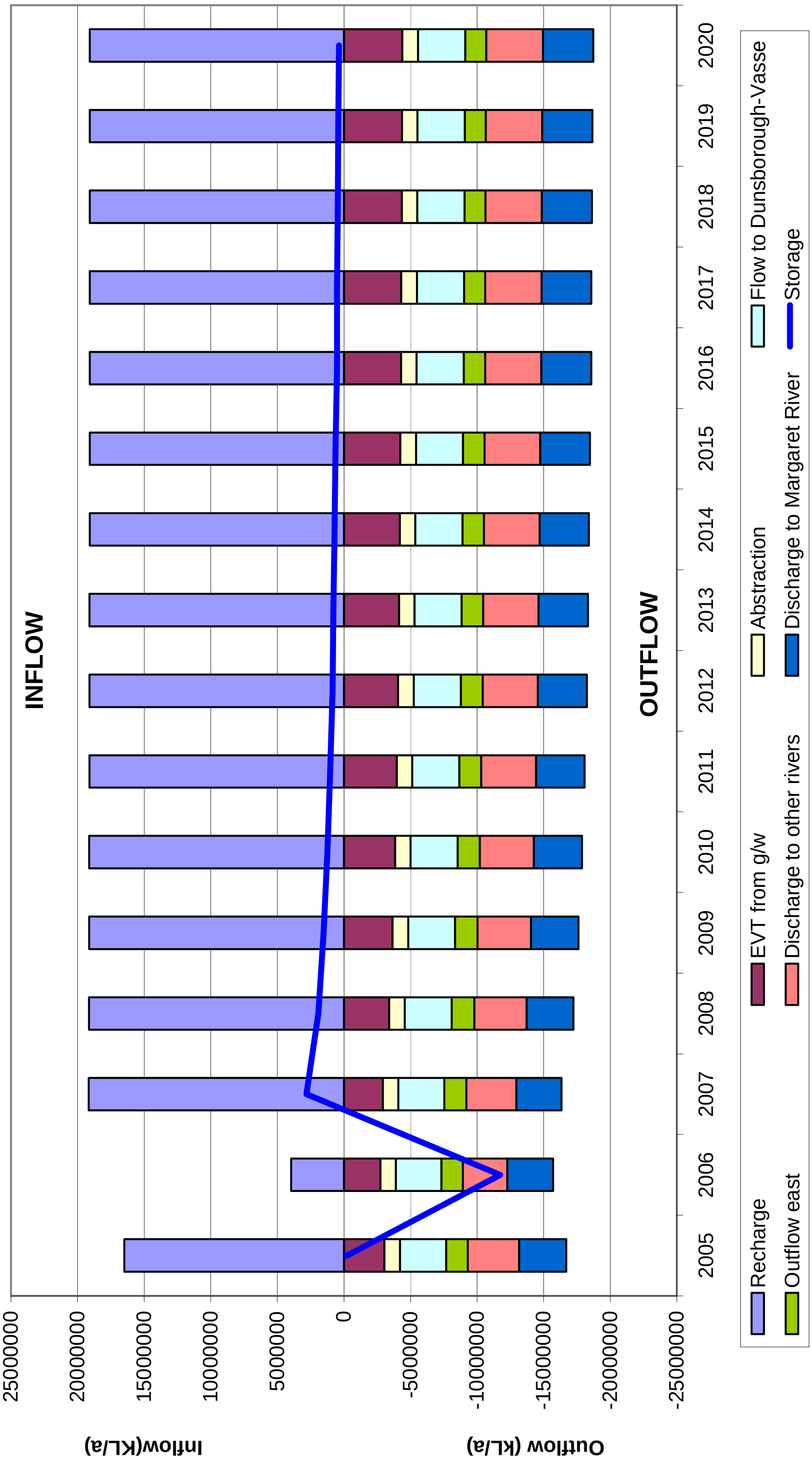


Appendix H6 Scenario 6 (climate 2 case)

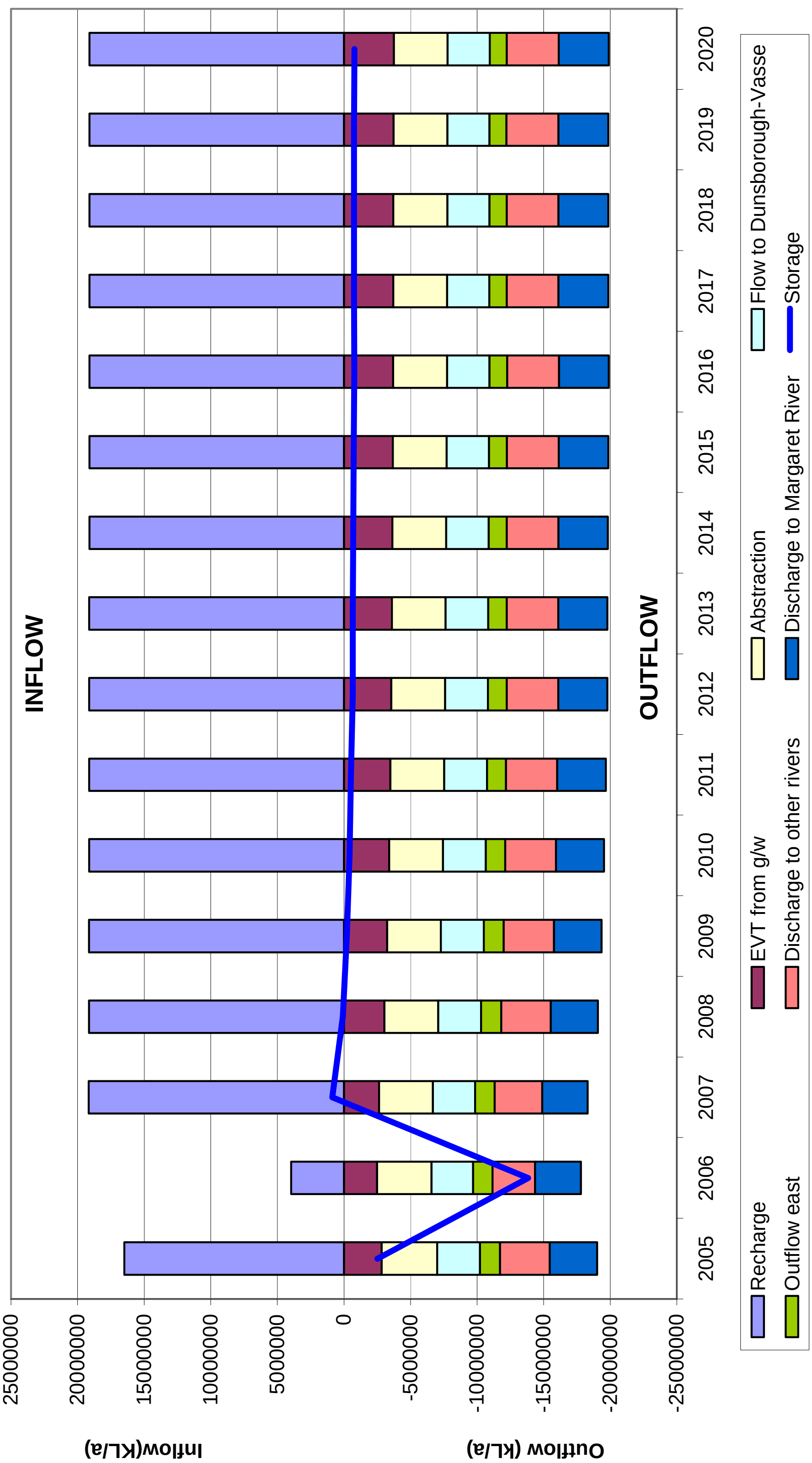


Appendix H7 Scenario 7 (climate 3 case)

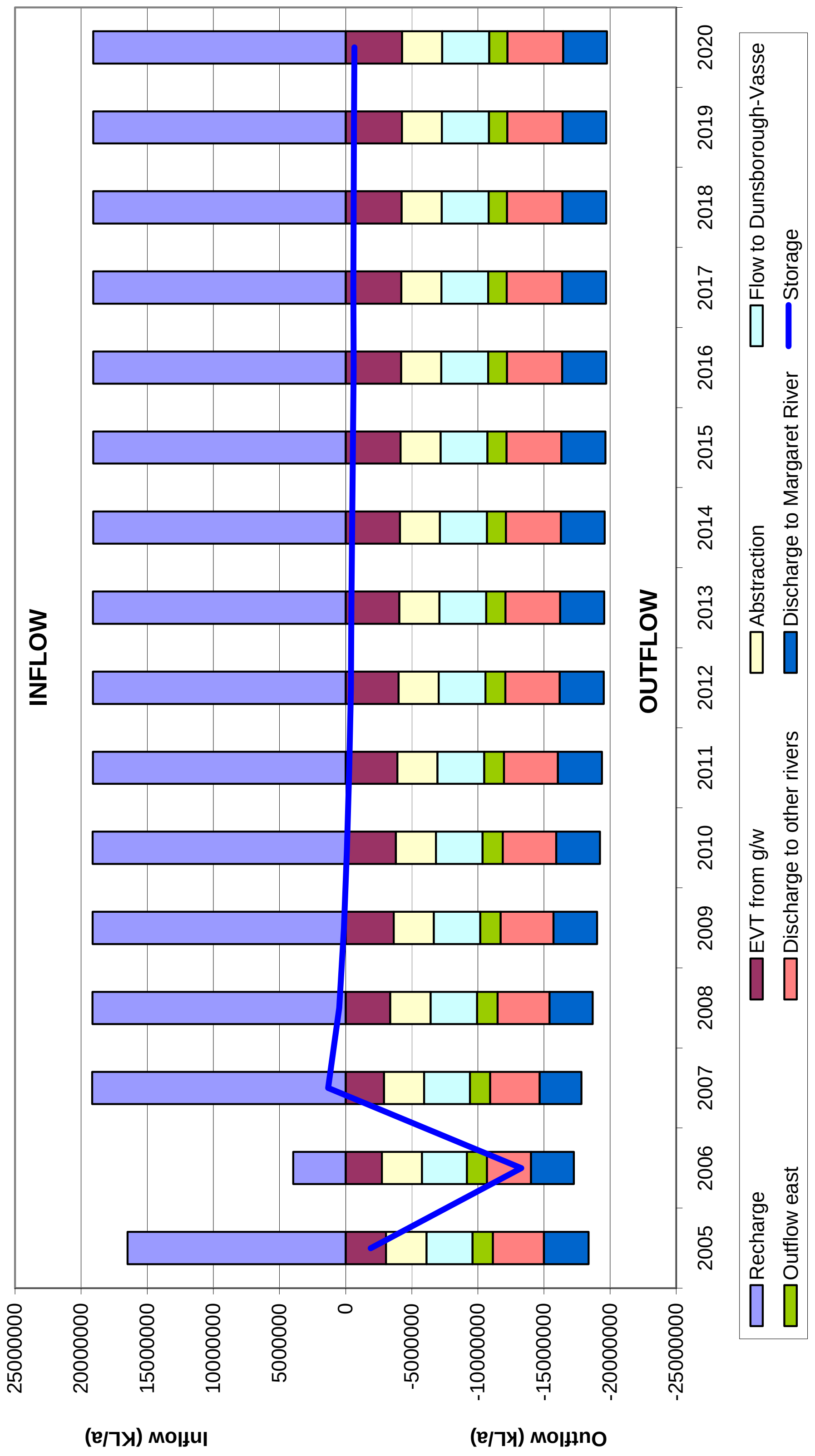
Appendix I — Annual water balances (2005 – 2020) for Cowaramup subarea



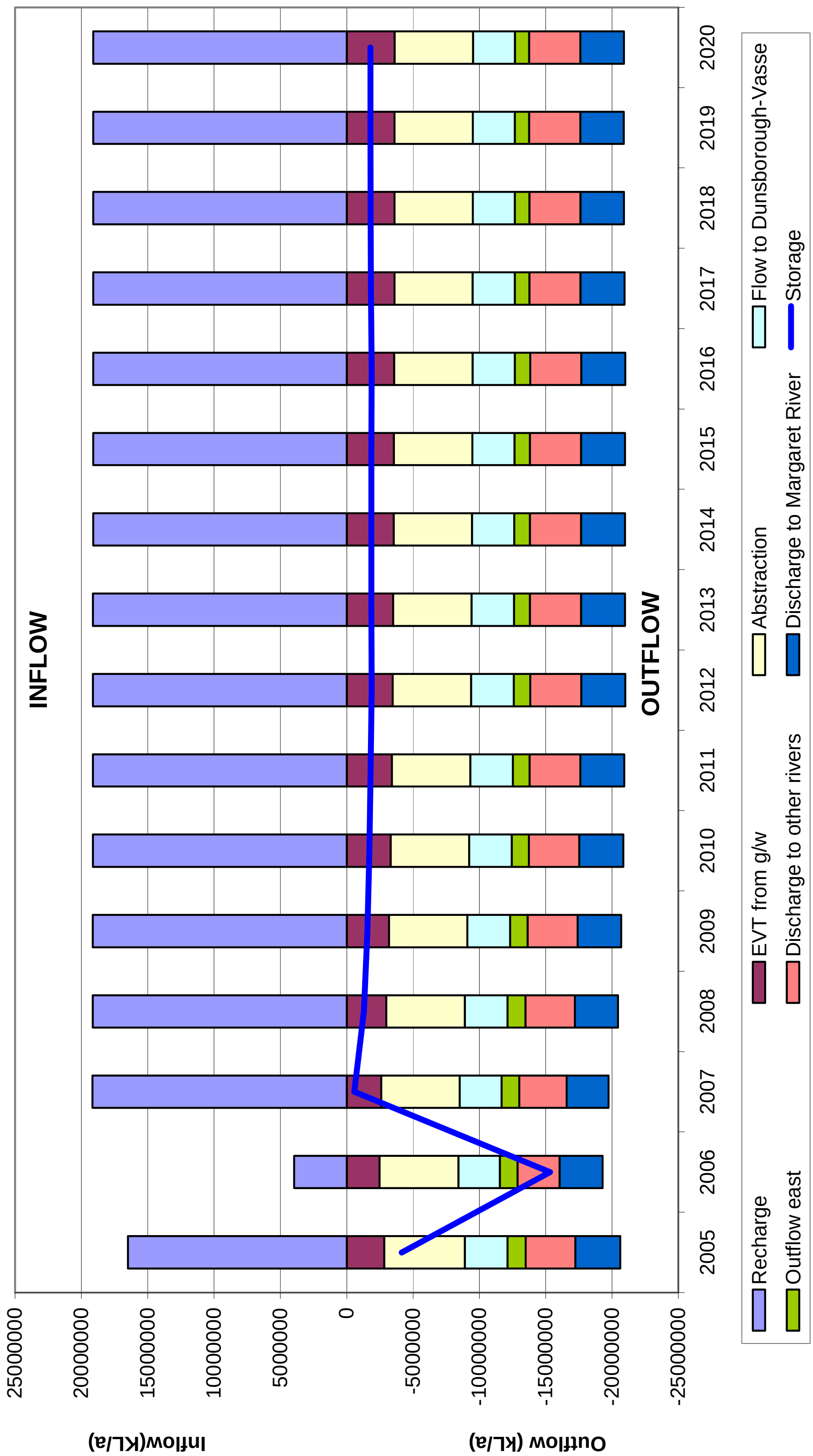
Appendix I1 Scenario 1 (base case)



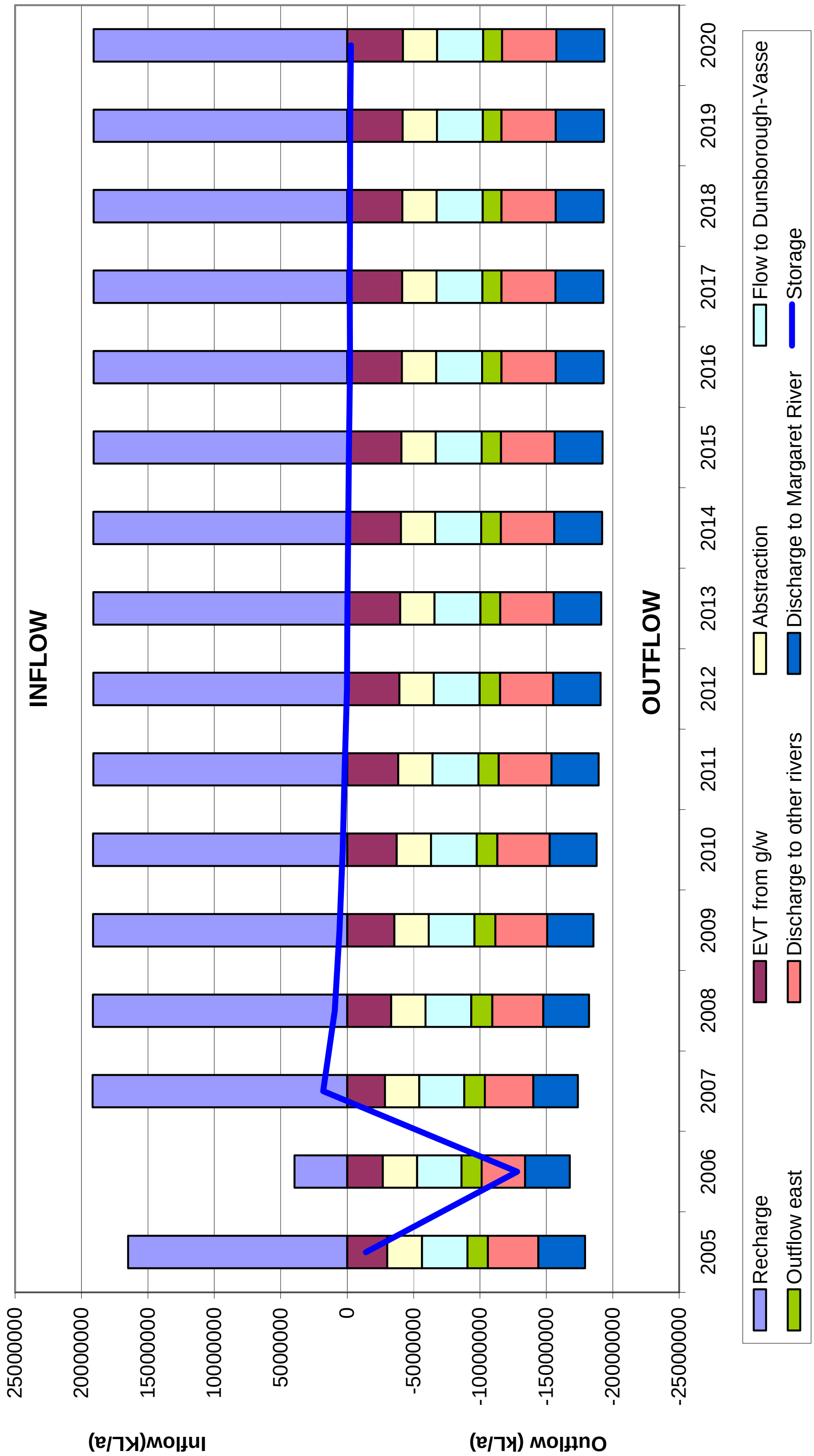
Appendix I2 Scenario 2 (northern case)



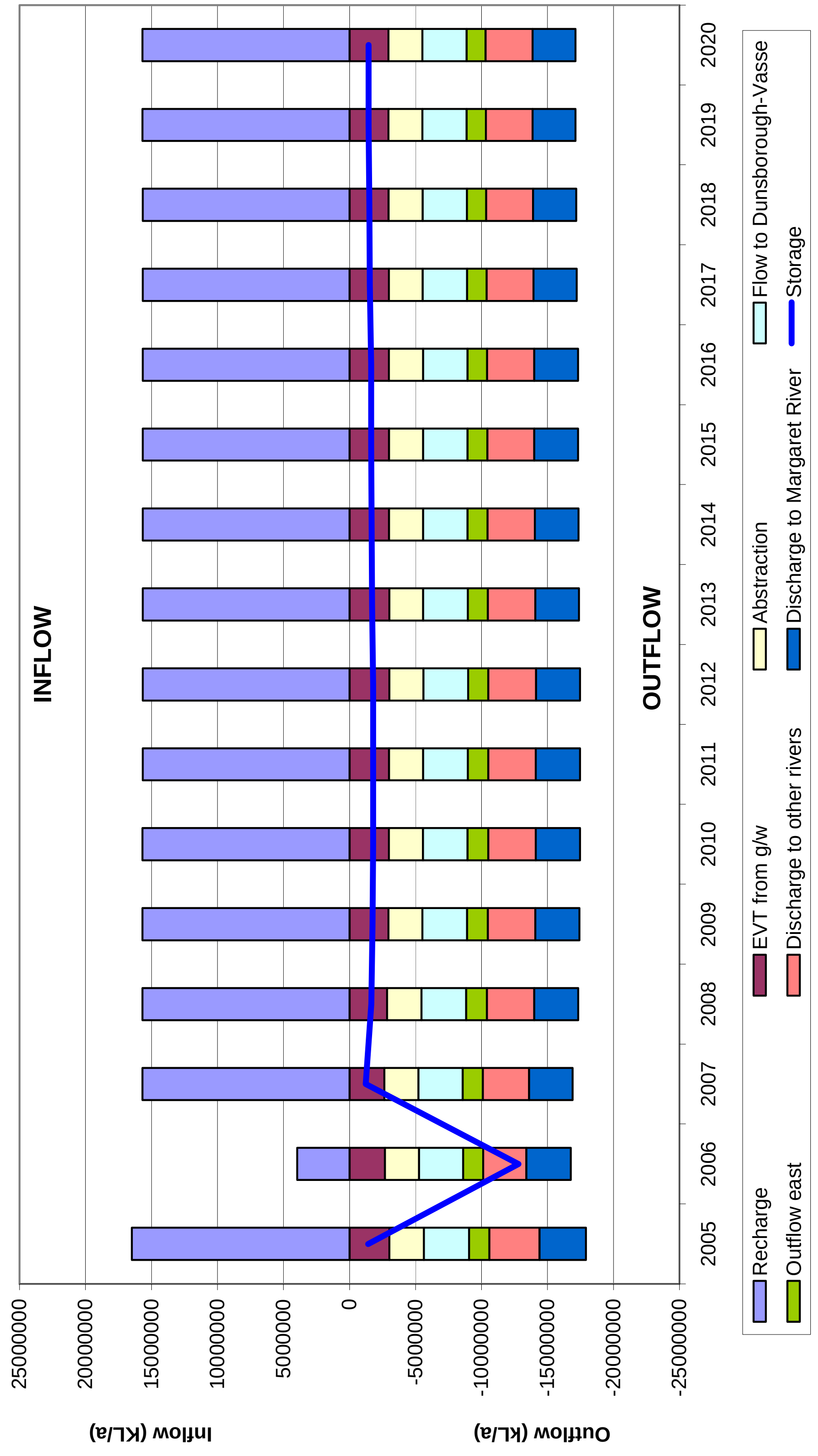
Appendix I3 Scenario 3 (southern case)



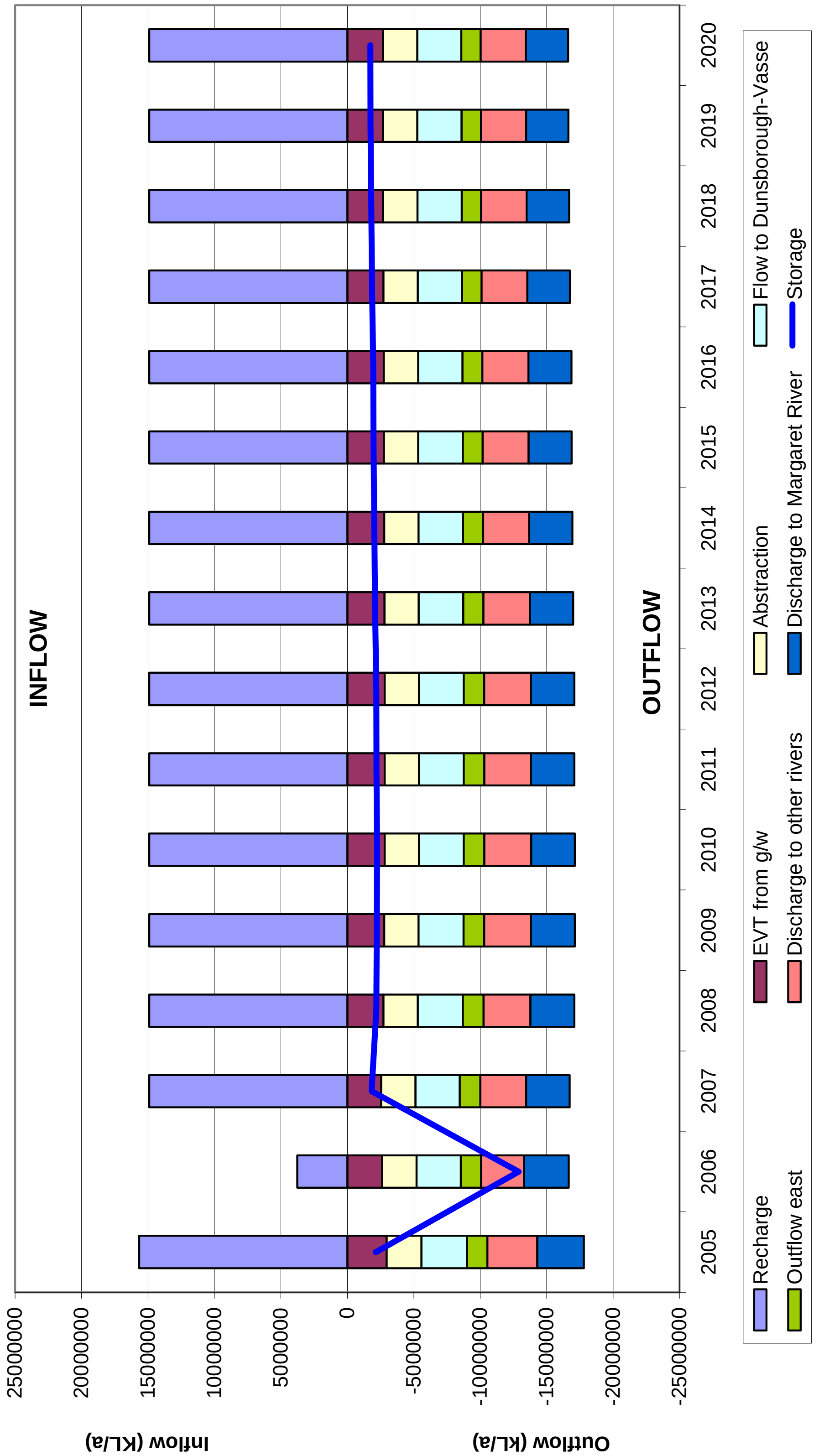
Appendix I4 Scenario 4 (combined case)



Appendix I5 Scenario 5 (climate 1 case)

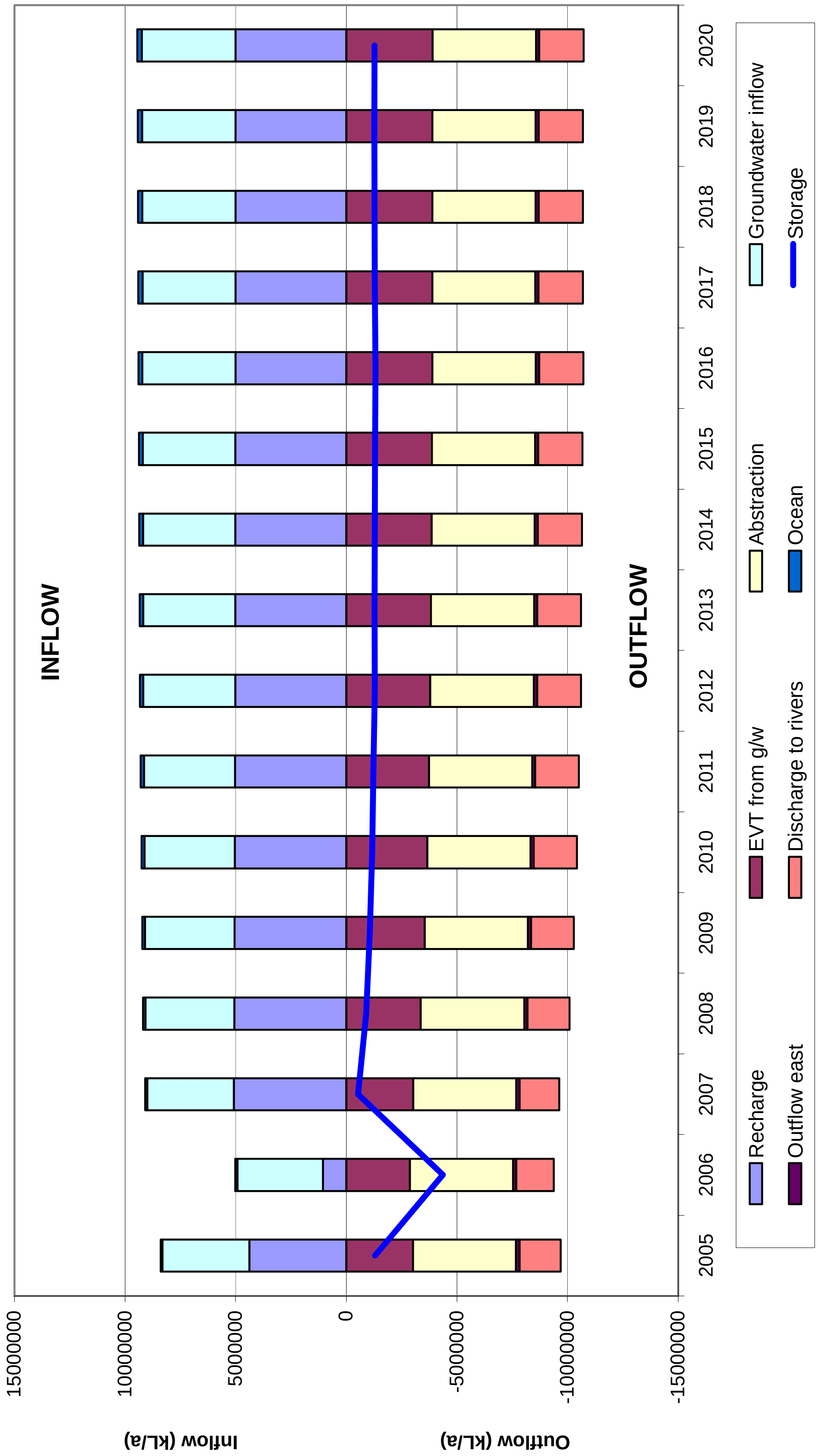


Appendix I6 Scenario 6 (climate 2 case)

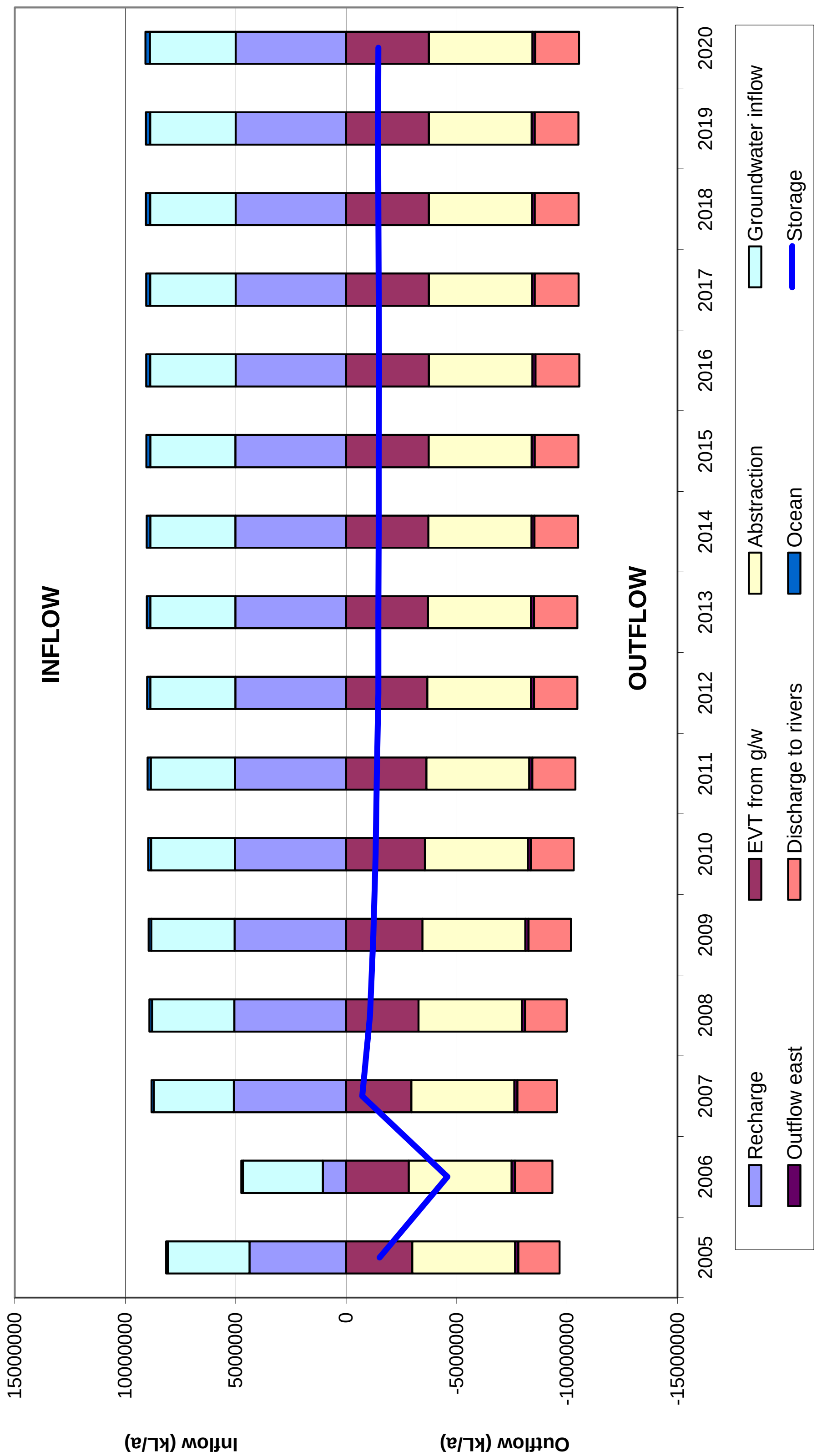


Appendix I7 Scenario 7 (climate 3 case)

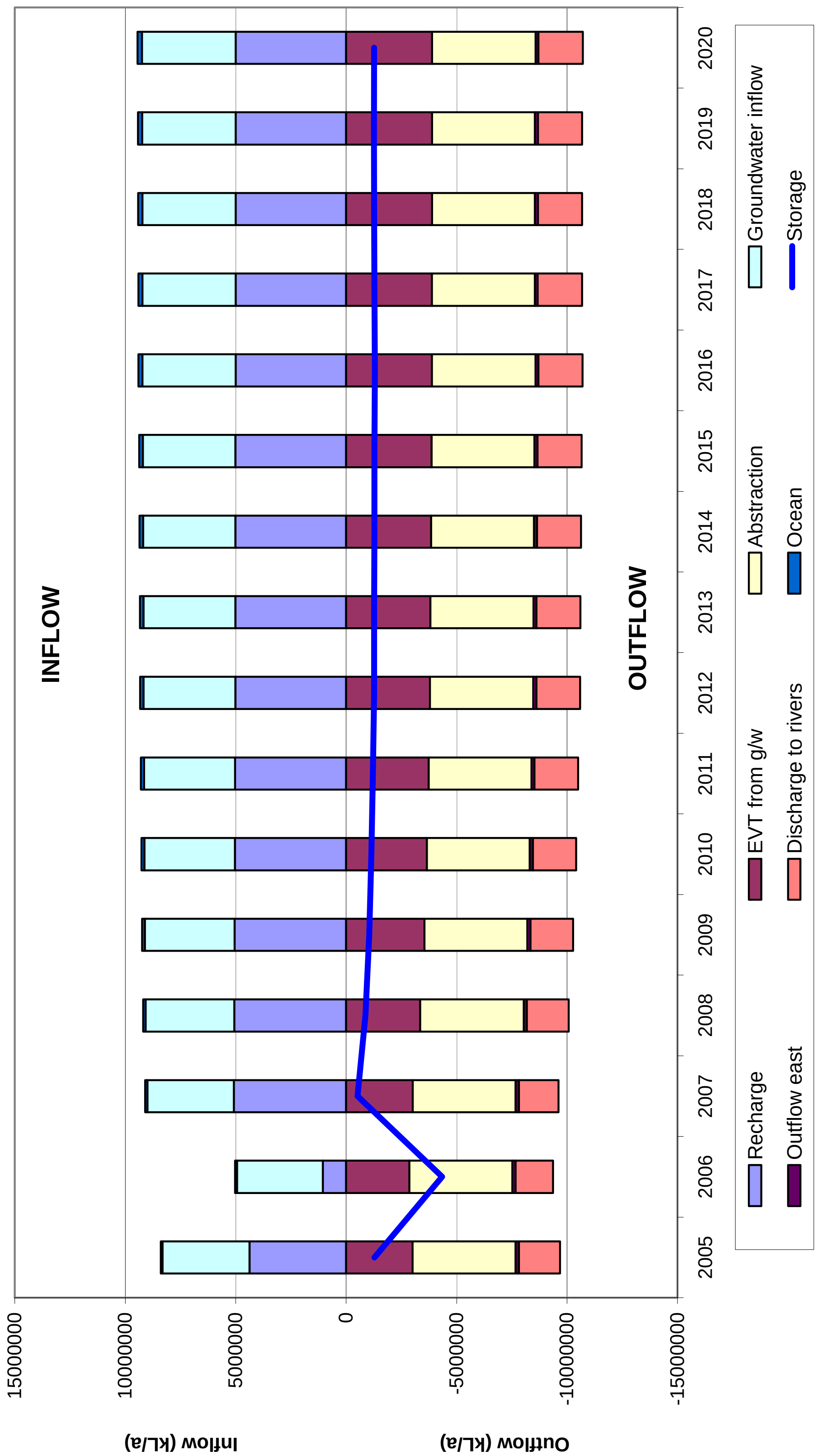
Appendix J — Annual water balances (2005 – 2020) for Dunsborough-Vasse subarea



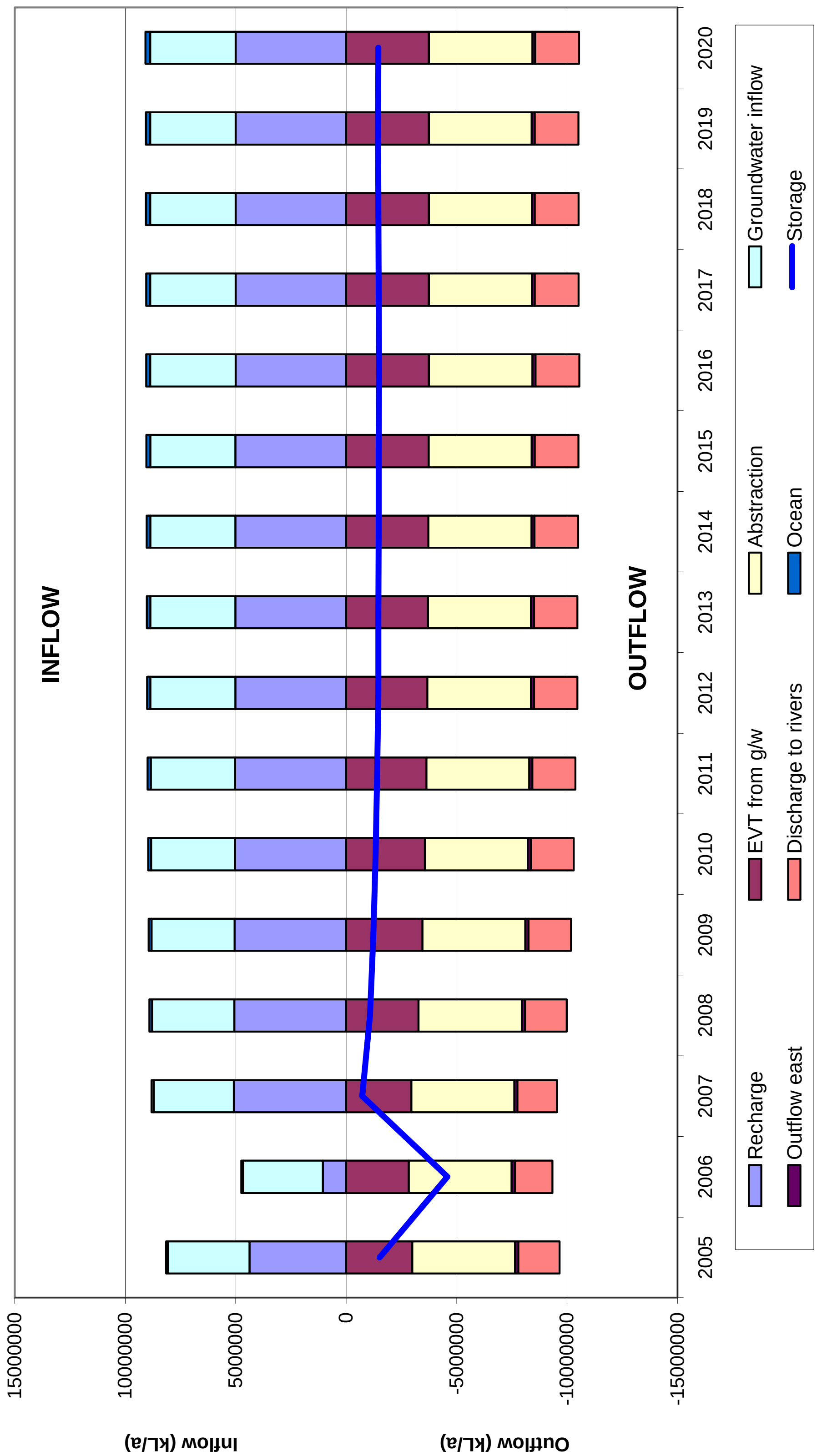
Appendix J1 Scenario 1 (base case)



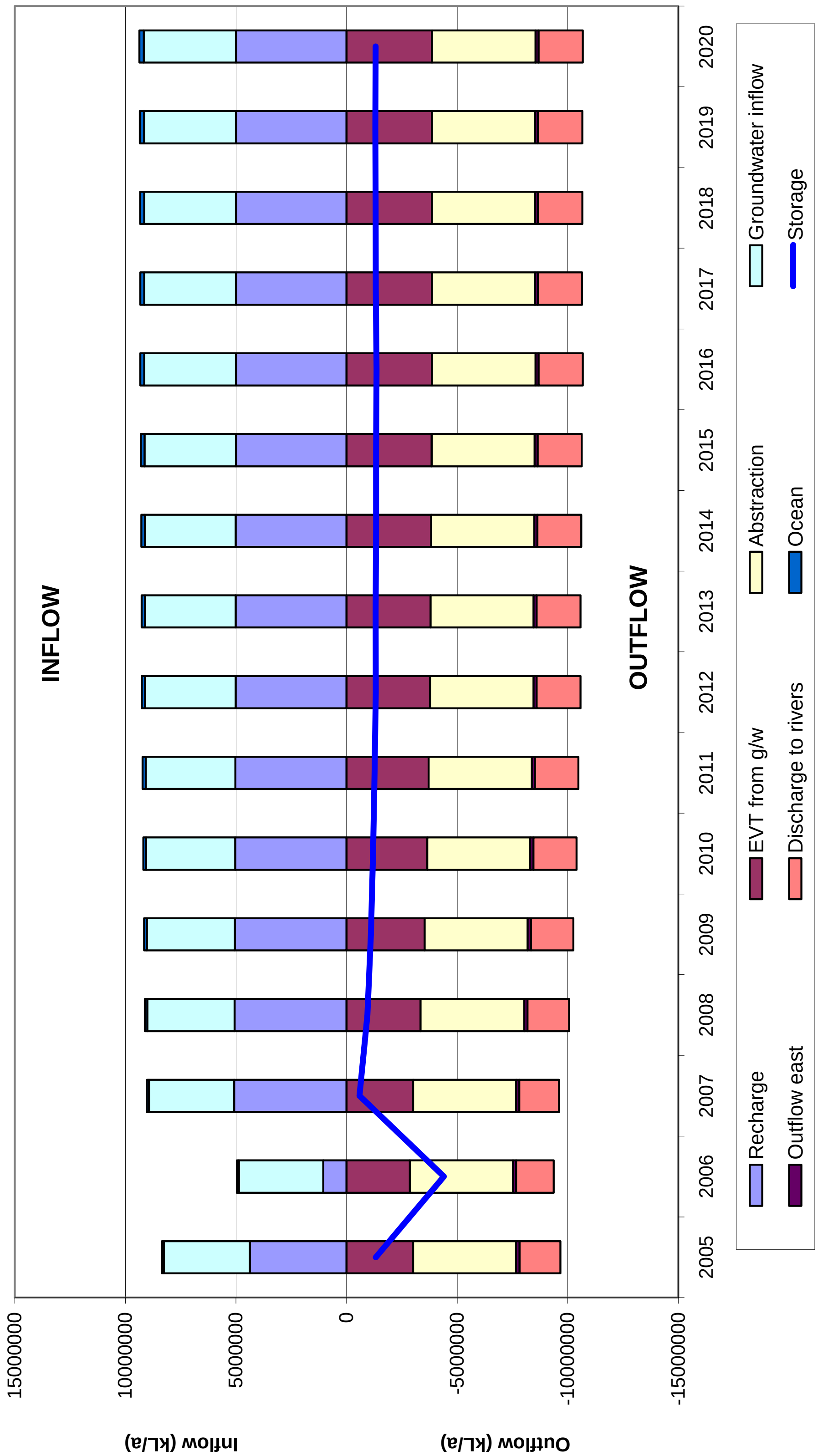
Appendix J2 Scenario 2 (northern case)



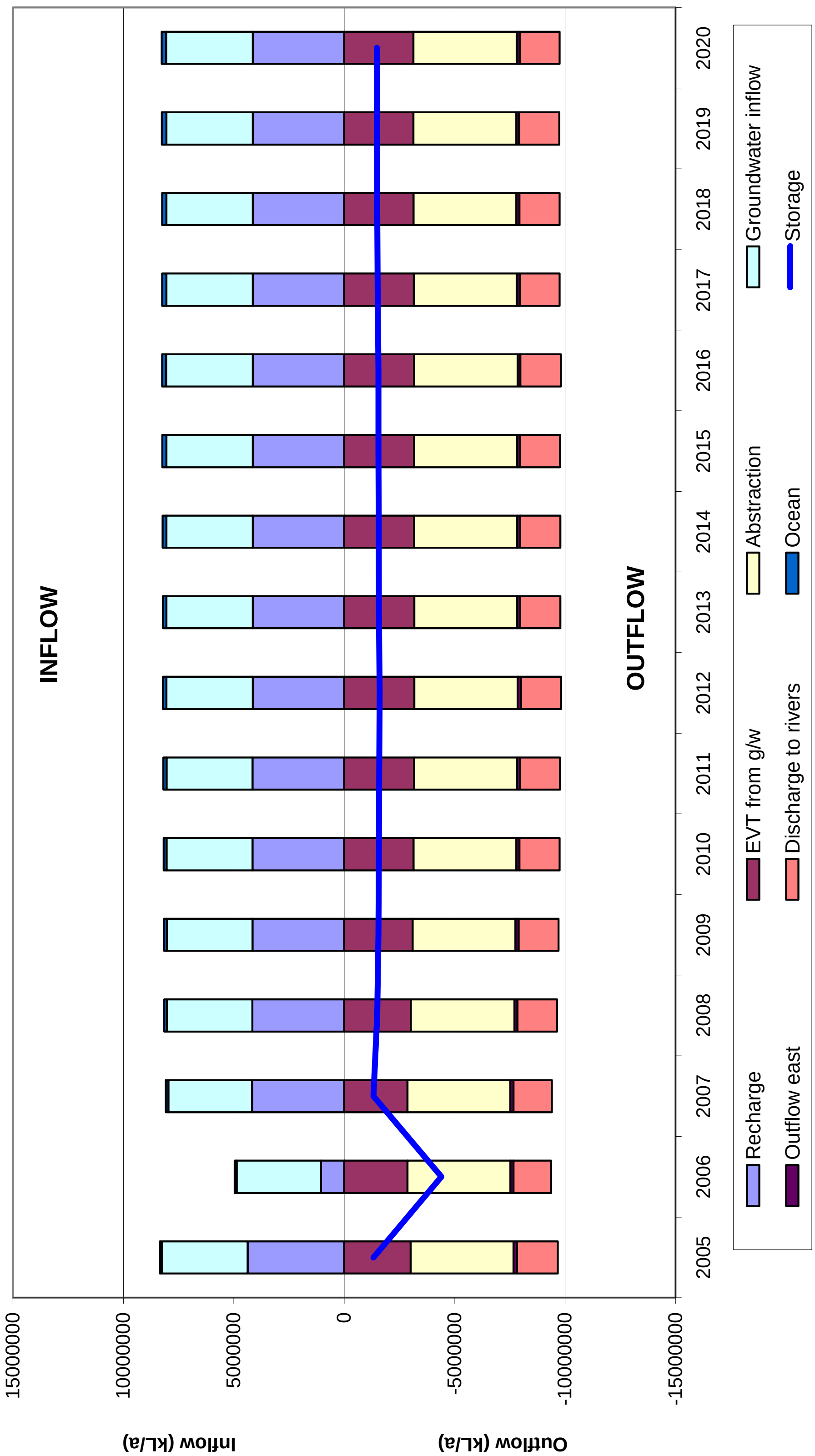
Appendix J3 Scenario 3 (southern case)



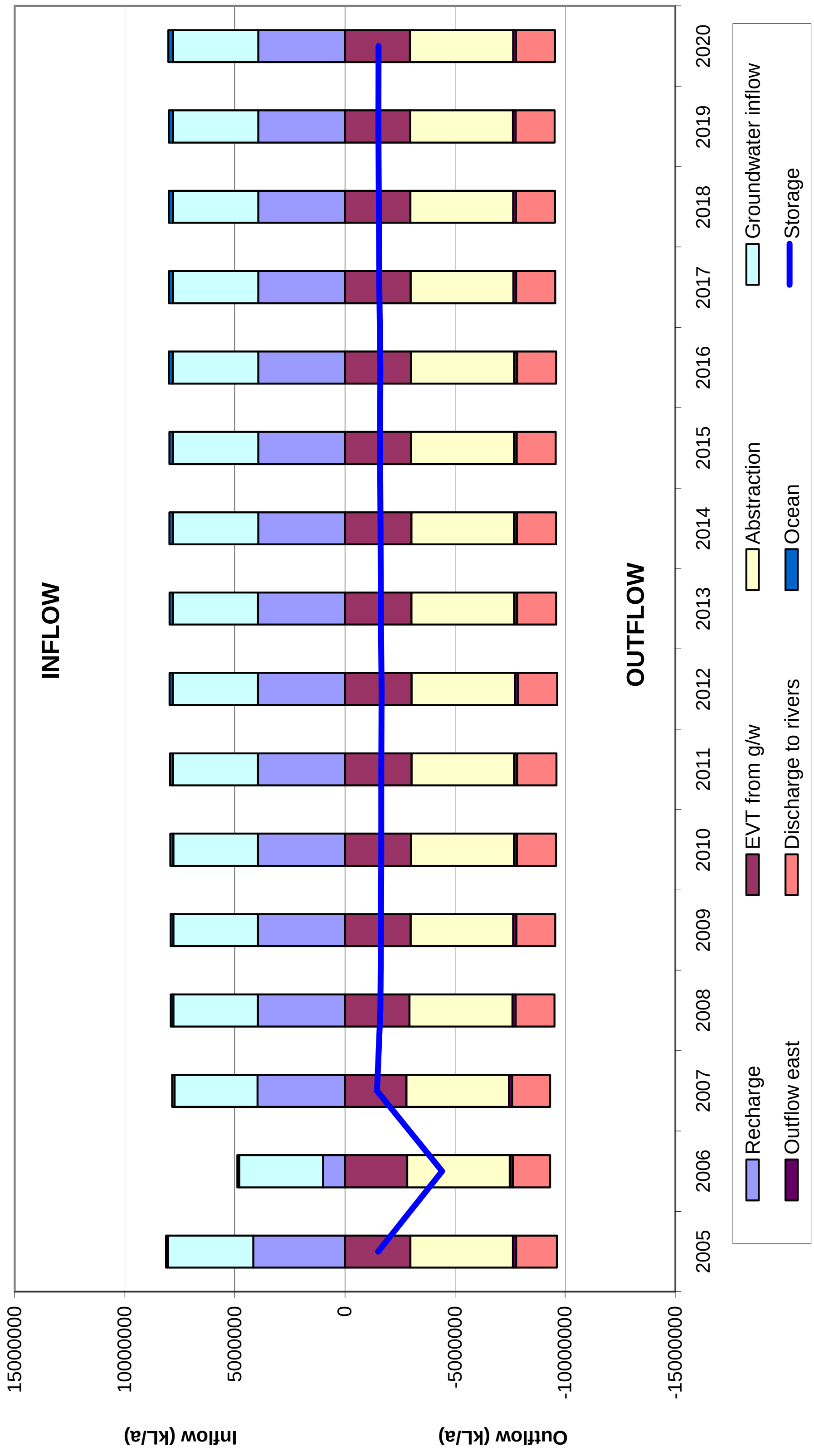
Appendix J4 Scenario 4 (combined case)



Appendix J5 Scenario 5 (climate 1 case)



Appendix J6 Scenario 6 (climate 2 case)



Appendix J7 Scenario 7 (climate 3 case)

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