TECHNICAL REPORT

GROUNDWATER FLOW MODEL OF COX CREEK CATCHMENT, MOUNT LOFTY RANGES, SOUTH AUSTRALIA

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Government of South Australia

Department for Water

GROUNDWATER FLOW MODEL OF COX CREEK CATCHMENT, MOUNT LOFTY RANGES, SOUTH AUSTRALIA

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PREFACE

On July 1st 2010, the Department for Water replaced the former Department of Water, Land and Biodiversity Conservation. The Department of Water, Land and Biodiversity Conservation and the abbreviation 'DWLBC' are referred to in several instances in this report. The reader is advised that these terms are retained in certain contexts within this document in order to provide a correct historical account of the investigation and the production of the technical report document.

FOREWORD

South Australia's Department for Water leads the management of our most valuable resource—water.

Water is fundamental to our health, our way of life and our environment. It underpins growth in population and our economy—and these are critical to South Australia's future prosperity.

High quality science and monitoring of our State's natural water resources is central to the work that we do. This will ensure we have a better understanding of our surface and groundwater resources so that there is sustainable allocation of water between communities, industry and the environment.

Department for Water scientific and technical staff continue to expand their knowledge of our water resources through undertaking investigations, technical reviews and resource modelling.

Scott Ashby
CHIEF EXECUTIVE
DEPARTMENT FOR WATER

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The development of the Cox Creek numerical groundwater model would not have been possible without holding numerous discussions regarding model fundamentals, technical issues and progress with Wei Yan. Many thanks to Dragana Zulfic who was available for discussions on model conceptualisation and development.

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SUMMARY

The Mount Lofty Ranges provides important surface water and groundwater resources for domestic, industrial and agricultural purposes locally, as well as metropolitan Adelaide's reticulated water supply. Water allocation in these areas needs to be actively managed to ensure that current and future uses of these resources are sustainable and that the environment is also recognised as a user of the resource.

To improve the management of groundwater resources in fractured rock aquifers, the understanding of groundwater flow mechanisms occurring in these systems needs to be enhanced.

A numerical groundwater flow model was developed by the Department of Water, Land and Biodiversity Conservation to increase the understanding of the fractured rock aquifers groundwater systems present in Cox Creek Catchment. This model incorporates the understanding of the groundwater flow system to date and is generally capable of simulating the regional aquifer system of Cox Creek Catchment and enables predictive modelling of future scenarios, such as land use and climate change.

Transient calibration resulted in a well matched qualitative comparison between the modelled and observed potentiometric head contours, which indicated that the modelled distribution closely represented the regional gradient of the observed distribution. This was further confirmed by the quantitative analysis of hydrographs for all observation wells in the model domain. Transient calibration calculations resulted in a normalised root mean square (RMS) value for the domain of 1.7% for 2008, which indicates a very good fit between modelled and observed data over the time period considered in the analyses.

Predictive modelling results indicate that the system is highly responsive to changes in both recharge and extraction and as such, the system should be managed to reflect these findings.

Under extended current conditions head levels are maintained and no new cones of depression are presented. Cones of depression present in the model domain are actually slightly minimised. Water levels across the catchment rise slightly and river outflow (loss from the aquifer to the rivers and drains) volume remains somewhat similar to that of the 10-year calibration period.

Increasing extraction in the project area results in declining head levels across the catchment and reducing river outflow, whilst decreases in extraction result in recovered head levels and increased groundwater flux into Cox Creek.

Reductions in recharge result in head level reductions across the whole project area; this in turn significantly diminishes flow to Cox Creek. It should be noted that the model responds similarly to reductions in recharge as it does to increases in extraction.

Modelled scenarios are compared with a baseline scenario, representing continuation of the current recharge and extraction rates, termed scenario 1.

Predictive modelling indicates that in the worst case scenario (and most likely due to drought conditions) where recharge is decreased and therefore extraction is increased, it is likely to cause an adverse effect to the aquifer and Cox Creek. The scenario results in significant declines in groundwater flow to Cox Creek and marked drops in head levels, where in some cases winter highs are close to summer lows occurring in scenario 1.

Predictive modelling indicates that decreased recharge in conjunction with decreased extraction results in very similar, but slightly lower, head levels to that produced in scenario 1. It should be noted that 20% of recharge does not equate volumetrically to 20% of extraction, therefore there is diminished flow of groundwater to Cox Creek in relation to scenario 1 results.

SUMMARY

In pristine conditions, the model indicates that with reduced recharge (due to evapotranspiration and interception) and no extraction, the seasonal variability of head levels is minimised. As a result the summer head levels are consistently higher than those of scenario 1 whilst the winter head levels are slightly lower than those of scenario 1. The potentiometric surface contains no cones of depression but is slightly lower than that of scenario 1. River outflow volume is the lowest of all scenarios, however it is more consistent with limited drastic highs and lows.

Decreases to recharge and increases to extraction both result in the reduction of groundwater flow to Cox Creek. This is likely to have an adverse effect on macroinvertebrates and fish species, such as climbing galaxias and mountain galaxias, surveyed to be present in Cox Creek. There are also a number of permanent pools (>15 m in length) located within Cox Creek which may act as ecological refuges during summer months or periods of extended drought. It should also be considered that diminished flow to Cox Creek in turn results in diminished flow within the Onkaparinga River which also acts as a refuge for many species.

As the model is highly responsive to changes in both recharge and extraction, management strategies should be employed to reflect these findings. To maintain the ecological value of Cox Creek and the integrity of the aquifers present, management strategies should be implemented to protect the permanent pools, current flow regime and water levels of the Cox Creek Catchment. These strategies would also need to take into account the high dependence of the catchment on recharge and extraction. Such strategies could include:

- The application of buffer zones between Cox Creek and groundwater extraction points to prevent direct impacts on stream flow;
- Applying restrictions on extraction in the modelled portion of Cox Creek Catchment such that it does not exceed current extraction levels; and
- Sustained decreases in recharge due to variation in climate over a decade time scale need to be offset by decreases in groundwater extraction if water levels and the Cox Creek flow regime are to be maintained.

1 INTRODUCTION

1.1 BACKGROUND

The Department of Water Land and Biodiversity Conservation (DWLBC) has been engaged to develop a numerical groundwater flow model of the Cox Creek Catchment (CCC) Fractured Rock Aquifer (FRA) for the Adelaide and Mount Lofty Ranges Natural Resources Management Board (AMLR NRM Board).

The aim of this project is to provide a tool to assist decision making in water resource management and water allocation planning in fractured rock aquifers (FRAs) of the Mount Lofty Ranges (MLR).

The MLR provide important surface water and groundwater resources for domestic, industrial and agricultural purposes locally, as well as metropolitan Adelaide's reticulated water supply. Water allocation in these areas needs to be actively managed to ensure that current and future uses of these resources are sustainable and that the environment is also recognised as a user of the resource.

To improve the management of groundwater resources in FRAs, the understanding of groundwater flow mechanisms occurring in these systems needs to be improved. The development of a numerical groundwater flow model of the CCC FRA system can assist in providing new understanding of these systems.

The way in which cleared and pristine catchments behave in response to similar climatic and geologic conditions is not well understood. One component of this project is to compare the outcomes of modelling a pristine catchment scenario versus a cleared catchment scenario.

The outcomes of modelling scenarios can be used in assessing the response of the FRA to various climate induced stresses, to enable more robust management practices which promote the sustainable management of the FRA resource and any dependant ecosystems.

1.2 OBJECTIVES

The objective of this study is to develop a numerical model of the groundwater systems in the CCC to achieve the following:

- assess the regional scale impacts of increased licensed groundwater use from the FRA
- assess the regional impact that climate change (decreased recharge) may have on the groundwater resource of the FRA
- assess the regional scale impacts of changed land use conditions.

These objectives will be met by undertaking predictive model runs to assess the impact that increases in existing water user allocations, reduced recharge rates and changes in land use (pristine or cleared) will have on the current groundwater system.

2 HYDROGEOLOGICAL CONCEPTUAL MODEL

2.1 WHY COX CREEK CATCHMENT?

CCC was chosen as the study site not only due to its good monitoring record, which is required for the purpose of confirmation and calibration of the model, but more importantly because groundwater has been extracted for the irrigation of vegetables and orchards in the area for over 40 years (Barnett & Zulfic 1999). Due to this extended period of extraction, the groundwater system has had sufficient time to reach equilibrium after the clearing which occurred in the 1960s.

This has resulted in an aquifer system which has changed very little over the past ten years (1998–2008). As a result of this equilibration, the potentiometric surfaces for both 1998 and 2008 are alike. As the system has proved to be in post clearing equilibration, the 1998 data will be used as the starting point for the model, in effect the steady state. Transient model calibration will involve successfully replicating groundwater heads during the 1998–2008 period. Scenario testing will involve imposing changes in stresses within the system from 2008–2028.

2.2 LOCATION

The CCC is situated 20 km east of Adelaide in the Western Mount Lofty Ranges (WMLR). It is a sub catchment of the Onkaparinga River catchment, contributing to 5.38% of the Onkaparinga River catchment area.

CCC covers a total area of 29.9 km^2, however the model domain, which represents a portion of the catchment, covers an area of 16.4 km^2 (Fig. 1).

The area included in the model domain has steep topography that varies in elevation from 700 m AHD near Mount Lofty Summit to 420 m AHD at the bottom of the model domain near the Woodhouse gauging station.

2.3 CLIMATE

The CCC is characterised by warm summers and cold, wet winters. Daily maximum temperatures at Mount Lofty average about 21°C in summer and 9°C in winter (Bureau of Meteorology 2009).

The average monthly rainfall in millimetres over the past 20 years (1988–2008) as measured by the Bureau of Meteorology at Uraidla station 23750 is shown in Table 1. The annual average rainfall is 1055 mm/year. Rainfall is winter dominant with 80% of all rainfall occurring between April and October.

Table 1. Average rainfall

Jan.	Feb.	Mar.	Apr.	Mar.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
34	28	37	61	121	162	163	144	121	84	59	51	1055

Source: BoM

2.4 CATCHMENT HYDROLOGY

Surface drainage is from the higher northern boundary of the catchment to the south-east where it discharges into the Onkaparinga River. The headwaters of Cox Creek originate from several small tributaries and converge less than a kilometre upstream of the gauging station (A5030526) located on

Swamp Road (Fig. 1). The depth of Cox Creek is typically less than 0.75 metres, but increases to depths greater than 1.5 metres during storm flow periods. The width of Cox Creek varies between one and six metres depending on the location within the catchment and the physical geology and topographic controls. Cox Creek is a perennial creek with an average annual flow measured at the gauging station of 1180 ML with a catchment area of 4.3 km^2. Continuous water level data has been recorded at the gauging station since 1976 and water quality data since 1994. During the summer month's baseflow is approximately 460 m^3/day (Banks 2010). An elementary conceptual model of CCC is shown in Figure 2.

2.5 CATCHMENT HYDROGEOLOGY

Groundwater in the CCC predominantly occurs in FRAs of Stonyfell Quartzite, Mundallio Subgroup and Barossa Complex. The majority of wells are completed in the Mundallio Subgroup, which typically have higher yields and suitable quality for domestic and agricultural purposes.

For the purpose of the model domain, CCC will be divided into five hydrogeological zones based on geology type (Fig. 3, Table 2). Each zone is categorised by different hydraulic properties. A major fault line is present along the margin of the Barossa Complex, traversing in a north-east–south-west direction. The fault separates the Barossa Complex from the Mundallio Subgroup and Stonyfell Quartzite.

The northern portion of the model domain is dominated by the Neoproterozoic Mundallio Subgroup consisting of Basket Range Sandstone and Woolshed Flat Shale members, whilst the Palaeoproterozoic Barossa Complex dominates the southern portion.

A minor area of the Neoproterozoic Stonyfell Quartzite is present in the western corner of the domain, whilst the south-eastern corner of the model is dominated by the Aldgate Sandstone member of the Neoproterozoic Emeroo Subgroup.

Table 2. Geologic distribution

Age	Subgroup	Stratagraphic name(s)	% of model
Neoproterozoic	Stonyfell Quartzite	Wattle Park Member	10.44
	Mundallio Subgroup	Woolshed Flat Shale	17.76
		Basket Range Sandstone	32.00
	Emeroo Subgroup	Aldgate Sandstone	5.60
Palaeoproterozoic	Barossa Complex		34.20

Regional groundwater flow is primarily north to south from the elevated areas close to the model boundary toward Cox Creek in the centre of the valley (Fig. 4). The direction of groundwater flow is controlled largely by the topography and the orientation of the higher permeability fracture zones relative to the gradient (Banks 2010).

2.5.1 STONYFELL QUARTZITE

The Stonyfell Quartzite formation is gently south-dipping quartzite, hard, pink to white, feldspathic, minor thin shale laminations, interbeds of medium to coarse sandstone (Preiss 1987).

Beneath the Mount Lofty Summit, the Stonyfell Quartzite contains a perched aquifer on top of the Woolshed Flat Shale with a limited areal extent and quite low salinities. A natural spring discharge has been developed by a spring water company. Elsewhere, domestic supplies are obtained from this unit around the southern margin of the catchment (Barnett & Zulfic 1999).

2.5.2 WOOLSHED FLAT SHALE

The Woolshed Flat Shale formation consists of a pale grey laminated siltstone, shale and sandy shale, approximately 90 m thick. It is generally located above the Montacute Dolomite (Preiss 1987).

The storage capacity of the Woolshed Flat Shale is mainly a function of fracture and joint development as the general permeability of the rocks is rather low. The fine grain-size and ready decomposition of these rocks may lead to some deterioration in the quality of the water, as does the presence of pyrite which may elevate iron levels (Barnett & Zulfic 1999).

2.5.3 BASKET RANGE SANDSTONE

The Basket Range Sandstone is a coarse-grained, thick bedded (>720 m), feldspathic sandstone passing up to medium and minor fine-grained sandstone within parasequences; lenticular black chert, in part cryptalgal laminates; a 20 m black shale; and dolomitic siltstone interbed is present near the top (Preiss 1997).

The Basket Range Sandstone aquifer has a primary permeability (intergranular porosity) in addition to the secondary joint system, which would significantly enhance its storage capabilities. High yields of good quality water are obtainable from these rocks. This aquifer is considered to be the best in the area and is extensively used for irrigation purposes (Barnett & Zulfic 1999).

2.5.4 ALDGATE SANDSTONE

The Aldgate Sandstone consists of pale brownish or greenish grey micaceous sandstone and quartzite with micaceous, shaly layers. Medium to coarse grained, flaggy to medium-bedded with cross bedding and wavy lenticular bedding are well developed (Preiss 1987).

The Aldgate Sandstone has similar aquifer properties to the Basket Range Sandstone. Due to the limited area of Aldgate Sandstone within the model domain ,it is assumed that the aquifer possesses the same properties as the Basket Range Sandstone.

2.5.5 BAROSSA COMPLEX

The Barossa Complex is represented by metamorphic rocks with retrograde metamorphism (possibly due to the Delamerian Orogeny), metasediments, strongly banded parallel to gnessic foliation, minor intrusive granitic, pregmatitic and amphibolitic dykes (Preiss 1987).

The Barossa Complex is generally considered to be a poor aquifer from which yields suitable for irrigation cannot be obtained. The fine grain-size and rapid decomposition of some of the schistose and granitic rocks to clay, considerably reduce permeability in the weathered zone and may lead to an increase in the salinity of the groundwater (Barnett & Zulfic 1999).

2.6 SUMMARY OF AQUIFER TEST RESULTS

Hydraulic conductivity and transmissivity for the Woolshed Flat Shale and Aldgate Sandstone were sourced from pumping tests carried out in the WMLR by DWLBC for recharge estimates (Green et al. 2007).

Bulk hydraulic conductivity for the Aldgate Sandstone was approximated using the Cooper-Jacobs straight-line approach (Table 3). Due to unsuccessful attempts in maintaining water level drawdown, the bulk hydraulic conductivity for the Woolshed Flat Shale was calculated using Darcy’s law. Given the uncertainty of the below Woolshed Flat Shale conductivity values, an average of numerous pumping test carried out in the aquifer material was used in the model instead.

Table 3. Hydraulic properties

Aquifer	Transmissivity (m^2/d)	Bulk Hydraulic Conductivity (m/d)
Stonyfell Quartzite		
Woolshed Flat Shale		2.1–15.9
Basket Range Sandstone		
Aldgate Sandstone	0.011–0.118	0.002–0.020
Barossa Complex		

2.7 SURFACE WATER–GROUNDWATER INTERACTIONS

Groundwater salinity in the CCC is especially fresh, ranging from 153 to 476 mg/L (Banks 2010). This salinity falls within the aesthetic guideline values of the *Australian Drinking Water Guidelines* (Australian Water and Wastewater Association 1996) and is suitable for crop irrigation and stock use. Such a low salinity is uncharacteristic for the MLR, where salinity is usually in the range of 300 to 3000 mg/L (Banks 2010; Green & Stewart 2008).

Results from a groundwater–surface water study Banks (2010) carried out in Cox Creek indicate that the groundwater and surface water in Cox Creek are highly connected (Fig. 5).

3 MODEL CONSTRUCTION

3.1 MODFLOW AND VISUAL MODFLOW

MODFLOW is a three-dimensional finite-difference mathematical code that was developed by the US Geological Survey (McDonald & Harbaugh 1988). It is universally recognised among scientists and is one of the most commonly used groundwater flow models.

Visual MODFLOW 2009 was used as the interface for pre- and post-processing of MODFLOW files.

3.2 MODEL DOMAIN AND SPATIAL DISCRETISATION

The modelled area simulates an area of 16 km^2, 3.4 km (north–south) by 4.6 km (east–west). The bounding coordinates of the model domain are south-west E290680 N6124570 and north-east E295780 N6129840, Map grid of Australia (MGA) Zone 54.

The rectangular model grid was divided into 102 columns and 106 rows. The grid size was 50 x 50 m (Fig. 6).

The project is presented as a simple to moderate complexity impact assessment model, which requires some understanding of the groundwater system dynamics and is suitable for predicting the impacts of changes in stresses or to develop appropriate resource management policies.

3.2.1 MODEL LAYERS

Simplifying model geometry by reducing the number of model layers can reduce the huge input data set, help avoid complications, reduce numerical errors and speed up the model calculation process (Yan et al. 2006). Due to the fractured rock nature of the aquifer present in the model domain, and as there are no confining layers present throughout the domain, the model was set up as a two layer model where layer 1 represents the active fracture zone, and layer 2 represents the fracture extinction zone.

3.2.1.1 Ground surface

The Department for Environment and Heritage (DEH) provided regional elevation data in the form of a digital elevation model (DEM) prepared in 2003. The DEM grid was imported into the model as the top of layer 1 with elevation ranging from 700 m AHD near Mount Lofty Summit to 420 m AHD.

3.2.1.2 Layer 1

Layer 1 represents the active unconfined fractured rock zone. A yield versus depth analysis for each geological type found that the aquifers became less yielding with depth; from these analyses (App. A) an active fracture zone was defined. Table 4 displays the thickness of layer 1 for the different geology types (Fig. 3).

Table 4. Layer 1 thickness zones

Aquifer	Thickness (m)
Stonyfell Quartzite	140
Woolshed Flat Shale	160
Basket Range Sandstone	170
Aldgate Sandstone	120
Barossa Complex	200

3.2.1.3 Layer 2

Layer 2 represents the lower part of the aquifer which has been defined as the fracture extinction zone, within this layer conductivity values are significantly lower than the corresponding layer 1 conductivities. This layer extends to a depth of 0 m AHD.

3.3 HYDRAULIC PARAMETERS

For the purpose of this model the equivalent porous medium approach is sufficient to represent hydraulic conductivity. Within this approach individual fractures are not explicitly treated in the model, and the hydraulic conductivity distribution is replaced with a continuous porous medium having equivalent hydraulic properties (Cook 2003).This is a reliable modelling approach if the representative elementary volume (REV), the smallest volume over which a measurement can be made that will yield a value representative of the whole, is defined. This means that each geological zone is considered to be homogeneous and isotropic and hence has consistent hydraulic conductivity values in all directions.

Hydraulic conductivity for the Aldgate Sandstone was sourced from pumping tests carried out in the WMLR by DWLBC for recharge estimates (Green et al. 2007). The hydraulic conductivity for the Woolshed Flat Shale has been sourced from numerous pumping tests carried out in the aquifer material. Hydraulic conductivity values for the Barossa Complex, Basket Range Sandstone and Stonyfell Quartzite are theoretical and have been sourced from *Groundwater* (Freeze & Cherry 1979).

Aquifer hydraulic parameters were altered slightly during steady state calibration to achieve the final values required for accurate calibration, including the introduction of both an area of high and low conductivity in the first layer, and a zone which represents the fault. Figure 7 illustrates the model conductivity zones and final calibrated conductivity figures.

Due to the unconfined nature of the aquifers, specific storage was irrelevant, however specific yield was discretised based on geology type in the model for layers 1 and 2, and a specific yield distribution is shown in Figure 8.

3.4 MODEL BOUNDARIES

The two layer model is of medium complexity, and therefore different boundary conditions were applied to simulate the aquifer, Cox Creek, and the connection between them.

3.4.1 LAYER 1: ACTIVE FRACTURE ZONE

Regional groundwater flow is from the model edge to Cox Creek within the model domain. The following boundary conditions were applied to layer 1 (Fig. 6):

- No-flow boundaries were used where groundwater flow is parallel to the model edge.

- General head boundaries (GHB) were used at the model edges to simulate groundwater flow into and out of the model
- Model river cells were used to simulate the middle to lower reaches of Cox Creek.
- Model drainage cells were used to simulate groundwater seepage from the highland into the tributaries in the upper reaches of Cox Creek.

3.4.2 LAYER 2: FRACTURE EXTINCTION ZONE

Due to this layer commencing at 120 to 200 m below the ground surface, it effectively acts as storage of water for layer 1. There is no significant lateral movement occurring within this layer, therefore no flow boundary conditions were applied to this layer.

3.5 RECHARGE

The major water input in to the catchment, and hence the model, is rainfall (Barnett & Zulfic 1999), with 80% of all rainfall occurring between April and October. Approximately 15% of all rainfall results as recharge.

Estimates of annual groundwater recharge to the different aquifers have been extrapolated from groundwater recharge investigations conducted by DWLBC (Green et al. 2007) between 2005 and 2007 at a number of investigation sites in the WMLR. The recharge is not represented as a percentage of rainfall but rather, an assessment for each individual geological structure based on the local rainfall and the recharge volumes found in the DWLBC recharge investigations. These estimates represent direct recharge into the aquifer from the surface but do not consider recharge into the aquifer from Cox Creek. Recharge distributions are shown in Figure 9 and Table 5.

Table 5. Recharge zones

Aquifer	Recharge (mm/y)
Stonyfell Quartzite	116
Woolshed Flat Shale	83
Basket Range Sandstone	117
Aldgate Sandstone	114
Barossa Complex	119
Cox Creek Channel	153
High recharge area	200
Low recharge area	50

Source: Green et al 2007

Watertable fluctuations appear to be highly correlated with rainfall and hence recharge (Fig. 10), therefore recharge was input into the model on a monthly basis. Temporal variation in recharge (App. B) is designated per month starting 1st January (i.e. days 0–30.5 represents January).

3.6 EVAPOTRANSPIRATION

There is limited data available to determine where evapotranspiration is taking place within the model. Whilst evapotranspiration from the aquifer itself is possible, it is thought that it is only presently occurring at a rate of 250 mm/year with an extinction depth of 2 m across the whole model domain.

3.7 GROUNDWATER USE

Currently as part of the prescription process of the WMLR, land and water use surveys of all licensed groundwater users, with the exemption of stock and domestic users, has been carried out in the majority of WMLR catchments. CCC is not currently considered a priority catchment for land and water use surveys, and as such only 49 land and water use surveys have been undertaken in the model area. Details of groundwater extraction as a function of theoretical crop usage requirements have been calculated for the 49 wells (Table 6).

Table 6. Extraction from wells

Geology type	Number of wells	Extraction (m^3/y)
Stonyfell Quartzite	1	2,736
Woolshed Flat Shale	11	124,256
Basket Range Sandstone	24	490,698
Aldgate Sandstone	2	20,660
Barossa Complex	11	83,967
Total	49	722,317

Well attributes such as elevation, production zone, yield and total depth were obtained from SA Geodata. Where the production zone was unknown the lower 20 m of the well was considered the production zone. Where ground elevation of the well was unknown a DEM was used to define an elevation. Where a total well depth was not attained from SA Geodata or from microfiche the well was not input into the model (four wells).

In transient mode, the yearly extraction is only active for six months of the year from 1st October to 31st March to replicate the irrigation season. The yearly irrigation has been evenly divided throughout these 183 days.

3.8 TIME DISCRETISATION

The model was set up with a 12 month (uniform 30.5 days per month) year to allow stress period alignment. Recharge represents a monthly stress period of 30.5 days, whilst extraction represents a six-month period of 183 days. The six-month summer season simulates limited recharge with groundwater extraction, while the six-month winter season simulates high recharge with no extraction.

The transient model was used to simulate the historical period (1998–2008) using one-month stress periods. For predictive modelling (2008–2028), one-month stress periods were continued.

4 MODEL CALIBRATION

4.1 STEADY STATE MODEL CALIBRATION

Steady state models are used to model equilibrium hydrologic conditions and/or conditions when changes in storage are insignificant. Transient models are used to model time dependent stresses and/or where water is released from, or taken into storage.

Calibration of the model with existing data must be conducted in order to have confidence in predictive modelling. Calibration is necessary to demonstrate that the model can replicate the behaviour of the aquifer system for at least one set of conditions. A sensitivity analysis must also be undertaken to determine the relative importance of model parameters (i.e. the system drivers) in achieving calibration.

Steady state calibration is undertaken to develop a broad-scale hydraulic conductivity distribution by matching modelled to observed potentiometric heads. Steady state calibration was performed by adjusting hydraulic conductivities within reasonable limits. Dynamic stresses and storage effects are excluded from steady state calibration.

The steady state model was calibrated using a constructed potentiometric surface of the CCC of 1998 head levels from observation data collected from the Cox Creek monitoring network (Fig. 11).

Observed potentiometric heads and modelled potentiometric head values correlated well (Fig. 12) and a modelled potentiometric surface was achieved that closely matches the constructed potentiometric surface (Fig. 13) in the Basket Range Sandstone, Stonyfell Quartzite and Woolshed Flat Shale. The Aldgate Sandstone and Barossa Complex were outside of the constructed surface area and therefore no match could be obtained in these geology types, however the model is considered to closely match the constructed surface on a regional scale. Figure 14 shows the 1:1 correlation of observed versus modelled head, which results in a R^2 = 0.9986 and a normalised root mean squared error between modelled and calibrated head value of 1.637%. This value is less than the 5% recommended by the *Groundwater flow modelling guideline* (MDBC 2001) and indicates a very good correlation between modelled and observed data.

4.2 TRANSIENT MODEL CALIBRATION

Transient calibration was undertaken on an iterative basis by adjusting hydraulic parameters, recharge rates and boundary conditions until a satisfactory match with observed data was obtained. The piezometric surface output from the steady state model was used as the starting point for transient model runs up to 2008. Each time a change to the boundary conditions and aquifer hydraulic parameters was made in the transient mode, the steady state model was altered and rerun, with the output being used as the starting point for the transient model.

Model calibration was achieved by the following actions:

1. qualitative comparison between modelled and observed potentiometric heads (contours)
2. quantitative comparison between modelled and observed potentiometric heads (hydrographs)
3. quantitative assessments of the (scaled RMS) iteration residual error (less than 5%)
4. water balance.

The majority of observation wells in the CCC are concentrated in the Basket Range Sandstone and Woolshed Flat Shale. Therefore, the observed data (water level contours and hydrographs) in the Basket

Range Sandstone and Woolshed Flat Shale were mainly used to compare the modelled head levels and trends in the calibration process.

There are no observation wells located in the Barossa Complex, Stonyfell Quartzite or Aldgate Sandstone, and as such the observed potentiometric surface for this area is interpolated and constructed with 2008 data from irrigation wells. Figure 7 displays the final hydraulic conductivity values used to achieve successful calibration.

4.2.1 QUALITATIVE COMPARISON OF POTENTIOMETRIC HEADS (CONTOURS)

Initial qualitative calibration of the transient model was undertaken by simulating the 2008 regional potentiometric heads. The modelled and observed potentiometric heads from 2008 were compared to determine the accuracy of the calibration.

Qualitative comparison between the modelled and observed potentiometric head contours indicates that the modelled distribution closely represents the regional gradient of the observed distribution (Fig. 15).

There is some discrepancy between the modelled and observed surface in the Woolshed Flat Shale and Stonyfell Quartzite area and this is thought to be due to the limited monitoring data available in this area.

4.2.2 QUANTITATIVE COMPARISON OF POTENTIOMETRIC HEADS (HYDROGRAPHS)

Quantitative calibration focused on layer 1 as this is the layer which contains the observation wells with the most data. Quantitative comparison between modelled and observed potentiometric heads (Fig. 16) indicates a similar match in most wells (Fig. 17).

4.2.3 ITERATION RESIDUAL ERROR RMS

The iteration residual error between modelled and observed potentiometric heads of the Cox Creek area was calculated using data from 1998 and 2008. The calculations (Figs. 18–19) indicate a normalised RMS value for 1998 (4.2%) and 2008 (1.67%) for the whole project area. These values are less than the 5% recommended by the *Groundwater flow modelling guideline* (MDBC 2001) and indicate a very good fit between modelled and observed data over the time period considered in the analyses.

4.2.4 WATER BALANCE

The water balance was used to evaluate the model and determine if the model results were consistent with the conceptual model. Table 7.1 shows the water budget for the calibrated transient model in selected years.

Table 7.1. Water balance for transient model

Flow source (ML/y)	1998	2000	2003	2005	2008
Recharge IN	1563	2343	1934	2271	1191
GHB IN	405	311	348	330	389
Evapotranspiration OUT	537	569	535	546	493
River OUT	989	1099	1015	1053	905
Wells OUT	577	759	759	759	759
Change in storage	135	201	8	233	-490
IN–OUT	1	26	-20	1	-87
Discrepancy %	0.02	-0.02	0.4	0.03	2.33

It should be noted that 2008 had significantly lower recharge that all other years in the calibration period. This resulted in a slight increase in the volume of water entering the model via the GHB and a slight decrease in evapotranspiration presumably due to lower water tables, and this has in turn lead to a reduction in flow from the aquifer to the river. Given that extraction rates do not change during the calibration period, the reduction in recharge has required a significant change in storage which doesn't fully compensate the models outputs, therefore there is a 2.3% discrepancy in inflow and outflow from the model.

Table 7.2. Summary of numerical water balance and conceptual model water balance

<table>
<tr><th>Flow source
(ML/y)</th><th>Average from model calibration period</th><th>Minimum modelled</th><th>Maximum modelled</th><th>Conceptual model estimate</th></tr>
<tr><td>Recharge IN</td><td>1863</td><td>1191</td><td>2343</td><td rowspan="2">2532</td></tr>
<tr><td>GHB IN</td><td>355</td><td>308</td><td>420</td></tr>
<tr><td>Evapotranspiration OUT</td><td>538</td><td>493</td><td>570</td><td>400</td></tr>
<tr><td>River OUT</td><td>1015</td><td>905</td><td>1099</td><td>1406</td></tr>
<tr><td>Wells OUT</td><td>743</td><td>577</td><td>759</td><td>722</td></tr>
</table>

Table 7.2 summarises how the water balance from the numerical model compares to that from the conceptual model. It demonstrates that total recharge (from GHB and direct recharge) and extraction, both modelled and conceptual, are quite similar. Evapotranspiration is estimated to be 250mm/year in all areas with an extinction zone of 2 m. Approximately only 10–15% of the model area has a depth to water of less than 2 m therefore the conceptualised evapotranspiration is 400 ML/year, corresponding well with that estimated by the model. Modelled river outflow is quite different to that of the gauged river flow. This could be due to the simplification of the model and using drains to simulate the upper reaches of the model. Or could be due to an overestimate of the conceptual model rive outflow which was extrapolated from gauged data.

4.2.5 TRANSIENT MODEL VERIFICATION

Due to the limited data available it was not possible to verify the model by running it in predictive mode to check whether the simulation reasonably matches the observations of a reserved data set. Instead, calibration verification has been carried out by comparing modelled and observed total recharge volumes.

An analysis of total recharge into the model from GHB and direct recharge indicate that approximately 15% of rainfall recharges the aquifer: this number corresponds very well with recharge estimates carried out in similar geology throughout the MLR by Green et al in 2007.

5 MODEL SENSITIVITY ANALYSIS

5.1 *SENSITIVITY ANALYSIS*

Sensitivity analysis is a procedure carried out to identify the key drivers of a system. It is the process of incrementally varying hydraulic parameters to quantify the aquifers modelled response.

The transient model has been calibrated for aquifer hydraulic parameters and recharge, but requires sensitivity testing to comply with the Murray–Darling Basin Commission's modelling guideline (2001).

All sensitivity tests were carried out to determine the impact on river outflow (ML), and the change in head at the ten-year time step. The estimated change is the change in head with respect to a datum height specific to the location of the observation point at the end of the 10 year modelling period. The river outflow represents the cumulative loss from the model ~~via~~ river cells and drainage cells at the end of the 10 year modelling period. This cumulative volume was then divided by ten to result in the approximate annual volume of river flow, which makes it comparative with observed flow measured at the gauging station.

5.1.1 SENSITIVITY TEST-1: VARIATION OF RECHARGE INCREASING/DECREASING BY 20%

This sensitivity test was conducted to test the impact of variations in recharge (mm/y) on the magnitude of the river outflow and head levels throughout the catchment. Whilst recharge has been estimated from other studies, fractured rock aquifers are highly variable and this sensitivity analysis is required to determine any impacts that differences in recharge may have on the river outflow and head levels throughout the catchment. This test will give an insight into the variations within the model due to under or overestimated recharge volumes.

Sensitivity testing was conducted by varying the recharge to all areas of the model by ±20% of the calibrated recharge. The model was run for ten years (1998–2008).

5.1.1.1 Sensitivity test-1 results

Sensitivity test results (Table 8.1) indicate that:

1. Changes of ±20% to the estimated recharge results in a predicted maximum 104 ML variation in river outflow annually: this is considered significant in comparison to the calibrated total river outflow of 1026 ML (a 10.14% change). Figure 20 shows the model sensitivity to changes in recharge in relation to river outflow.
2. Changes of ±20% to the estimated recharge results in an average 0.79 m variation in head levels at the 10 year-time step: this is considered significant in comparison to the calibrated head levels (a 5% change). Figure 20 shows the model sensitivity to changes in recharge in relation to head levels.

5.1.2 SENSITIVITY TEST-2: VARIATION OF MODEL DOMAIN HORIZONTAL HYDRAULIC CONDUCTIVITY DOUBLING (INCREASING BY 100%) AND HALVING (DECREASING BY 50%)

This sensitivity test was conducted to test the impact of variations in horizontal hydraulic conductivity (m/day) on the magnitude of the river outflow and head levels throughout the catchment. Sensitivity testing was conducted by doubling the hydraulic conductivity in all conductivity zones simultaneously in the model, and by decreasing the hydraulic conductivity by half in all zones simultaneously in the model. The model was run for ten years (1998–2008).

5.1.2.1 Sensitivity test-2 results

Sensitivity test results (Table 8.2) indicate that:

1. Doubling the estimated hydraulic conductivity in all zones results in a predicted maximum 695 ML variation in river outflow annually: this is considered very significant in comparison to the calibrated total river outflow of 1026 ML (a 67% change).
2. Halving the estimated hydraulic conductivity in all zones results in a predicted -413 ML variation in river outflow annually: this is considered significant in comparison to the calibrated total river outflow of 1026 ML (a 40% change). Figure 21 shows the model sensitivity to changes in hydraulic conductivity in relation to river outflow.
3. Doubling the estimated hydraulic conductivity in all zones results in an average 1.19 m variation in head levels at the 10 year-time step: this is considered significant in comparison to the calibrated head levels (a 7% change).
4. Halving the estimated hydraulic conductivity in all zones results in an average 0.86 m variation in head levels at the 10 year-time step: this is considered to be significant in comparison to the calibrated head levels (a 5.07% change). Figure 22 shows the model sensitivity to changes in hydraulic conductivity in relation to head levels.

5.1.3 SENSITIVITY TEST-3: VARIATION OF EACH ZONE HORIZONTAL HYDRAULIC CONDUCTIVITY DOUBLING (INCREASING BY 100%) AND HALVING (DECREASING BY 50%)

This sensitivity test was conducted to test the impact of variations in horizontal hydraulic conductivity (m/day) on the magnitude of the river outflow and head levels throughout the catchment. Sensitivity testing was conducted by doubling the hydraulic conductivity in each conductivity zone separately and by halving the hydraulic conductivity in each zone separately. The model was run for ten years (1998–2008).

5.1.3.1 Sensitivity test-3 results

Sensitivity test results (Table 8.2) indicate that:

1. Doubling the estimated hydraulic conductivity in each zone individually shows significant sensitivity to changes in the Basket Range Sandstone and the Barossa Complex resulting in 352 ML and 205 ML variation in annual flow respectively in comparison to the calibrated total river outflow of 1026 ML (34% and 20% change respectively).
2. Halving the estimated hydraulic conductivity in each zone individually shows significant sensitivity to changes in the Basket Range Sandstone and the Barossa Complex resulting in 371 ML and 179 ML variation in annual flow respectively in comparison to the calibrated total river outflow of 1026 ML (36% and 17.5% change respectively). Figure 21 shows the model sensitivity to changes in hydraulic conductivity in relation to river outflow.
3. Doubling the estimated hydraulic conductivity in each zone individually shows significant sensitivity to changes in the Barossa Complex resulting average head variations of 1.23 m at the 10 year-time step: this is considered significant in comparison to the calibrated head levels (a 7.2% change).
4. Halving the estimated hydraulic conductivity in each zone individually shows significant sensitivity to changes in the Barossa Complex resulting in average head variations of 0.88 m at the 10 year-time step: this is considered significant in comparison to the calibrated head levels (a 5.15%

change). Figure 22 shows the model sensitivity to changes in hydraulic conductivity in relation to head levels.

5.1.4 SENSITIVITY TEST-4: VARIATION OF SPECIFIC YIELD DOUBLING (INCREASING BY 100%) AND HALVING (DECREASING BY 50%)

This sensitivity test was conducted to test the impact of variations in specific yield on the magnitude of the river outflow and head levels throughout the catchment. Sensitivity testing was conducted by doubling the specific yield in all storage zones in the model and by halving the specific yield in all zones in the model. The model was run for ten years (1998–2008).

5.1.4.1 Sensitivity test-4 results

Sensitivity test results (Table 8.1) indicate that:

1. Doubling the estimated specific yield results in a predicted maximum 4.64 ML variation in river outflow annually: this is considered insignificant in comparison to the calibrated total river outflow of 1026 ML (a 0.45% change).
2. Halving the specific yield results in a predicted 3.84 ML variation in river outflow annually: this is considered insignificant in comparison to the calibrated total river outflow of 1026 ML (a 0.37% change). Figure 23 shows the model sensitivity to changes in specific yield in relation to river outflow.
3. Doubling the estimated specific yield results in an average 0.7 m variation in head levels at the 10 year-time step: this is considered insignificant in comparison to the calibrated head levels (a 4.13% change).
4. Halving the calibrated specific yield results in an average 0.64 m variation in head levels at the 10 year-time step: this is considered to be significant in comparison to the calibrated head levels (a 3.79% change). Figure 23 shows the model sensitivity to changes in specific yield in relation to head levels.

Table 8.1. Results of sensitivity testing of variation in storage and recharge

	Recharge (mm/y)			Specific yield		
Parameter value	-20%	50–200	+20%	-50%	0.02–0.2	+100%
Cumulative river outflow (ML)	923	1026	1130	1030	1026	1021
Difference (ML)	102	-	104	3.8	-	4.6
Relative head (m)	16.21	17	17.75	16.63	17	17.71
Difference (m)	0.79	-	0.75	0.64	-	0.70

Table 8.2. Results of sensitivity testing of variation in hydraulic conductivity

	Hydraulic conductivity (m/day)							
Conductivity zone	Parameter Value	-50%	0.001–1	+100%	Parameter Value	-50%	0.001–1	+100%
All	River outflow (ML)	613	1026	1721	Relative head (m)	17.87	17.00	15.81
	Difference (ML)	413	-	695	Difference (m)	0.86	-	1.19

Stonyfell Quartzite	River outflow (ML)	1024	1026	1029	Relative head (m)	17.01	17.00	17.00
	Difference (ML)	2	-	3	Difference (m)	0.01	-	0.00
Woolshed Flat Shale	River outflow (ML)	980	1026	1081	Relative head (m)	16.68	17.00	17.45
	Difference (ML)	45	-	54	Difference (m)	0.32	-	0.44
Basket Range Sandstone	River outflow (ML)	1398	1026	1378	Relative head (m)	17.26	17.00	16.36
	Difference (ML)	371	-	352	Difference (m)	0.26	-	0.65
Barossa Complex	River outflow (ML)	847	1026	1231	Relative head (m)	17.88	17.00	15.75
	Difference (ML)	179	-	205	Difference (m)	0.88	-	1.23
Aldgate Sandstone	River outflow (ML)	1018	1026	1034	Relative head (m)	16.97	17.00	17.04
	Difference (ML)	8	-	7	Difference (m)	0.03	-	0.04

5.1.5 SUMMARY OF SENSITIVITY TESTING

In all cases the sensitivity analysis showed a linear fashion change in observed outputs with change in parameter. Table 9 shows the normalised RMS value for each sensitivity analysis at the end of the calibration period (day 3650).

Table 9. Calibration statistics for the various sensitivity analysis scenarios

Sensitivity analysis scenario	Normalised RMS range
Calibrated model	1.67%
Sensitivity test-1	2.56–2.65%
Sensitivity test-2	3.47–4.46%
Sensitivity test-3	1.45–4.43%
Sensitivity test-4	2.46–2.58%

Overall it can be seen that the model shows significant sensitivity in river outflow and changes to potentiometric heads with changes to:

- increases/decreases in recharge
- increases/decreases to horizontal hydraulic conductivity in all zones simultaneously
- increases/decreases to horizontal hydraulic conductivity in the Basket Range Sandstone and Barossa Complex when varied separately.

It should be noted that the model does not show significant sensitivity in river outflow and changes to potentiometric head with changes to:

- increases/decreases in specific yield
- increases/decreases to horizontal hydraulic conductivity in the Stonyfell Quartzite, Woolshed Flat Shale or Aldgate Sandstone when varied separately.

6 MODEL SCENARIOS AND PREDICTIONS

Once satisfactory calibration of the model has been achieved, the transient model provides a useful predictive tool to quantify the potential impacts of specific stresses on potentiometric heads and other model outputs, over periods that may range from tens to hundreds of years.

6.1 SCENARIOS

The modelling scenarios are summarised in Table 10, and are discussed in detail in the following section. These scenarios have been developed to evaluate the impact of increased abstraction and decreased recharge in response to climatic change within the WMLR, and what affect these stresses may have on regional groundwater head level and river outflow from the catchment.

Table 10. Summary of modelled scenarios and conditions

Scenario	Name	Model run	Recharge	Extraction
S-1	Current conditions continued	1998–2028	No change	No change
S-2	Increased extraction	2008–2028	No change	**20% increase**
S-3	Decreased recharge	2008–2028	**20% reduction**	No change
S-4	Decreased recharge, increased extraction	2008– 2028	**20% reduction**	**20% increase**
S-5	Decreased extraction	2008–2028	No change	**20% reduction**
S-6	Decreased recharge, decreased extraction	2008–2028	**20% reduction**	**20% reduction**
S-7	Pristine conditions	2008–2028	**85/40% reduction**	**No extraction**

6.2 SCENARIO-1: CURRENT CONDITIONS CONTINUED

Transient Scenario-1 predicts the groundwater head values and river outflow expected to occur between 2008–2028 assuming there is no change in extraction rates and recharge remains constant.

6.2.1 SCENARIO-1: CONDITIONS

The following conditions are applied to the transient model:

1. recharge to the area is continued for 2008–2028 as a repeated cycle of 1998–2008 recharge rates
2. constant extraction occurs at the current level.

6.2.2 SCENARIO-1: PREDICTION RESULTS

Scenario-1 prediction results represent the current conditions continued scenario and hence provide a baseline for all other scenarios to be compared to.

Groundwater hydrographs (Figs. 24–30), with the exception of ONK014 (which continues to decrease), remain steady with seasonal fluctuations. The potentiometric surfaces for December 2008 and December 2028 are similar in shape, with the exception of the area around ONK014, however the watertable is slightly higher across the whole catchment (Fig. 32).

Losses from the aquifer to Cox Creek appear to be well correlated with recharge, in years of high rainfall, and hence recharge, there is a response, although slightly delayed, which results in a higher loss from the aquifer to the creek (Fig. 31).

6.3 SCENARIO-2: INCREASED EXTRACTION

Transient Scenario-2 predicts the groundwater head values and river outflow expected to occur between 2008–2028 assuming an increase in extraction rates of 20%, where recharge remains constant.

6.3.1 SCENARIO-2: CONDITIONS

The following conditions are applied to the transient model:

1. recharge to the area is continued for 2008–2028 as a repeated cycle of 1998–2008 recharge rates
2. extraction occurs at a rate increased by 20% on current extraction.

6.3.2 SCENARIO-2: PREDICTION RESULTS

Increasing extraction by 20% results in predicted head levels which are slightly lower than S-1 predicted head levels in all wells (Figs. 24–30). The potentiometric surface for 2028 for S-2 is very similar to the 2028 potentiometric surface predicted for S-1, with slight discrepancies near ONK014 due to the increased extraction rate which causes a more pronounced cone of depression around well 662812793 (Fig. 33).

Increasing extraction by 20% results in a predicted 3.1% (average) reduction in flow from the aquifer to Cox Creek (Appendix C), in relation to S-1 predictions (Fig. 31).

6.4 SCENARIO-3: DECREASED RECHARGE

Transient Scenario-3 predicts the groundwater head values and river outflow expected to occur between 2008–2028 assuming there is no change in extraction rates, but recharge is decreased by 20%.

6.4.1 SCENARIO-3: CONDITIONS

The following conditions are applied to the transient model:

1. recharge to the area is decreased by 20% for the period 2008-2028
2. constant extraction occurs at the current level.

6.4.2 SCENARIO-3: PREDICTION RESULTS

Reducing recharge by 20% results in predicted head levels which are slightly lower than S-1 predicted head levels in all wells (Figs. 24–30). These head levels are very similar to the S-2 predicted results. The potentiometric surface for 2028 for S-3 is similar in shape to the 2028 potentiometric surface predicted for S-1, however there are slight discrepancies near ONK014, and there is an overall lower watertable across the project area (Fig. 34).

Reducing recharge by 20% results in a predicted 10.7% (average) reduction in flow from the aquifer to Cox Creek (Appendix C), in relation to S-1 predictions (Fig. 31).

It should be noted that a decrease in recharge of 20% has a very similar effect on head levels as a 20% increase in extraction. Given that there is an approximate 2000 ML/year difference between extraction and recharge, the volume of water further removed from the aquifer in S-2 (increased extraction) does not equate to the volume of water withheld from the aquifer in S-3 (decreased recharge). A 20% increase in extraction (S-2) involves removing a further 151ML/year from the aquifer, whilst a 20% reduction in recharge (S-3) results in withholding 314ML/year recharge from the aquifer. The majority of the 163ML/year difference in these volumes can be accounted for by decreased flows to Cox Creek during S-3.

6.5 SCENARIO-4: DECREASED RECHARGE, INCREASED EXTRACTION

Transient Scenario-4 predicts the groundwater head values and river outflow expected to occur between 2008–2028 assuming an increase in extraction rates of 20%, with a decrease in recharge of 20%.

6.5.1 SCENARIO-4: CONDITIONS

The following conditions are applied to the transient model:

1. recharge to the area is decreased by 20% for the period 2008–2028
2. extraction occurs at a rate increased by 20% on current extraction.

6.5.2 SCENARIO-4: PREDICTION RESULTS

S-4 represents the worst case scenario, in which recharge is decreased and extraction is subsequently increased.

Reducing recharge by 20% in conjunction with increasing extraction by 20% results in predicted head levels which are significantly lower than S-1 predicted head levels in all wells (Figs 24–30). The potentiometric surface for 2028 for S-4 is similar in shape to the 2028 potentiometric surface predicted for S-1, however there are slight discrepancies near ONK014, and there is an overall lower watertable across the project area (Fig. 35).

Reducing recharge by 20% in conjunction with increasing extraction by 20% results in a predicted 13.5% (average) reduction in flow from the aquifer to Cox Creek (Appendix C), compared to S-1 predictions (Fig. 31).

6.6 SCENARIO-5: DECREASED EXTRACTION

Transient Scenario-5 predicts the groundwater head values and river outflow expected to occur between 2008–2028 assuming a decrease in extraction rates of 20%.

6.6.1 SCENARIO-5: CONDITIONS

The following conditions are applied to the transient model:

1. recharge to the area is continued for 2008–2028 as a repeated cycle of 1998–2008 recharge rates
2. extraction occurs at a rate decreased by 20% on current extraction.

6.6.2 SCENARIO-5: PREDICTION RESULTS

Reducing extraction by 20% results in predicted head levels which are significantly higher than S-1 predicted head levels in all wells (Figs. 24–30). The potentiometric surface for 2028 for S-5 is similar in shape to the 2028 potentiometric surface predicted for S-1, however there are slight discrepancies near ONK014 where the cone of depression is decreased in size due to the reduction in extraction, and there is an overall slightly higher watertable across the project area (Fig. 36).

Reducing extraction by 20% results in a predicted 3% (average) increase in flow from the aquifer to Cox Creek (Appendix C), in relation to S-1 predictions (Fig. 31).

6.7 SCENARIO-6: DECREASED RECHARGE, DECREASED EXTRACTION

Transient Scenario-6 predicts the groundwater head values and river outflow expected to occur between 2008–2028 assuming a decrease in both extraction rates and recharge of 20%.

6.7.1 SCENARIO-6: CONDITIONS

The following conditions are applied to the transient model:

1. recharge to the area is decreased by 20% for the period 2008–2028
2. extraction occurs at a rate decreased by 20% on current extraction.

6.7.2 SCENARIO-6: PREDICTION RESULTS

Reducing recharge by 20% in conjunction with reducing extraction by 20% produces predicted head levels which are very similar to those of S-1 predicted head levels in all wells (Figs. 24–30). This may be used to indicate that to maintain current water levels with climatic induced reductions in recharge (i.e. lower rainfall), a 20% (or slightly higher) reduction in extraction may be required. The potentiometric surface for 2028 for S-6 is similar in shape to the 2028 potentiometric surface predicted for S-1, however there is a slightly lower watertable present across the project area (Fig. 37).

Reducing recharge by 20% in conjunction with reducing extraction by 20% results in a predicted 7.7% (average) reduction in flow from the aquifer to Cox Creek (Appendix C), in relation to S-1 predictions (Fig. 31).

6.8 SCENARIO-7: PRISTINE CONDITIONS

Transient S-7 predicts the groundwater head values and river outflow expected to occur between 2008–2028 assuming pristine land conditions, this involves simulating no extraction and decreased recharge rates. It is assumed that under highly vegetated conditions 85% of summer recharge is intercepted by vegetation, whilst 40% of winter recharge is intercepted by vegetation.

6.8.1 SCENARIO-7: CONDITIONS

The following conditions are applied to the transient model:

1. recharge to the area is decreased by 85% in summer months and by 40% in winter months for the period 2008–2028 to represent a pristine environment where vegetation is intercepting a significant volume of rainfall and limits recharge
2. extraction does not occur.

6.8.2 SCENARIO-7: PREDICTION RESULTS

Reducing recharge by 85% in summer months and 40% in winter months in conjunction with turning off all extraction produces predicted head levels which are very significantly less seasonally variable in all wells than those predicted in S-1 (Figs. 24–30). The summer head levels also appear to be consistently higher than those of S-1 whilst the winter head levels are slightly lower than those of S-1. The potentiometric surface for 2028 for S-7 is similar in shape to the 2028 potentiometric surface predicted for S-1, however the cone of depression located near ONK014 is absent, and the watertable is slightly lower across the whole project area (Fig. 38).

Reducing recharge by 85% in summer months and 40% in winter months in conjunction with turning off all extraction results in a predicted 25% (average) reduction in flow from the aquifer to Cox Creek (Appendix C), in relation to S-1 predictions (Fig. 31).

After completing groundwater–surface water interaction studies in three contrasting hydrologic environments in the MLR and Kangaroo Island (KI), Green (2010) has determined that pristine catchments have the capacity to increase the residence time of water in the surface system when compared with the open channels observed in cleared catchments. This is due to fallen trees and large amounts of organic matter damming the creeks causing water to spread out laterally to form a swamp like environment.

In pristine catchments, winter and occasional summer rain is buffered in the swamp systems resulting in a perennial state of the surface water system without the need for connection to the regional groundwater system. This is in contrast to cleared catchments, which rapidly drain the catchment of surface runoff and groundwater derived baseflow due to the absence of vegetation, and channelled creek lines.

If the Cox Creek fractured rock catchment retained native vegetation, it would slow the rate of surface runoff, potentially increasing stream bed recharge. Thereafter, if deposited vegetation detritus were to slow the drainage of baseflow through the surface system during summer, similarly to the pristine catchment, the duration of surface stream flow may be significantly greater than in the current cleared state of these catchments. This effect of slowing of surface water runoff by native vegetation was not replicated in the model. Hence, the reduction in discharge to Cox Creek that is predicted by the model does not express the combined effects of pristine vegetation on the creek system, which may be to ultimately increase the summer flow duration.

Table 11. Summary of predictive scenario river outflow variances from S-1

Prediction scenario	River outflow change %
Scenario-2	-3.1%
Scenario-3	-10.7%
Scenario-4	-13.5%
Scenario-5	3%
Scenario-6	-7.7%
Scenario-7	-25%

7 MODEL LIMITATIONS AND UNCERTAINTIES

> *It is important to recognise that there is no such thing as a perfect model, and all models should be regarded as works in progress of continuous improvement as hydrogeological understanding and data availability improves. By definition, model limitations comprise relatively negative statements, and they should not necessarily be viewed as serious flaws that affect the fitness for purpose of the model, but rather as a guide to where improvements should be made during work* (MDBC 2001).

As with all computer simulated groundwater flow models of natural systems, the assumptions and simplifications of both the conceptual and numerical models cause limitations to their appropriate use and to the interpretations of predictive simulation results.

The following factors are considered to be the most significant in influencing model accuracy and uncertainty in results.

7.1 GROUNDWATER EXTRACTION

Groundwater extraction data was estimated from 49 land water use surveys undertaken in the catchment area. As Cox Creek was not a priority area for the prescription process of the WMLR, not all irrigators had been surveyed at the time of data collation. Data came in the form of crop type and area, which then had to be converted to a volumetric extraction. To complete this conversion, PIRSA supplied theoretical crop requirement (TCR) numbers which were utilised. As such there may be some discrepancies with modelled and actual groundwater use given that not all land owners were surveyed and that stock and domestic use in the catchment was omitted. It should be noted, however that groundwater extraction is likely to be overestimated rather than underestimated as the TCR numbers are generally considered, by previous experience using these numbers, to be quite generous. It is likely that the total volume of water extracted from the aquifer is similar to actual extraction volumes, however the model displays the extraction as concentrated use from a minimal number of wells rather than a spatial distribution of use. This may have implications for the spatial response of the aquifer to increased or decreased extraction rates.

7.2 HYDRAULIC PARAMETERS

Hydraulic conductivity and storage values throughout the catchment are not well understood. Due to the fractured rock nature of the aquifers the hydraulic conductivity is neither homogeneous nor isotropic, however this is how the model has been constructed. There is limited data available to determine the direction of anisotropy for the various aquifers, and minimal aquifer tests have been undertaken to determine the spatial distribution of the conductivity of the aquifers. As such the model shows a simplified version of the natural system. Sensitivity tests (Figs. 22–23) indicate that the model is only significantly sensitive to changes of conductivity within the Basket Range Sandstone and the Barossa Complex aquifers.

It should be noted that the potentiometric surface in the area surrounding ONK014, in the Woolshed Flat Shale, was very difficult to replicate. This area is not well understood—the aquifer in this location is known to have uncharacteristically high yielding wells, however the source of water and properties of the aquifer in this location have yet to be defined. It is thought that some highly conductive fractures may be present in this area which, due to our limited knowledge, were not modelled.

Two wells located in the Mount Lofty Botanic Garden (Fig. 11, green extraction wells) which have a combined use of 261.01 ML/year needed to be omitted from the model to allow potentiometric surfaces in the area near ONK014 to be realistic. There is obvious discrepancy between modelled and observed heads in ONK014 due to the lack of knowledge of hydraulic properties in this area.

7.3 MODEL LAYERS

Given the fractured rock nature of the aquifers it was considered that the quaternary or weathered basement sediments overlying the rock were negligible and had limited influence over the model and therefore were omitted. Model layers were simplified to suit our purpose of the model to only include two layers which represent the active fracture zone and the fracture extinction zone. It is possible however that there are changes in geology with depth that have not been considered.

7.4 SIMPLIFICATION OF COX CREEK

Cox Creek has many tributaries, most of which are ephemeral. As such only the lower reaches or perennial section of Cox Creek was modelled. The larger two tributaries were modelled with drain cells which allow groundwater to enter the drain cells but do not allow the water in the drains to enter the aquifer. This means that the surface water–groundwater interactions in the upper reaches were not modelled to simulate real conditions, and as such water balances may not completely reflect the natural system balances.

7.5 BOUNDARY CONDITIONS

The model predictions are likely to be impacted by constraining boundary conditions, in particular the GHB. As recharge to the model includes both that of direct recharge through the first layer and recharge through the GHB, decreases to GHB fluxes should have been applied in predictions where recharge was decreased, however this did not occur. The GHB shows an increase of flux into the model in Scenarios 3, 4, 6 and 7 due to the decreased recharge rates applied. Changes to the GHB by recharge decreases alone (excluding extraction stresses applied in Scenarios 4, 6 and 7) result in an additional 8.4% of flux through the GHB to the model domain, however this volume equates only to 2.6% of total (direct and GHB) recharge. It is therefore unlikely that this additional recharge would have significant influence on the predictions which involved decreased recharge rates.

Due to the above assumptions and uncertainties this model should only be used to observe regional scale trends as there is limited knowledge to extrapolate the model to a local or intermediate scale, and to confirm the conceptual model.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 MODELLING RESULTS

Predictive modelling results indicate that the system is responsive to changes in both recharge and extraction and as such, the system should be managed to reflect these findings.

Under extended current conditions (baseline scenario) head levels are maintained and no new cones of depression are presented. The depression around well 662812793, located near ONK014, is actually slightly minimised. Water levels across the catchment rise slightly and river outflow (loss from the aquifer to the rivers and drains) volume remains somewhat constant to that of the ten-year calibration period.

Increasing extraction in the project area causes declines in head levels across the catchment and reduces river outflow, whilst decreases in extraction result in recovered head levels and increased groundwater flux into Cox Creek.

Reductions in recharge result in head level reductions across the whole project area, this in turn significantly diminishes flow to Cox Creek. It should be noted that the model responds similarly to reductions in recharge as it does in increases in extraction.

Predictive modelling indicates that in the worst case scenario where recharge is decreased and therefore extraction is increased, a likely response to climate variability, it is likely to cause an adverse effect to the aquifer and Cox Creek. The scenario results in significant declines in groundwater flow to Cox Creek and drastic drops in head levels where in some cases winter highs are nearly equivalent to baseline summer lows.

Decreased recharge in conjunction with decreased extraction results in very similar, but slightly lower, head levels to that produced in the baseline scenario. It should be noted that 20% of recharge does not equate volumetrically to 20% of extraction, therefore there is diminished flow of groundwater to Cox Creek compared to the baseline scenario.

In simulated pristine conditions the model indicates that with reduced recharge, due to evapotranspiration and interception from vegetation and no extraction, the seasonal variability of head levels is minimised. As a result the summer head levels are consistently higher than those of the baseline scenario whilst the winter head levels are slightly lower than those of the baseline scenario. The potentiometric surface contains no cones of depression but is slightly lower than that of the baseline scenario. River outflow volume is the lowest of all scenarios, however it is more consistent throughout the year, with less extreme highs and lows.

Prediction scenario	River outflow change %
Scenario-2	-3.1%
Scenario-3	-10.7%
Scenario-4	-13.5%
Scenario-5	3%
Scenario-6	-7.7%
Scenario-7	-25%

8.2 RECOMMENDATIONS FOR MANAGEMENT

The model suggests the CCC surface and groundwater systems are highly responsive to changes in both recharge and extraction, therefore management strategies should consider these findings. It is also imperative to maintain the ecological value of Cox Creek and the integrity of the aquifers present. Decreases to recharge and increases to extraction both result in the reduction of groundwater flow to Cox Creek. This is likely to have potential adverse impacts on macroinvertebrates and fish species, such as climbing galaxias and mountain galaxias, surveyed to be present in Cox Creek (Hammer, Wedderburn & van Weenan 2009). There are also a number of permanent pools (>15 m in length) located within Cox Creek which may act as ecological refuges during summer months or periods of extended drought. It should also be considered that diminished flow to Cox Creek in turn results in diminished flow within the Onkaparinga River, which also acts as a refuge for many species.

Management strategies should consider the implications of these findings on the permanent pools, current flow regime and water levels of the CCC. These strategies should also take into account the high dependence of the catchment on recharge and extraction. Such strategies could include:

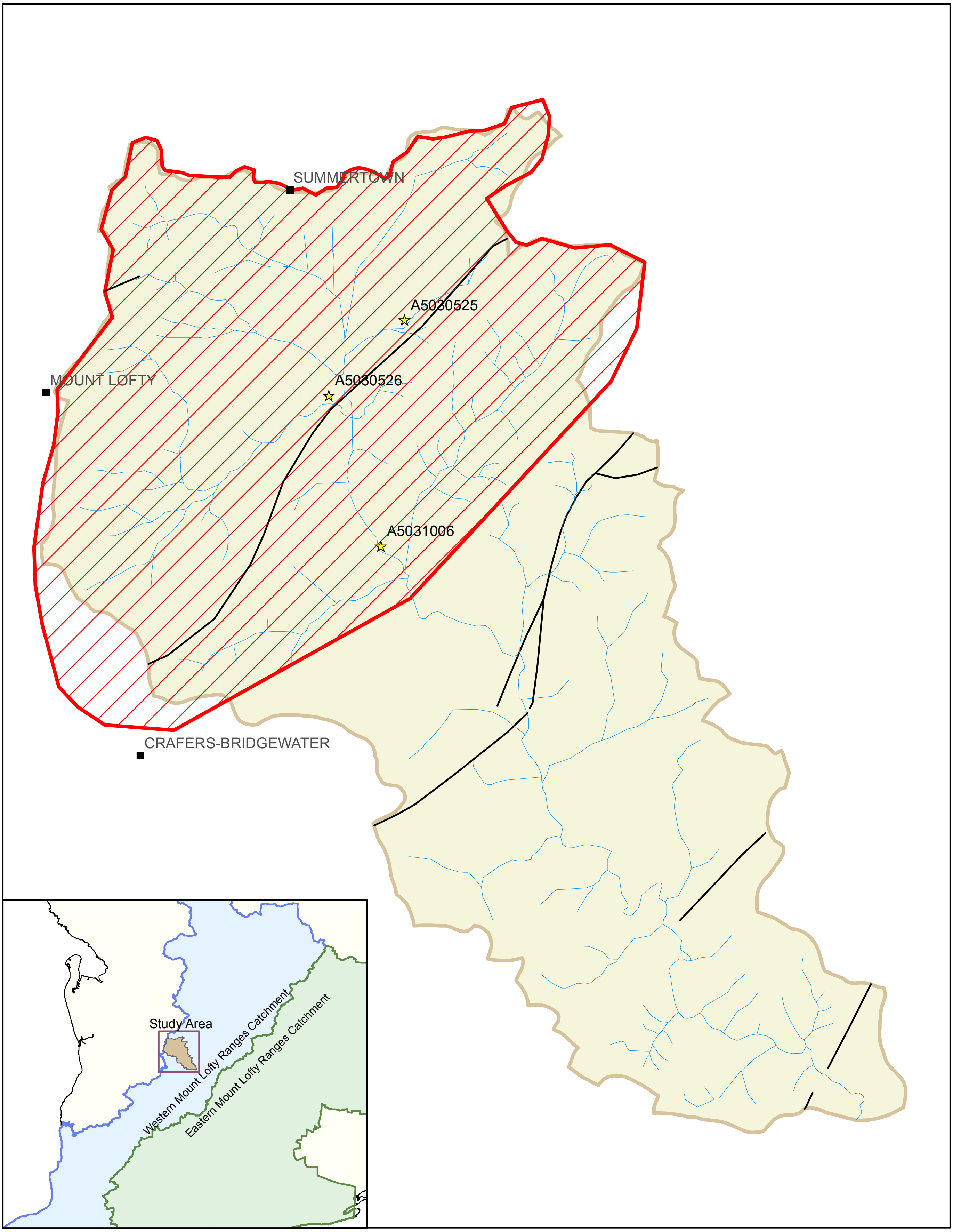
1. The application of buffer zones between Cox Creek and groundwater extraction points to prevent direct impacts on stream flow;
2. Applying restrictions on extraction in the modelled portion of CCC, such that it does not exceed current extraction levels; and
3. Sustained decreases in recharge due to variation in climate over a decade time scale need to be offset by decreases in groundwater extraction if water levels and the Cox Creek flow regime are to be maintained.

8.3 RECOMMENDATIONS FOR FUTURE MODELLING

To address some of the model limitations, the following work is recommended:

- Extraction occurring in the model domain should be revised to include all irrigation and commercial wells. The use of stock and domestic wells should also be considered;
- More investigations and sampling is required to further refine the hydraulic parameters of the Woolshed Flat Shale in the area near the Botanic Gardens and ONK014;
- The shallow sedimentary layer should be modelled where present as this may give a better indication of the surface water–groundwater interactions taking place in the CCC;
- Cox Creek should be modelled in more detail using gauged data as a calibration tool; and
- Scenarios in which direct recharge is decreased should be remodelled to include the corresponding GHB flow reductions.

FIGURES



Guaging Stations
Localities
Cox Creek
Faultlines
Model Domain
Cox Creek Catchment

Figure 1. Cox Creek Catchment and Model Domain

0 0.5 1 1.5 2 km

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Science, Monitoring and Information Division
Department of Water, Land and Biodiversity Conservation
Projection: Transverse Mercator
Datum: Geocentric Datum of Australia 1994
Date: March 2010

Government of South Australia
Department of Water, Land and Biodiversity Conservation

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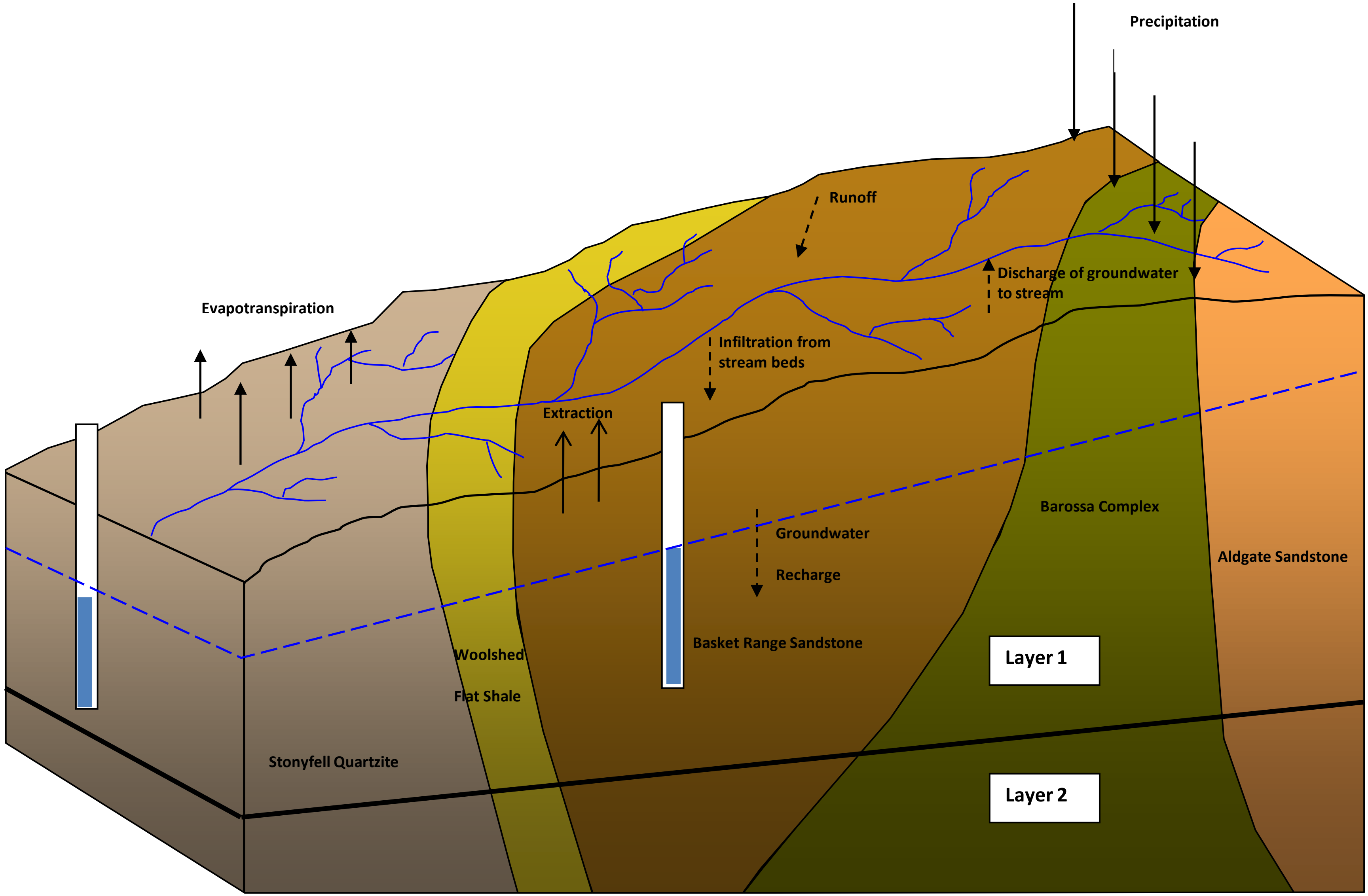

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Figure 2: Elementary conceptual hydrogeological model and numerical model structure

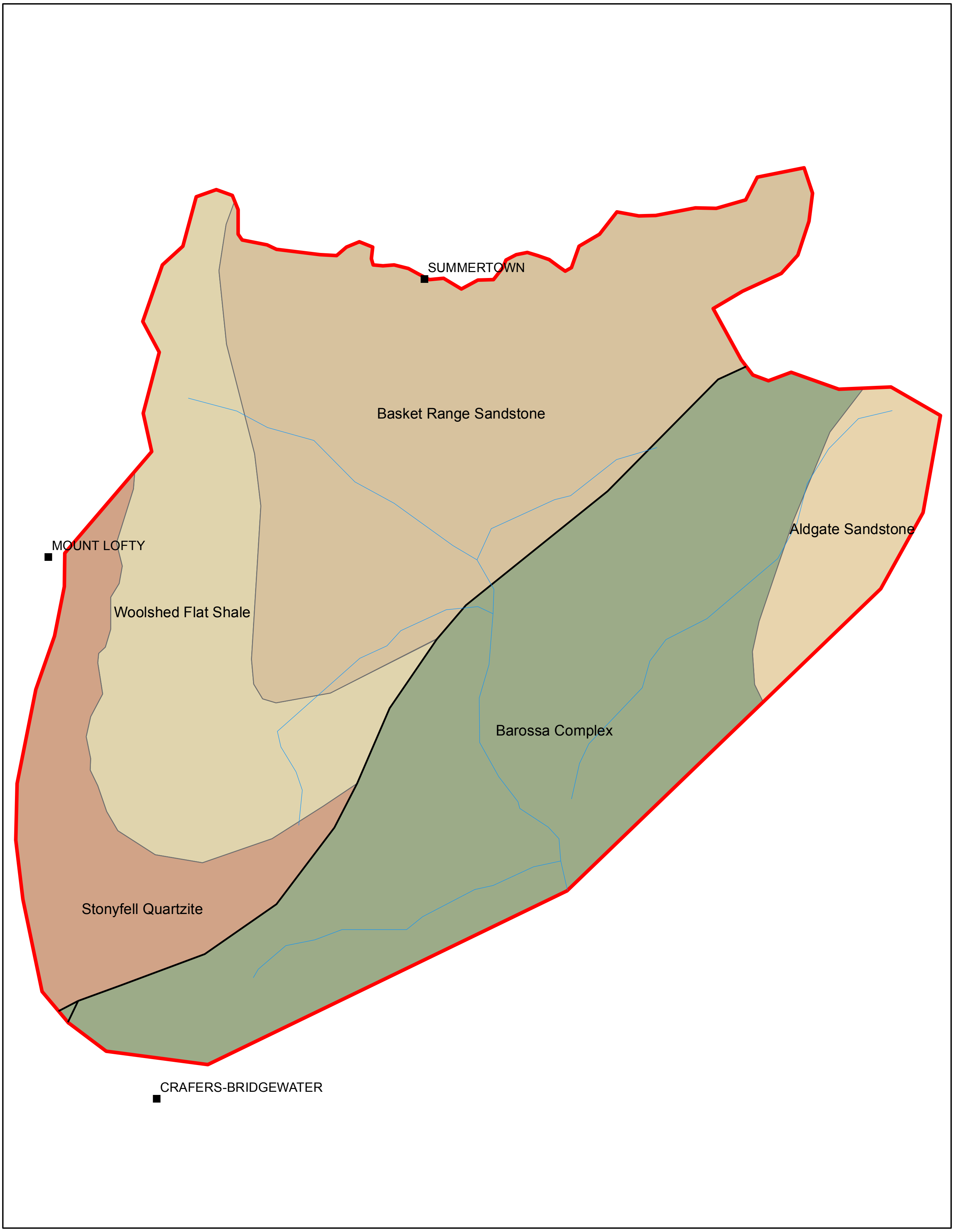

Figure 3. Aquifer Zones

- Drainage
- Faults
- Model Domain
- Basket Range Sandstone
- Stonyfell Quartzite
- Woolshed Flat Shale
- Aldgate Sandstone
- Barossa Complex

0 0.5 1 1.5 2 km

Produced By: Groundwater Group
Science, Monitoring and Information Division
Department of Water, Land and Biodiversity Conservation
Projection: Transverse Mercator
Datum: Geocentric Datum of Australia 1994
Date: March 2010

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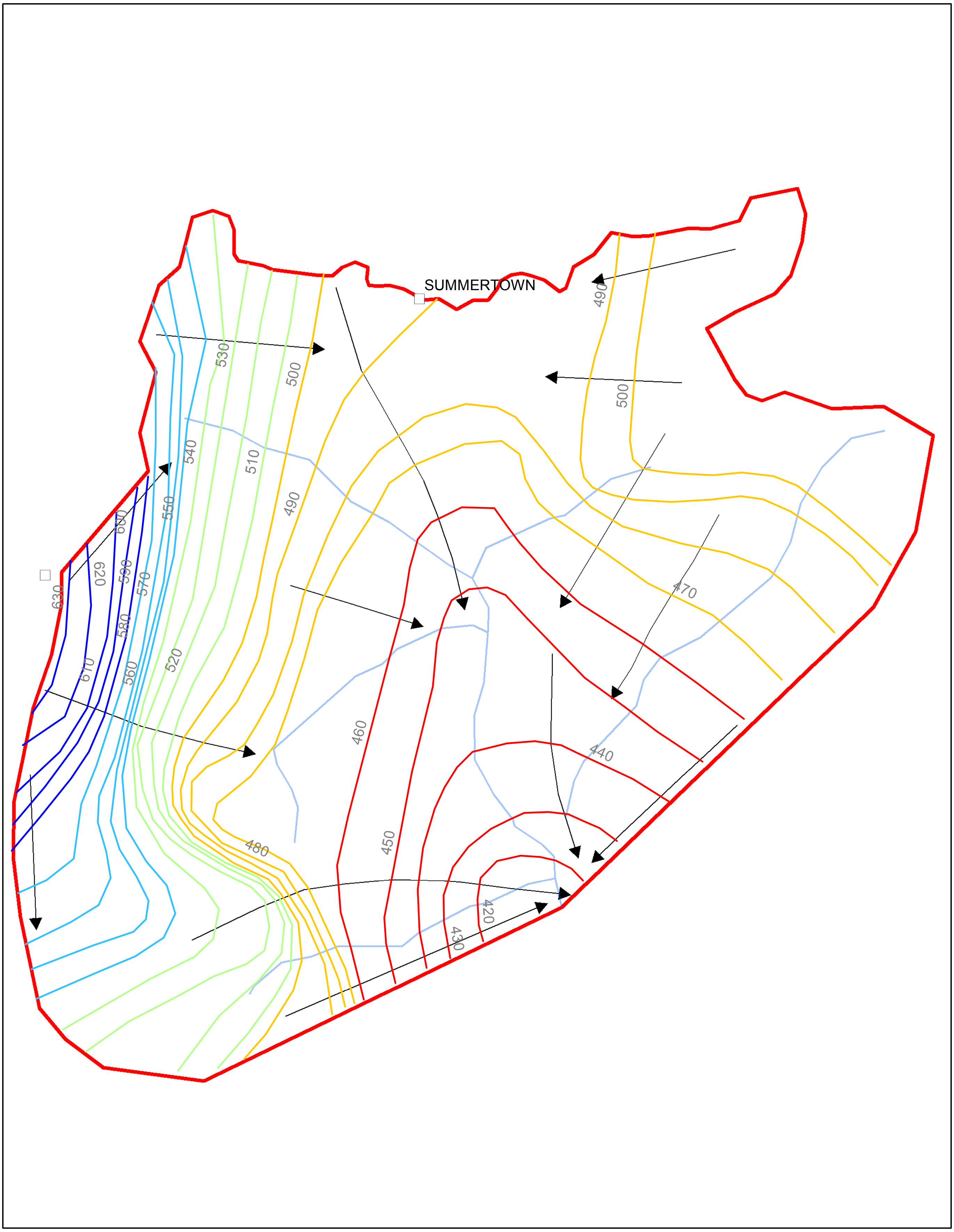

Figure 4. Potentiometric Surface and Groundwater Flow Direction

Potentiometric Surface

- 400 - 450
- 451 - 500
- 501 - 540
- 541 - 600
- 601 - 670
- Flow Directions

0 0.4 0.8 1.2 1.6 km

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Projection: Transverse Mercator
Datum: Geocentric Datum of Australia 1994
Date: March 2010

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M:\Projects_GW\MLR\Western MLR\Cox Creek_Gis\Outputs\Potentiometric Surface & Groundwater Flow Direction.mxd May 2009 S.Stewart

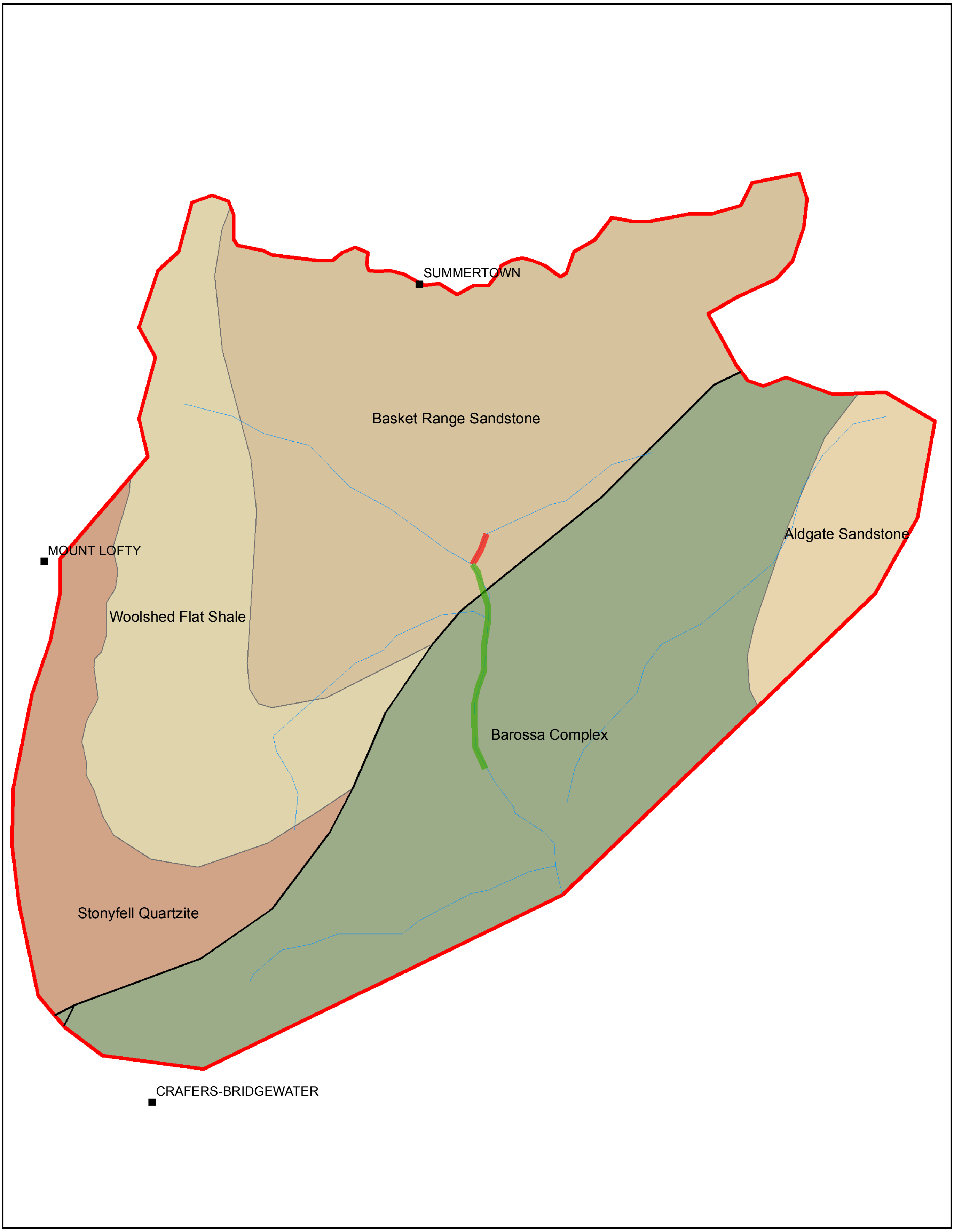

Figure 5. Locations of groundwater-surface water interaction

GW SW Interaction

- Occasional gw-sw interaction
- gw-sw interaction occurring
- Model Domain

0 0.4 0.8 1.2 1.6 km

Produced By: Groundwater Group
Science, Monitoring and Information Division
Department of Water, Land and Biodiversity Conservation
Projection: Transverse Mercator
Datum: Geocentric Datum of Australia 1994
Date: March 2010

M:\Projects_GW\Mt_Lofty_Ranges\Western MLR\Cox Creek_Gis\Outputs\Aquifer_zones.mxd August 2008 S.Stewart

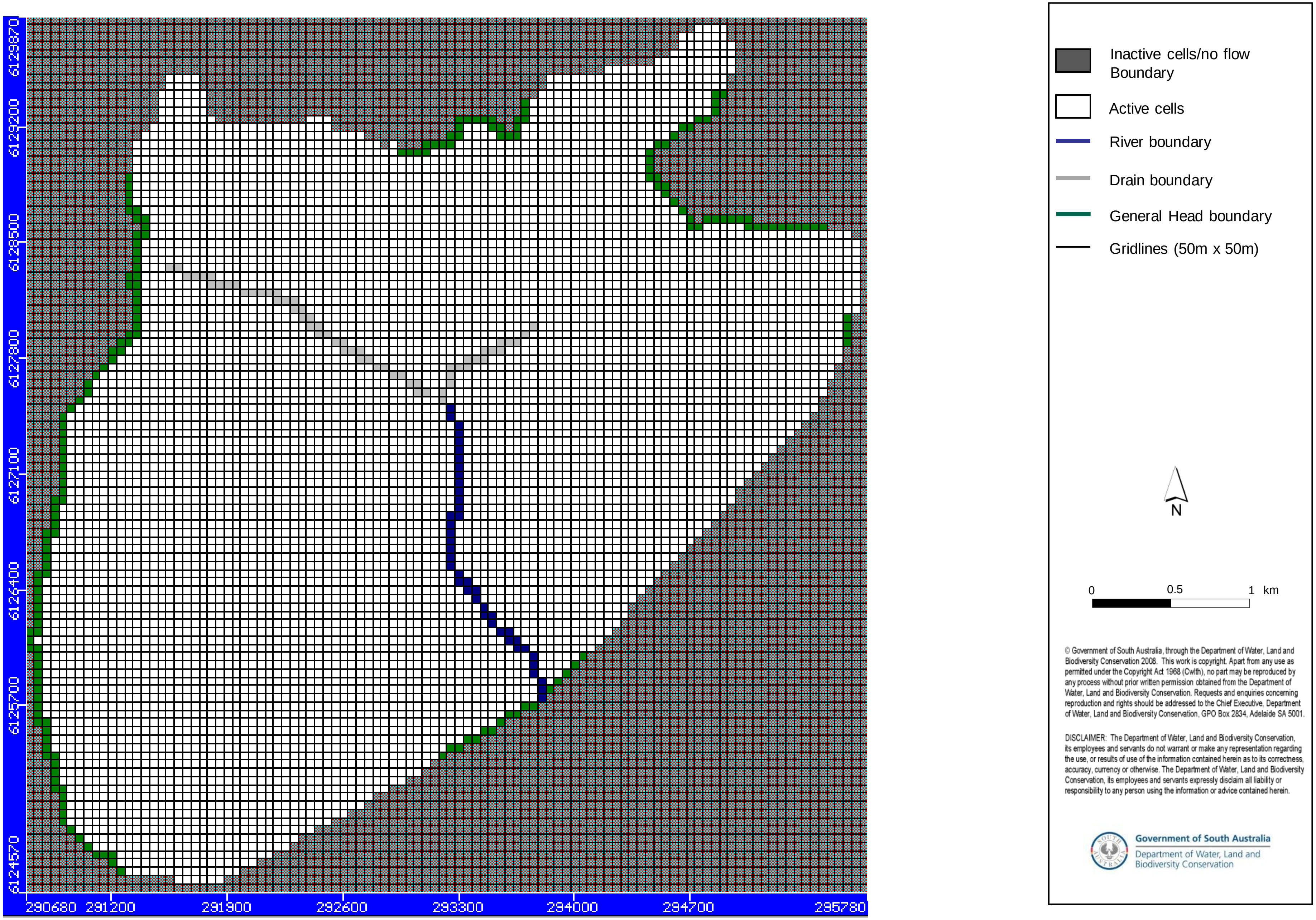

Figure 6: Model domain, grid and boundary conditions

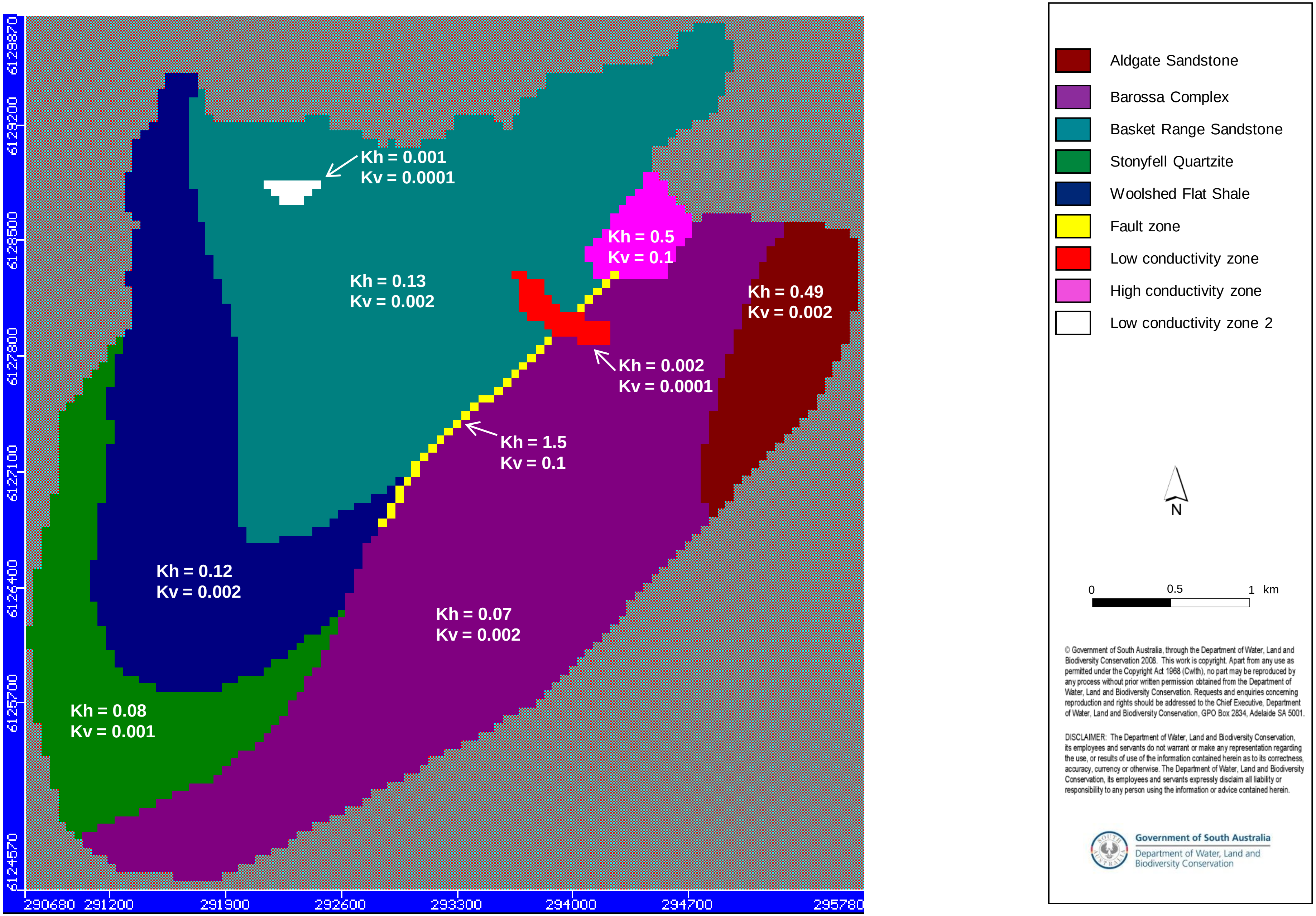

Figure 7: Model hydraulic conductivity zones and values

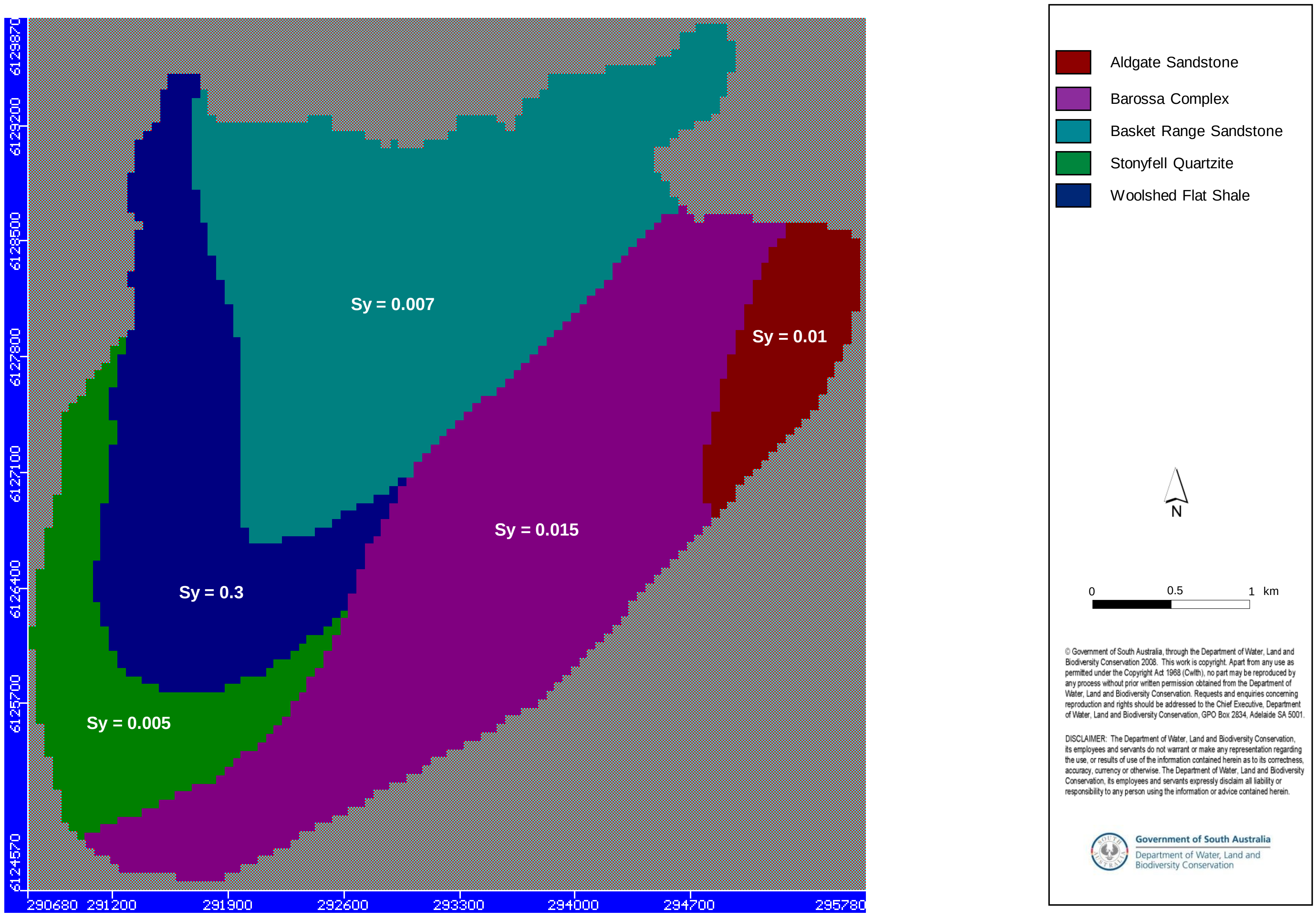

Figure 8: Specific yield distribution

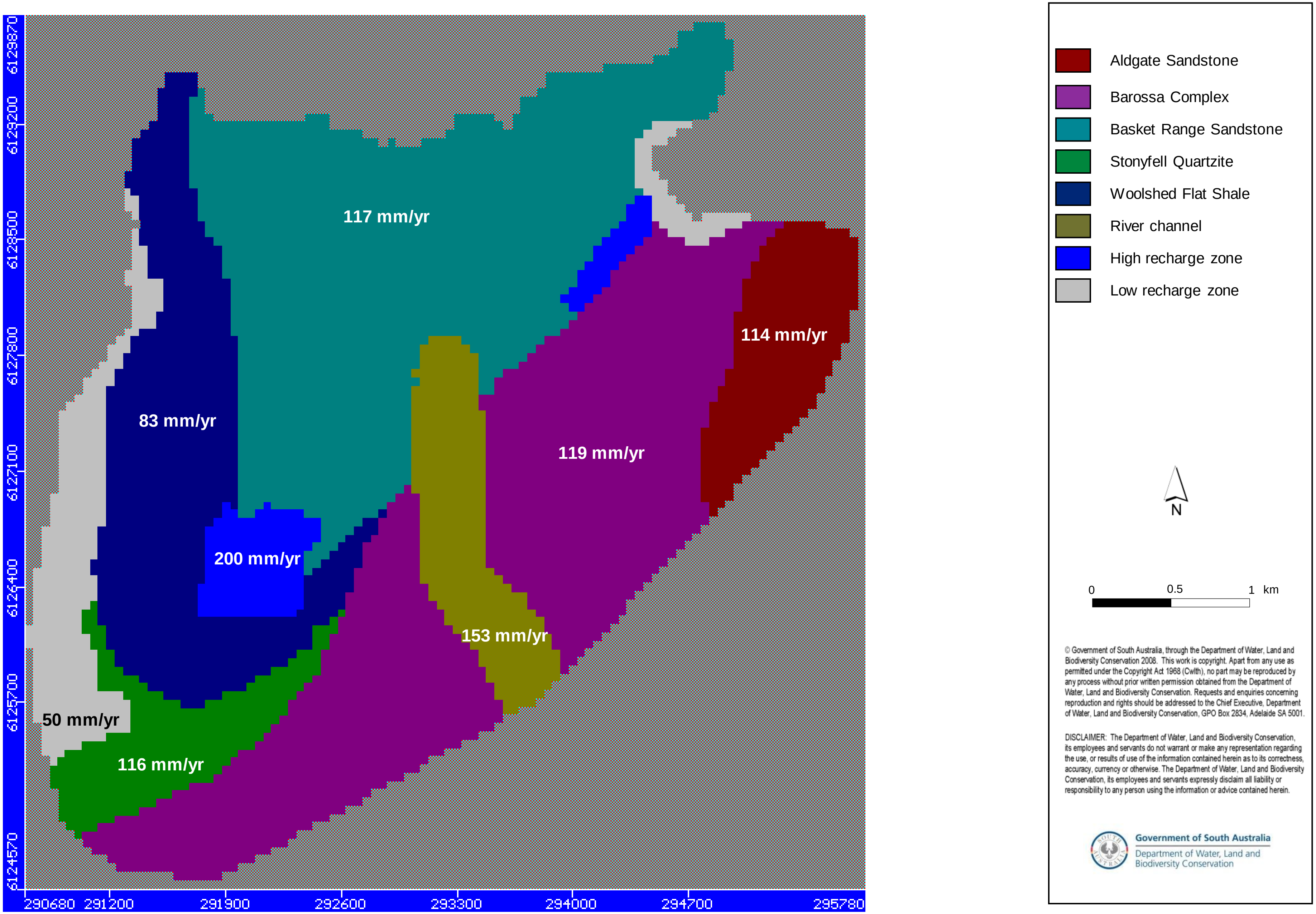

Figure 9: Recharge distribution

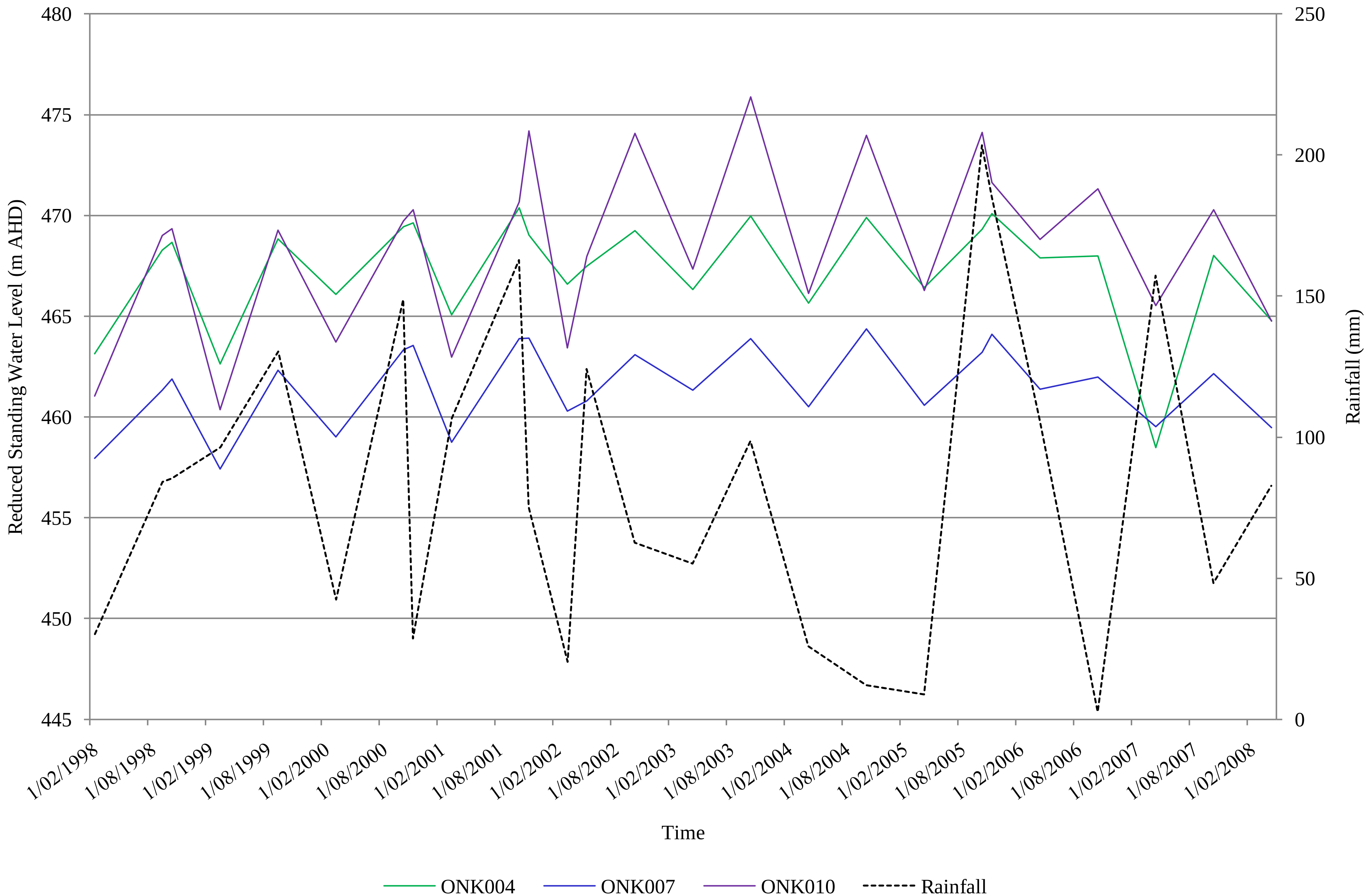

Figure 10: Rainfall water table correlation (ONK004, ONK007, ONK010)

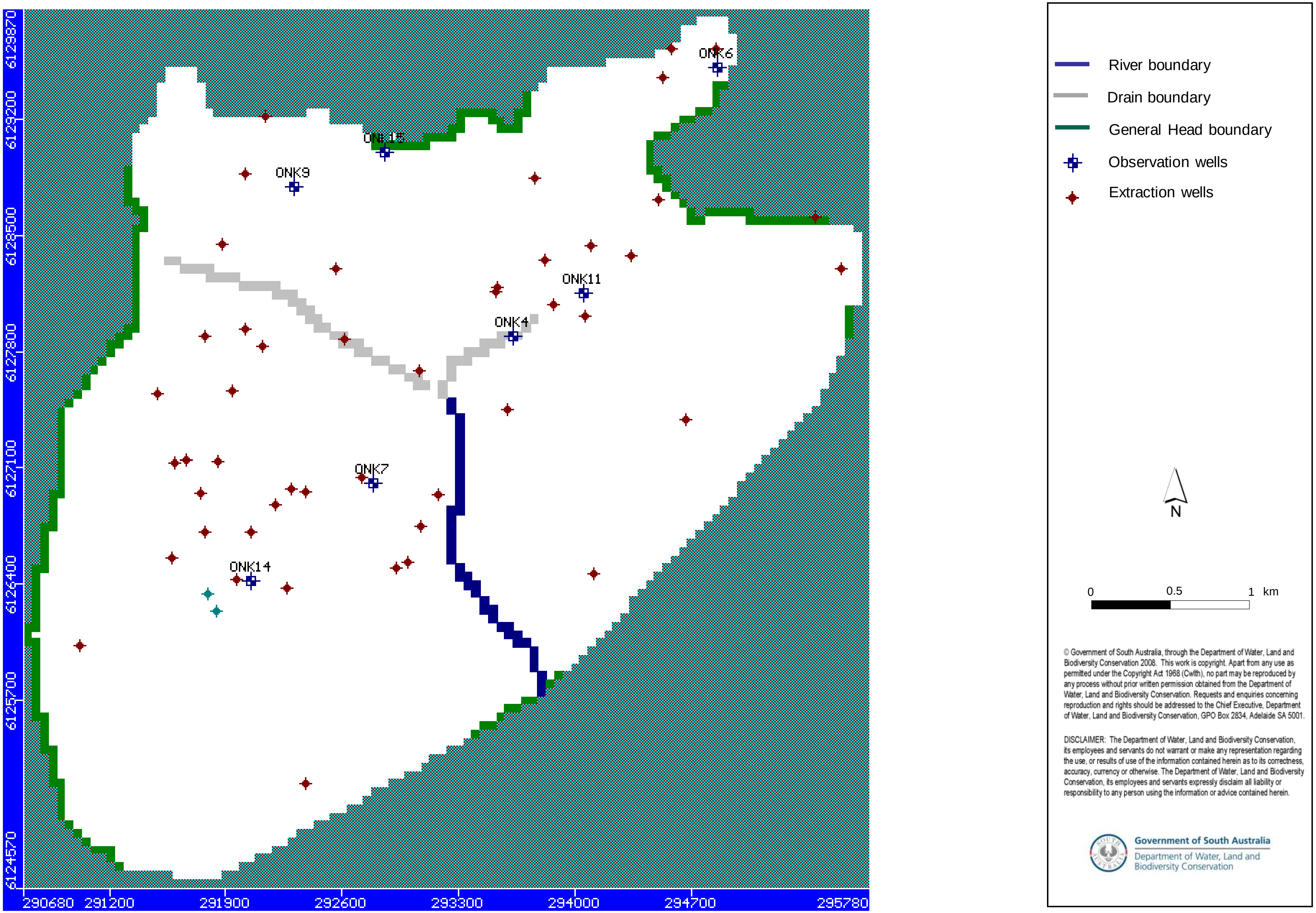

Figure 11: Location of monitored observation wells and extraction wells in the Cox Creek Catchment

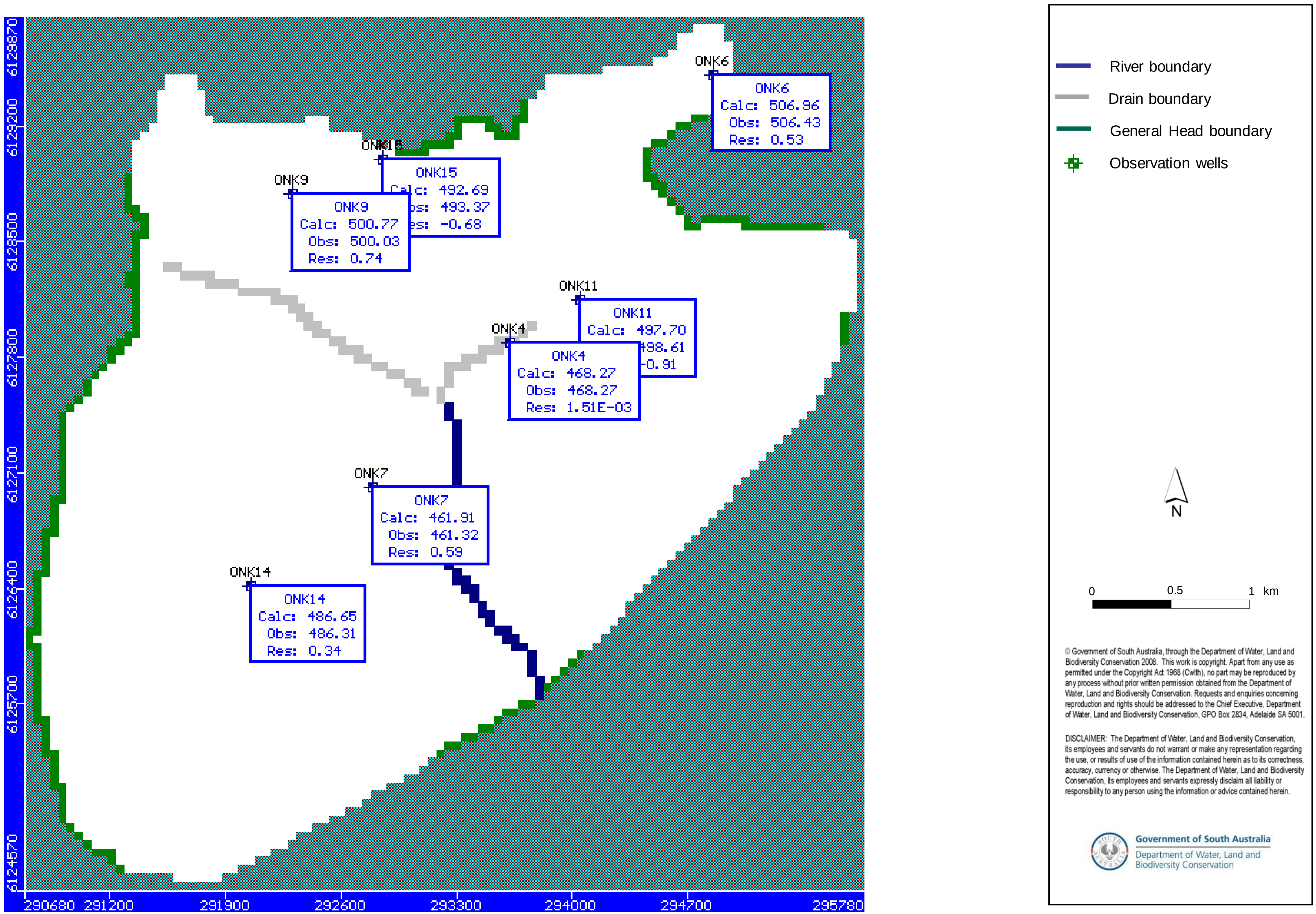

Figure 12: Comparison of observed and modelled 1998 head values in project area (steady state)

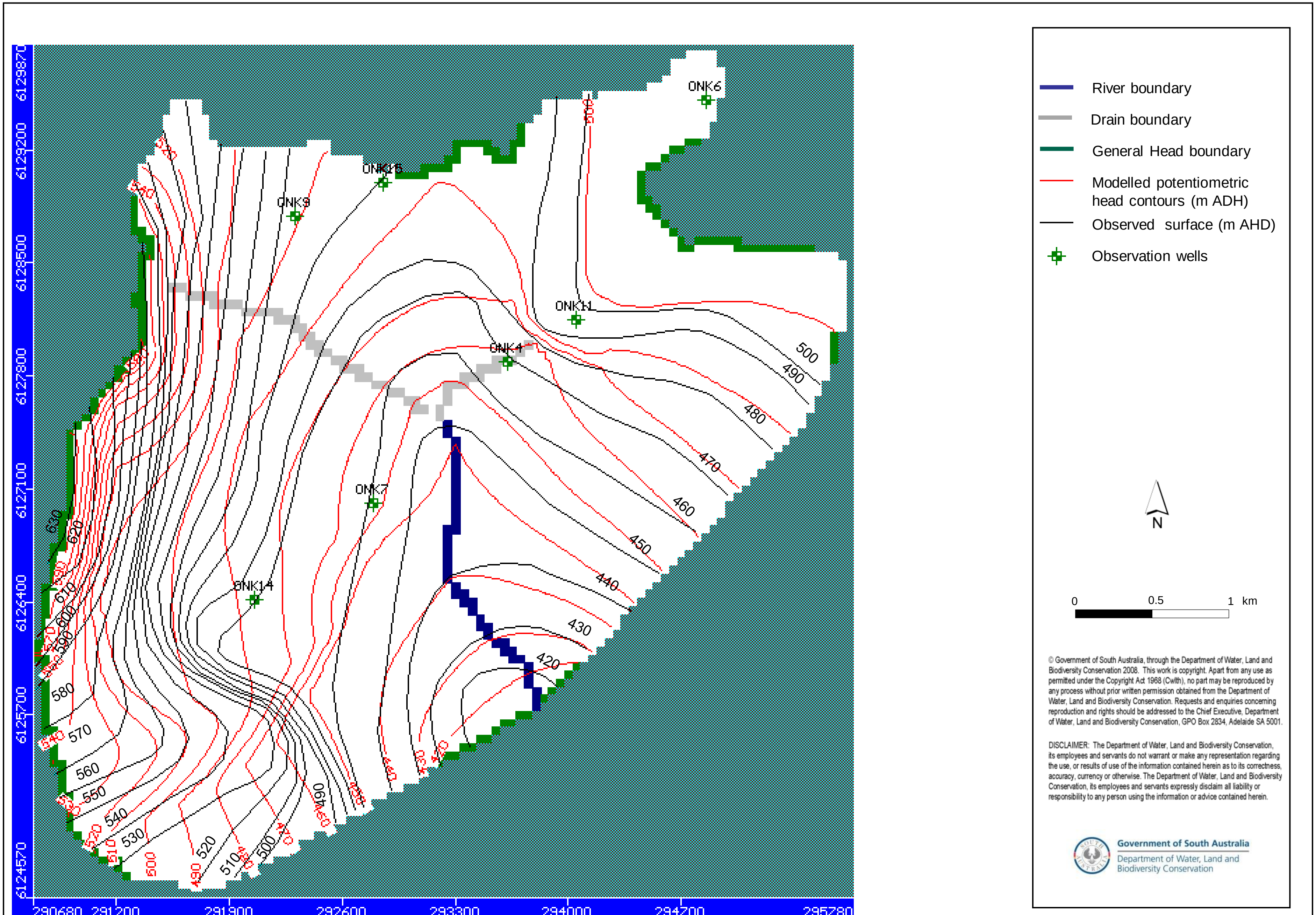

Figure 13: Comparison of observed and modelled 1998 potentiometric surface in project area (steady state)

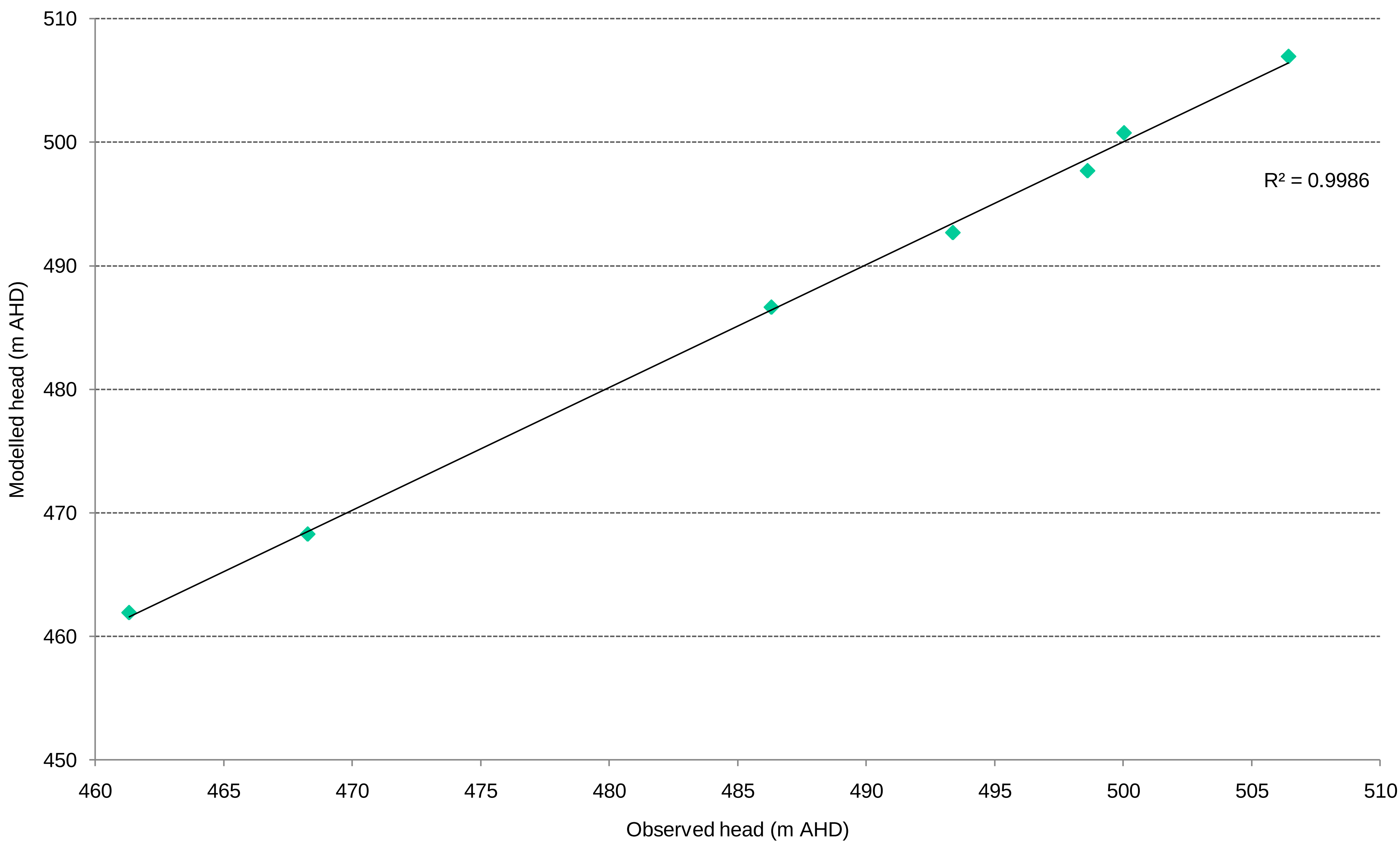

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Figure 14: Steady state calibration results along 1:1 correlation line

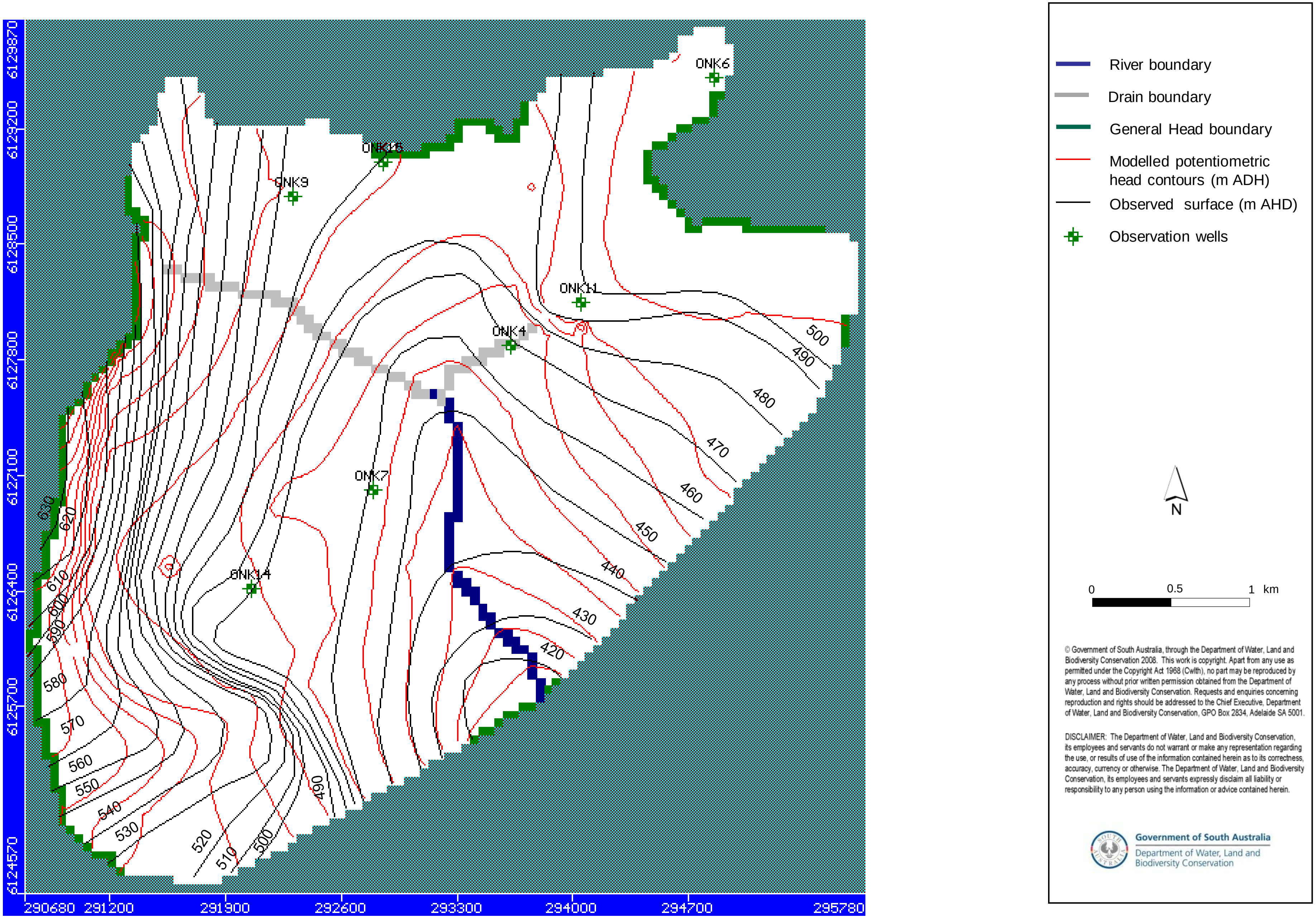


Figure 15: Comparison of observed and modelled 2008 potentiometric surface in project area (Transient)

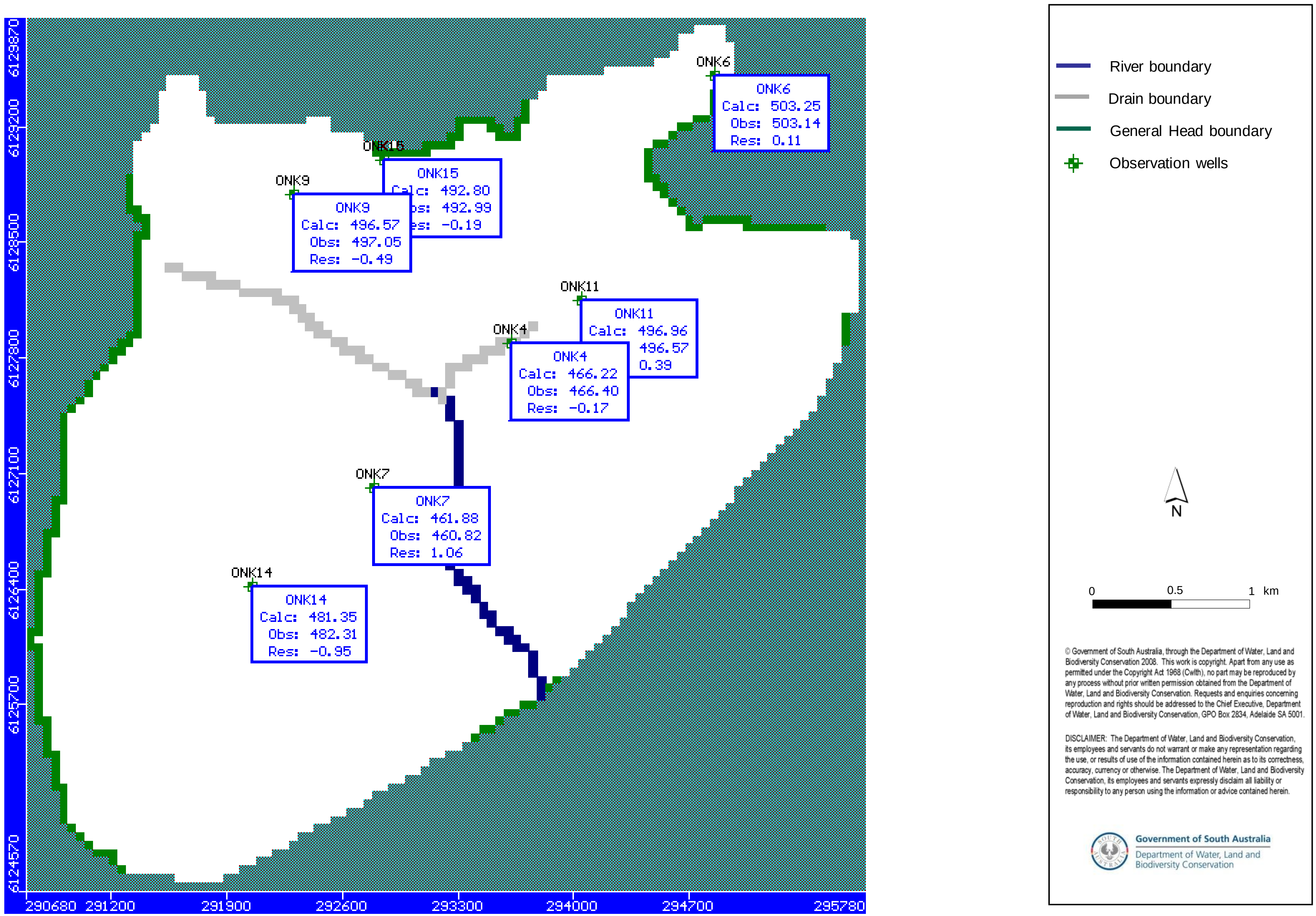


Figure 16: Comparison of observed and modelled 2008 head values in project area (Transient)

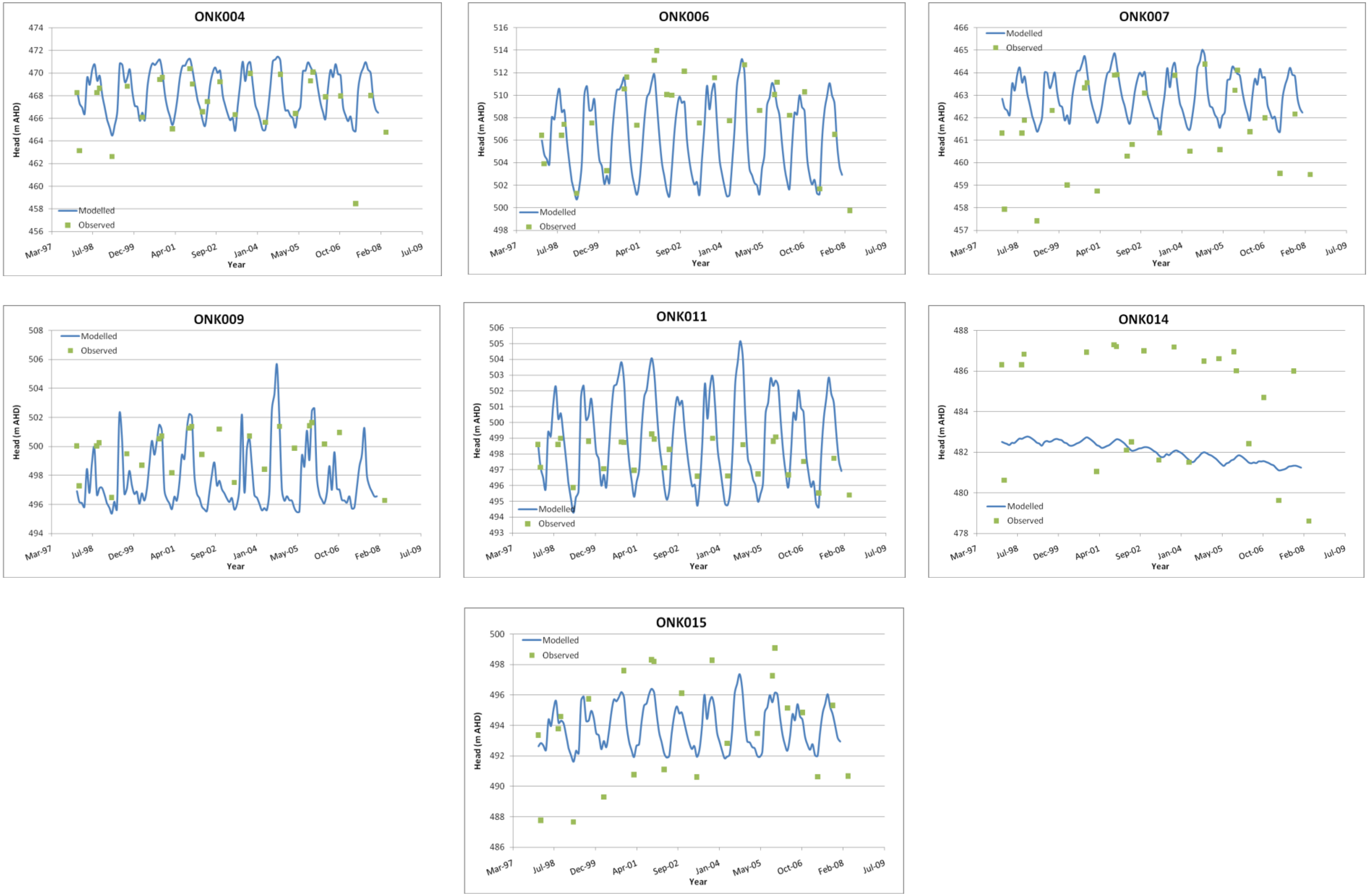
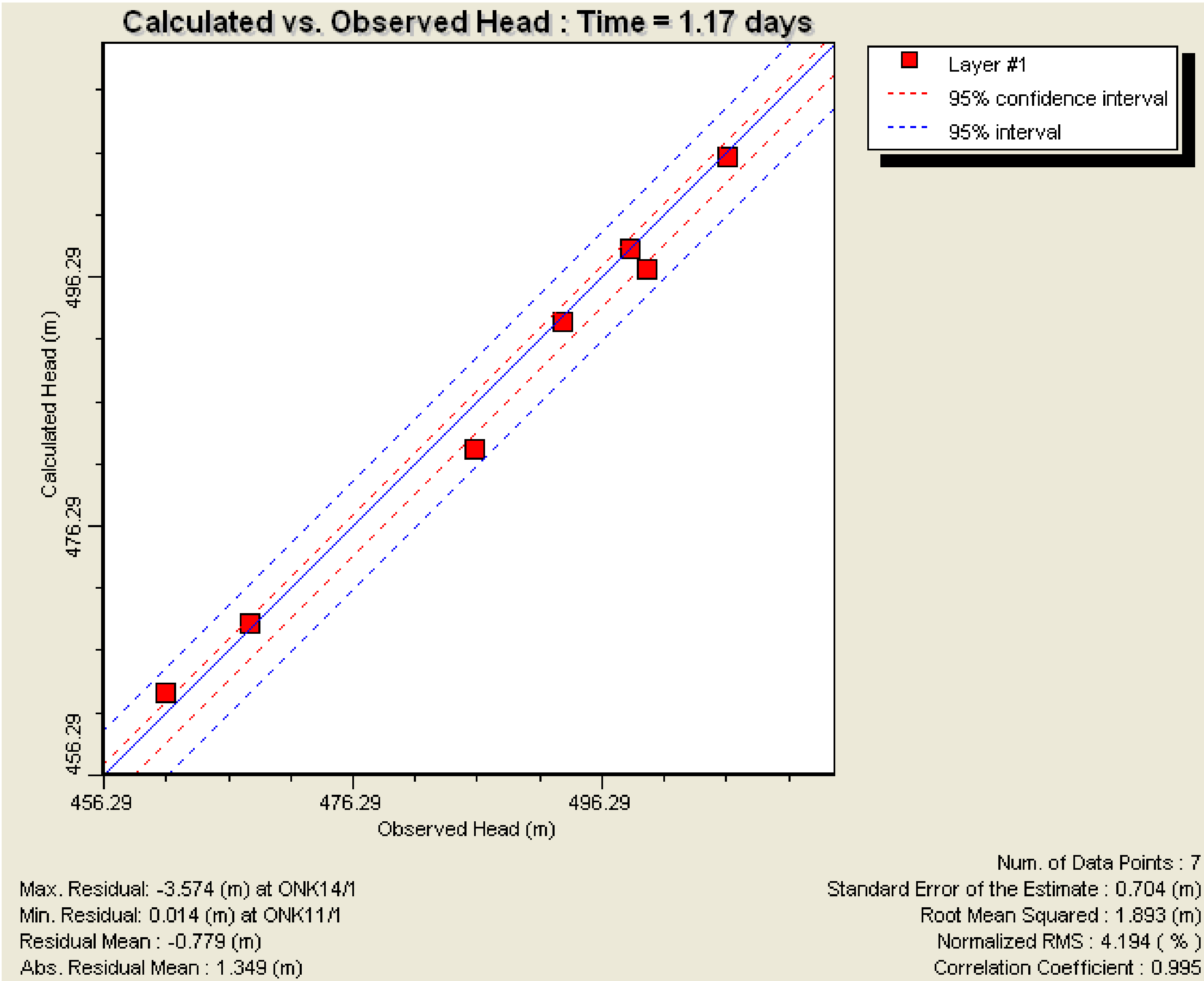


Figure 17: Comparison of observed and modelled potentiometric head



Included OBSwells

ONK004
ONK006
ONK007
ONK009
ONK011
ONK014
ONK015

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Figure 18: Calibration results 1998 (time step 1)

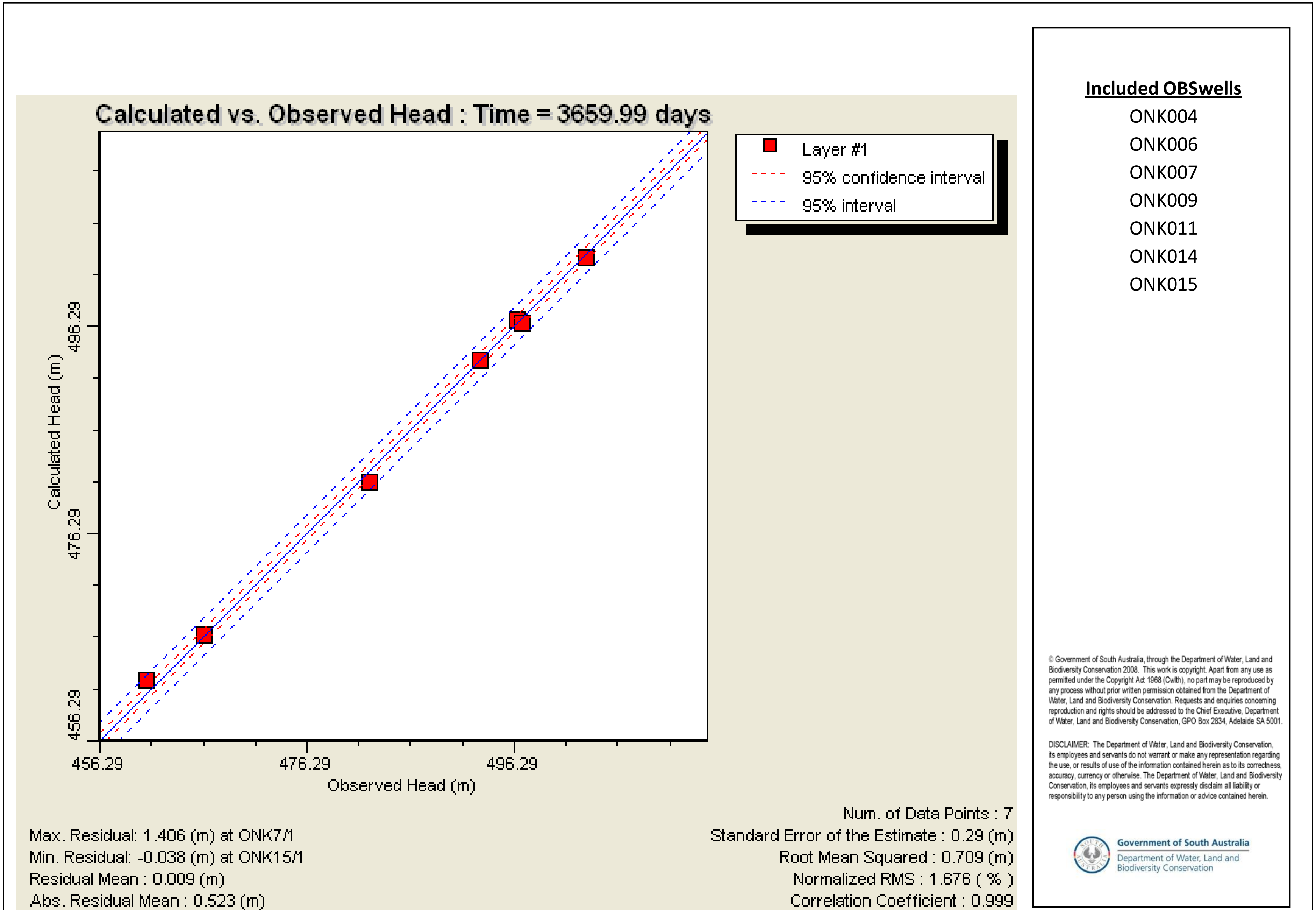

Figure 19: Calibration results 2008 (10 years)

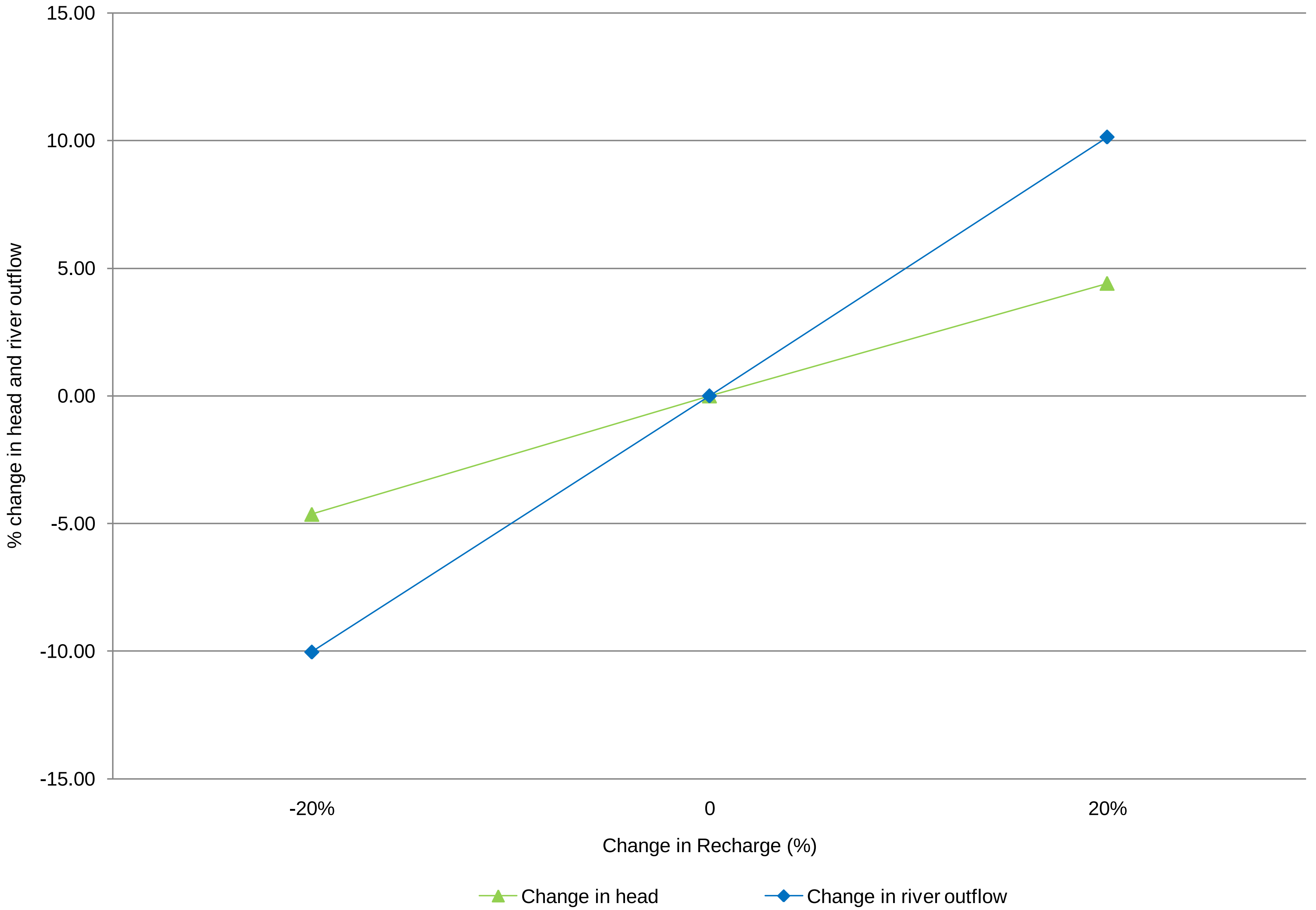

Figure 20: Model sensitivity to changes in recharge

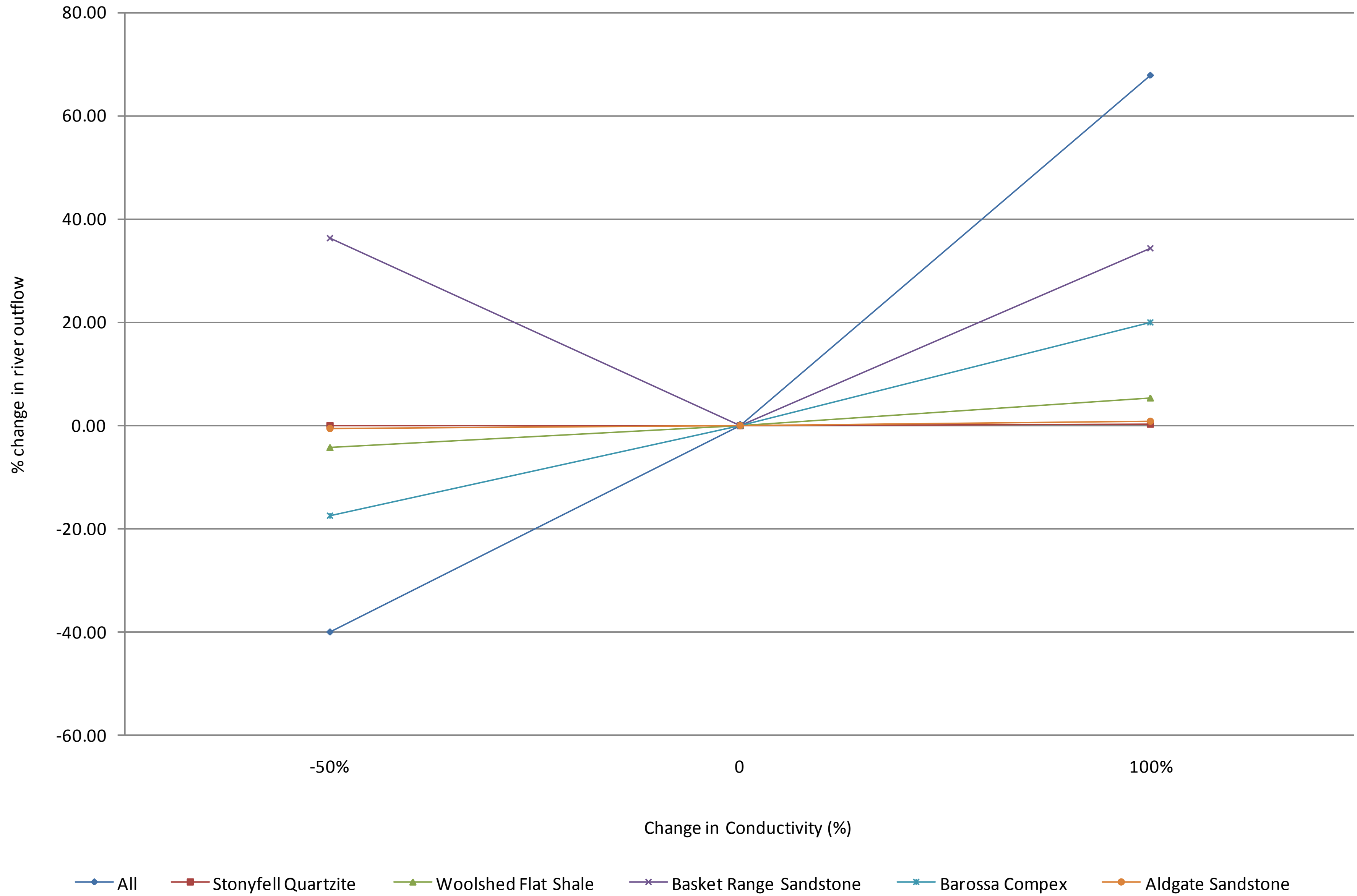

Figure 21: Model sensitivity of river outflow to changes in horizontal hydraulic conductivity

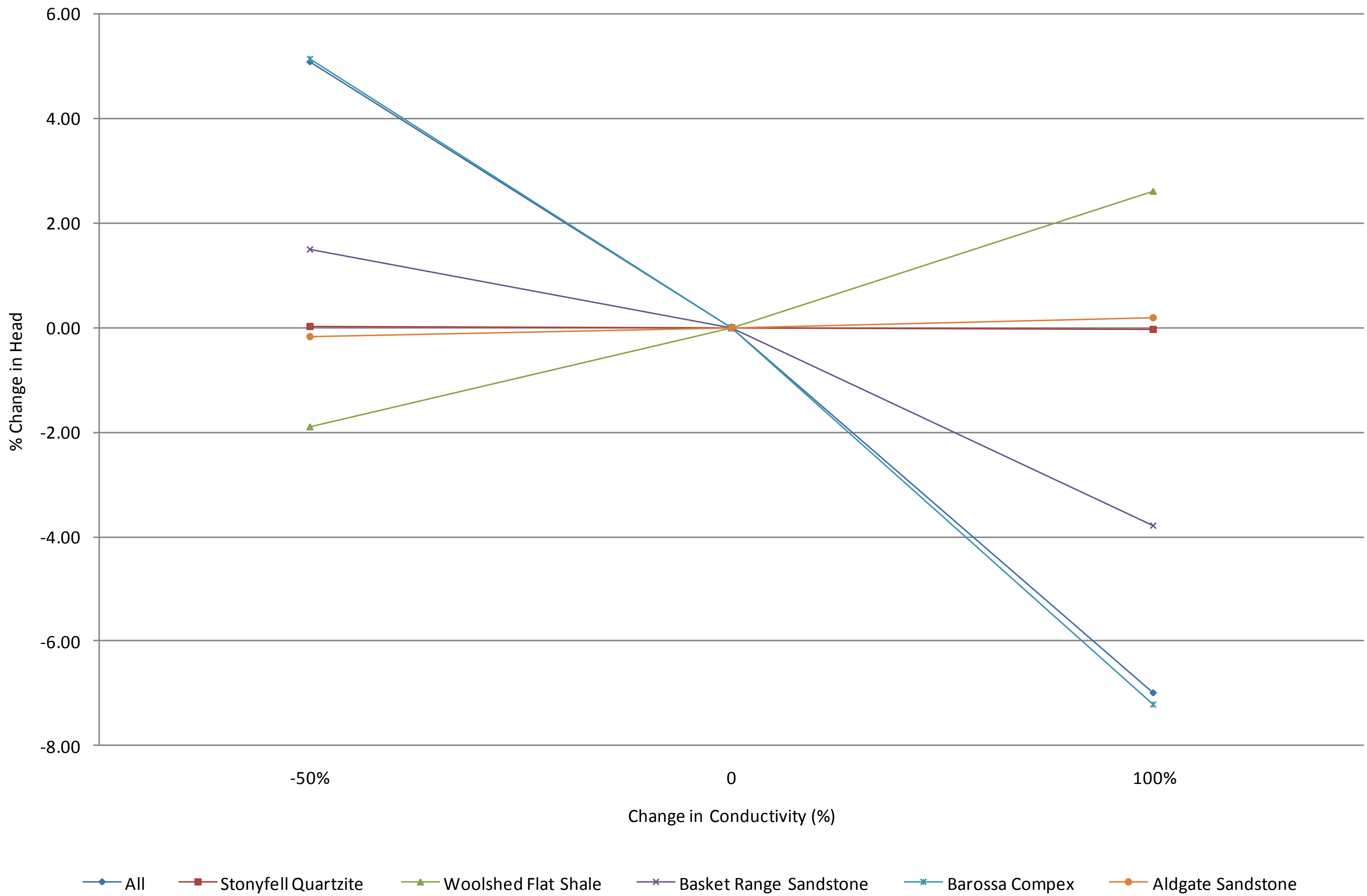

Figure 22: Model sensitivity of head levels to changes in horizontal hydraulic conductivity

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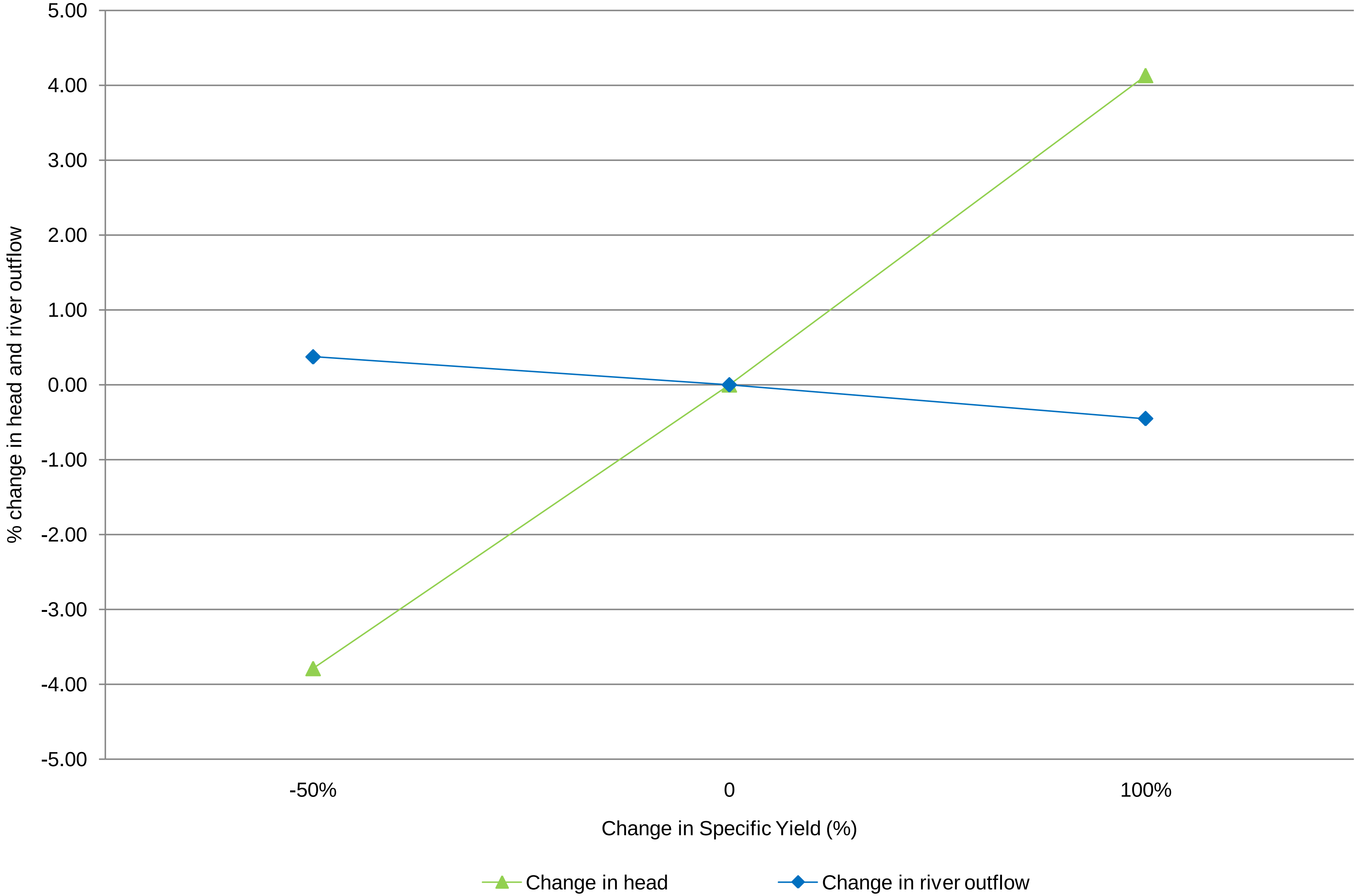

Figure 23: Model sensitivity to changes in specific yield

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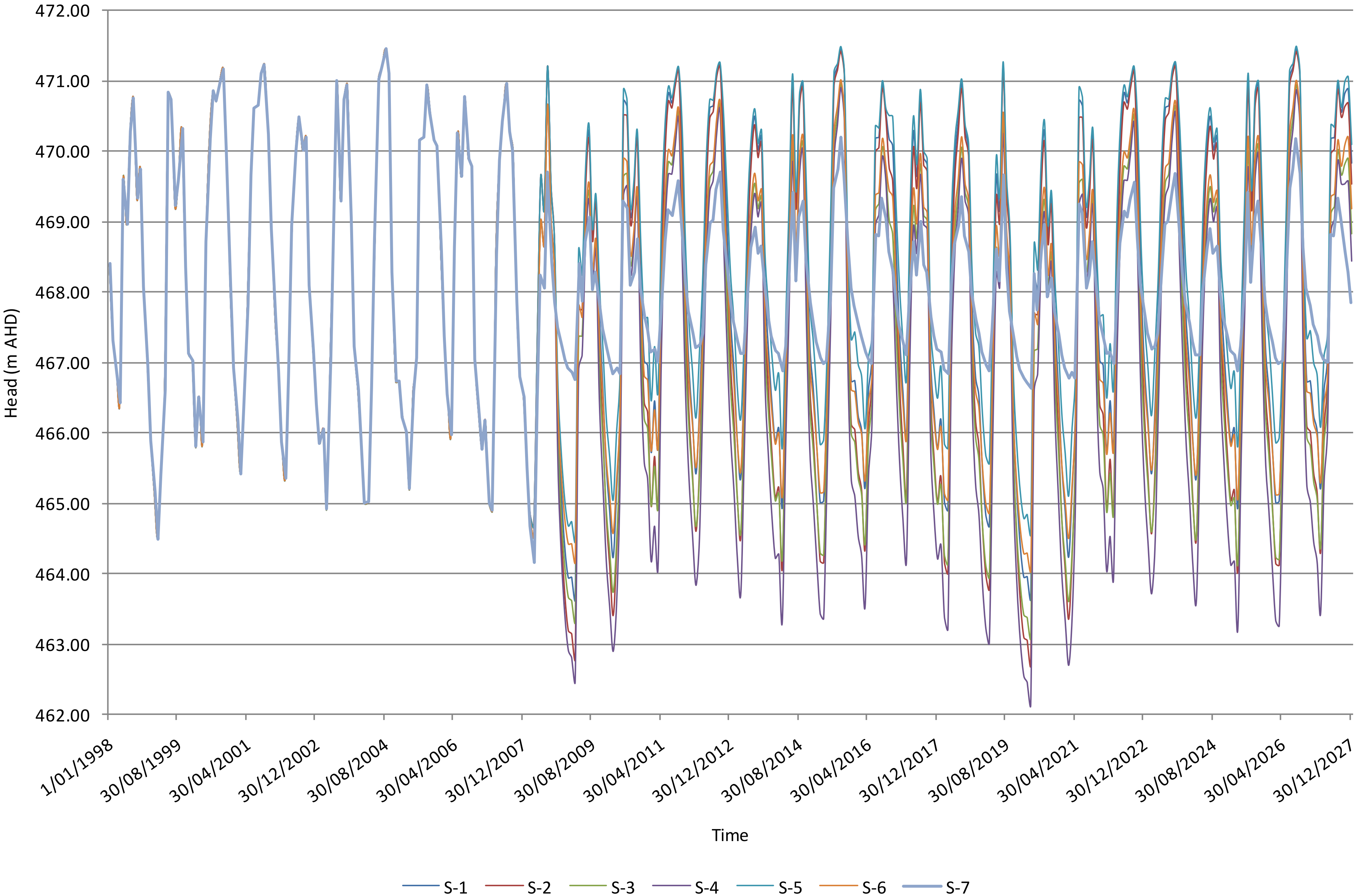

Figure 24: Predicted head variations with time for all scenarios (ONK004)

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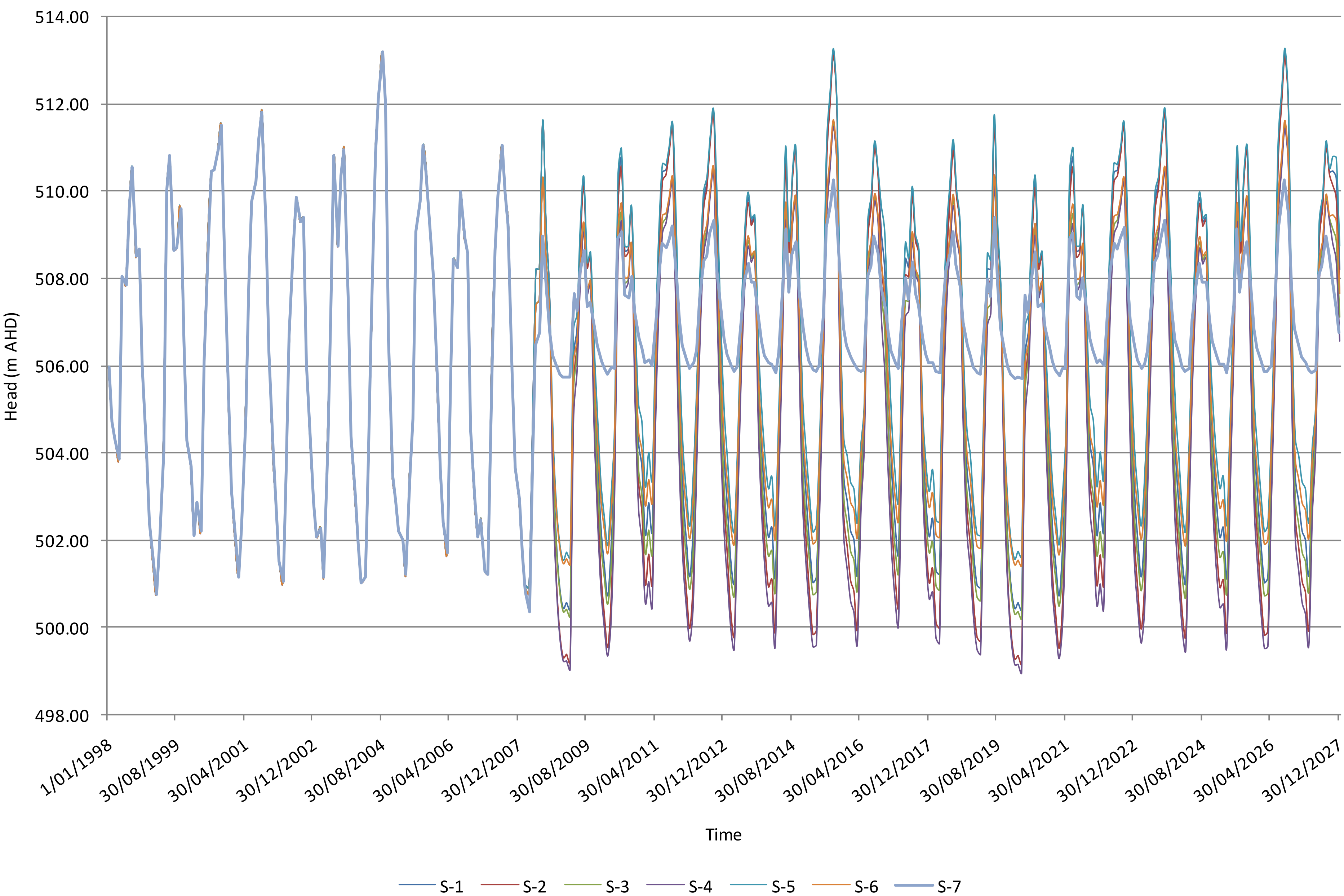

Figure 25: Predicted head variations with time for all scenarios (ONK006)

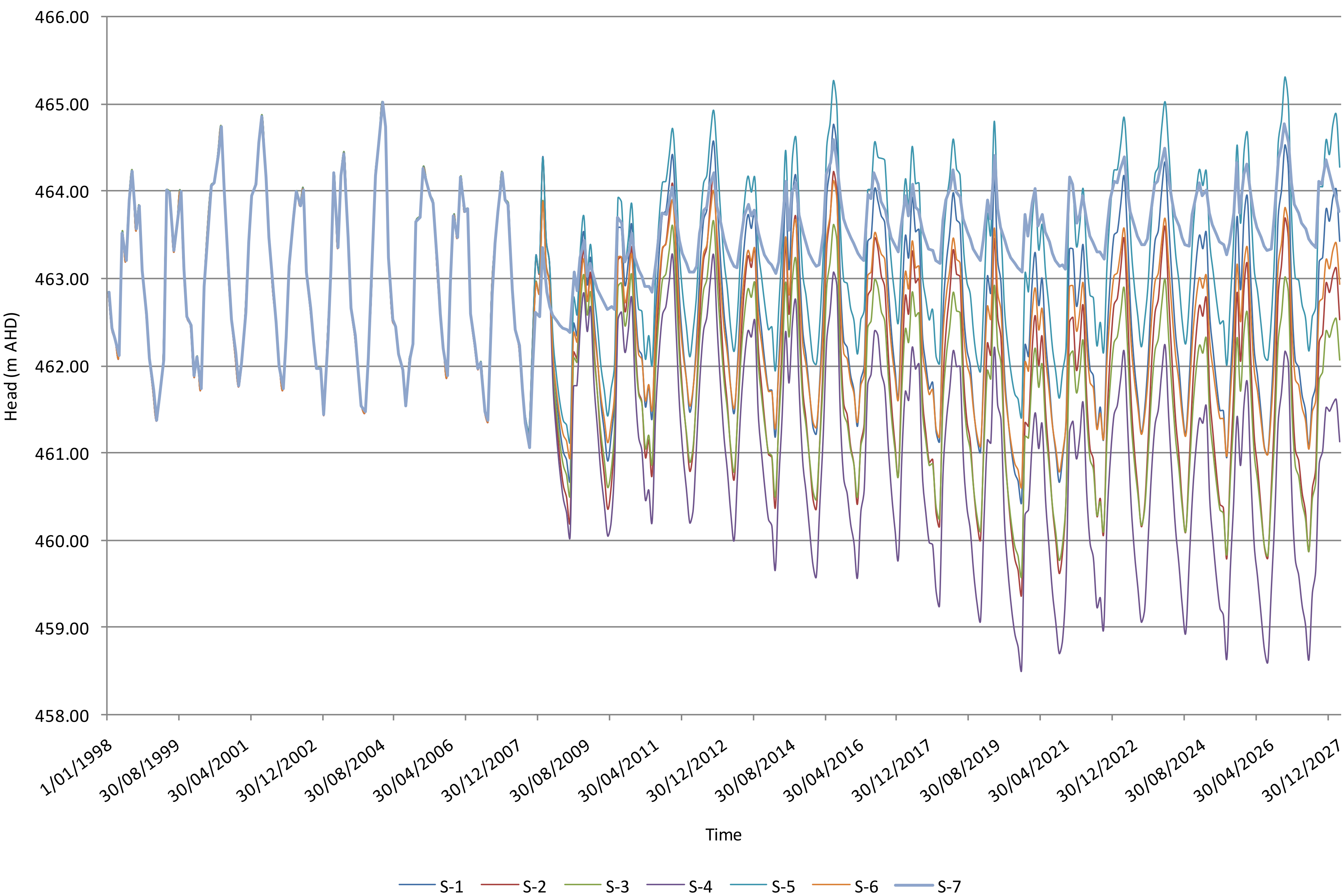

Figure 26: Predicted head variations with time for all scenarios (ONK007)

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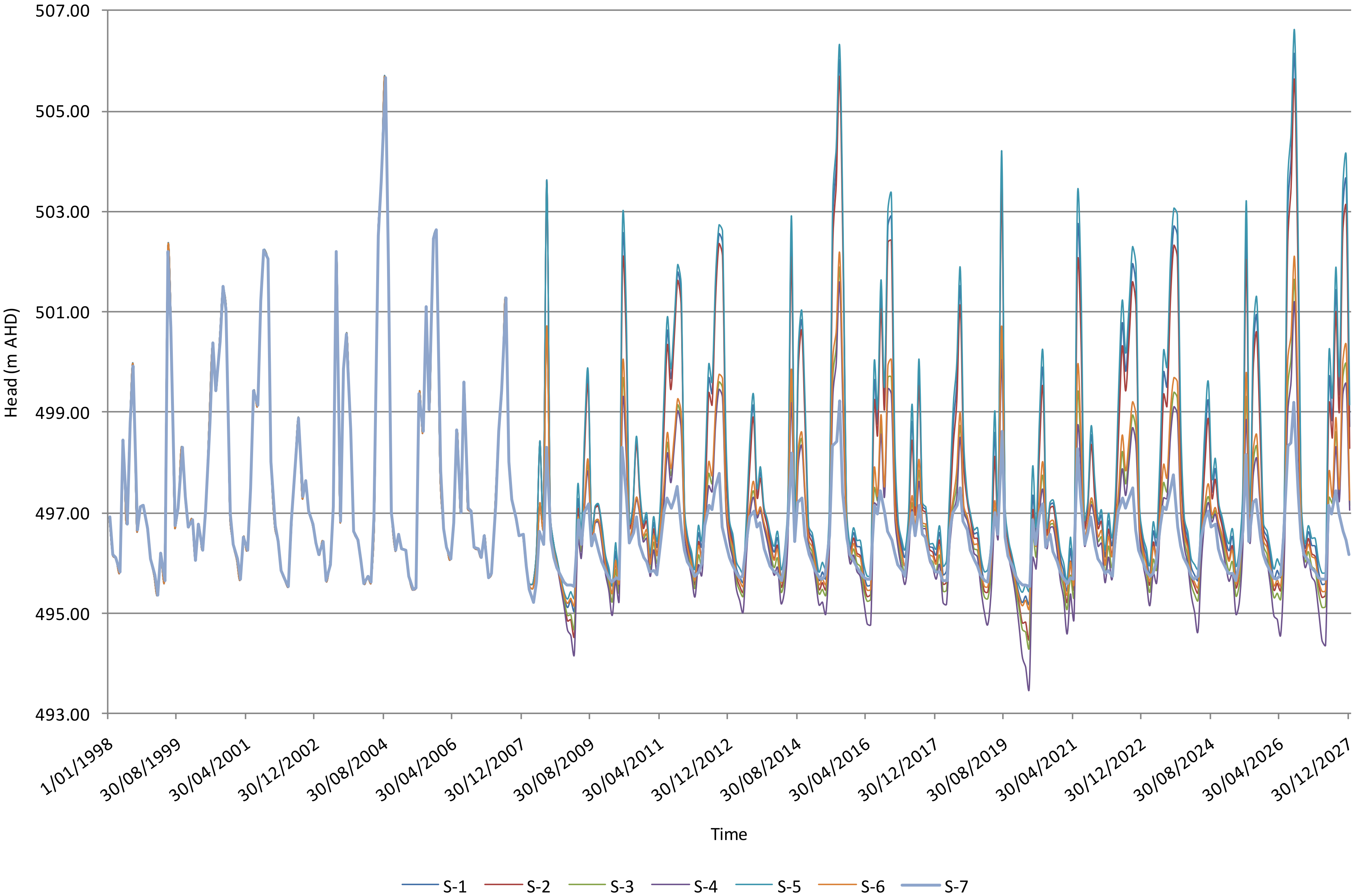

Figure 27: Predicted head variations with time for all scenarios (ONK009)

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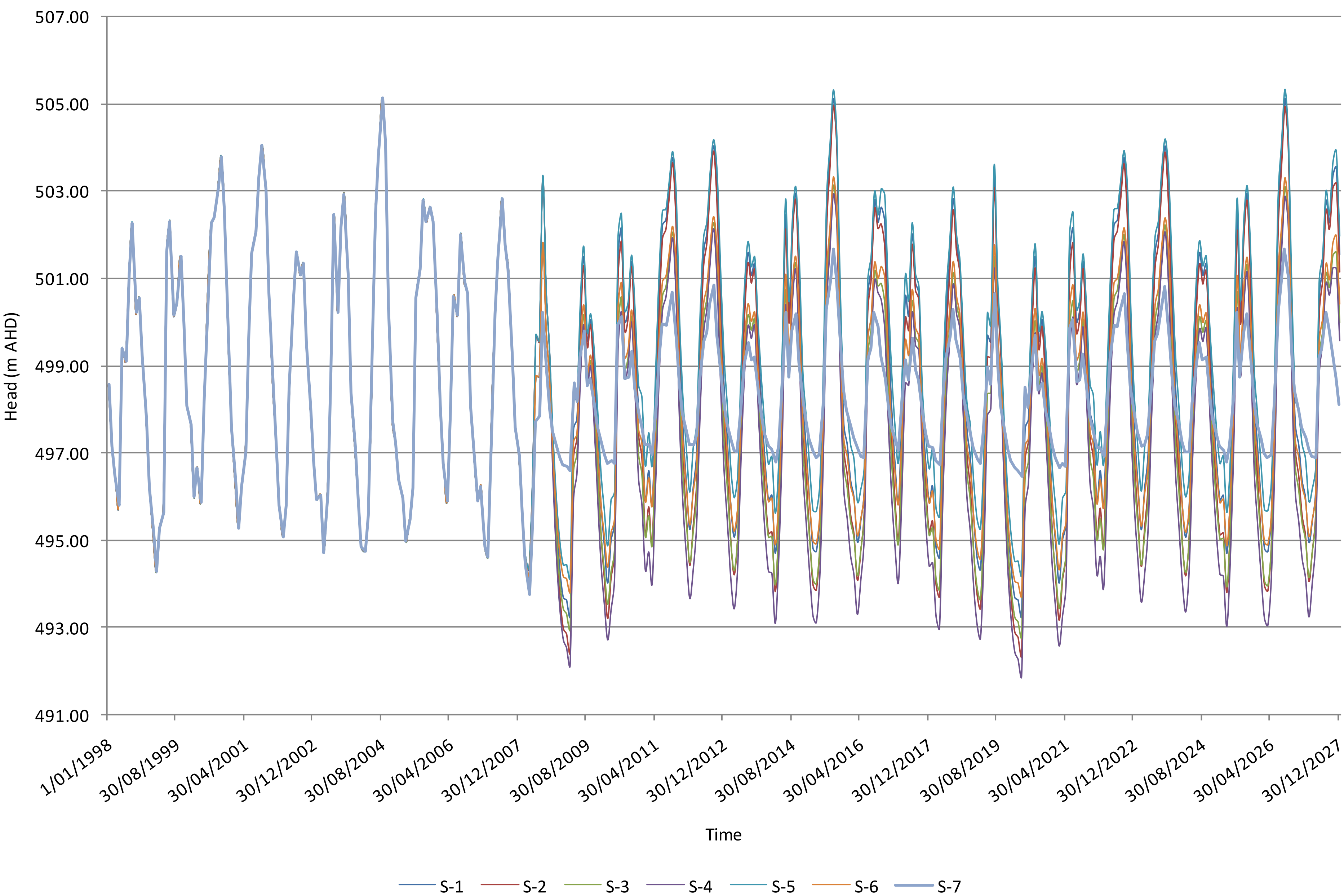

Figure 28: Predicted head variations with time for all scenarios (ONK011)

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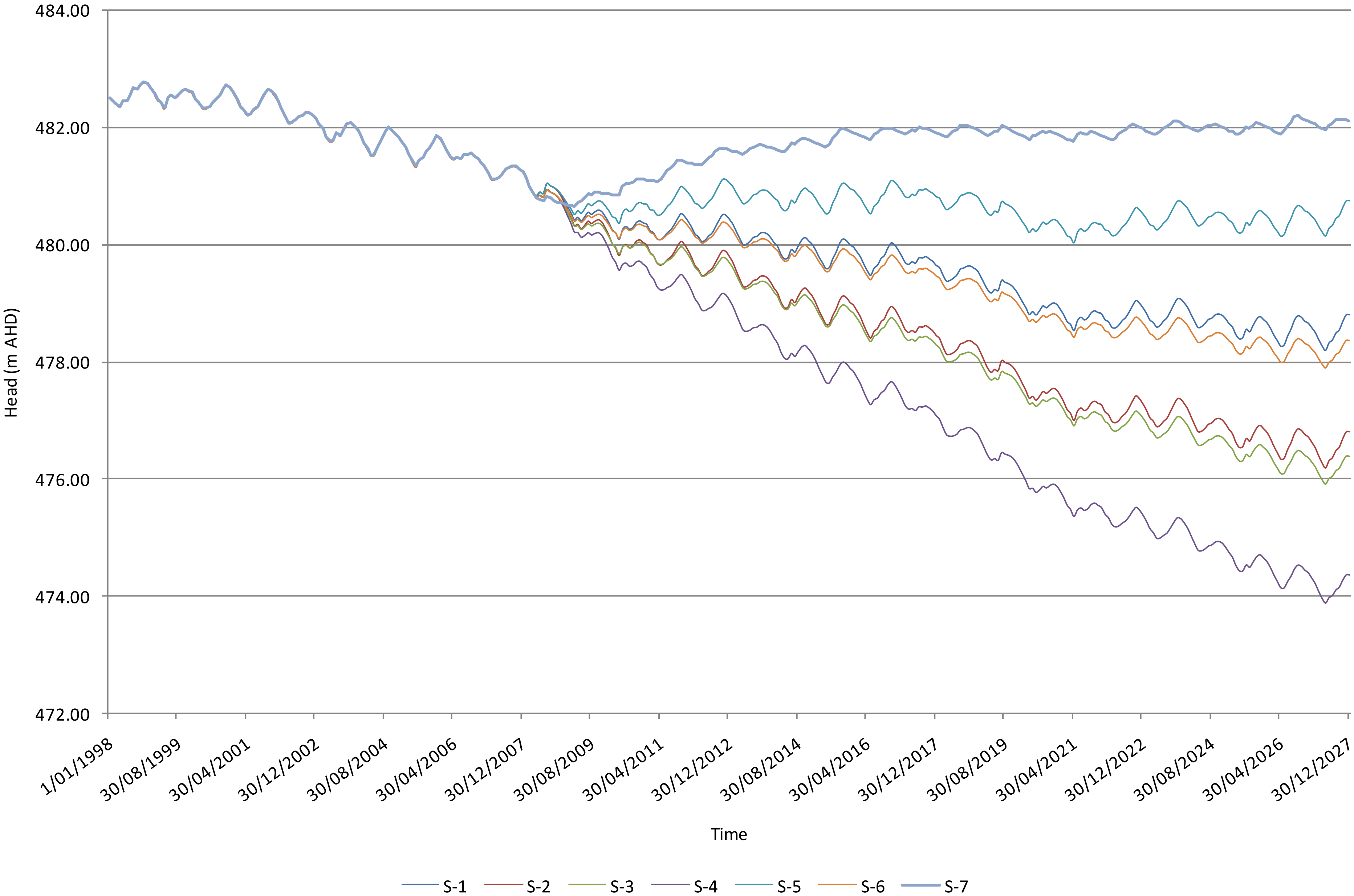

Figure 29: Predicted head variations with time for all scenarios (ONK014)

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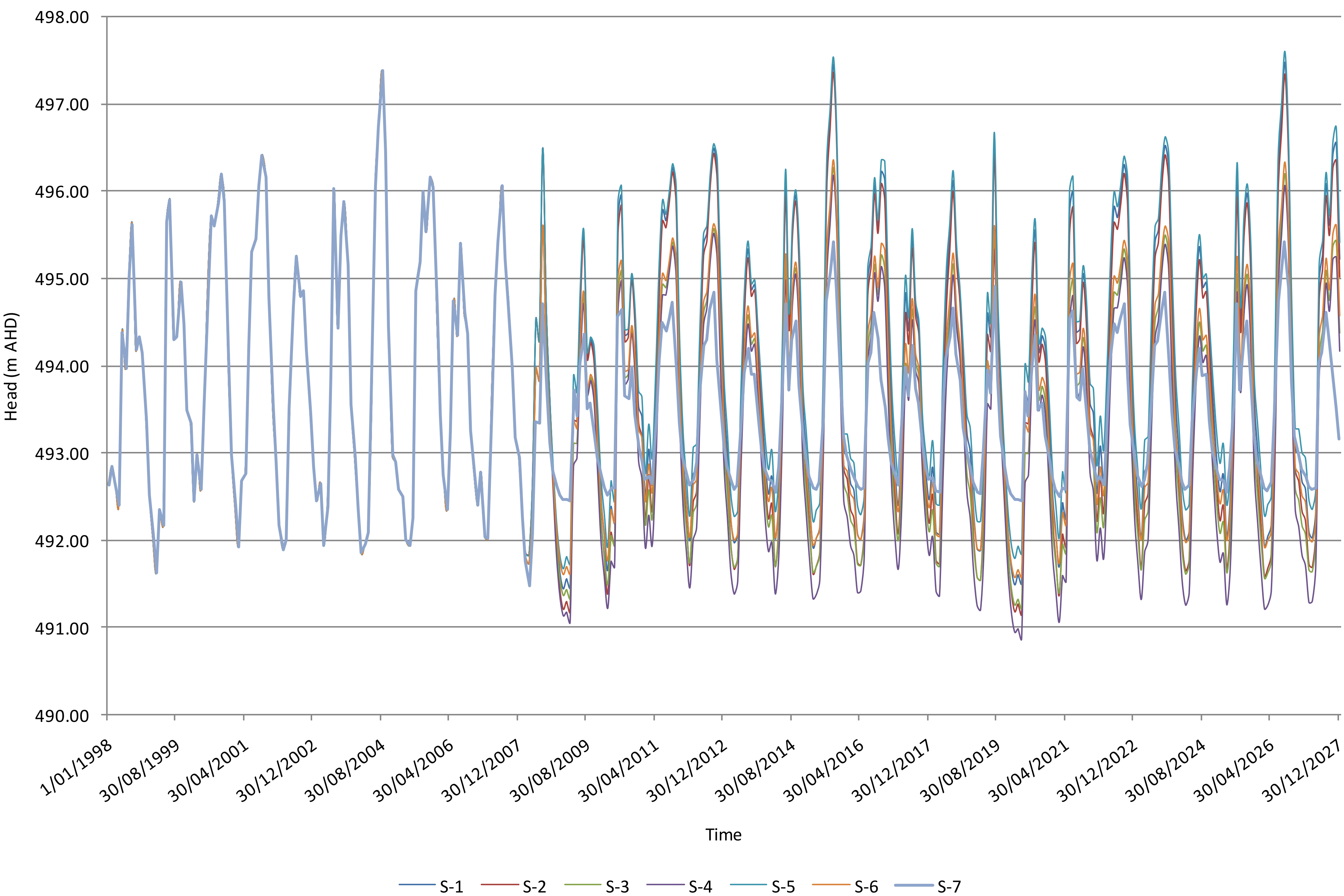

Figure 30: Predicted head variations with time for all scenarios (ONK015)

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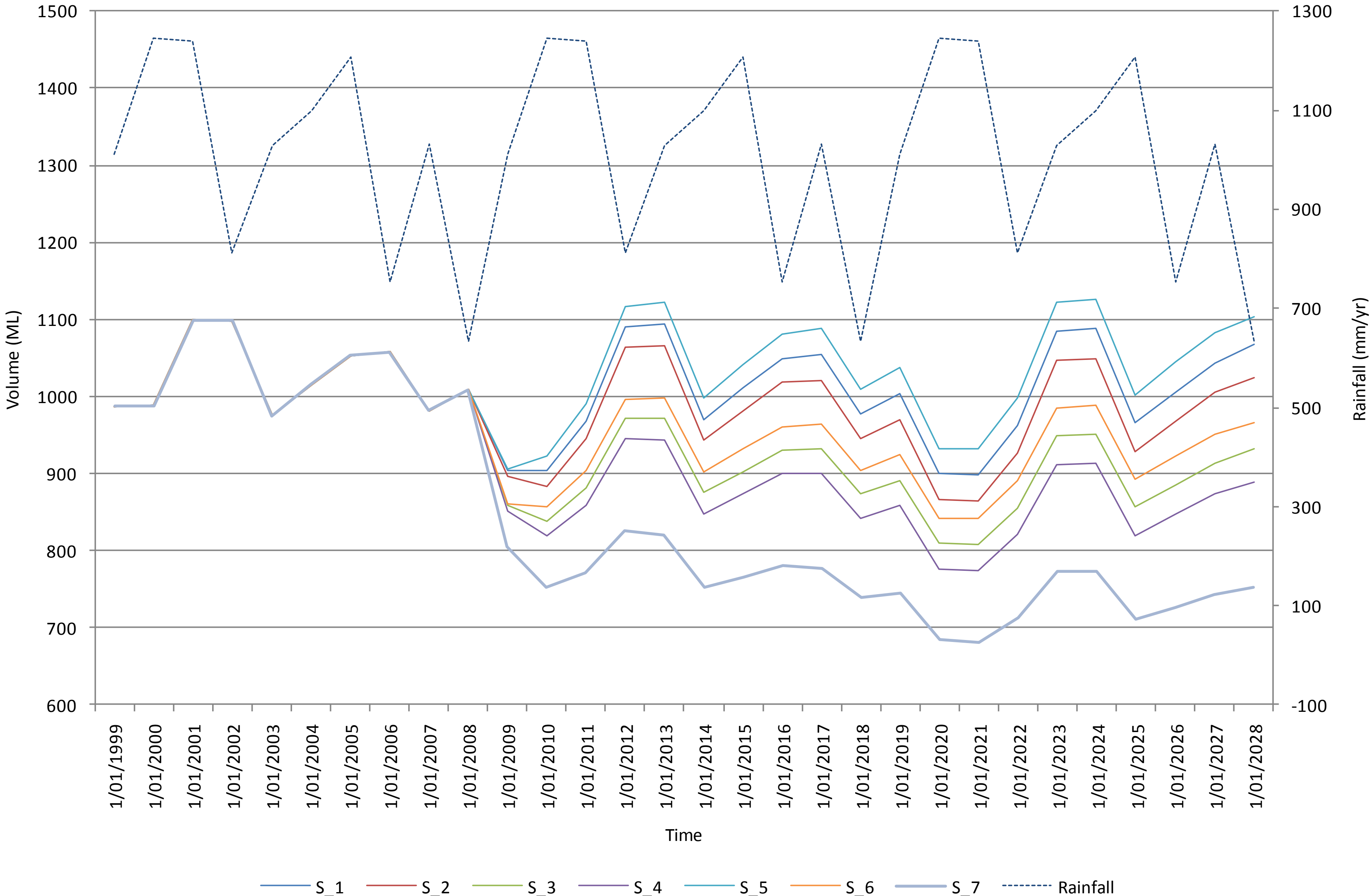

Figure 31: Predicted annual loss from aquifer via river and drains for all scenarios

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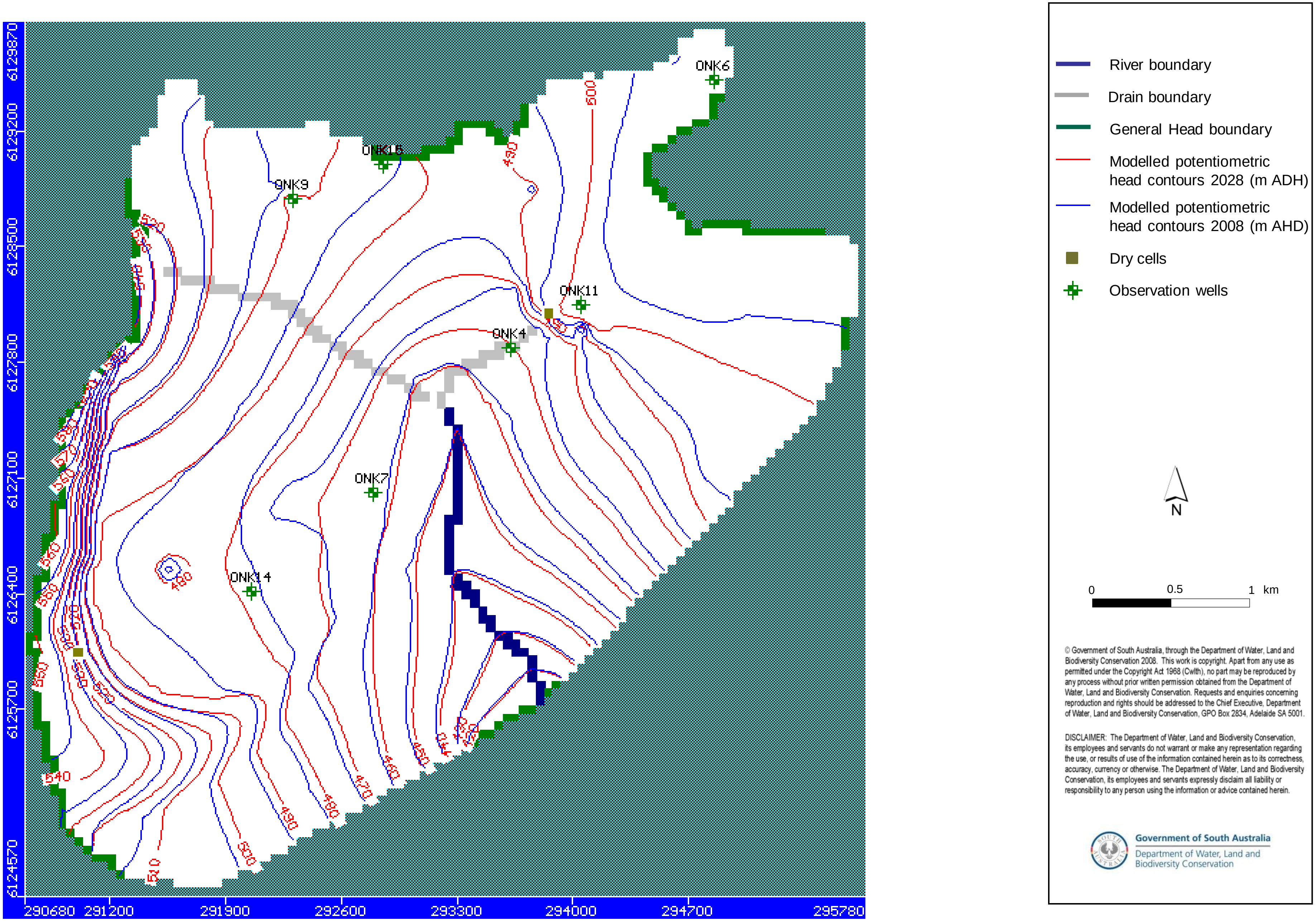

Figure 32: Comparison of 2008 and 2028 potentiometric surfaces in project area for S-1

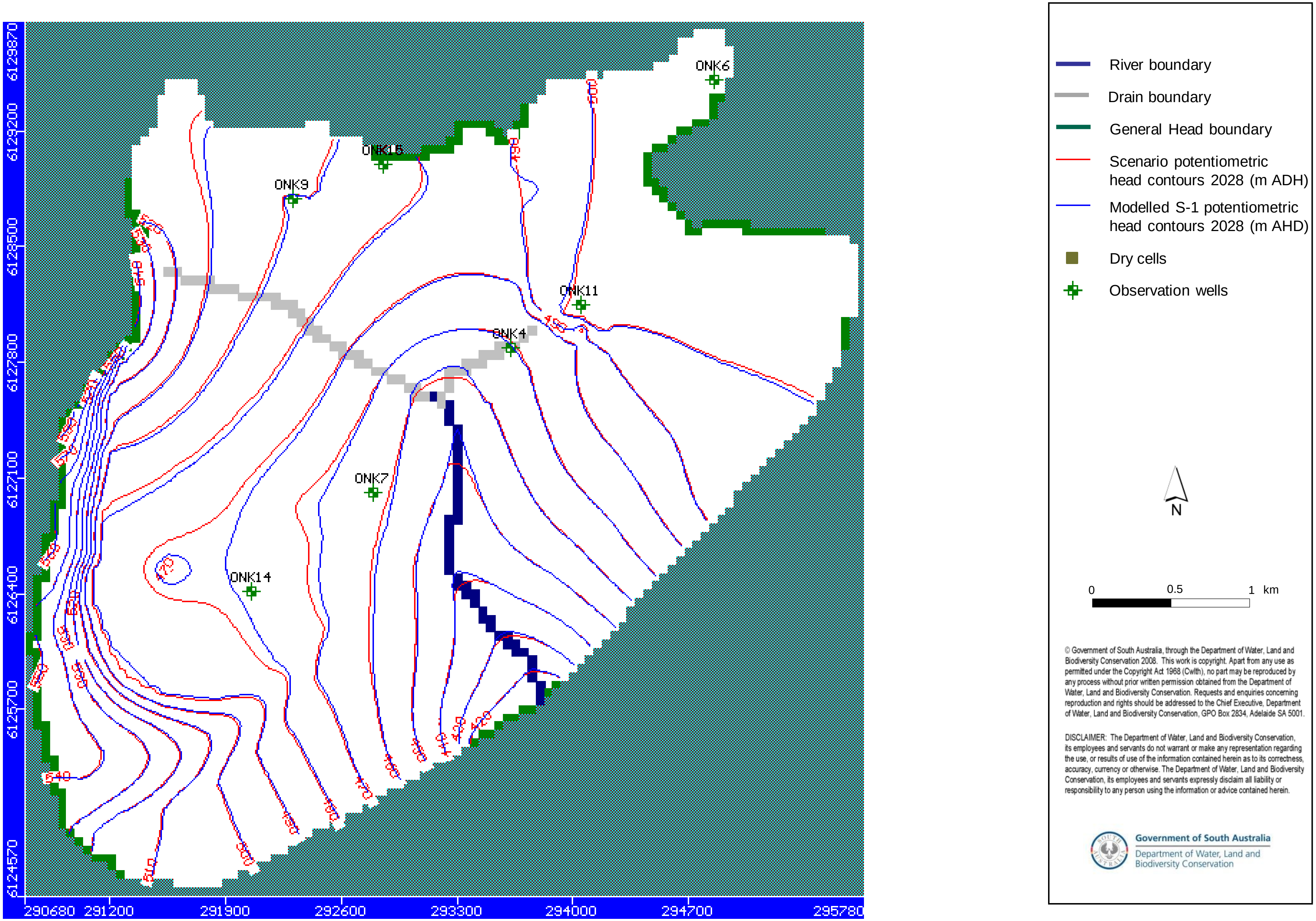

Figure 33: Comparison of S-1 and S-2 potentiometric surfaces for 2028

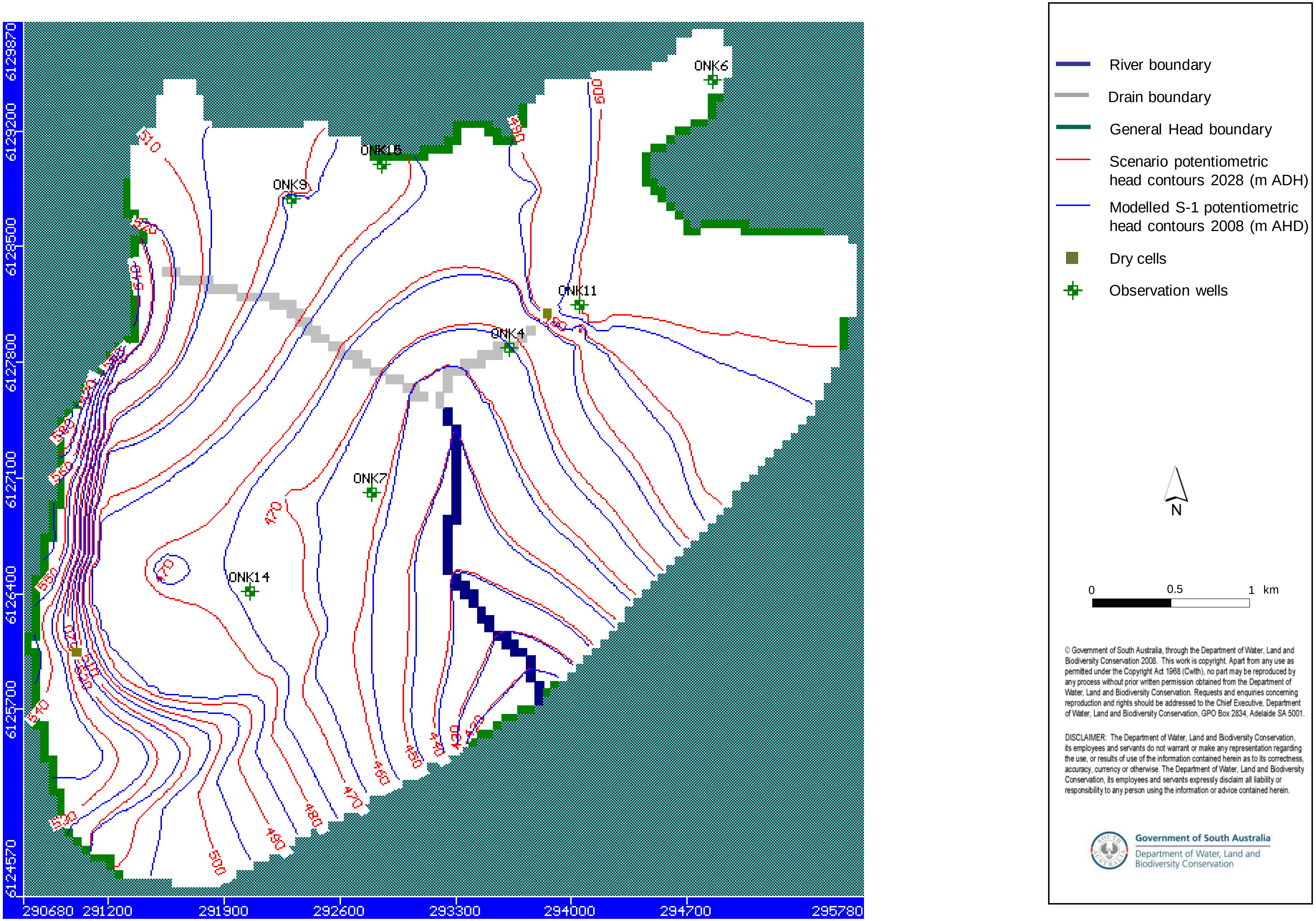

Figure 34: Comparison of S-1 and S-3 potentiometric surfaces for 2028

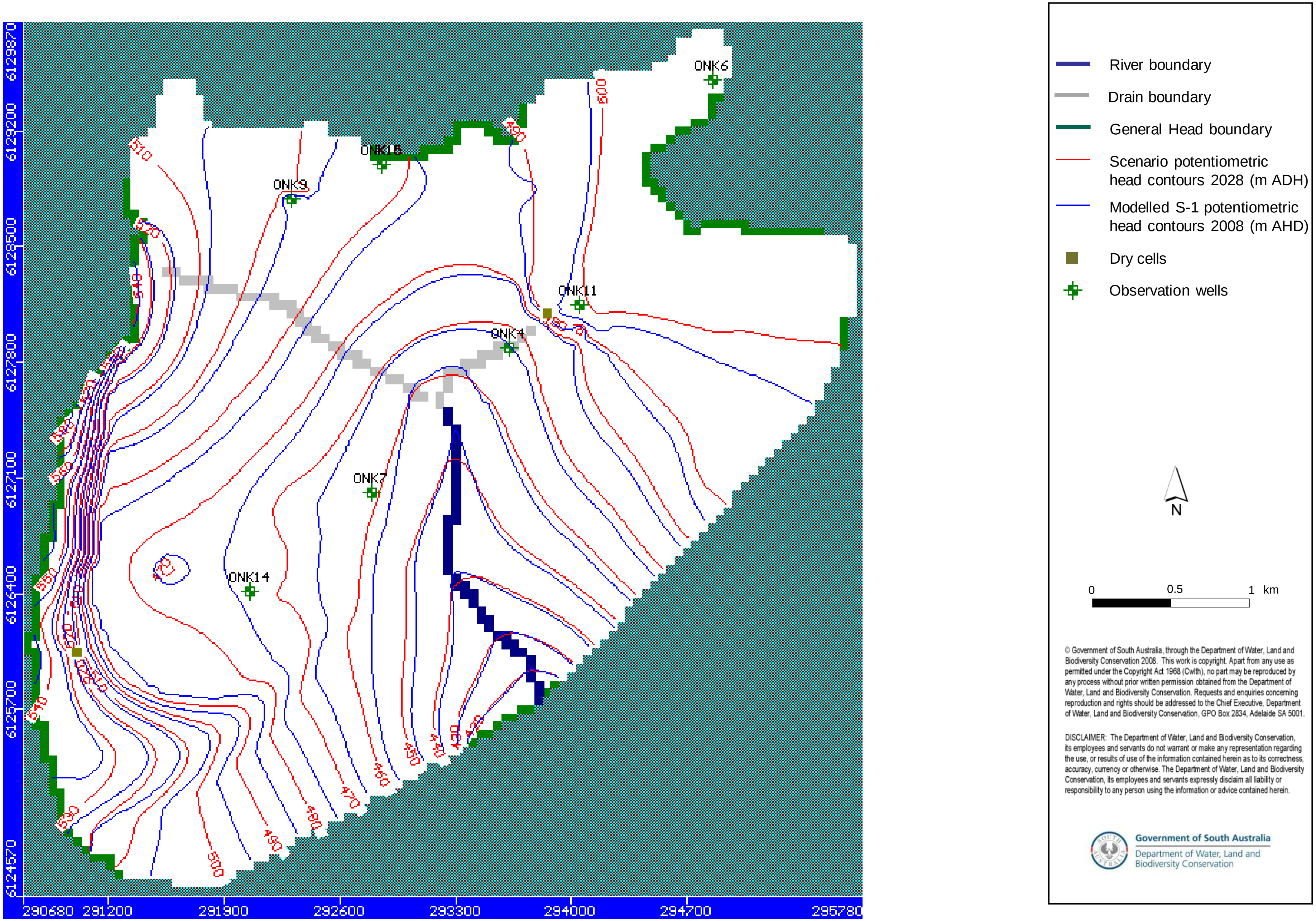

Figure 35: Comparison of S-1 and S-4 potentiometric surfaces for 2028

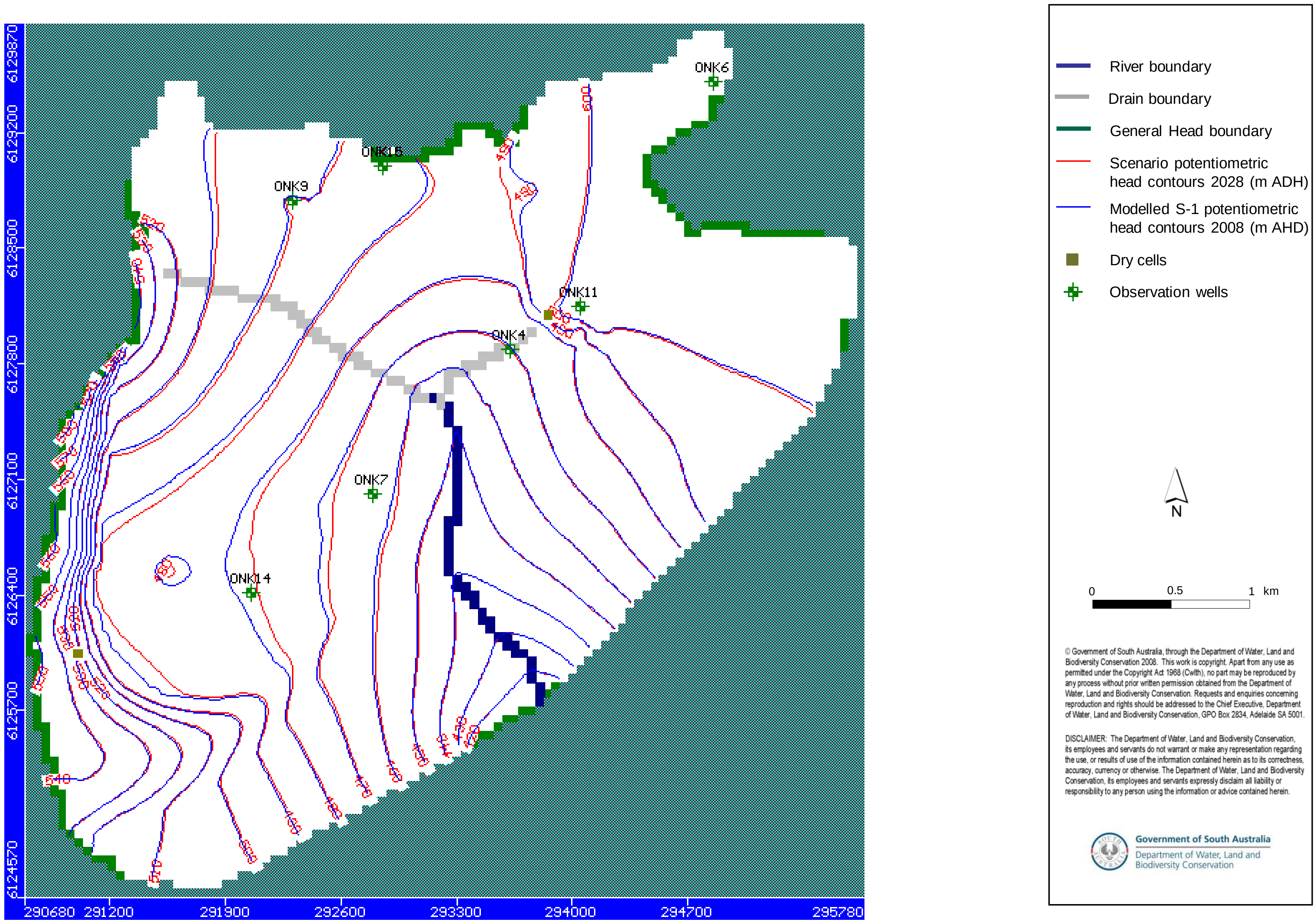

Figure 36: Comparison of S-1 and S-5 potentiometric surfaces for 2028

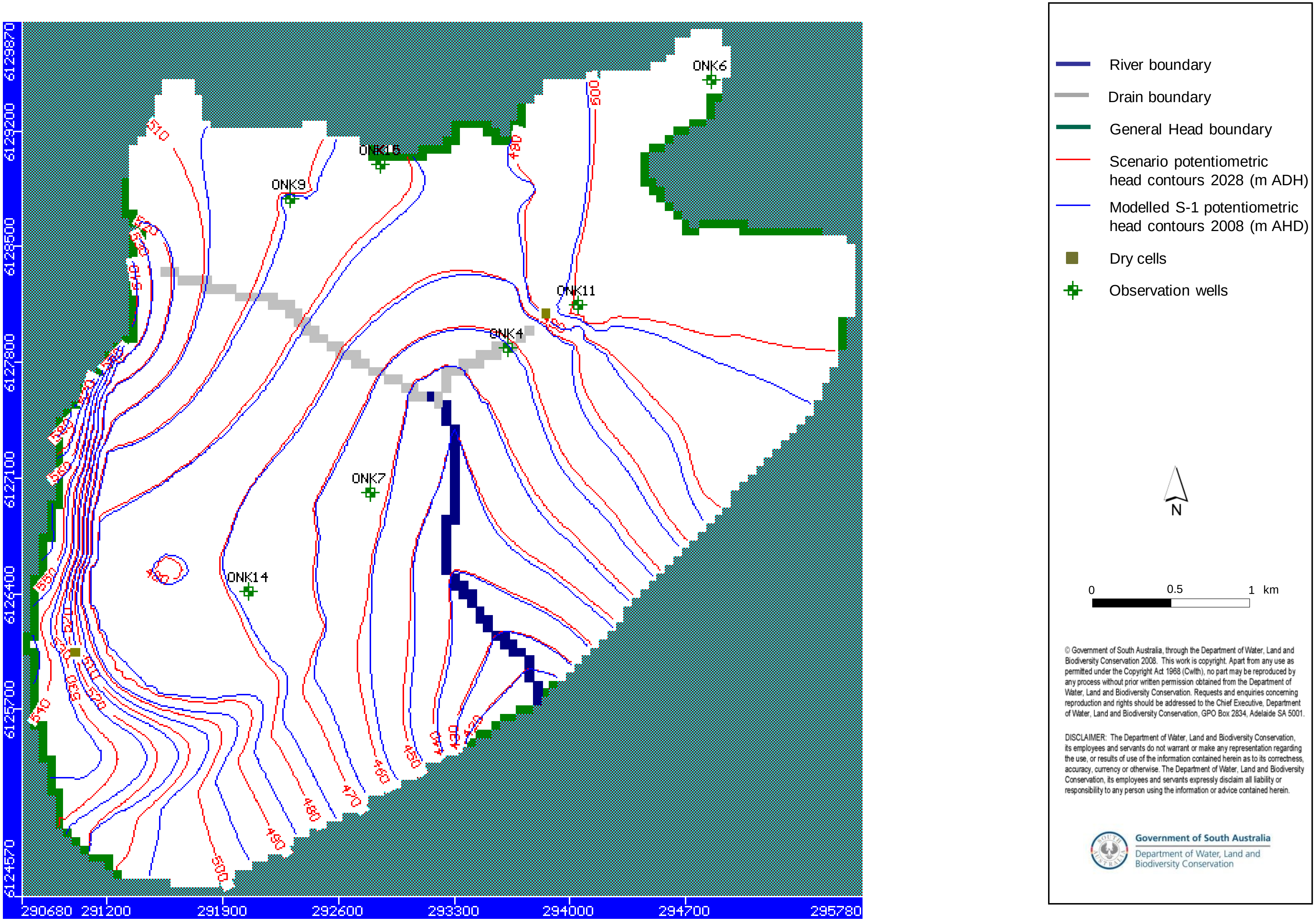

Figure 37: Comparison of S-1 and S-6 potentiometric surfaces for 2028

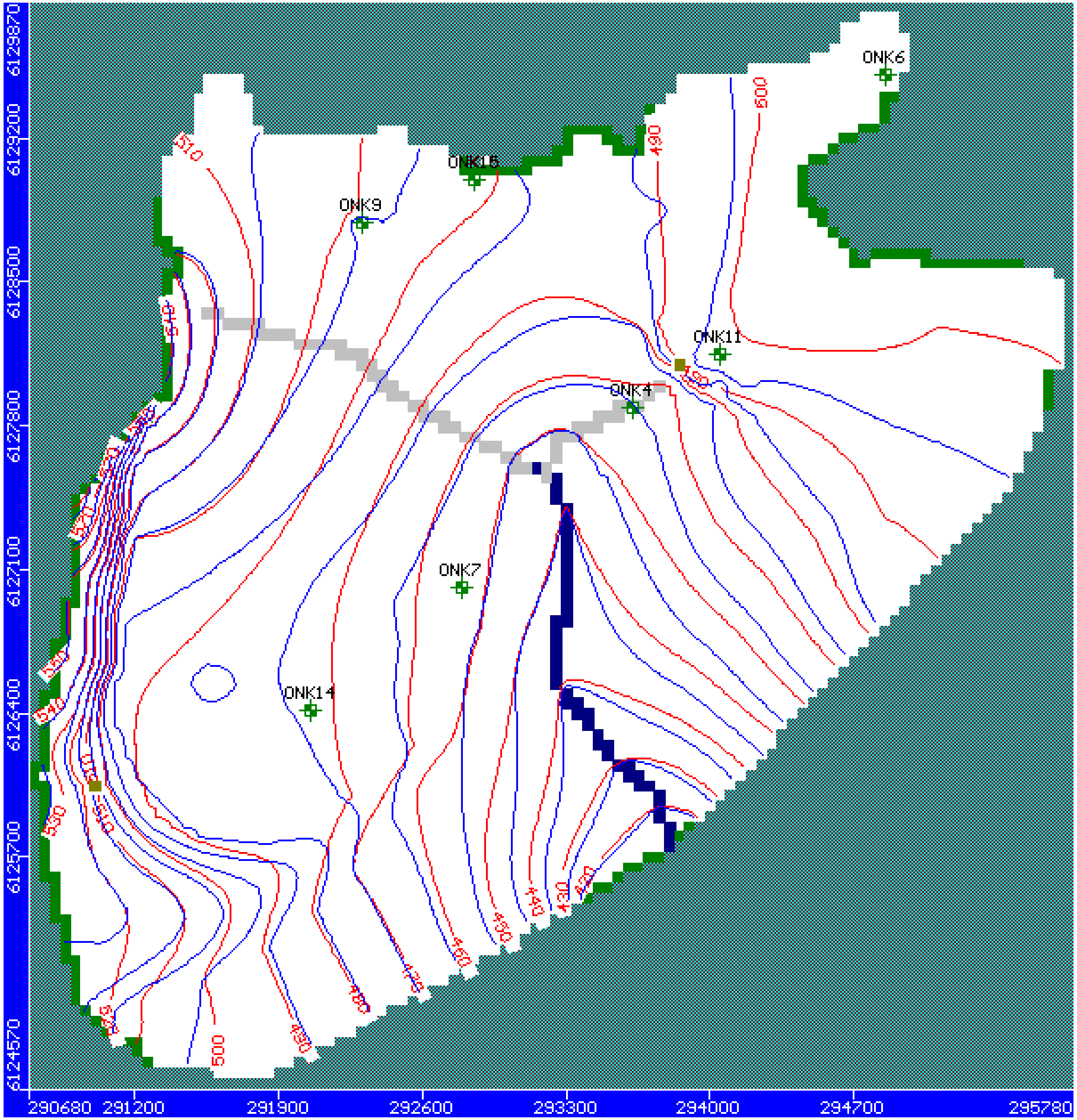

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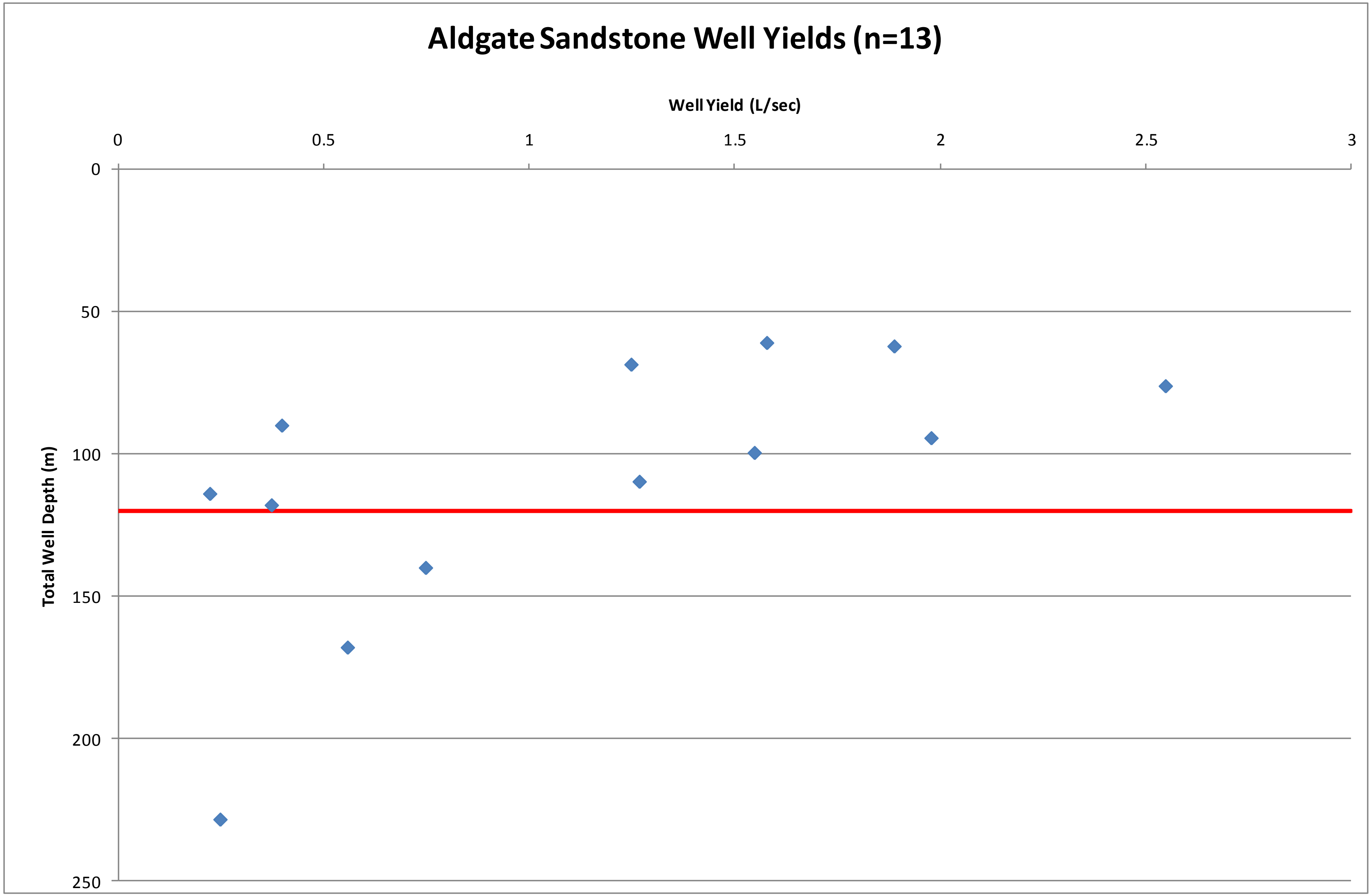
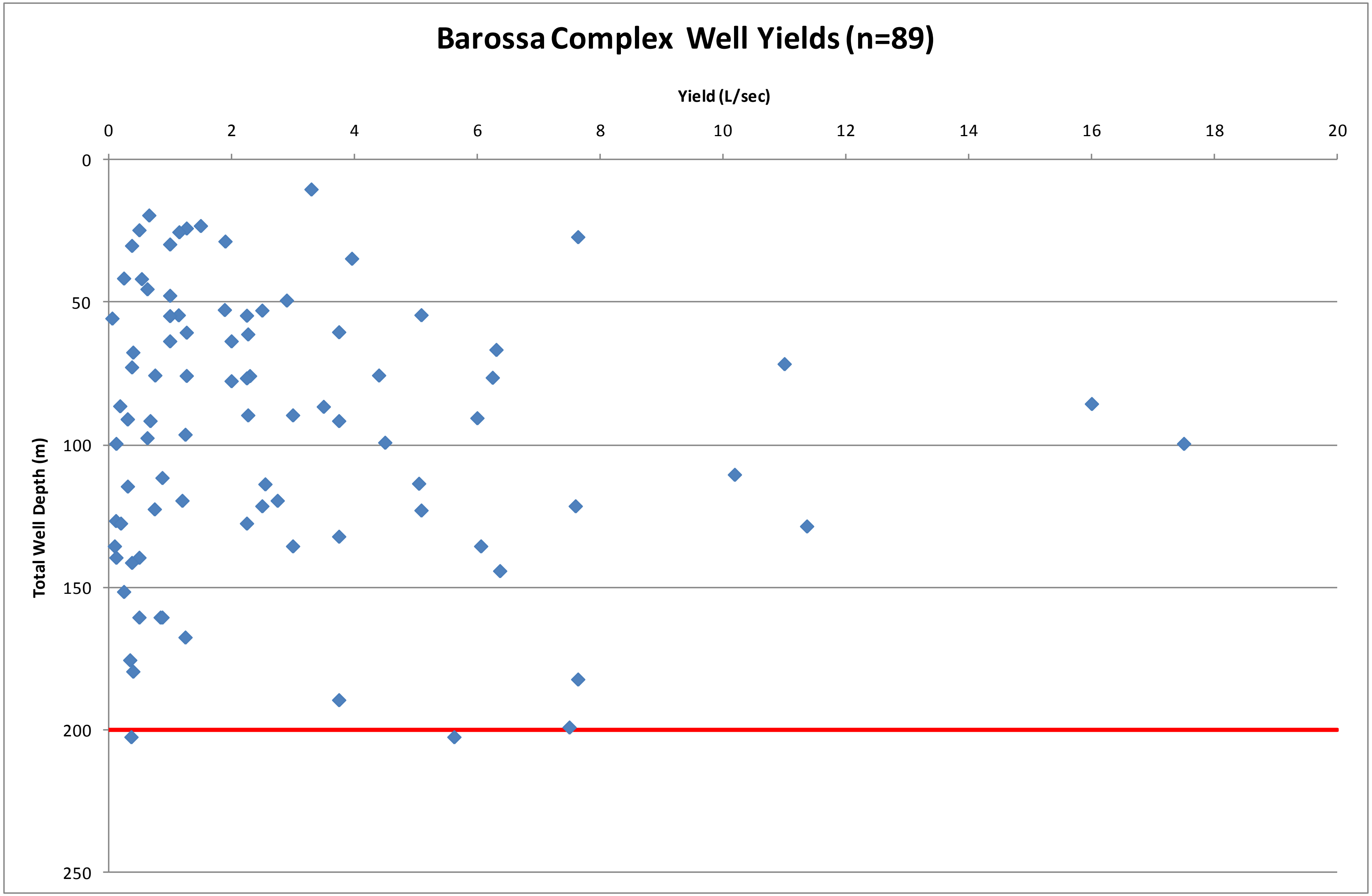
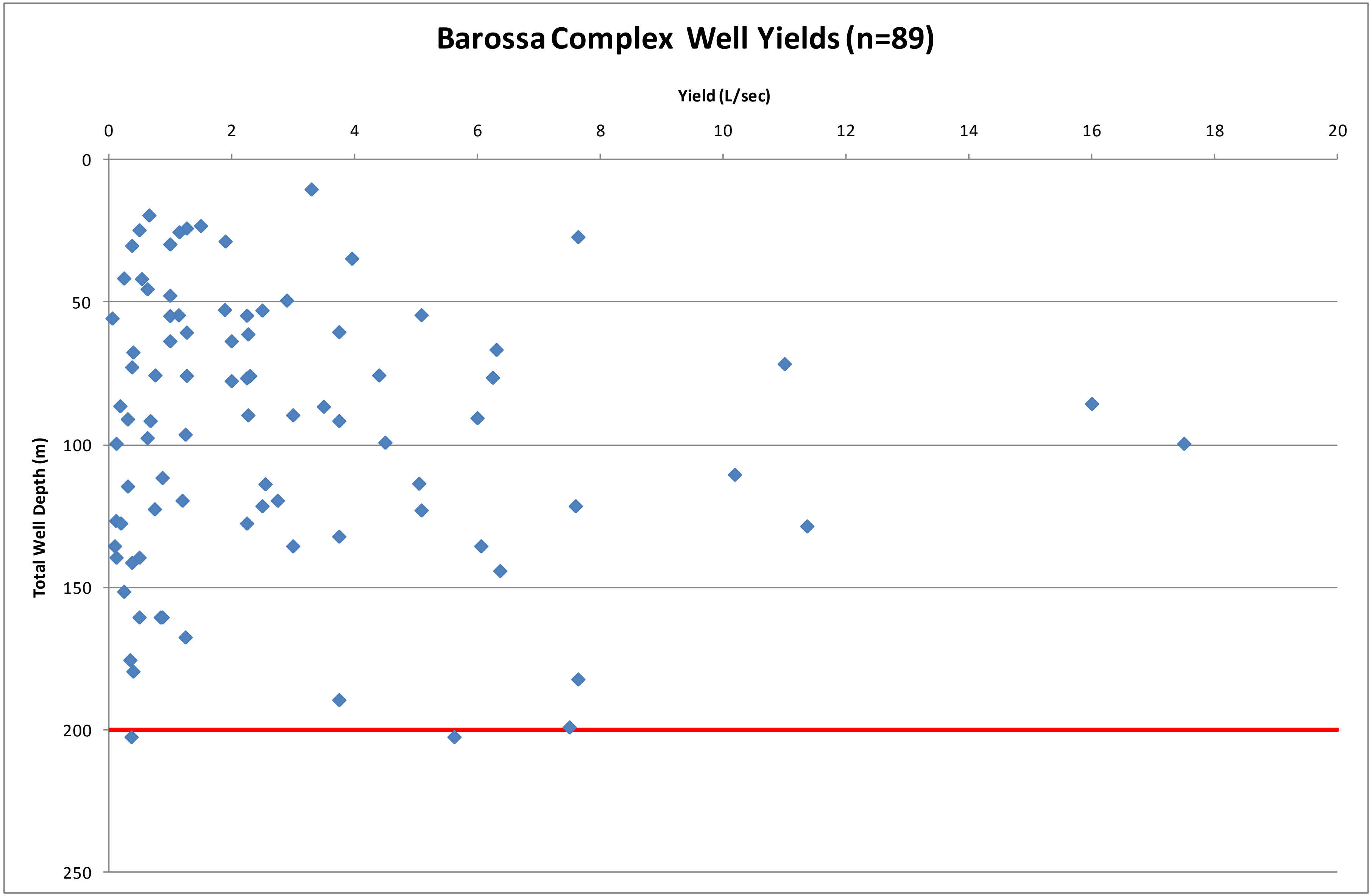
Figure 38: Comparison of S-1 and S-7 potentiometric surfaces for 2028

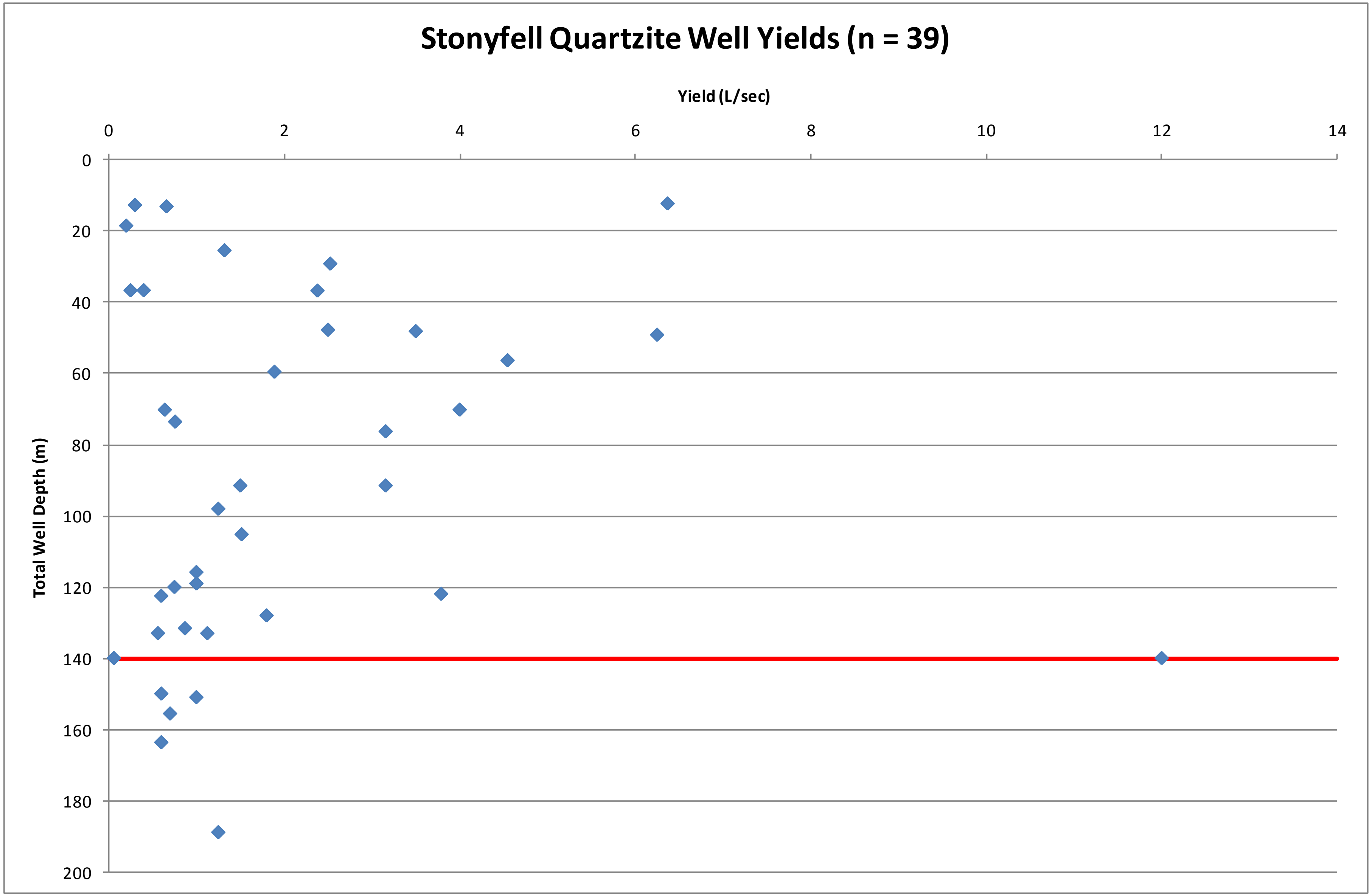
APPENDICES

A. WELL YIELD WITH DEPTH


Aldgate Sandstone Well Yields (n=13)
Well Yield (L/sec)
0
0.5
1
1.5
2
2.5
3
Total Well Depth (m)
0
50
100
150
200
250


Barossa Complex Well Yields (n=89)
Yield (L/sec)
0
2
4
6
8
10
12
14
16
18
20
Total Well Depth (m)
0
50
100
150
200
250


Barossa Complex Well Yields (n=89)
Yield (L/sec)
0
2
4
6
8
10
12
14
16
18
20
Total Well Depth (m)
0
50
100
150
200
250


Stonyfell Quartzite Well Yields (n = 39)
Yield (L/sec)
0
2
4
6
8
10
12
14
Total Well Depth (m)
0
20
40
60
80
100
120
140
160
180
200

Woolshed Flat Shale Well Yields (n=84)
Yield (L/sec)
0
20
40
60
80
100
120
140
Total Well Depth (m)
0
20
40
60
80
100
120
140
160
180
200

B. TRANSIENT RECHARGE RATE DISTRIBUTION

Start Date	Stop Date	Start Day	Stop Day	Rainfall	Stonyfell Quartzite	Barossa Complex	Woolshed Flat Shale	Aldgate Sandstone	Basket Range Sandstone	River	High Recharge zone	Low Recharge Zone
				(mm)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)
1/01/1998	30/01/1998	0	30.5	7.8	10.52	10.67	7.59	10.64	10.64	17.83	23.34	5.88
1/02/1998	30/02/1998	30.5	61	30.2	40.73	41.30	29.39	41.20	41.20	69.03	90.35	22.77
1/03/1998	30/03/1998	61	91.5	15.4	20.77	21.06	14.99	21.01	21.01	35.20	46.07	11.61
1/04/1998	30/04/1998	91.5	122	194.8	262.72	266.42	189.61	265.76	265.76	445.26	582.80	146.87
1/05/1998	30/05/1998	122	152.5	40.4	54.49	55.25	39.32	55.12	55.12	92.34	120.87	30.46
1/06/1998	30/06/1998	152.5	183	157	211.74	214.73	152.81	214.19	214.19	358.86	469.71	118.37
1/07/1998	30/07/1998	183	213.5	151	203.65	206.52	146.97	206.00	206.00	345.15	451.76	113.84
1/08/1998	30/08/1998	213.5	244	null	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1/09/1998	30/09/1998	244	274.5	84.1	113.42	115.02	81.86	114.73	114.73	192.23	251.61	63.41
1/10/1998	30/10/1998	274.5	305	85.4	115.18	116.80	83.12	116.51	116.51	195.20	255.50	64.39
1/11/1998	30/11/1998	305	335.5	50.6	68.24	69.20	49.25	69.03	69.03	115.66	151.39	38.15
1/12/1998	30/12/1998	335.5	366	14.2	19.15	19.42	13.82	19.37	19.37	32.46	42.48	10.71
1/01/1999	30/01/1999	366	396.5	17.6	23.74	24.07	17.13	24.01	24.01	40.23	52.66	13.27
1/02/1999	30/02/1999	396.5	427	6.2	8.36	8.48	6.03	8.46	8.46	14.17	18.55	4.67
1/03/1999	30/03/1999	427	457.5	96.4	130.01	131.84	93.83	131.51	131.51	220.35	288.41	72.68
1/04/1999	30/04/1999	457.5	488	14.4	19.42	19.69	14.02	19.65	19.65	32.91	43.08	10.86
1/05/1999	30/05/1999	488	518.5	305	411.35	417.14	296.87	416.10	416.10	697.15	912.50	229.95
1/06/1999	30/06/1999	518.5	549	144.8	195.29	198.04	140.94	197.55	197.55	330.97	433.21	109.17
1/07/1999	30/07/1999	549	579.5	null	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1/08/1999	30/08/1999	579.5	610	80.4	108.43	109.96	78.26	109.69	109.69	183.77	240.54	60.62
1/09/1999	30/09/1999	610	640.5	130.4	175.87	178.35	126.92	177.90	177.90	298.06	390.13	98.31
1/10/1999	30/10/1999	640.5	671	84.4	113.83	115.43	82.15	115.14	115.14	192.92	252.51	63.63
1/11/1999	30/11/1999	671	701.5	45.2	60.96	61.82	43.99	61.66	61.66	103.32	135.23	34.08
1/12/1999	30/12/1999	701.5	732	86	115.99	117.62	83.71	117.33	117.33	196.57	257.30	64.84
1/01/2000	30/01/2000	732	762.5	10.4	14.03	14.22	10.12	14.19	14.19	23.77	31.11	7.84
1/02/2000	30/02/2000	762.5	793	108	145.66	147.71	105.12	147.34	147.34	246.86	323.11	81.42
1/03/2000	30/03/2000	793	823.5	42.4	57.18	57.99	41.27	57.84	57.84	96.92	126.85	31.97
1/04/2000	30/04/2000	823.5	854	127.2	171.55	173.97	123.81	173.53	173.53	290.75	380.56	95.90
1/05/2000	30/05/2000	854	884.5	162.4	219.03	222.11	158.07	221.56	221.56	371.20	485.87	122.44
1/06/2000	30/06/2000	884.5	915	167.4	225.77	228.95	162.94	228.38	228.38	382.63	500.83	126.21

Start Date	Stop Date	Start Day	Stop Day	Rainfall	Stonyfell Quartzite	Barossa Complex	Woolshed Flat Shale	Aldgate Sandstone	Basket Range Sandstone	River	High Recharge zone	Low Recharge Zone
				(mm)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)
1/07/2000	30/07/2000	915	945.5	118.8	160.22	162.48	115.63	162.07	162.07	271.55	355.43	89.57
1/08/2000	30/08/2000	945.5	976	148.6	200.41	203.24	144.64	202.73	202.73	339.66	444.58	112.03
1/09/2000	30/09/2000	976	1006.5	162.6	219.30	222.39	158.26	221.83	221.83	371.66	486.47	122.59
1/10/2000	30/10/2000	1006.5	1037	148.8	200.68	203.51	144.83	203.00	203.00	340.12	445.18	112.19
1/11/2000	30/11/2000	1037	1067.5	28.6	38.57	39.12	27.84	39.02	39.02	65.37	85.57	21.56
1/12/2000	30/12/2000	1067.5	1098	20.2	27.24	27.63	19.66	27.56	27.56	46.17	60.43	15.23
1/01/2001	30/01/2001	1098	1128.5	23.6	31.83	32.28	22.97	32.20	32.20	53.94	70.61	17.79
1/02/2001	30/02/2001	1128.5	1159	12	16.18	16.41	11.68	16.37	16.37	27.43	35.90	9.05
1/03/2001	30/03/2001	1159	1189.5	106.8	144.04	146.07	103.95	145.70	145.70	244.12	319.52	80.52
1/04/2001	30/04/2001	1189.5	1220	48.2	65.01	65.92	46.91	65.76	65.76	110.17	144.20	36.34
1/05/2001	30/05/2001	1220	1250.5	146.8	197.99	200.78	142.89	200.27	200.27	335.55	439.20	110.68
1/06/2001	30/06/2001	1250.5	1281	162.2	218.76	221.84	157.87	221.28	221.28	370.75	485.27	122.29
1/07/2001	30/07/2001	1281	1311.5	123.8	166.97	169.32	120.50	168.90	168.90	282.97	370.39	93.34
1/08/2001	30/08/2001	1311.5	1342	171.2	230.90	234.15	166.63	233.56	233.56	391.32	512.20	129.07
1/09/2001	30/09/2001	1342	1372.5	170.2	229.55	232.78	165.66	232.20	232.20	389.03	509.20	128.32
1/10/2001	30/10/2001	1372.5	1403	162.8	219.57	222.66	158.46	222.10	222.10	372.12	487.07	122.74
1/11/2001	30/11/2001	1403	1433.5	75.2	101.42	102.85	73.19	102.59	102.59	171.89	224.98	56.70
1/12/2001	30/12/2001	1433.5	1464	36.2	48.82	49.51	35.23	49.39	49.39	82.74	108.30	27.29
1/01/2002	30/01/2002	1464	1494.5	38.4	51.79	52.52	37.38	52.39	52.39	87.77	114.89	28.95
1/02/2002	30/02/2002	1494.5	1525	6	8.09	8.21	5.84	8.19	8.19	13.71	17.95	4.52
1/03/2002	30/03/2002	1525	1555.5	20.4	27.51	27.90	19.86	27.83	27.83	46.63	61.03	15.38
1/04/2002	30/04/2002	1555.5	1586	20.2	27.24	27.63	19.66	27.56	27.56	46.17	60.43	15.23
1/05/2002	30/05/2002	1586	1616.5	124.2	167.51	169.87	120.89	169.44	169.44	283.89	371.58	93.64
1/06/2002	30/06/2002	1616.5	1647	142.6	192.32	195.03	138.80	194.54	194.54	325.95	426.63	107.51
1/07/2002	30/07/2002	1647	1677.5	136	183.42	186.00	132.37	185.54	185.54	310.86	406.89	102.54
1/08/2002	30/08/2002	1677.5	1708	69.2	93.33	94.64	67.35	94.41	94.41	158.17	207.03	52.17
1/09/2002	30/09/2002	1708	1738.5	97.2	131.09	132.94	94.61	132.61	132.61	222.17	290.80	73.28
1/10/2002	30/10/2002	1738.5	1769	62.6	84.43	85.62	60.93	85.40	85.40	143.09	187.29	47.20
1/11/2002	30/11/2002	1769	1799.5	56.1	75.66	76.73	54.60	76.54	76.54	128.23	167.84	42.30
1/12/2002	30/12/2002	1799.5	1830	39.8	53.68	54.43	38.74	54.30	54.30	90.97	119.07	30.01
1/01/2003	30/01/2003	1830	1860.5	36	48.55	49.24	35.04	49.11	49.11	82.29	107.70	27.14
1/02/2003	30/02/2003	1860.5	1891	74.8	100.88	102.30	72.81	102.05	102.05	170.97	223.79	56.39

Start Date	Stop Date	Start Day	Stop Day	Rainfall	Stonyfell Quartzite	Barossa Complex	Woolshed Flat Shale	Aldgate Sandstone	Basket Range Sandstone	River	High Recharge zone	Low Recharge Zone
				(mm)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)
1/03/2003	30/03/2003	1891	1921.5	null	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1/04/2003	30/04/2003	1921.5	1952	55.2	74.45	75.50	53.73	75.31	75.31	126.17	165.15	41.62
1/05/2003	30/05/2003	1952	1982.5	136.4	183.96	186.55	132.76	186.09	186.09	311.77	408.08	102.84
1/06/2003	30/06/2003	1982.5	2013	241.8	326.11	330.71	235.35	329.88	329.88	552.69	723.42	182.30
1/07/2003	30/07/2003	2013	2043.5	null	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1/08/2003	30/08/2003	2043.5	2074	173.2	233.59	236.88	168.58	236.29	236.29	395.89	518.18	130.58
1/09/2003	30/09/2003	2074	2104.5	150.2	202.57	205.43	146.19	204.91	204.91	343.32	449.37	113.24
1/10/2003	30/10/2003	2104.5	2135	98.6	132.98	134.85	95.97	134.52	134.52	225.37	294.99	74.34
1/11/2003	30/11/2003	2135	2165.5	17.6	23.74	24.07	17.13	24.01	24.01	40.23	52.66	13.27
1/12/2003	30/12/2003	2165.5	2196	44	59.34	60.18	42.83	60.03	60.03	100.57	131.64	33.17
1/01/2004	30/01/2004	2196	2226.5	21.3	28.73	29.13	20.73	29.06	29.06	48.69	63.73	16.06
1/02/2004	30/02/2004	2226.5	2257	6.4	8.63	8.75	6.23	8.73	8.73	14.63	19.15	4.83
1/03/2004	30/03/2004	2257	2287.5	44.4	59.88	60.73	43.22	60.57	60.57	101.49	132.84	33.47
1/04/2004	30/04/2004	2287.5	2318	25.8	34.80	35.29	25.11	35.20	35.20	58.97	77.19	19.45
1/05/2004	30/05/2004	2318	2348.5	130.5	176.00	178.48	127.02	178.04	178.04	298.29	390.43	98.39
1/06/2004	30/06/2004	2348.5	2379	257.8	347.69	352.59	250.93	351.71	351.71	589.26	771.29	194.36
1/07/2004	30/07/2004	2379	2409.5	195.4	263.53	267.24	190.19	266.58	266.58	446.63	584.60	147.32
1/08/2004	30/08/2004	2409.5	2440	220.6	297.52	301.71	214.72	300.96	300.96	504.23	659.99	166.32
1/09/2004	30/09/2004	2440	2470.5	115.8	156.18	158.38	112.71	157.98	157.98	264.69	346.45	87.31
1/10/2004	30/10/2004	2470.5	2501	12	16.18	16.41	11.68	16.37	16.37	27.43	35.90	9.05
1/11/2004	30/11/2004	2501	2531.5	null	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1/12/2004	30/12/2004	2531.5	2562	68.3	92.12	93.41	66.48	93.18	93.18	156.12	204.34	51.49
1/01/2005	30/01/2005	2562	2592.5	42.5	57.32	58.13	41.37	57.98	57.98	97.14	127.15	32.04
1/02/2005	30/02/2005	2592.5	2623	51.9	70.00	70.98	50.52	70.81	70.81	118.63	155.27	39.13
1/03/2005	30/03/2005	2623	2653.5	13	17.53	17.78	12.65	17.74	17.74	29.71	38.89	9.80
1/04/2005	30/04/2005	2653.5	2684	8.8	11.87	12.04	8.57	12.01	12.01	20.11	26.33	6.63
1/05/2005	30/05/2005	2684	2714.5	14.8	19.96	20.24	14.41	20.19	20.19	33.83	44.28	11.16
1/06/2005	30/06/2005	2714.5	2745	227.1	306.29	310.60	221.04	309.82	309.82	519.09	679.44	171.22
1/07/2005	30/07/2005	2745	2775.5	118.2	159.41	161.66	115.05	161.26	161.26	270.17	353.63	89.12
1/08/2005	30/08/2005	2775.5	2806	176.4	237.91	241.26	171.70	240.66	240.66	403.20	527.75	132.99
1/09/2005	30/09/2005	2806	2836.5	97.7	131.77	133.62	95.09	133.29	133.29	223.32	292.30	73.66
1/10/2005	30/10/2005	2836.5	2867	203.4	274.32	278.19	197.98	277.49	277.49	464.92	608.53	153.35

Start Date	Stop Date	Start Day	Stop Day	Rainfall	Stonyfell Quartzite	Barossa Complex	Woolshed Flat Shale	Aldgate Sandstone	Basket Range Sandstone	River	High Recharge zone	Low Recharge Zone
				(mm)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)
1/11/2005	30/11/2005	2867	2897.5	185.4	250.05	253.57	180.46	252.93	252.93	423.78	554.68	139.78
1/12/2005	30/12/2005	2897.5	2928	68	91.71	93.00	66.19	92.77	92.77	155.43	203.44	51.27
1/01/2006	30/01/2006	2928	2958.5	33.4	45.05	45.68	32.51	45.57	45.57	76.34	99.93	25.18
1/02/2006	30/02/2006	2958.5	2989	29.2	39.38	39.94	28.42	39.84	39.84	66.74	87.36	22.01
1/03/2006	30/03/2006	2989	3019.5	30.2	40.73	41.30	29.39	41.20	41.20	69.03	90.35	22.77
1/04/2006	30/04/2006	3019.5	3050	105.8	142.69	144.70	102.98	144.34	144.34	241.83	316.53	79.77
1/05/2006	30/05/2006	3050	3080.5	162.4	219.03	222.11	158.07	221.56	221.56	371.20	485.87	122.44
1/06/2006	30/06/2006	3080.5	3111	51	68.78	69.75	49.64	69.58	69.58	116.57	152.58	38.45
1/07/2006	30/07/2006	3111	3141.5	164.4	221.72	224.85	160.02	224.28	224.28	375.78	491.85	123.95
1/08/2006	30/08/2006	3141.5	3172	42.2	56.91	57.72	41.07	57.57	57.57	96.46	126.25	31.82
1/09/2006	30/09/2006	3172	3202.5	61.9	83.48	84.66	60.25	84.45	84.45	141.49	185.19	46.67
1/10/2006	30/10/2006	3202.5	3233	2.6	3.51	3.56	2.53	3.55	3.55	5.94	7.78	1.96
1/11/2006	30/11/2006	3233	3263.5	35.1	47.34	48.01	34.16	47.89	47.89	80.23	105.01	26.46
1/12/2006	30/12/2006	3263.5	3294	35.8	48.28	48.96	34.85	48.84	48.84	81.83	107.11	26.99
1/01/2007	30/01/2007	3294	3324.5	86.6	116.80	118.44	84.29	118.15	118.15	197.94	259.09	65.29
1/02/2007	30/02/2007	3324.5	3355	0.1	0.13	0.14	0.10	0.14	0.14	0.23	0.30	0.08
1/03/2007	30/03/2007	3355	3385.5	39.1	52.73	53.48	38.06	53.34	53.34	89.37	116.98	29.48
1/04/2007	30/04/2007	3385.5	3416	157.2	212.01	215.00	153.01	214.46	214.46	359.32	470.31	118.52
1/05/2007	30/05/2007	3416	3446.5	152.3	205.40	208.30	148.24	207.78	207.78	348.12	455.65	114.82
1/06/2007	30/06/2007	3446.5	3477	142.7	192.46	195.17	138.89	194.68	194.68	326.17	426.93	107.59
1/07/2007	30/07/2007	3477	3507.5	170	229.28	232.51	165.47	231.92	231.92	388.58	508.61	128.17
1/08/2007	30/08/2007	3507.5	3538	67.6	91.17	92.46	65.80	92.22	92.22	154.52	202.25	50.97
1/09/2007	30/09/2007	3538	3568.5	66.4	89.55	90.81	64.63	90.59	90.59	151.77	198.66	50.06
1/10/2007	30/10/2007	3568.5	3599	48.2	65.01	65.92	46.91	65.76	65.76	110.17	144.20	36.34
1/11/2007	30/11/2007	3599	3629.5	39.8	53.68	54.43	38.74	54.30	54.30	90.97	119.07	30.01
1/12/2007	30/12/2007	3629.5	3660	61.2	82.54	83.70	59.57	83.49	83.49	139.89	183.10	46.14

C. WATER BALANCE OUTPUTS

	Rates for last time step day 10980 (m3/day)													
	S_1		S_2		S_3		S_4		S_5		S_6		S_7	
	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
Storage	2535	413	2681	403	2238	298	2415	299	2408	434	2080	300	1516	5
Wells	0	2074	0	2537	0	2074	0	2537	0	1691	0	1691	0	0
Drains	0	861	0	763	0	729	0	653	0	888	0	750	0	670
Recharge	4194	0	4194	0	3355	0	3355	0	4194	0	3355	0	629	0
ET	0	1665	0	1604	0	1471	0	1412	0	1728	0	1524	0	1354
River Leakage	1	2140	2	2090	7	1905	8	1852	1	2188	7	1955	23	1604
General-Head	1967	1544	2035	1515	2208	1332	2279	1305	1901	1573	2137	1359	2577	1111
Total	8698	8697	8912	8912	7809	7808	8057	8057	8503	8503	7579	7579	4746	4744
IN-OUT	0.27		0.33		0.23		0.24		0.30		0.18		1.91	
Discrepancy	0%		0%		0%		0%		0%		0%		0.04%	

D. MODELLED GROUNDWATER DISCHARGE

Time		Annual Discharge to Cox Creek - Volume (ML)						
Year	Day	S_1	S_2	S_3	S_4	S_5	S_6	S_7
1	365	987	987	987	987	987	987	987
2	732	988	988	988	988	988	988	988
3	1098	1099	1099	1099	1099	1099	1099	1099
4	1464	1099	1099	1099	1099	1099	1099	1099
5	1830	975	975	975	975	975	975	975
6	2196	1015	1015	1015	1015	1015	1015	1015
7	2562	1053	1053	1053	1053	1053	1053	1053
8	2928	1058	1058	1058	1058	1058	1058	1058
9	3294	982	982	982	982	982	982	982
10	3660	1008	1008	1008	1008	1008	1008	1008
11	4026	905	897	858	851	906	860	804
12	4392	903	884	838	819	923	857	753
13	4758	968	945	881	858	991	903	770
14	5124	1090	1064	971	946	1117	996	825
15	5490	1093	1066	971	944	1122	998	821
16	5856	971	943	875	848	998	902	752
17	6222	1011	982	903	874	1041	932	765
18	6588	1049	1019	930	900	1080	960	780
19	6954	1054	1021	932	900	1088	965	777
20	7320	977	946	874	842	1009	905	738
21	7686	1004	970	891	858	1037	924	745
22	8052	900	867	809	776	933	842	685
23	8418	899	864	807	773	933	841	681
24	8784	963	927	855	821	999	891	713
25	9150	1085	1047	948	911	1123	985	774
26	9516	1088	1050	950	913	1127	988	774
27	9882	965	928	856	820	1002	893	711
28	10248	1006	967	885	847	1044	923	725
29	10614	1044	1005	913	874	1083	951	742
30	10980	1067	1024	931	890	1103	967	753

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

Shortened forms

EC electrical conductivity (µS/cm)

K hydraulic conductivity (m/d)

GLOSSARY

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer test — A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resources available for development from the well

Baseflow — The water in a stream that results from groundwater discharge to the stream; often maintains flows during seasonal dry periods and has important ecological functions

BoM — Bureau of Meteorology, Australia

Catchment — That area of land determined by topographic features within which rainfall will contribute to run-off at a particular point

CCC — Cox Creek Catchment

Cone of depression — An inverted cone-shaped space within an aquifer caused by a rate of groundwater extraction that exceeds the rate of recharge; continuing extraction of water can extend the area and may affect the viability of adjacent wells, due to declining water levels or water quality

Confining layer — A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

DEM — Digital elevation model

DWLBC — Department of Water, Land and Biodiversity Conservation (Government of South Australia)

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies

FRA — Fractured rock aquifer

GHB — General head boundaries

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Irrigation — Watering land by any means for the purpose of growing plants

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

MLR — Mount Lofty Ranges

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm run-off, assessing the impacts of dams or predicting ecological response to environmental change

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals, and other living things

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m^2/d

Piezometer — A narrow tube, pipe or well; used for measuring moisture in soil, water levels in an aquifer, or pressure head in a tank, pipeline, etc

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface

Recharge area — The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. See also artificial recharge, natural recharge

REV — Representative elementary volume

RMS — Root mean square

SA Geodata — A collection of linked databases storing geological and hydrogeological data, which the public can access through the offices of PIRSA. Custodianship of data related to minerals and petroleum, and groundwater, is vested in PIRSA and DWLBC, respectively. DWLBC should be contacted for database extracts related to groundwater

Specific storage (S_s) — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; it is dimensionless

Specific yield (S_y) — The volume ratio of water that drains by gravity, to that of total volume of the porous medium. It is dimensionless

(S) — Storativity; storage coefficient; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; it is dimensionless

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

T — Transmissivity; a parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow), measured in m^2/d

TCR — Theoretical crop requirement

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

Water allocation — (1) In respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence. (2) In respect of water taken pursuant to an authorisation under s.11 means the maximum quantity of water that can be taken and used pursuant to the authorisation

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

WMLR — Western Mount Lofty Ranges

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