TECHNICAL REPORT

TATIARA PILOT ADAPTIVE MANAGEMENT GROUNDWATER FLOW MODEL

2011/13

Government of South Australia
Department for Water

TATIARA PILOT ADAPTIVE MANAGEMENT GROUNDWATER FLOW MODEL

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PREFACE

On 1 July 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

ACKNOWLEDGEMENTS

The work detailed in this report could not have been conducted without the assistance of several people, whom the author would like to take this opportunity to thank. From DFW, Paul O'Connor for help with formatting spatial data and water use data, Brian Latcham and Nick McIntyre for help with scoping the level of complexity required for the model and Drew Laslett for providing useful information on appropriate scenarios to run. Glenn Harrington from CSIRO is thanked for providing advice on model construction, as is Brian Barnett from SKM for providing additional technical advice.

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SUMMARY

This report documents work undertaken as part of the Resource Sustainability component of the South East National Water Initiative project 'Integrated Water Resource Management' (IWRM). In this part of the project, a numerical groundwater flow model has been developed for a subsection of the Tatiara Prescribed Wells Area (herein referred to as the 'Pilot Trial Zone' or 'PTZ') in the Upper South East of South Australia. The purpose of this model was to act as a decision support tool for the Adaptive Management (AM) component of the IWRM project, and to assist in developing 'trial' adaptive management scenarios.

The model domain area was based on hydrogeological boundaries delineated by REM Pty Ltd in the early stages of the AM project. These boundaries reflected conditions such as aquifer depth and water level trends but were adjusted for the modelling project to assist in dealing with licensed extraction data. The model was based on the management areas of Stirling, Willalooka, Wirrega and North Pendleton. This particular area was selected for the AM trial because the groundwater resources have been experiencing declines in level and increases in salinity in recent years (water level declines and salinity increases) and at the time of completing this work, there were proposals contained in the review of the Tatiara Water Allocation Plan that have since been implemented to reduce licensed water allocations for a number of management areas. Also, the area had a good level of existing data with which to develop a numerical model (there was little scope in this project to undertake technical investigations for this model).

The model was constructed in *Visual MODFLOW v 4.1* and developed in line with the Murray-Darling Basin Commission guidelines for groundwater modelling in Australia (Middlemis 2001). A steady state model was initially constructed and calibrated and a transient model was then developed from this, running from 1970 to 2009 and calibrated using measured groundwater levels from 54 wells (the earliest observation records date from 1975). For all transient model run times, a normalised root mean squared error between modelled and measured water levels of 3.98% was achieved, which was considered adequate based on our current understanding of the hydrogeology in the area and the purpose of the model. Areas of uncertainty and poor model performance have been identified so that future work may address these issues.

During 2008 and 2009, two workshops were held with community members, technical staff and other key stakeholders in the PTZ to develop pilot guidelines for Adaptive Management. Through this process, several Resource Condition Limits based on groundwater levels were developed for the PTZ. The groundwater model was then used to run a number of scenarios to see how different extraction regimes would perform against the RCLs under various climate conditions. It was found that extraction rates of 70% of proposed volumetric allocations (with proposed allocation cuts implemented) under average rainfall/recharge conditions would meet most of the RCLs set for groundwater levels.

The new Water Allocation Plan (WAP) for the Tatiara Prescribed Wells Area (PWA) was still being developed and implemented while this project was underway; hence, the work conducted here (in conjunction with that done in the AM project) has not had an immediate impact on groundwater management. However, it has provided a useful foundation for future management review in the Tatiara area.

1. INTRODUCTION

1.1. BACKGROUND

The groundwater resources of the South East are important for South Australia. These resources support a wide array of industry, predominantly wine; wool; meat; dairy; forestry and timber; fishing and aquaculture; vegetables; and seed production. Furthermore, groundwater is the primary source of water for town supply throughout the region.

The South East National Water Initiative project 'Integrated Water Resource Management in South East South Australia' involved a number of programs investigating such areas as resource sustainability, water accounting and adaptive management options for managing groundwater resources. One of the requirements of the Resource Sustainability sub-program was to develop a numerical groundwater model to be used as a decision support tool in line with the Adaptive Management sub-program.

As part of the Adaptive Management (AM) sub-program, Resource and Environmental Management Pty Ltd (REM) was contracted by DWLBC in 2008 to provide a report on establishing AM frameworks in the South East of South Australia. Part of this involved delineating hydrogeological boundaries for AM that differed from current groundwater management boundaries in the South East. These new Pilot Adaptive Management Zones (PAMZs) were based on geology, aquifer thickness and aquifer behaviour (Harrington et al. 2008). For a number of reasons (such as data availability, resource condition, level of community engagement, proposed reductions in groundwater allocation), Pilot Adaptive Management Zone 2 (Figure 1), located in the Upper South East within the Tatiara Prescribed Wells Area, was selected as the area in which a pilot adaptive management trial would be conducted. Herein, this zone will be referred to as the 'Pilot Trial Zone (PTZ)'.

This report outlines the development of a groundwater flow model for the PTZ. It describes the hydrogeology of the PTZ, the design and calibration of the model and the model scenarios run to assess various AM arrangements. Areas of poor model performance are identified and recommendations for future work are also made.

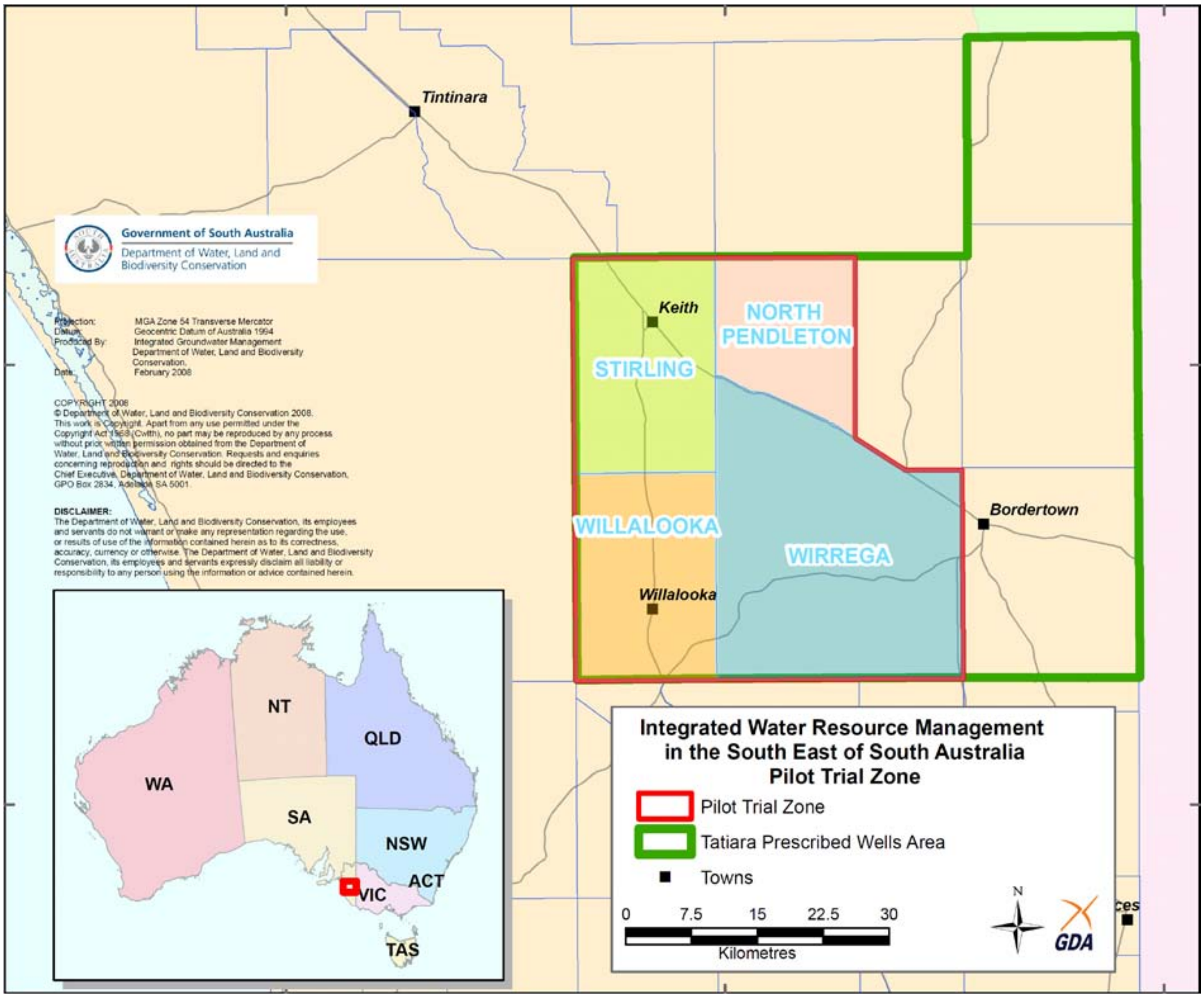


Figure 1. The Pilot Trial Zone (PTZ) for Adaptive Management (AM) in the Upper South East of South Australia

1.2. OBJECTIVES

In consultation with community groups in the PTZ, as well as relevant technical and policy staff, the AM project developed pilot guidelines for possible future groundwater management based on groundwater level response. That is, management of the water resource and allocation of the groundwater resource in these areas, largely depends on groundwater response to seasonal recharge (rather than allocation based on long-term estimates of recharge). As part of this, target limits of acceptable groundwater decline were set, based on values of the groundwater resource (maintaining water levels in the productive zones of the aquifer, maintaining aquifer through-flow, etc.).

The aim of this part of the project was to develop a numerical groundwater flow model of moderate to high complexity that was well-calibrated and could be used to run scenarios for AM. The main types of scenarios the model was needed to run relate to how changes in groundwater recharge and extraction affect groundwater levels—specifically, what levels of groundwater extraction can be supported in order to keep groundwater levels within acceptable limits for future management.

2. HYDROGEOLOGY

The Pilot Trial Zone (PTZ) is located in the Upper South East of South Australia, centring on the Groundwater Management Areas of Stirling, North Pendleton, Wirrega and Willalooka (Figure 1, total area ~1840 km^2). The area can be characterised as semi-arid, with mean annual rainfall in Keith of 463 mm/y, approximately 60% of which falls between May and September (BoM 2008). Potential evapotranspiration in the Stirling management area is approximately 1700 mm/y (Wohling 2006). The major land use in the area is dryland agriculture (~83% land area). Other land uses are irrigated agriculture (~10%), native vegetation and urban areas (Figure 2).

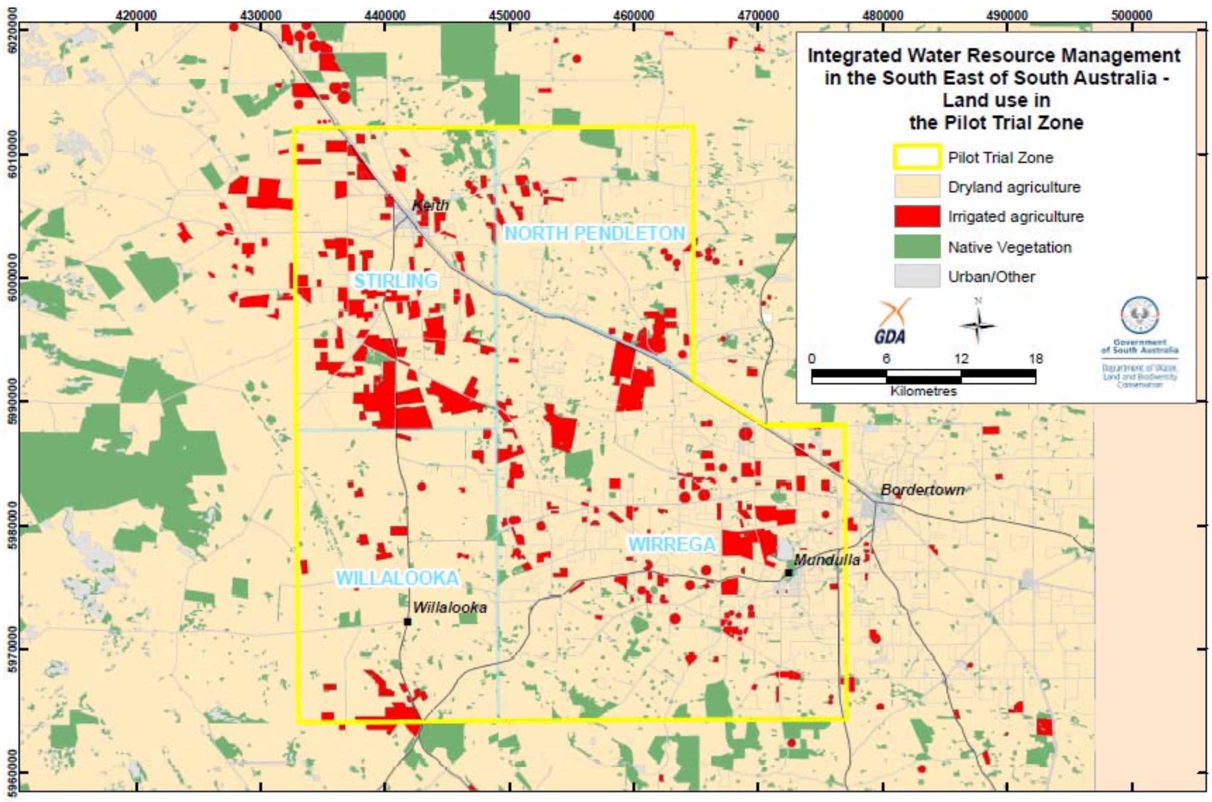


Figure 2. Land uses in the PTZ

2.1. GEOLOGY

The PTZ is located in the south-western portion of the Murray Basin, in the South East Natural Resources Management Board (SENRMB) region. The PTZ can be separated into two land types: a low-lying coastal plain in the west and the uplifted Pinnaroo Block in the east. These two land units are separated by the Marmon Jabuk Fault in the north and the Kanawinka Fault in the south. The fault scarps from both features are covered by a remnant dune ridge that extends approximately 50 m to 70 m above the plain (see Figure 3 and Figure 4 from Cobb & Brown 2000).

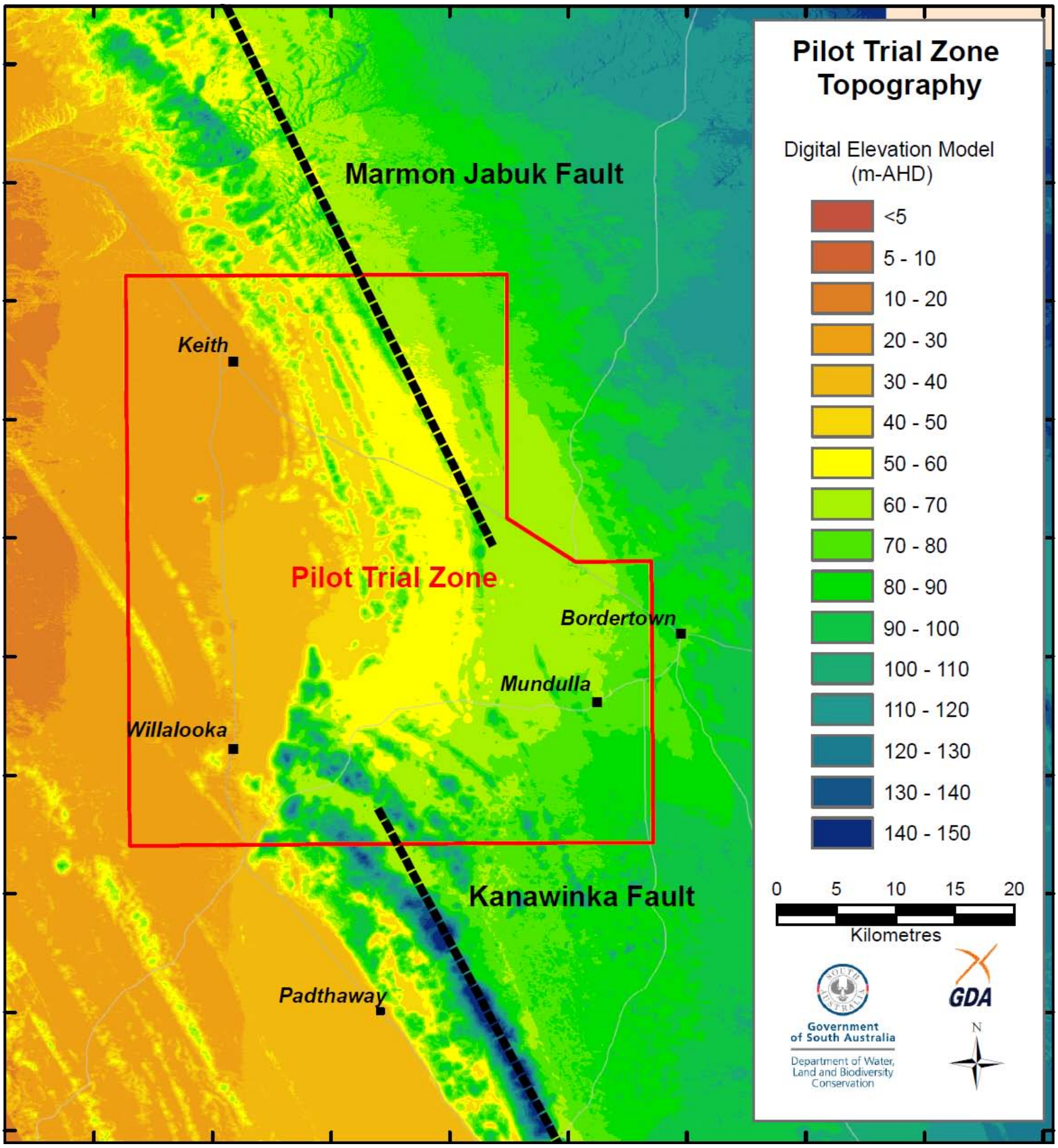


Figure 3. Surface elevation and structural features in the Pilot Trial Zone (after Cobb & Brown 2000)

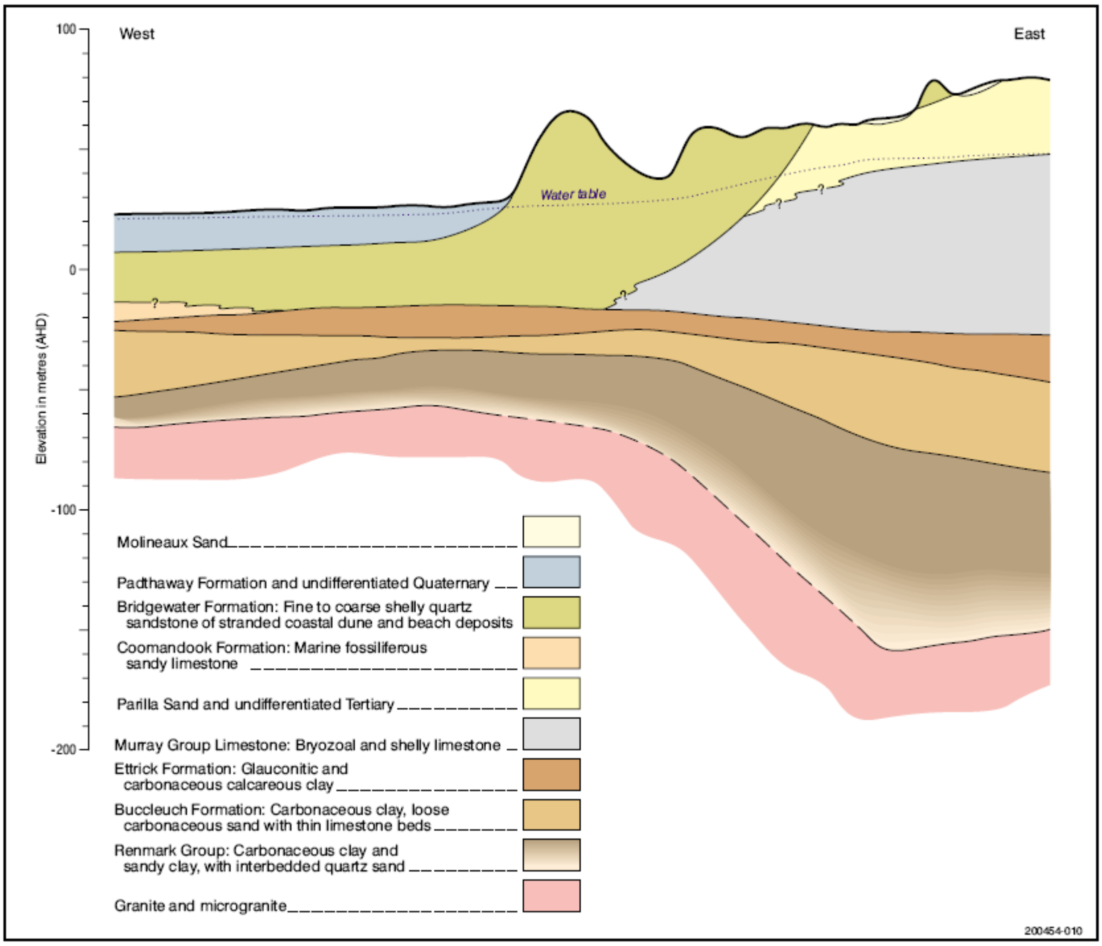


Figure 4. Geological cross section of the Tatiara Prescribed Wells Area (from Cobb & Brown 2000), which is representative of the PTZ

The western region is characterised by a series of Quaternary stranded coastal dunes that run sub-parallel to the coastline, known as the 'Bridgewater Formation'. A succession of low-lying inter-dunal flats separate the ridges and consist of the Padthaway Formation (also Quaternary). These formations are underlain by carbonaceous clays and marls, which grade into the Renmark Group. The geologic basement of the Padthaway Ridge—which consists of either Ordovician granite or porphyry, or Cambrian meta-sediments comprising white, pale green/blue clays (Stadter & Love 1987)—outcrops periodically in the lower lying western plains, creating features such as Mt Monster, south of the township of Keith.

The eastern region is characterised by undulating plains, increasing in elevation to the north-east. Remnant sand dunes and east to south-east trending sand sheets overlie these plains (Cobb & Brown 2000). Underlying these sediments is the Murray Group Limestone, a Tertiary formation consisting of bryozoal limestone. The sequence of clays and marls that grade into the Renmark Group underlie the Murray Group Limestone in the east.

2.2. HYDROGEOLOGY

Groundwater flow in the PTZ is generally towards the west to north-west (Figure 5), through both the regional unconfined and regional confined aquifers. The unconfined aquifer is a multi-lithological formation that consists of the Tertiary limestone aquifer (TLA—the Murray Group Limestone) east of the Marmon Jabuk Fault and the Quaternary sand aquifers (QSA—Padthaway, Bridgewater and Coomandook Formations) in the western region. The unconfined aquifer watertable is generally quite flat; however, a steep gradient zone occurs in the middle of the region. The cause of this steep gradient zone has not been properly investigated but is thought to be caused either by:

- low aquifer permeabilities in the transition zone from the TLA to the Bridgewater Formation, or
- aquifer displacement or some other process caused by the Marmon Jabuk fault (similar to the steep watertable gradient zone observed in the Lower South East over the Tartwaup fault).

Groundwater levels in the unconfined aquifer show the greatest seasonal fluctuation west of this steep gradient zone, particularly in the Stirling management area. This is because of the shallow depth to water (typically <10 m), which makes it particularly responsive to rainfall recharge, and the concentration of large-scale irrigation in the area, which produces a noticeable drawdown in the watertable over summer. Figure 5 displays seasonal watertable elevations in the unconfined aquifers (TLA and Quaternary aquifers). For groundwater management and investigation purposes, the unconfined Tertiary and Quaternary aquifers are considered to be one continuous aquifer unit.

The Tertiary confined sand aquifer (TCSA) consists of the Renmark Group of sands and clays. The TLA is separated from the TCSA by a low permeability Tertiary aquitard (Ettrick Formation and Buccleuch Beds). Figure 6 (from Cobb & Brown 2000) outlines the hydrostratigraphy of the study area.

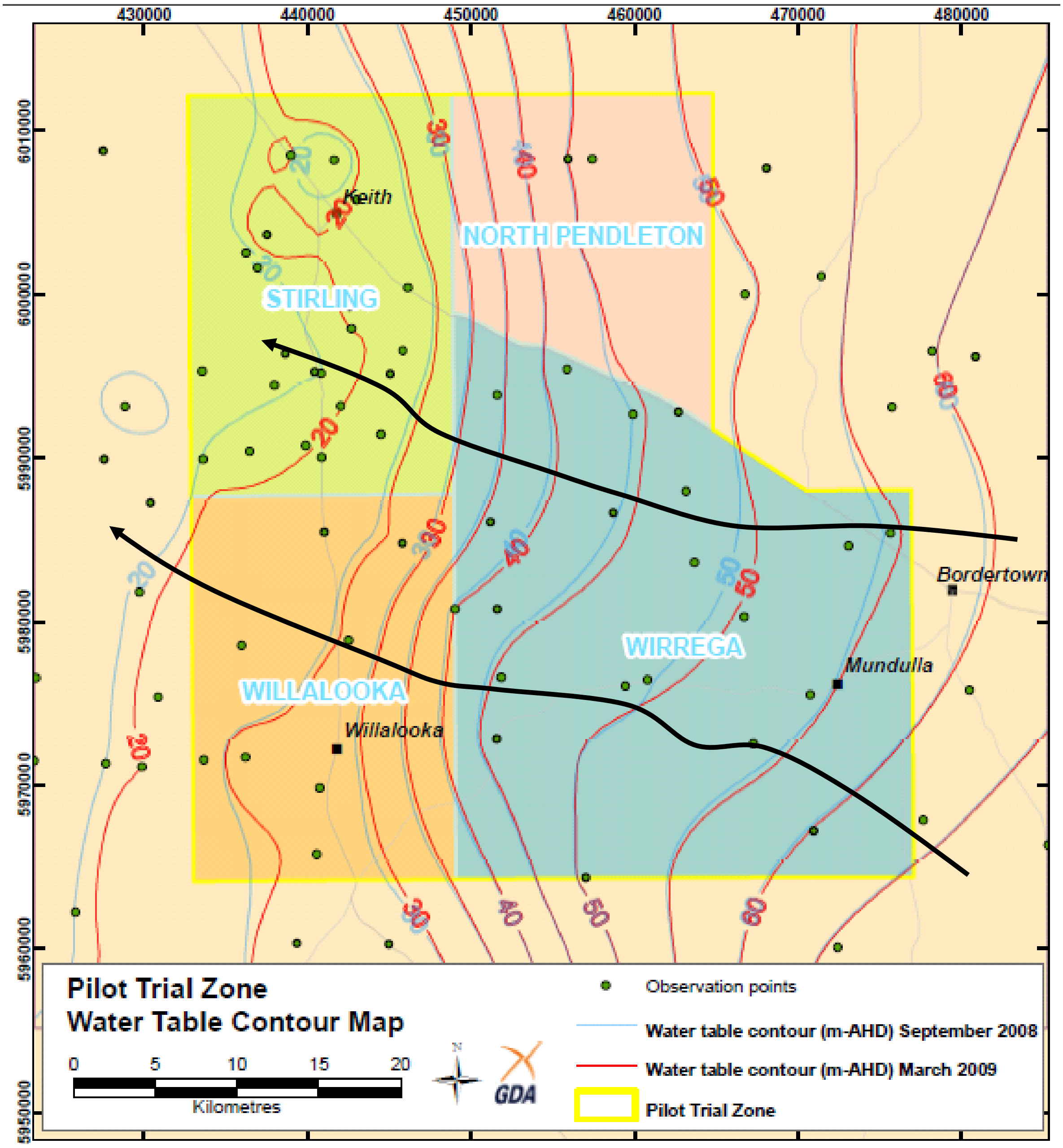


Figure 5. Measured potentiometric surface (m-AHD) in the unconfined aquifers in the PTZ

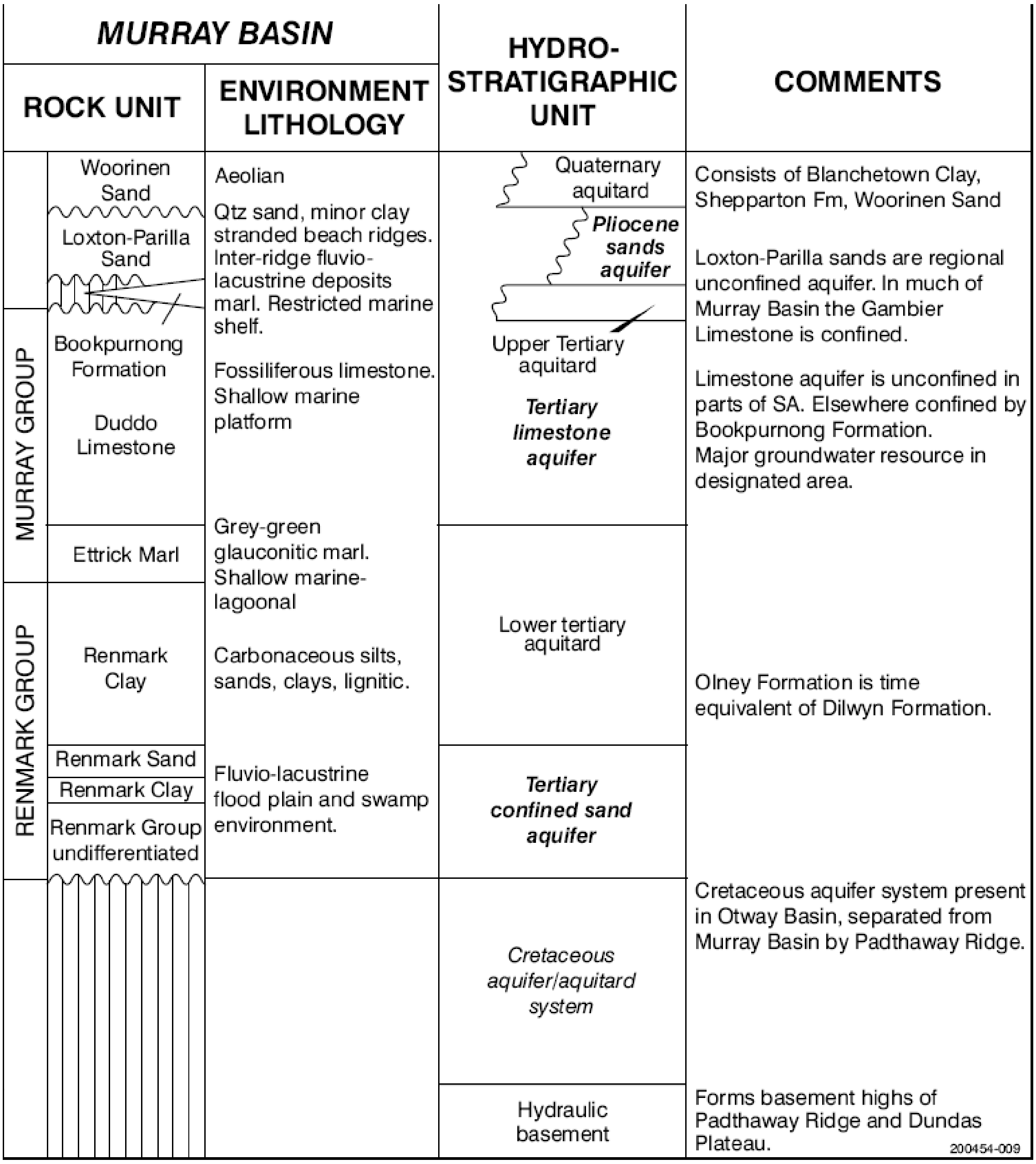


Figure 6. Hydrostratigraphy of the Murray Basin (from Cobb & Brown 2000)

2.2.1. TERTIARY CONFINED SAND AQUIFER

The TCSA in the PTZ is the Renmark Group formation, which consists of the Warina Sand and Olney Formation. These units are comprised of a series of thin, interbedded limestone and sand aquifers separated by thin carbonaceous clay units (Cobb & Brown 2000). The TCSA is not as extensively used in the PTZ, due to the availability of water in the TLA and QSA and the low reported well yields (10–20 L/s).

Recharge to the TCSA in the PTZ is largely via lateral through-flow, with the main rainfall recharge area for the aquifer thought to be the Dundas Plateau in Western Victoria (Cobb & Brown 2000). Little is known of the connection between the TLA and TCSA in the PTZ. While there is some evidence of potential for leakage between the two aquifers (Stadter & Love 1987), this connection has never been quantified or investigated in the PTZ.

2.2.2. TERTIARY AQUITARD

The Tertiary aquitard that separates the unconfined aquifers and the TCSA throughout the PTZ consists of the Ettrick Formation and the Bueccleuch Beds. The Ettrick Formation (maximum known thickness 31 m) consists of dark green/grey marl with sand interbeds, is glauconitic and fossiliferous, with minor carbonaceous clay and occasional thin, cemented limestone and dolomite interbeds. The Bueccleuch Beds (maximum known thickness 40 m) consist of fossiliferous dark grey to brown carbonaceous clays and quartz sand, with interbeds of limestone (Stadter & Love 1987). There are no reported hydraulic values for the Tertiary aquitard in the Upper South East; however, estimates of the hydraulic conductivity of the Tertiary aquitard in the Lower South East (which is a different geological unit but can be considered similar in lithology) range from 3.4×10^{-6} m/d to 7.2×10^{-6} m/d (Brown et al. 2001).

2.2.3. UNCONFINED TERTIARY LIMESTONE AQUIFER

East of the Marmon Jabuk Fault, the unconfined aquifer in the PTZ is dominated by the Tertiary limestone sediments of the Murray Basin (the Murray Group Limestone, maximum known thickness 108 m). These sediments are the result of a marine transgression during the late Eocene to middle Miocene. The Murray Group consists mainly of shallow marine fossiliferous limestone and sandstone with minor clay and silt. It includes the Mannum Limestone, Finnis Clay, Winnambool Formation and Geera Clay (Rogers 1995; Stadter & Love 1987).

Further sequences were deposited during the late Miocene to late Pliocene, including the Bookpurnong Formation (a shallow-water marine deposit), the Loxton Sands (a regressive sequence of shallow-water marine and marginal marine into beach and coastal barrier deposits) and the Parilla Sands (a non-marine deposit). However, these sequences are unsaturated where present in the PTZ.

Transmissivity values of 500–3000 m^2/d have been reported for the Murray Group Limestones, with one very high transmissivity reported (14 040 m^2/d), thought to be caused by cavity development in the limestone. Well yields range from 50 L/s to 200 L/s (Stadter & Love 1987).

Monitoring of groundwater levels in the PTZ commenced in the late 1970s. In the Murray Group Limestone formation (the eastern section of the PTZ), depth to water is generally >15 m. This means that significant seasonal fluctuations in the watertable are generally not observed (the exception being some shallower areas, where the effect of seasonal pumping on water levels is observed). Figure 7 displays representative hydrographs for the TLA in the Wirrega management area. As can be seen, water levels have been reasonably static over the past 25 years, with some decline in the past 15 years. The likely explanation for this decline is decreased rainfall recharge. Similar trends are seen further north in North Pendleton (Figure 8). Figure 9 shows the cumulative deviation in mean annual rainfall measured at Keith weather station, along with the hydrograph from WRG111. As can be seen, there is a strong correlation between the two. However, increased groundwater extraction in response to decreased rainfall is also thought to have played a part in groundwater level decline (MacKenzie 2000).

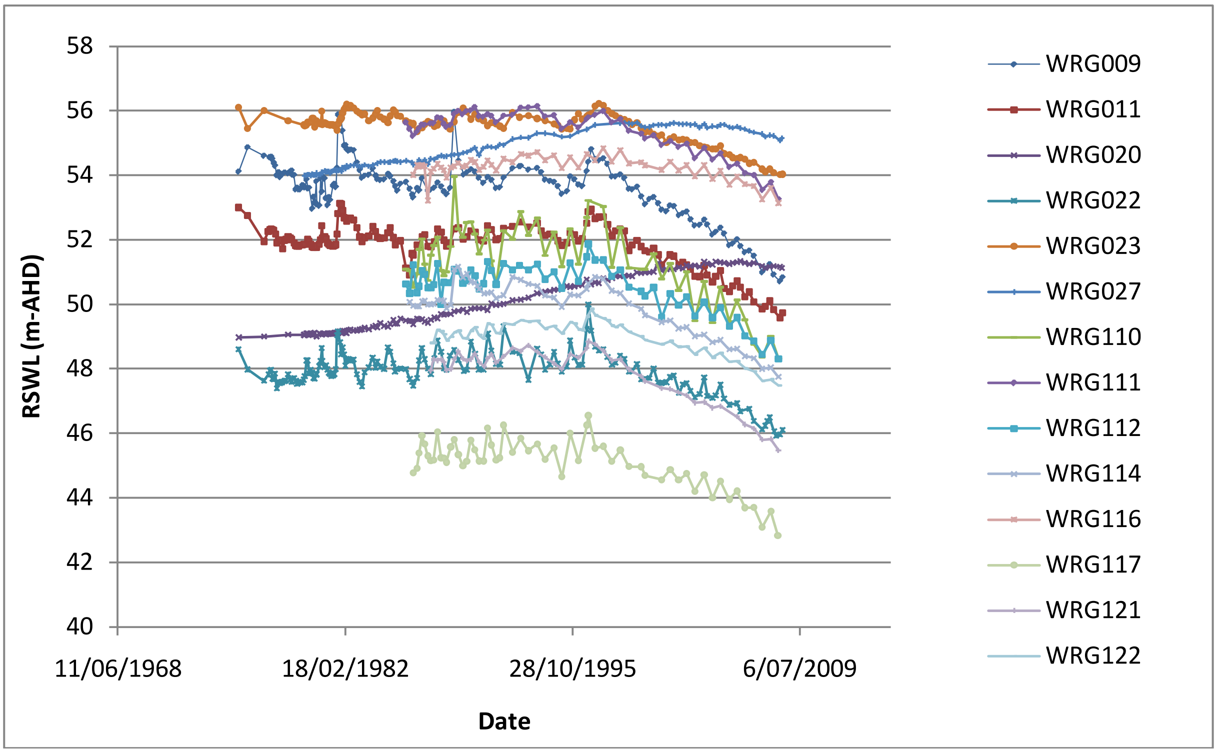


Figure 7. Measured groundwater levels (m-AHD) in the unconfined Tertiary limestone aquifer in the Wirrega management area

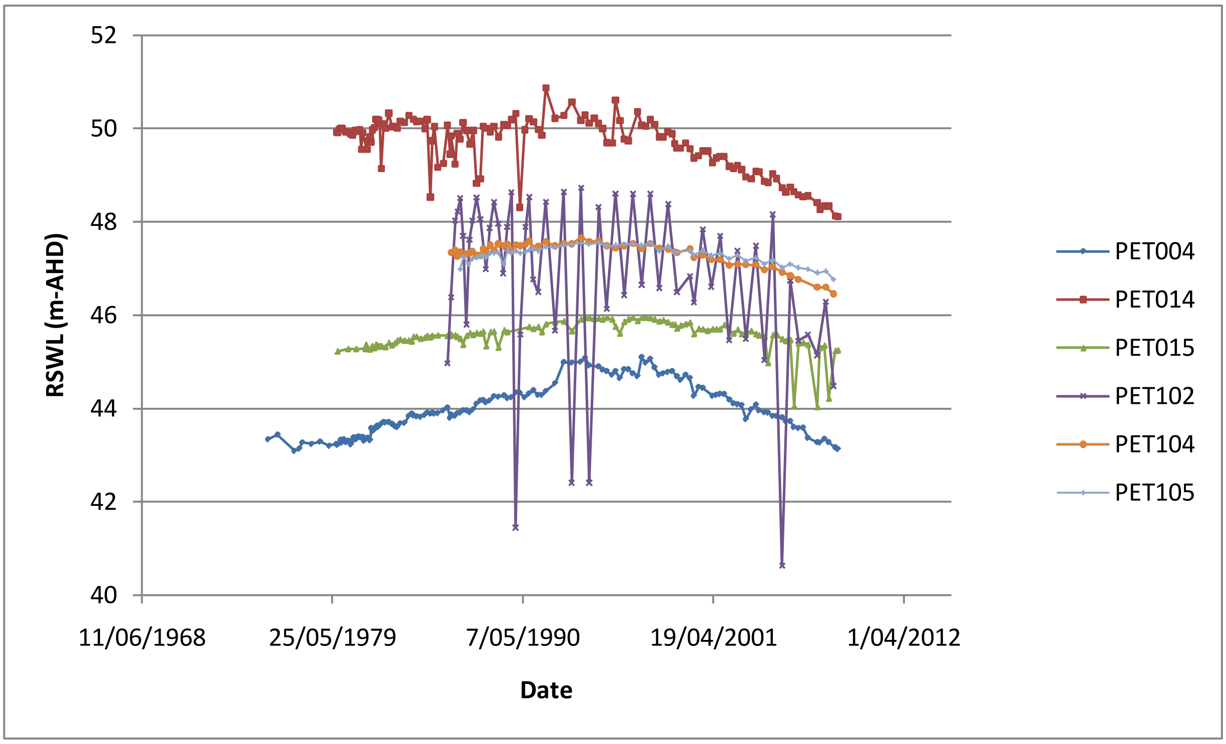


Figure 8. Measured groundwater levels (m-AHD) in the unconfined Tertiary limestone aquifer in the North Pendleton management area

A rising trend in some hydrographs (for example, WRG018 and WRG020) of up to 0.1 m/y has been observed between 1980 and 2005 and is thought to be due to increased recharge in response to historical clearance of native vegetation (Cobb & Brown 2000). The trend is also observed in some locations in North Pendleton (Figure 10). Similar trends have been observed and quantified in the Naracoorte Ranges further south (Wohling 2005); however, this type of work has not been done in the PTZ. The current trends in WRG018 and WRG020 show water levels levelling off and even declining.

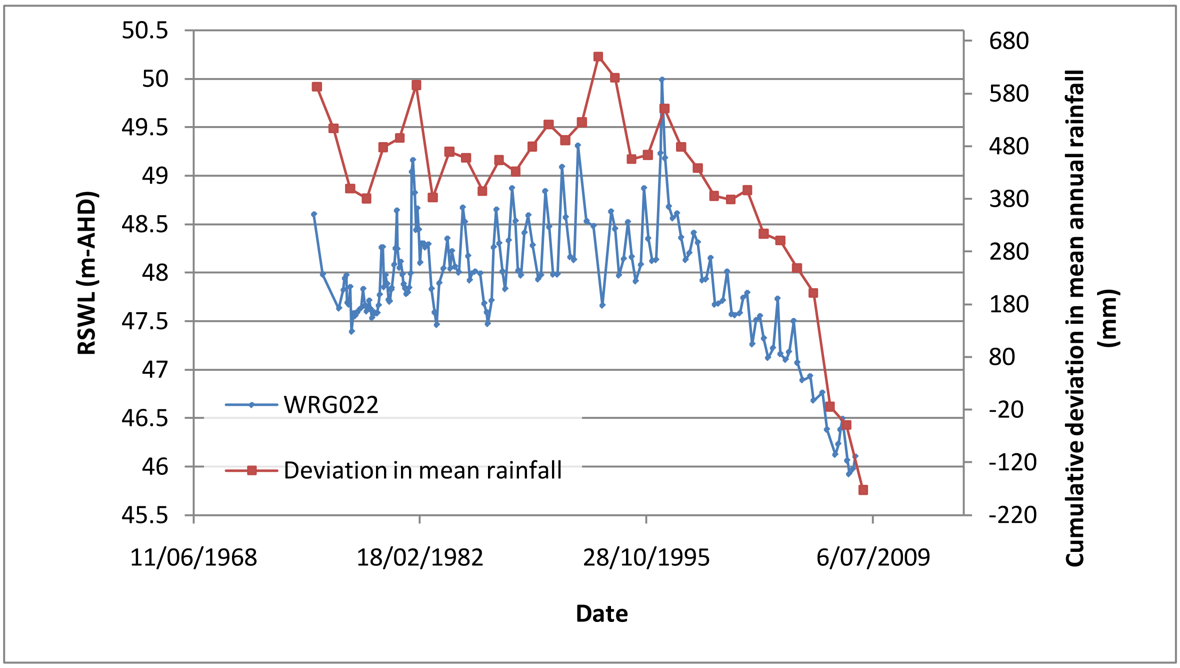


Figure 9. Relationship between cumulative deviation in mean annual rainfall (measured at Keith weather station) and water levels in the Tertiary limestone aquifer (measured in WRG022) in the PTZ

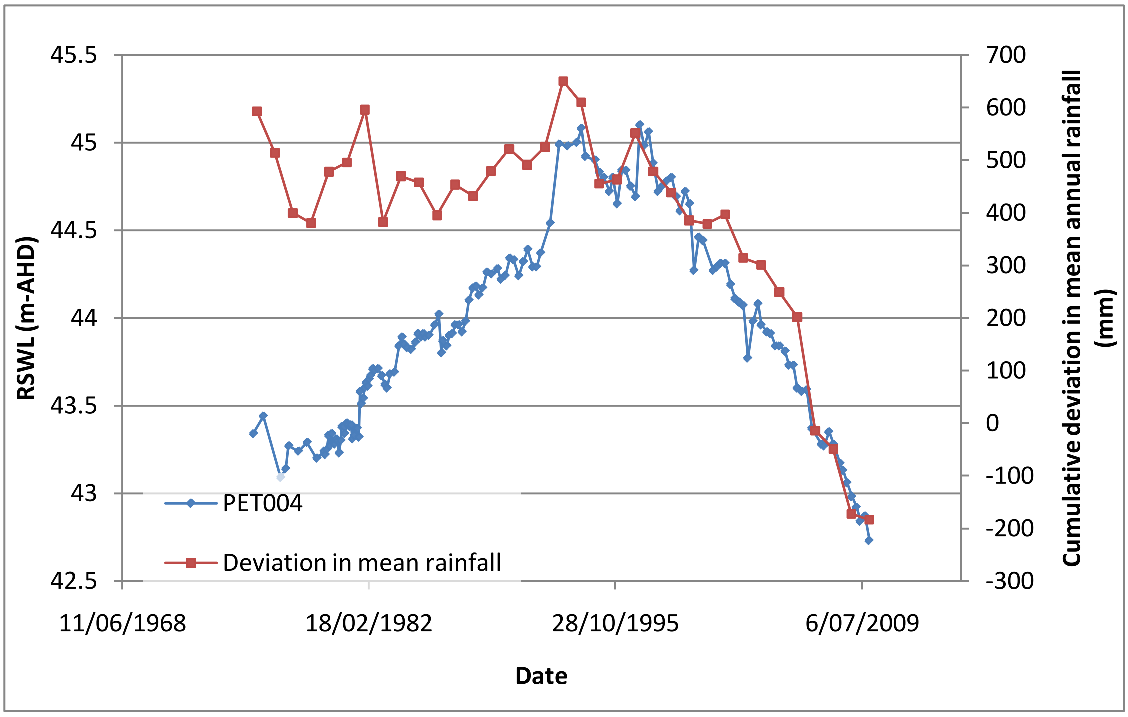


Figure 10. Relationship between cumulative deviation in mean annual rainfall (measured at Keith weather station) and water levels in the Tertiary limestone aquifer (measured in PET004) in the PTZ

Recharge to both the unconfined Quaternary and Tertiary aquifers in the region occurs predominantly through diffuse infiltration of rainfall. Estimates of recharge range from 2 mm/y to 55 mm/y under cleared land and 0.1–0.2 mm/y under native vegetation (Stadter & Love 1987; Wohling 2008; Wood 2010). These relatively low recharge rates reflect the semi-arid conditions of the region. Point source recharge to the unconfined aquifers may also occur through sinkholes and runaway holes (see section 2.3). Due to extensive irrigation development in the region, including a large proportion of flood irrigation, recharge to the unconfined aquifers may also occur via deep drainage of irrigation water, with rates ranging from 0 mm/y to 1727 mm/y (Wohling 2008).

2.2.4. UNCONFINED QUATERNARY SAND AQUIFER

The western part of the PTZ is dominated by Quaternary sediments of the Murray Basin, deposited in the early Pleistocene. These sediments were a result of high energy swell from the Southern Ocean and prevailing onshore westerly winds depositing bioclastic beach, barrier and transgressive dune complexes (Belperio 1995). A series of marine transgressions have reworked these complexes and formed the Coomandook and Bridgewater Formations. The Coomandook Formation (maximum known thickness 13 m) consists of sandy limestone, calcareous and shelly sandstones and clay lithologies and is generally not utilised as an aquifer unit (Belperio 1995; Stadter & Love 1987).

The Bridgewater Formation (maximum known thickness 88 m) is characterised by a series of topographic ridges that run sub-parallel to the coast. It consists of skeletal calcarenite and marl with seaward dipping, medium to coarse carbonate and quartz sands and sandstones with abundant broken shells (Belperio 1995; Stadter & Love 1987).

The uppermost geological unit in the Quaternary sequence is the Padthaway Formation (maximum known thickness 20 m), which occurs largely in the inter-dune flats, overlying the Bridgewater Formation (Cobb & Brown 2000). It consists of dense, white, calcitic and dolomitic mudstone with interbedded greenish clay and clayey quartz sand (Belperio 1995; Stadter & Love 1987). Transmissivity values of 1100–6500 m^2/d have been reported for the Padthaway and Bridgewater Formations and high well yields (up to 300 L/s) have been obtained in the past (Stadter & Love 1987).

Groundwater levels in the QSA show a different trend from those of the TLA. Given the shallower depth to water and more intensive irrigation development, a much more pronounced seasonal fluctuation in the watertable is observed. Figures 11 and 12 plot hydrographs from the Stirling and Willalooka management areas. As can be seen, fluctuations of up to 2 m/y are observed. The fluctuations can be attributed to the higher transmissivities and more intensive irrigation development—that is, groundwater extraction during the irrigation seasons and recoveries from rainfall recharge, plus increased drainage from irrigation (a strong percentage of the irrigation in this part of the PTZ is flood irrigation). As with observation wells in the TLA, groundwater levels have been declining over the past 12 years, which is likely due to declining rainfall and increased extraction in response to this (see Figure 13).

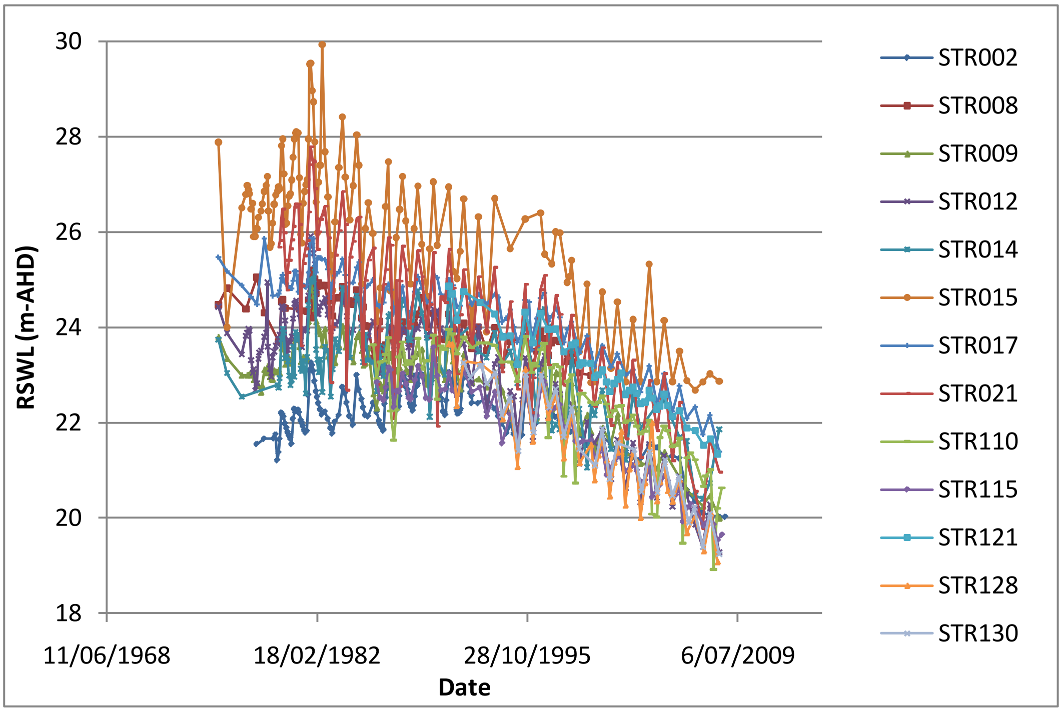


Figure 11. Measured groundwater levels (m-AHD) in the unconfined Quaternary sand aquifer in the Stirling management area

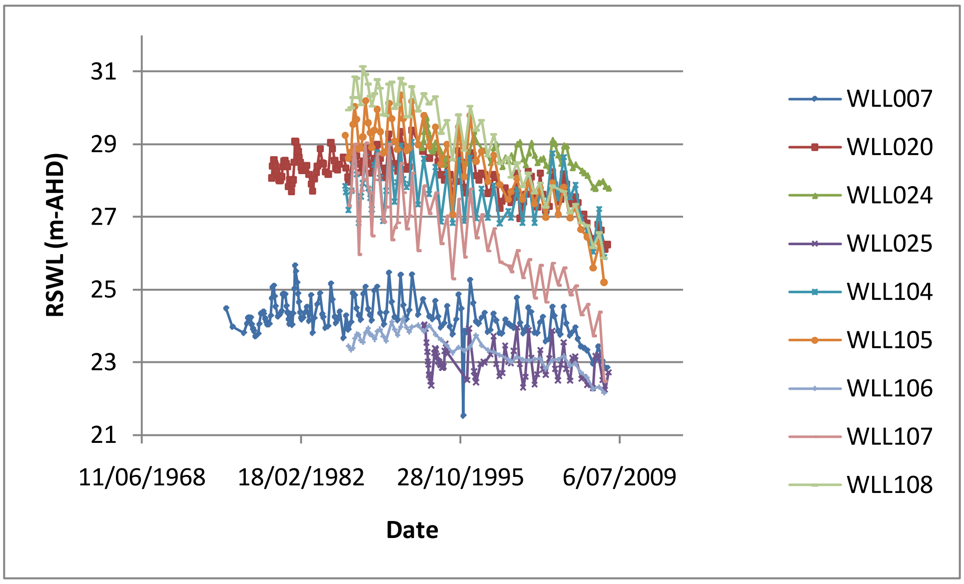


Figure 12. Measured groundwater levels (m-AHD) in the unconfined Quaternary sand aquifer in the Willalooka management area

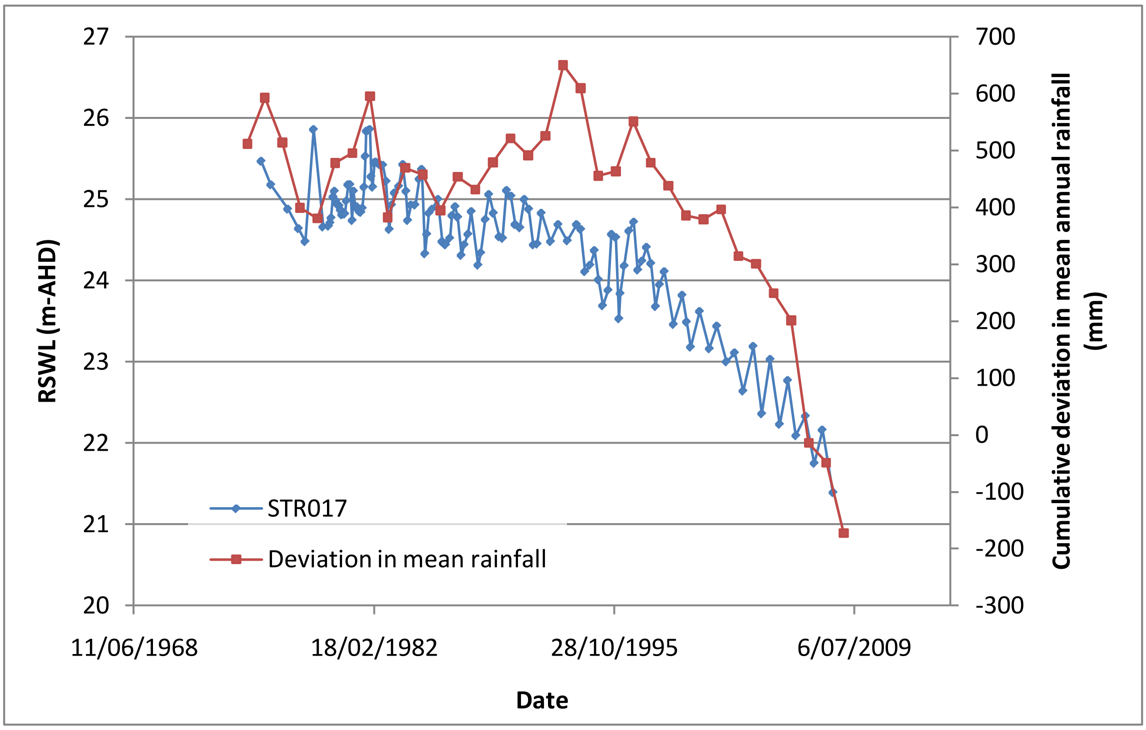


Figure 13. Relationship between cumulative deviation in mean annual rainfall (measured at Keith weather station) and water levels in the unconfined Quaternary sand aquifer (measured in Obswell STR017) in the PTZ

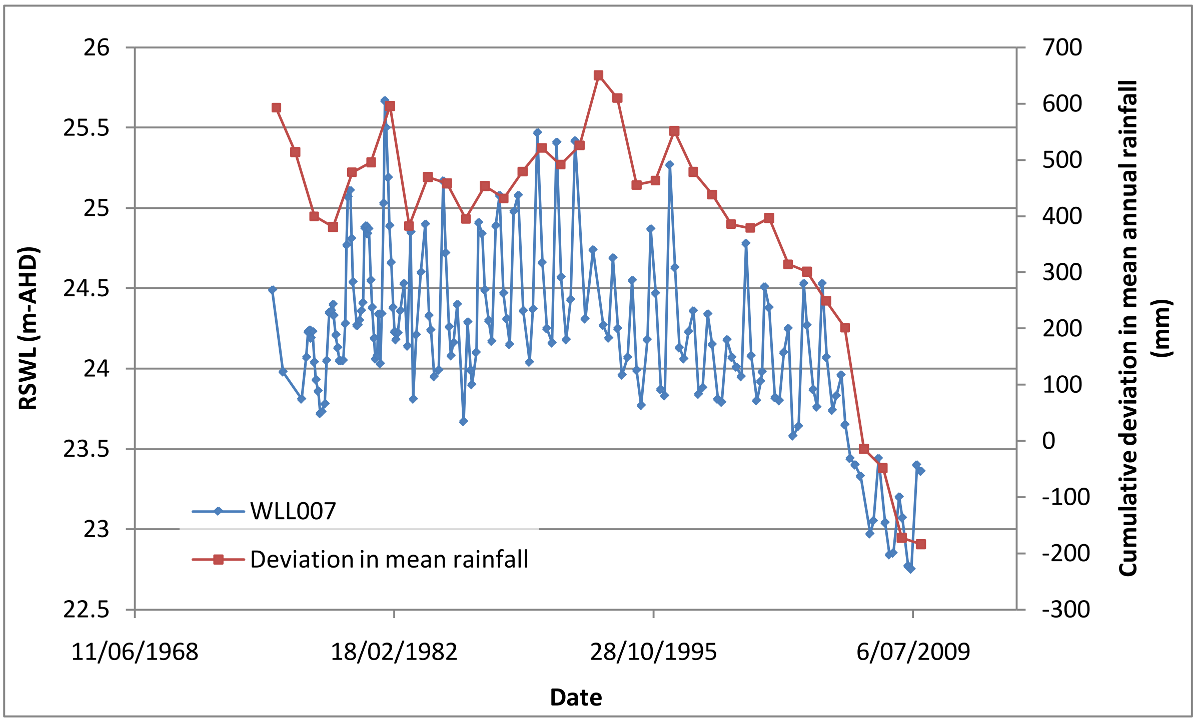


Figure 14. Relationship between cumulative deviation in mean annual rainfall (measured at Keith weather station) and water levels in the unconfined Quaternary sand aquifer (measured in Obswell WLL007) in the PTZ

2.2.5. UNCONFINED AQUIFER PROPERTIES

The properties of the unconfined aquifer vary between the different units and can vary spatially within the same unit. Reported transmissivities range from 190 m^2/d to 14 040 m^2/d. This wide range is likely due to the development of secondary porosity (karst features forming conduits to flow) in the carbonate formations. Figure 15 shows the spatial distribution of transmissivity in the unconfined aquifers (the Quaternary sand and Tertiary limestone aquifers, taken from Stadter and Love 1987). For the purposes of this study, these transmissivity values have been converted to hydraulic conductivity by dividing transmissivity by aquifer saturated thickness (see Table 1). Borehole depths and production zone intervals were used to determine which aquifer to assign conductivity values to in locations where multiple aquifers were present.

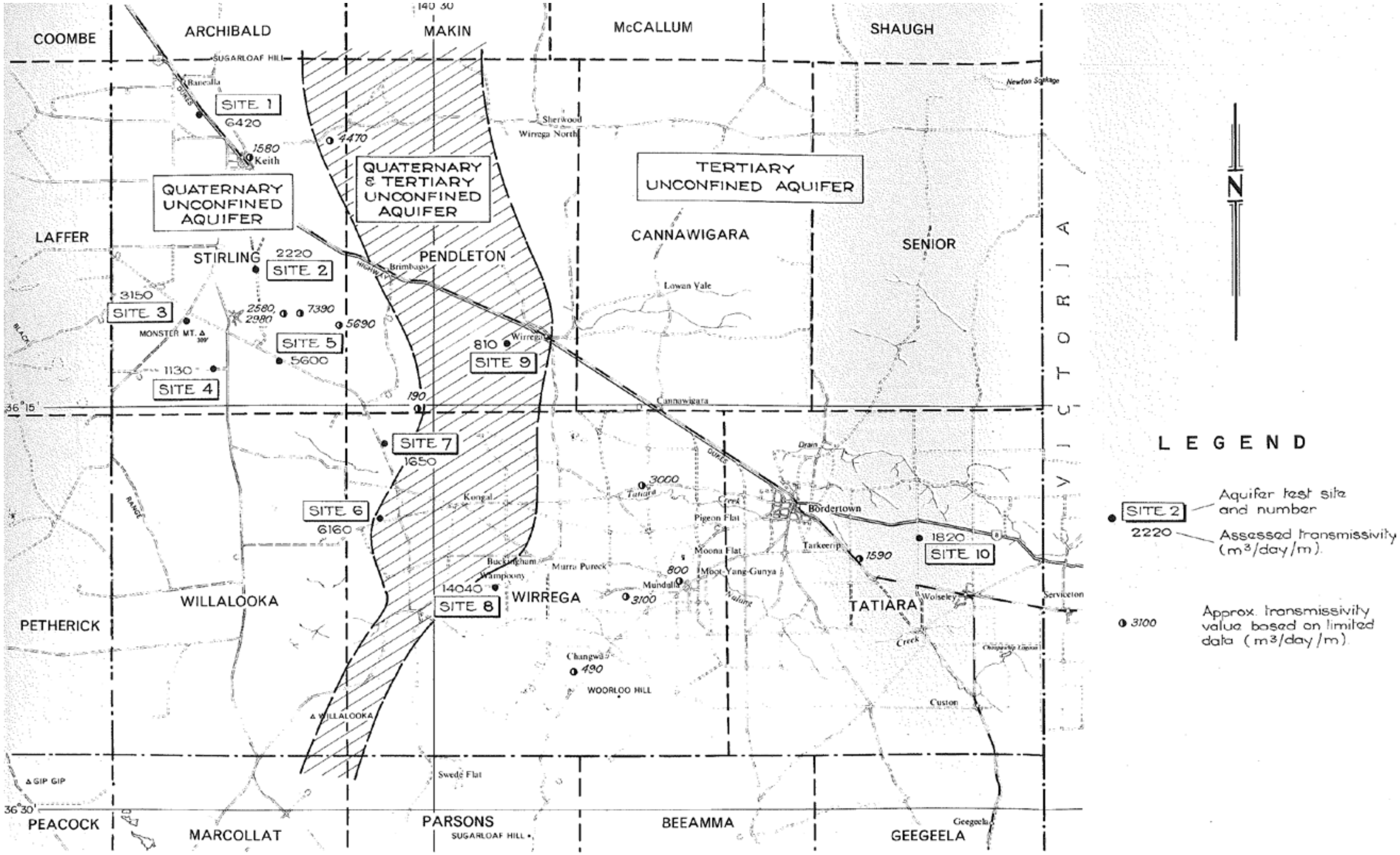


Figure 15. Transmissivity values for the PTZ, taken from Stadter and Love (1987)

Well unit #	E	N	Prod zone top (m-bgl)	Prod zone bottom (m-bgl)	Aquifer	Aquifer saturated thickness (m)	Transmissivity (m^2/d)	Interpreted conductivity (K) (m/d)*
6925-2744	438979	6008488	10	16	Padthaway, Bridgewater	40	6420	160.50
6925-2717	442708	5997886	5	25	Padthaway, Bridgewater	40	2220	55.50
6925-2731	437994	5994430	3	14	Padthaway, Bridgewater	25	3150	126.00
6925-2730	439902	5990746	5	14	Padthaway, Bridgewater	25	1130	45.20
6925-2736	444510	5991425	10	32	Bridgewater	30	5600	186.67
6925-2771	451645	5980729	unknown	unknown	Padthaway (assumed based on depth)	26	6160	236.92
6925-2732	451226	5986052	16	86	Bridgewater and Coomandook	70	1650	23.57
7025-2720	459459	5976046	13	40	Murray	70	14040	200.57
7025-2736	459940	5992661	12	13	Bridgewater	10	810	81.00
7025-2781	488285	5979470	35	55	Murray	28	1820	65.00
7025-2615	469261	5982848	16	26.3	Murray	78	3000	38.46
7025-0679	468264	5975110	12	31	Murray	70	3100	44.28
7025-0545	464751	5970030	unknown	20	Murray	50	490	9.80
6925-2497	448434	5993908	4	18	Bridgewater	18	5690	316.11
6925-0026	442088	6005398	46	59	Murray	13	1580	121.53
6925-00471	453892	5988170	9	12	Bridgewater	17	190	11.17
Unknown	445852	5994869	unknown	unknown	Padthaway	13	7390	568.46

Table 1. Transmissivity and interpreted hydraulic conductivity (K) data for the PTZ (*conductivity interpreted by dividing transmissivity by aquifer depth)

2.3. UNCONFINED AQUIFER SALINITY

Salinity in the unconfined aquifers in the PTZ ranges from less than 500 mg/L to more than 8000 mg/L TDS. Figure 16 shows the spatial distribution of salinity (values measured late 2008). As can be seen, the highest salinities are observed in the Stirling management area and trends show salinity levels on the rise. This is thought to be because groundwater extraction in Stirling exceeds annual vertical recharge, thereby reducing lateral groundwater flow out of the area. Consequently, irrigation water is 'recycled', and salinity levels increase (Cobb & Brown 2000). Figure 17 shows one of the more drastic examples of the salinity trend in Stirling, measured in Obswell STR111.

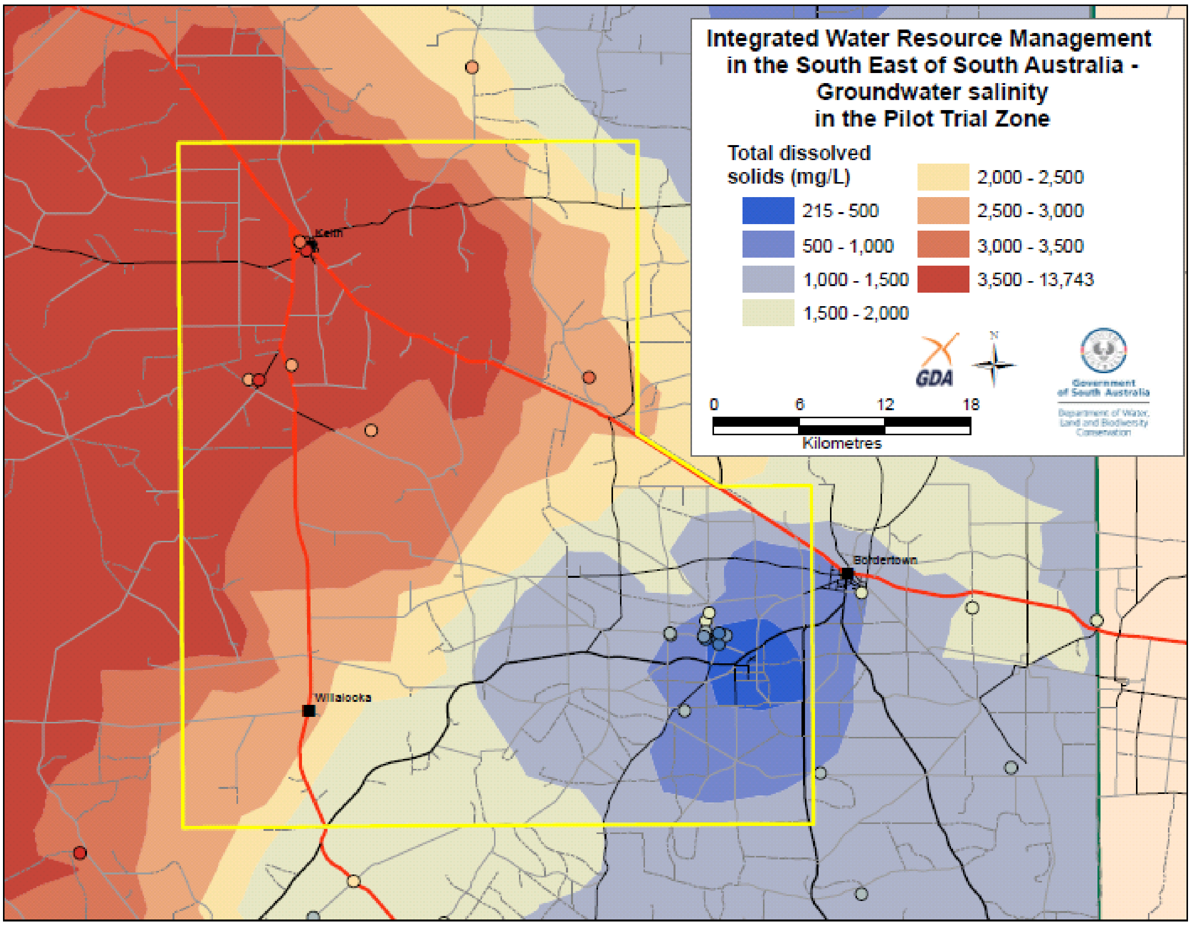


Figure 16. Unconfined aquifer salinities in the PTZ

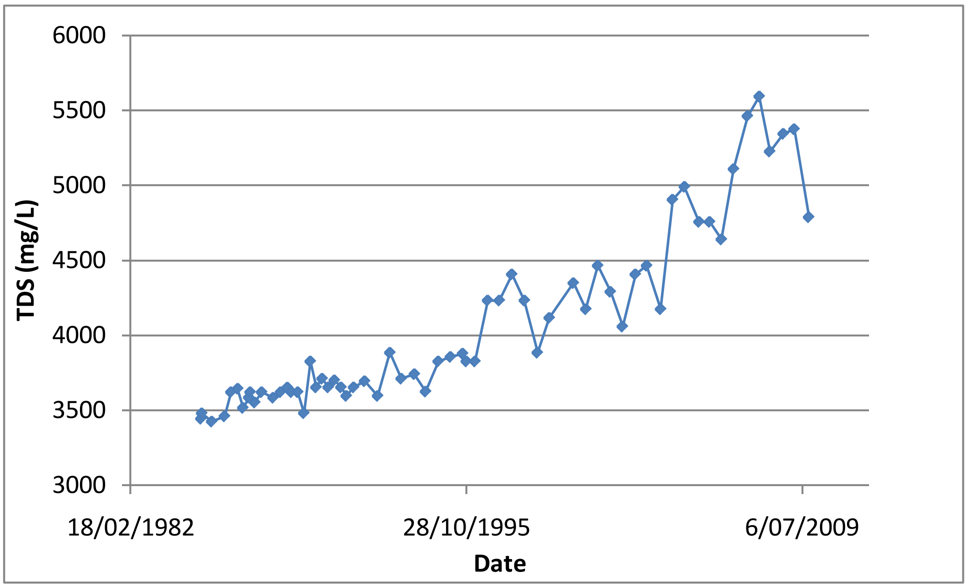


Figure 17. Salinity trend observed in well STR111 in Stirling. The long-term trend shows salinity rising by ~70 mg/L/y

2.4. SURFACE WATER – GROUNDWATER INTERACTIONS

Two ephemeral creeks flow into the PTZ, Tatiara Creek and Nalang Creek (Figure 18). The catchments for both extend into western Victoria. Tatiara Creek discharges into Poochers Swamp and Scowns runaway hole, and Nalang Creek discharges into Mundulla Swamp. Flow in these creeks is dependent on seasonal rainfall. If flows are sufficient, the discharge areas form small lakes. The estimated total capacity of Poochers Swamp is 425 ML, and Mundulla Swamp is 3500 ML (Cobb & Brown 2000). Water in these swamps may recharge the TLA via runaway holes or sinkholes. These are karst features that provide a preferred path or 'point source' entry for surface water to recharge the aquifer. Herczeg et al. (1997) estimated that this point source recharge accounted for less than 10% of total recharge in the Tatiara area. In times of severe flooding, surface water from these water courses may overflow and flood into the eastern portions of the PTZ (Hoey & Stadter 1982).

Two constructed drains are present in the eastern part of the PTZ, the Mt Charles drain and the Rosemary Downs drain (Figure 18). These drains are primarily flood mitigation drains, which act to drain surface water in times of flooding. Being only ~0.5 m deep, they are not thought to have an impact on groundwater in the PTZ (Michael Bruno, DWLBC, pers. comm.).

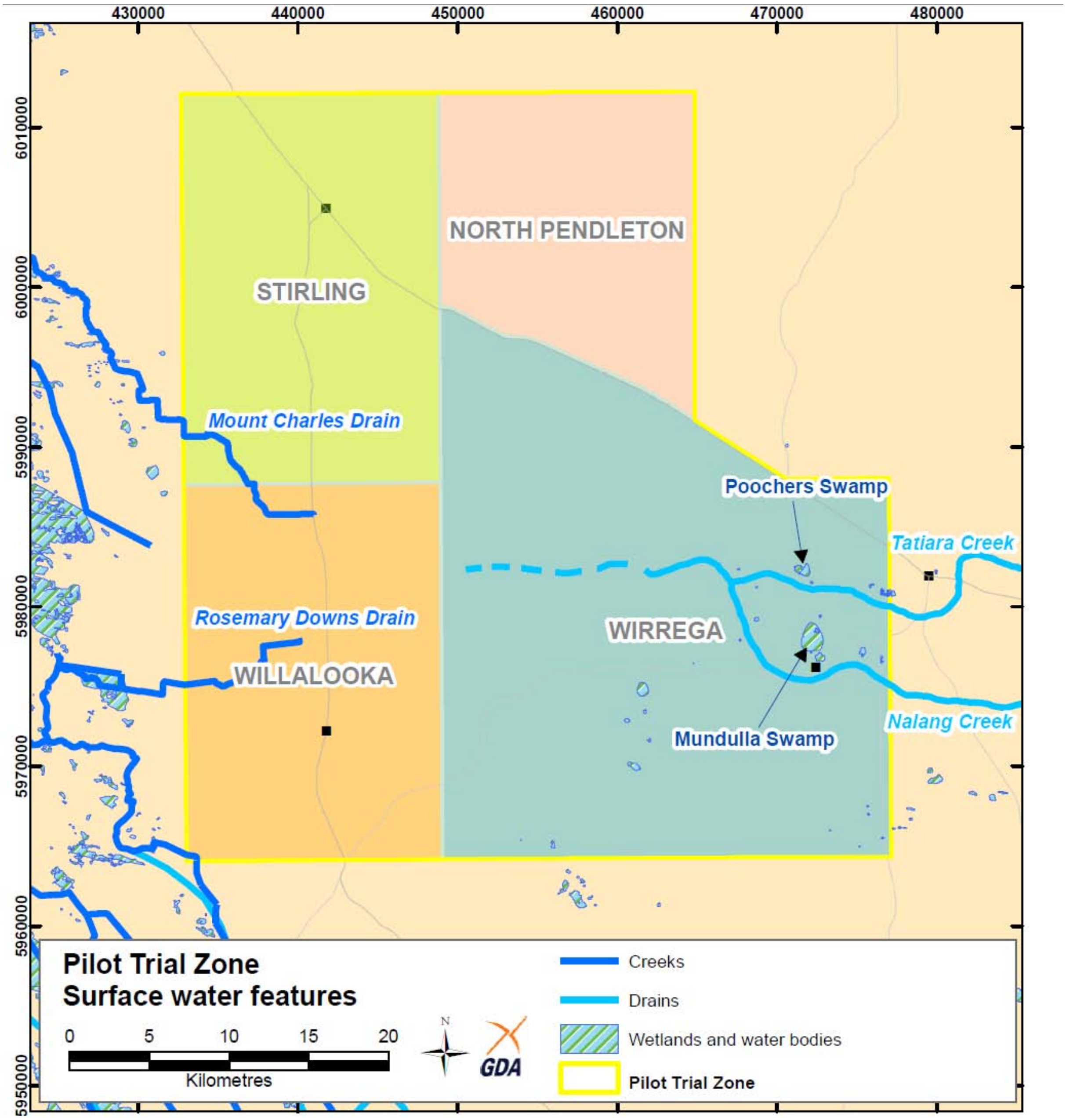


Figure 18. Surface water features in the PTZ

3. CONCEPTUAL MODEL

Considering that very little is known about the water resources of the TCSA in the PTZ and also that it is not extensively utilised, it will not form part of the conceptual or numerical model for this exercise, other than as a possible source or sink for water from the TLA and QSA (through vertical leakage). The following section therefore details all inflows to and outflows from the unconfined aquifers.

3.1. INFLOWS

3.1.1. LATERAL INFLOW

Lateral inflow into the areas covered by the PTZ has previously been estimated by Stadter and Love (1987), using Darcy's Law:

$$Q = TiL$$

where Q is the volume of lateral inflow [L^3/T], T is the transmissivity of the aquifer [L^2/T], i is the observed hydraulic gradient [L/L], and L is the width of the aquifer flow path [L].

As the eastern margin of the PTZ is essentially the eastern border of the management areas of North Pendleton and Wirrega, it is these margins that will be considered as the north-south extent of cross sectional aquifer area that provides flow into the PTZ. Stadter and Love (1987) estimated 12 130 ML/y of flow into the northern three quarters of the Hundred of Pendleton and 11 980 ML/y across an area encompassing Wirrega and the quarter of Pendleton (see Figure 19 for schematics of Stadter and Love's [1987] sub-areas).

Estimates made using current observation well levels and existing transmissivity data (from Stadter & Love 1987) give estimates of 7384.5 ML/y for North Pendleton and 12 895.5 ML/y for Wirrega. Compared to the figures from Stadter and Love (1987), these are over- and underestimates, respectively. While it is uncertain why an underestimate is given for North Pendleton, an overestimate for Wirrega may be caused by declining watertables in that area causing a steepening of the hydraulic gradient on the eastern boundary.

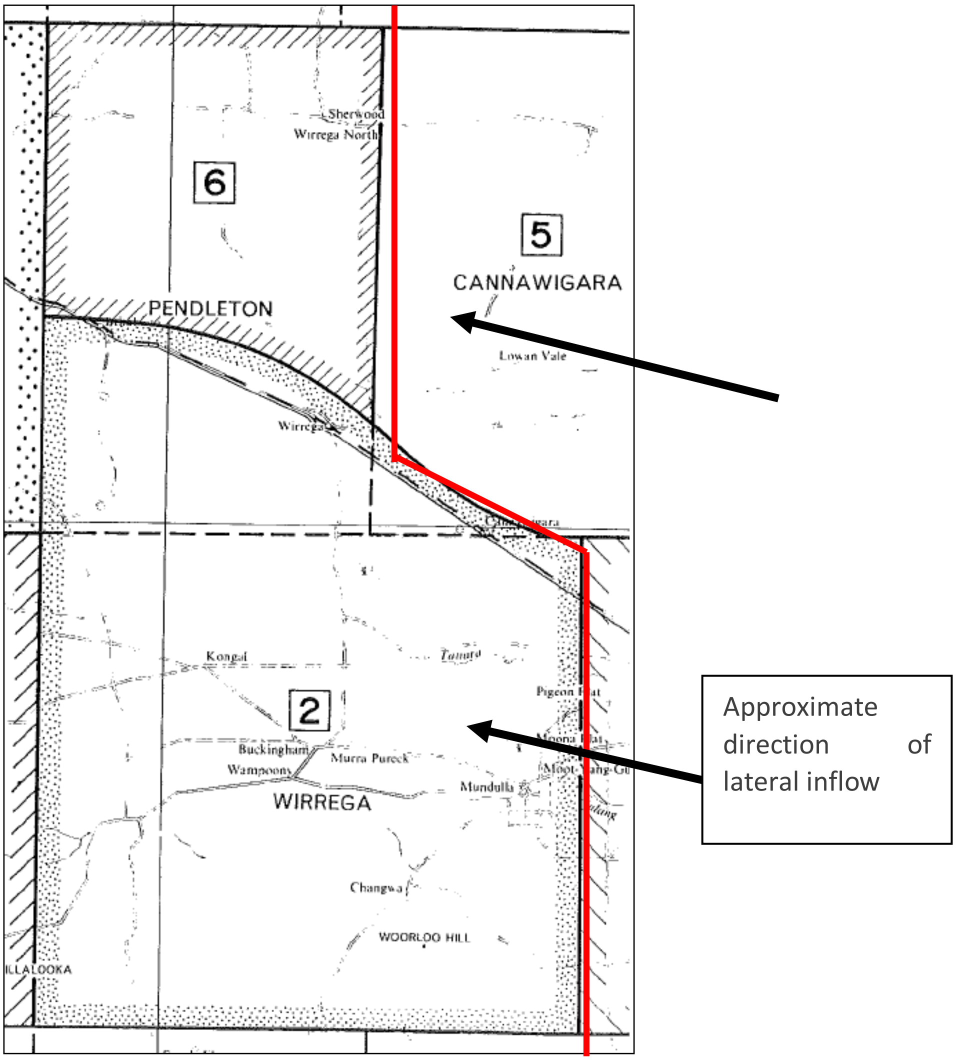


Figure 19. Lateral inflow borders used by Stadter and Love (1987)

3.1.2. DIFFUSE RECHARGE

A number of studies have looked at estimating diffuse recharge in the PTZ. Stadter and Love (1987) used the chloride mass balance to estimate recharge under cleared land and native vegetation and reported rates ranging from 0.1 mm/y under native vegetation up to 55 mm/y under cleared land. Wohling (2008) also used hydrochemical as well as modelling techniques to estimate recharge under cleared land and drainage under irrigated land. Wood (2010) gives estimates of recharge for the PTZ based on estimates from areas with a similar soil type/land use/climate type combination. Table 2 summarises the outcomes of all of these studies.

Study	Method	Land use	Recharge rate (mm/y)
Stadter and Love 1987	Chloride mass balance	Native vegetation	0.1 to 0.2
Stadter and Love 1987	Chloride mass balance	Dryland agriculture	12 to 30
Stadter and Love 1987	Changes in GW storage and watertable fluctuations	Dryland agriculture	40 to 55
Brown et al. 2006	Estimates adopted in the current Water Allocation Plan	Dryland agriculture	30 to 50
Wohling 2008	Chloride mass balance and CFCs	Cleared land	2.3 to 85
Wohling 2008	Chloride, CFCs, and water balance modelling	Irrigated agriculture	0 to 1727 (mean ~403)
Wood 2008	Chloride mass balance and CFCs	Dryland agriculture	2 to 30

Table 2. Summary of estimated average annual recharge rates for the PTZ

Using the estimates reported by Brown et al. (2006)—which are those currently recommended for the Tatiara Water Allocation Plan—and summing the total recharge for all management areas in the PTZ, the total rainfall recharge into the PTZ is 65 488 ML/y.

3.1.3. DRAINAGE FROM IRRIGATION

A large portion of the irrigation in the PTZ is flood irrigation, which results in a high amount of return drainage to the aquifer. Latcham et al. (2007) estimated the total amount of drainage from irrigation in the PTZ to be 35 291 ML/y. This is likely to be an overestimate of total drainage from irrigation, as it is based on the assumption that 100% of indicative volumetric allocations are being used. Considering only the percentage of allocation used (as reported in Hodge 2009), a more accurate figure for drainage from irrigation is 20 526 ML/y.

3.1.4. POINT SOURCE RECHARGE

The presence of sinkholes and runaway holes in the PTZ allows for point source inflow to the unconfined aquifers. Tatiara Creek and Nalang Creek are the two main water courses in the PTZ, with catchments that extend into western Victoria. Nalang Creek discharges into Mundulla Swamp and Tatiara Creek discharges into Poochers Swamp and Scowns runaway hole (Cobb & Brown 2000). Stadter and Love (1987) provided an approximate estimate of point source recharge, based on average streamflow in Tatiara Creek, of 2300 ML/y. This estimate should be considered an absolute upper limit, as it includes exceptionally high flow measured in 1981. Leaney and Herczeg (1995) estimated input to Poocher Swamp between 1982 and 1988 to be approximately 500–2000 ML/y.

3.1.5. UPWARD LEAKAGE FROM CONFINED AQUIFER

There is the potential for groundwater leakage between the TCSA and unconfined aquifers. For example, observation wells STR131 (confined aquifer) and STR110 (unconfined aquifer), which are 470 m apart, show a head difference of 2.55 m (confined head level minus unconfined head level), a difference that would allow for upward leakage from the confined to the unconfined. However, other areas show a reverse trend, with higher head level in the unconfined aquifer, indicating downward leakage. Considering the lack of knowledge on the hydraulic connection between the two aquifers, it is recommended that leakage be set to zero for the time being.

3.2. OUTFLOWS

3.2.1. LATERAL OUTFLOW

Estimated lateral outflow for the PTZ, based on gradients from STR121 and LAF001 and a transmissivity value of 1680 m^2/d (Stadter & Love 1987), is 9966.2 ML/y. Obviously, this is much less than estimated lateral inflow. Possible explanations for this are the presence of the hydraulic basement high in the western portion of the PTZ, which has been suggested to limit groundwater outflow (Brown et al. 2006) and also the effects of watertable drawdown within the Stirling management area.

3.2.2. EVAPOTRANSPIRATION

Evapotranspiration from shallow watertables can occur where groundwater is seasonally close to the surface (generally within 1–2 m). However, estimating this loss is difficult. In order to provide an initial estimate of loss via evapotranspiration, a map of depth to water was prepared. It revealed that very little of the region has a depth to water within 2 m of the surface; therefore, evaporative loss from the watertable is considered negligible to the water balance for the current conditions in the PTZ. However, the aim of this model is to be used as a predictive tool for future scenario modelling. This type of modelling may include scenarios in which the watertable comes within 2 m of the land surface and evaporative loss would then become important. Therefore, for the purposes of the initial water balance, evapotranspiration from shallow watertables is not quantified; however, it will be included in the numerical model using numerical values derived by Aquaterra in their model for the Padthaway area (Wallis 2007).

3.2.3. SURFACE WATER EVAPORATION

Evaporation of water from surface water bodies is not considered a significant component of the water balance for the PTZ. The only interaction between surface water and groundwater considered in this conceptualisation is point source recharge into runaway holes (little is known of any direct surface water – groundwater interaction in Tatiara or Nalang Creek), which may be incorporated into the water balance without the need to account for evaporation of surface water.

3.2.4. GROUNDWATER DISCHARGE TO SURFACE WATER

Two drains are present in the western portion of the PTZ. However, they are not believed to interact with groundwater, because of their shallow depth (Sheldon 2009).

3.2.5. GROUNDWATER EXTRACTION

Historically, groundwater use in the South East has not been metered. Metering of groundwater extraction wells was implemented in 2003. However, ongoing records of metered groundwater use have not been collected until recently. For the 2008/09 water use year, a combination of metered and estimated use was compiled for the PTZ (Hodge 2009), and indicative extracted volume for the year was 90 402 ML/y. Estimated stock and domestic use for the Zone was 1386 ML/y (Brown et al. 2006).

Extraction for industrial and town water supply is assumed to be the same as full allocation for these purposes, and is therefore estimated to be 1096 ML/y. This gives a total of 92 884 ML/y of groundwater extracted.

3.2.6. DOWNWARD LEAKAGE TO CONFINED AQUIFER

As discussed earlier, there is insufficient data to quantify any upward or downward leakage between the confined and unconfined aquifers; therefore, this component of the water balance is provisionally set at zero.

3.3. SUMMARY

Table 3 presents a summary of the estimated total inflows to and outflows from the PTZ.

Inflows (ML/y)	
Lateral inflow	20 279.95
Diffuse recharge from rainfall	65 448
Drainage from irrigation	20 526
Point source recharge through runaway holes	2300
Upward leakage from confined aquifer	0
Total inflows	*108 553.95*
Outflows (ML/y)	
Lateral outflows	9966.23
Evapotranspiration	0
Surface water evaporation	0
Groundwater extraction	92 884
Downward leakage to confined aquifer	0
Total outflows	*102 850.23*
Water balance (inflows - outflows) (ML/y)	***5703.72***

Table 3. Water balance for the PTZ

As can be seen, there is a net gain in the water balance of ~5700 ML/y. This is not reflected in the declining watertable across much of the PTZ and is likely due to the broad assumptions made in putting together a static water balance for a dynamic area (i.e. where rainfall recharge and groundwater use varies from year to year, and where drainage from irrigation is known to be an overestimate). Also, the error in the water balance is only 5%, which should be considered very good in light of the assumptions made.

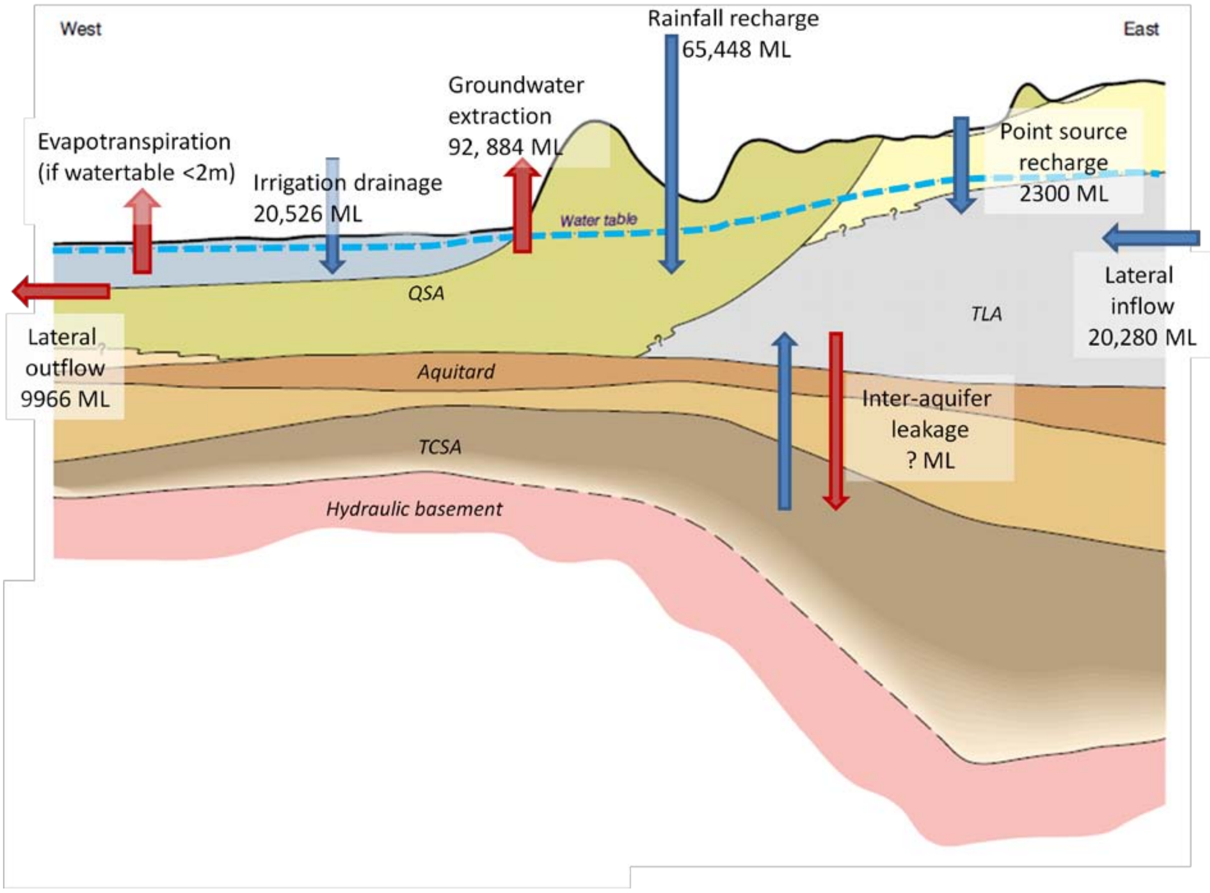


Figure 20. Conceptual model of groundwater balance in the PTZ

4. MODEL DESCRIPTION

4.1. MODEL SELECTION

Given the intended use of the numerical model for this study, and referring to section 2.1 of the Murray-Darling Basin Groundwater Modelling Guidelines, it is considered that a model of 'Moderate' to 'Complex' complexity is appropriate. Visual MODFLOW v4.1 was selected as the appropriate modelling software for this exercise. The model is purely a groundwater flow model and not a solute transport model.

4.2. MODEL DOMAIN, GRID STRUCTURE AND LAYERING

The original boundary for the PTZ, developed by REM, was based on geologic conditions and aquifer behaviour (watertable trends). This boundary was later altered by DWLBC to fit existing groundwater management boundaries, as it was considered much simpler to deal with licensed extraction data on a management area basis. Nevertheless, the boundary is still considered suitable for a groundwater model. A 10 km buffer zone around this area forms the extent of the model domain, so that potential edge effects do not detrimentally affect model processes in the area of interest. The buffer is extended in the north-western corner of the domain to accommodate the geometry of the PTZ. In total, the area modelled is approximately 64 km x 68 km, and is discretised into grid cells of 250 m x 250 m. The bounding coordinates in the south-west corner are E422646 N5953652, and in the north-east corner are E486850 N6022350, using the coordinate system GDE 1994 MGA Zone 54 (Figure 21).

The model consists of three layers. The top layer consists of the unconfined Quaternary sand aquifers (Padthaway and Bridgewater Formations) in the western, low-lying region of the model, and the TLA in the eastern region. Layer two consists of the Bridgewater Formation in the western region, underlying the Padthaway Formation, and the TLA in the eastern areas. The Coomandook Formation is not present in layer two, as little is known of the hydraulic properties of the formation. It is therefore considered part of the TLA, following what was implemented in the Padthaway model (PadMod1, Aquaterra 2007). The third layer consists entirely of the TLA (Murray Group Limestone). The top elevation of layer one was based on the digital elevation model (DEM) for the region, which has a cell resolution of 10 m x 10 m.

The spatial extent of aquifer formations within each layer was based on a spatial interpolation of existing borehole data. Three important conductivity zones were added in addition to these interpolated zones:

1. A lower conductivity zone through the middle of the model domain to simulate the steep gradient zone. The extent of this zone was initially based on the 'transition zone' between the Tertiary and Quaternary aquifers (mapped by Stadter and Love [1987] and reproduced in Figure 15), and modified during model calibration.
2. A higher conductivity zone in the top two layers around the Stirling management area. This was introduced to reflect the generally higher transmissivity of the Quaternary aquifers in this region, as seen in Figure 21. The extent of this zone was refined during calibration.

3. Very low conductivity zones associated with granite outcrops. These were not included in the first iteration of the model but were added during calibration. Appendix A gives further details.

Figure 21 displays an aerial view of layer one of the model, showing the spatial extent of all the above mentioned features. Figure 22 shows an east to west cross section through the model domain.

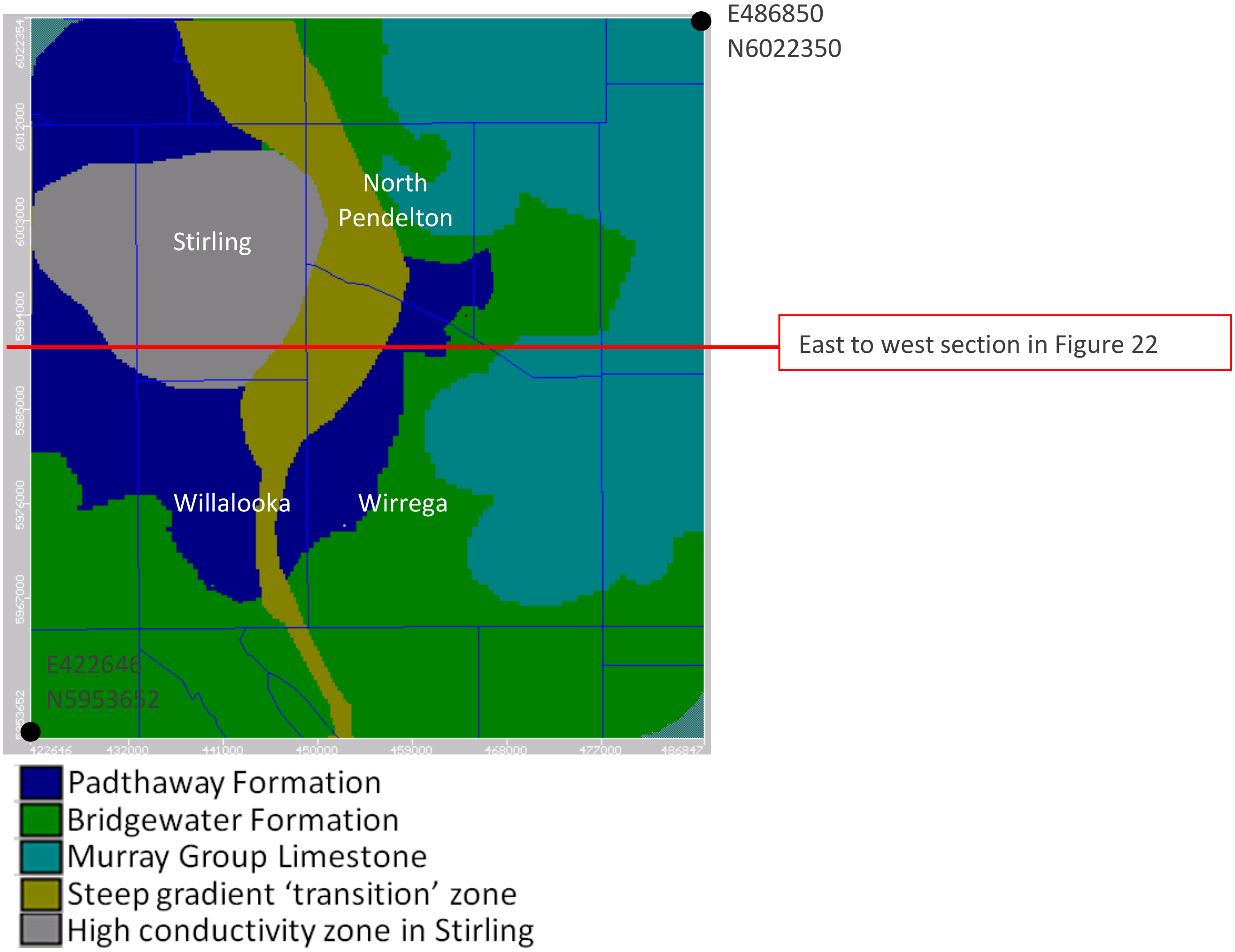


Figure 21. Aerial view of conductivity zones in layer one of the model

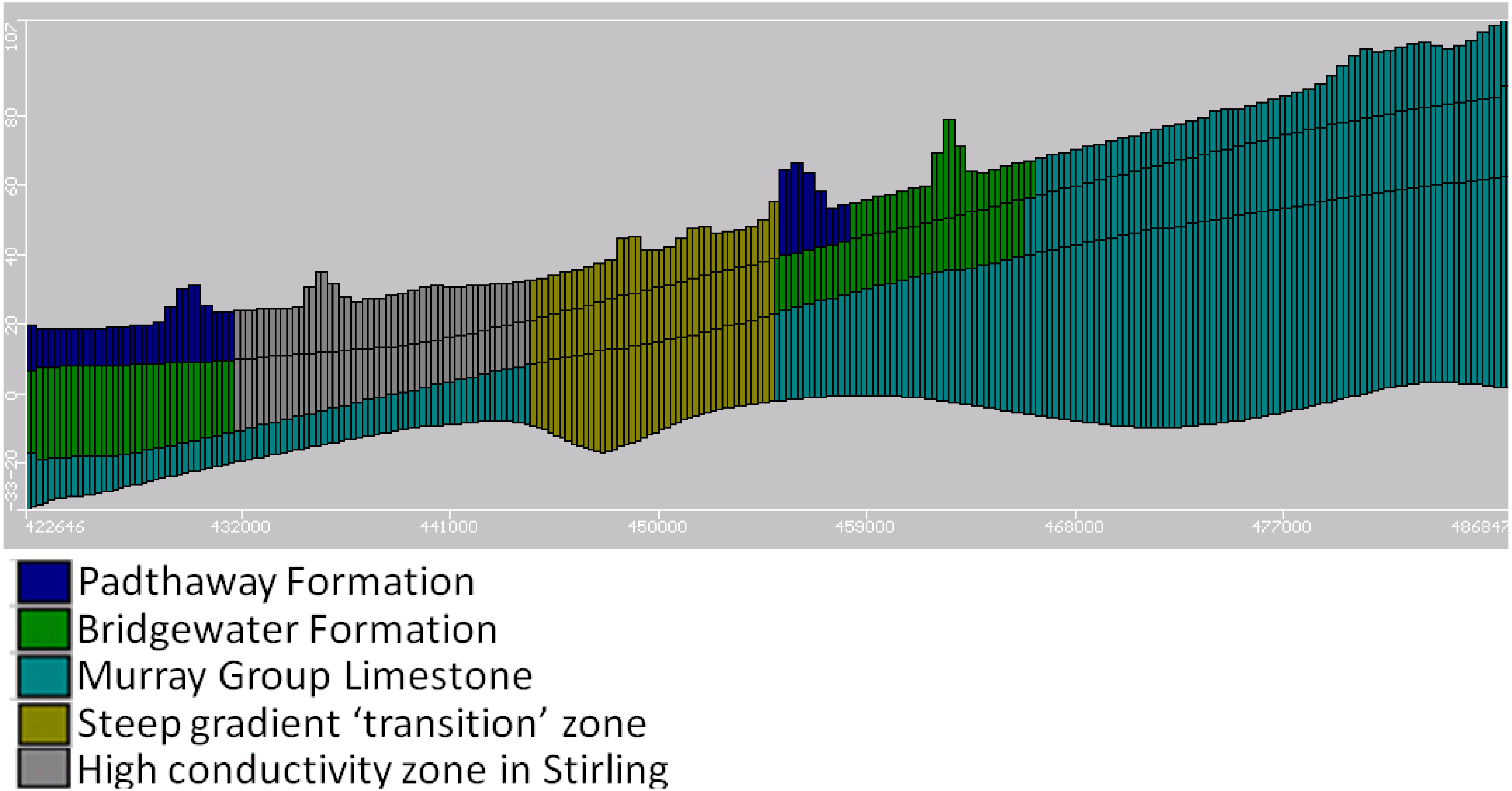


Figure 22. East to west cross section through model domain

4.3. AQUIFER PROPERTIES

Hydraulic conductivity values were taken from pump test data reported by Stadter and Love (1987, reproduced in Figure 15). Average values were taken for each aquifer unit and used as initial conductivities in the model (Table 4). Storage parameters were taken from previously used values for these formations (Aquaterra 2007). Unfortunately, no specific data existed to provide a basis for assigning conductivities in the middle of the domain to replicate the steep gradient zone mentioned in section 2.2; therefore, it was set arbitrarily at 10 m/d.

Formation	Horizontal K (m/d)	Vertical K (m/d)	Specific storage	Specific yield
Padthaway	104	10	0.0001	0.2
Bridgewater	75	7	0.0001	0.2
Murray	44	4	0.0001	0.2
Stirling high K zone	600	60	0.0001	0.2
Transition zone of low K	10	1	0.0001	0.2

Table 4. Initial hydraulic properties of aquifer units used in the model

4.4. BOUNDARY CONDITIONS

General head boundaries were set for the eastern and western domain boundaries. Given the west to north-west groundwater flow direction and the orientation of the watertable in this direction, the boundaries were extended to cover the south-eastern corner of the model and also the north-western corner (see Figure 23). The boundary condition to the east was assigned in layer three, as both layers one and two are dry along this boundary (representing unsaturated Quaternary deposits). Boundary conditions were assigned to all layers on the western edge of the domain, as all layers are saturated there. Initial head levels for the boundaries were based upon observed head levels for September–October 2008. Values were assigned at the end points of each boundary and a linear gradient used to calculate heads in between. An arbitrary conductance value of 100 m^2/d was used on both boundaries.

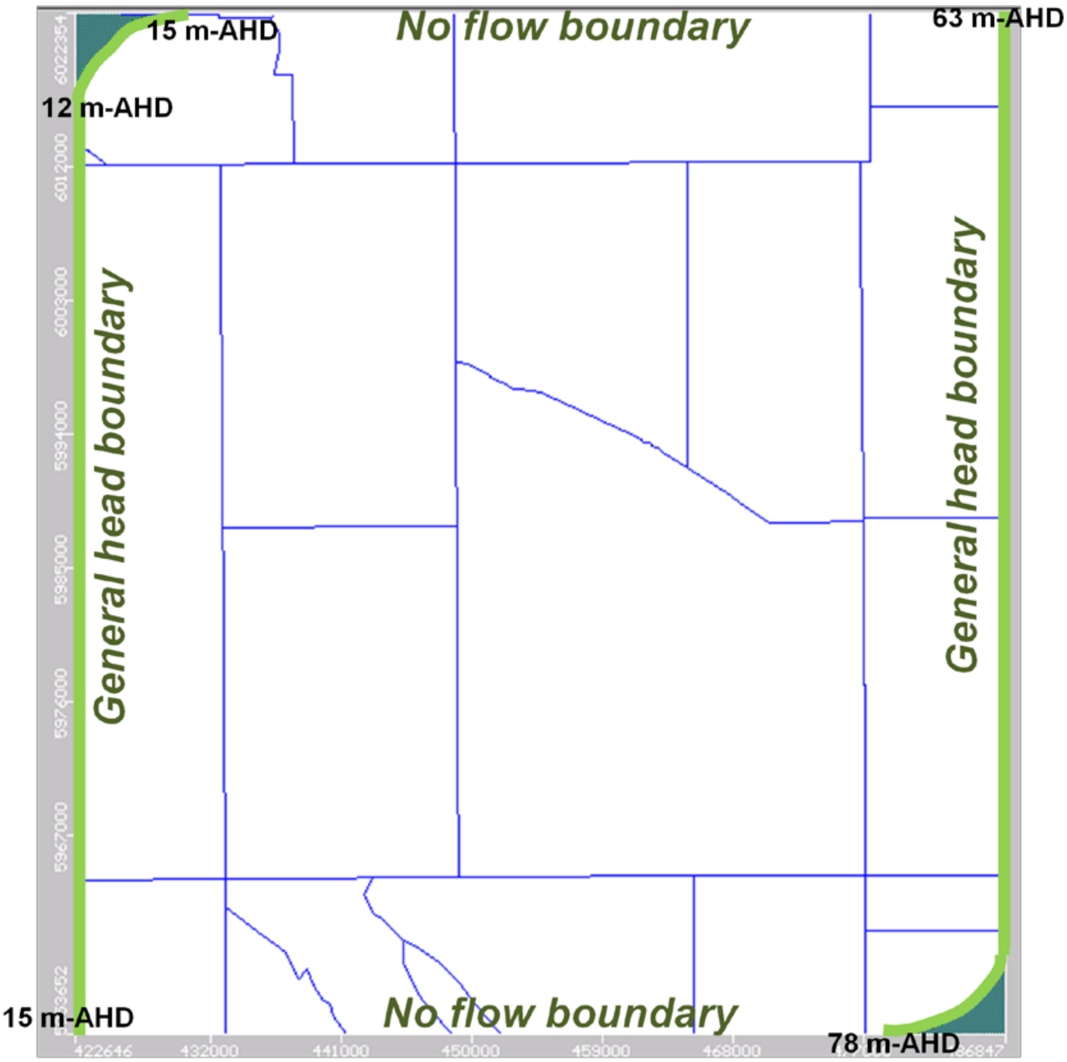


Figure 23. Model domain for PTZ showing general head boundaries (eastern and western extent) in green

4.5. RECHARGE AND EVAPOTRANSPIRATION

As discussed earlier, most observation wells in the model area display a good correlation with cumulative deviation in rainfall, which provides a good argument for basing model recharge on rainfall records. Rainfall data from the Bureau of Meteorology (BoM 2009) was used to calculate recharge, based on a method outlined by Harrington (2008). On average, rainfall exceeds evapotranspiration in winter months; therefore, it is assumed that recharge is largely driven by winter rainfall (even though there is a lag time between winter rain and watertable rise in some of the higher elevated areas). Winter rainfall (rainfall from the start of May to the end of September) was summed each year from 1970 to 2008 and used to calculate a winter rainfall average ($WRain_{avg}$). An average recharge rate (R_{avg} = 37.5 mm/y) for the PTZ was then taken as the average of adopted rates given by Brown et al. (2006) for the individual management areas. Average recharge was subtracted from average winter rainfall to give a recharge wetting amount (W):

$$W = WRain_{avg} - R_{avg}$$

Annual recharge amounts (R) were then calculated for each year by subtracting the wetting amount from winter rainfall for each year:

$$R = WRain - W$$

where WRain is the winter rainfall for the given year. This gave rates ranging from 0 mm/y (recharge in recent years) to 188 mm/y (recharge in 1981, see Figure 24). The latter rate may seem high considering the rates reported in section 3.1.2 of this report; however, it correlates well with observed watertable rises in 1981, when excessive rainfall led to flooding in the Tatiara area (Hoey & Stadter 1982). The rates of 0 mm/y may also seem unrealistically low; however, many observation wells have shown little winter recovery in recent years, suggesting that recharge has been minimal.

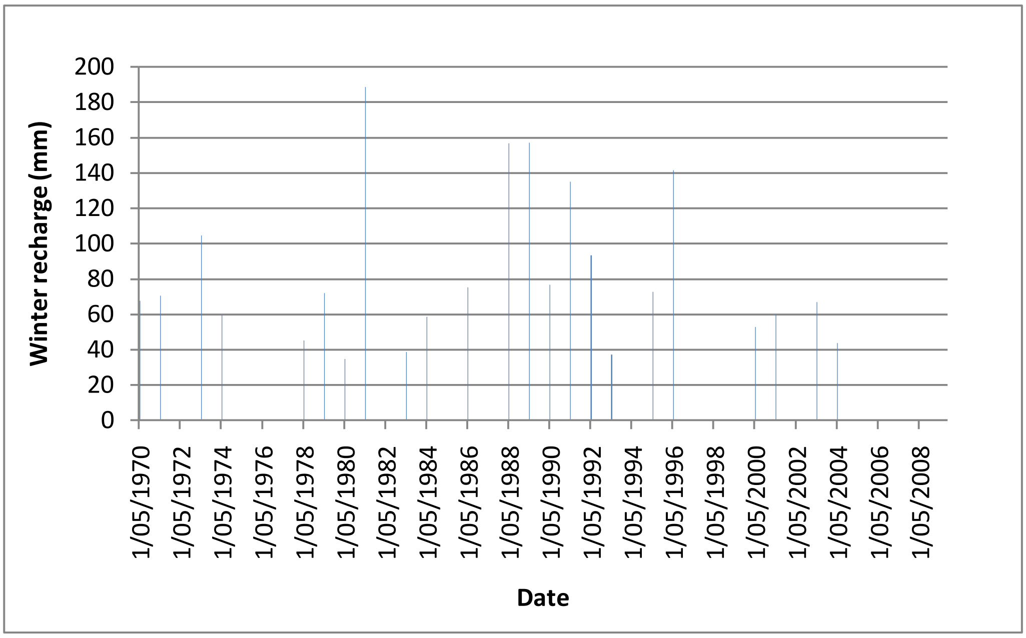


Figure 24. Recharge schedule applied in model

Recharge was applied in the model from April to September each year to approximately simulate winter rainfall (i.e. recharge taking place during the period when groundwater extraction is not taking place). Additional recharge was applied to areas where flood irrigation was shown to be the land use practiced. Wohling (2008) reported 403 mm/y as the mean irrigation drainage rate under flood irrigation in Stirling and this was used in the model. Additionally, no recharge was applied to areas covered by native vegetation. Figure 25 shows the spatial extent of recharge zones in the PTZ.

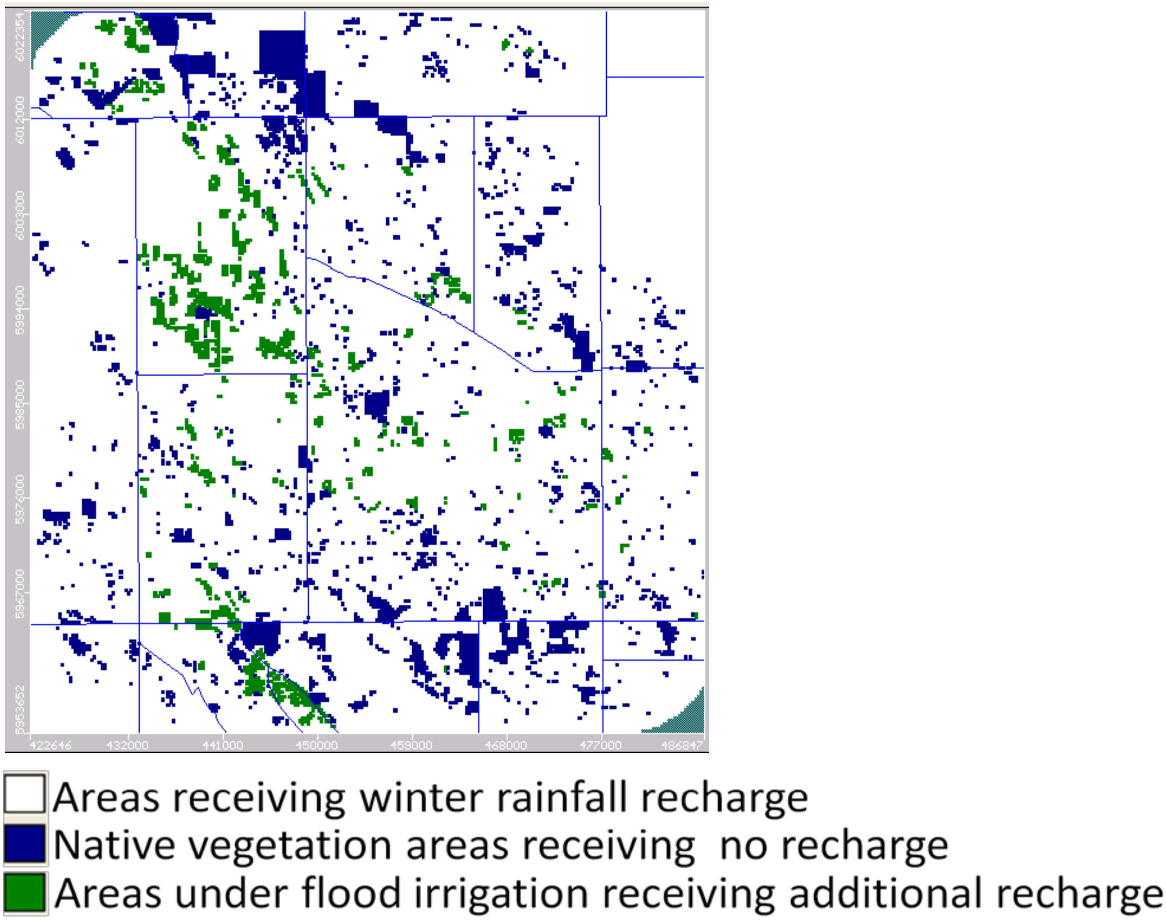


Figure 25. Recharge zones representing the various land uses in the PTZ

Evapotranspiration of groundwater from shallow watertables in the model was set at 500 mm/y, following that used in the Padthaway model (Aquaterra 2007). This rate is based on CSIRO measurements of evapotranspiration in the Padthaway area and as such, may be an underestimate for the PTZ. An extinction depth of 2 m was set.

4.6. GROUNDWATER EXTRACTION DATA

Historically, groundwater extraction has not been metered in the PTZ. While metering was implemented in the mid-2000s, reliable metering data has not been collected until recent years. Therefore, extraction values for 2008/09 are based on water use reports and meter readings from DWLBC staff and irrigation users, while historical extraction data is based on estimates of use. Given the large number of extraction wells (~450), it was not feasible to implement each well in the model based on its drill date. Therefore, all extraction wells present in 2008/09 (see Figure 26) were active throughout the entire model run

(1970–2009) and pumping rates set as a fraction of 2007/08 rates based on estimates of use. For example, for all wells, the extraction rate for 1977/78 was 18% of the 2007/08 extraction rate. Estimates of use were not available prior to 1977/78; therefore, extraction was not implemented in the model prior to 1977 (also, there was scant groundwater level data prior to 1977 to which to calibrate). Figure 27 plots the estimates of use over time for the PTZ. As can be seen, a rapid increase in estimated extraction occurs after 1977. Estimated use is relatively constant from the mid-1980s until the past five years, when it increases again (likely a response to low rainfall years). In the model, extraction was set for a 181-day period from October of each year to April of the following year, to approximately simulate the 'irrigation season'. The lack of reliable historic groundwater use data is a recognised limitation in this modelling study.

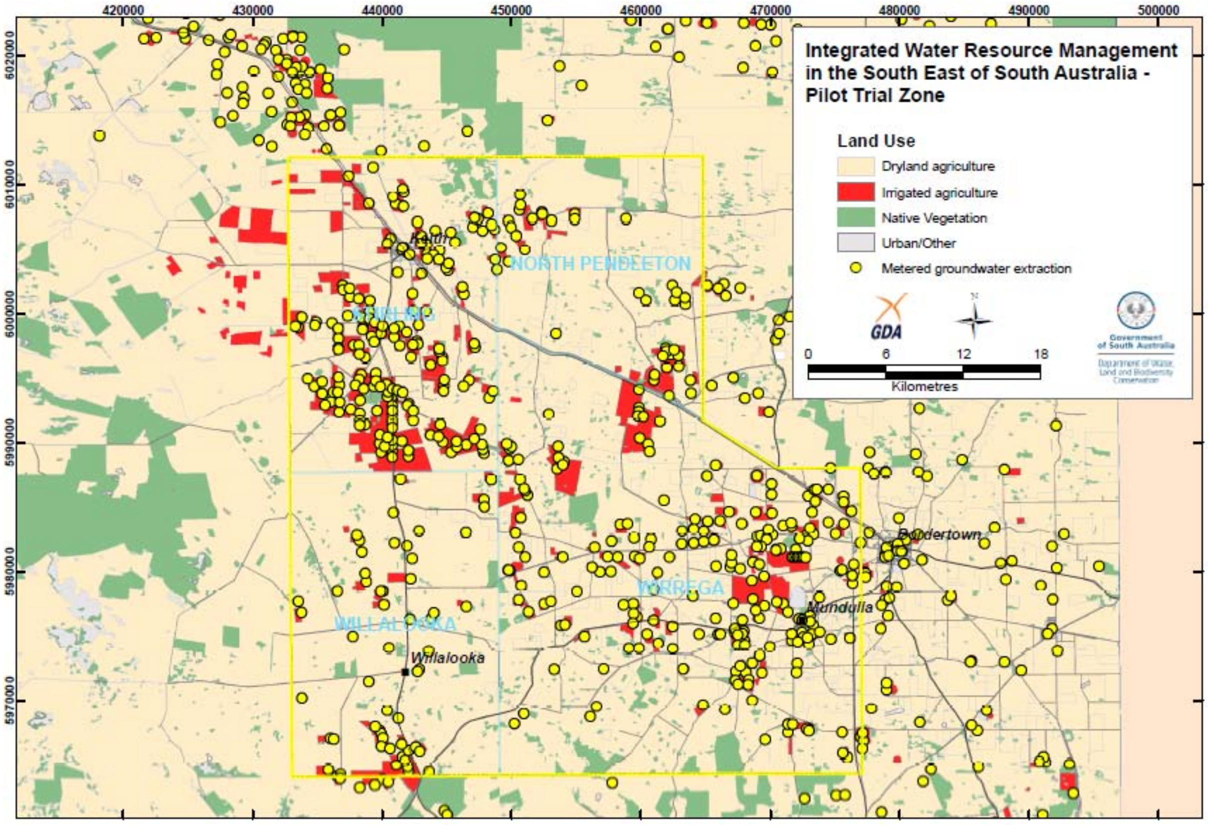


Figure 26. Irrigation and industrial extraction wells in the PTZ

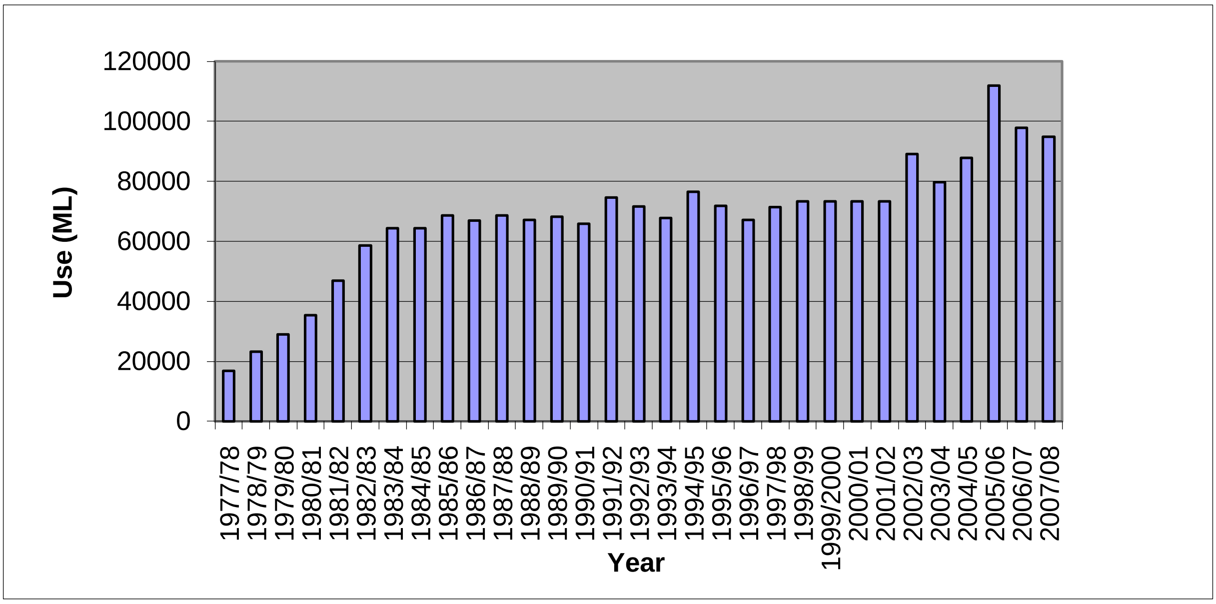


Figure 27. Estimated water use in the PTZ over time, based on metered extraction for 2007/08 and estimates from Cobb and Brown (2000), Stadter and Love (1987) and Latcham et al. (2007) for previous years

4.7. TIME DISCRETISATION

The model was effectively discretised into two stress periods per year, each with ten time steps. The stress periods ran for 181 days and 184 days, respectively, in order to approximately represent an irrigation season commencing in October of one year and finishing at the end of March of the following year and a recharge period that takes place from the start of April (when irrigation stops) until the beginning of October (when irrigation commences again). The application of extraction and recharge over broad time periods that may not necessarily reflect real world conditions is an acknowledged model limitation.

5. MODEL CALIBRATION

5.1. STEADY STATE CALIBRATION

An initial steady state calibration was carried out by modelling pre-development conditions—that is, no groundwater extraction was occurring and recharge rates were low (set at 15 mm/y in shallow watertable areas and 0.5 mm/y in deeper areas). Modelled water levels were compared qualitatively and quantitatively to the March–April 2009 groundwater levels in the area (generally the lowest hydraulic head levels on record). Hydraulic conductivities were altered to achieve calibration. Figure 28 shows the steady state equipotentials in the modelled zone. Given that groundwater levels in the PTZ are heavily influenced by extraction and changes in storage, this is considered to be a relatively good fit. The regional groundwater flow direction is obtained and the steep watertable zone is replicated.

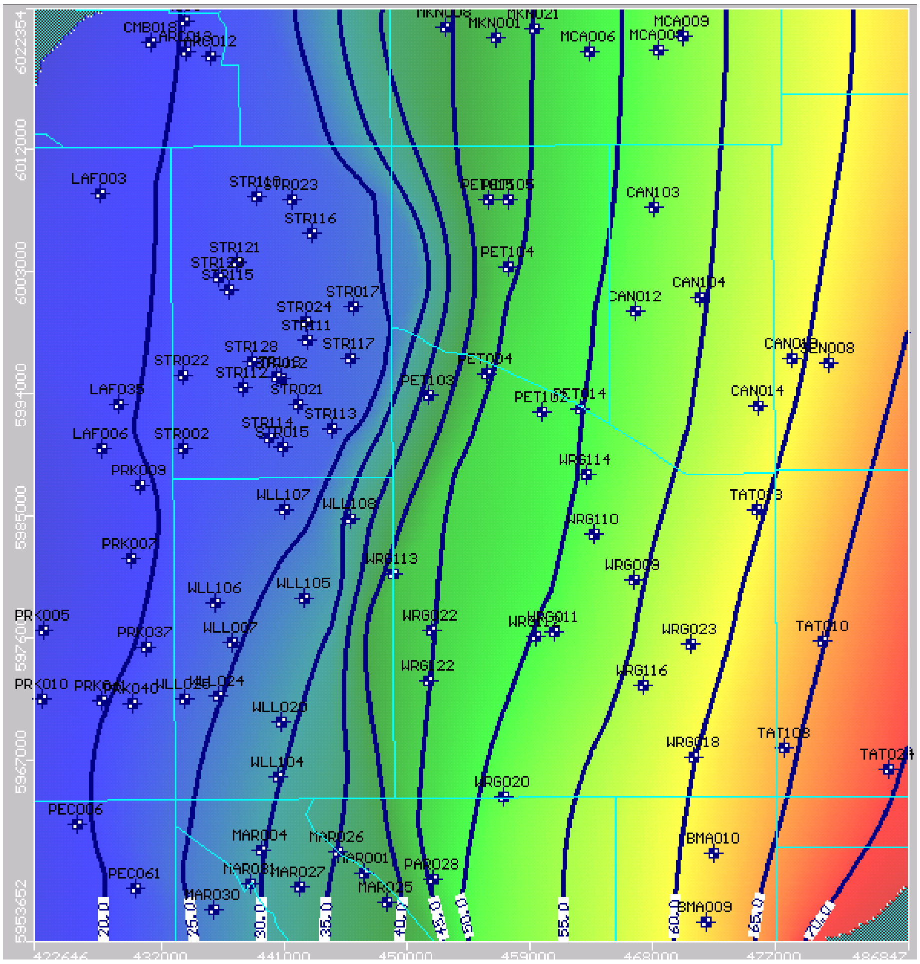


Figure 28. Modelled potentiometric surface (m-AHD) in the unconfined aquifer (steady state simulation)

Figure 29 shows modelled and observed heads for the steady state model. As can be seen, there is a reasonably good correlation. A normalised root mean squared error of 6.78% is achieved, with correlation coefficient between observed and modelled heads of 0.98. The greatest error is observed in wells outside of the PTZ (those closest to model boundaries, in the 10 km ‘buffer’ zone). Removing these wells from the calibration statistics and concentrating only on those in the PTZ lowers the normalised root mean squared error to 6.26% (see Figure 30).

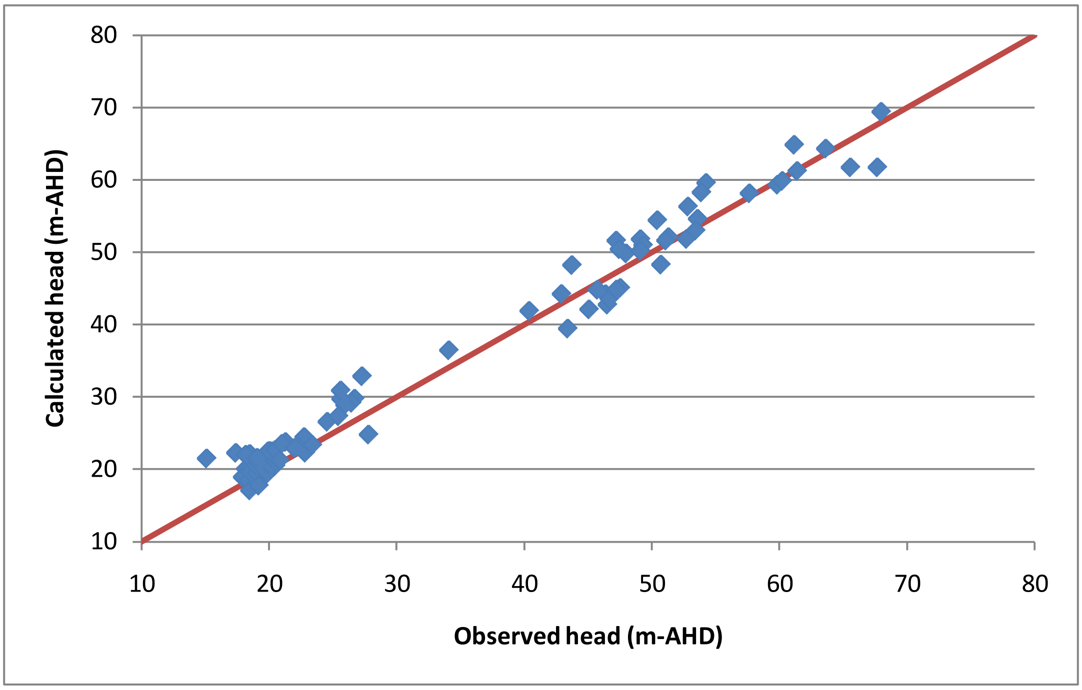


Figure 29. Steady state calibration statistics, including all observation wells in model domain area

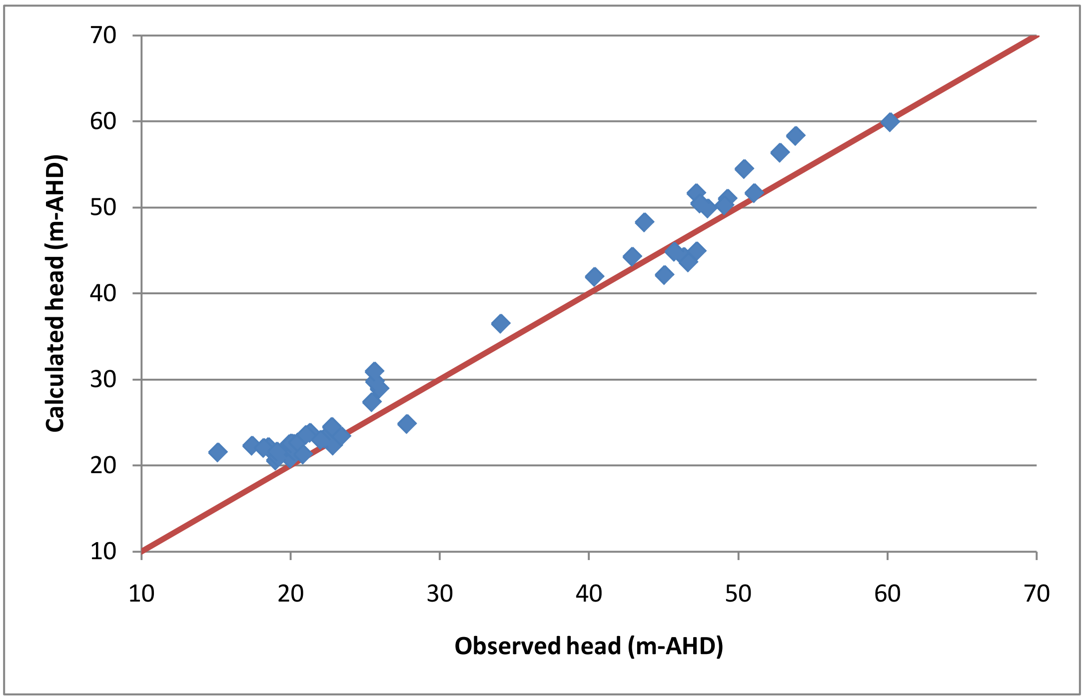


Figure 30. Steady state calibration statistics using only observation wells located in the Pilot Trial Zone

5.2. TRANSIENT CALIBRATION

The transient model was run from 1970 until 2009. Transient calibration was performed by iteratively running simulations and altering aquifer properties and boundary conditions within realistic constraints until a good fit between modelled and observed head was achieved.

Initial model runs showed water levels to be too high in some areas, especially areas around flood irrigation. Consequently, rainfall recharge was lowered, giving a new average rate from 1970 to 2009 of 31.9 mm/y (see Figure 31), and recharge under flood irrigation was lowered to 200 mm/y.

Aquifer properties were also varied to achieve better calibration (see Table 5). Most significantly, the extent of the low transmissivity zone was altered to better reflect the steep gradient zone in the watertable. Additional low conductivity zones were added based on the location of granite outcrops (details in Appendix A), particularly in the western portion of the Wirrega management area through to Willalooka. Some observation wells in Wirrega, particularly those close to known ‘runaway holes’, showed modelled water levels that were much higher than observed. High conductivity zones were introduced in these areas to reflect the secondary (karst) porosity that is likely to be present in these areas; however, these did not initially improve calibration, so it was decided not to include them in areas where their characteristics and extent were not known (see Appendix A for further discussion).

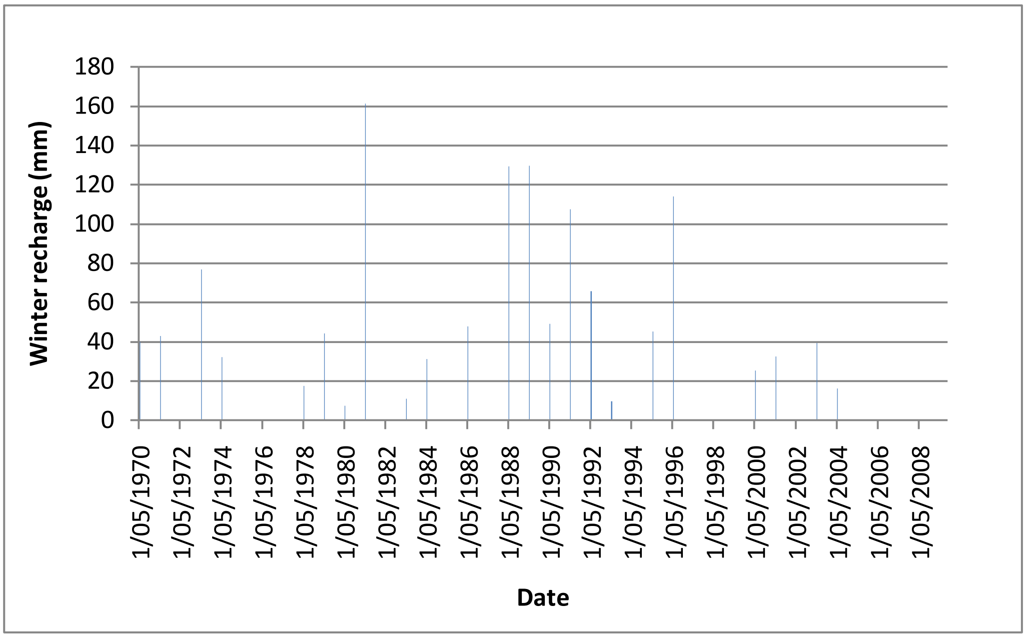


Figure 31. Final recharge schedule used in transient model

	Horizontal K (m/d)	Vertical K (m/d)	Specific storage	Specific yield
Padthaway	104	10	0.00001	0.15
Bridgewater	115	11	0.00001	0.15
Murray	30	3	0.00001	0.15
Stirling high K zone	450	45	0.000001	0.15
Low K zone around granites	0.00001	0.000001	0.00001	0.15
Transition zone of low K	15	1	0.00001	0.15

Table 5. Final hydraulic properties from the transient calibrated model

Figure 32 displays the modelled versus measured head after 14 000 days of simulation (i.e. in May 2008). As can be seen, a good fit is achieved. As with the steady state model, the largest errors are observed closer to model boundaries. For all observation wells, the normalised RMS is 4.10%. Considering only those wells within the PTZ as calibration points lowers the RMS to 3.6% (see Table 6 for further calibration statistics). Figure 33 plots calculated versus observed head for wells in the PTZ for various time periods over the model calibration period (note that the number of calibration points increases with time as more observation wells become operational). For all times, normalised RMS ranges from 3.8% to 4.9%. All of these statistics suggest good model performance. Appendix B shows observation well records with modelled water levels for the 48 observation wells in the PTZ. A good fit is observed for most wells in the PTZ in terms of water level trend. Exceptions to this are wells in the western areas, which have shown a gradual rise in the past 15 years (WRG020 and WRG018) as a result of historic land clearance and increased recharge. It was acknowledged during the model construction that this process would not be included in the model; hence, this discrepancy is considered acceptable. In some cases, absolute water levels do not match (for example, WRG023 and WRG114). This can be seen in Figure 34, in which modelled and measured potentiometric levels are not well-matched in eastern areas. However, the trends in water levels are well-matched, which is considered adequate given the overall calibration, and adequate for the purposes of this study (see Appendix A for further discussion). Further contour plots from different model output times are available in Appendix B.

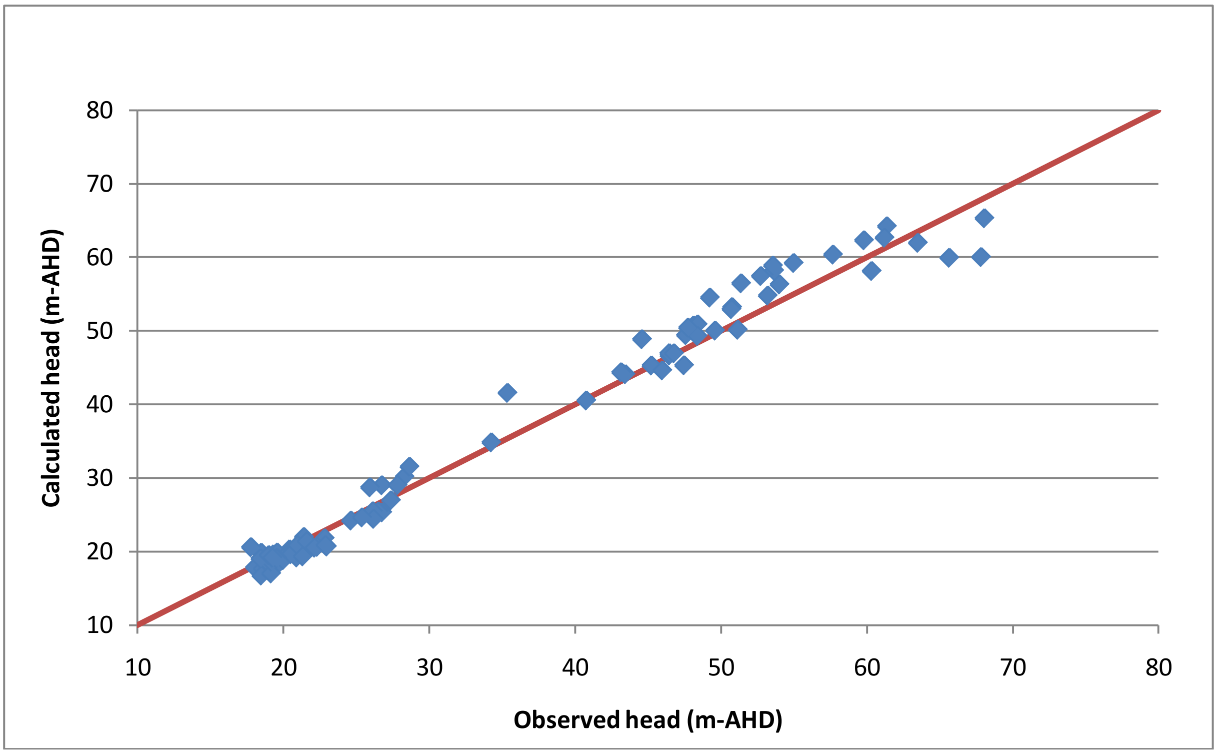
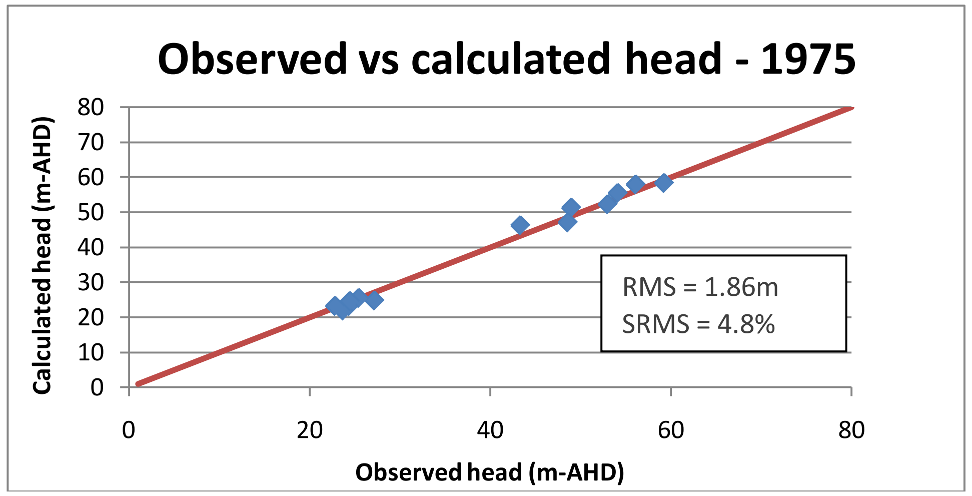
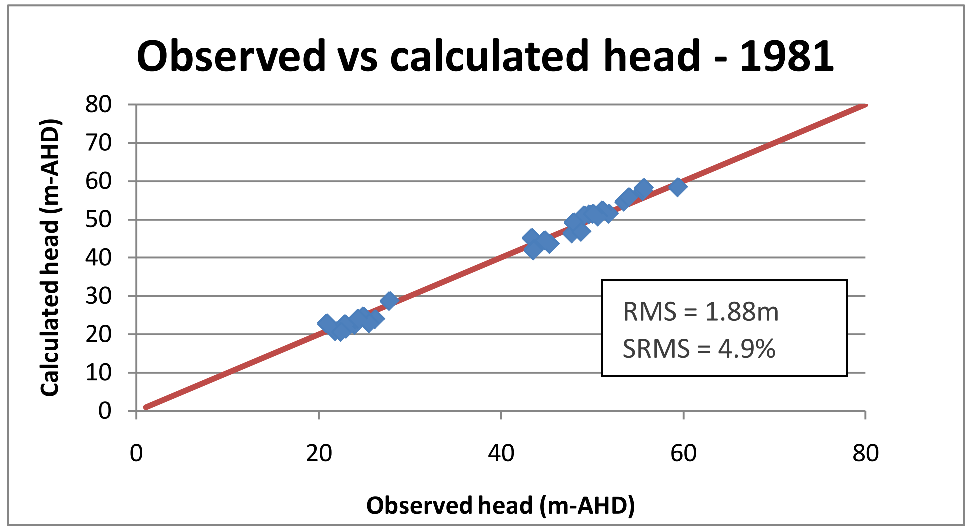
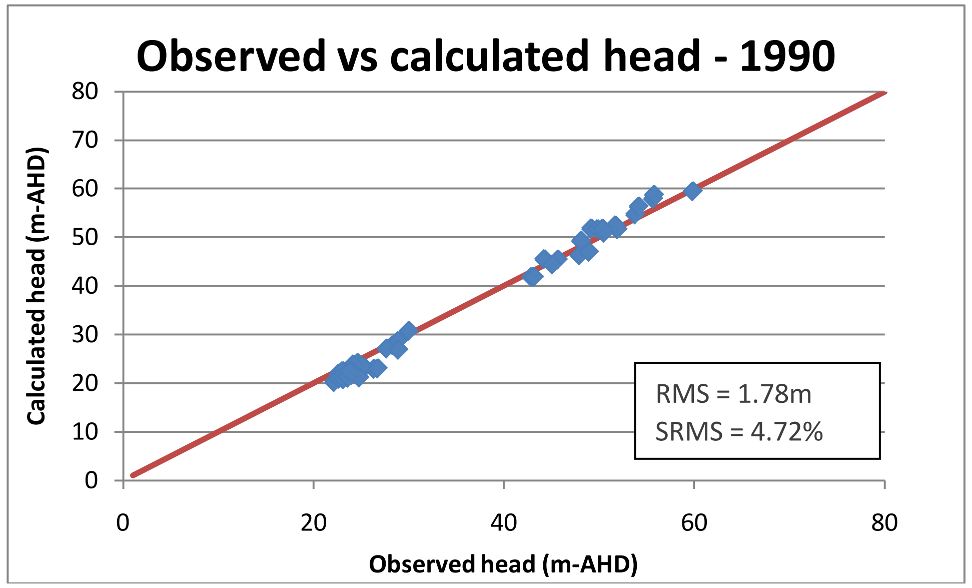
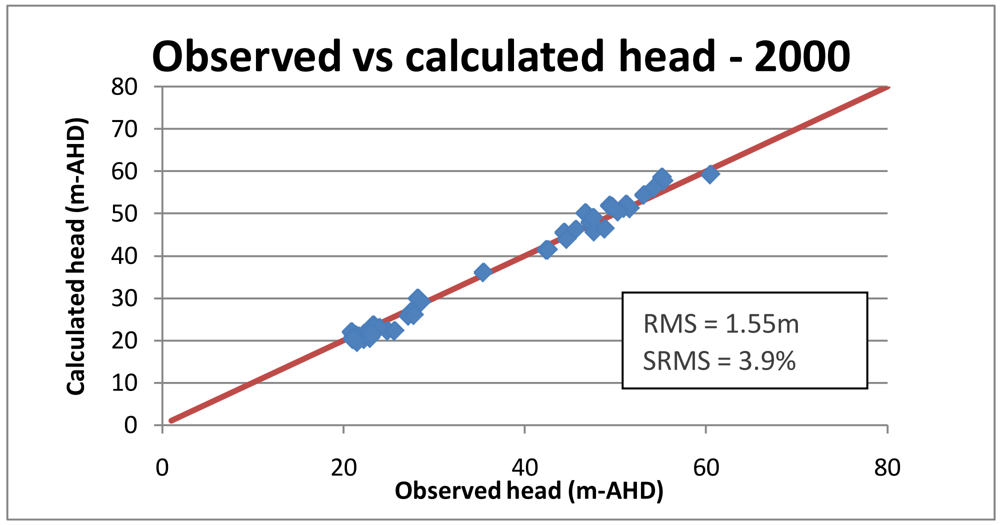


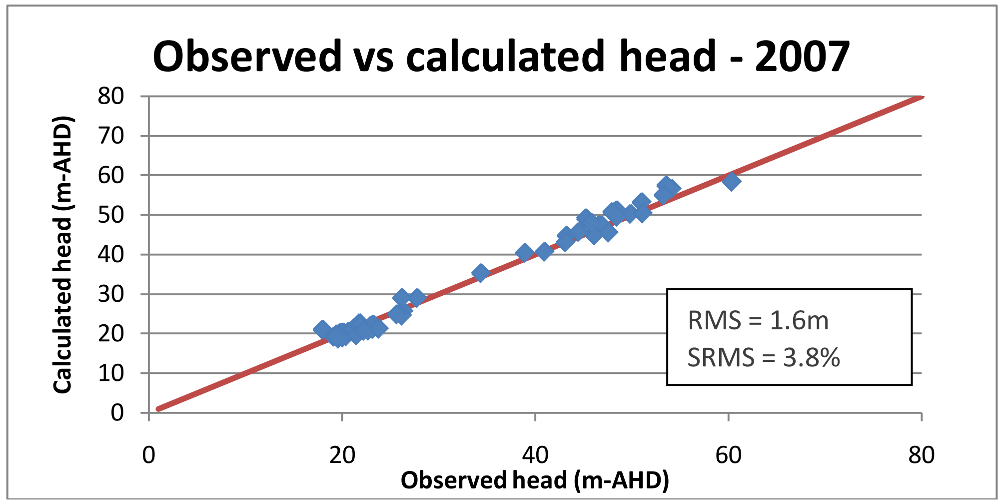
Figure 32. Calibration statistics for model after 14 000 days of simulation (i.e. modelled v. observed water levels for May 2008, all observation wells included)











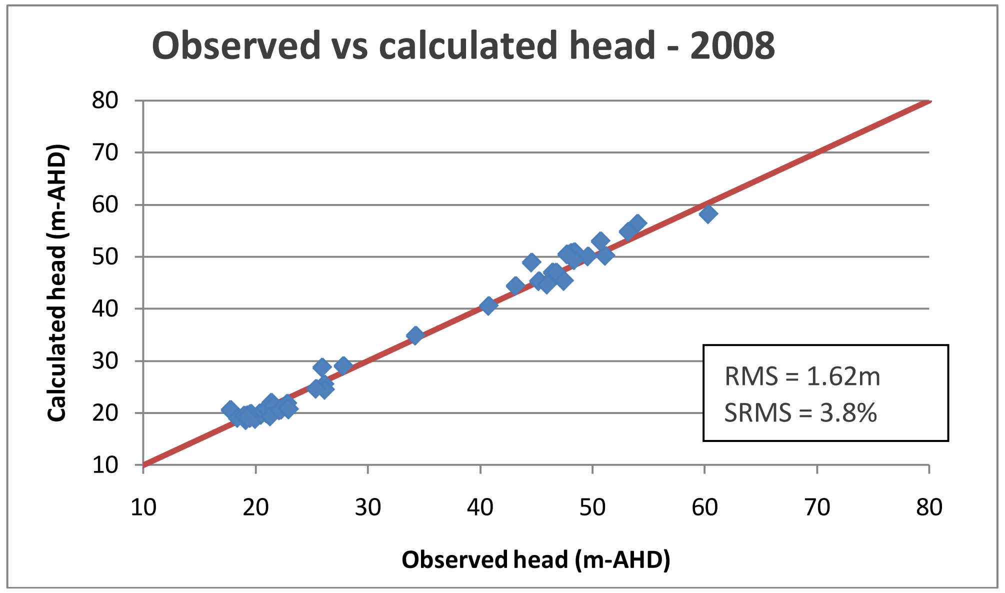


Figure 33. Measured and modelled groundwater levels for various times during model calibration. Calibration points increase with time, reflecting the expansion of the groundwater monitoring network in the South East since the late 1970s

Calibration parameter	Value
Root Mean Square (RMS)	1.82 m
Normalised RMS	3.98%

Table 6. Calibration statistics for transient model for all run times, 1970–2009 (only observation wells within the PTZ included)

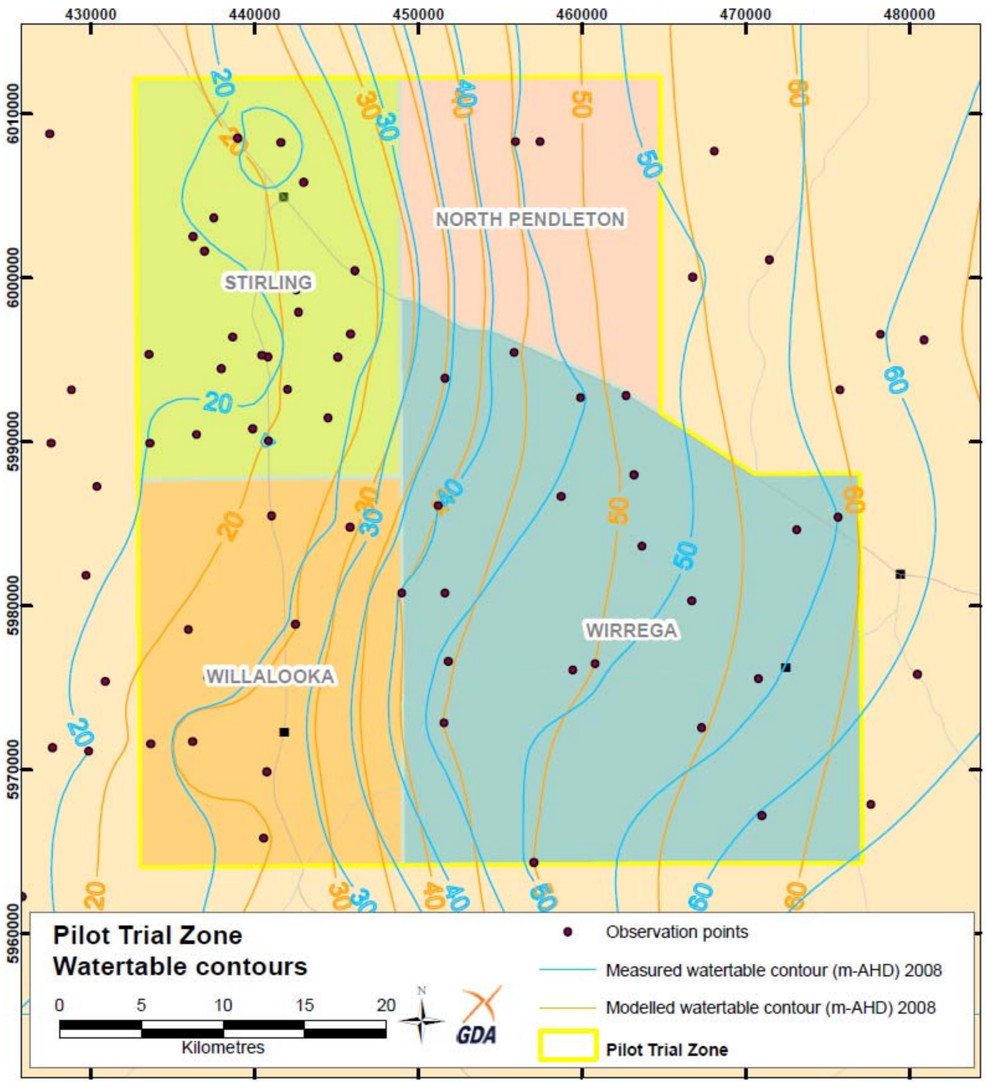


Figure 34. Simulated v. measured potentiometric surface after 14 000 days of model simulation (i.e. in May 2008)

For the purposes of this project, it was important that the model replicate the observed declines in water levels in recent years well, particularly in identified ‘key observation wells’, so that model scenarios could be considered to give an accurate indication of water level response to changes in extraction volumes and rainfall recharge. Figure 35 plots modelled groundwater level decline (from initial levels) against observed groundwater level decline measured in key observation wells over the past 20 years. As can be seen, in most cases, decline is well-matched. Even in cases in which absolute water levels are not well-matched (such as WRG111), the trend is observed. WLL108 shows a modelled underestimate of decline, thought to be due to underestimates of historical groundwater use in Willalooka. Also worth noting is that the magnitude of seasonal flux in observation points in Stirling (STR110–STR114) is not perfectly matched, probably due to the fact that stresses such as pumping and recharge are averaged over a longer period in the model than they would generally take in reality.

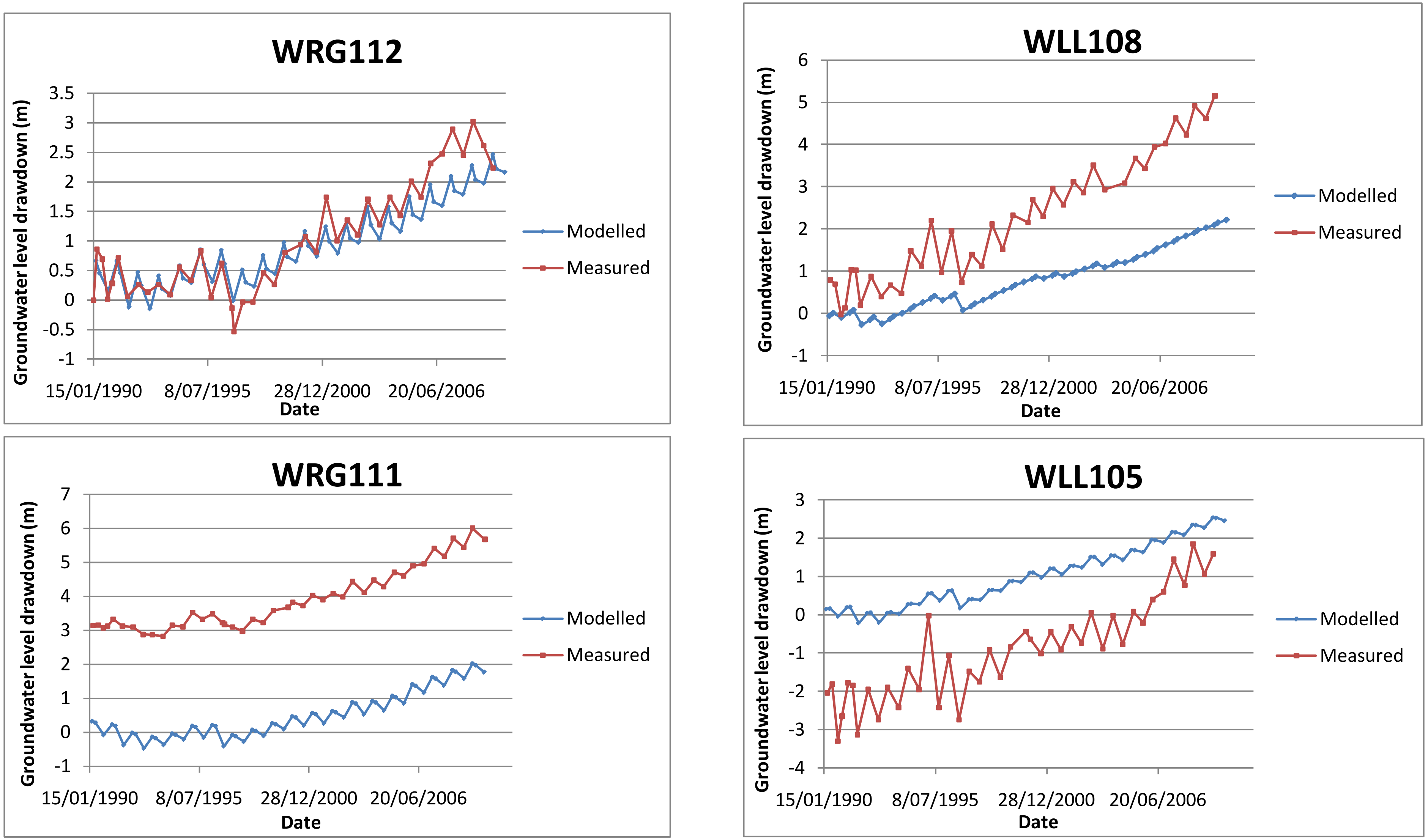


Figure 35a. Modelled and measured groundwater level drawdown in key observation wells (1990–present)

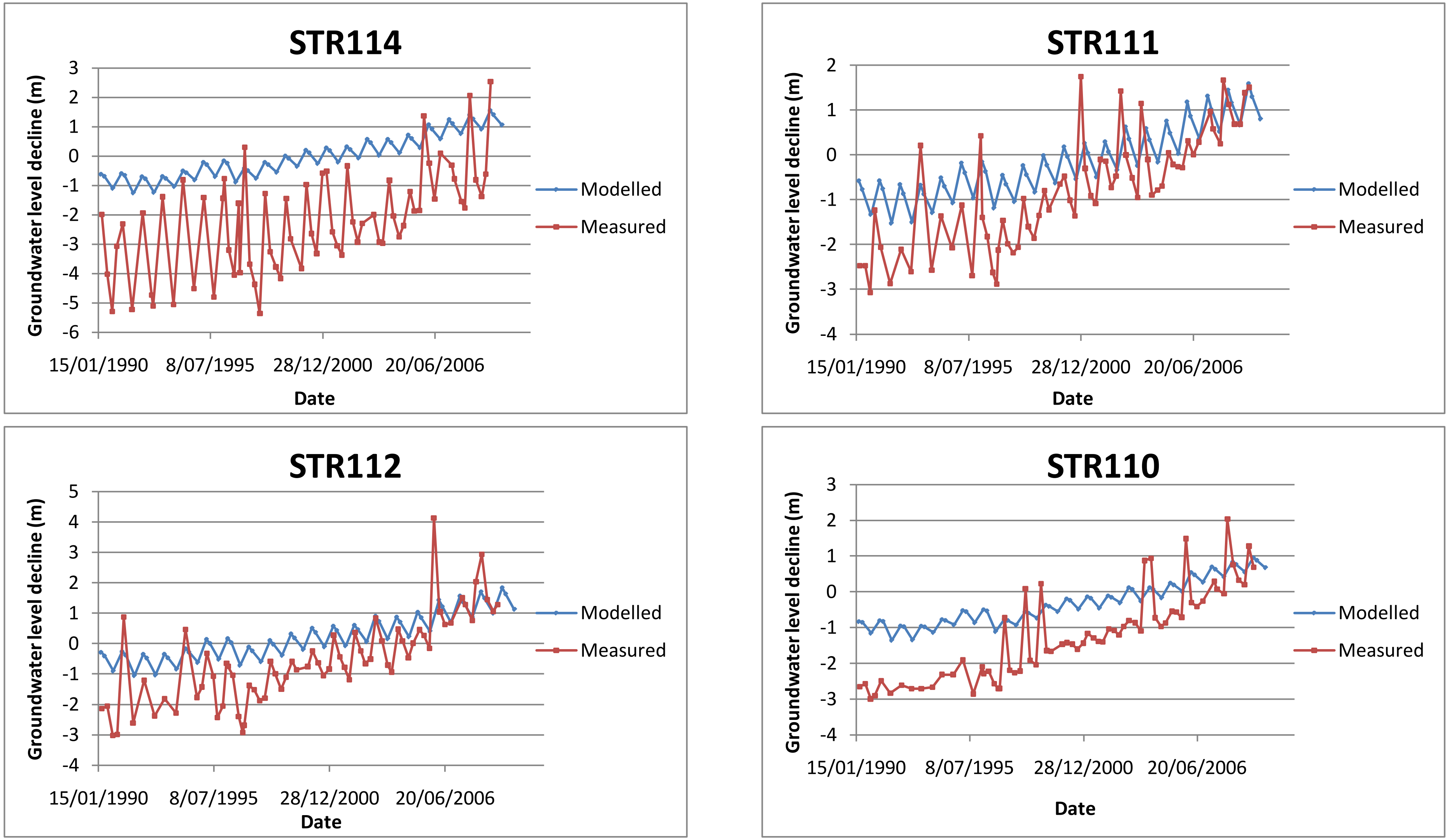


Figure 35b. Modelled and measured groundwater level drawdown in key observation wells (1990–present)

	1975	1981	1990	2000	2007
Recharge IN (ML/y)	-	277 211	91 127	51 587	9386
Boundary flow IN (ML/y)	20 973	9313	13 554	15 710	18 241
Pumping wells OUT (ML/y)	-	26 112	58 947	62 481	77 322
Evapotranspiration OUT (ML/y)	15 646	21 503	11 946	5356	2613
Boundary flow OUT (ML/y)	17 399	19 043	17 588	15 584	14 417

Table 7. Modelled water balance for the PTZ transient model

Table 7 shows the water balance for the transient model in selected years. It shows no recharge and no extraction occurring in 1975, as this was a low rainfall period and extraction was not implemented until 1977. Recharge is high in 1981, corresponding to the flood that was experienced in that year. Recharge then decreases into the 2000s as the climate becomes much drier. It also shows evapotranspiration decreasing as the watertable in the shallow western parts of the model declines beyond the extinction depth of 2 m below ground level (boundary flows out of the model also decrease as a result of watertable decline, as the hydraulic gradient out of the PTZ is lowered and a cone of depression forms in the Stirling area). Groundwater extraction increases over time, as has been observed. All of these patterns fit well with the conceptual model of the groundwater balance over time.

	Average from model calibration period	**Minimum modelled**	**Maximum modelled**	**Conceptual model estimate**
Recharge IN (ML/y)	56 355	0	277 211	88 274
Boundary flow IN (ML/y)	16 471	9300	20 899	20 280
Pumping wells OUT (ML/y)	56 111	15 173	88 786	92 884
Evapotranspiration OUT (ML/y)	36 058	7967	63 292	Not estimated
Boundary flow OUT (ML/y)	17 622	13 980	19 043	9966

Table 8. Summary of numerical model water balance and conceptual model water balance

Table 8 summarises how the water balance from the numerical model compares to that from the conceptual model. The average modelled recharge (including drainage from flood irrigation) is less than the conceptual model estimate; however, the modelled ranges encompass the conceptual model figure. Given that the recharge volumes used in the conceptual model are the adopted management figures, this discrepancy is considered acceptable.

Boundary flow into the model domain was slightly overestimated in the conceptual model and flow out of the domain was underestimated in the conceptual model. This is thought to be because of the different methods used to calculate boundary flow in the conceptual model and the numerical model. The conceptual model used gradients from wells within the PTZ and a transmissivity based on local values, whereas boundary flow in the numerical model was estimated by the General Head Boundary package, using head and transmissivity values that were adjusted during calibration. Therefore, the discrepancy in boundary flow is considered acceptable.

The difference between groundwater extraction in the numerical and conceptual models is also considered acceptable. The maximum modelled extraction rate is based on data from the same year as the figures in the conceptual model, and given that no extraction from stock and domestic wells was modelled and that there was expected to be a certain level of error in the modelled extraction figures, a discrepancy of 5% is not considered significant.

5.3. CALIBRATION SUMMARY

The model is considered to be well-calibrated overall. Quantitatively, the model can be considered to be well-calibrated given that the RMS is consistently below 5%. Qualitatively, it can be considered well-calibrated as it is modelling the processes that are of key interest (watertable decline in key areas). Given these two facts, the model can be used with some confidence to assess how changes in extraction and recharge may influence water levels in the future.

It is worth noting that model calibration is not perfect; however, in most cases, the reasons for poor model performance have been identified. The assumptions and limitations in this model are discussed in more detail in Section 8.

6. SENSITIVITY ANALYSIS

Sensitivity analysis was conducted on the model by assessing uncertainty in the parameters that were altered in calibration: recharge and hydraulic conductivity. Sensitivity analysis was also performed to investigate uncertainty in extraction data. Table 9 summarises the sensitivity analysis scenarios that were run.

Scenario	Extraction	Recharge	Conductivity
Calibrated model	*Metered use (07/08), estimated use prior to this*	*Based on rainfall, long-term average of 31 mm/y, 200 mm/y under flood*	*See calibrated values in Table 5*
1. Sensitivity to extraction	Calibrated values plus 20%	As calibrated	As calibrated
2. Sensitivity to extraction	Calibrated values minus 20%	As calibrated	As calibrated
3. Sensitivity to recharge	As calibrated	Calibrated values plus 20%	As calibrated
4. Sensitivity to recharge	As calibrated	Calibrated values minus 20%	As calibrated
5. Sensitivity to conductivity (K) in Stirling high K zone	As calibrated	As calibrated	Increased K in Stirling high K zone by 20%
6. Sensitivity to conductivity (K) in Stirling high K zone	As calibrated	As calibrated	Decreased K in Stirling high K zone by 20%
7. Sensitivity to conductivity (K) in steep gradient zone	As calibrated	As calibrated	Increased K in steep gradient zone by 50%
8. Sensitivity to conductivity (K) in steep gradient zone	As calibrated	As calibrated	Decreased K in steep gradient zone by 50%

Table 9. Sensitivity analysis scenarios run in PTZ model

Table 10 summarises the influence of changes in parameters on calibration statistics. The most sensitive parameters seem to be hydraulic conductivity within the Stirling high conductivity zone and the steep gradient zone. Scenarios 6 and 8, which decrease both conductivities, produce the greatest deviation from calibrated values. Table 10 also shows the statistics from the calibrated model, which shows that overall model calibration is best for the adopted values.

Appendix C presents the change in modelled water levels in selected observation wells for the various sensitivity scenarios. On close examination, it becomes apparent that while some scenarios seem to improve calibration in certain areas, they result in decreased model performance in other areas. For example, Scenario 1 (increasing calibrated extraction Figures by 20%) seemed to improve calibration in observation well PET103 by lowering the watertable and providing a closer match to absolute water levels. However, this scenario also lowered the watertable in other areas, decreasing model performance (for example, see observation well WLL007 in Appendix C). A likely explanation for this is that the calibrated values for groundwater extraction are closer to real values in Willalooka than in Pendleton (i.e. extraction is possibly being underestimated for Pendleton). This issue will only be resolved in the future as more metered extraction data becomes available. It is recommended that some post-auditing of the model be carried out in future, when more reliable data on extraction is available.

Scenario	**Root Mean Squared (RMS) error (m)**	**Normalised RMS (%)**	**Mean residual of error**	**Calibration coefficient**
Sensitivity analysis 1	2.55	4.77	-0.1	0.98
Sensitivity analysis 2	2.63	4.93	0.37	0.98
Sensitivity analysis 3	2.69	5.03	0.48	0.98
Sensitivity analysis 4	2.54	4.75	-0.05	0.98
Sensitivity analysis 5	2.49	4.66	0.11	0.98
Sensitivity analysis 6	2.73	5.1	0.14	0.98
Sensitivity analysis 7	2.49	4.66	0.11	0.98
Sensitivity analysis 8	3.54	6.62	0.19	0.98
Calibrated model	1.82	3.98	-0.35	0.99

Table 10. Calibration statistics for the various uncertainty analysis scenarios

7. SCENARIO MODELLING

7.1. PREDICTION SCENARIOS

The model was used to run a number of scenarios aimed at assessing the effectiveness of the currently proposed cuts in allocations while also assessing what sort of extraction regime would satisfy the Resource Condition Limits (RCLs) developed through the AM workshop series. As part of the AM project, key observation wells were identified within which to monitor RCLs. The selection of key observation wells was further refined to include locations where the model is well-calibrated. Details on the influence of each scenario on the RCLs in the selected wells can be found in Appendix F.

The scenarios were run from 1970 to 2060. Extraction and recharge values from the calibrated model were used to simulate flow from 1970 to 2009 before scenario values were implemented. In all, three different extraction scenarios were tested and each was run under three different climatic (i.e. recharge) conditions, as summarised below:

- Scenario 1: Groundwater extraction continues at its current rate (2008/09 use figures). Recharge rates are repeated on a ten-year cycle, based on 1999–2009 recharge rates (i.e. dry climate continues).

- Scenario 2: Same extraction scenario as Scenario 1, long-term average recharge is applied (31.9 mm/y).

- Scenario 3: Same as Scenarios 1 and 2 (i.e. use remains near current levels) but recharge is a repeated cycle of that applied in the model from 1970 to 2009 (i.e. recharge rates range from 0 mm/y to 161 mm/y).

- Scenario 4: Volumetric allocations are introduced, as are the cutbacks over the following three years, and all licences use 100% of their volumetric allocations. Recharge rates are repeated on a ten-year cycle, based on 1999–2009 recharge rates (i.e. dry climate continues).

- Scenario 5: Same extraction scenario as Scenario 4, long-term average recharge is applied (31.9 mm/y).

- Scenario 6: Same extraction scenario as Scenarios 4 and 5 but recharge is a repeated cycle of that applied in the model from 1970 to 2009 (i.e. recharge rates range from 0 mm/y to 161 mm/y).

- Scenario 7: Volumetric allocations are introduced, as are the cutbacks over the following three years, and all licences use only 70% of their full allocations. Recharge rates are repeated on a ten-year cycle, based on 1999–2009 recharge rates (i.e. dry climate continues).

- Scenario 8: Same extraction scenario as Scenario 7, only long-term average recharge is applied (31.9 mm/y).

- Scenario 9: Same extraction scenario as Scenarios 7 and 8 but recharge is a repeated cycle of that applied in the model from 1970 to 2009 (i.e. recharge rates range from 0 mm/y to 161 mm/y).

7.2. RESULTS OF PREDICTION SCENARIOS

This section of the report discusses the outputs from the scenarios. For hydrograph plots, drawdown contours and potentiometric surfaces from the Scenarios, see Appendices D and E.

7.2.1. SCENARIOS 1–3

Scenarios 1, 2 and 3 assessed what would happen under different climate conditions if extractions were to remain at current levels for another 50 years. As with the sensitivity analysis, the results were different in the different management scenarios. In Stirling and Wirrega, Scenario 1 (dry climate) produced the lowest overall water levels, with all hydrographs showing continual decline. In some cases, Scenario 1 took groundwater levels below the proposed RCL (i.e. keeping the Padthaway Formation saturated in Stirling and preventing groundwater from declining a further 2 m in Wirrega; see Appendix F for further details).

Scenario 2 (average recharge) resulted in groundwater levels in all management areas being stopped at their current levels and maintained there, with only a small amount of decline (and still with seasonal fluctuations). Scenario 3 showed groundwater levels to recover from current levels, following the increased recharge experienced from the 1970 to 2009 recharge schedule being repeated. However, the overall trend from Scenario 3 shows water levels lower in many areas in the year 2060 than they are currently.

In all of these scenarios, a reduction in pumping over time was observed and this is thought to be caused by watertable decline, which led to an increase in dry cells and meant a number of shallow extraction wells became non-functional. In reality, if this were to occur, it is likely that groundwater users would lower the level of their extraction wells to continue to access water; hence, the scenario is slightly unrealistic. Also, in all of these scenarios, there was a reduction in the rate of outflow from the head-dependent boundaries with time, which suggests that in none of these scenarios does lateral through-flow out of the PTZ increase (see Table 10). Therefore, maintaining water use at current levels of extraction is unlikely to mitigate salinity by maintaining and improving the east to west gradient.

7.2.2. SCENARIOS 4–6

Scenarios 4, 5 and 6 assessed what would happen under different climate conditions if volumetric allocations were introduced (including the currently proposed cuts in allocation) and 100% of allocations were being used. Scenario 4 (dry climate) produced the lowest overall water levels in North Pendleton and Willalooka, suggesting (when compared with Scenario 1) that volumetric allocations are greater than the level of current use in these management areas; therefore, the scenario is somewhat unrealistic.

Scenario 5 (average recharge) and Scenario 6 (1970–2009 recharge) had the same effect as Scenarios 2 and 3. That is, groundwater level decline was arrested by implementing long-term average recharge, and recoveries followed by declines back to current levels were observed by repeating recharge from 1970 to 2009. As with Scenarios 1 to 3, RCLs were breached in many key observation wells for Scenarios 4, 5 and 6.

As with Scenarios 1 to 3, the rate of outflow from head-dependent boundaries did not increase with time, suggesting that a situation where 100% of volumetric allocations were used would not improve the hydraulic gradient in the region and thus mitigate salinity increases in the western low-lying areas.

7.2.3. SCENARIOS 7–9

Scenarios 7, 8 and 9 assessed what would happen if only 70% of volumetric allocations were used. These scenarios were developed because there was some uncertainty as to how volumetric conversion figures would compare to current use figures (see section 8.3 of this report for further discussion). Scenarios 1–3 and 4–6 showed that in some areas, full use of volumetric allocations resulted in an increase in extraction (even with cuts in allocation implemented), while in other areas, extraction decreased slightly. In consultation with appropriate DWLBC staff, 70% use of volumetric allocations was decided upon as a realistic figure based on current knowledge of use and allocation. It also gave a ‘most conservative’ scenario to help meet the RCLs.

Scenario 7 (dry climate) still leads to continued groundwater decline in some wells but it satisfies the RCL in more wells than Scenario 4 (dry climate, full use of volumetric allocations). Scenario 8 (average recharge) and Scenario 9 (1970–2009 recharge) lead to recoveries in water levels and satisfy RCLs in all the nominated observation wells by keeping water levels within desired aquifer formations and/or preventing groundwater levels from declining by a further 2 m from current levels.

While Scenario 7 shows a decline in the rate of flow out of the head-dependent boundaries with time, Scenarios 8 and 9 both show an increase. This suggests that, assuming all licensees are using 70% of their allocation (an overestimate and underestimate in certain cases), the proposed reductions in allocations may help mitigate salinity by increasing the rate of lateral groundwater through-flow. Needless to say, the degree of increase is heavily dependent upon rainfall recharge.

7.3. SUMMARY

As with the sensitivity analysis, the different prediction scenarios produced different results in the different management areas. This is because of the uncertainty in how a move to volumetric allocation and the associated cuts will influence groundwater use. At this stage, it seems that the proposed cuts in allocation, assuming only 70% of volumetric allocations will be used (a realistic assumption based on our current knowledge of water use), will prevent groundwater levels from declining further and potentially lead to recoveries in many areas, as shown by Scenarios 7, 8 and 9. These conditions also help satisfy the draft RCLs for the AM pilot (see Appendix F for a further discussion of the development of RCLs in the PTZ and how the different scenarios met them).

Realistically, though, this model will need to be re-run in a further two to five years' time as part of a post-audit exercise once sufficient metered extraction data has been collected. Only with a good record of metered groundwater extraction will it be possible to assess and model the change in groundwater use with volumetric conversion and any future reductions in allocation.

	Recharge IN (ML/y)	Boundary flow IN (ML/y)	Pumping wells OUT (ML/y)	Evapotranspiration OUT (ML/y)	Boundary flow OUT (ML/y)
Scenario 1 – 2020	51 587	19 940	69 349	338	12 479
Scenario 1 – 2060	51 587	21 903	64 149	-	9947
Scenario 2 – 2020	62 469	16 820	63 431	2532	14 847
Scenario 2 – 2060	62 469	18 328	62 978	2812	14 736
Scenario 3 – 2020	21 680	18 766	70 814	1305	13 706
Scenario 3 – 2060	21 680	19 365	69 133	697	13 059
Scenario 4 – 2020	51 587	19 865	71 884	361	12 465
Scenario 4 – 2060	51 587	22 173	66 245	2	9549
Scenario 5 – 2020	62 469	18 503	74 385	1592	13 968
Scenario 5 – 2060	62 469	17 139	72 504	1513	13 826
Scenario 6 – 2020	21 680	18 644	74 165	982	13 390
Scenario 6 – 2060	21 680	19 572	70 431	569	12 710
Scenario 7 – 2020	51 587	19 510	56 921	1360	13 565
Scenario 7 – 2060	51 587	21 220	52 454	402	11 952
Scenario 8 – 2020	62 469	16 701	57 467	3585	15 010
Scenario 8 – 2060	62 469	17 892	57 467	3853	15 295
Scenario 9 – 2020	21 680	18 316	57 467	2292	14 212
Scenario 9 – 2060	21 680	18 604	57 467	2708	14 297

Table 11. Water balance at selected output times for the model scenarios

8. ASSUMPTIONS AND LIMITATIONS

The model developed here is based on currently available data sets and estimates made using the best available data. Consequently, a number of assumptions have been made which may limit the usefulness of this model to accurately and adequately predict changes in groundwater flow into the future. However, as Middlemis (2004) states, '*the fundamental guiding principle for best practice modelling is that model development is an ongoing process of refinement.*' Therefore, this section of the report serves to identify the main limitations in the model at the present time and give an insight into the degree of non-uniqueness in the current calibrated model. It is hoped that further research and data collection in the future may help refine the model and reduce uncertainty.

8.1. AQUIFER PROPERTIES

A number of assumptions relating to aquifer properties have been made in this modelling exercise. The main limitation is the assumption of homogeneity within aquifer units. As Figure 15 and Table 1 show, transmissivity values within one formation may vary by two orders of magnitude, a result of karst development in the carbonate formations. Future research into aquifer characterisation in this area and perhaps a stochastic approach to modelling in the future may help refine the model.

Further assumptions have been made about both the steep gradient zone in the middle of the model domain and granite outcrops in the western areas. The steep gradient zone has previously been explained as being caused either by faulting or a transition zone between Tertiary and Quaternary aquifer units (Stadter & Love 1987; Cobb & Brown 2000). Assigning an arbitrary 'low K' value to this transition zone may not reflect the controlling processes accurately and therefore presents a limitation. Further work in the future may help characterise the steep gradient zone and allow it to be better modelled.

Appendix A outlines how granite intrusives were included in the model to improve calibration. The sub-surface extent of granite intrusives is not known; therefore, future work relating to the mapping of these features (possibly using geophysical techniques) would greatly improve model performance. Likewise, further investigation into karst development in the eastern part of Wirrega would help improve model calibration.

8.2. GROUNDWATER EXTRACTION

Estimates of groundwater use consistently cause problems in groundwater models, where groundwater extraction has not historically been metered. Initial model calibration was based on metered extraction for the 2007/08 irrigation season and estimates of use for all years prior to this. Furthermore, the irrigation 'footprint' was kept consistent throughout the model—that is, all extraction wells present in 2007/08 where kept present in the model throughout simulation rather than being added over time based on the date on which they were drilled or the years in which groundwater licences were sought. Extraction from each well was then adjusted to reflect changes in estimated use historically. This creates a limitation in the model. With continued meter-reading in the future, the model may be better calibrated to realistic groundwater use figures.

Also, the model neglects to include any extraction in the Hundred of Laffer in the western part of the model buffer zone. This is because the area is un-prescribed and records of groundwater use are not kept. Barnett and MacKenzie (2009) estimated use in Laffer to be ~12 700 ML/y, most of which is located in the east of the hundred and included in the PTZ model domain; however, this was not included in the model due to the lack of reliable data, and presents a limitation.

Stock and domestic (S and D) use of groundwater has not been accounted for in the model, either. Again, this is because of a lack of reliable data on the volume of water extracted for S and D use. Referring to the initial water balance, estimated S and D use is only 1.25% of total extraction; therefore, an argument may be made that it does not need to be accounted for in the model. Nevertheless, its absence presents a limitation.

8.3. VOLUMETRIC CONVERSION

The move to volumetric allocation of water licences presents a challenge in running predictive model scenarios. In many cases, licence holders are likely not to be extracting the full volume of groundwater allocated to them. For example, Hodge (2009) estimated between 36% and 67% of indicative allocation (i.e. estimated volumetric allocation prior to volumetric conversion) was being used in the PTZ in 2008/09. Volumetric conversion of water licences then allocates licensees a volume of water that may be well above what they actually use. For example, see Figure 36, which displays the pumping schedule for one extraction well in the PTZ from the start of the model run (1970) until 2020 (this was from an early scenario run not documented in this report). The initial extraction volumes are based on historical estimates of use and the volumes from 2010 onwards are based on full use of volumetric allocation. As can be seen, there is a large and likely unrealistic increase in extraction with the adoption of volumetric conversion in 2009.

Figure 36 reflects only one scenario that was tested and other scenarios have been run that are thought to better reflect realistic conditions (70% use of volumetric allocations). However, the current uncertainty in use versus allocation presents a limitation. It is hoped that in coming years, with the implementation of volumetric allocations and ongoing reading of meters on extraction wells, there will be better data available to make predictions about the future of groundwater resources in the PTZ as well as better calibrate the model.

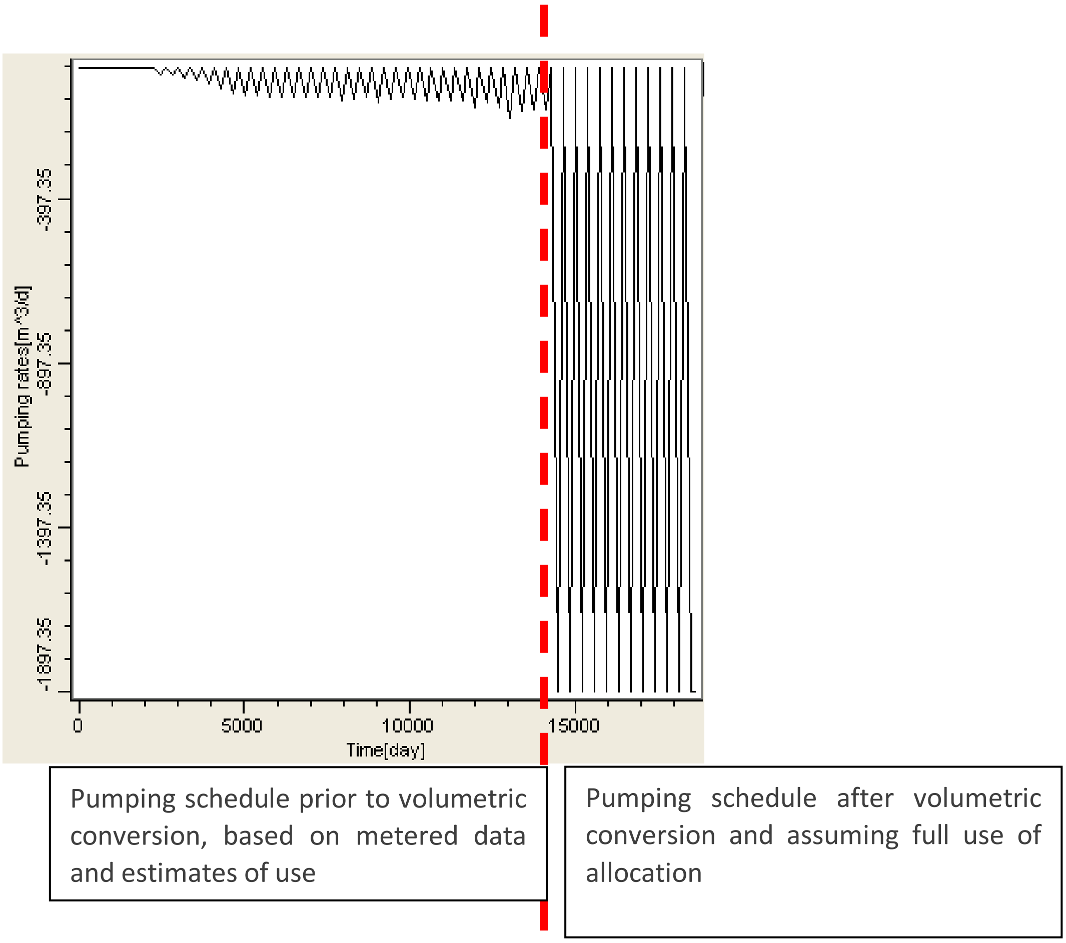


Figure 36. Pumping schedule for a licensed extraction well in the PTZ under one scenario in which volumetric conversion is implemented and full allocation is used (note: 15 000 days equates to January 2011 in the model's time scale)

8.4. SURFACE WATER – GROUNDWATER INTERACTIONS

Point source recharge to groundwater through drainage bores, runaway holes and other karst features has not been included in the model. Also, creeks and surface water drains have not been included in the model domain where present, the assumption being that these surface water systems are not in direct connection with groundwater. Based on ground surface elevations and watertable elevations, this assumption may be valid, although drainage features within these creeks may provide significant amounts of groundwater recharge in times of high rainfall. These processes were not included in the model, due to the level of complexity they presented. There is the potential to include these features in the model in the future if that degree of complexity is thought necessary. However, it is likely that further research into surface water behaviour in the PTZ would be required.

8.5. RECHARGE

Clearance of native vegetation in the Naracoorte Ranges in the 1960s has previously been seen to have an impact on recharge to the unconfined aquifer over the past 40 years (Wohling et al. 2005). Some observation wells in the elevated areas of the model domain also show trends suggesting native vegetation clearance has impacted on recharge (WRG018 and WRG020, see Appendix B for calibration plots). However, this has not been modelled, as there was not sufficient data to implement it. Should this data become available in the future, it may be incorporated.

8.6. POOR MODEL PERFORMANCE IN EARLY TIME OUTPUT

It is worth mentioning that while the transient model showed good calibration against observed water levels, there was an initial imbalance during early run times. The imbalance was observed as water levels in shallow wells in Stirling increased initially and heads in deeper wells in North Pendleton showed an initial decrease. This is thought to be because the initial heads used in the model (those generated by the steady state model) are not in balance with the boundary conditions and stresses in the transient model. Middlemis (2000) discusses this type of inconsistency (between steady state outputs and initial conditions in transient modelling) in the MDBC Groundwater Flow Modelling Guideline and states that this initial re-adjustment in the transient model may be acceptable where early time output is not critical. As early time output is considered not critical in this study (and given the lack of Obswell data to calibrate to prior to 1975) and the emphasis is on recent trends and declines in groundwater levels, this initial imbalance is not considered problematic. Given the large seasonal fluctuations in the watertable, particularly in Stirling, it is fair to say that stresses on the system (i.e. changes in storage between summer and winter) are quite large; therefore, such a discrepancy between steady state (i.e. no stresses on the system) and transient state (stresses applied to the system) is expected.

8.7. SALINITY

Solute transport was not modelled as part of this study, due to limited data. However, solute transport in the PTZ is of great interest, especially in the Stirling management area, where unconfined aquifer salinities have been observed to be rising at rates of more than 70 mg/L/y. Presently, scenarios that have been modelled to manage salinity relate to maintaining the hydraulic gradient and increasing lateral through-flow out of the western boundary. While this may help prevent salinity increasing further, without actually modelling solute transport, the problem of managing salinity has not been conclusively addressed.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1. CONCLUSIONS

In this project, a transient numerical groundwater flow model centred around the groundwater management areas of Stirling, Willalooka, North Pendleton and Wirrega in the Upper South East of South Australia has been developed. It has been constructed and calibrated to the groundwater level information available, and the MDBC Modelling Guidelines (Middlemis 2001) have been used to guide this process.

Calibration was considered successful. Quantitative assessment of calibration showed the model to be well-calibrated overall (normalised root mean squared error was <5%); however, qualitative assessment showed modelled water levels in some observation wells to not be calibrated. However, in these cases, water level trends were well-matched, which was considered adequate for the purposes of this model.

Several scenarios were run to assess the impact of volumetric conversion and cuts in allocation, while also assessing how pilot RCLs for groundwater management (developed for this area in a complementary Adaptive Management Pilot Trial project) might be met under these conditions. It was found that based on our current knowledge of groundwater use, the implementation of volumetric conversion and the proposed reductions in allocation will reduce groundwater level decline in the area and lead to a recovery in groundwater levels in some circumstances. It still remains that the degree of groundwater level recovery is largely dependent upon rainfall.

9.2. RECOMMENDATIONS

While the conclusions made from this modelling exercise provide a promising outlook for groundwater resources in the Tatiara area (eg. recovering water levels following allocation reductions), it is worth noting that a number of assumptions have been made which may limit the usefulness of this model. These assumptions have been identified as model limitations and it is hoped that they may be addressed in the future to improve model performance.

As stated earlier in the report, the Adaptive Management pilot trial run in parallel with this modelling project has provided a possible template for future groundwater management review in the area. It is therefore recommended that the model be re-run during the next five years to 'post-audit' the results. In this time, there will be a much better record of metered groundwater extraction to help model calibration. If this proves a successful exercise, then the model may be used with some confidence to help guide groundwater management decision-making in the future.

ASSUMPTIONS AND LIMITATIONS

APPENDICES

A. TRANSIENT MODEL INCLUDING GRANITES AND RUNAWAY HOLES

Granite outcrops in the PTZ have long been thought to play a part in influencing groundwater flow. Initially, it was decided not to incorporate them in the model, as they have only been mapped on the surface and little is known of their sub-surface extent. However, concerns were raised after the transient model produced erroneous results in areas around granite outcrops. Therefore, a version of the model was constructed with zones of low conductivity (horizontal K = 0.00001 m/d, vertical K = 0.000001 m/d) placed in all three model layers in areas where granite outcrops have been mapped. Figure 37 shows the location of these zones in layer one.

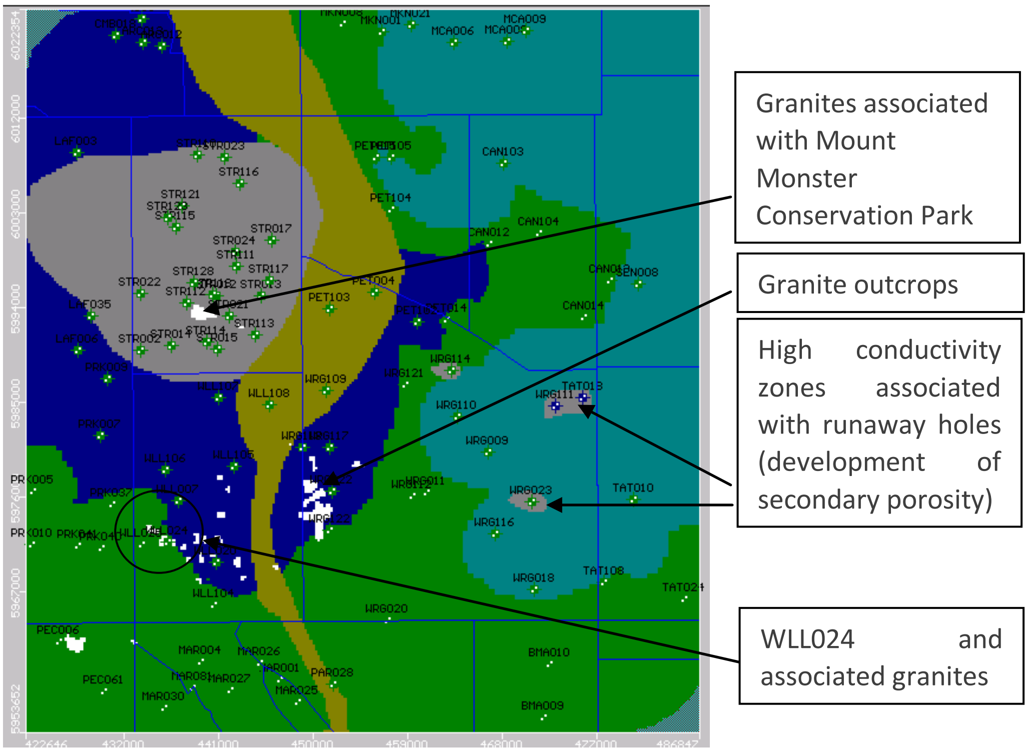


Figure 37. Location of granite outcrops in model domain

This improved calibration in areas around granite outcrops—for example, WLL024 (see following Figures). It also improved the overall model RMS. Therefore, low conductivity zones associated with granites were included in the final model, even though their sub-surface extent is not known. Their extent was based on GIS layers of surface geology. The GIS layers did not show any intrusive volcanic rocks in the area around Mt Monster Conservation Park, which is a well-known granite outcrop. Therefore, a low conductivity zone representing Mt Monster was mapped in the model based on the native vegetation coverage.

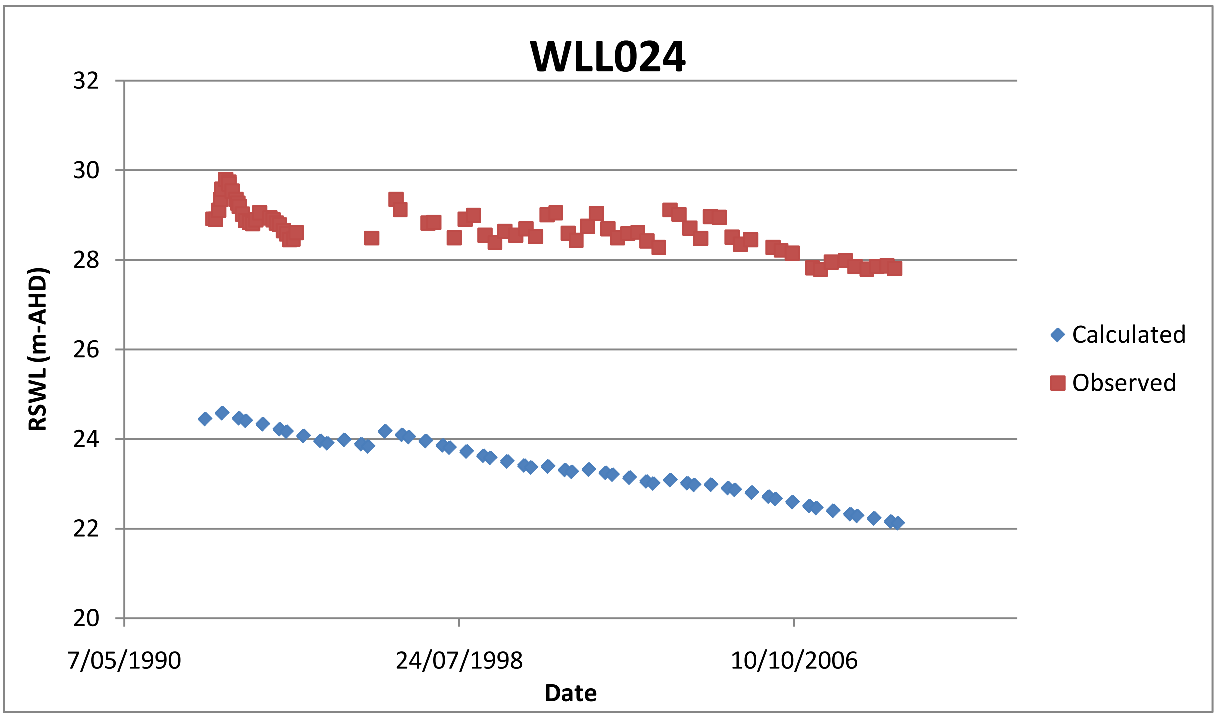


Figure 38. Modelled v. observed head in WLL024, from earlier version of the model without granite outcrops included

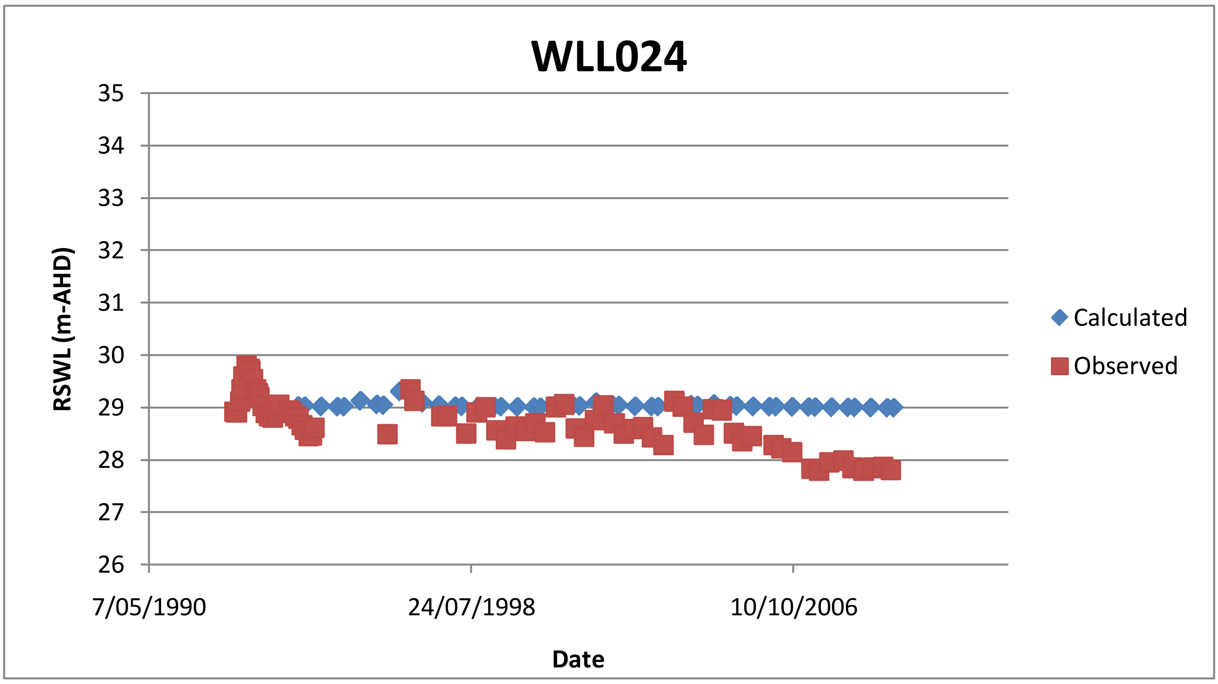
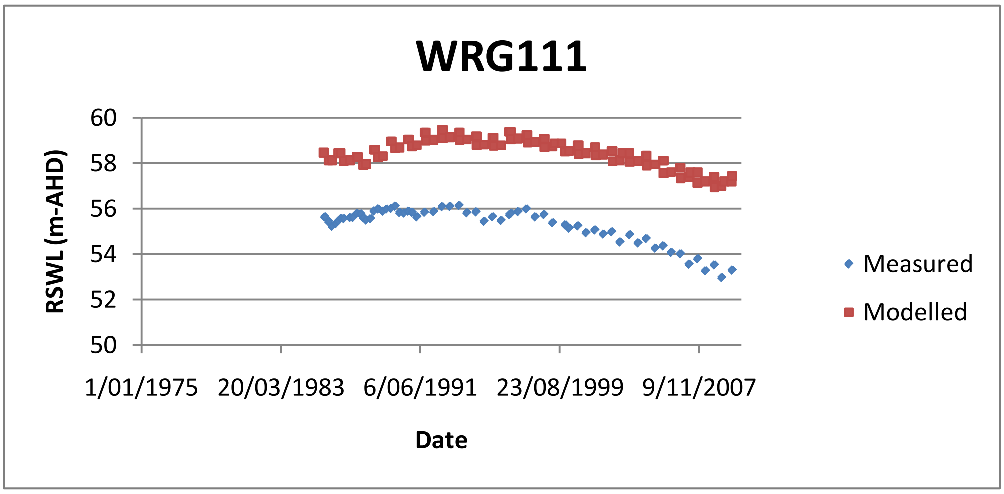


Figure 39. Modelled v. observed head in WLL024, from calibrated version of the model with granites included

The development of secondary porosity in the carbonate aquifers in the PTZ further complicates simulation of flow. Several observation wells in the eastern part of the Wirrega management area initially showed modelled water levels that were higher than those observed. Some of these wells were located around well-known ‘runaway holes’, such as Poocher’s Swamp west of Bordertown and Moot-Yung Gunnya swamp near Mundulla. These runaway holes are essentially sinkholes that act as the terminal point of Tatiara and Nalang Creeks. In times of excess rainfall and high creek flow, these features may provide point source recharge of surface water to the aquifer. It is likely that conduits to flow (caves and other karst features) extend further into the aquifer, resulting in high localised transmissivity. In an attempt to try and calibrate to these conditions, high conductivity zones (horizontal K = 450 m/d, vertical K = 45 m/d) were placed in some of these areas to reflect the karst development and improve overall model calibration. However, this exercise did not improve overall calibration; therefore, it was decided that adding this level of complexity to the model was unnecessary given the available data sets. Furthermore, while the absolute water levels in the eastern part of Wirrega do not match in some cases, trends in groundwater level in recent times are well-matched (see Figure 40 showing WRG111, which is 3 km north-east of Poochers Swamp), which is considered adequate for the current purpose of the model.



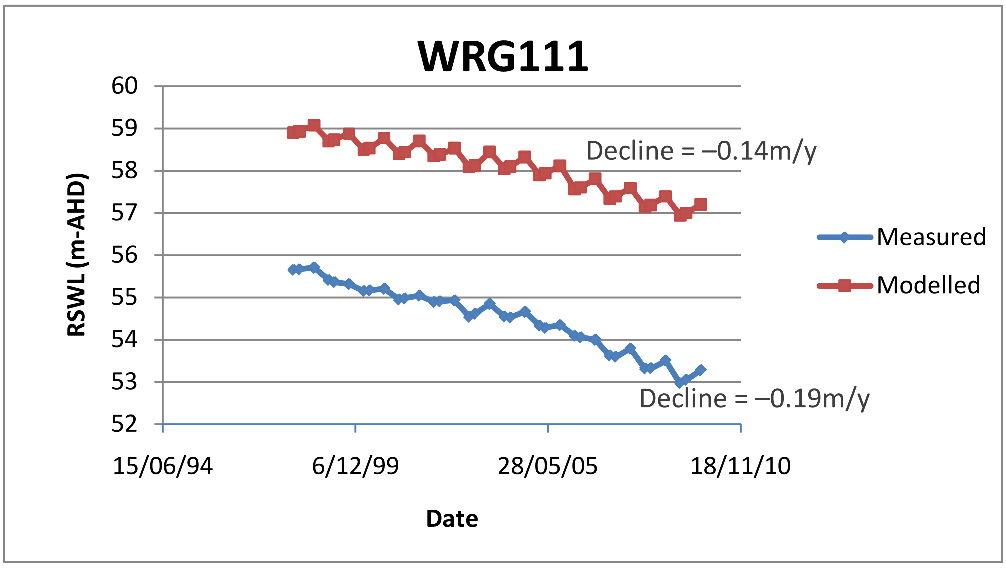
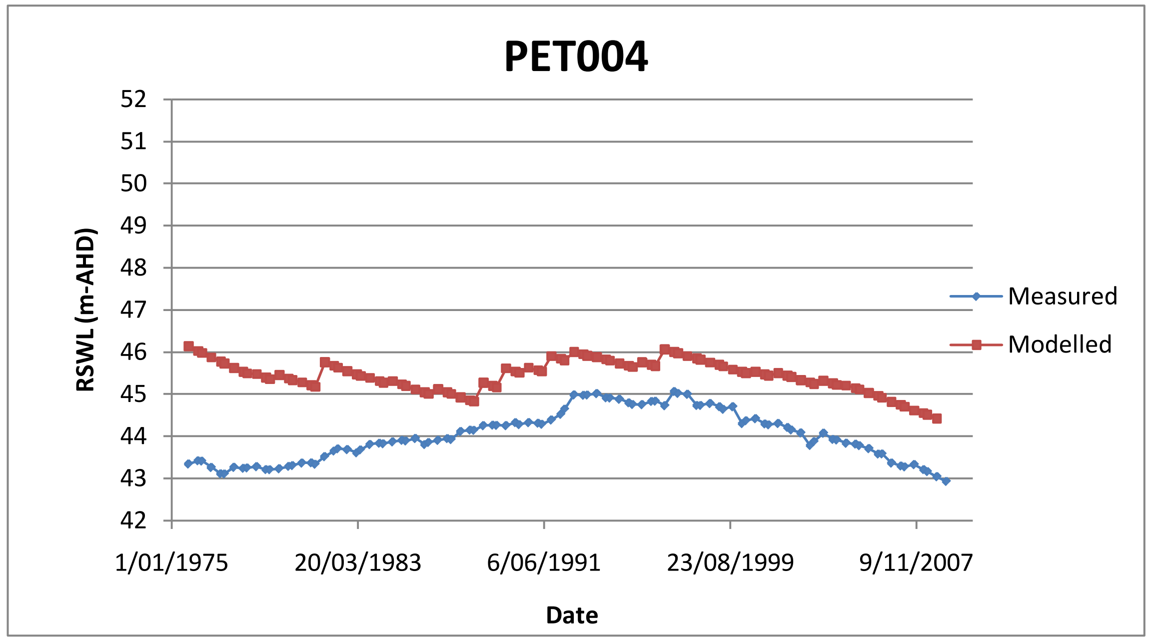
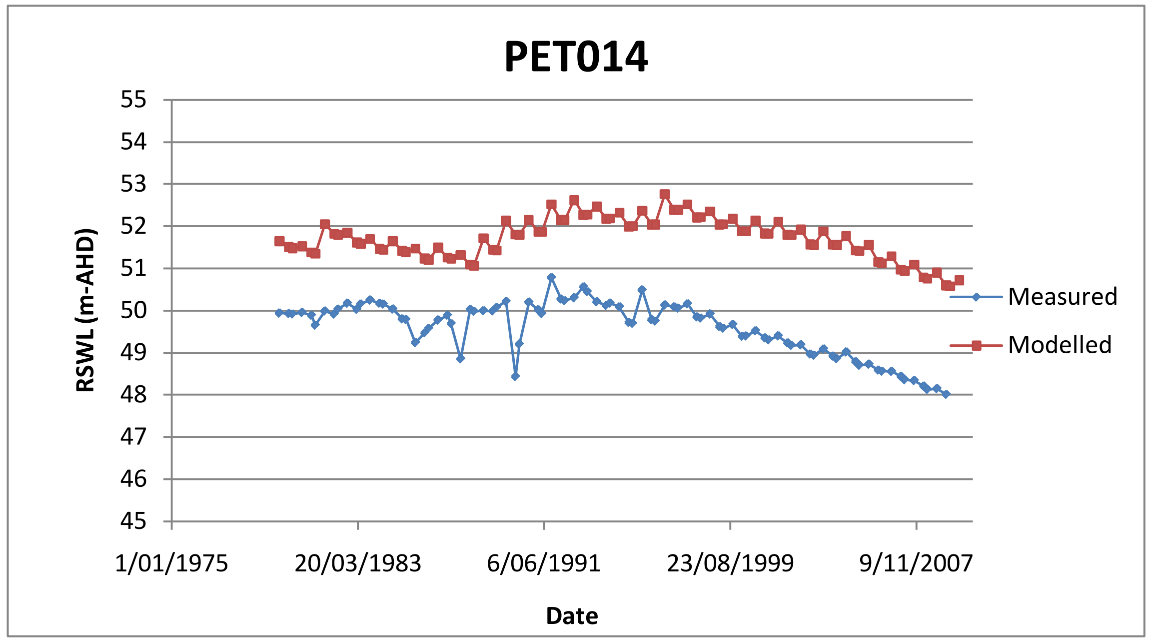


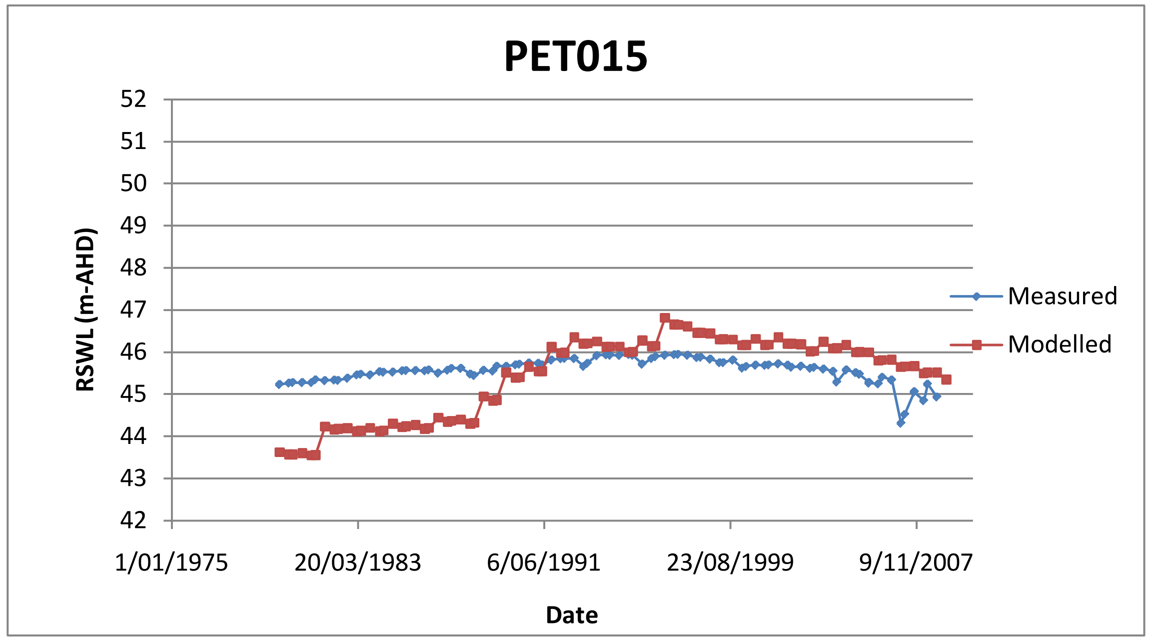
Figure 40. Modelled v. measured water levels in WRG111, where the development of secondary porosity is thought to have an influence on calibration

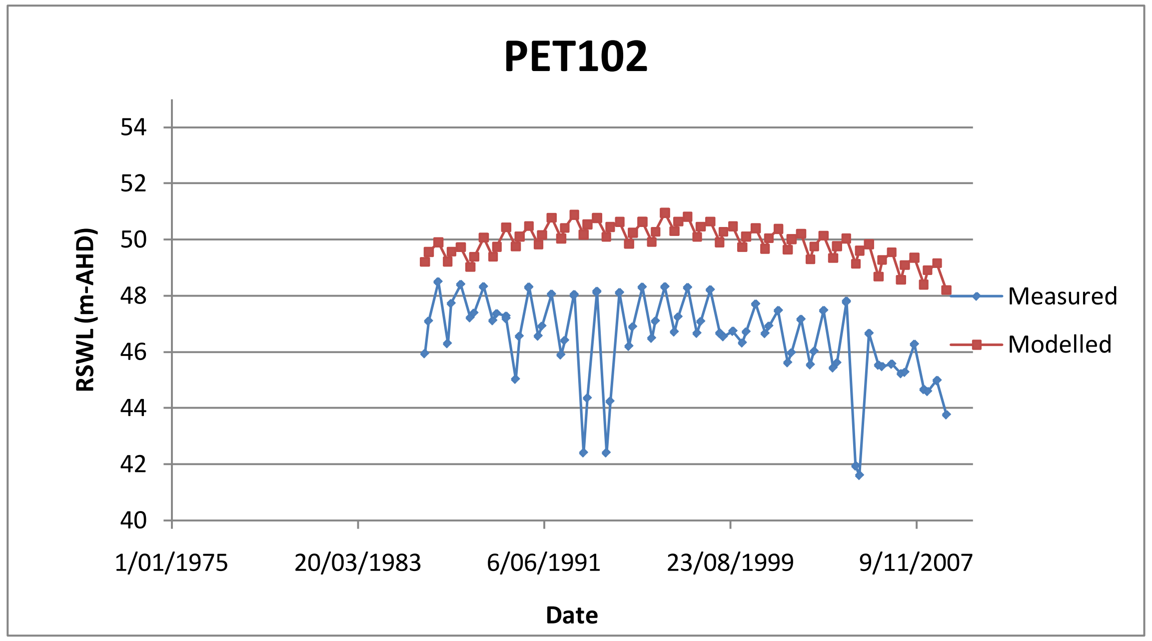
APPENDICES

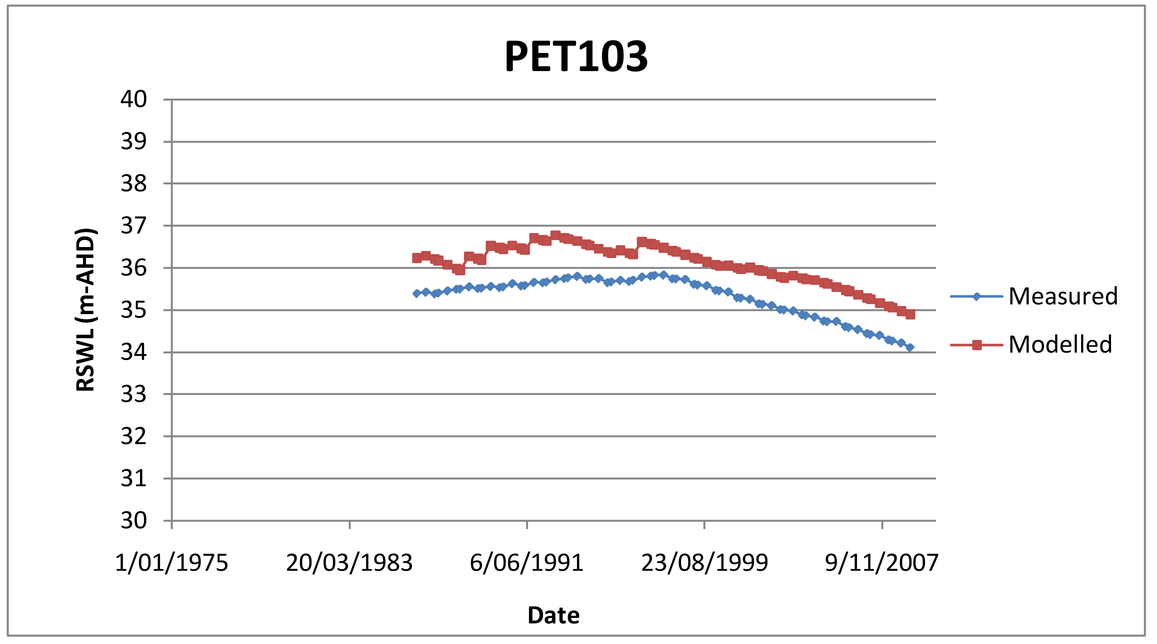
B. TRANSIENT CALIBRATION PLOTS AND WATERTABLE CONTOURS










PET103
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RSWL (m-AHD)
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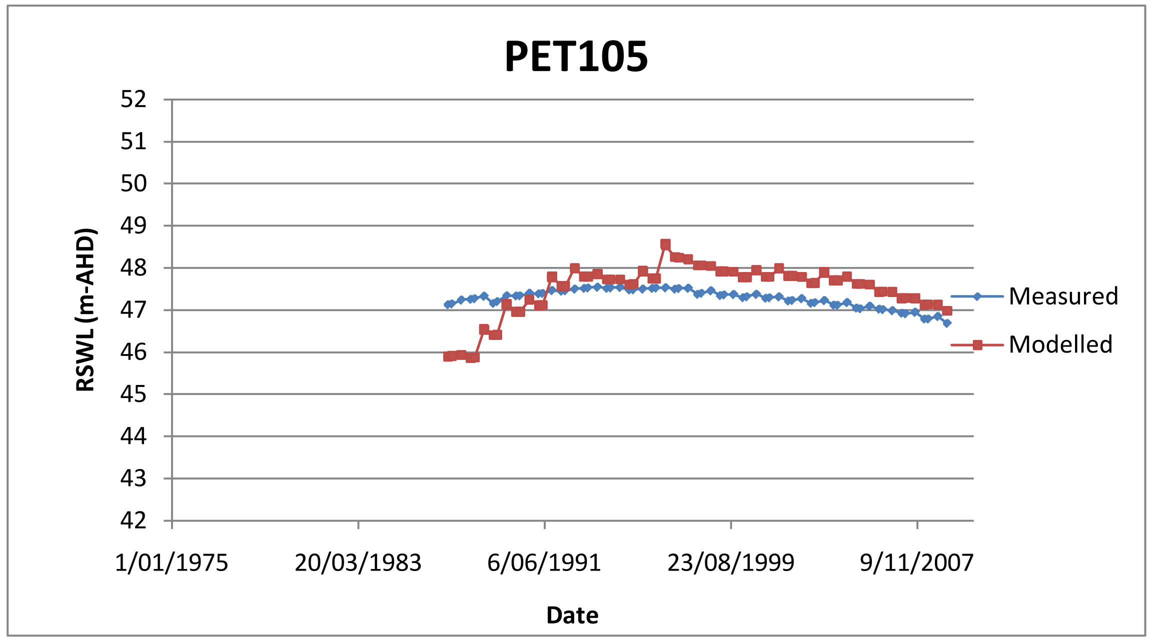
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled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Date
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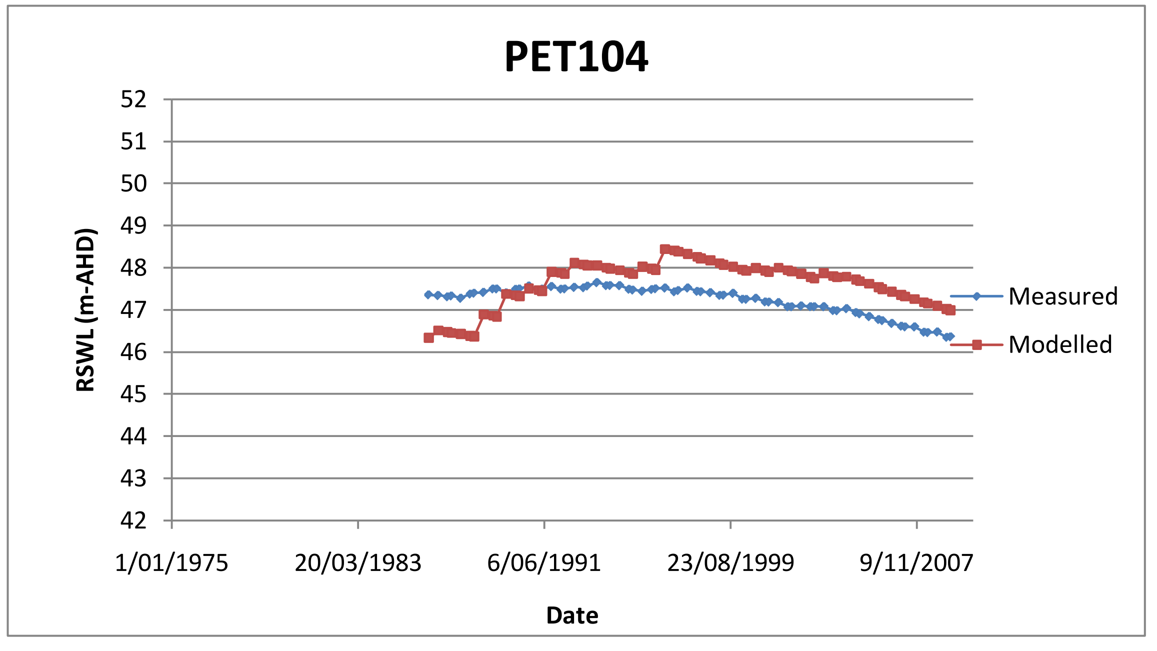
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9/11/2007
Date
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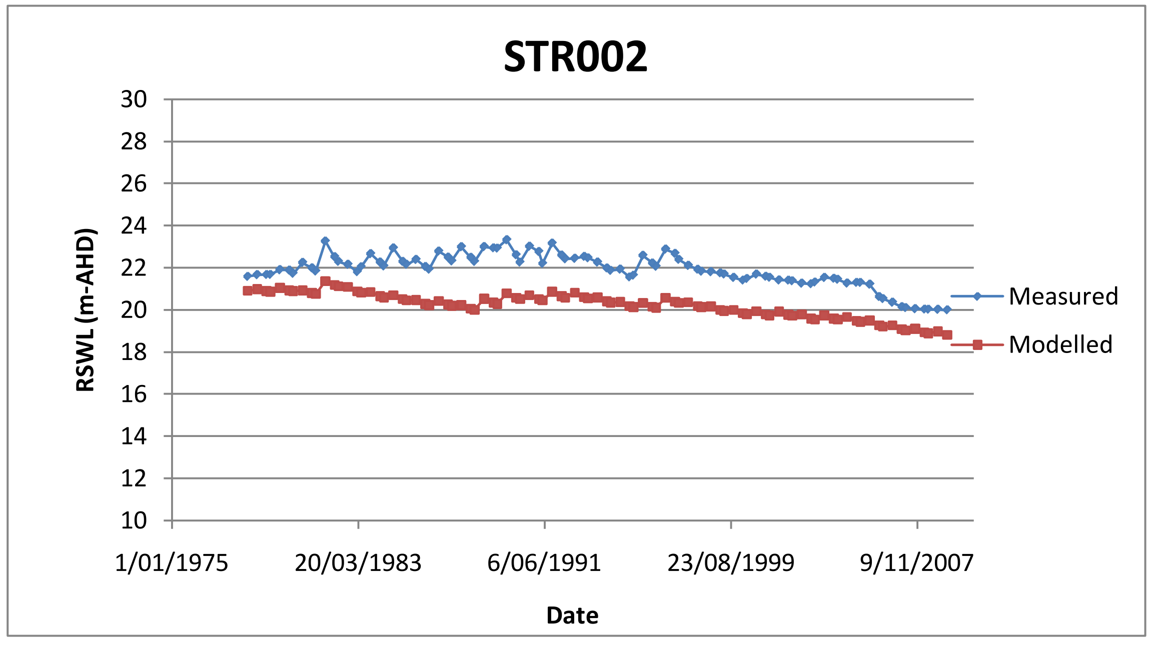
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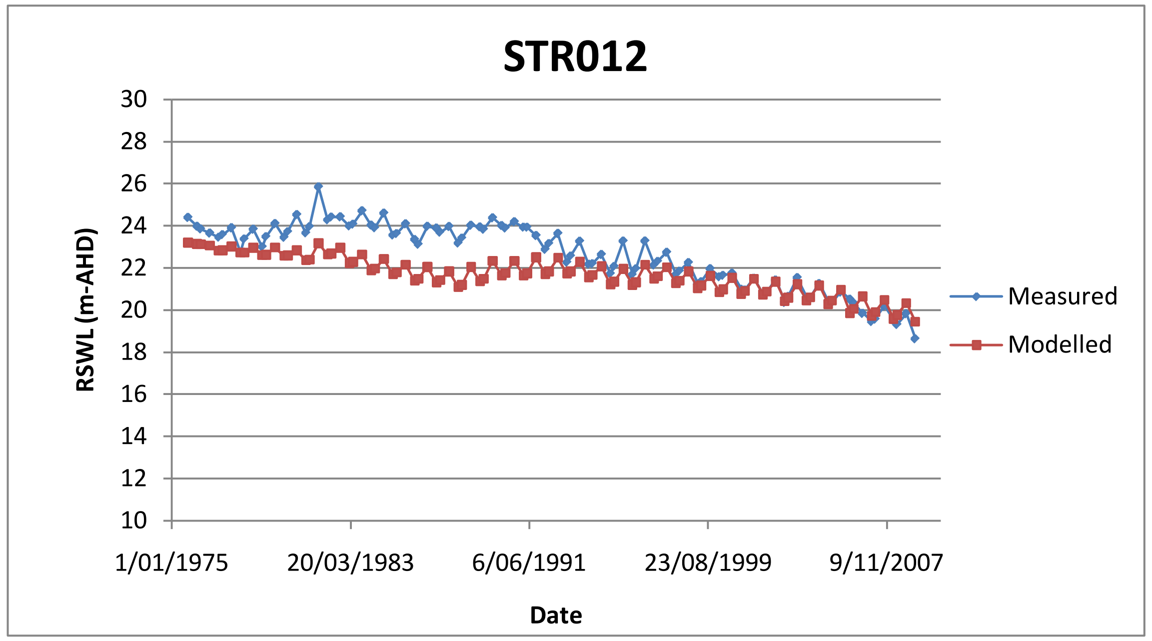
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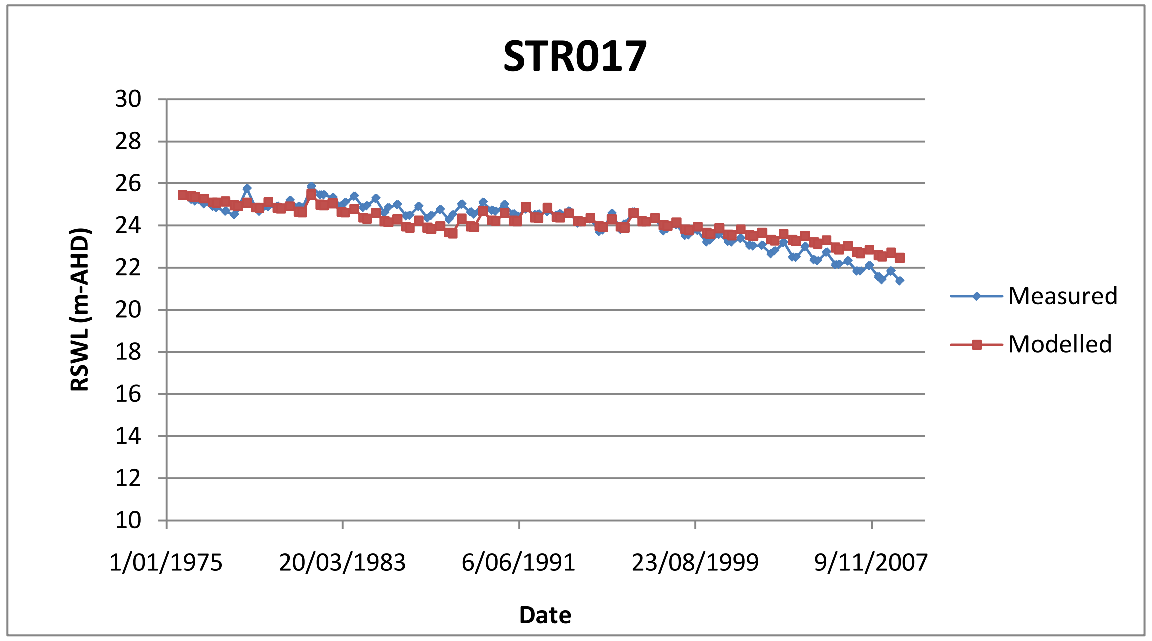
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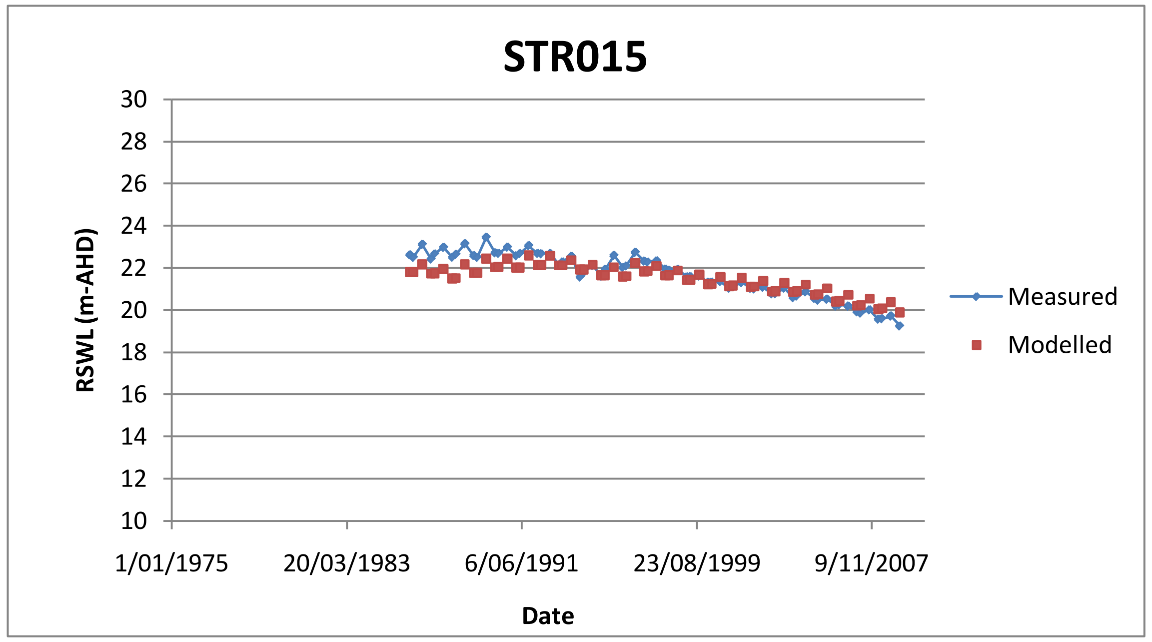
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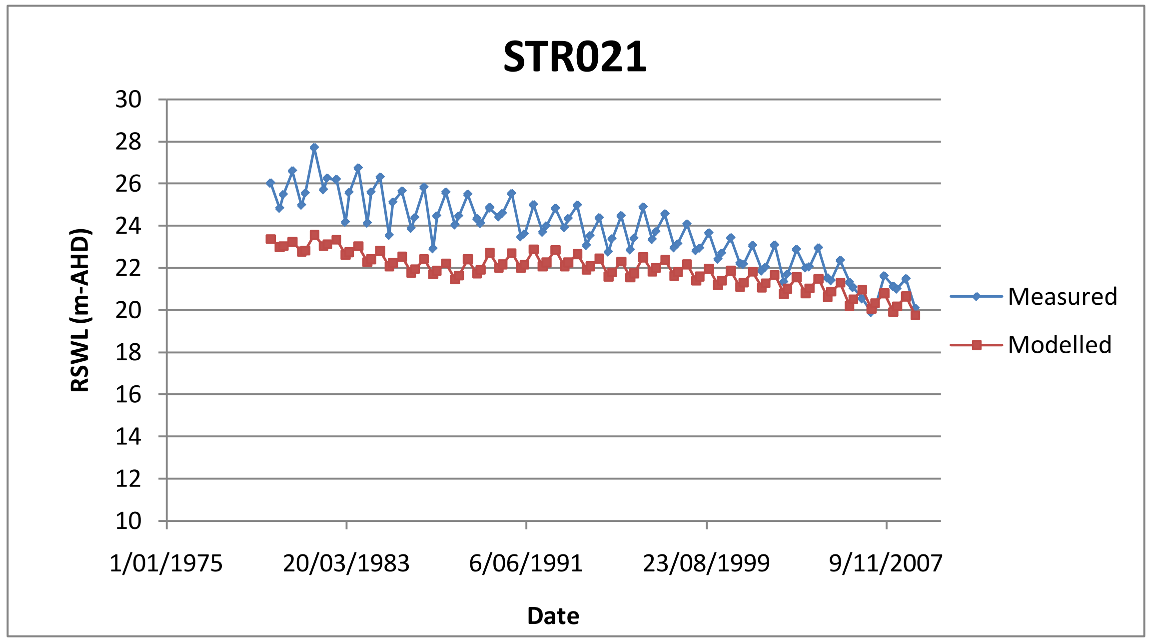
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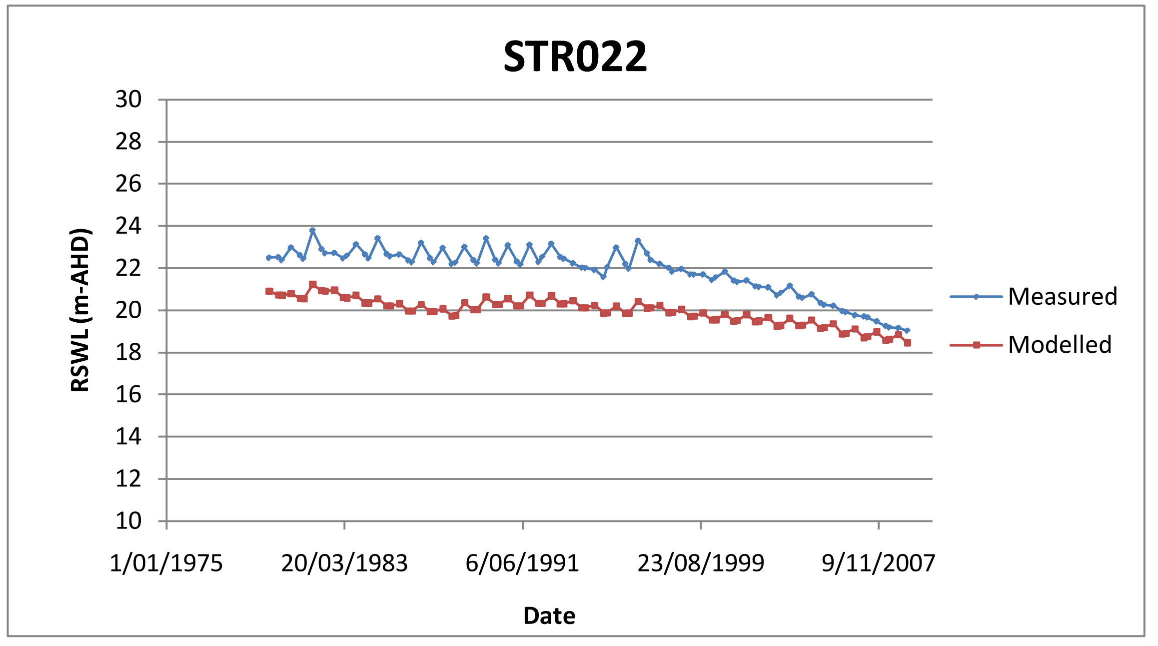
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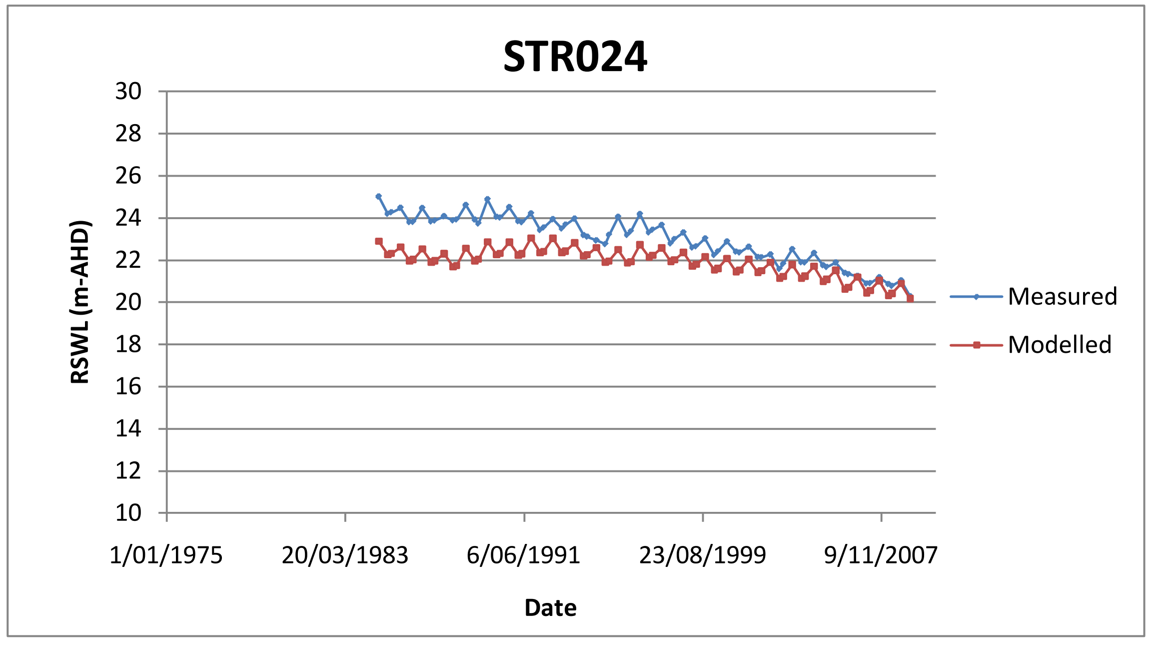
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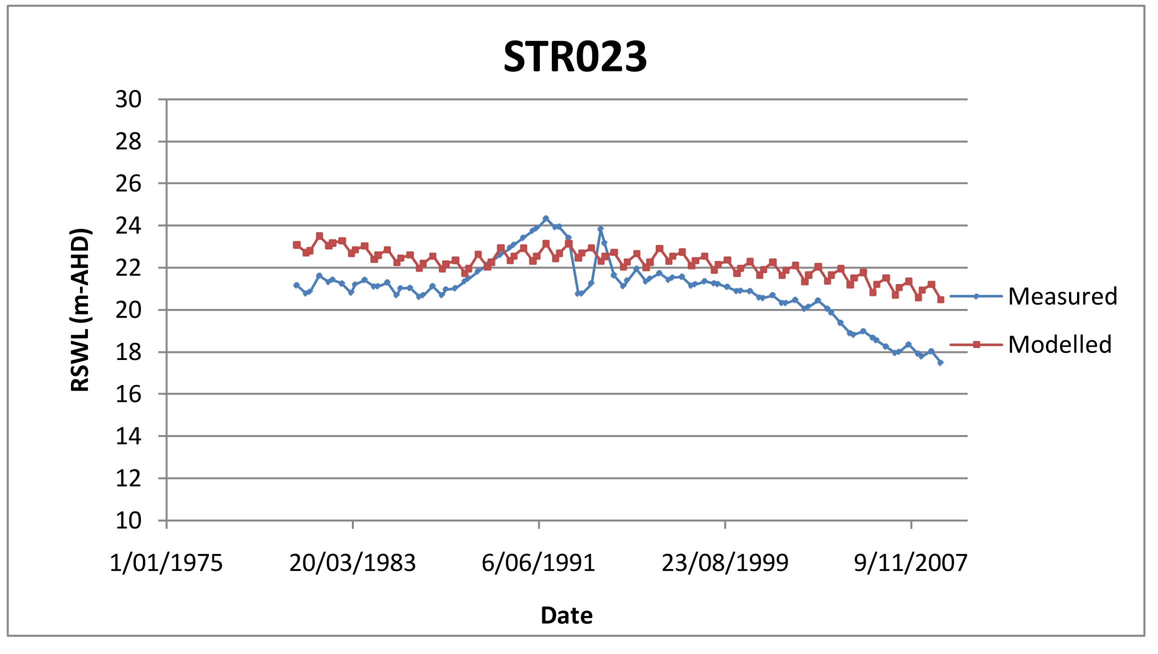
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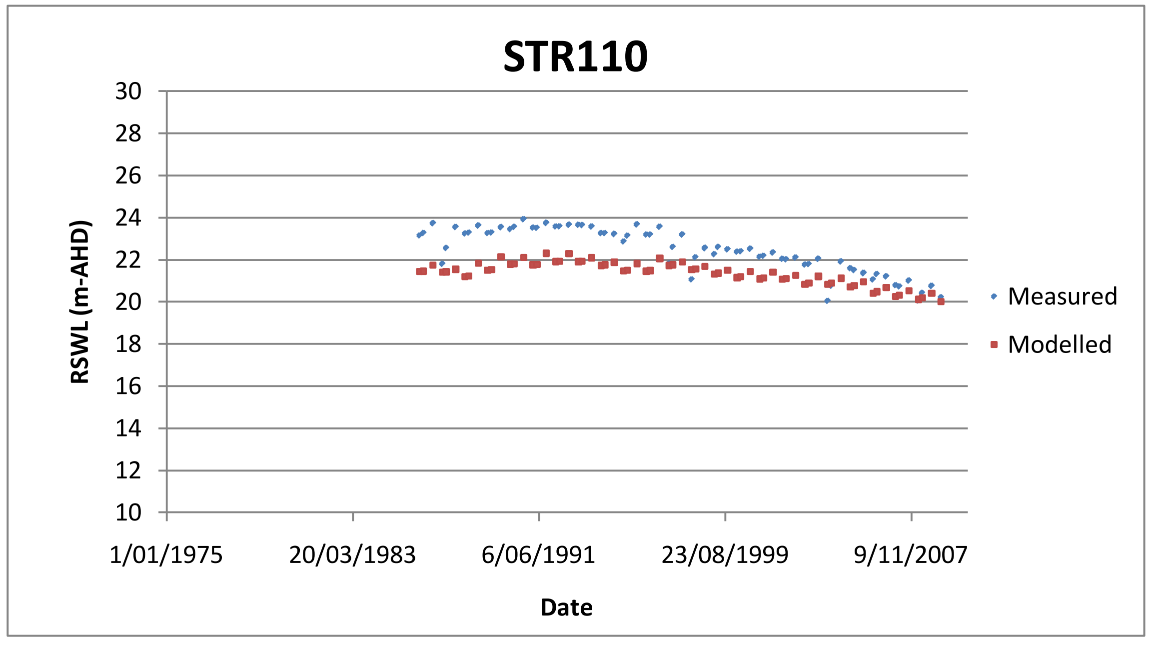
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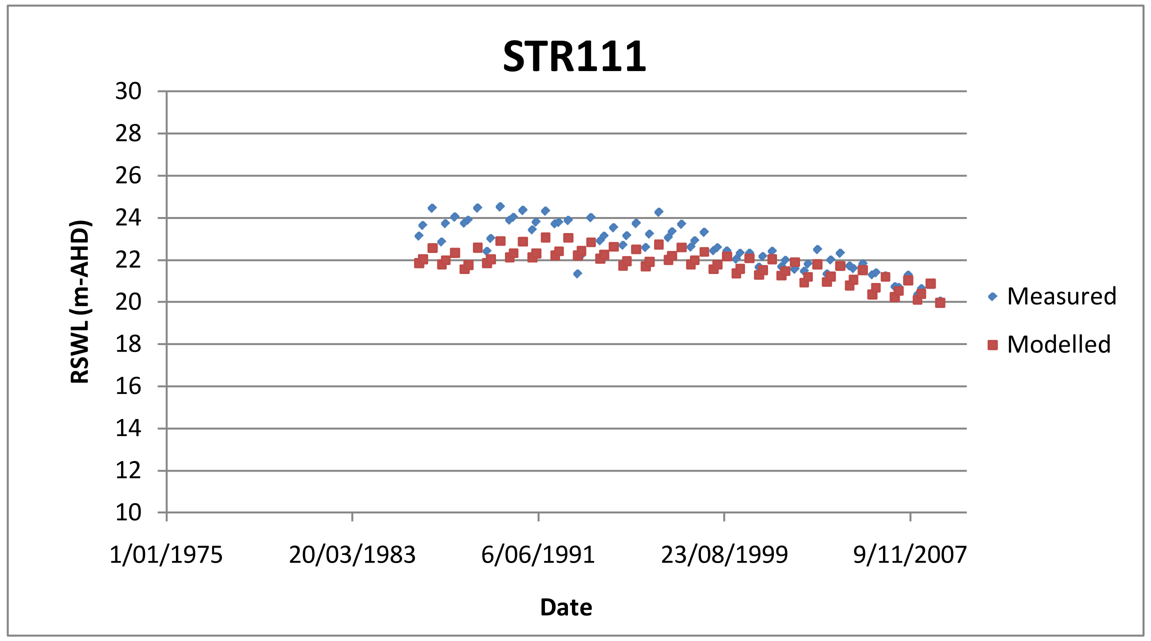
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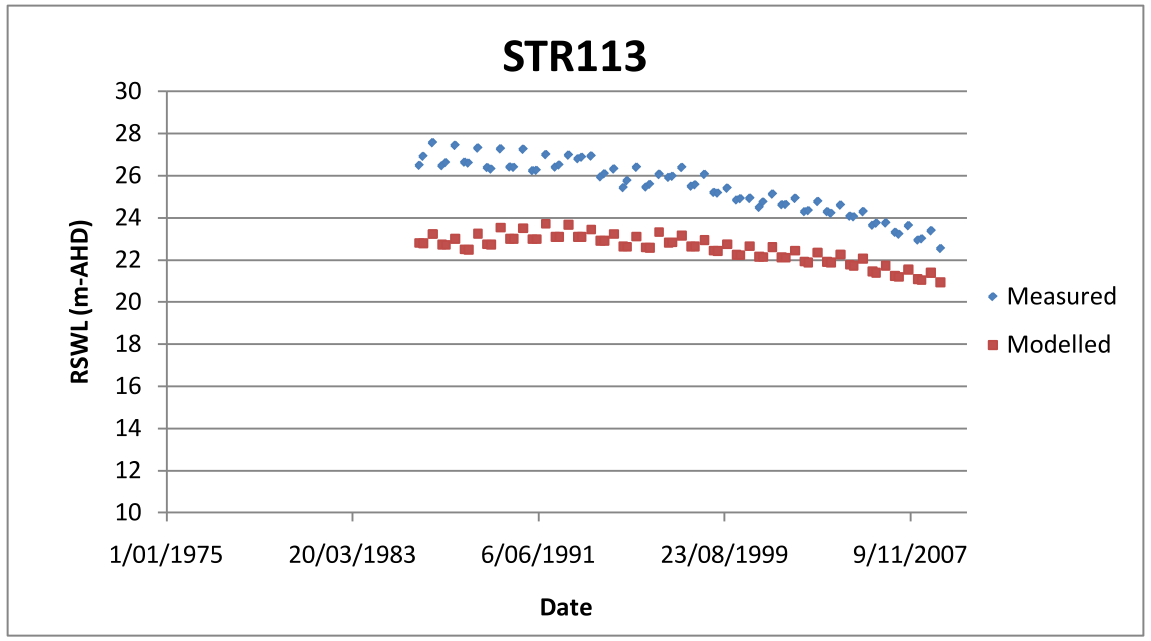
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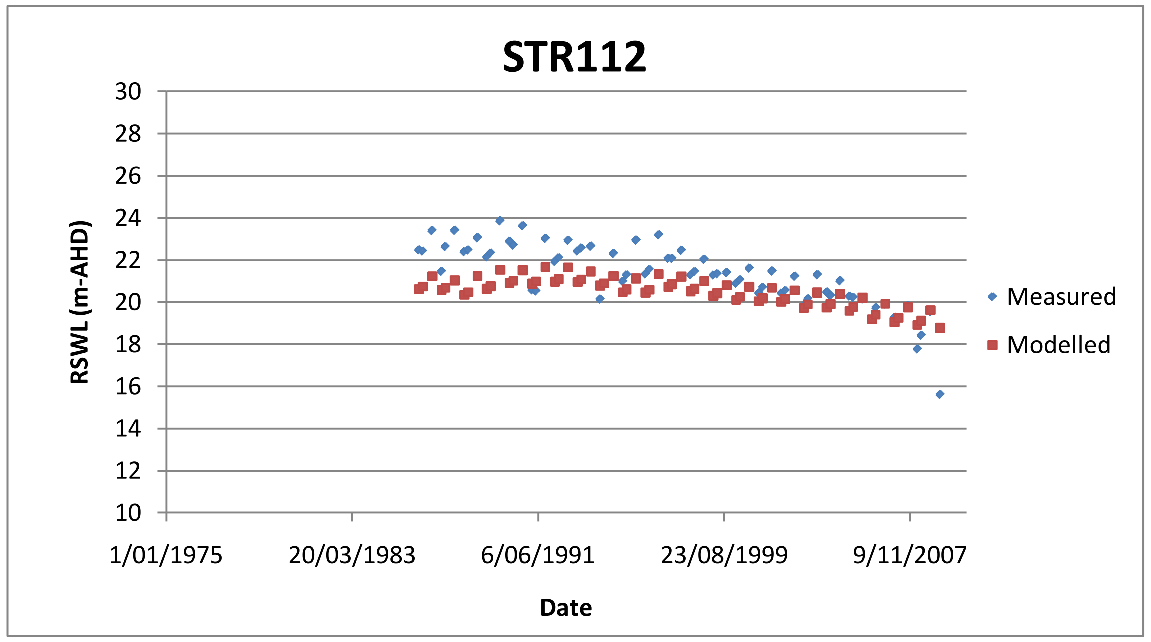
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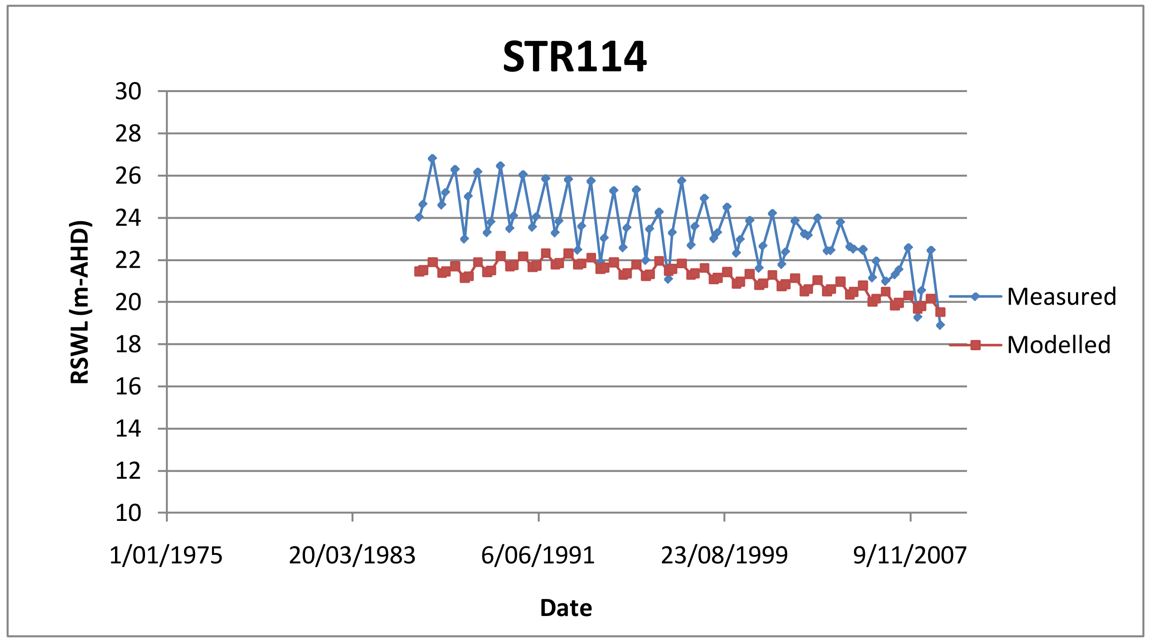
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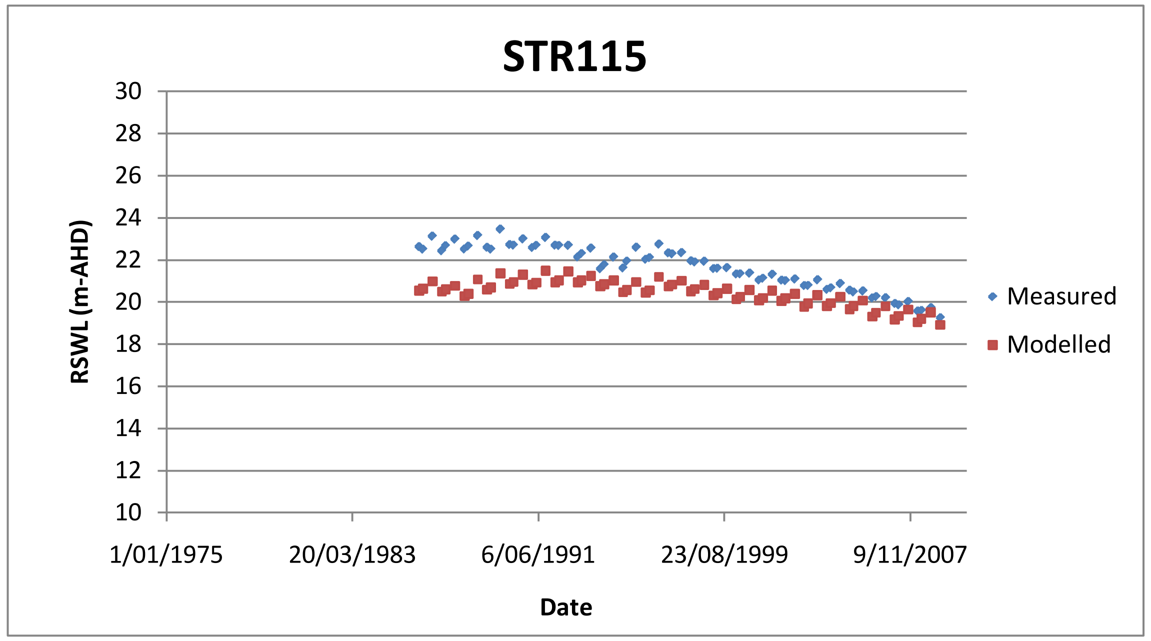
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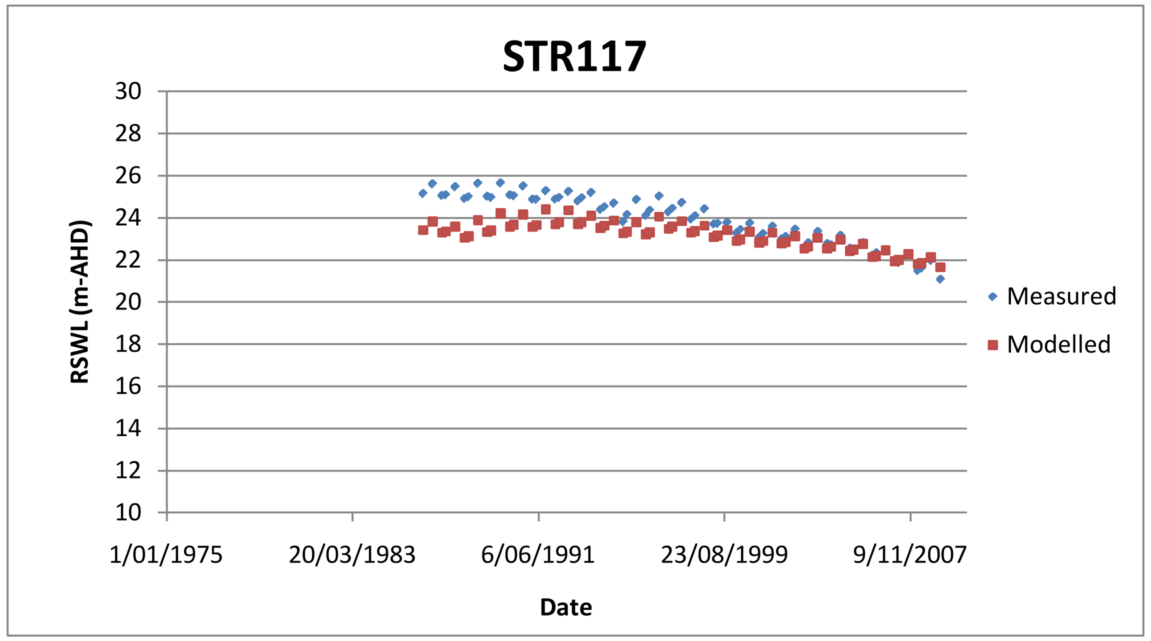
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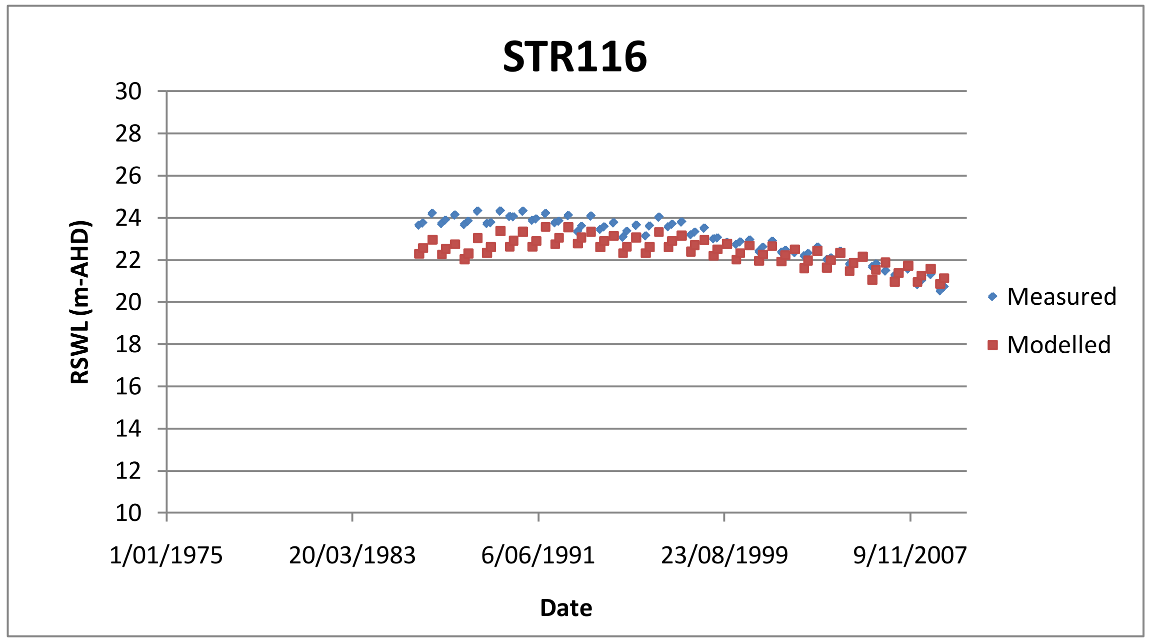
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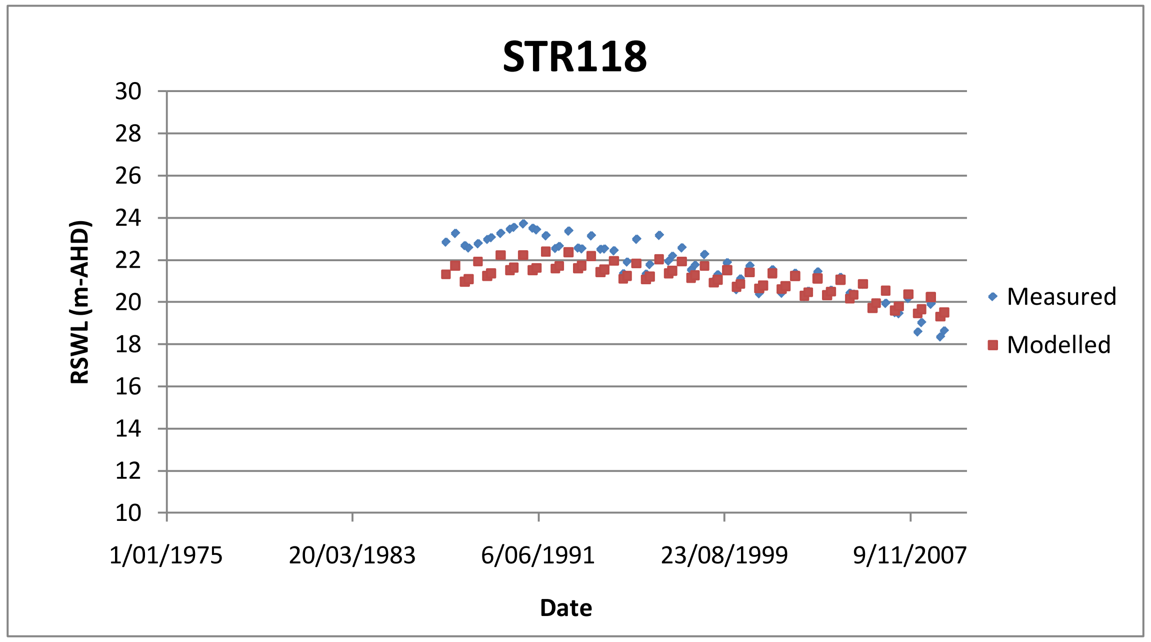
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Date
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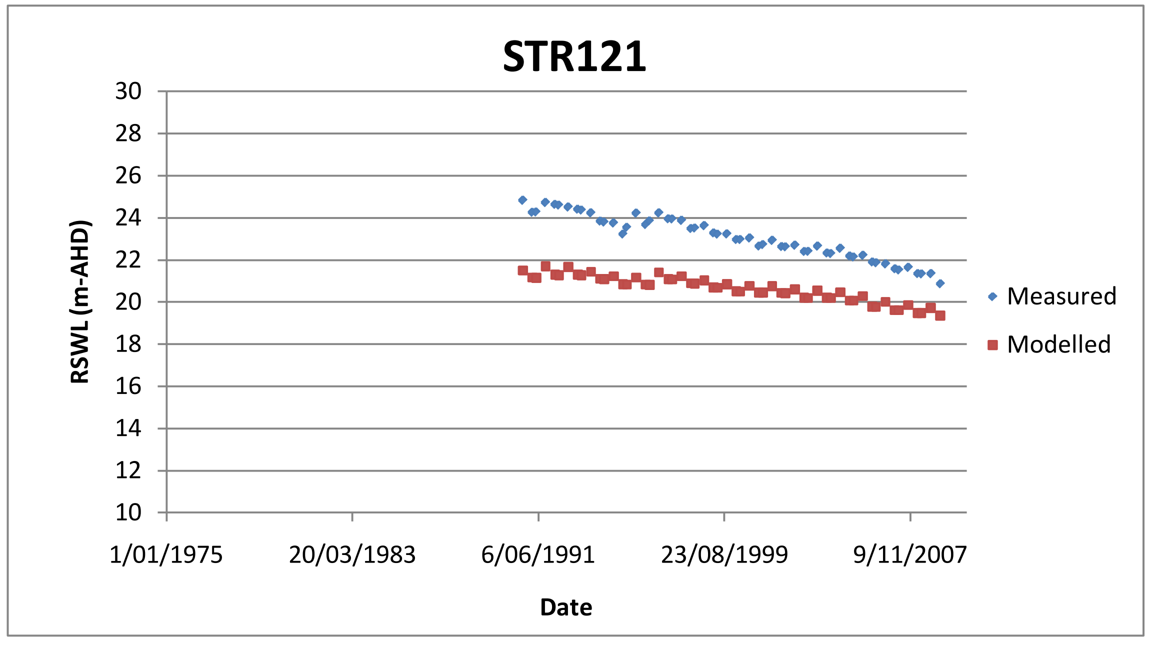
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Date
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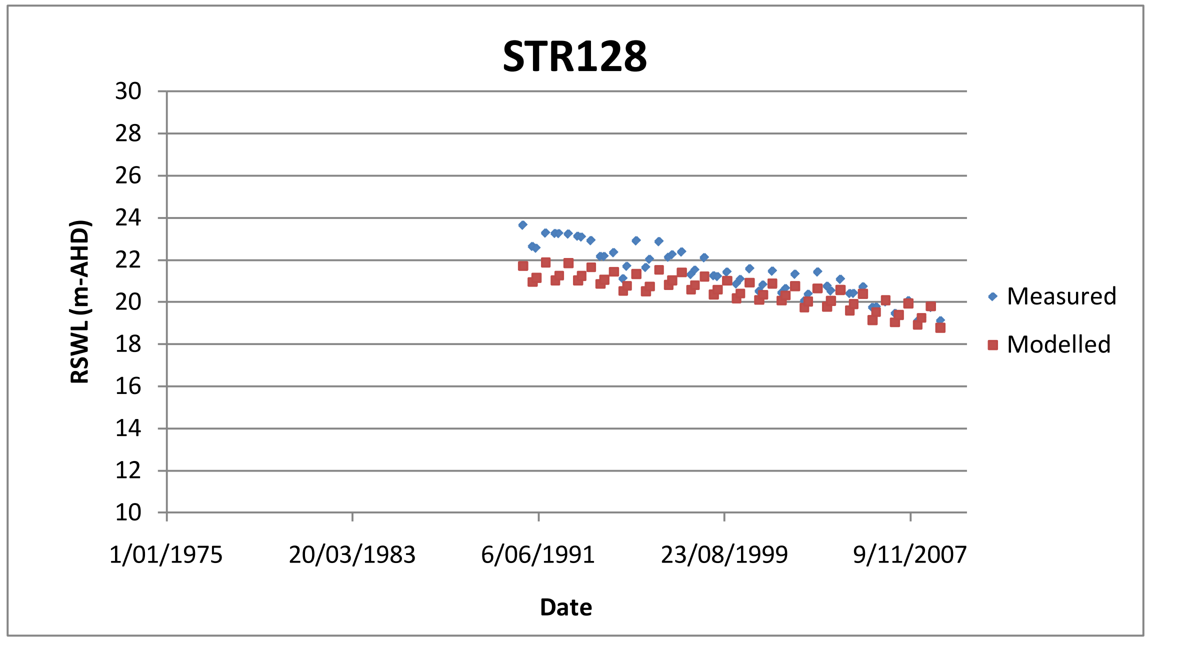
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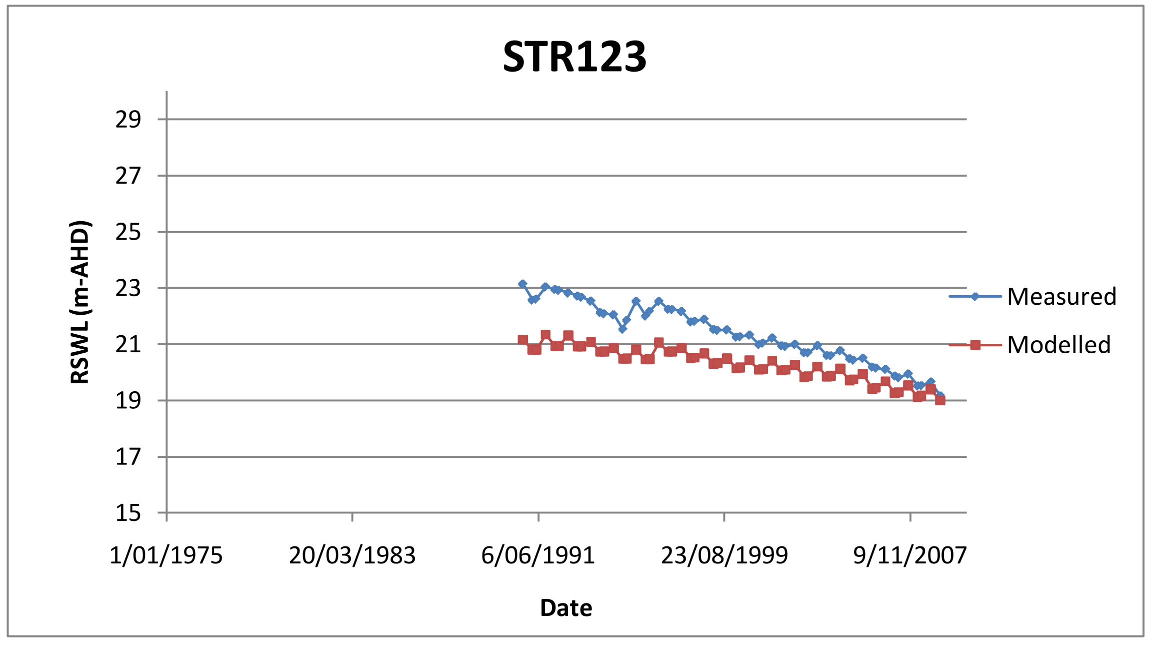
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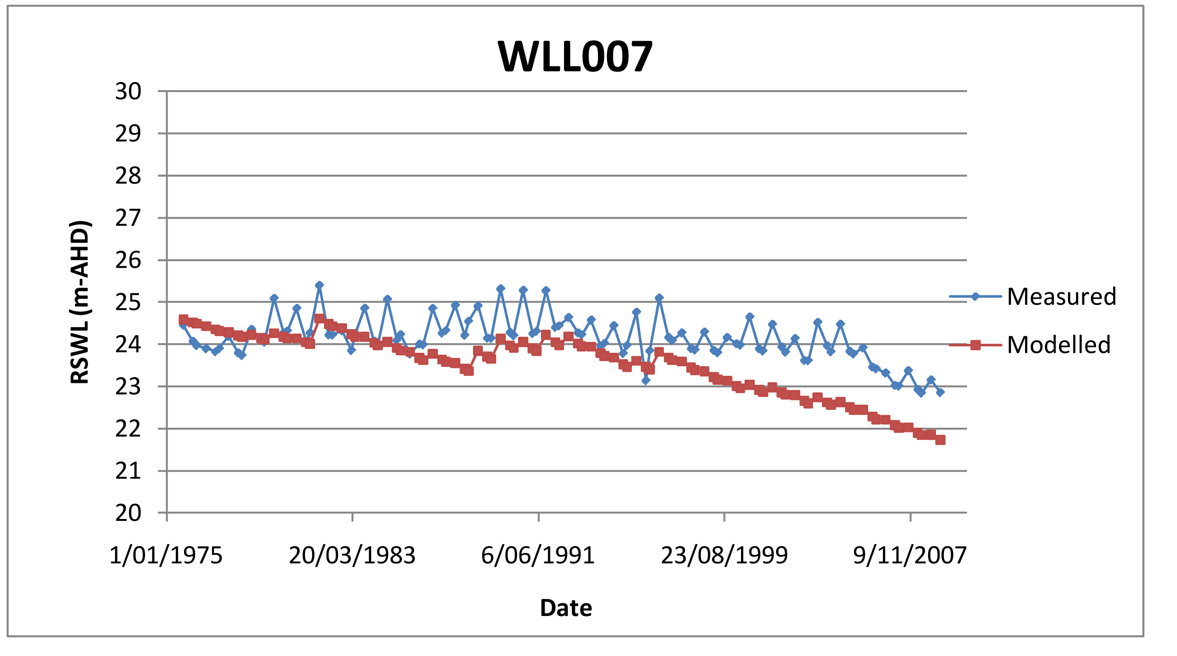
Date
Measured
Modelled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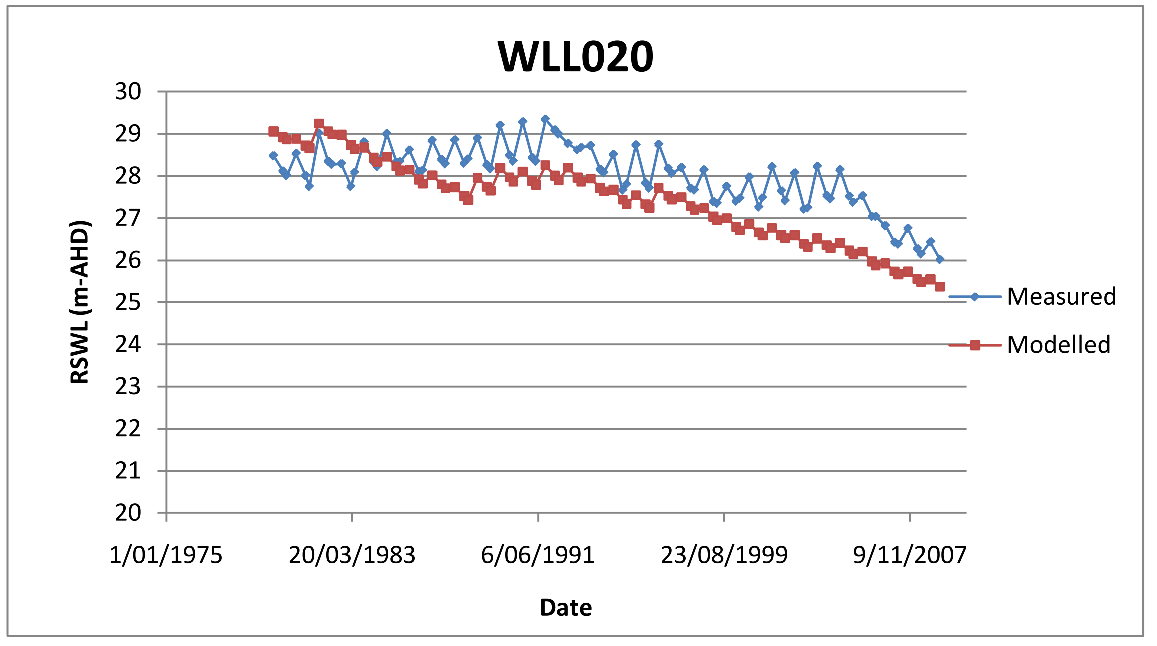
9/11/2007
Date
Measured
Modelled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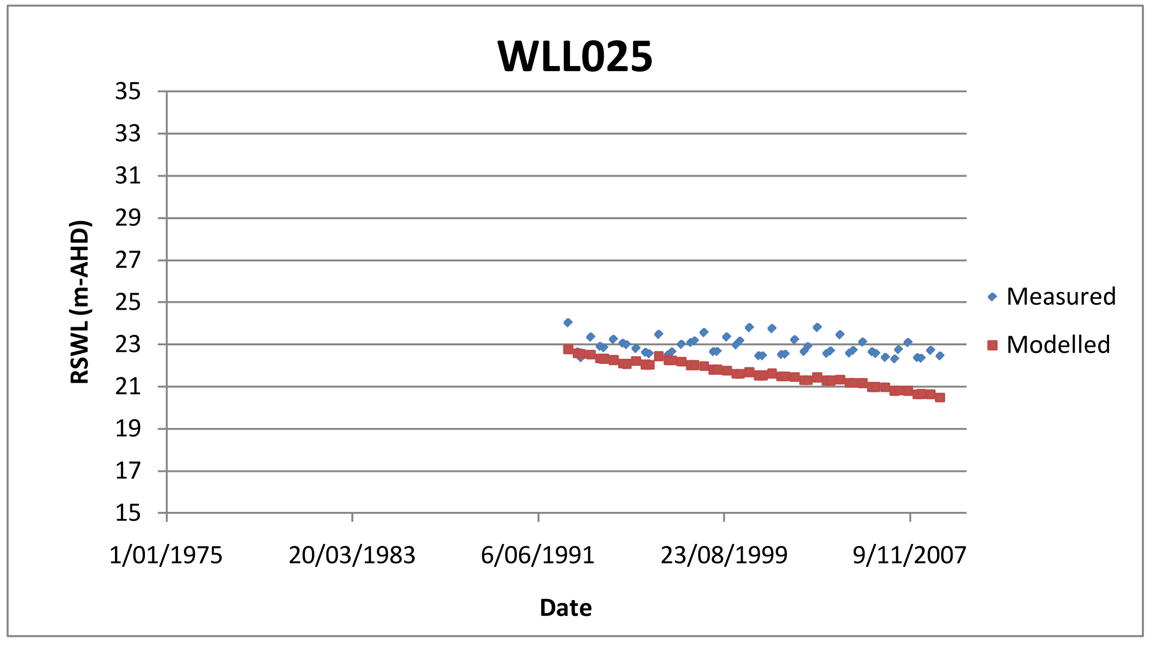
Date
Measured
Modelled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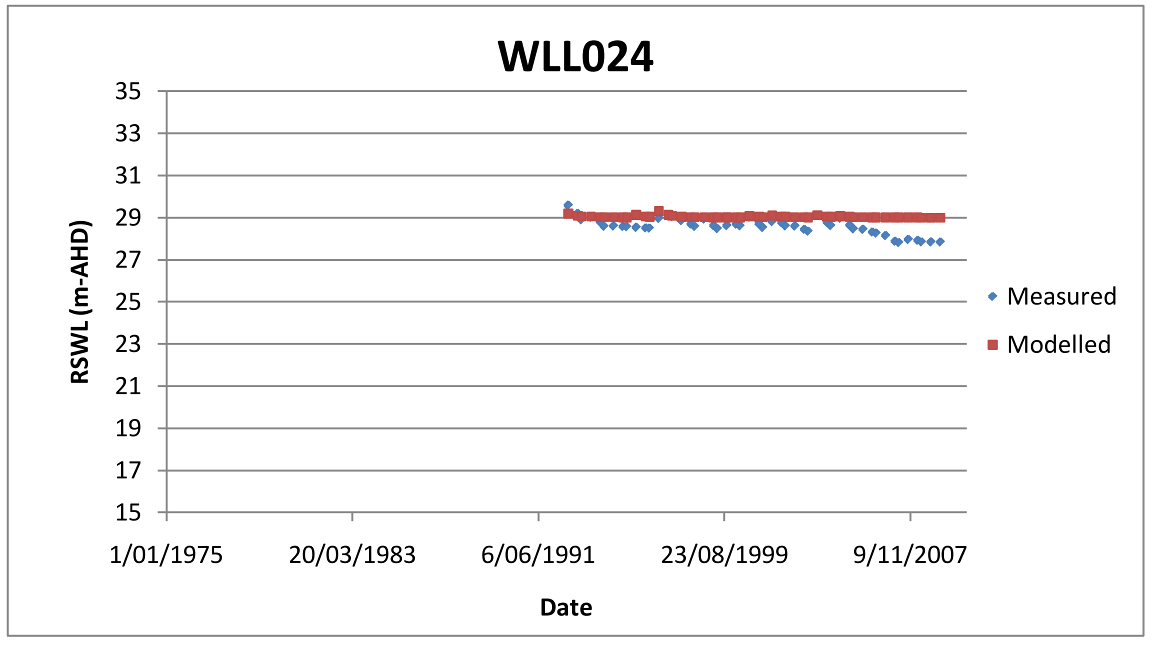
23/08/1999
9/11/2007
Date
Measured
Modelled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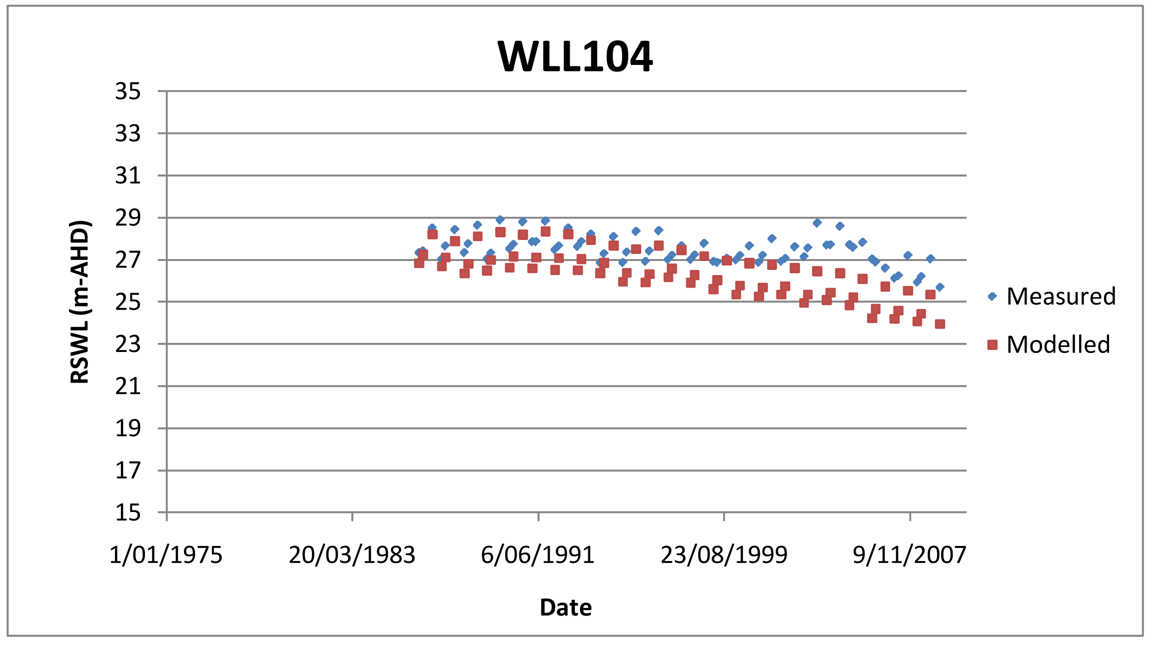
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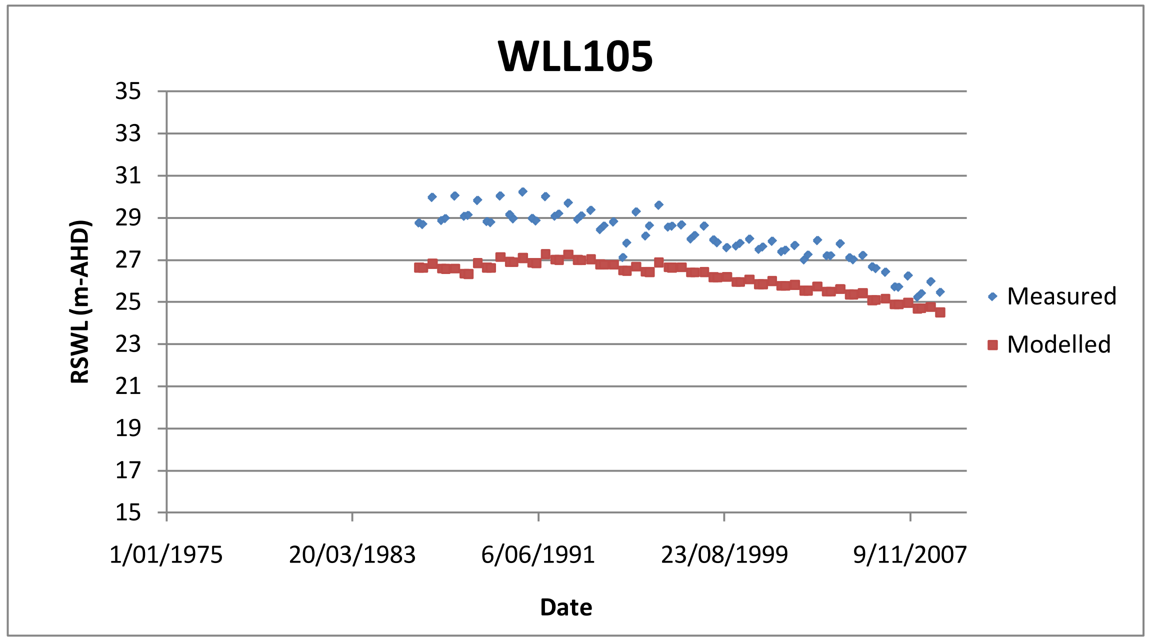
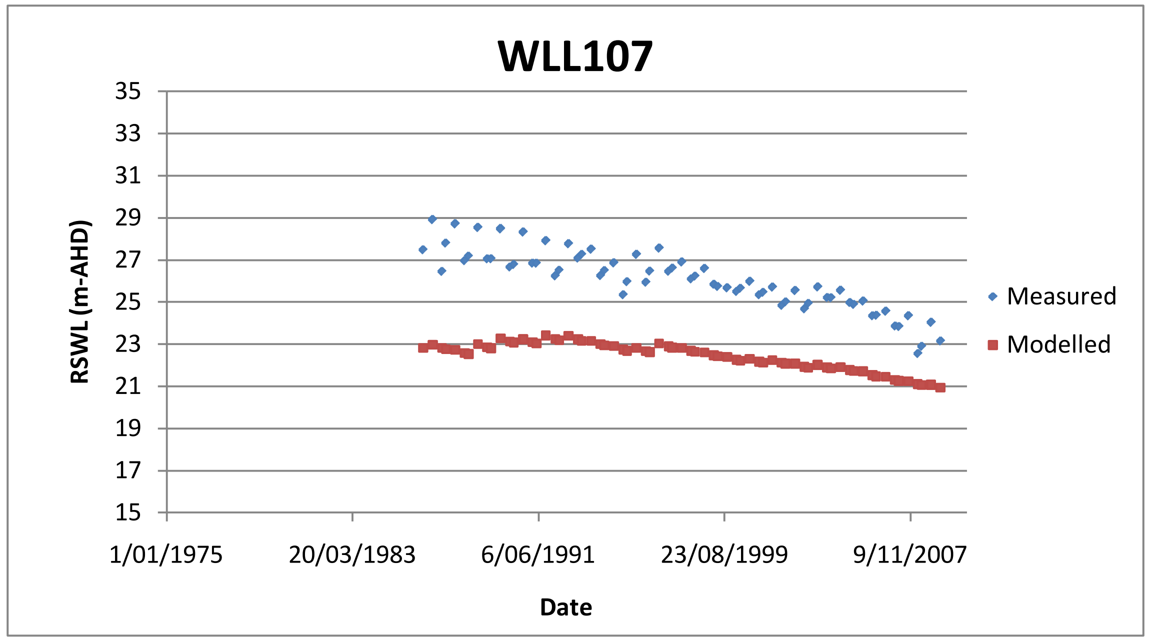
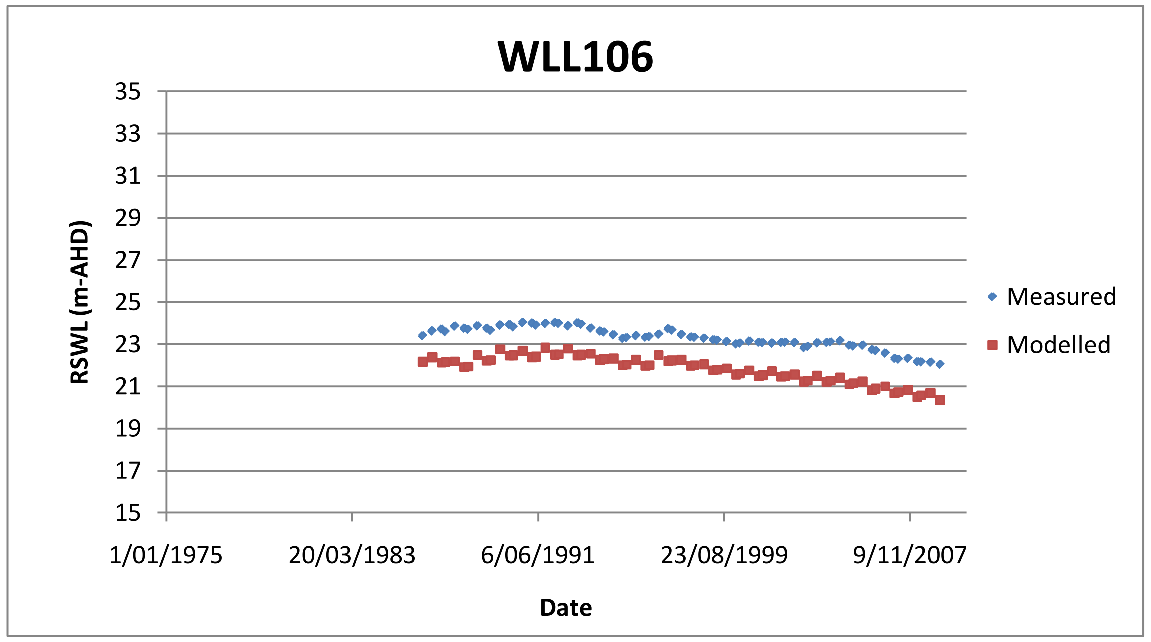
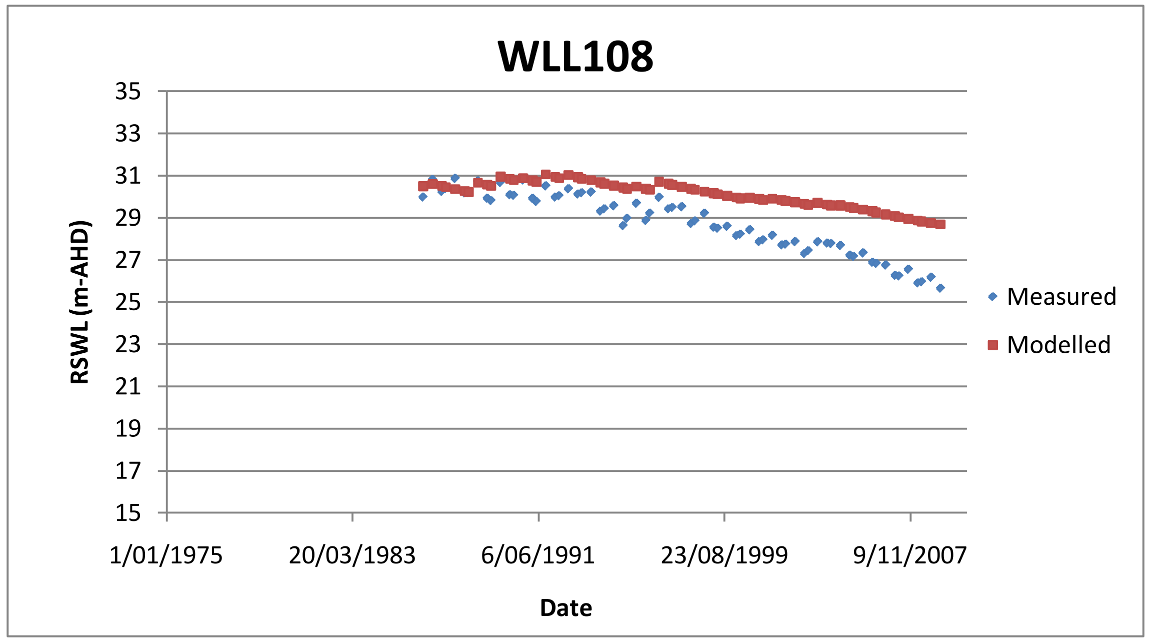
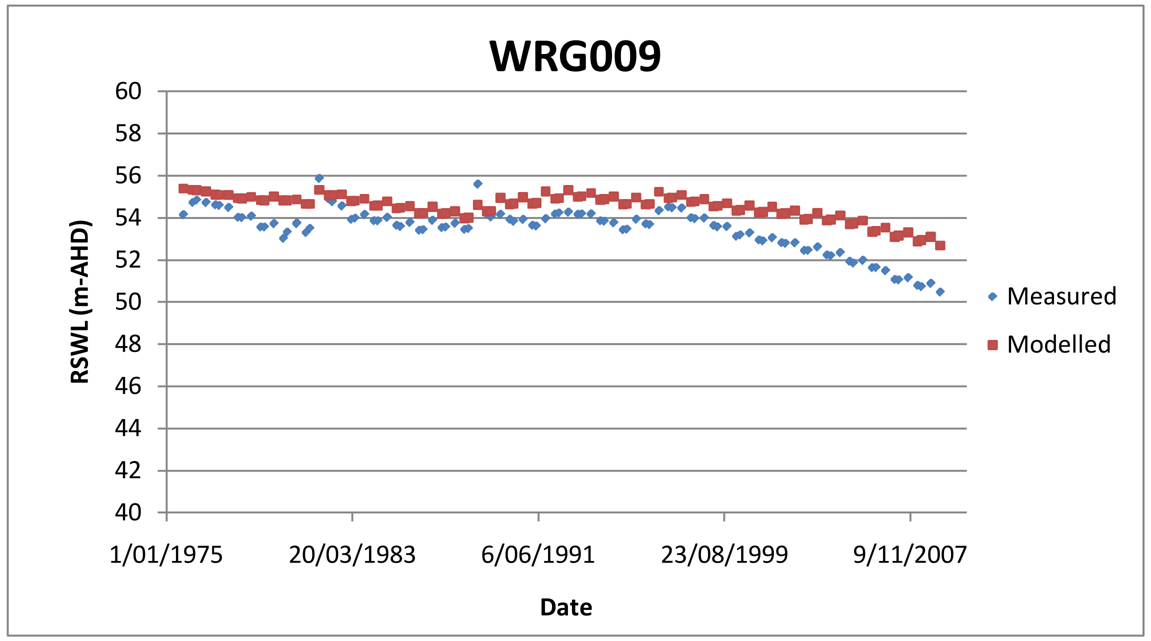
23/08/1999
9/11/2007
Date
Measured
Modelled

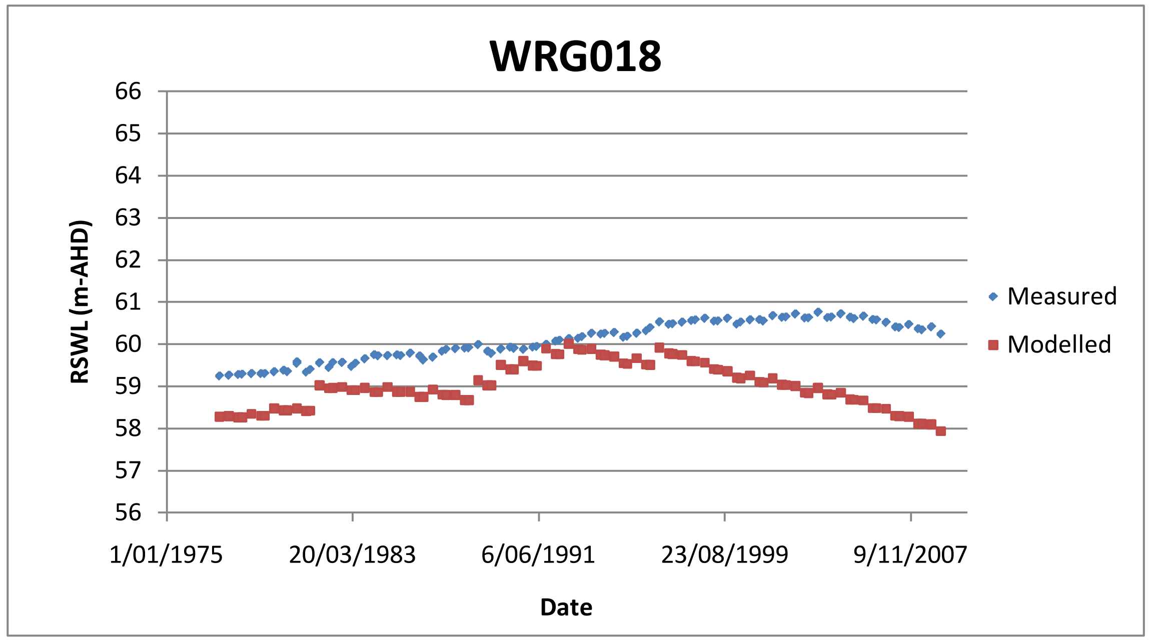

WLL105
35
33
31
29
27
25
23
21
19
17
15
RSWL (m-AHD)
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

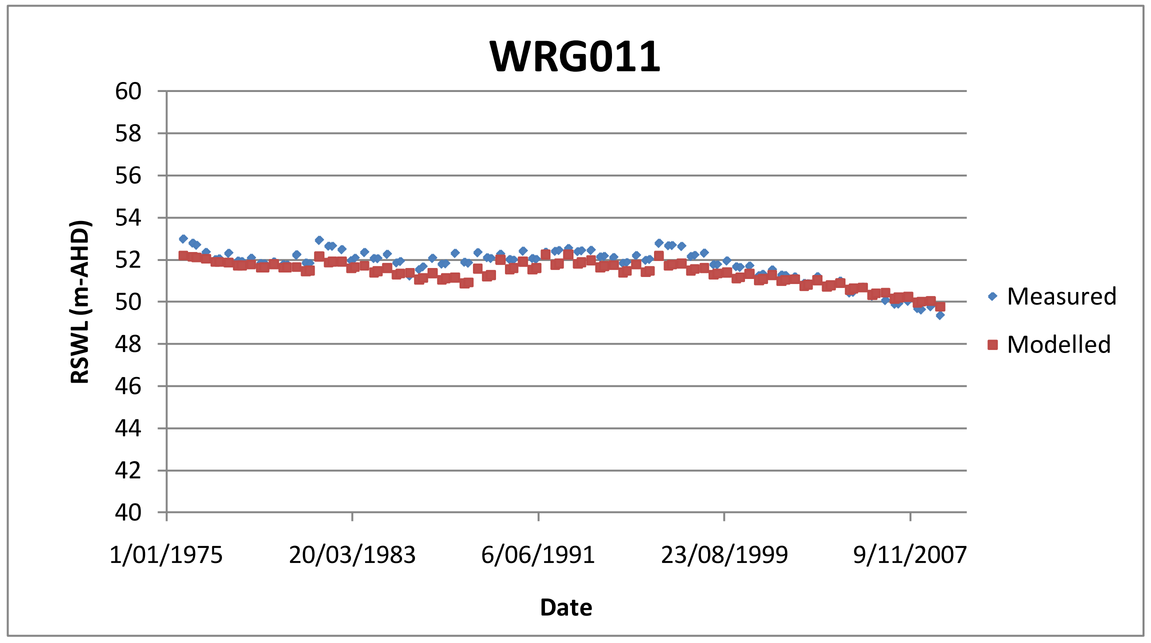

WLL107
35
33
31
29
27
25
23
21
19
17
15
RSWL (m-AHD)
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

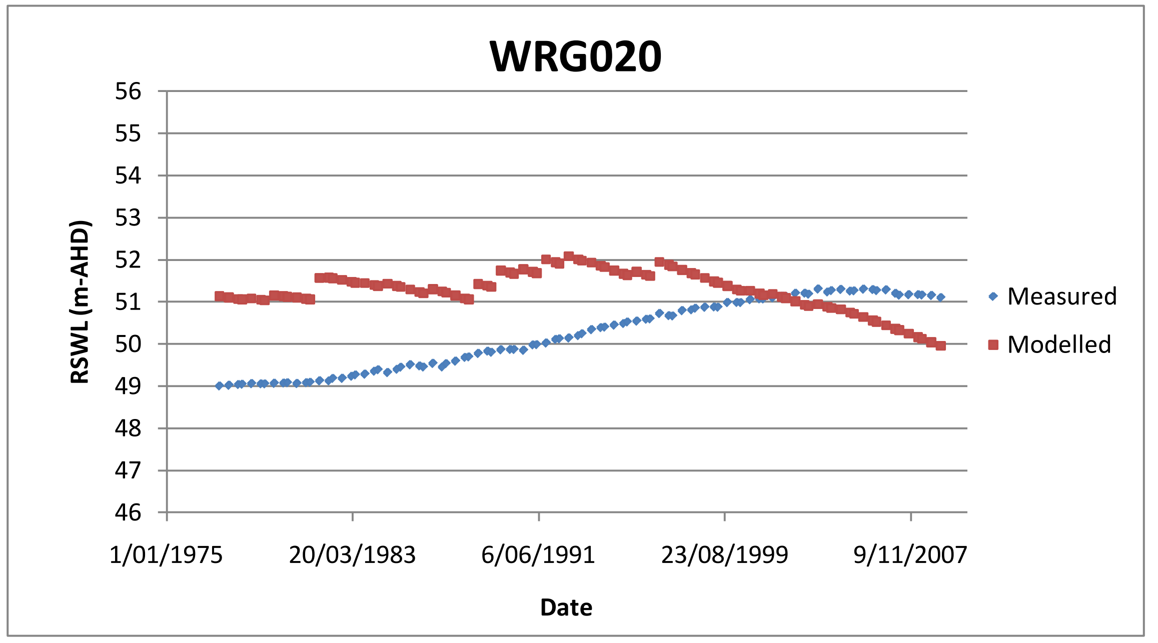

WLL106
35
33
31
29
27
25
23
21
19
17
15
RSWL (m-AHD)
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

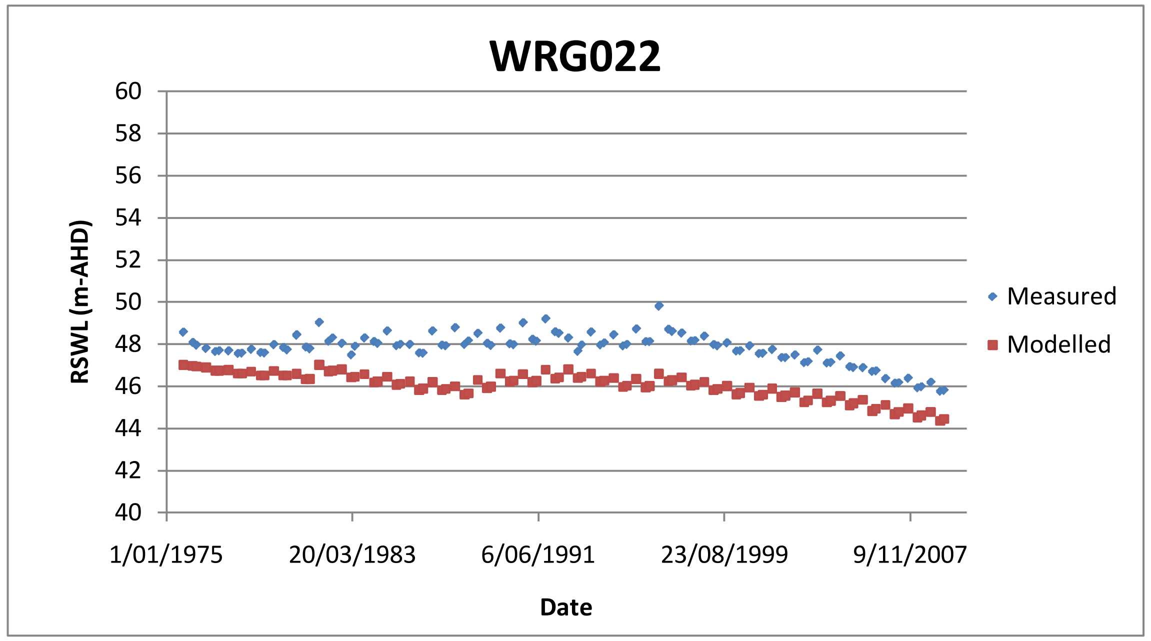

WLL108
35
33
31
29
27
25
23
21
19
17
15
RSWL (m-AHD)
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

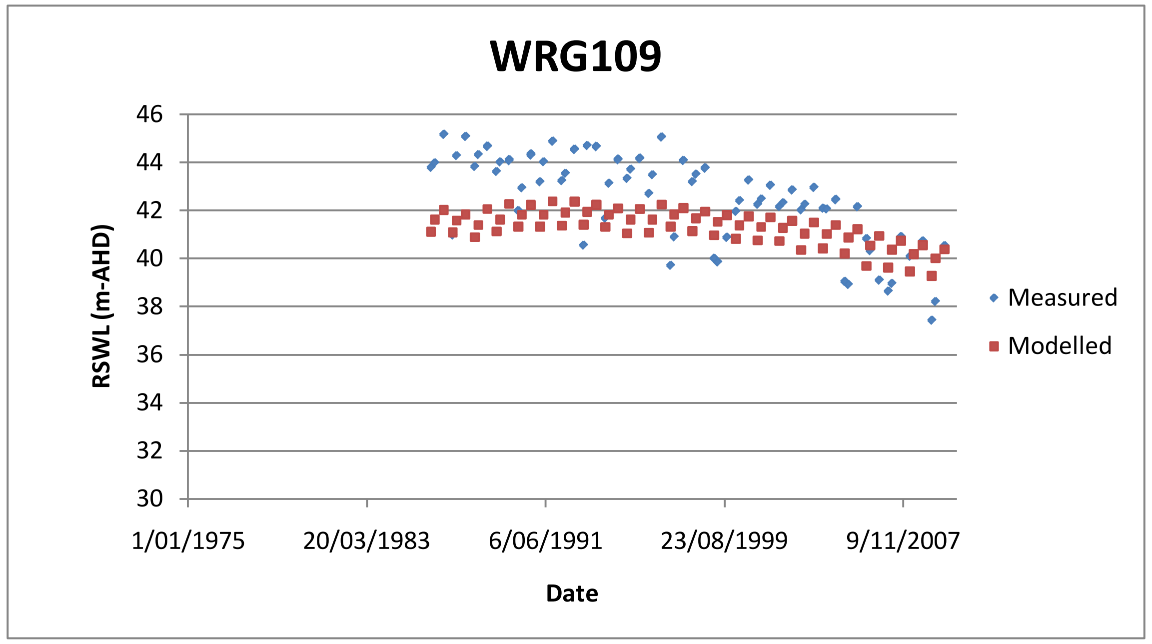

WRG009
60
58
56
54
52
50
48
46
44
42
40
RSWL (m-AHD)
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

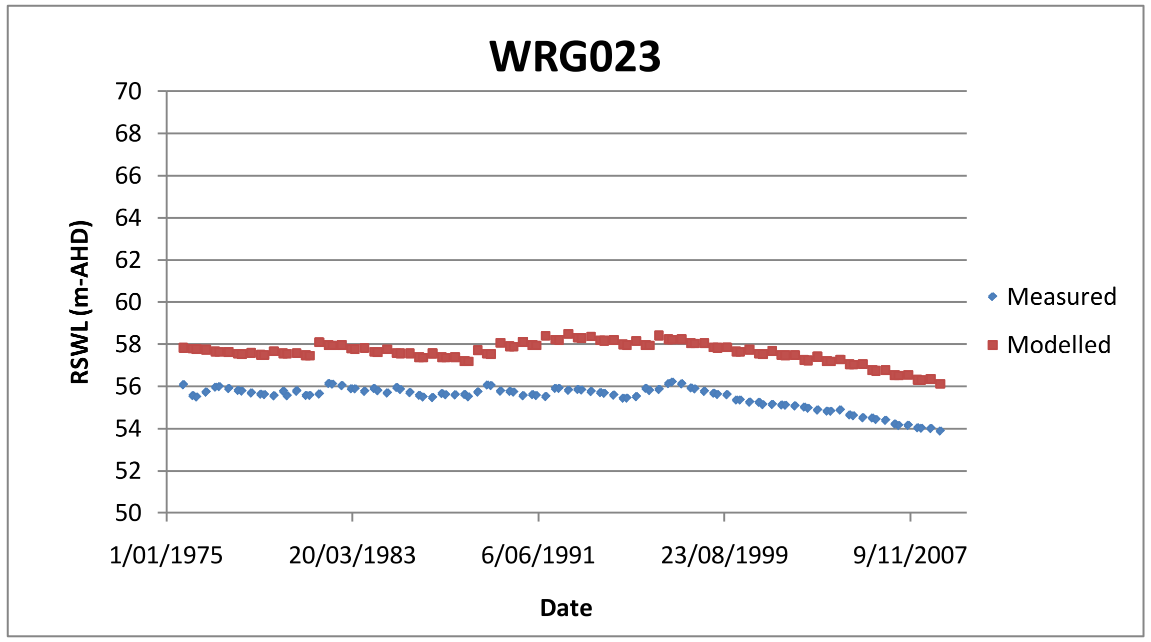

WRG018
66
65
64
63
62
61
60
59
58
57
56
RSWL (m-AHD)
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

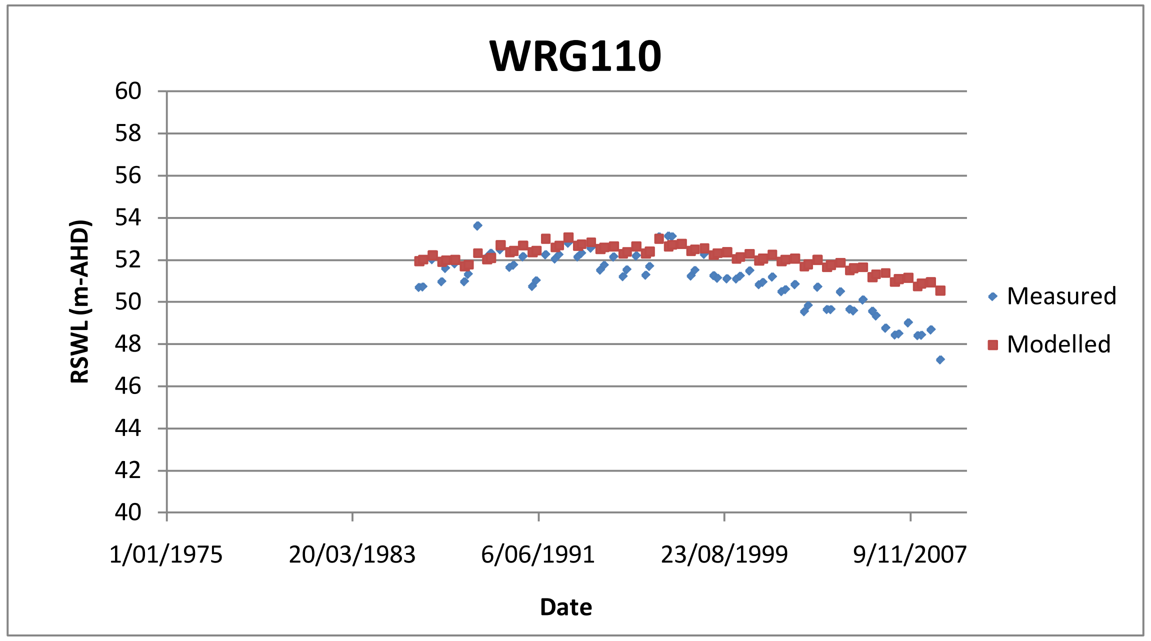

WRG011
60
58
56
54
52
50
48
46
44
42
40
RSWL (m-AHD)
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

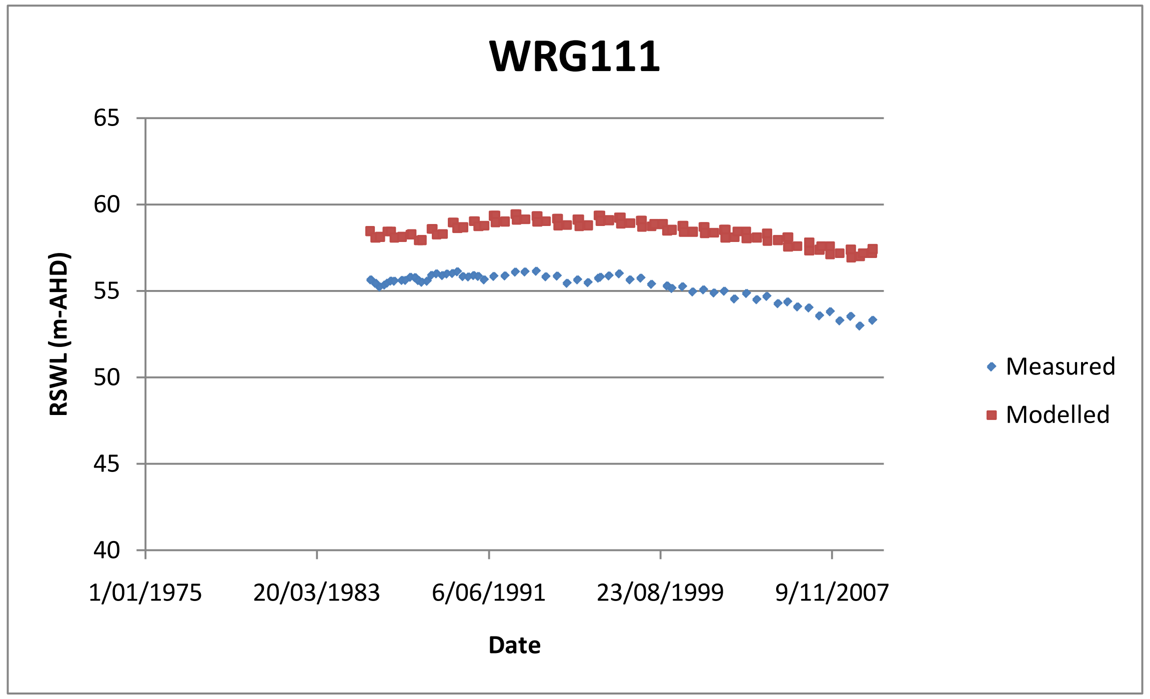

WRG020
56
55
54
53
52
51
50
49
48
47
46
RSWL (m-AHD)
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

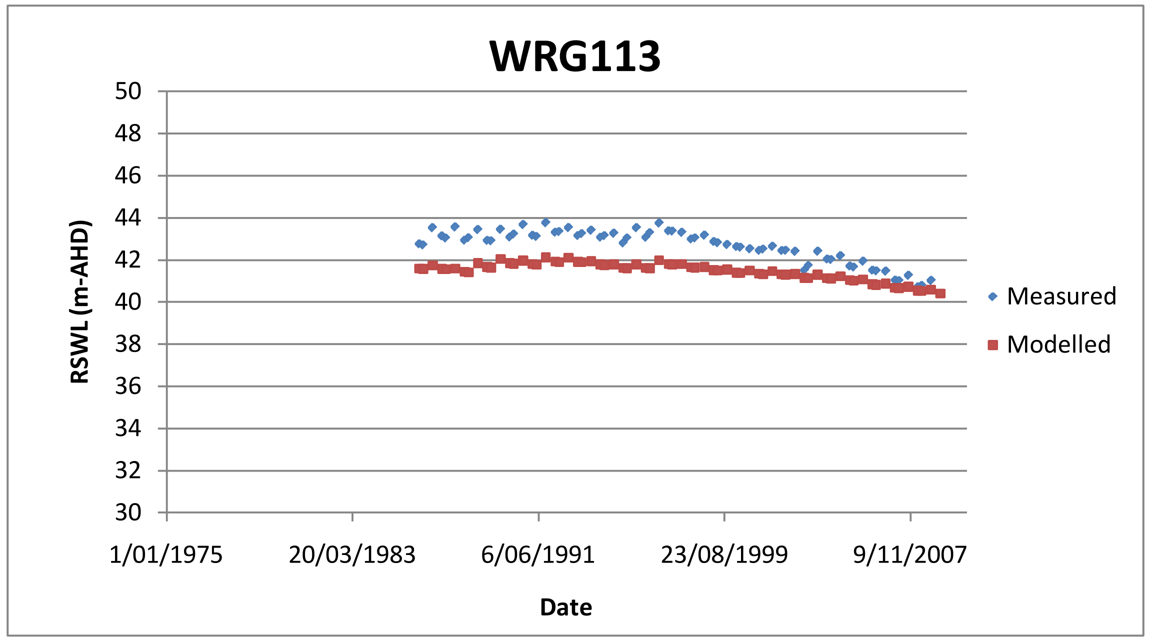

WRG022
RSWL (m-AHD)
60
58
56
54
52
50
48
46
44
42
40
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

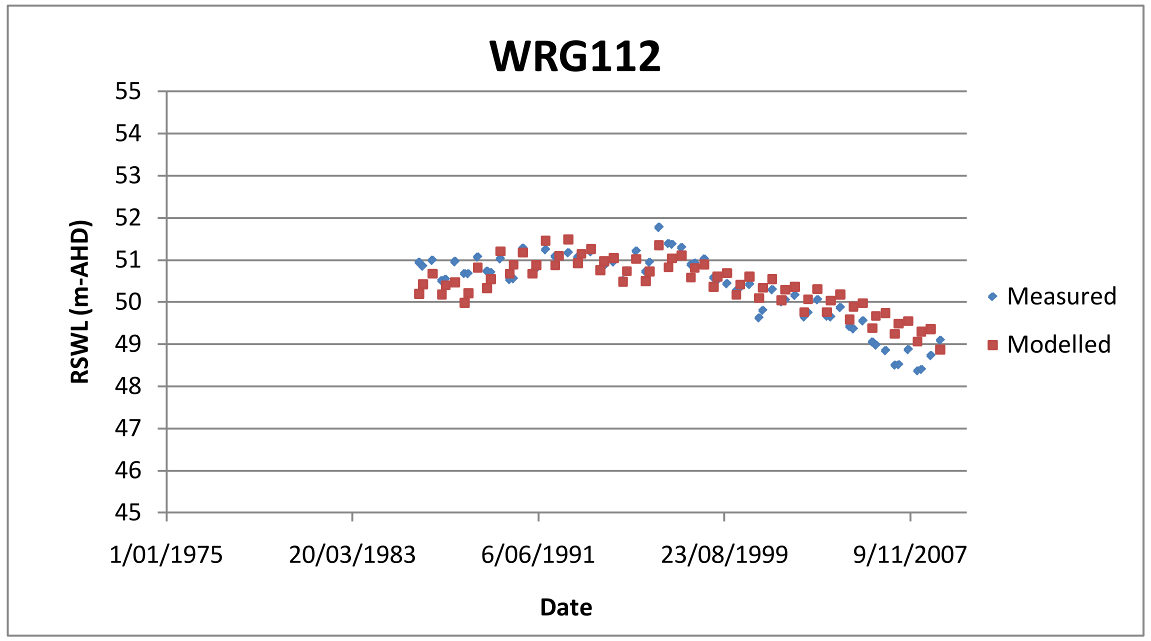

WRG109
RSWL (m-AHD)
46
44
42
40
38
36
34
32
30
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

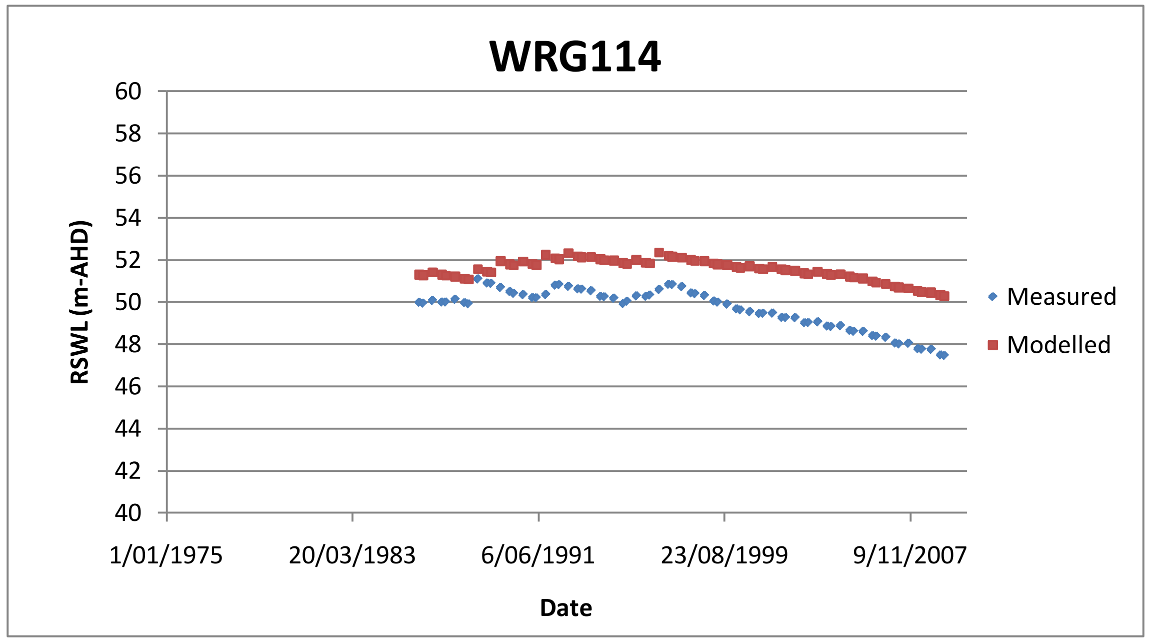

WRG023
RSWL (m-AHD)
70
68
66
64
62
60
58
56
54
52
50
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

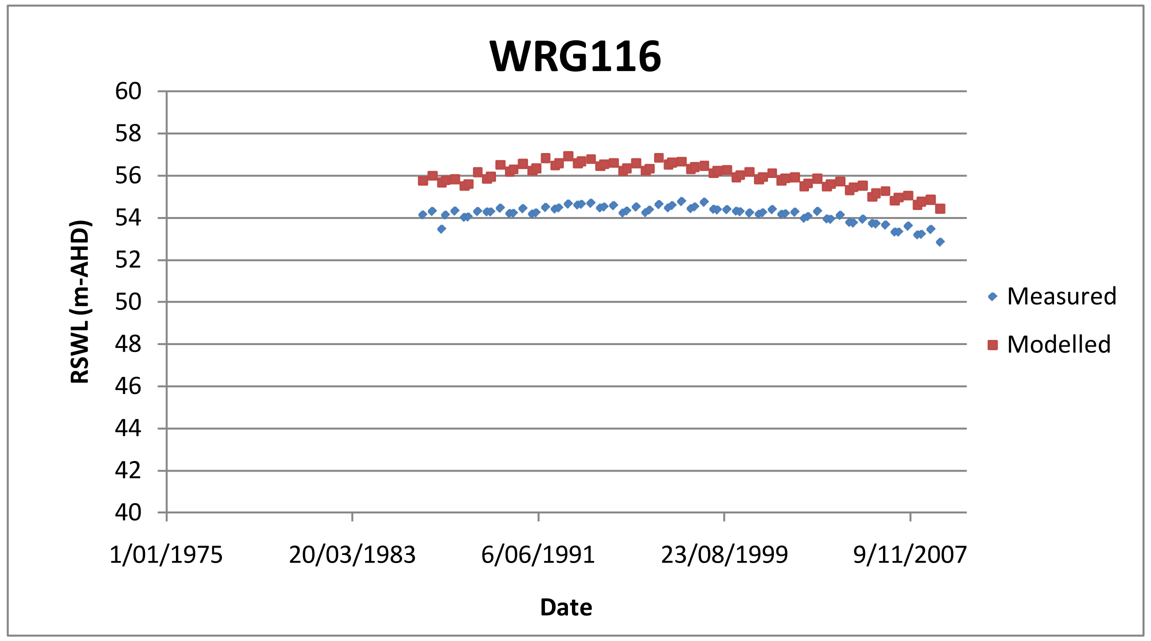

WRG110
RSWL (m-AHD)
60
58
56
54
52
50
48
46
44
42
40
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

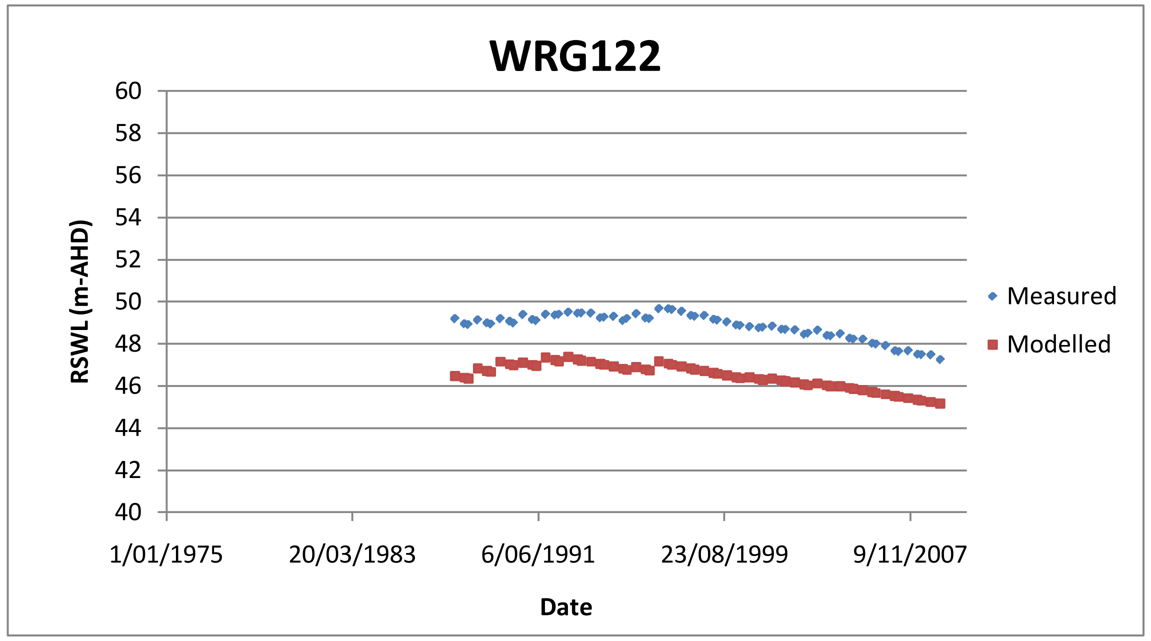

WRG111
RSWL (m-AHD)
65
60
55
50
45
40
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

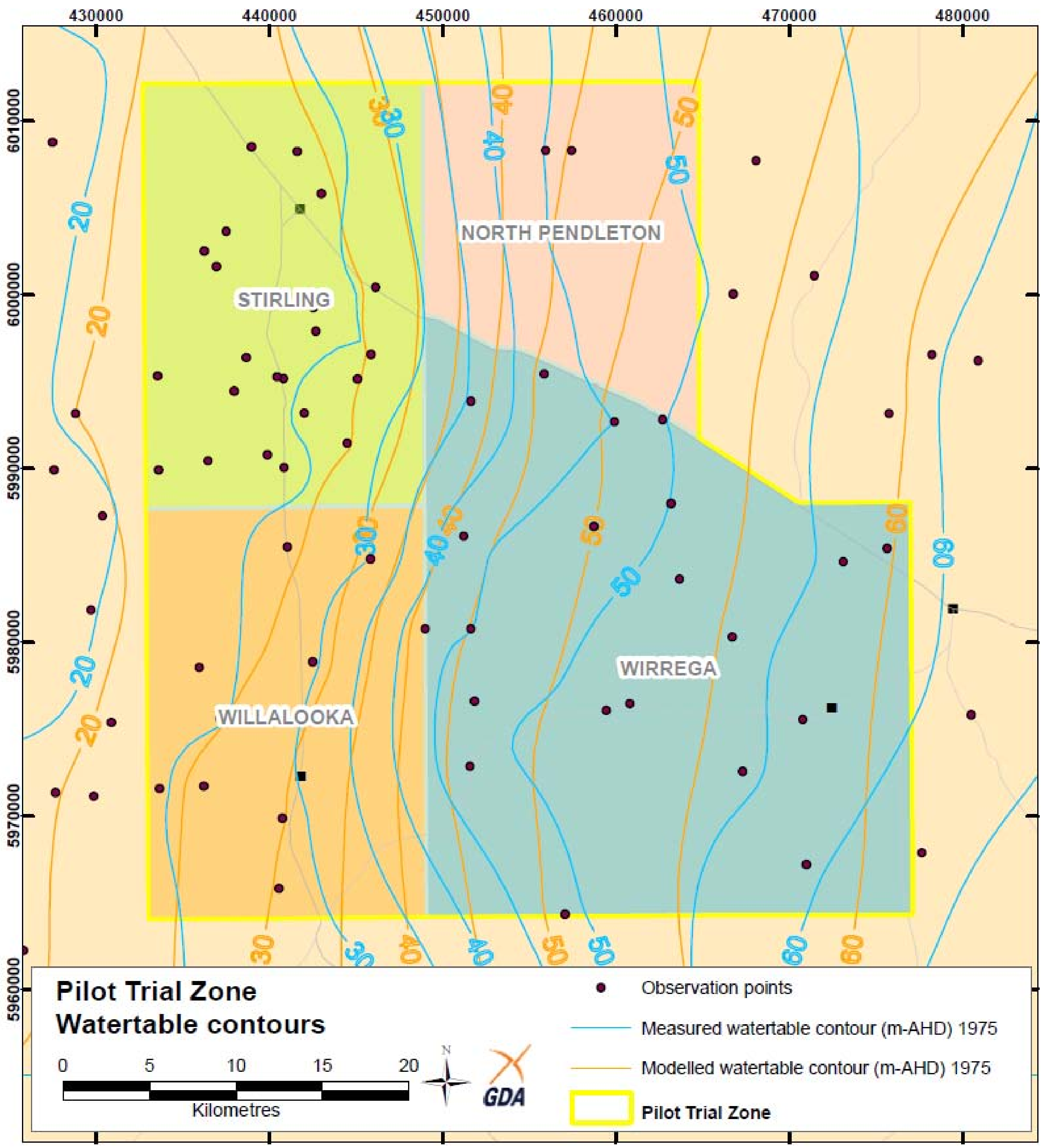

WRG113
RSWL (m-AHD)
50
48
46
44
42
40
38
36
34
32
30
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

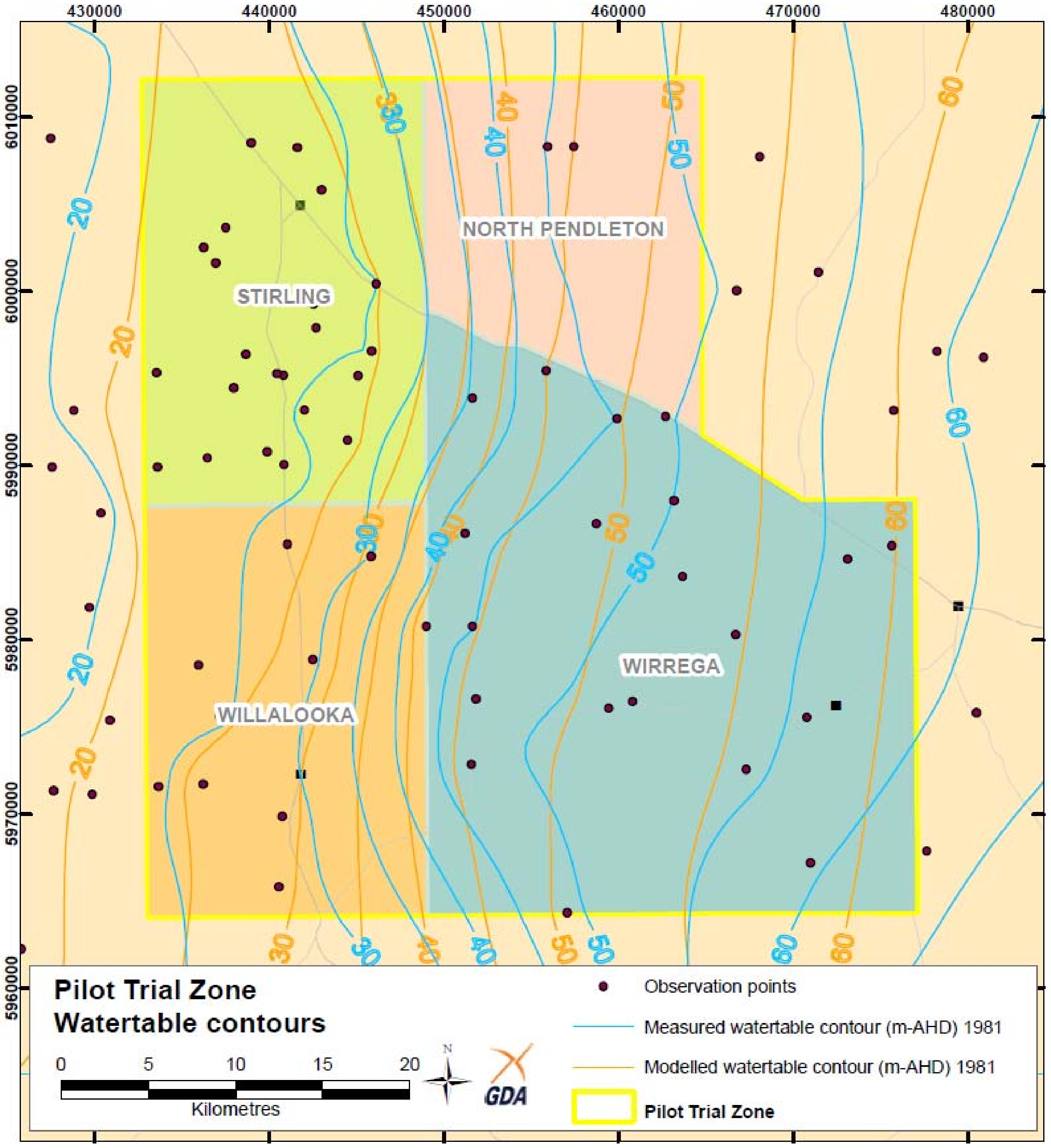

WRG112
RSWL (m-AHD)
55
54
53
52
51
50
49
48
47
46
45
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

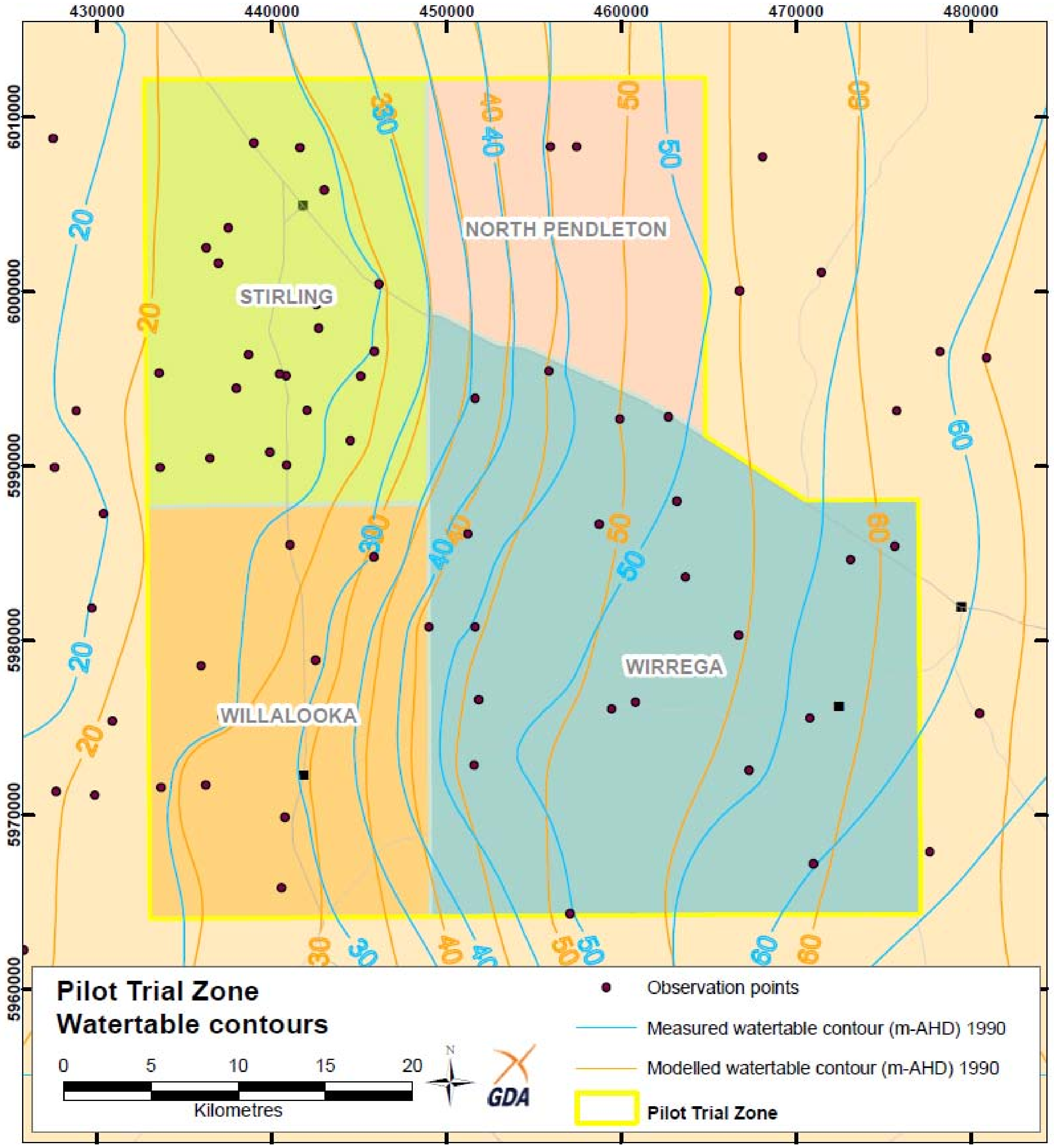

WRG114
RSWL (m-AHD)
60
58
56
54
52
50
48
46
44
42
40
1/01/1975
20/03/1983
6/06/1991
23/08/1999
9/11/2007
Date
Measured
Modelled

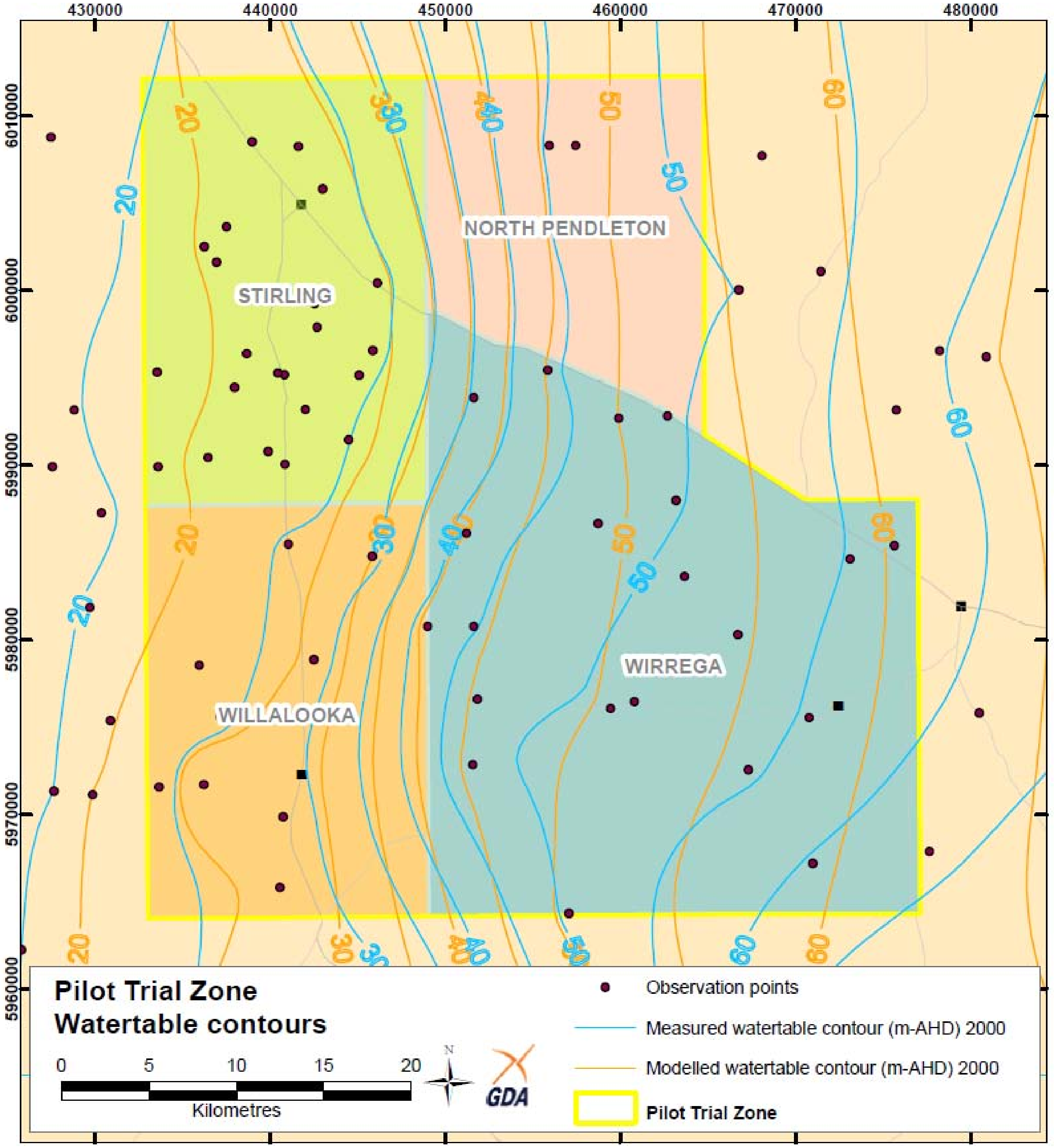

WRG116
RSWL (m-AHD)
Date
Measured
Modelled


WRG122
RSWL (m-AHD)
Date
Measured
Modelled


STIRLING
NORTH PENDLETON
WILLALOOKA
WIRREGA
Pilot Trial Zone
Watertable contours
Kilometres
Observation points
Measured watertable contour (m-AHD) 1975
Modelled watertable contour (m-AHD) 1975
Pilot Trial Zone
GDA

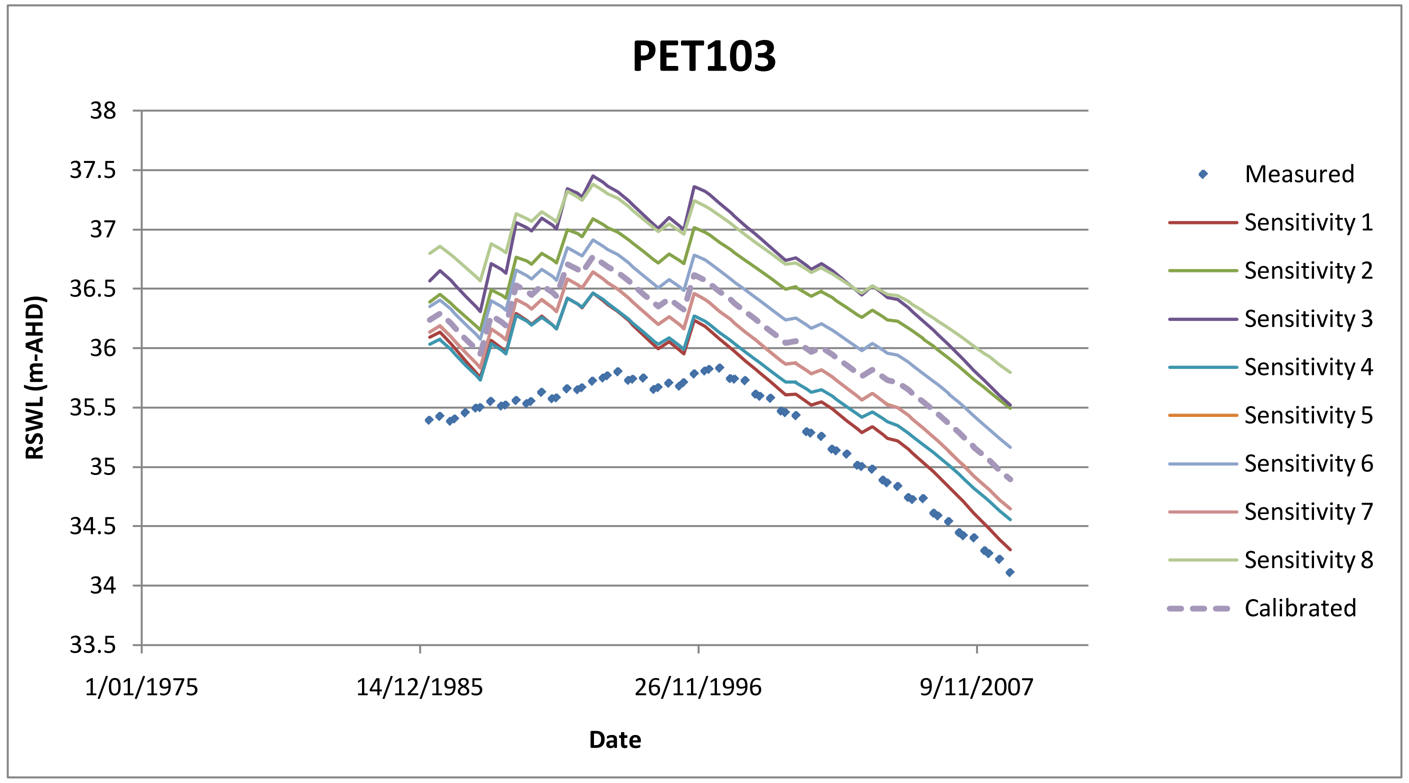

430000
440000
450000
460000
470000
480000
6010000
6000000
5990000
5980000
5970000
5960000
NORTH PENDLETON
STIRLING
WIRREGA
WILLALOOKA
Pilot Trial Zone
Watertable contours
0 5 10 15 20
Kilometres
GDA
Observation points
Measured watertable contour (m-AHD) 1981
Modelled watertable contour (m-AHD) 1981
Pilot Trial Zone

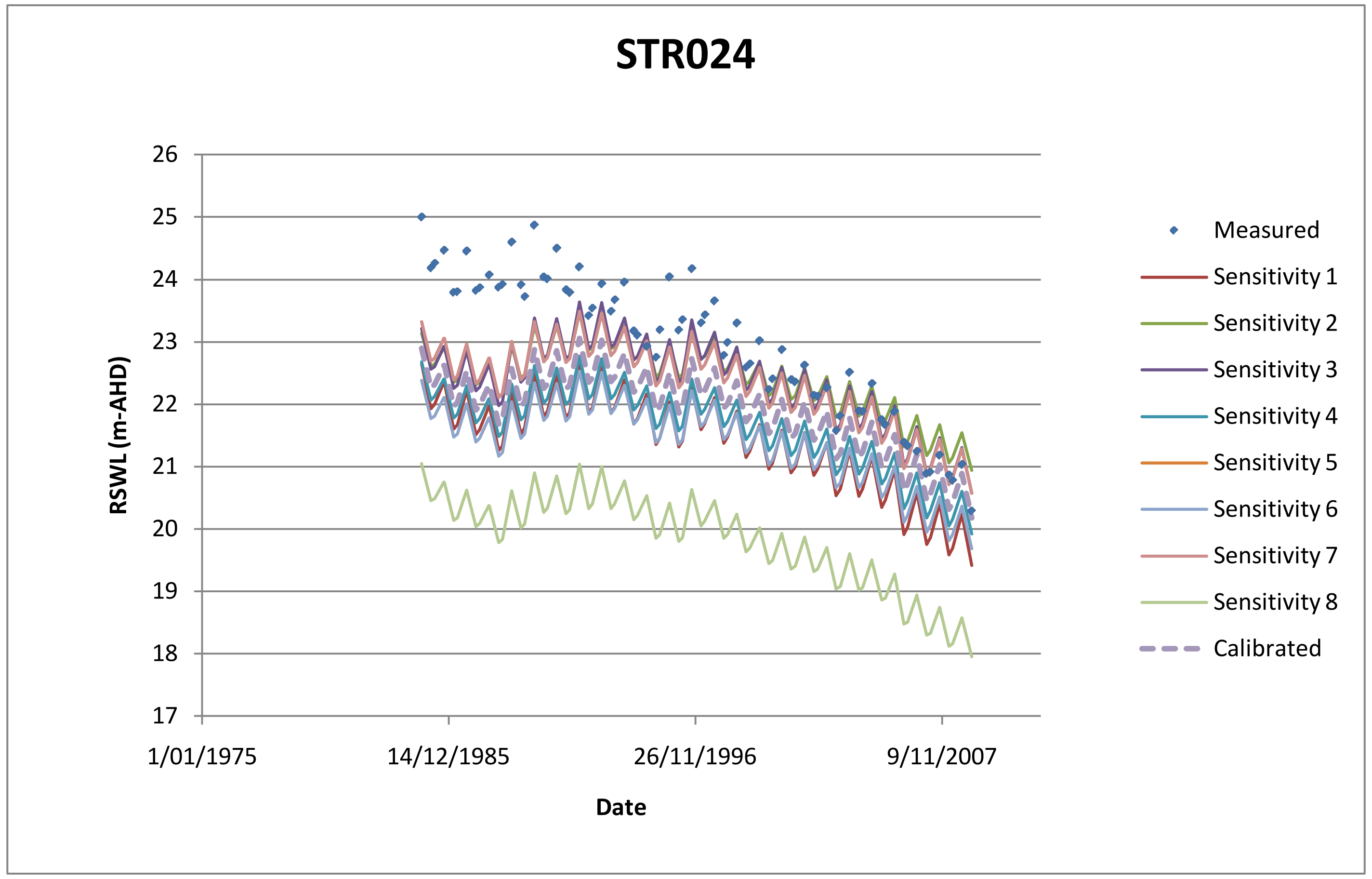

430000
440000
450000
460000
470000
480000
6010000
6000000
5990000
5980000
5970000
5960000
NORTH PENDLETON
STIRLING
WIRREGA
WILLALOOKA
Pilot Trial Zone
Watertable contours
0 5 10 15 20
Kilometres
GDA
Observation points
Measured watertable contour (m-AHD) 1990
Modelled watertable contour (m-AHD) 1990
Pilot Trial Zone

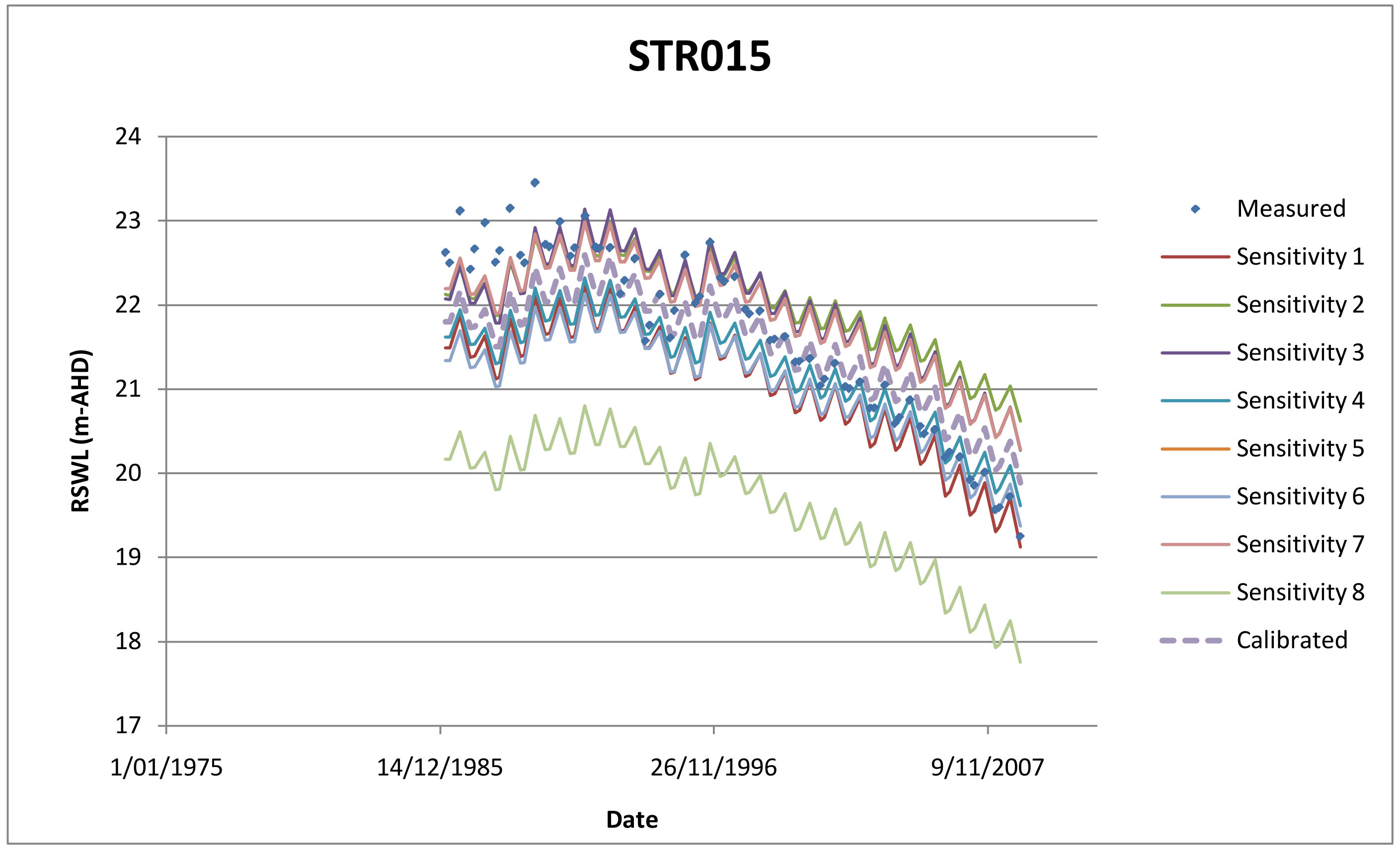


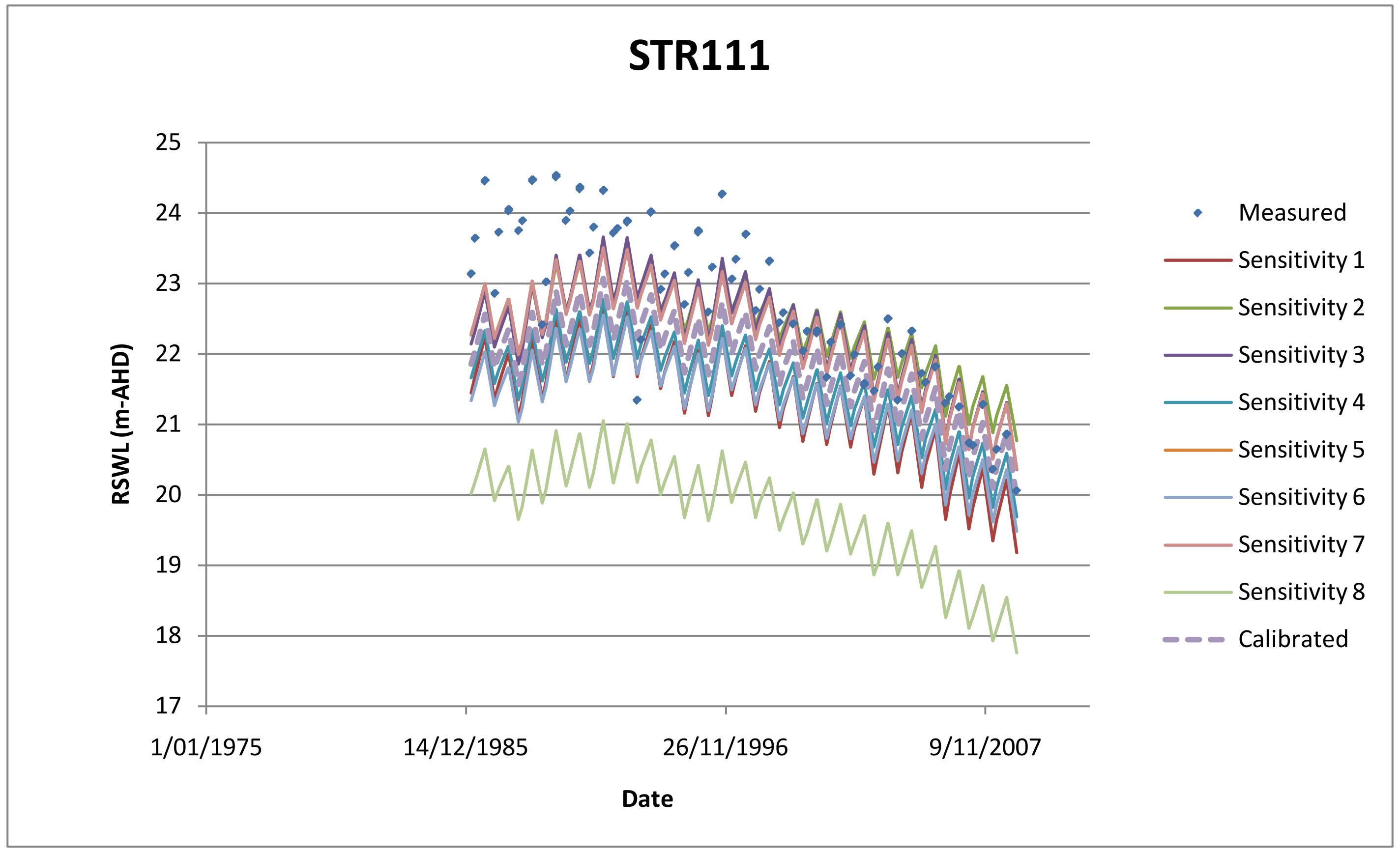
430000
440000
450000
460000
470000
480000
6010000
6000000
5990000
5980000
5970000
5960000
NORTH PENDLETON
STIRLING
WIRREGA
WILLALOOKA
20
30
40
50
60
Pilot Trial Zone
Watertable contours
0
5
10
15
20
Kilometres
GDA
Observation points
Measured watertable contour (m-AHD) 2000
Modelled watertable contour (m-AHD) 2000
Pilot Trial Zone

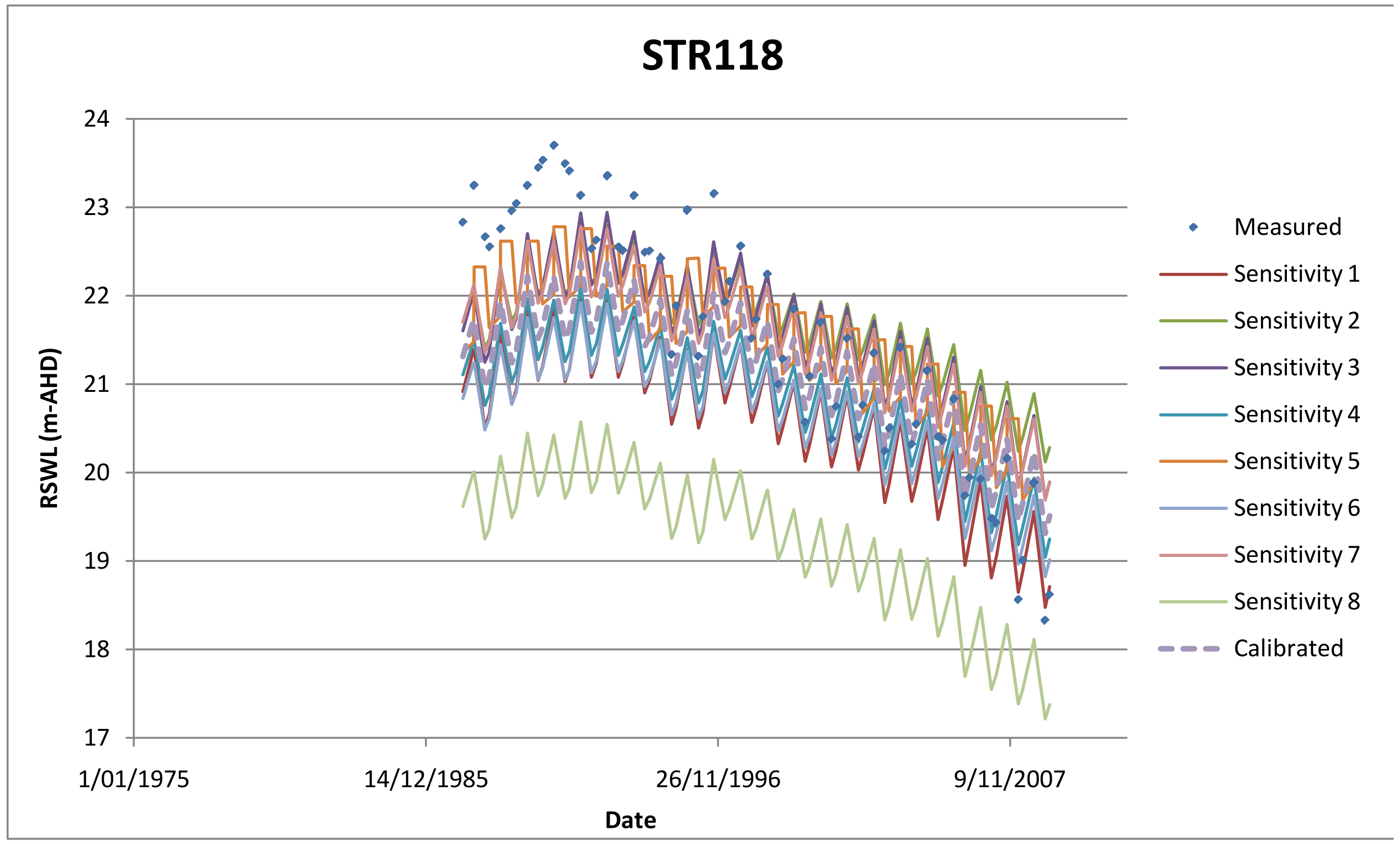
C. SENSITIVITY ANALYSIS

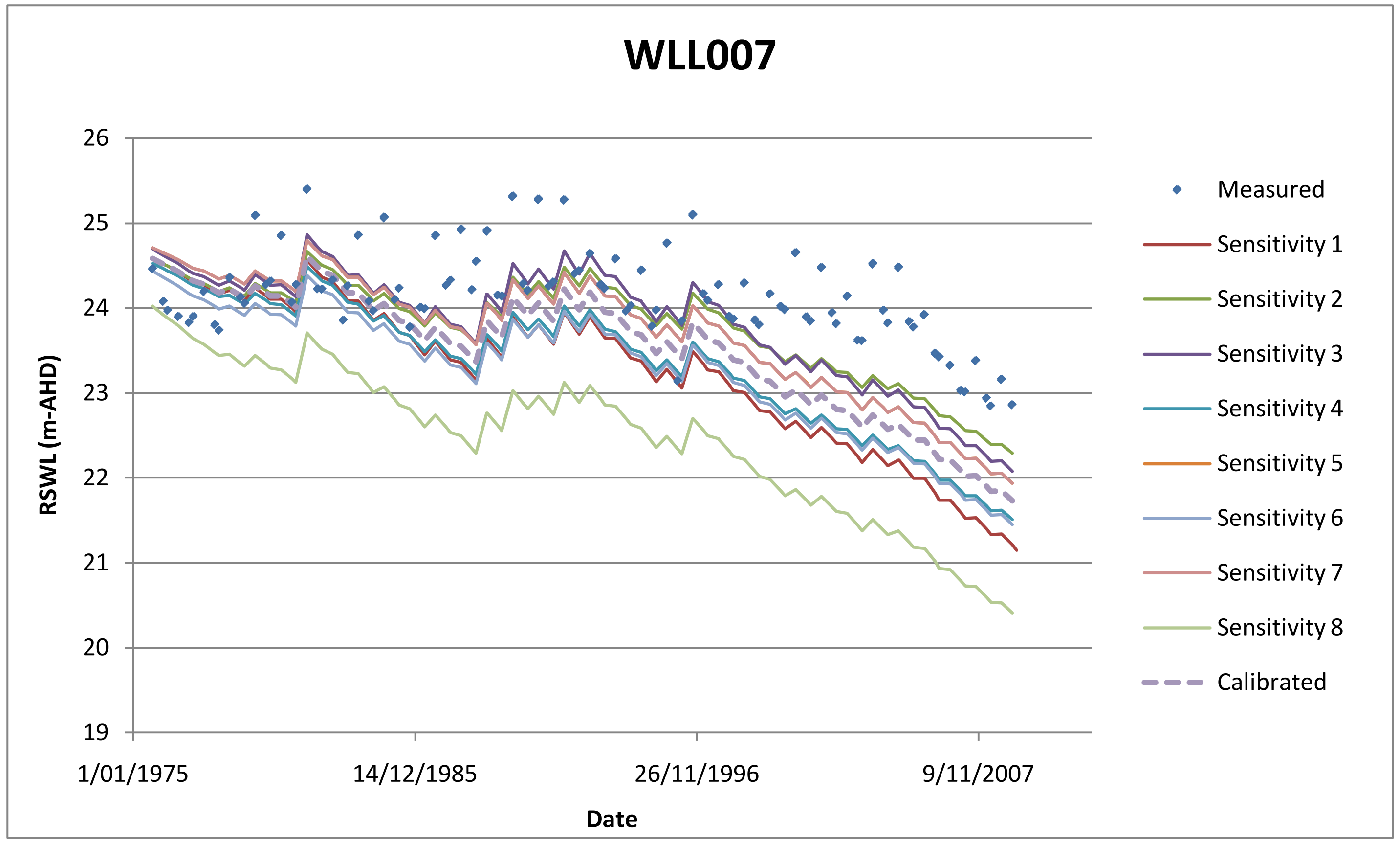


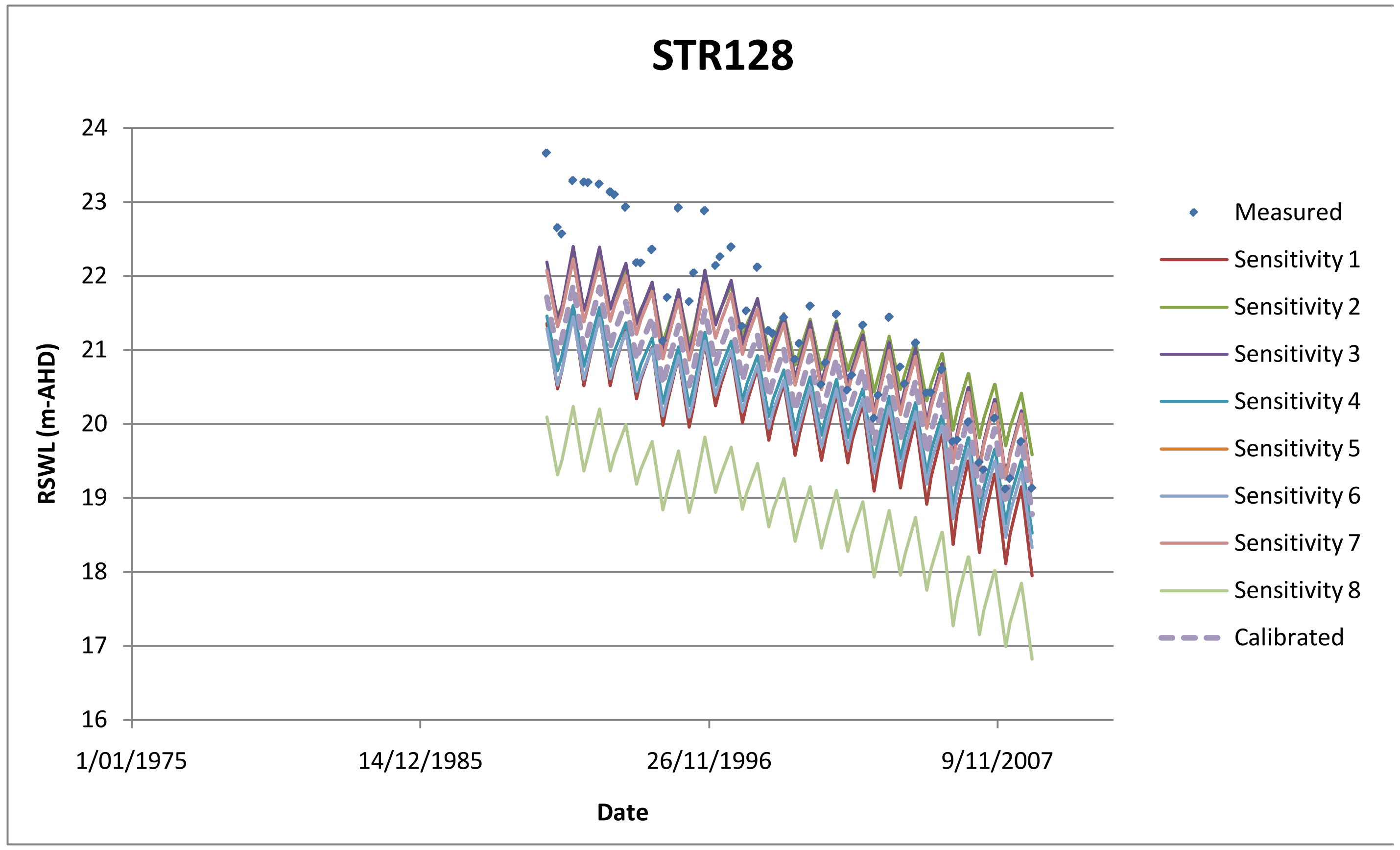


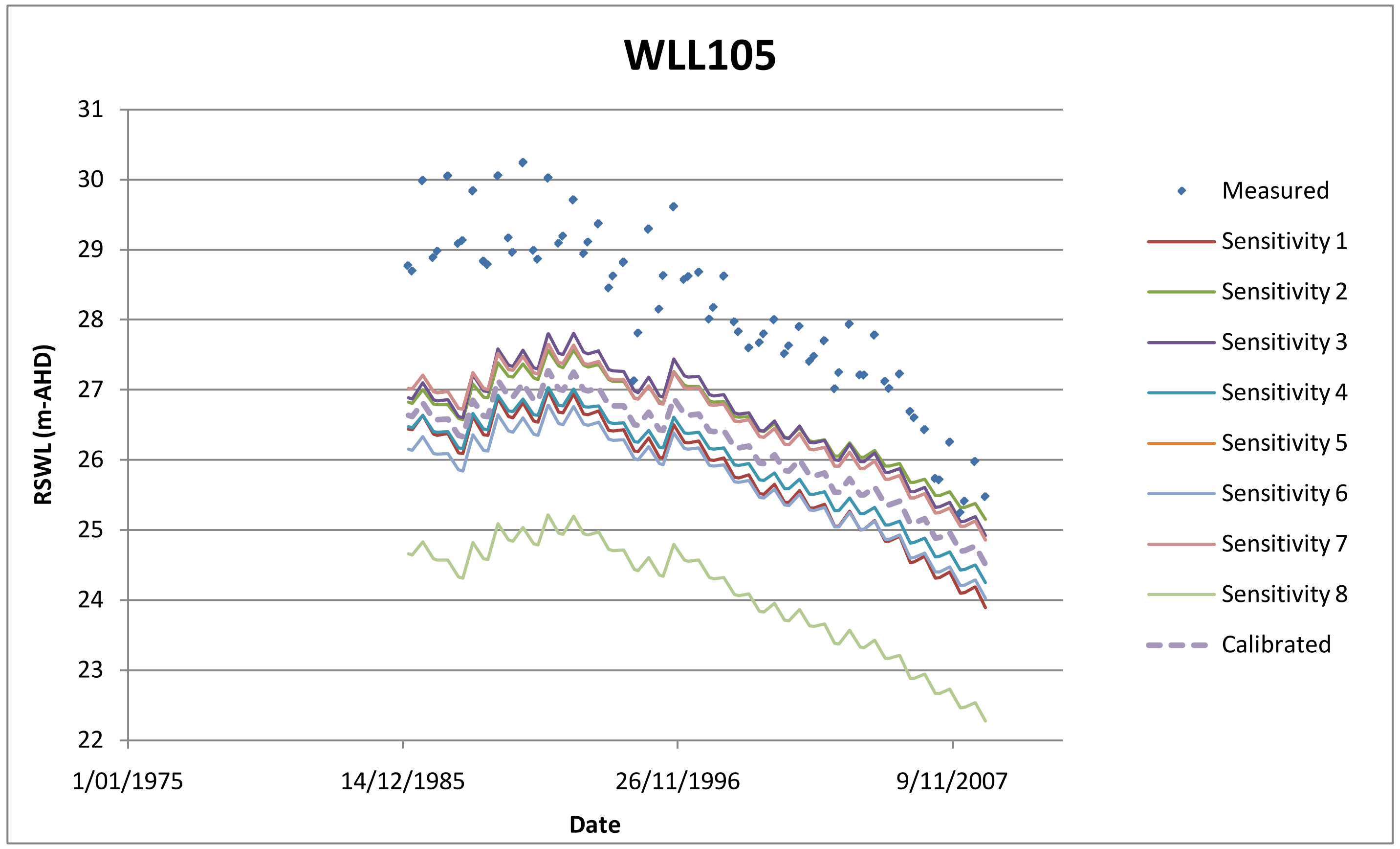


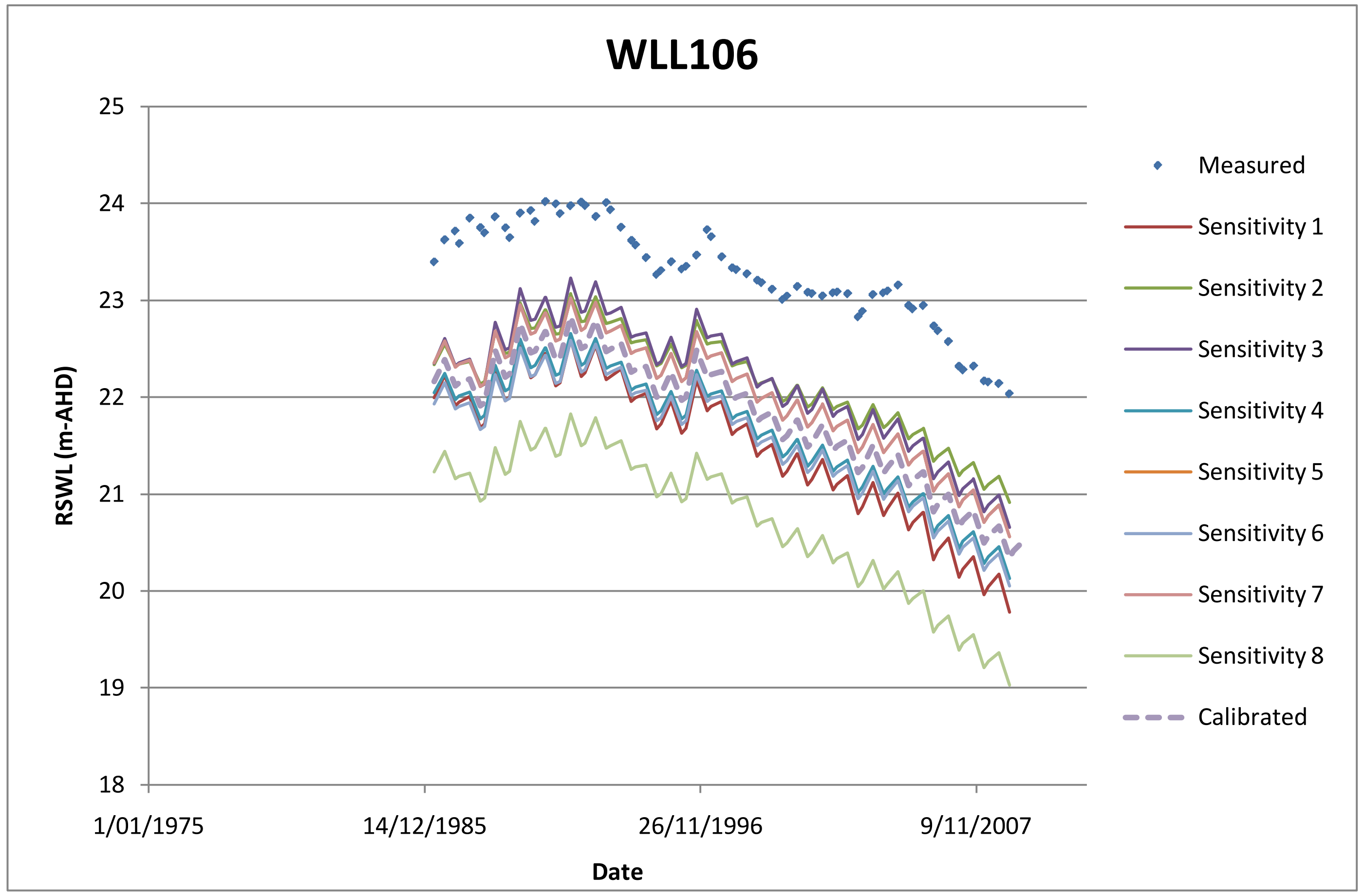


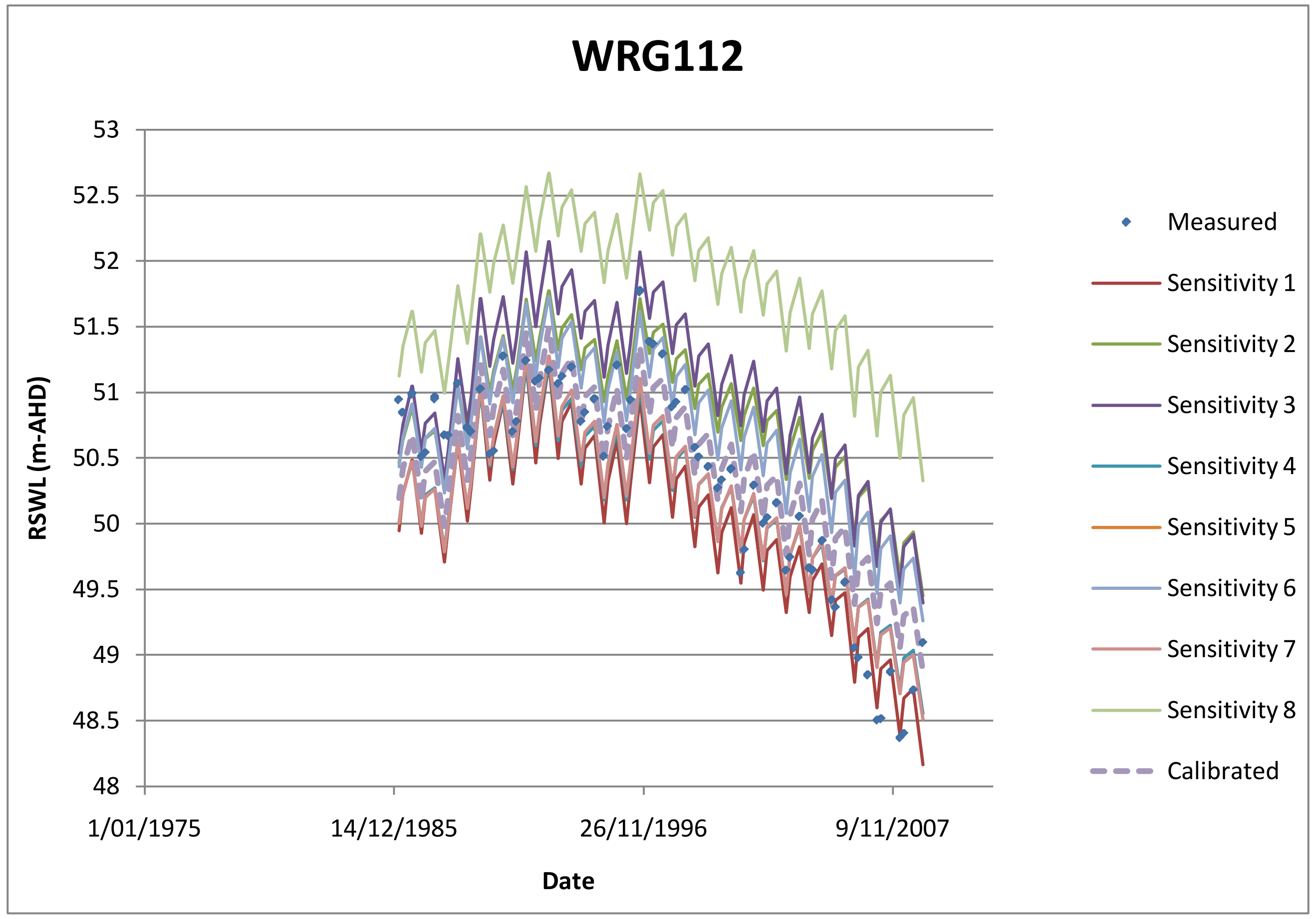

STR118
RSWL (m-AHD)
24
23
22
21
20
19
18
17
1/01/1975
14/12/1985
26/11/1996
9/11/2007
Date
Measured
Sensitivity 1
Sensitivity 2
Sensitivity 3
Sensitivity 4
Sensitivity 5
Sensitivity 6
Sensitivity 7
Sensitivity 8
Calibrated

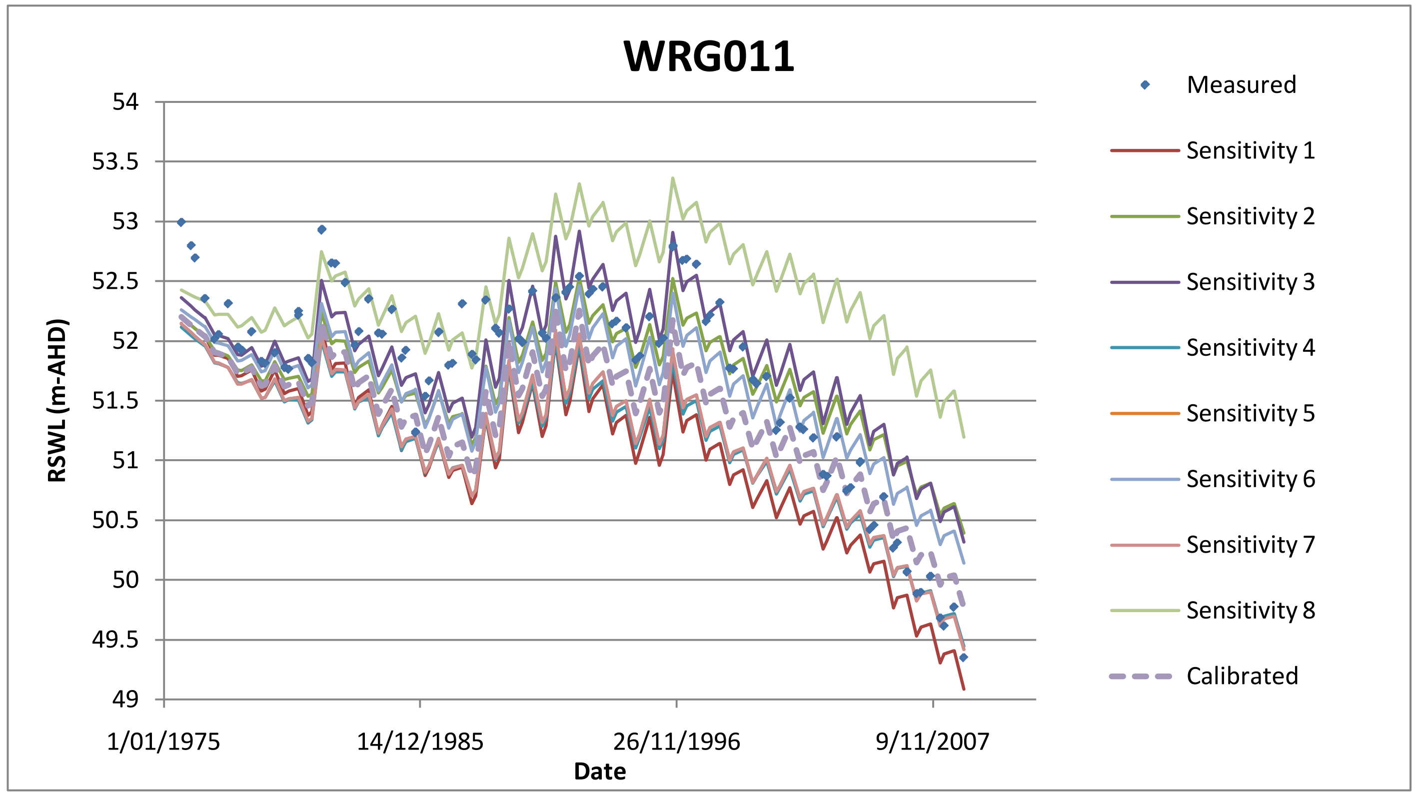

WLL007
RSWL (m-AHD)
26
25
24
23
22
21
20
19
1/01/1975
14/12/1985
26/11/1996
9/11/2007
Date
Measured
Sensitivity 1
Sensitivity 2
Sensitivity 3
Sensitivity 4
Sensitivity 5
Sensitivity 6
Sensitivity 7
Sensitivity 8
Calibrated


STR128
RSWL (m-AHD)
24
23
22
21
20
19
18
17
16
1/01/1975
14/12/1985
26/11/1996
9/11/2007
Date
Measured
Sensitivity 1
Sensitivity 2
Sensitivity 3
Sensitivity 4
Sensitivity 5
Sensitivity 6
Sensitivity 7
Sensitivity 8
Calibrated

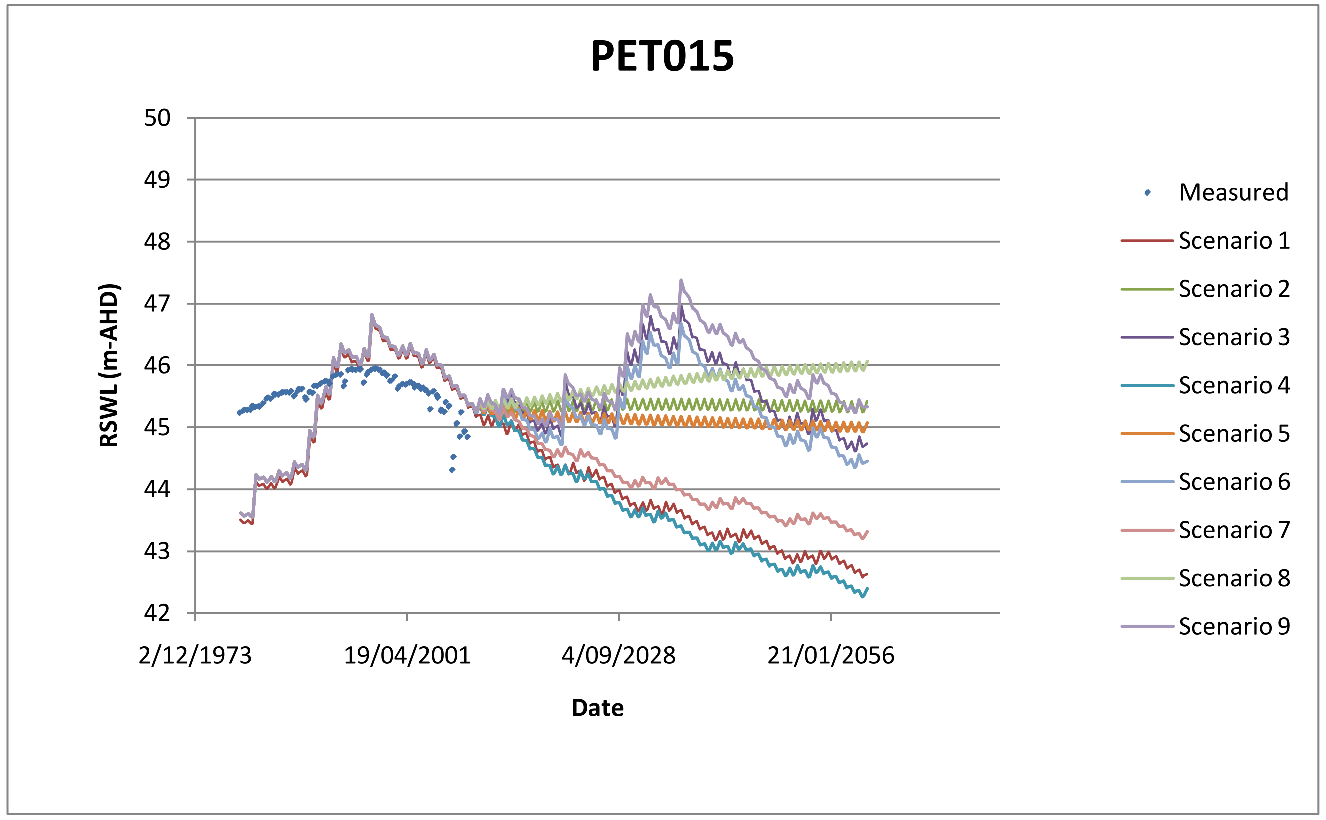

WLL105
RSWL (m-AHD)
31
30
29
28
27
26
25
24
23
22
1/01/1975
14/12/1985
26/11/1996
9/11/2007
Date
Measured
Sensitivity 1
Sensitivity 2
Sensitivity 3
Sensitivity 4
Sensitivity 5
Sensitivity 6
Sensitivity 7
Sensitivity 8
Calibrated

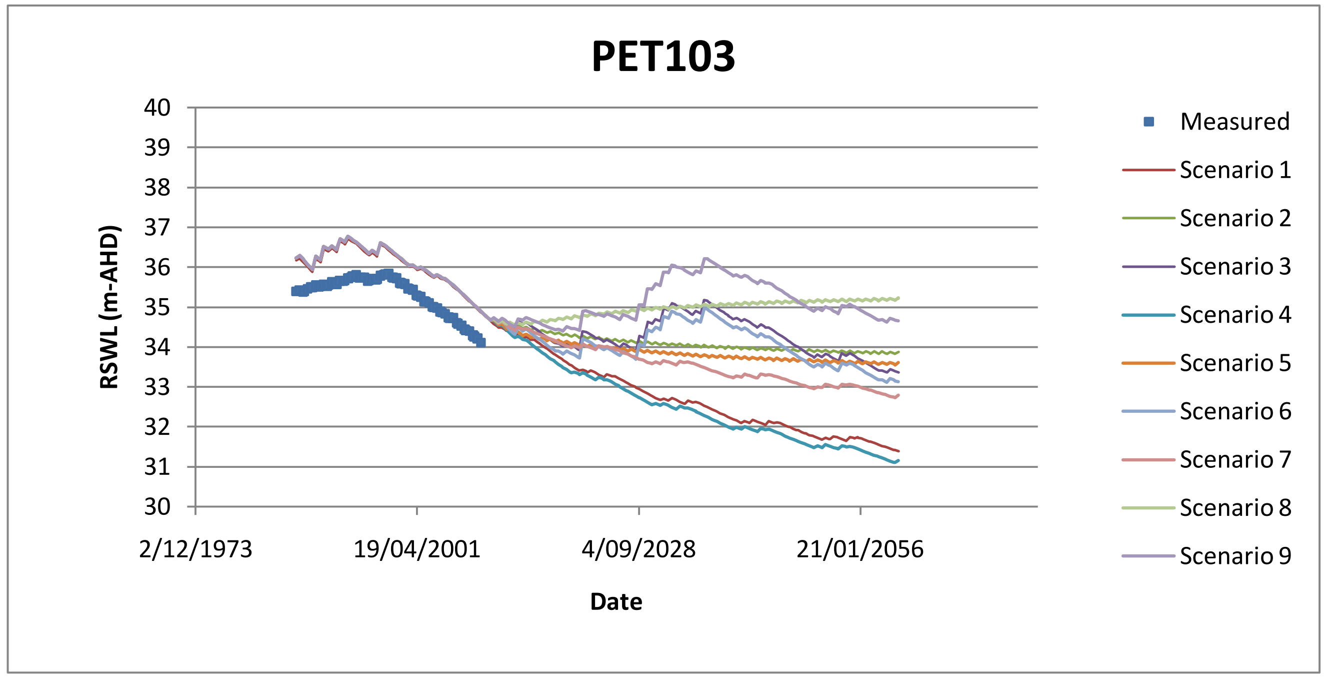

WLL106
25
24
23
22
21
20
19
18
RSWL (m-AHD)
1/01/1975
14/12/1985
26/11/1996
9/11/2007
Date
Measured
Sensitivity 1
Sensitivity 2
Sensitivity 3
Sensitivity 4
Sensitivity 5
Sensitivity 6
Sensitivity 7
Sensitivity 8
Calibrated

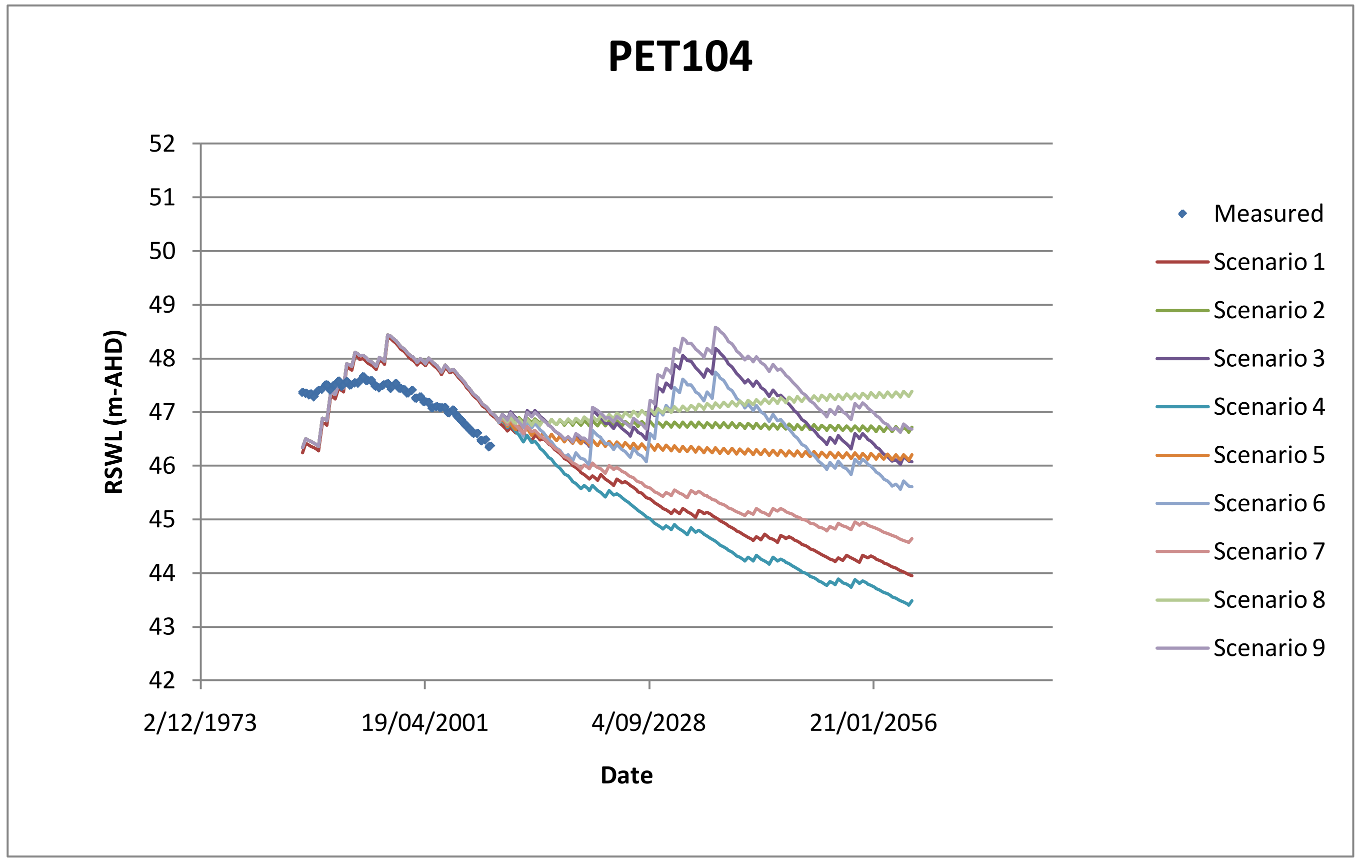

WRG112
53
52.5
52
51.5
51
50.5
50
49.5
49
48.5
48
RSWL (m-AHD)
1/01/1975
14/12/1985
26/11/1996
9/11/2007
Date
Measured
Sensitivity 1
Sensitivity 2
Sensitivity 3
Sensitivity 4
Sensitivity 5
Sensitivity 6
Sensitivity 7
Sensitivity 8
Calibrated

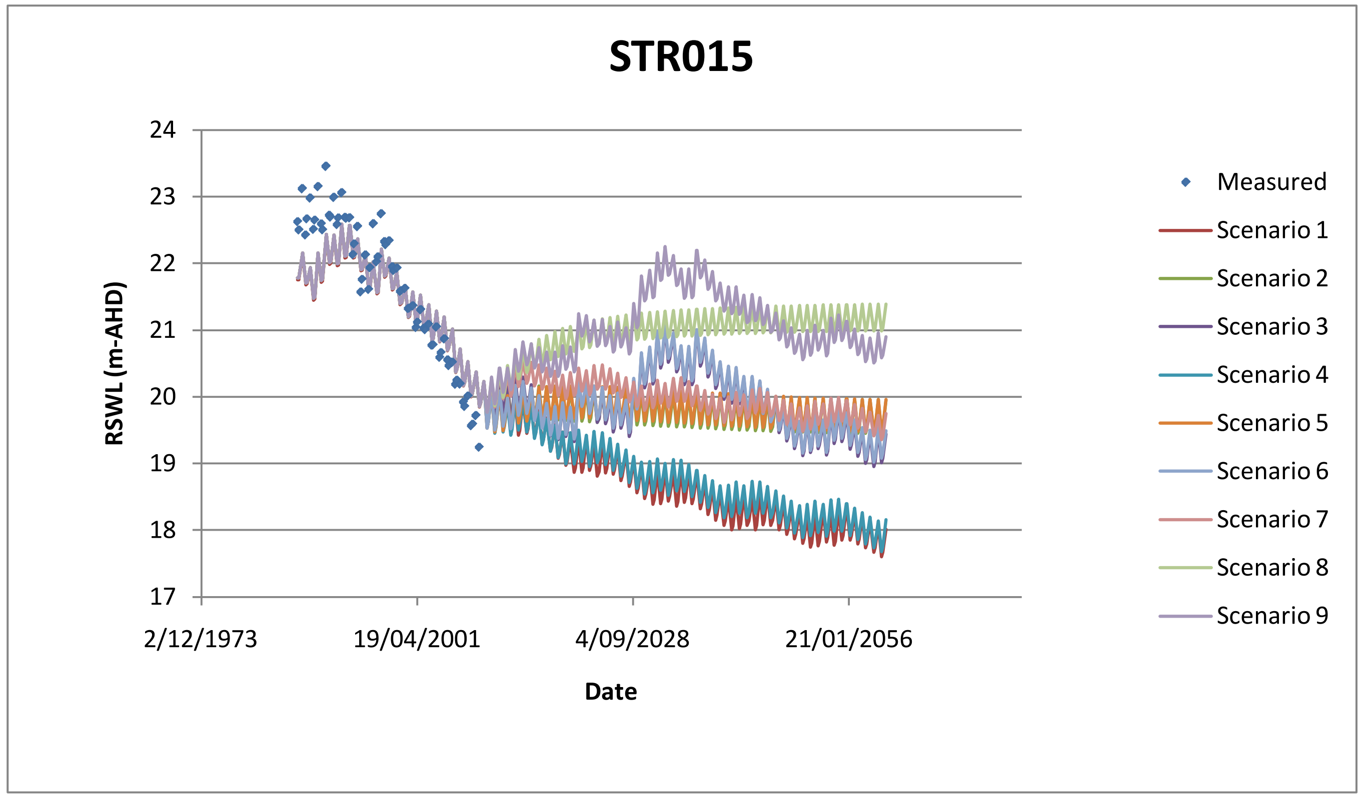

WRG011
54
53.5
53
52.5
52
51.5
51
50.5
50
49.5
49
RSWL (m-AHD)
1/01/1975
14/12/1985
26/11/1996
9/11/2007
Date
Measured
Sensitivity 1
Sensitivity 2
Sensitivity 3
Sensitivity 4
Sensitivity 5
Sensitivity 6
Sensitivity 7
Sensitivity 8
Calibrated

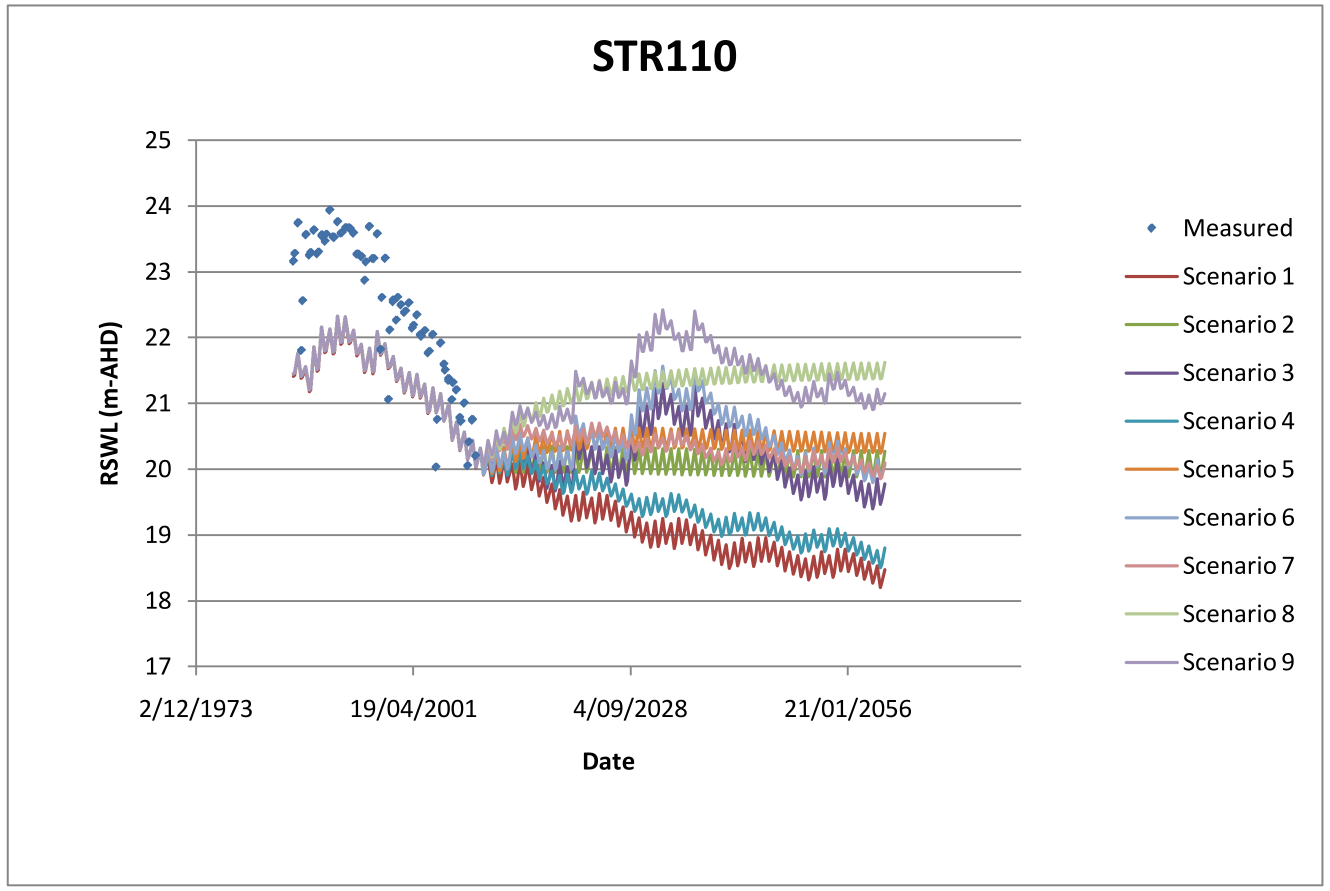
D. SCENARIO WATER LEVELS AND WATERTABLE DRAWDOWN

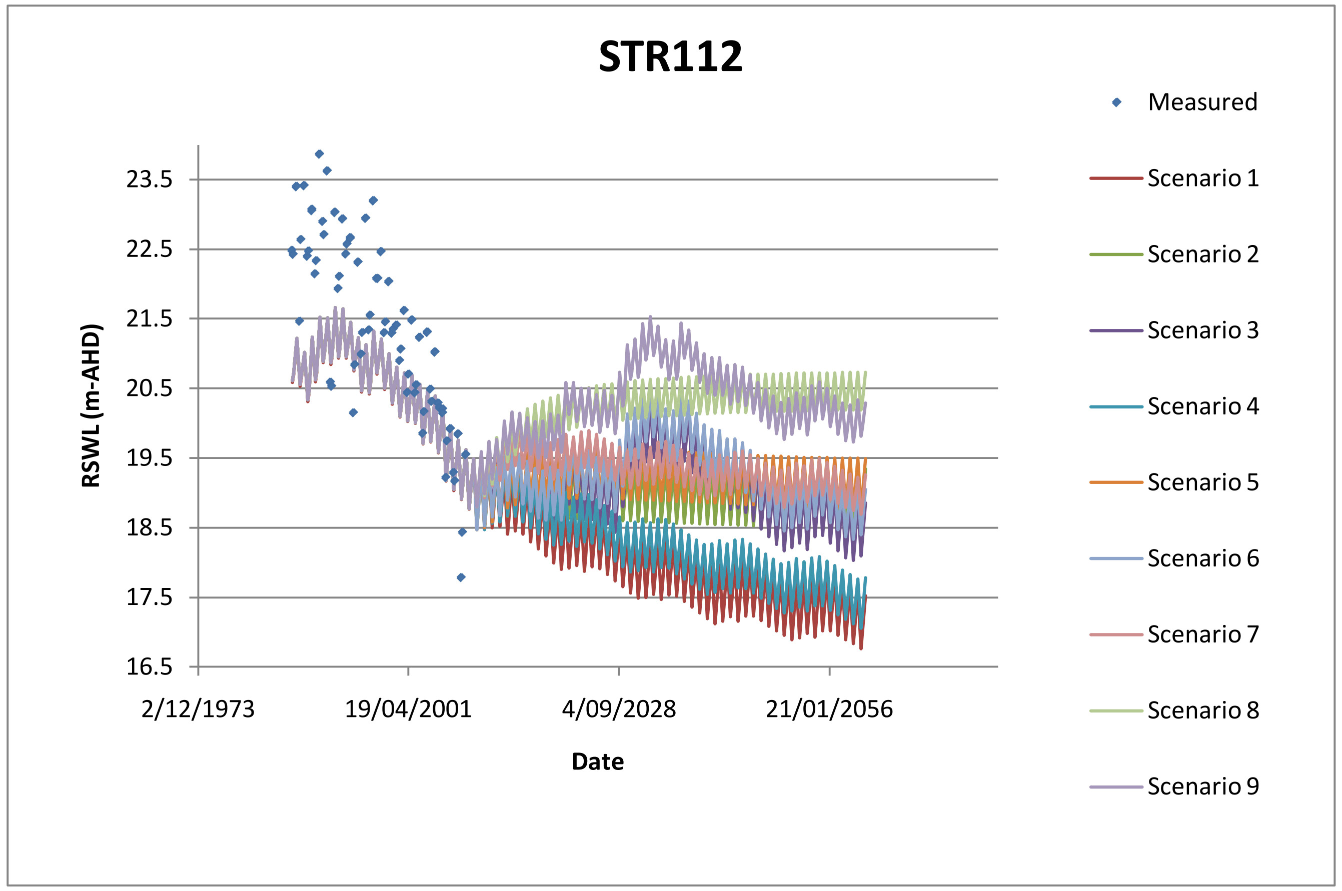


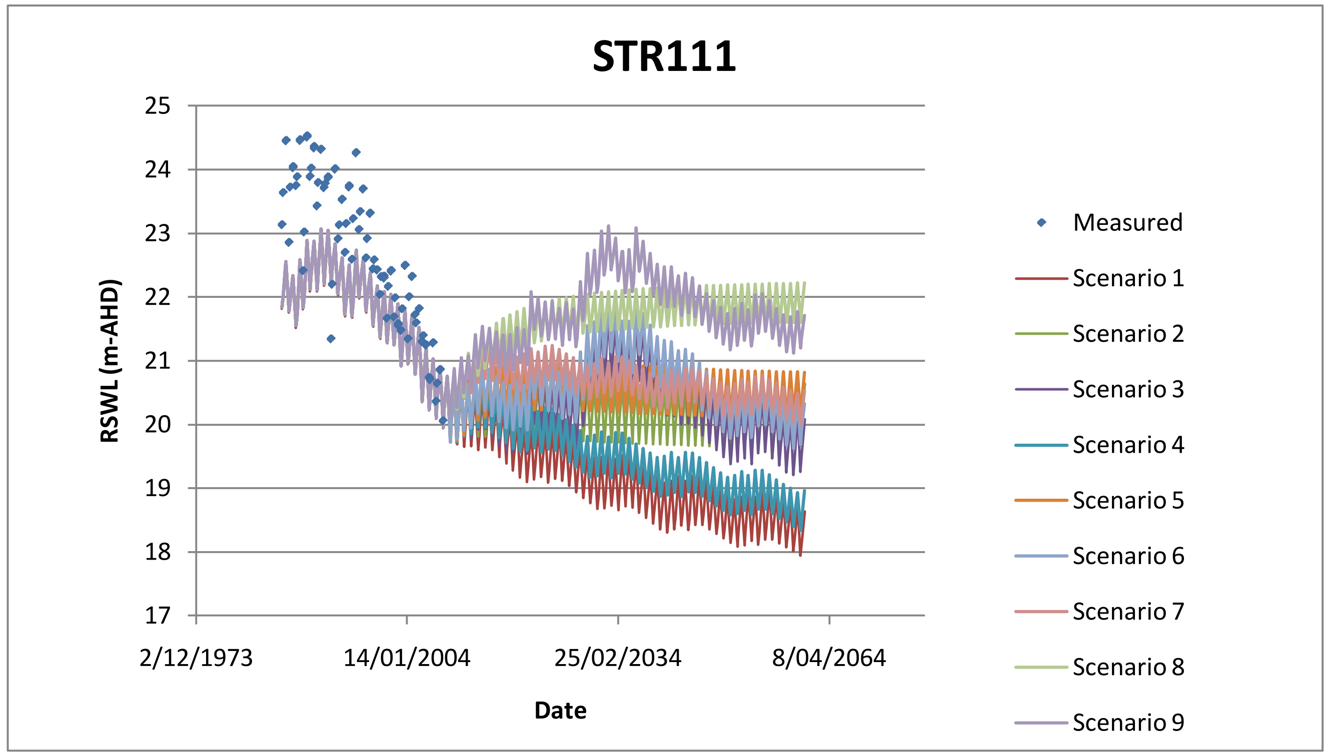


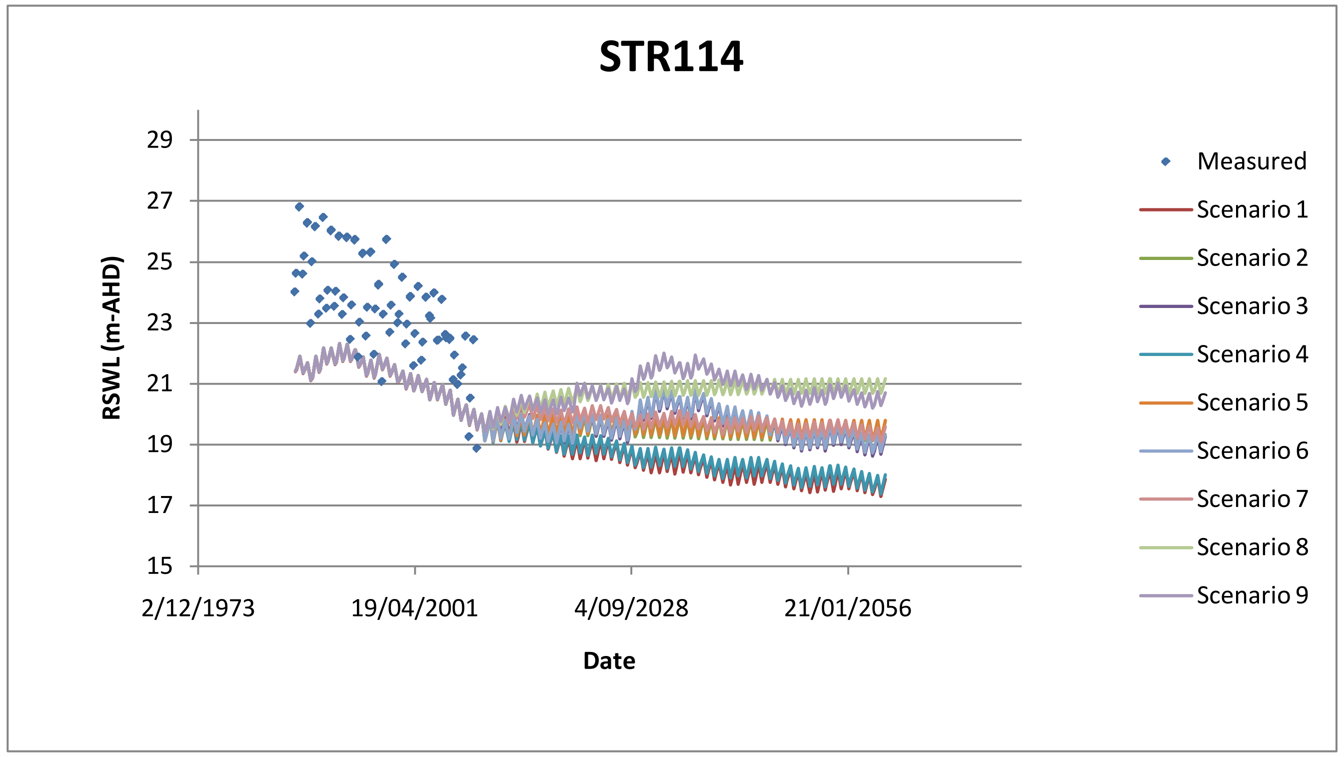


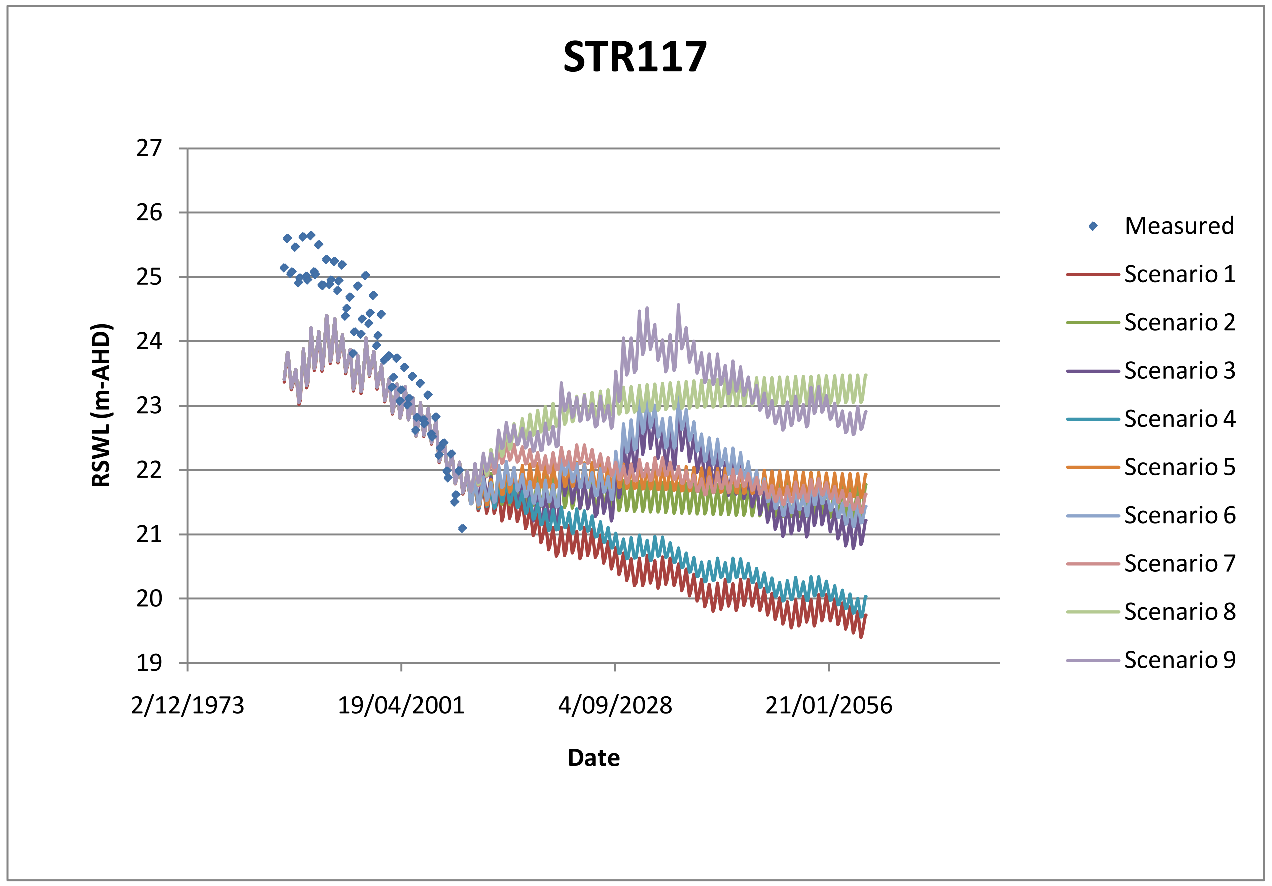


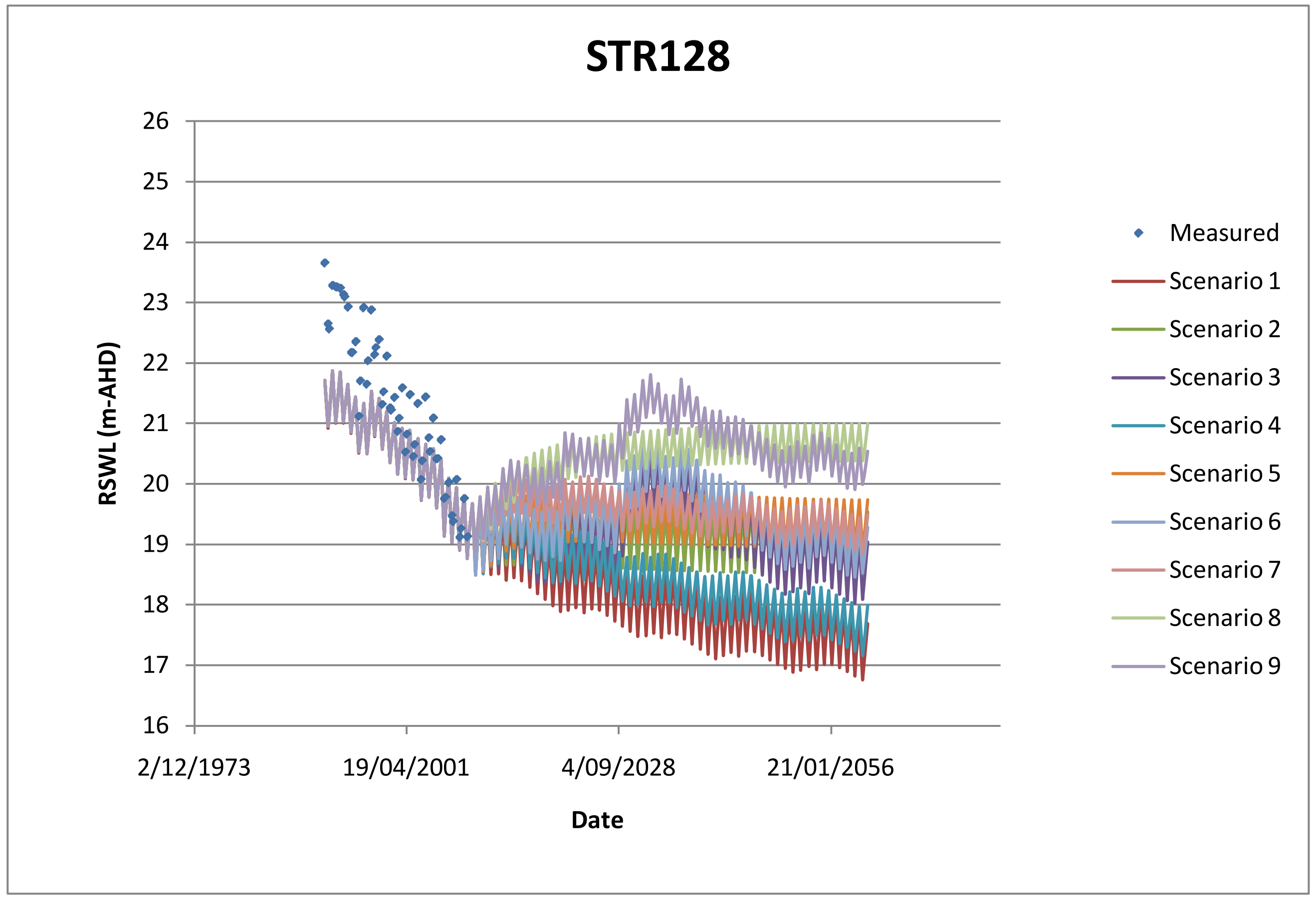

STR110
RSWL (m-AHD)
25
24
23
22
21
20
19
18
17
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9


STR112
RSWL (m-AHD)
23.5
22.5
21.5
20.5
19.5
18.5
17.5
16.5
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9


STR111
RSWL (m-AHD)
25
24
23
22
21
20
19
18
17
2/12/1973
14/01/2004
25/02/2034
8/04/2064
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9


STR114
RSWL (m-AHD)
29
27
25
23
21
19
17
15
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9


STR117
27
26
25
24
23
22
21
20
19
RSWL (m-AHD)
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9


STR128
26
25
24
23
22
21
20
19
18
17
16
RSWL (m-AHD)
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
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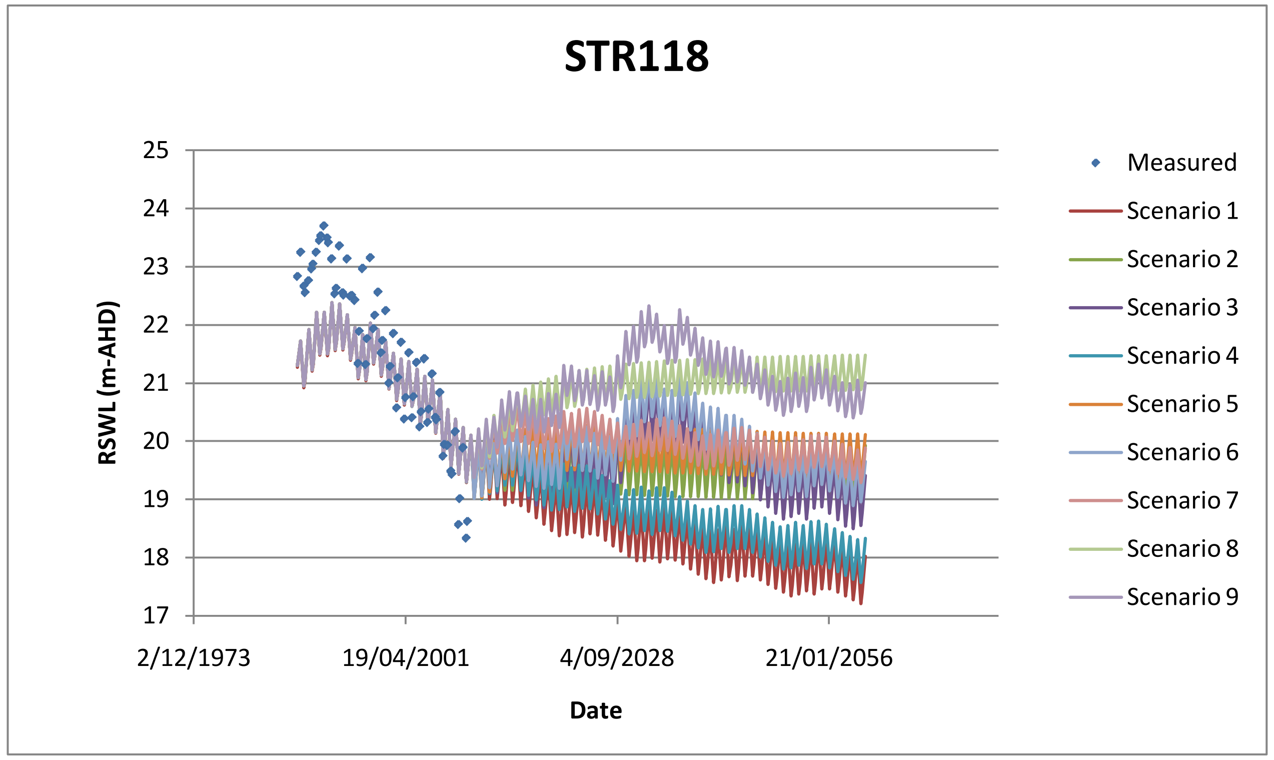
Scenario 8
Scenario 9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RSWL (m-AHD)
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
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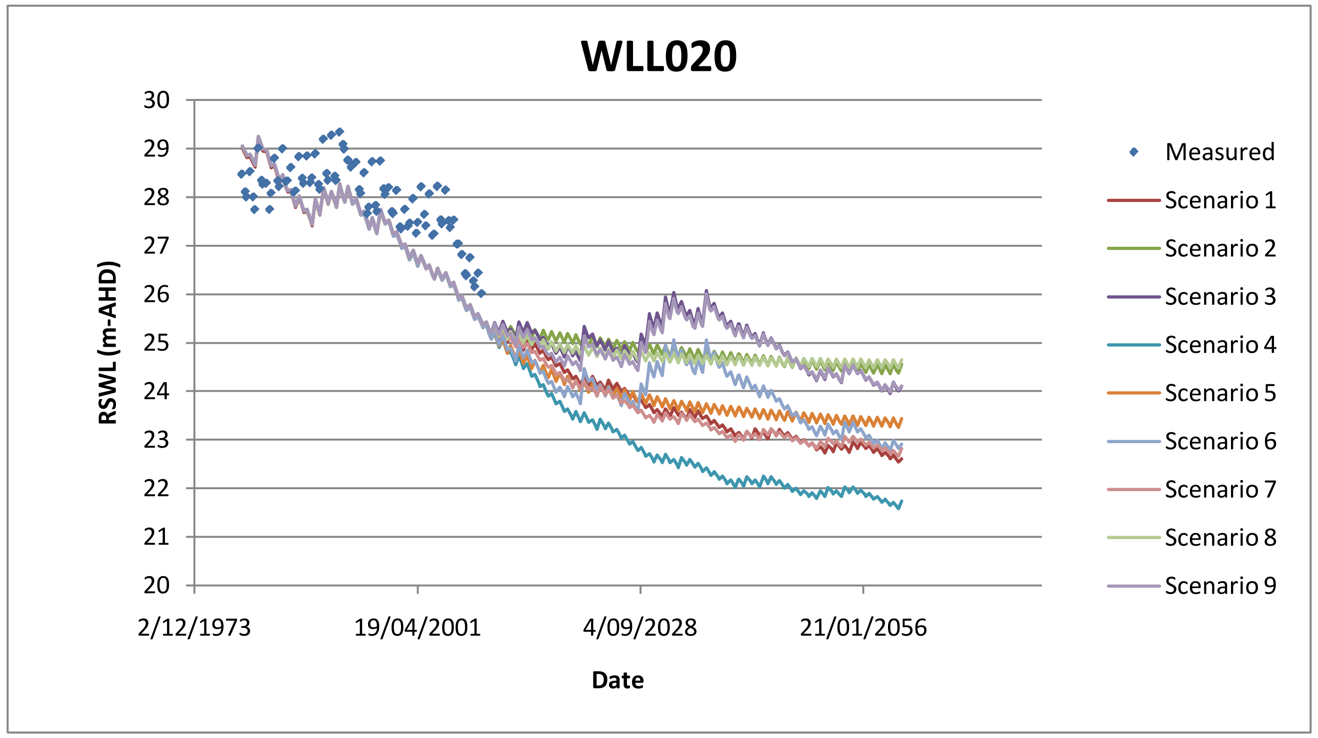
Scenario 9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2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
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Scenario 4
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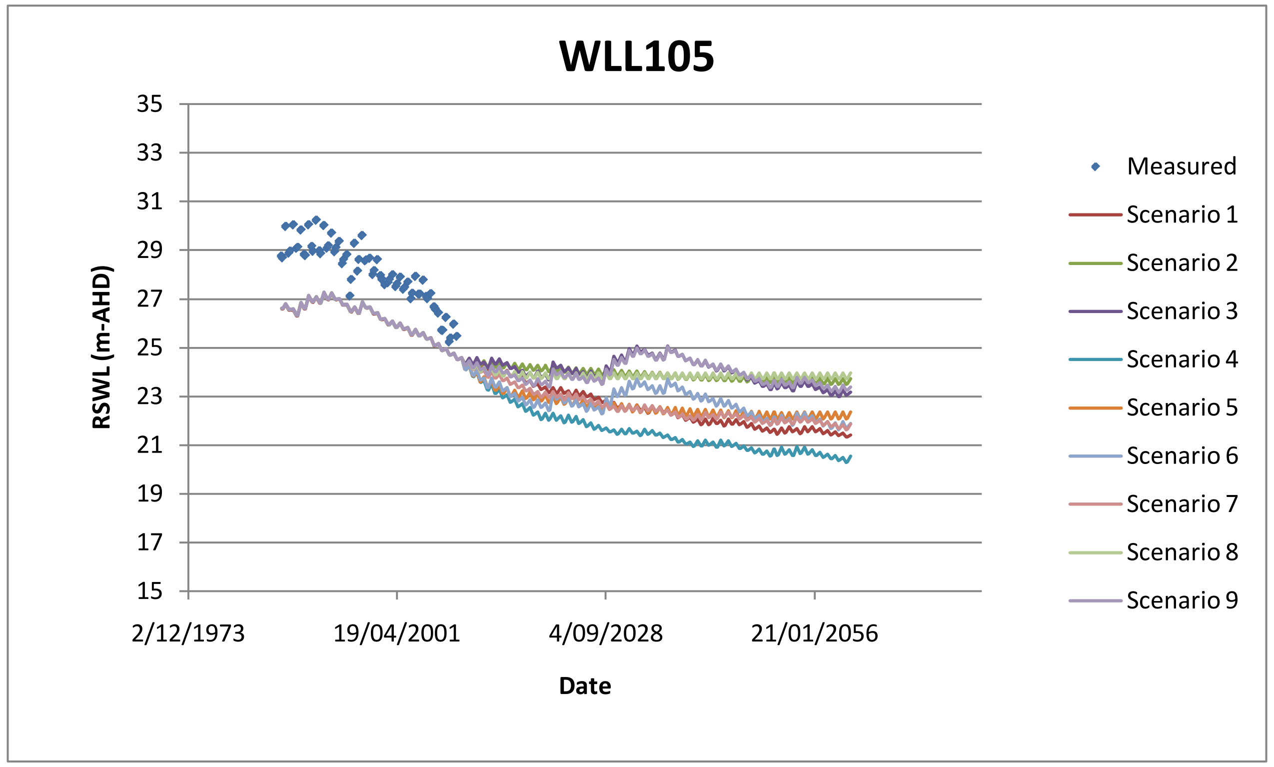
Scenario 7
Scenario 8
Scenario 9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19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
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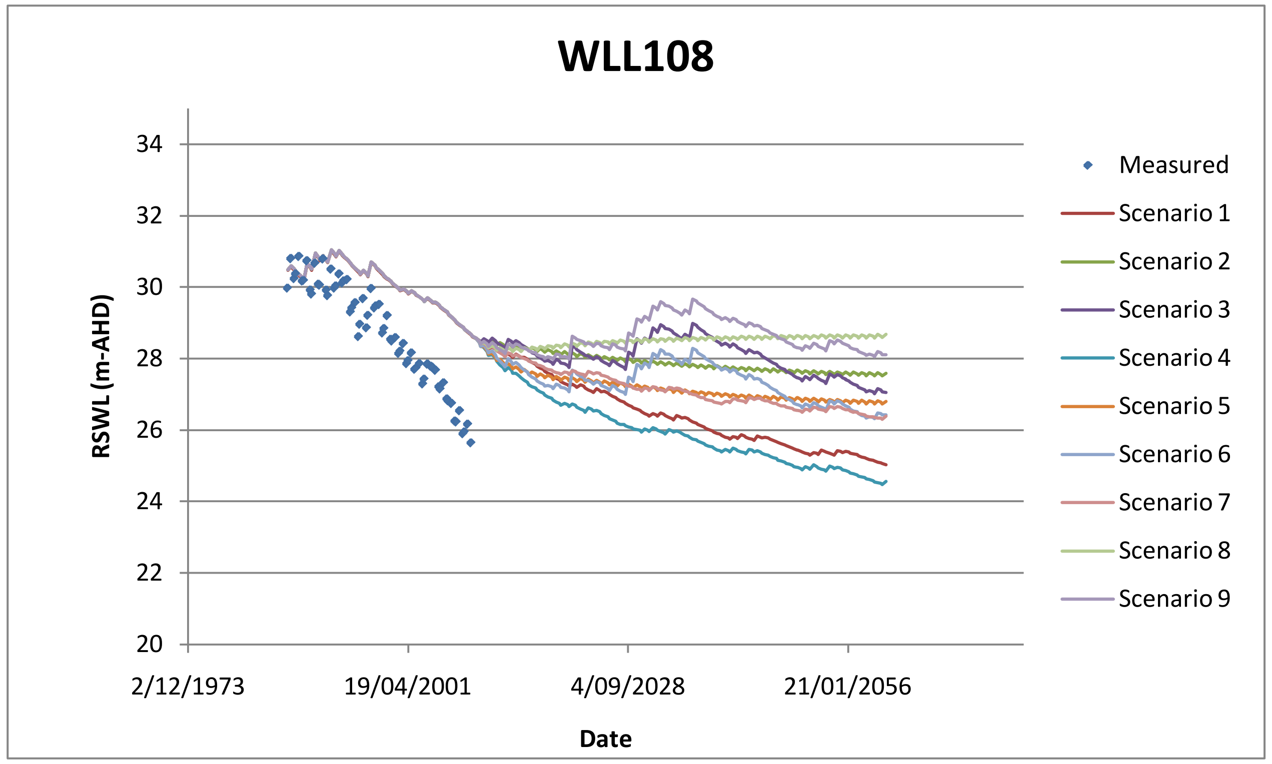
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9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RSWL (m-AHD)
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
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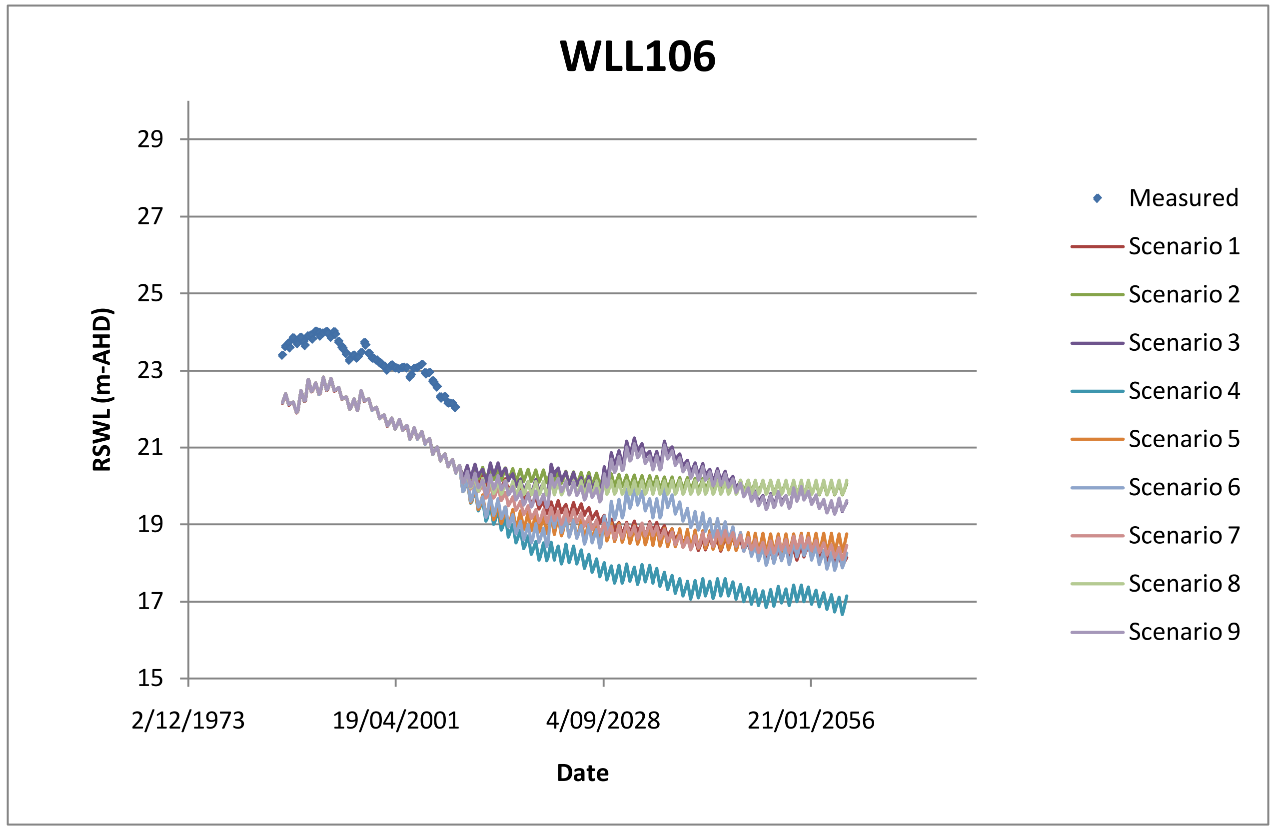
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9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RSWL (m-AHD)
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21/01/2056
Date
Measured
Scenario 1
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Scenario 4
Scenario 5
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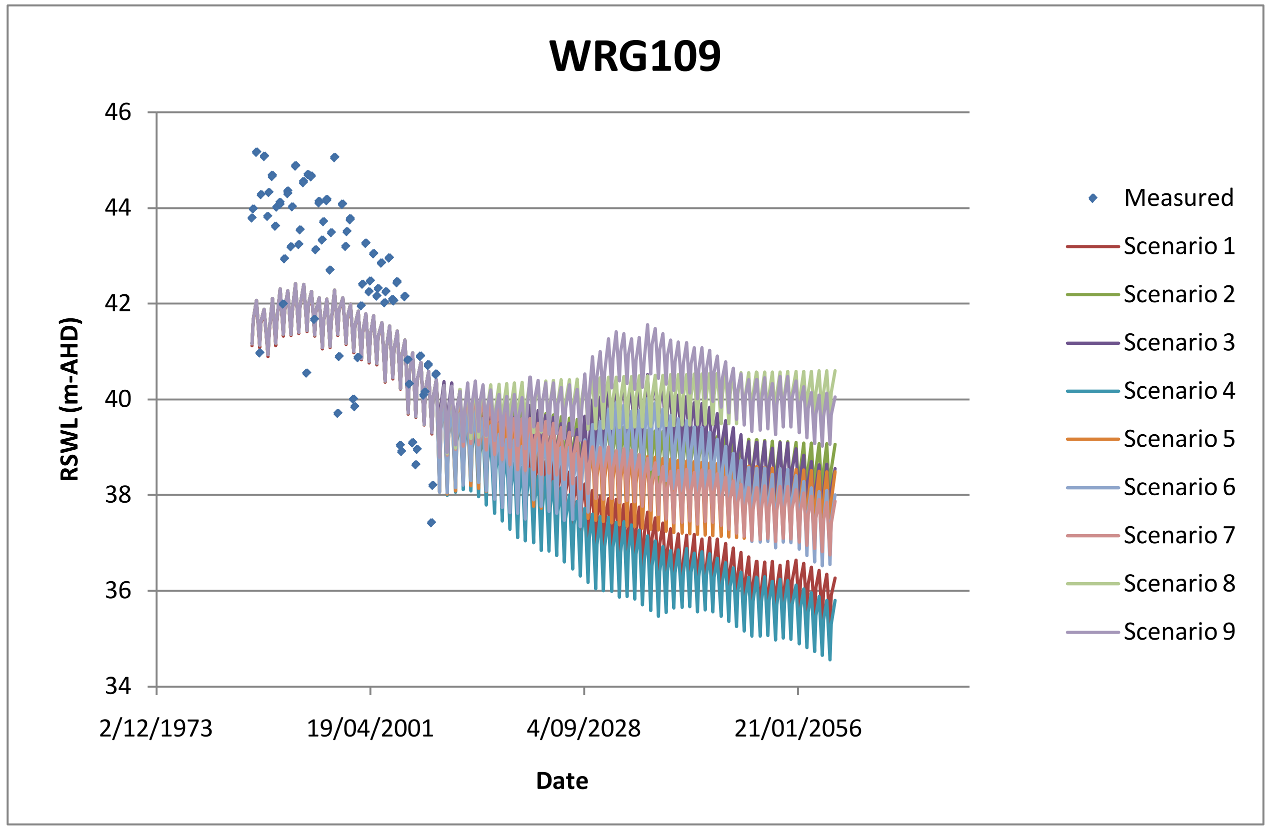
Scenario 7
Scenario 8
Scenario 9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RSWL (m-AHD)
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
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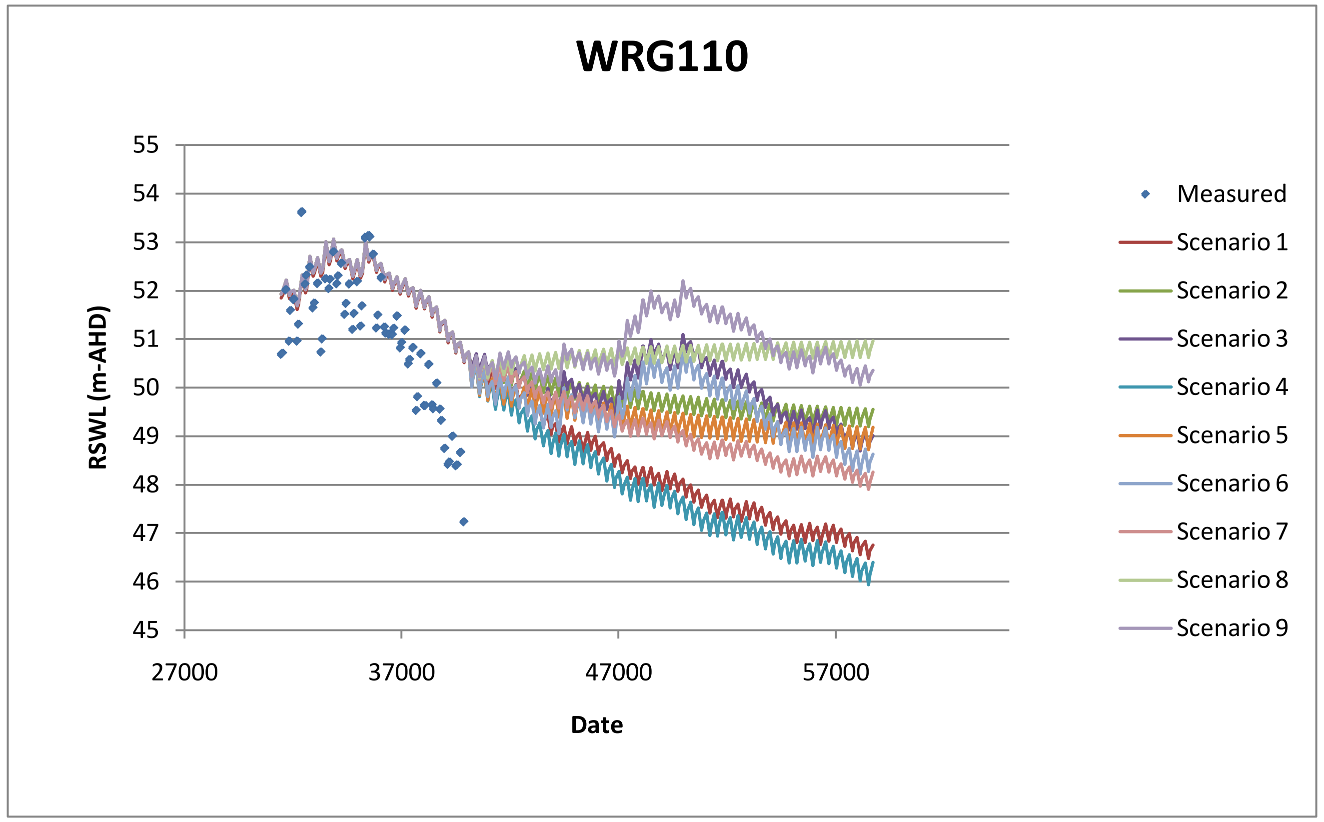
Scenario 7
Scenario 8
Scenario 9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RSWL (m-AHD)
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27000
37000
47000
57000
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
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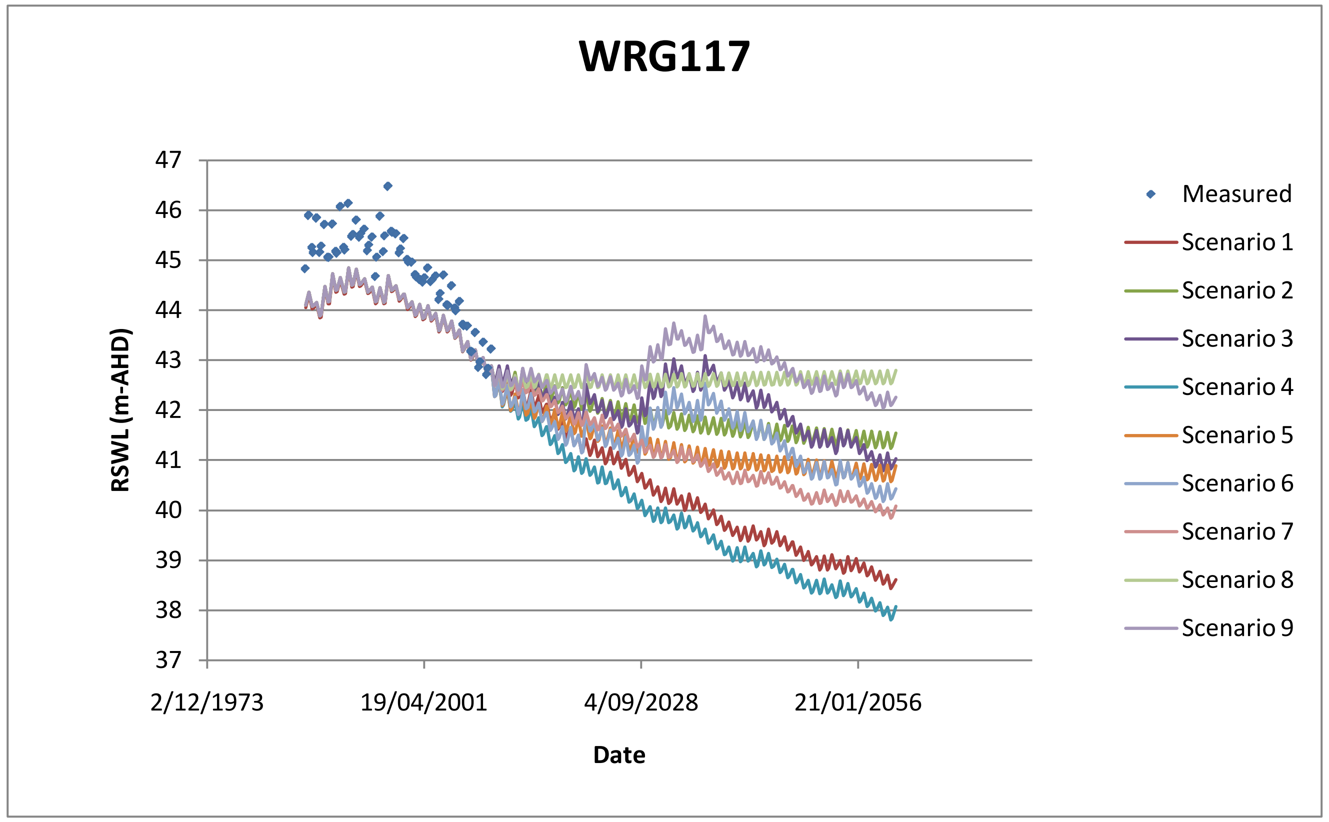
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2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
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Scenario 6
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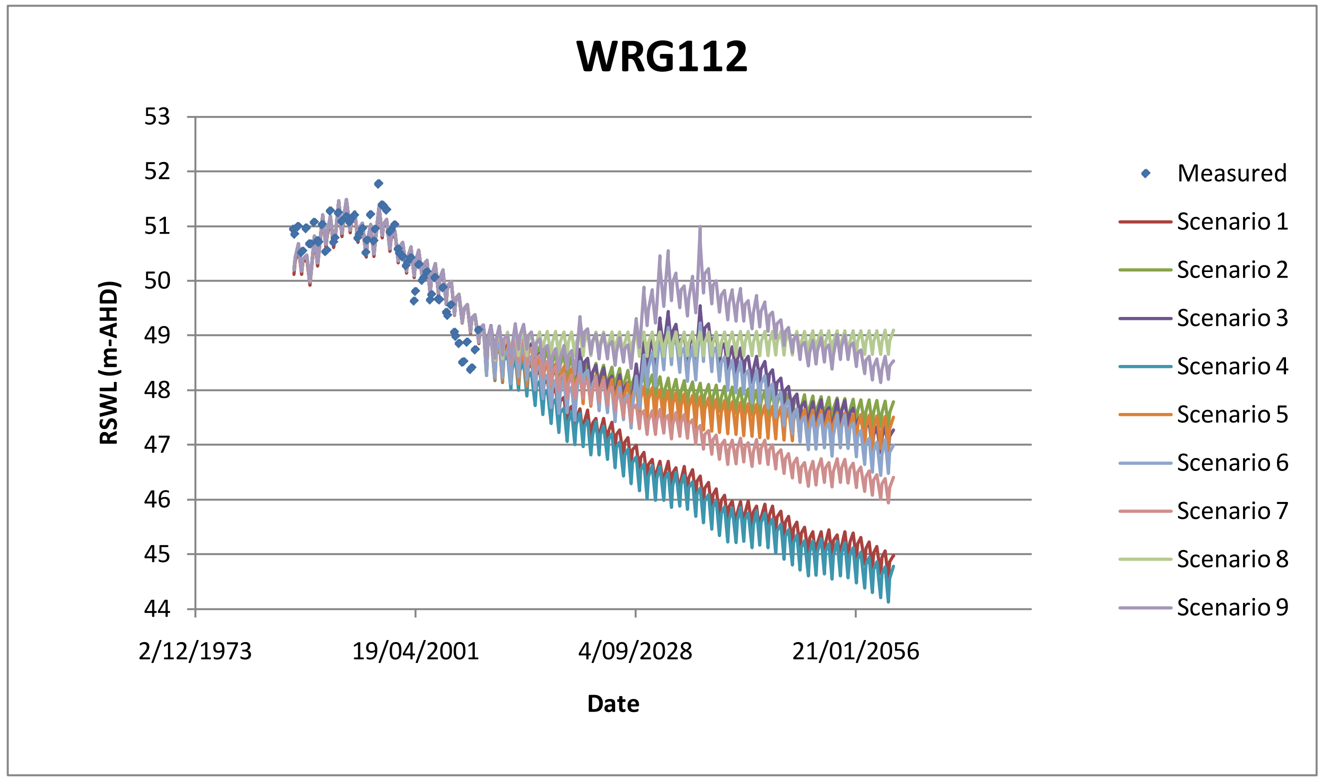
Scenario 9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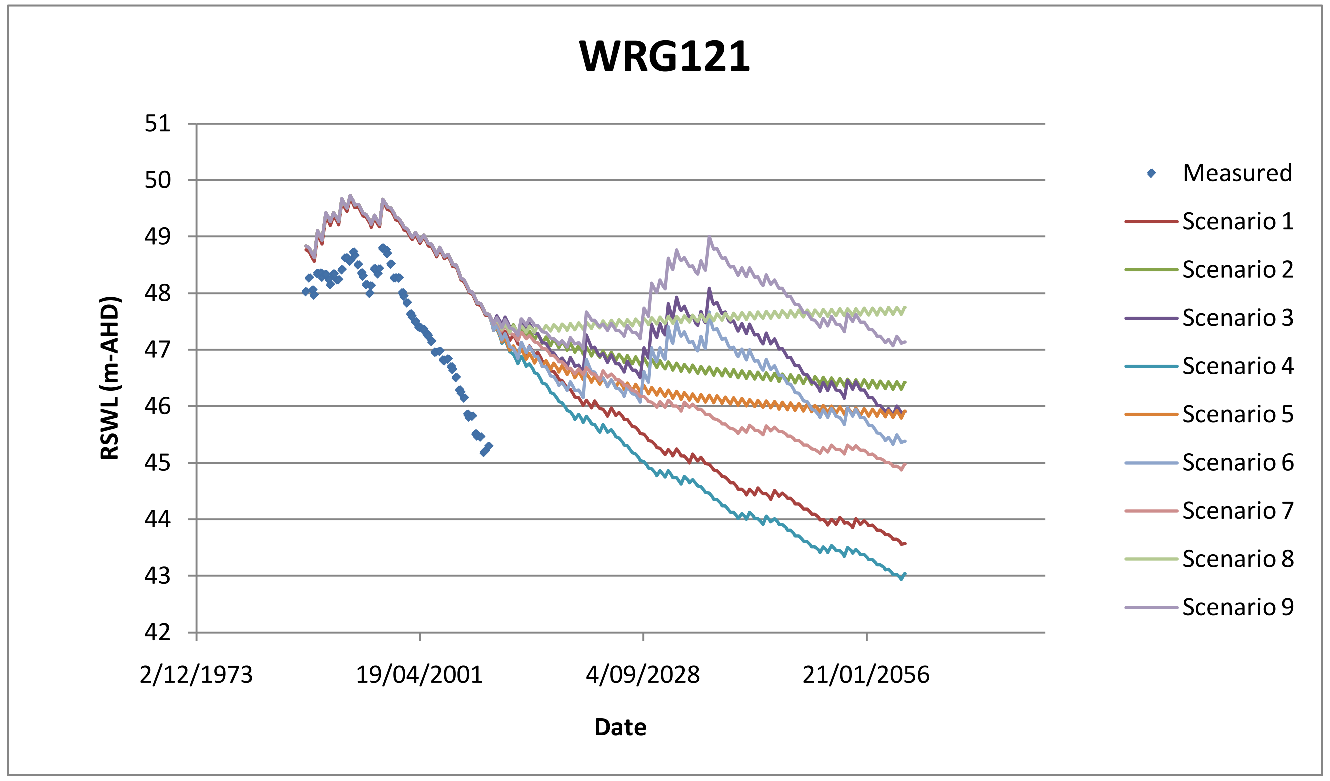
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9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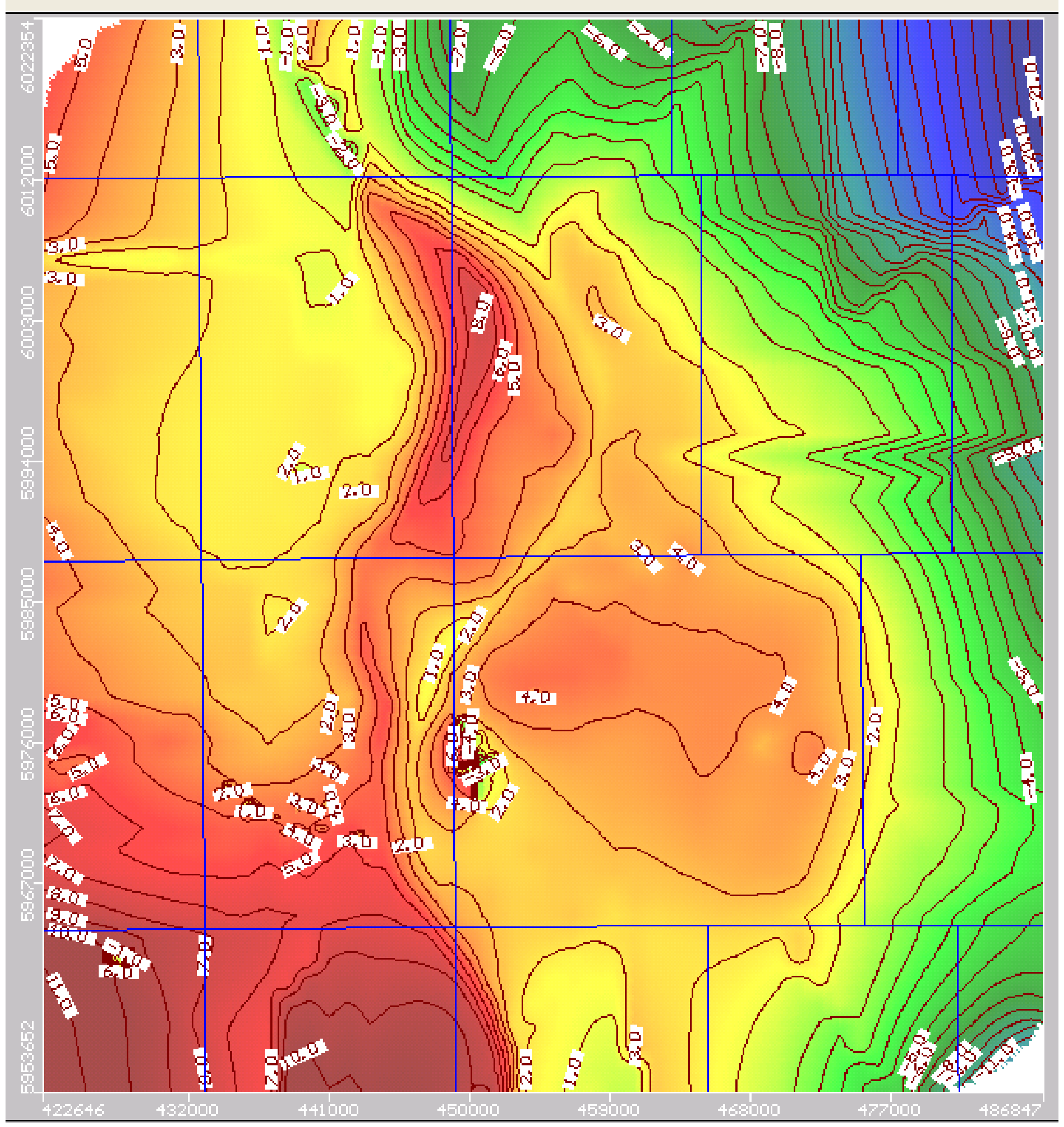
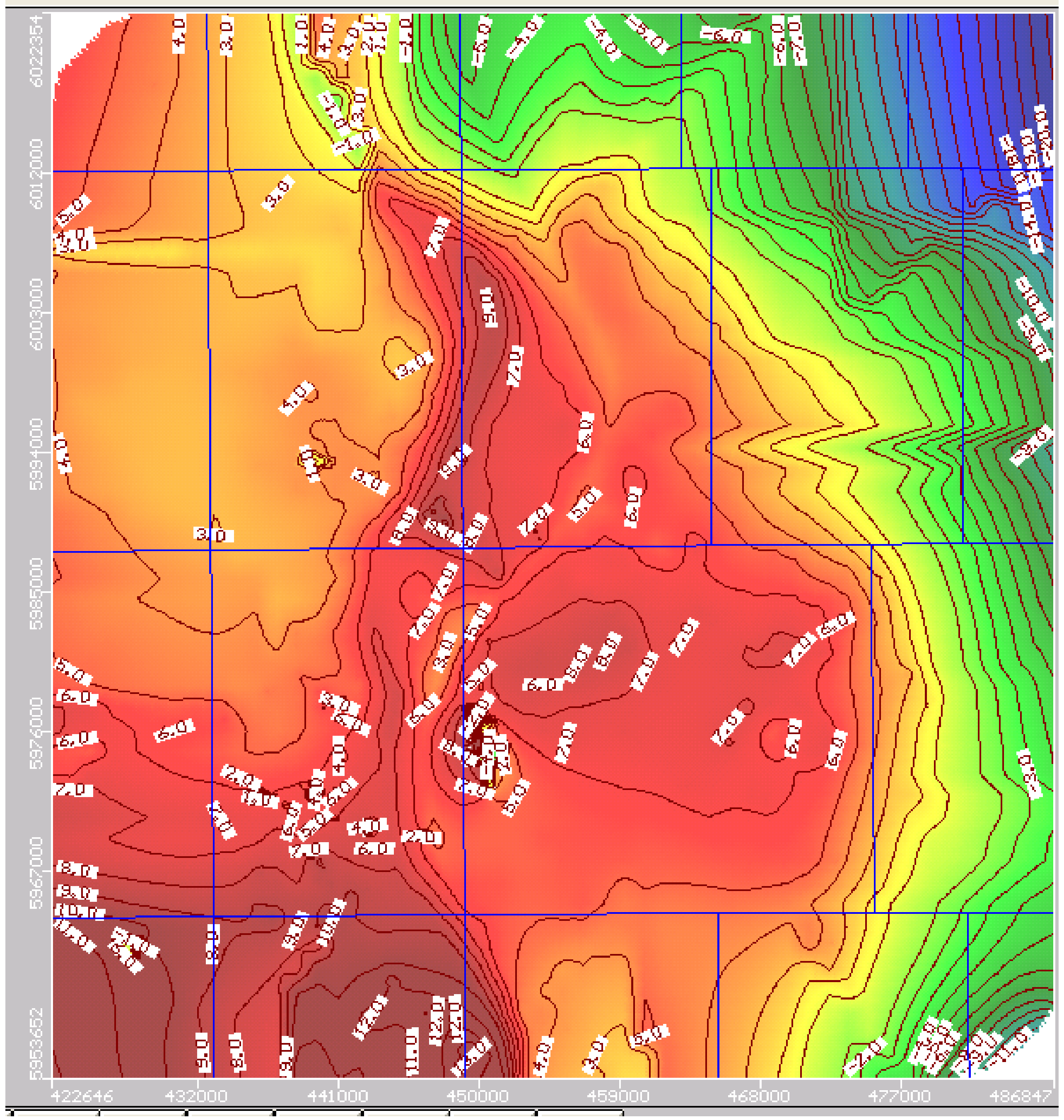
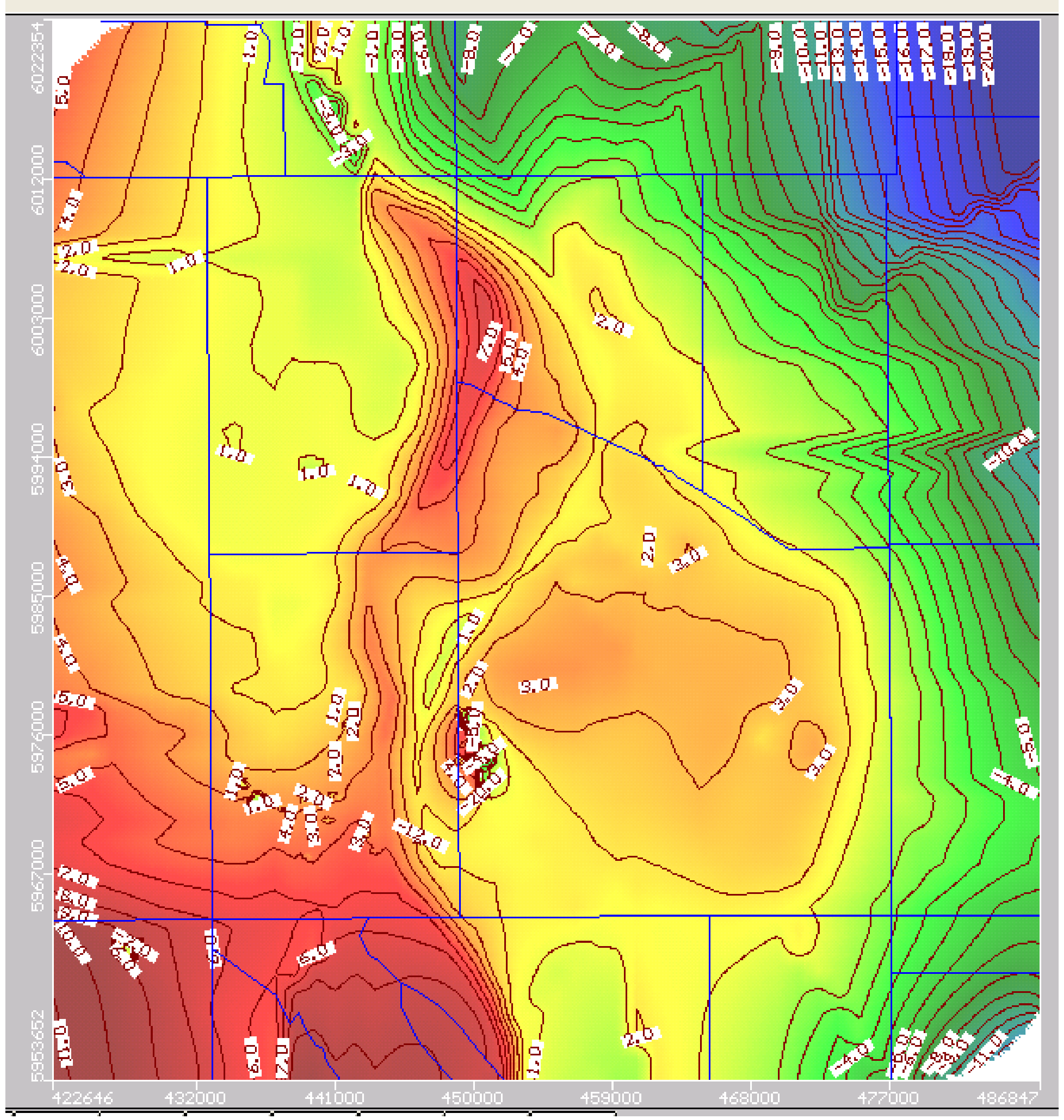
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Scenario 7
Scenario 8
Scenario 9



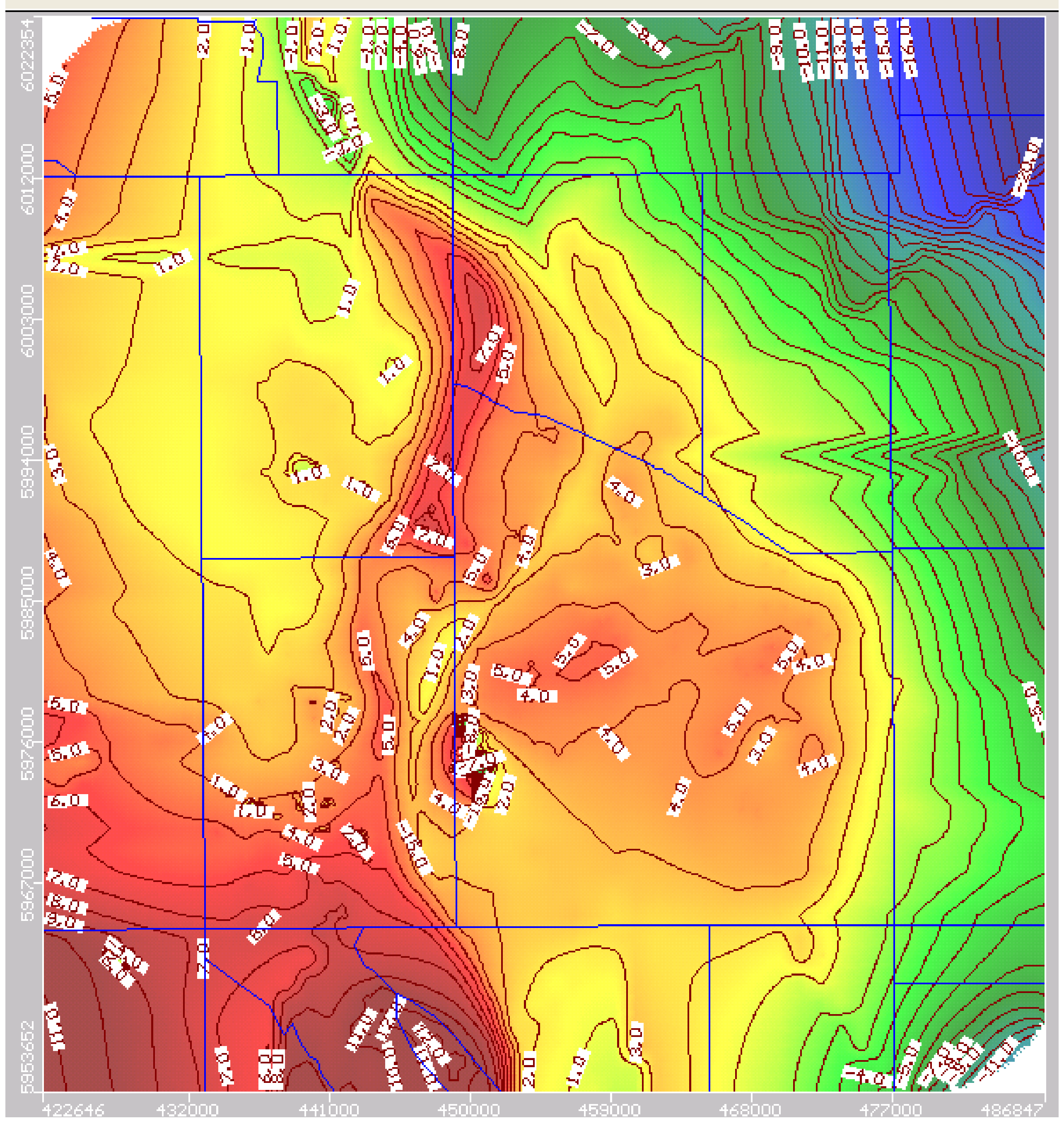
Scenario 1—2020 watertable drawdown (m)



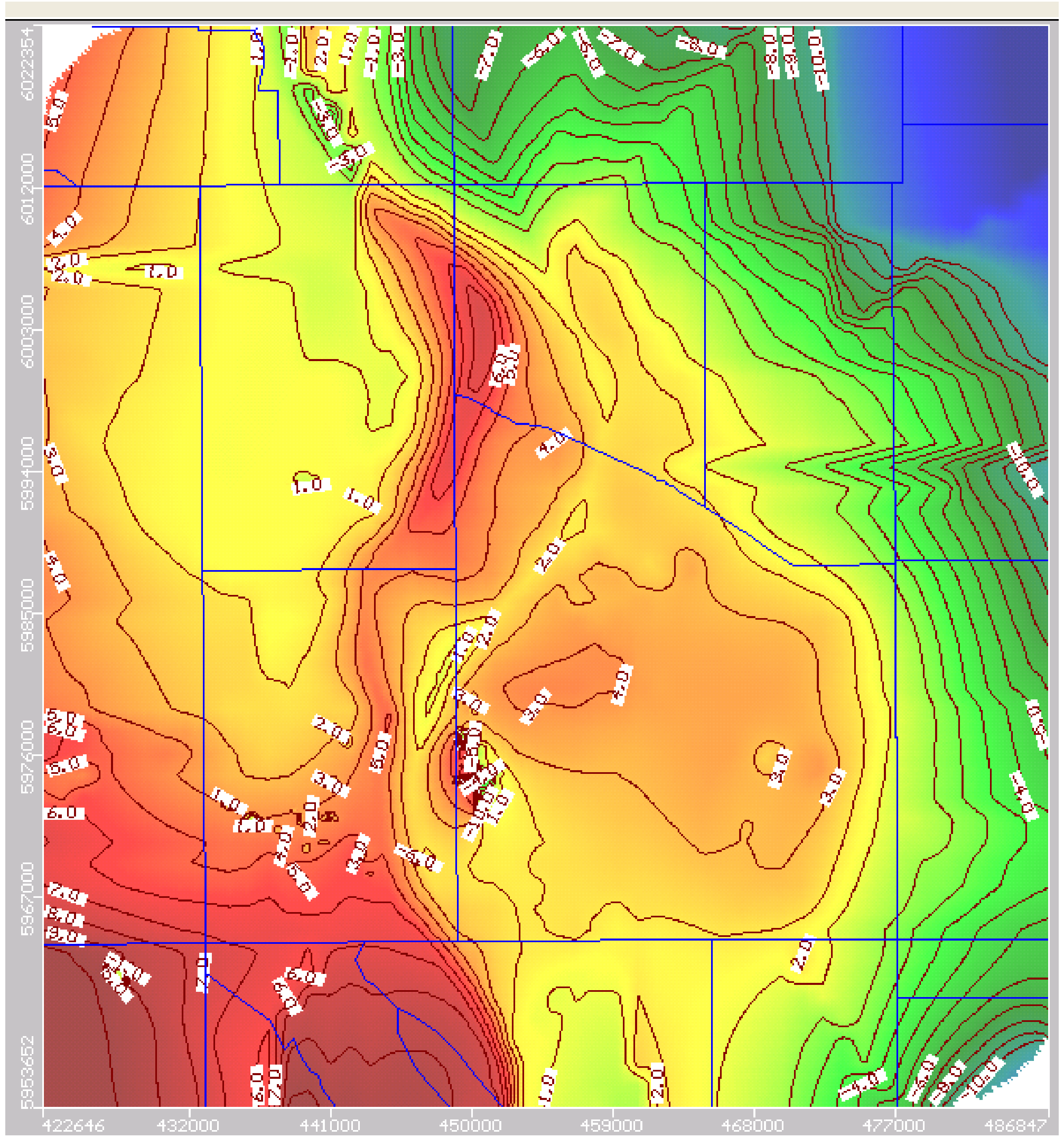
Scenario 1—2060 watertable drawdown (m)



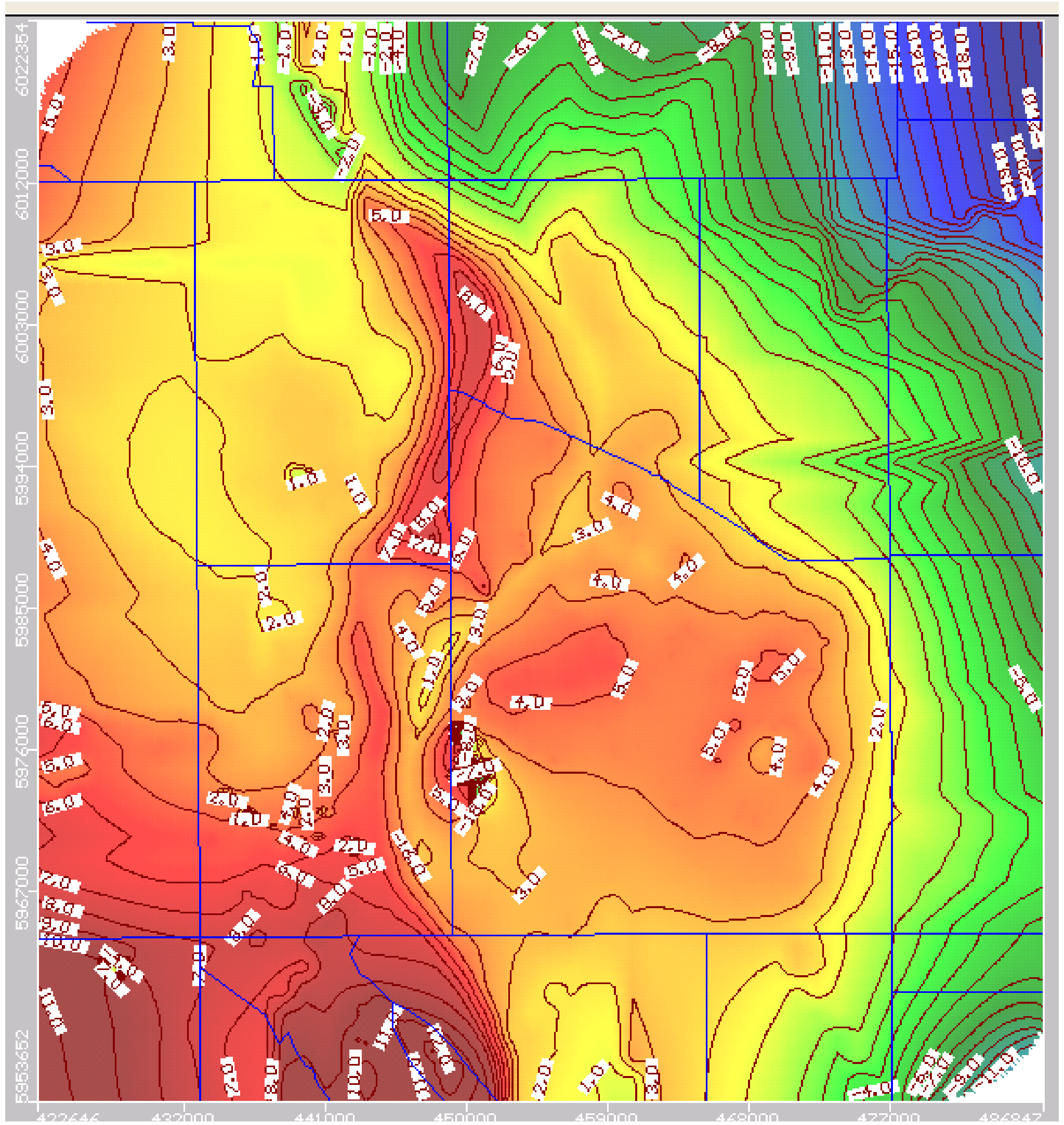
Scenario 2—2020 watertable drawdown (m)



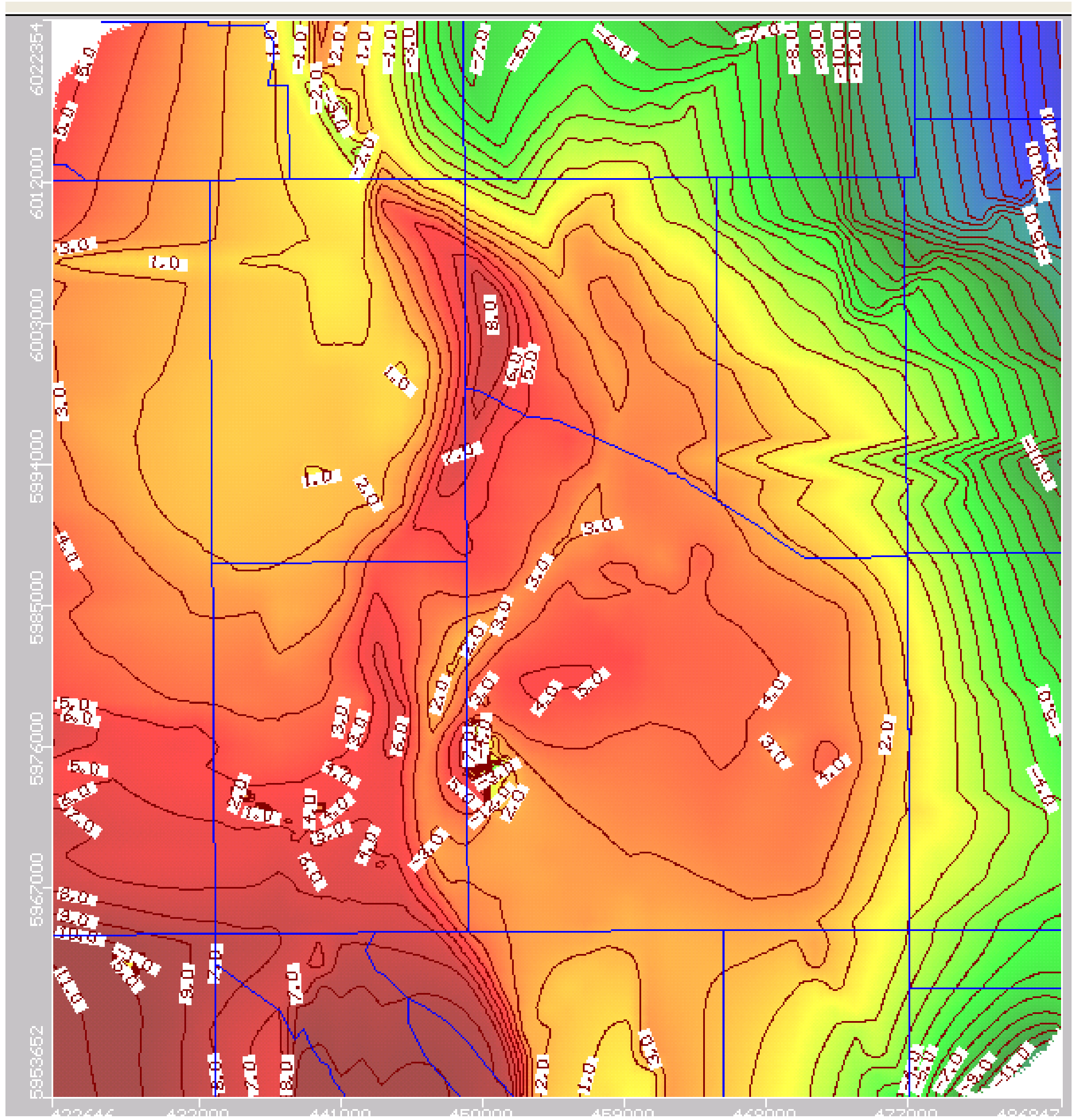
Scenario 2—2060 watertable drawdown (m)



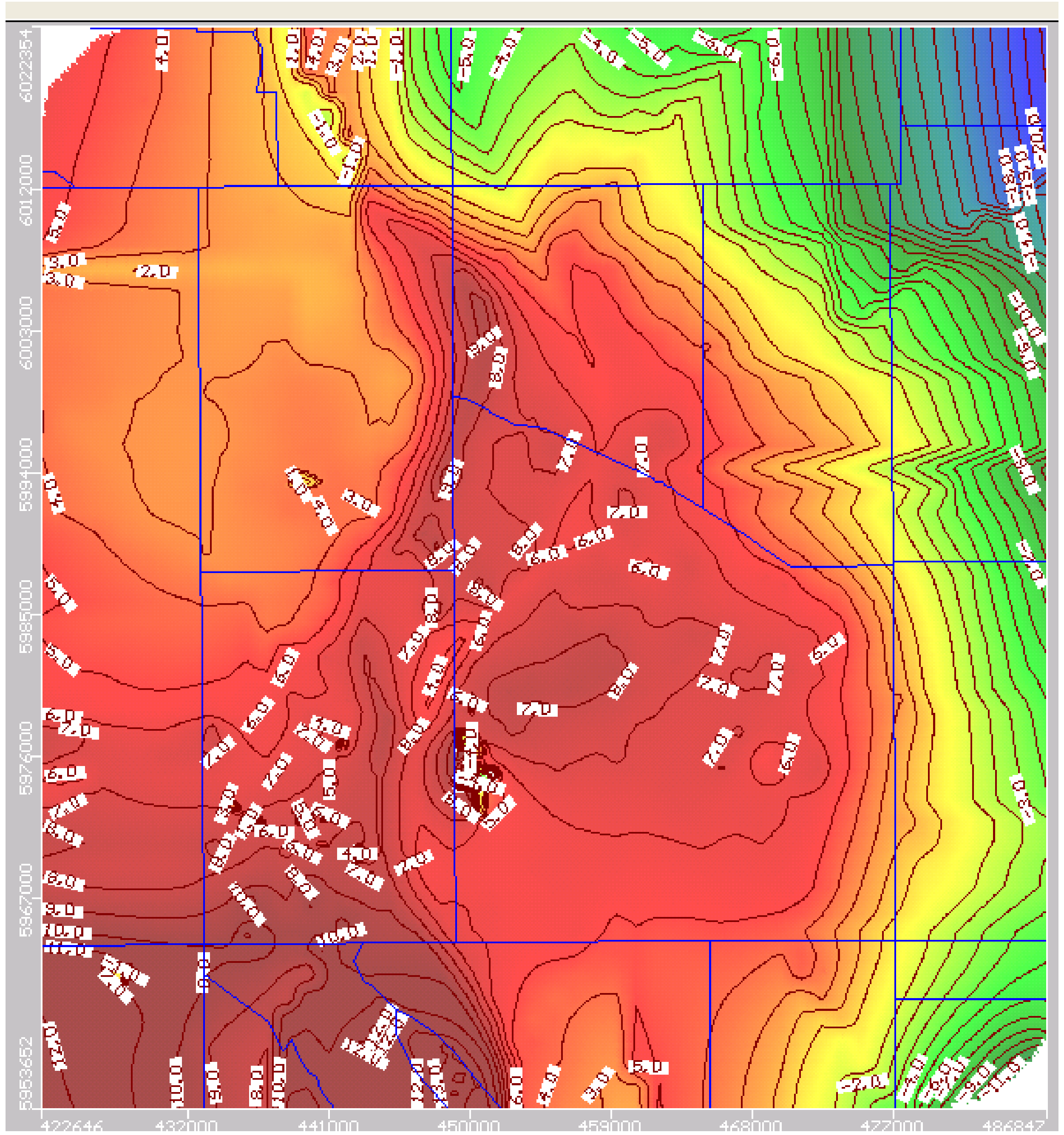
Scenario 3—2020 watertable drawdown (m)



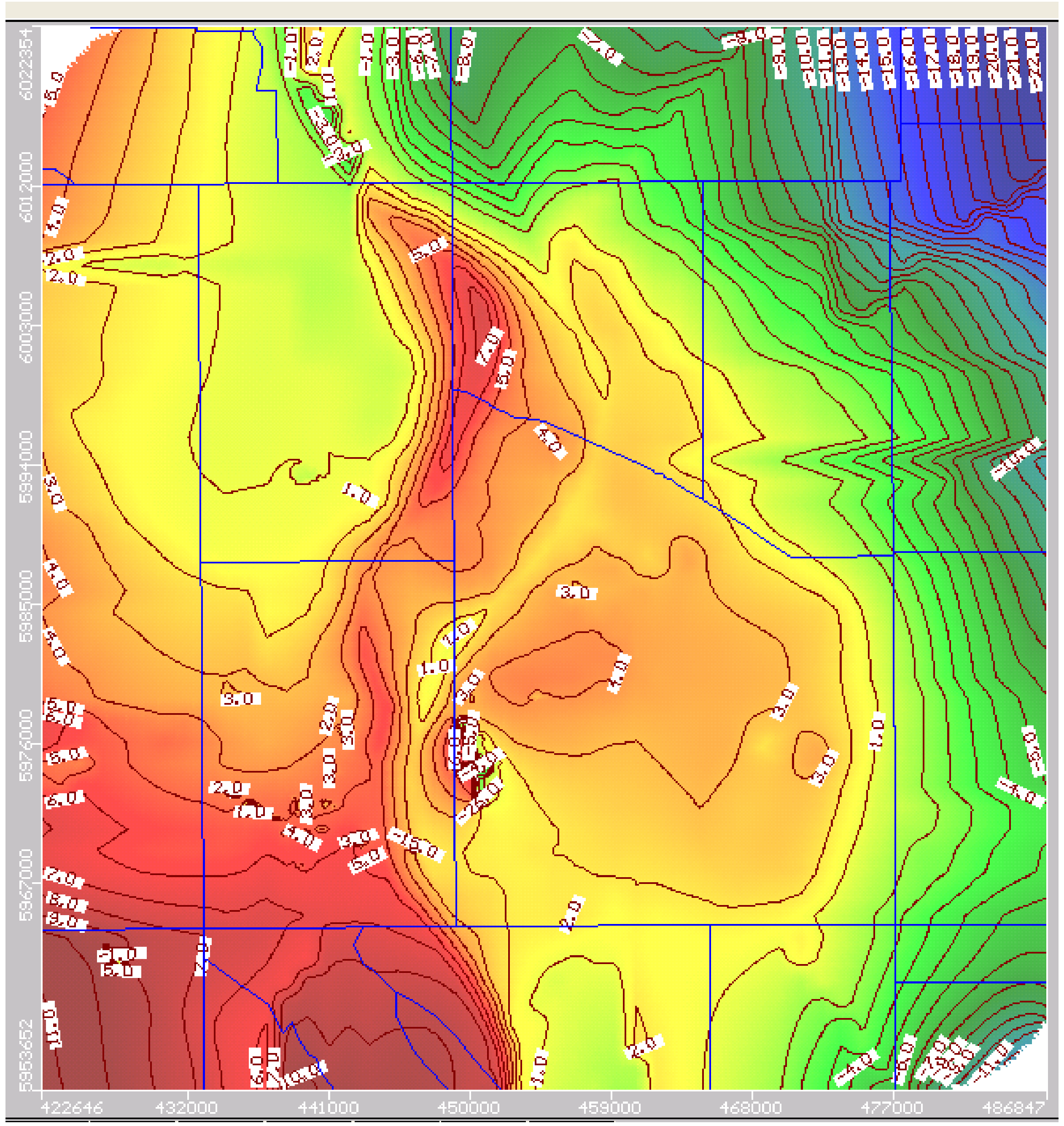
Scenario 3—2060 watertable drawdown (m)

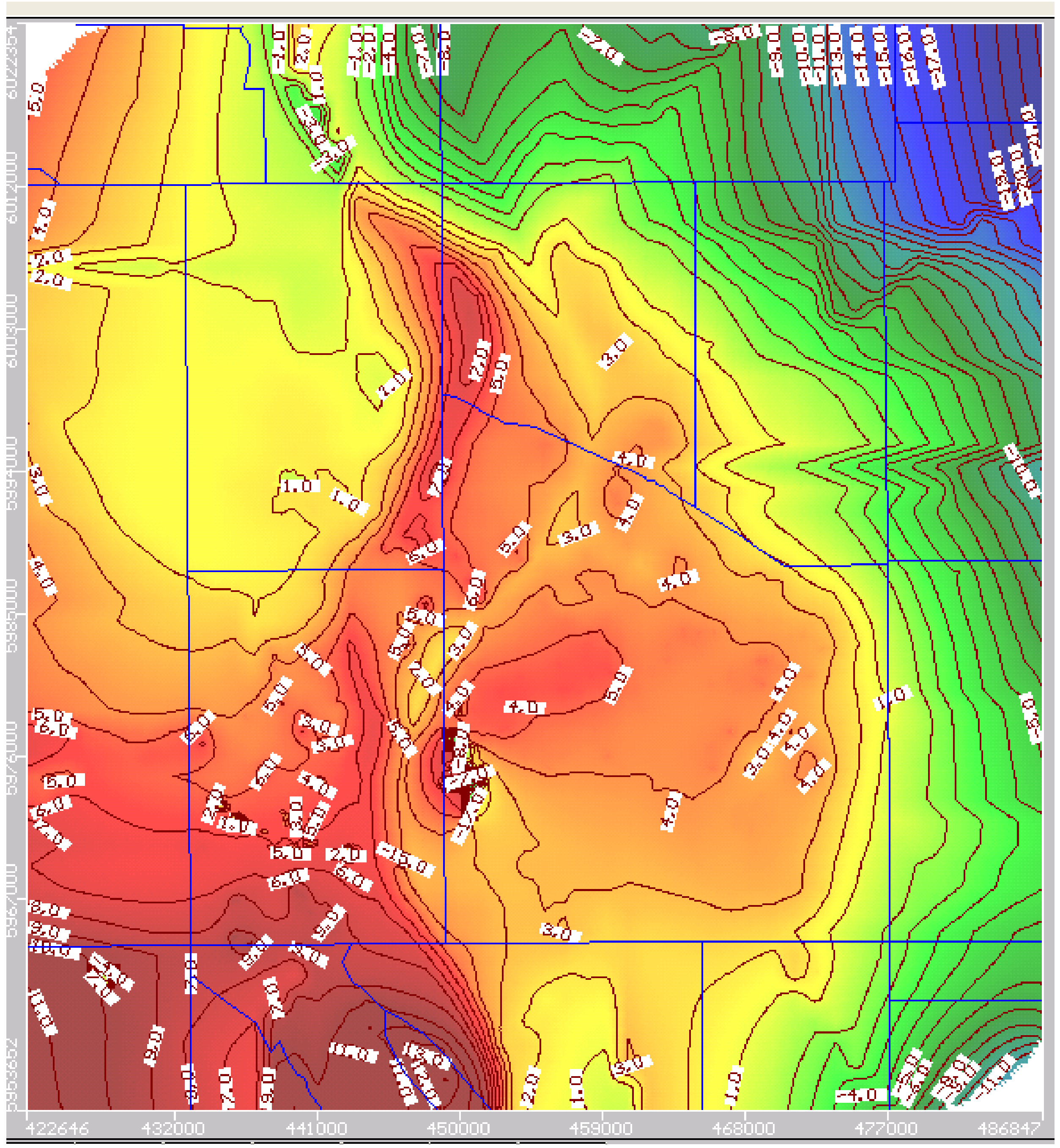


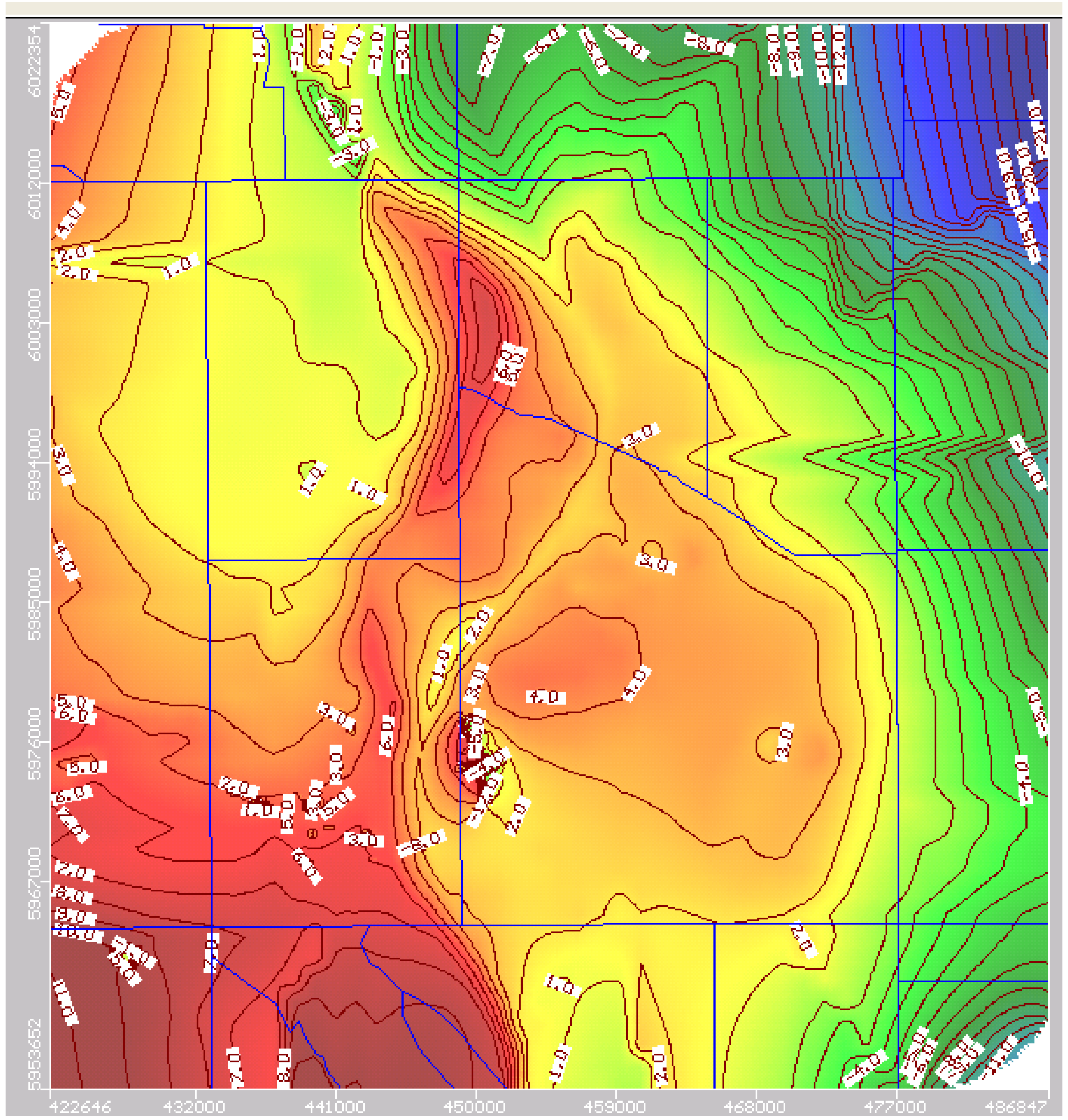
Scenario 4—2020 watertable drawdown (m)



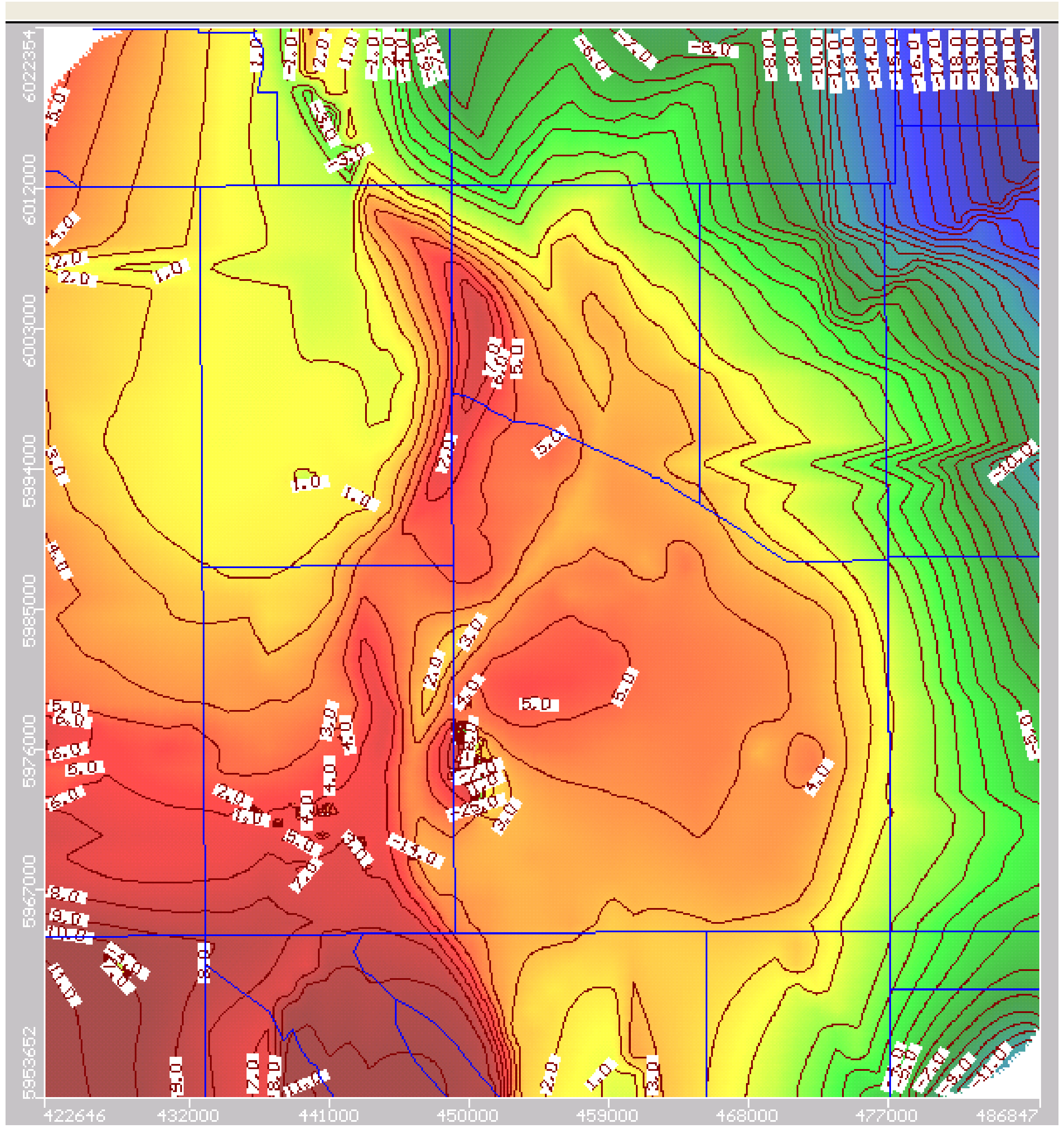
Scenario 4—2060 watertable drawdown (m)


Scenario 5—2020 watertable drawdown (m)

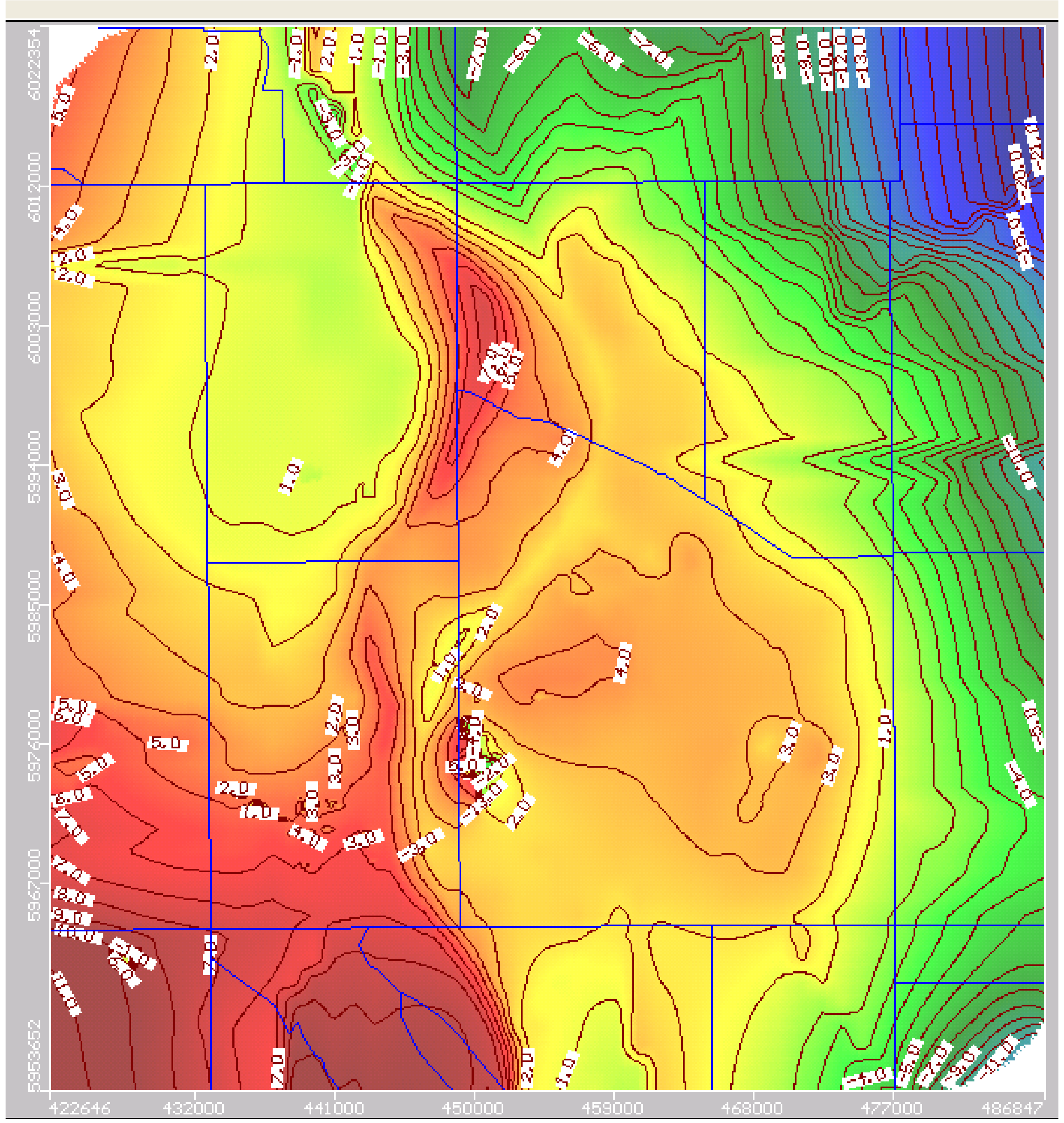

Scenario 5—2060 watertable drawdown (m)



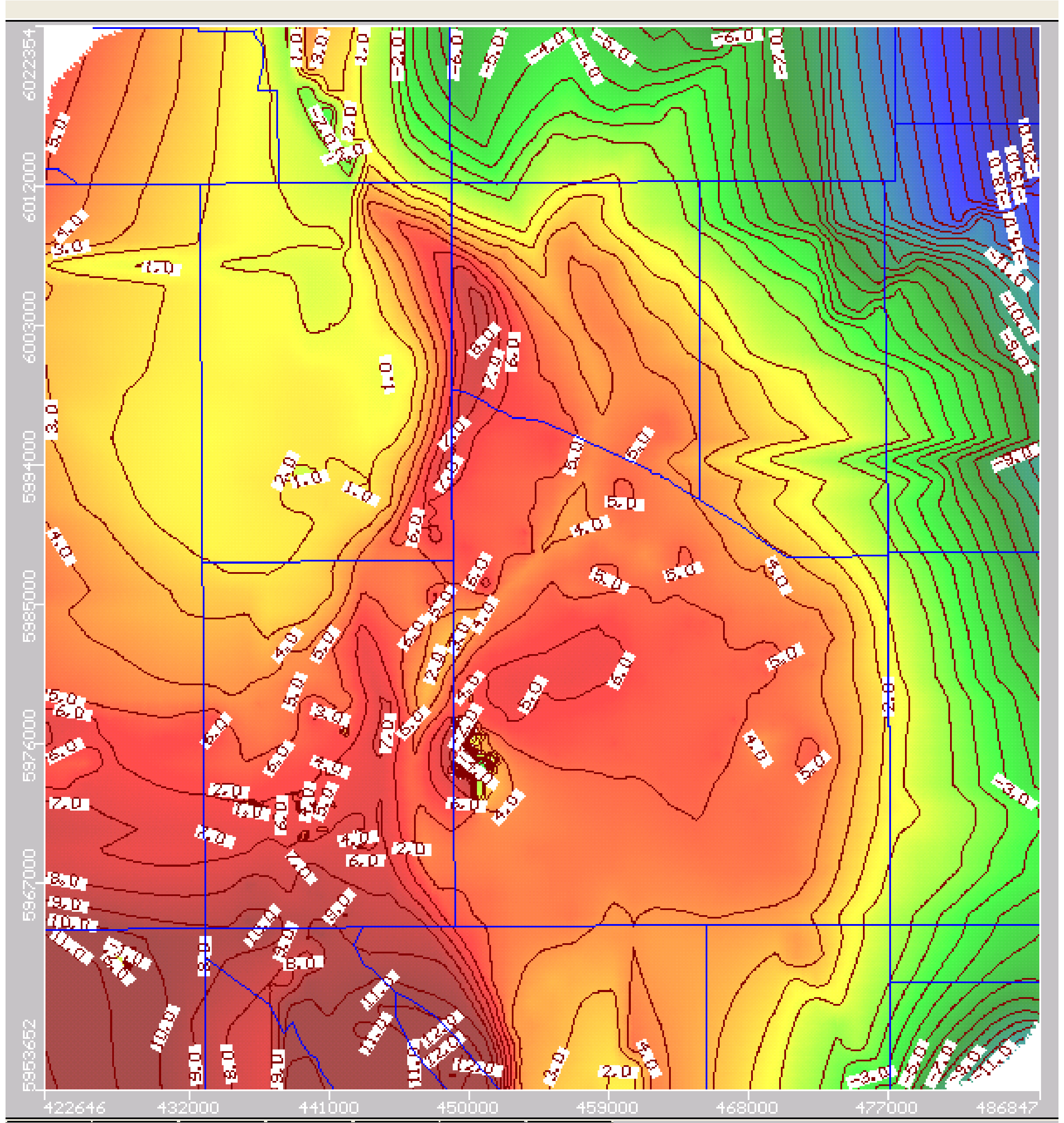
Scenario 6—2020 watertable drawdown (m)



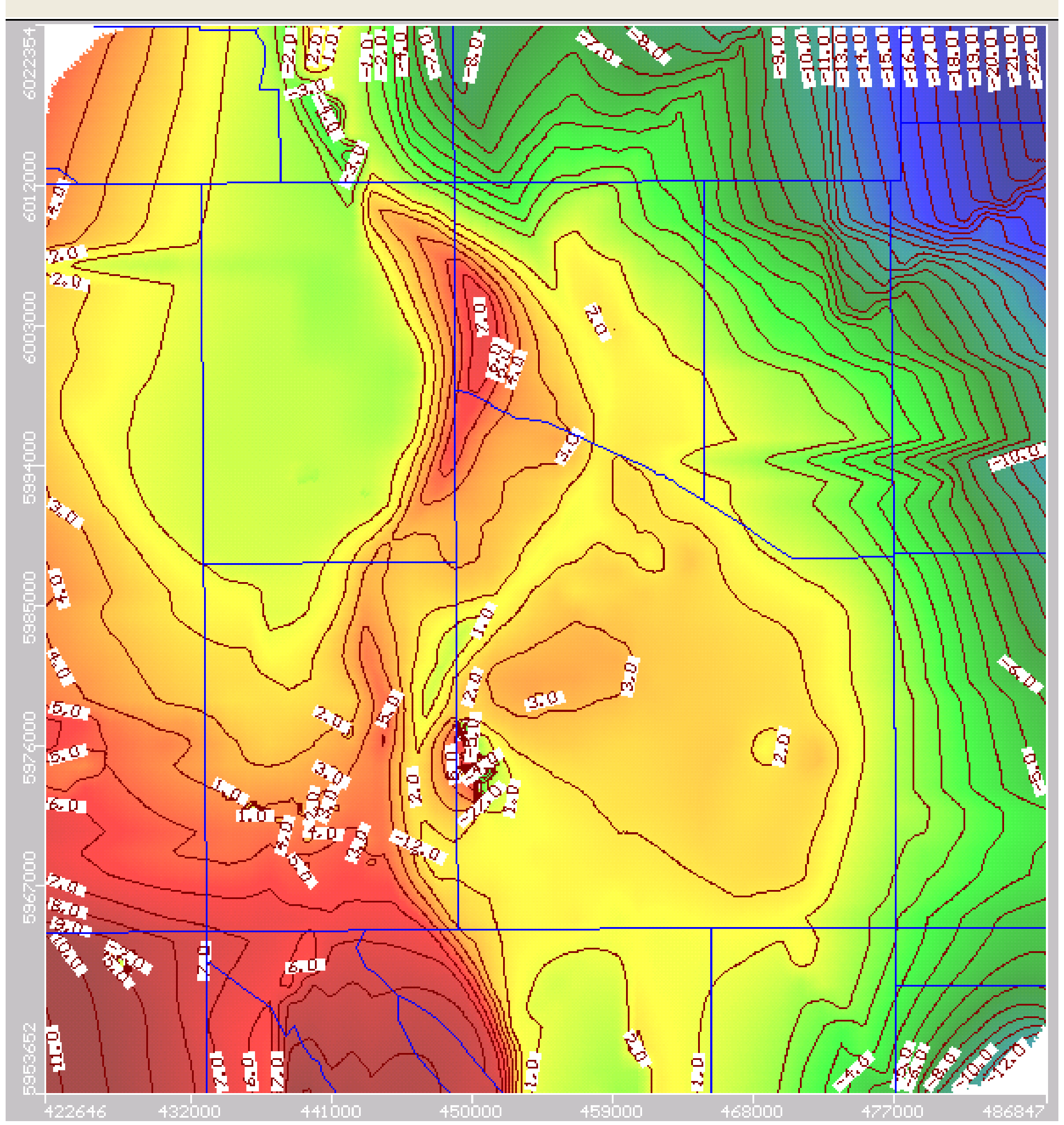
Scenario 6—2060 watertable drawdown (m)



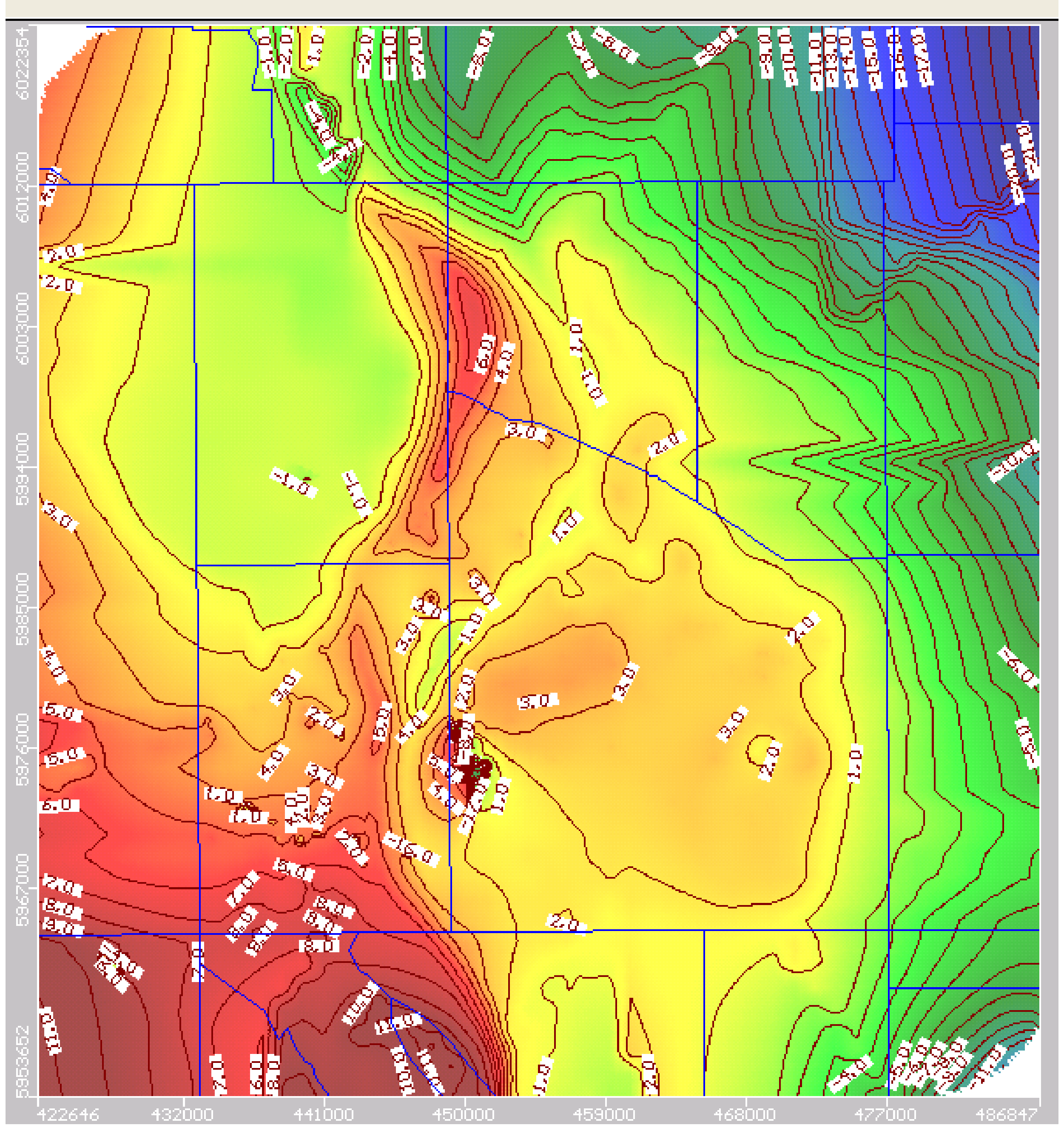
Scenario 7—2020 watertable drawdown (m)



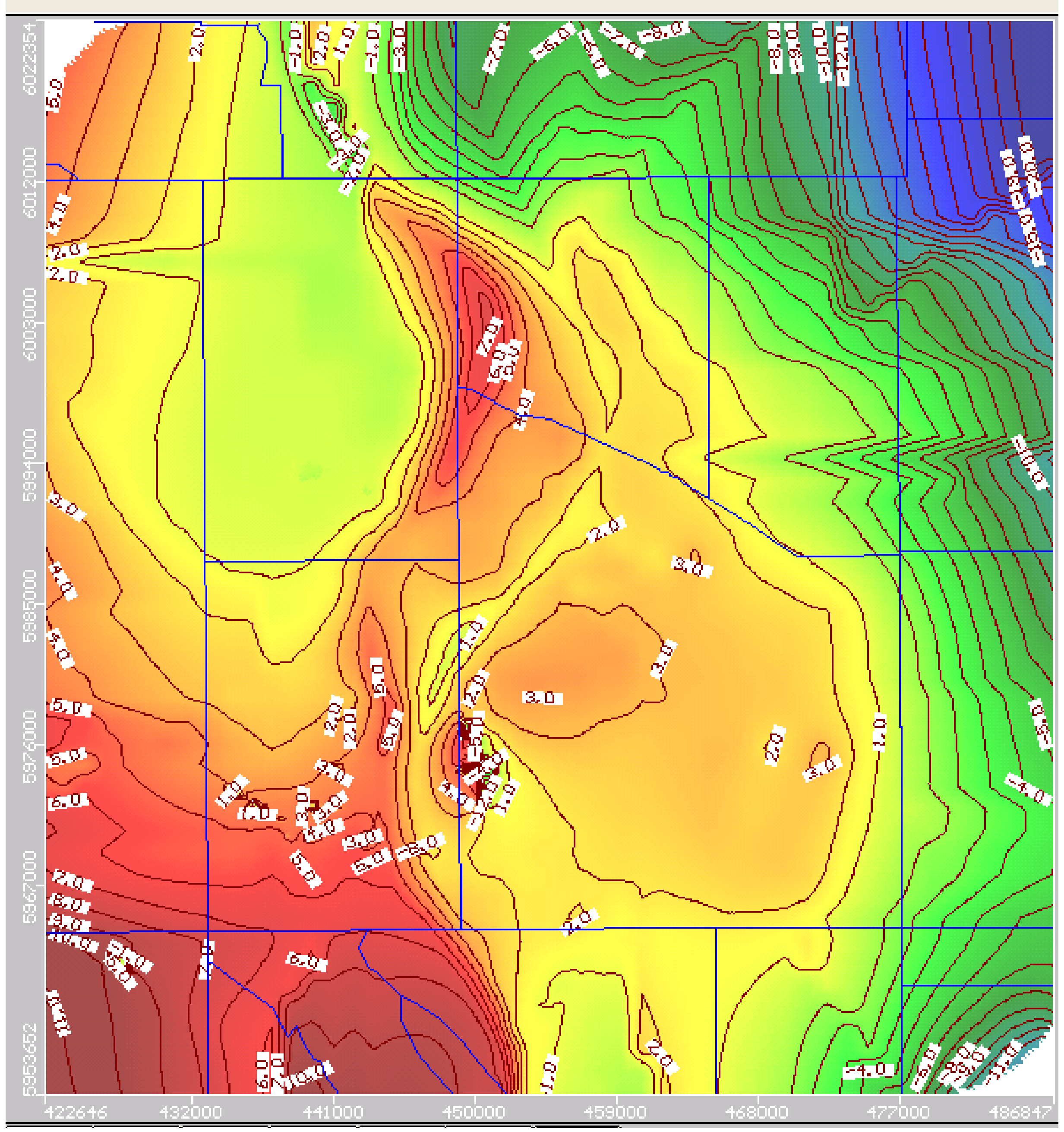
Scenario 7—2060 watertable drawdown (m)



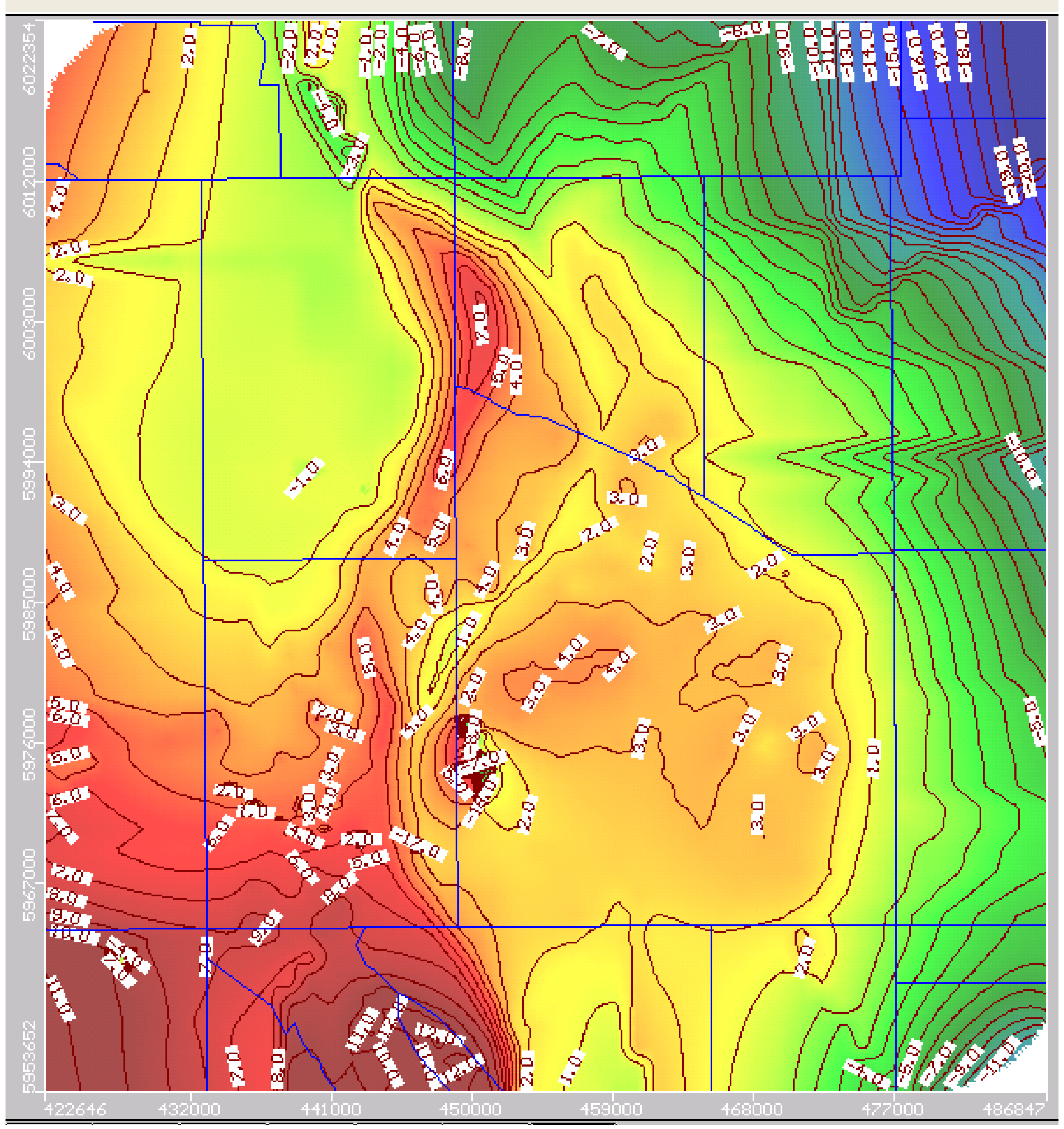
Scenario 8—2020 watertable drawdown (m)



Scenario 8—2060 watertable drawdown (m)

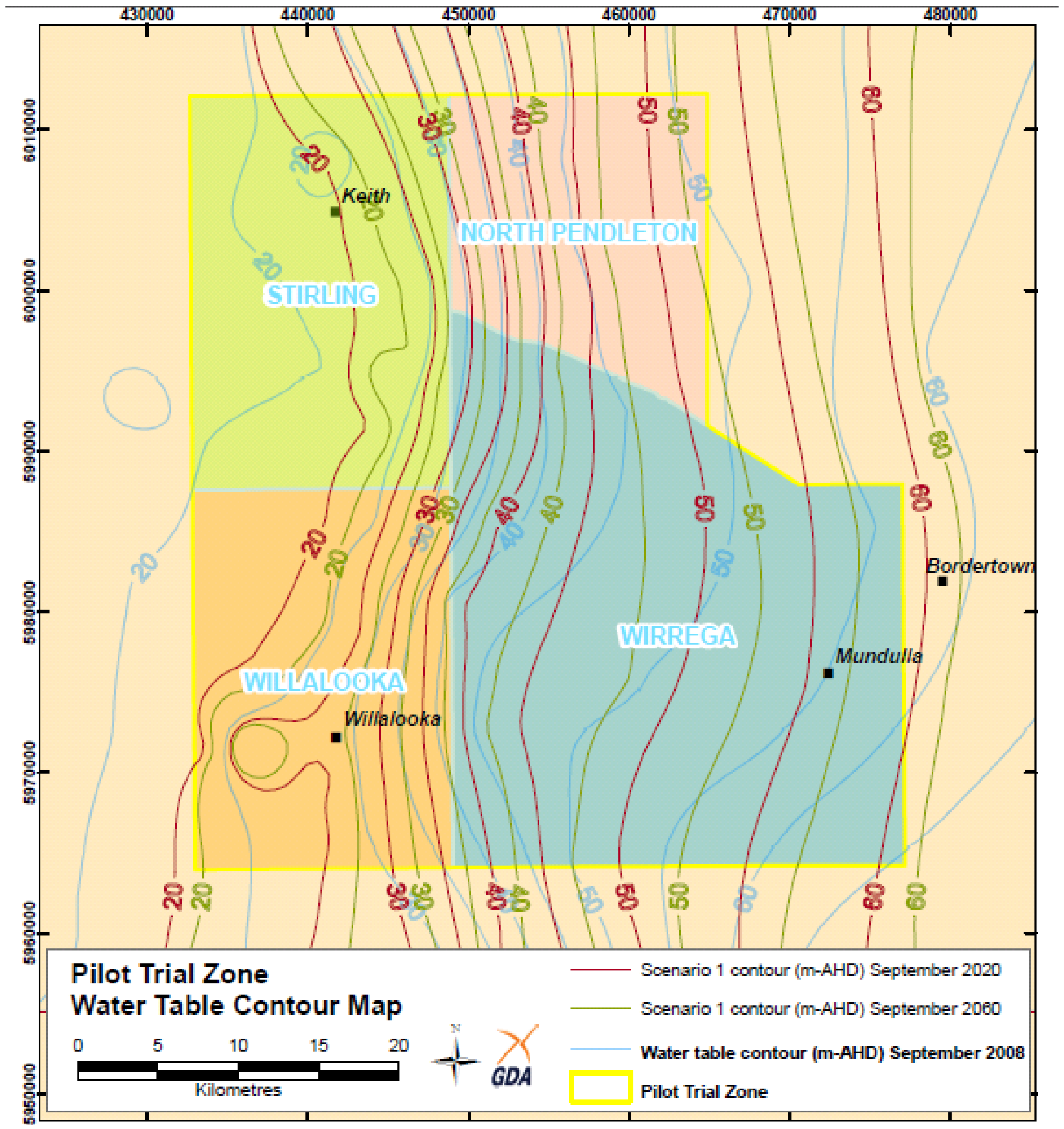


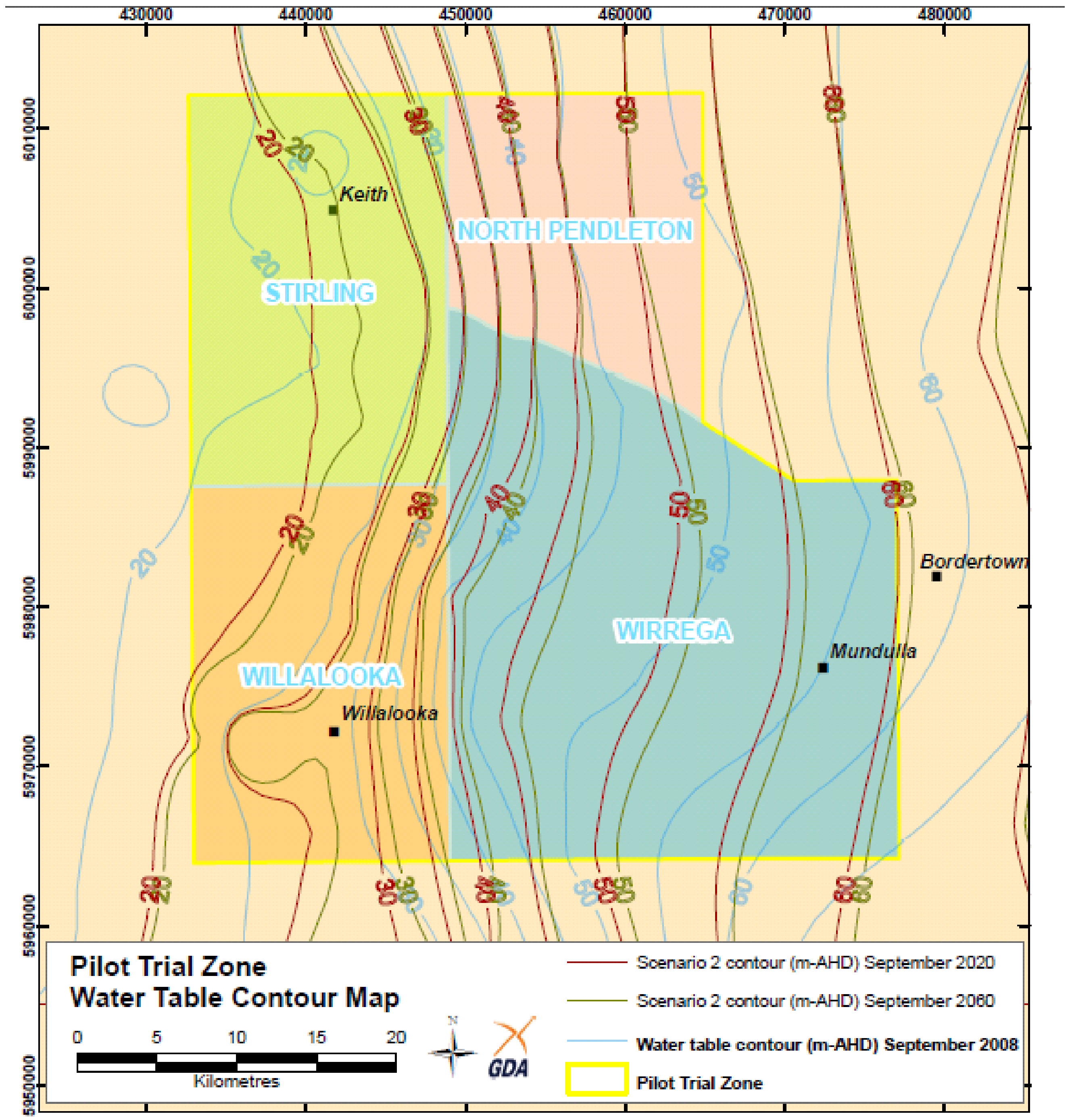
Scenario 9—2020 watertable drawdown (m)

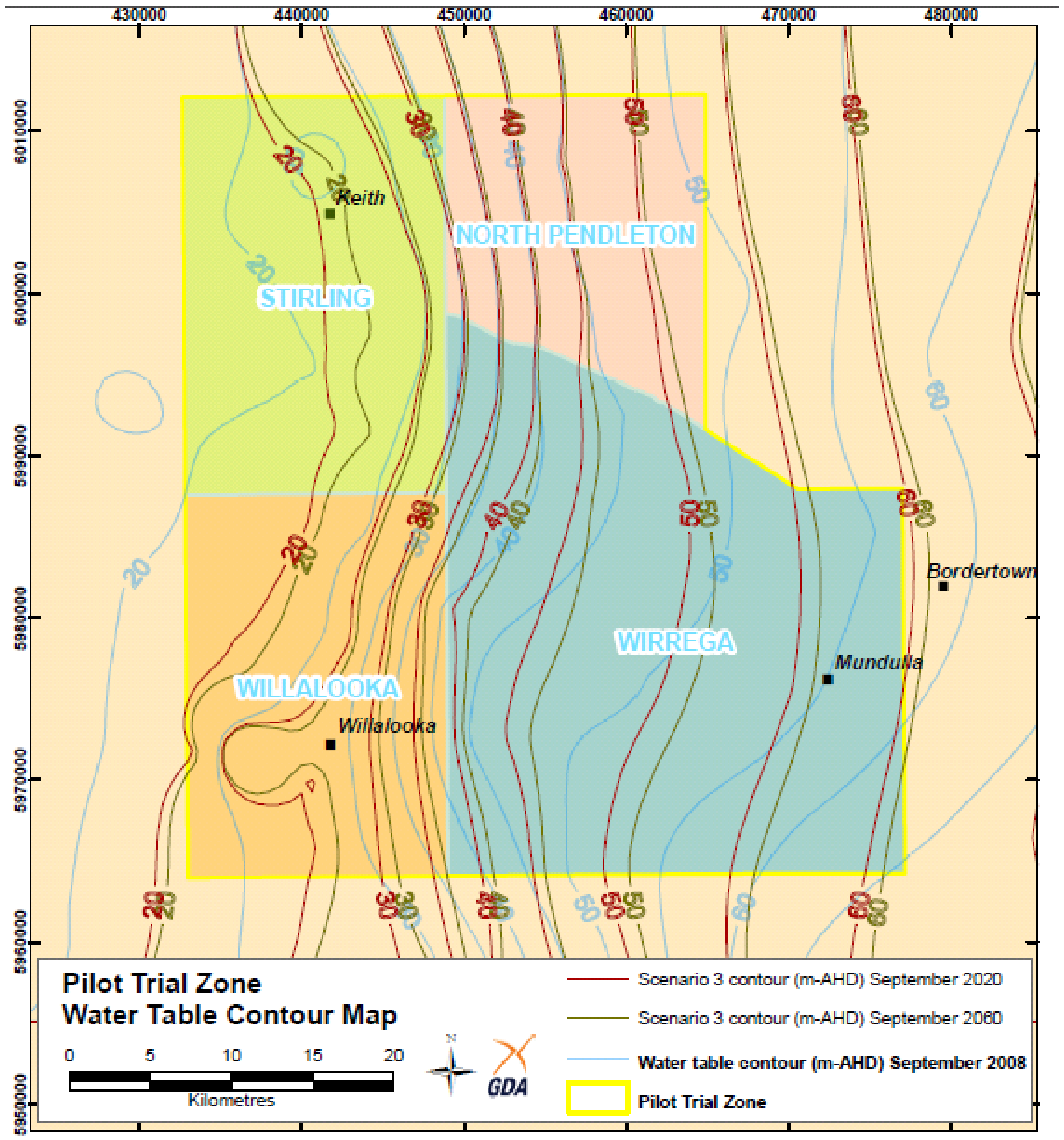


Scenario 9—2060 watertable drawdown (m)

E. SCENARIO POTENTIOMETRIC MAPS







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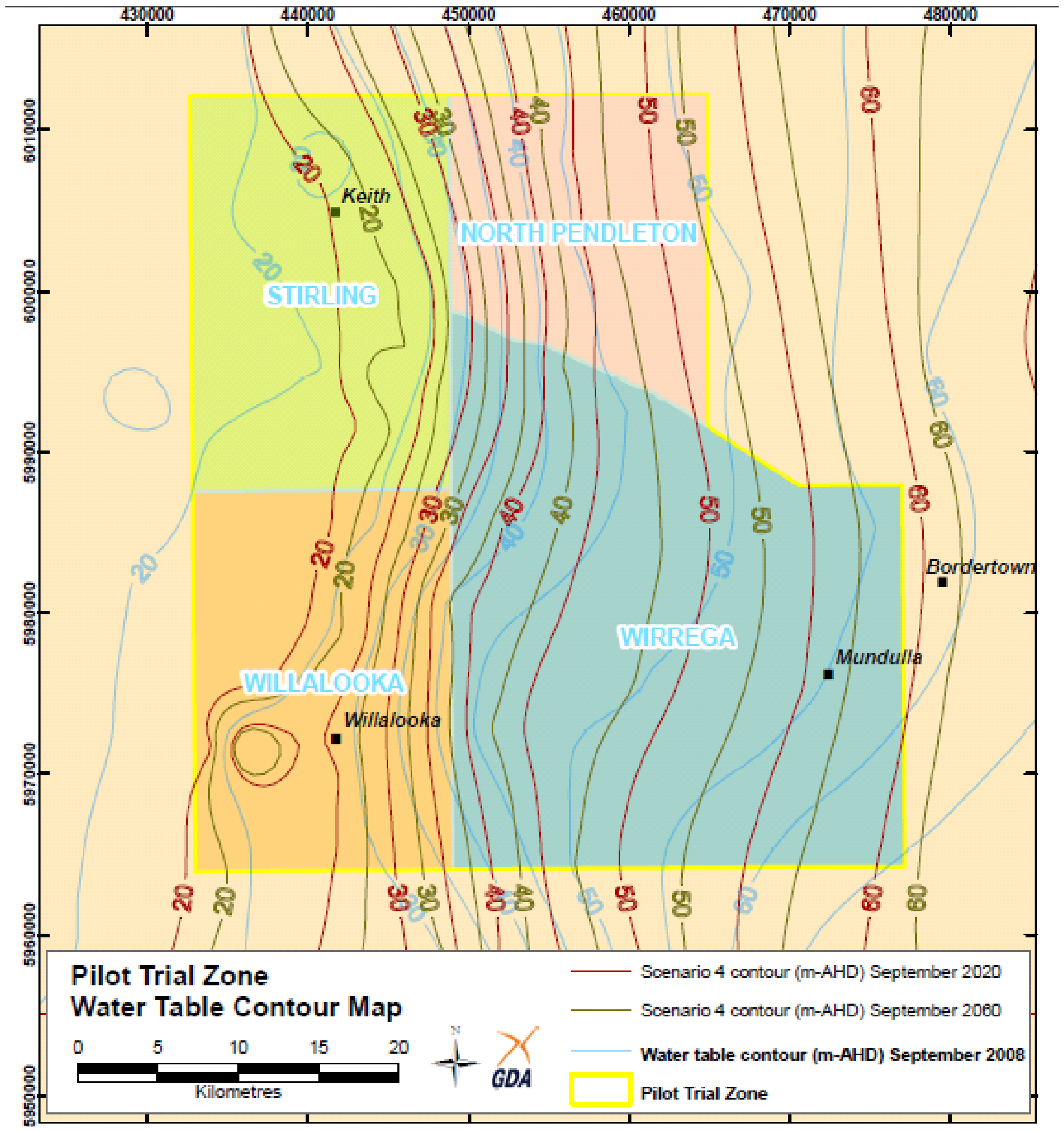
Keith
STIRLING
NORTH PENDLETON
WIRREGA
WILLALOOKA
Willalooka
Mundulla
Bordertown
Pilot Trial Zone
Water Table Contour Map
0
5
10
15
20
Kilometres
GDA
Scenario 3 contour (m-AHD) September 2020
Scenario 3 contour (m-AHD) September 2060
Water table contour (m-AHD) September 2008
Pilot Trial Zone



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STIRLING
NORTH PENDLETON
WIRREGA
WILLALOOKA
Willalooka
Mundulla
Bordertown
Pilot Trial Zone
Water Table Contour Map
0
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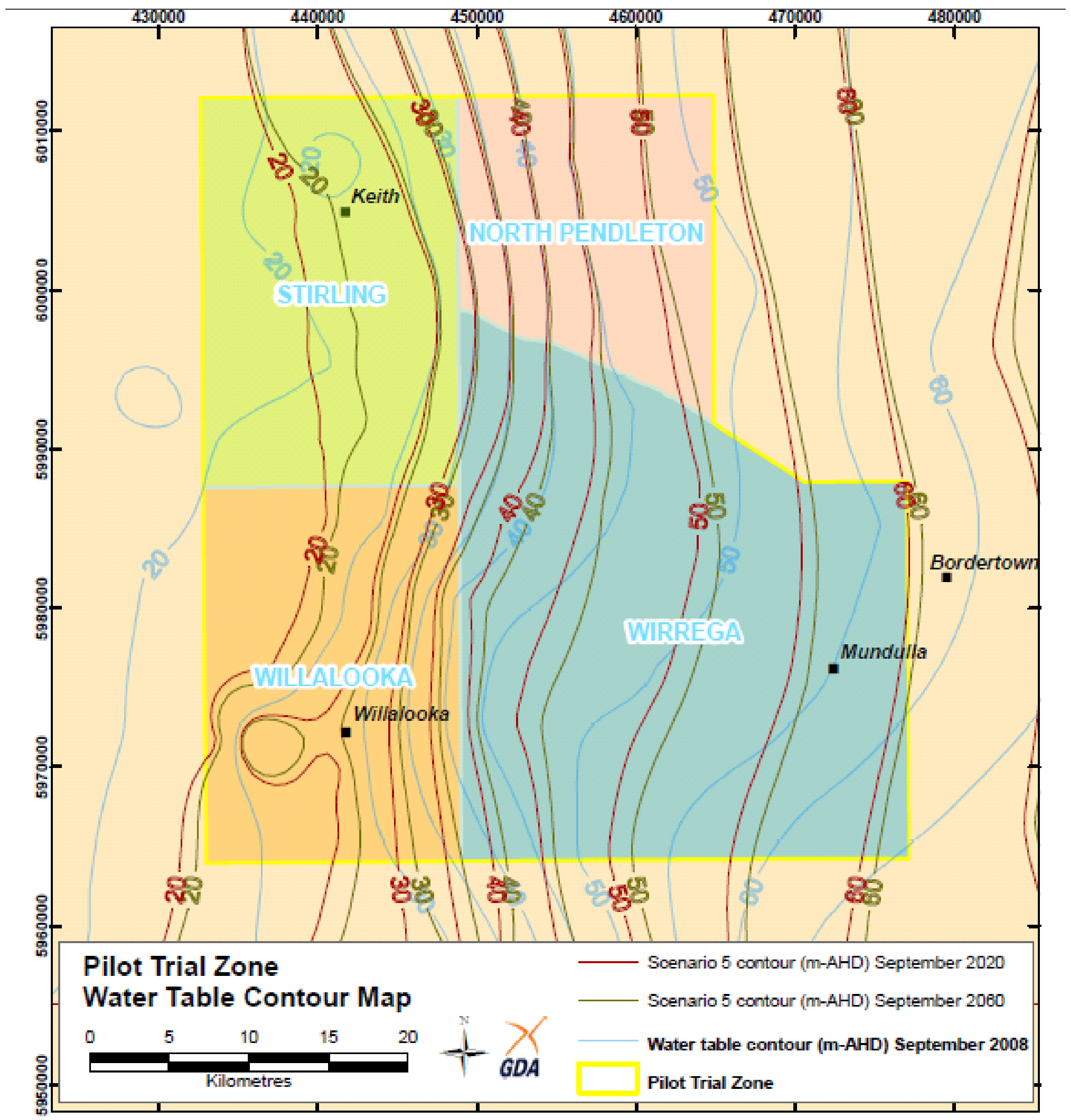
Kilometres
GDA
Scenario 4 contour (m-AHD) September 2020
Scenario 4 contour (m-AHD) September 2060
Water table contour (m-AHD) September 2008
Pilot Trial Zone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WIRREGA
WILLALOOKA
Keith
Bordertown
Mundulla
Willalooka
Pilot Trial Zone
Water Table Contour Map
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Kilometres
GDA
Scenario 5 contour (m-AHD) September 2020
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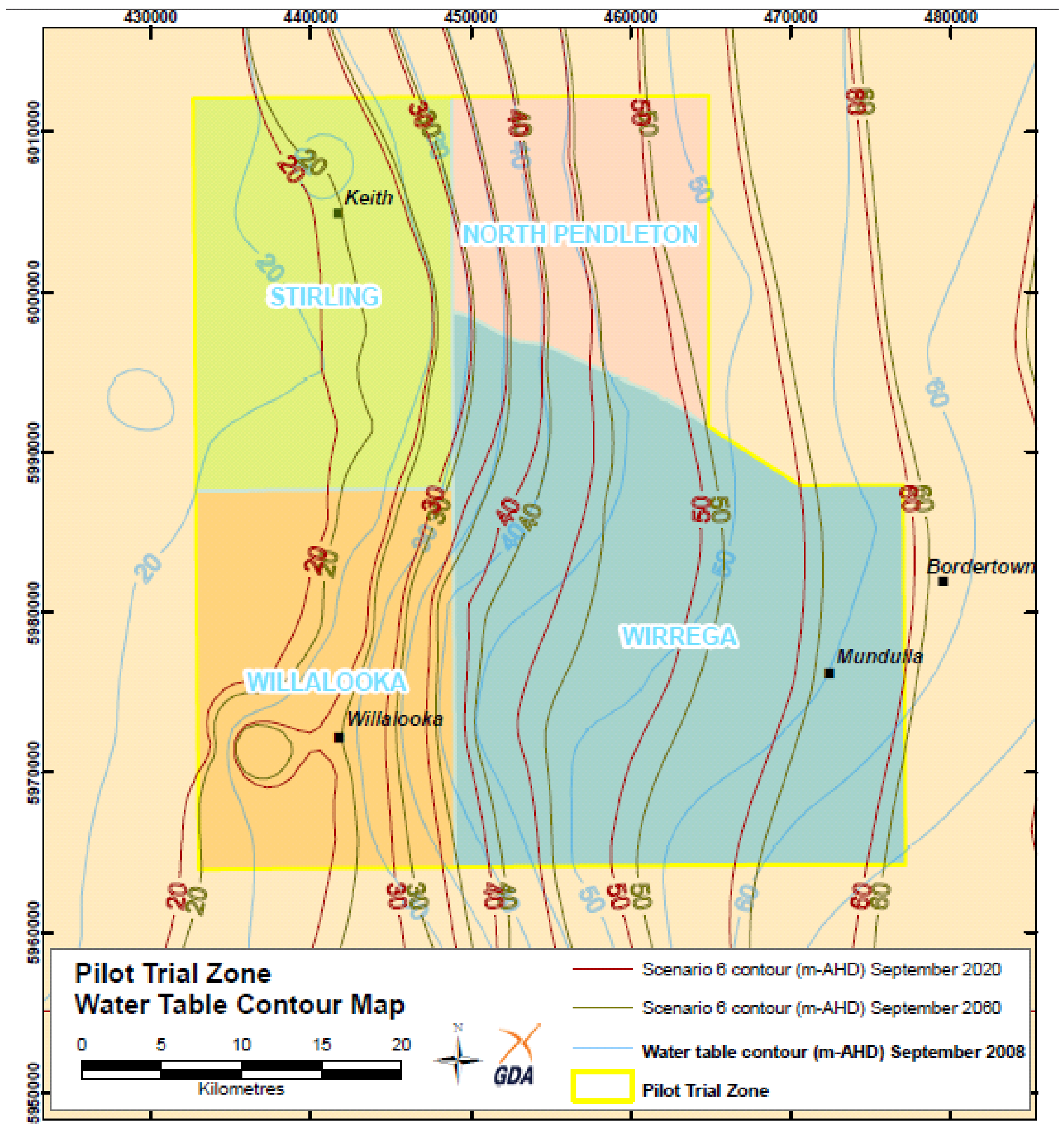
Water table contour (m-AHD) September 2008
Pilot Trial Zone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WIRREGA
WILLALOOKA
Keith
Bordertown
Mundulla
Willalooka
Pilot Trial Zone
Water Table Contour Map
0
5
10
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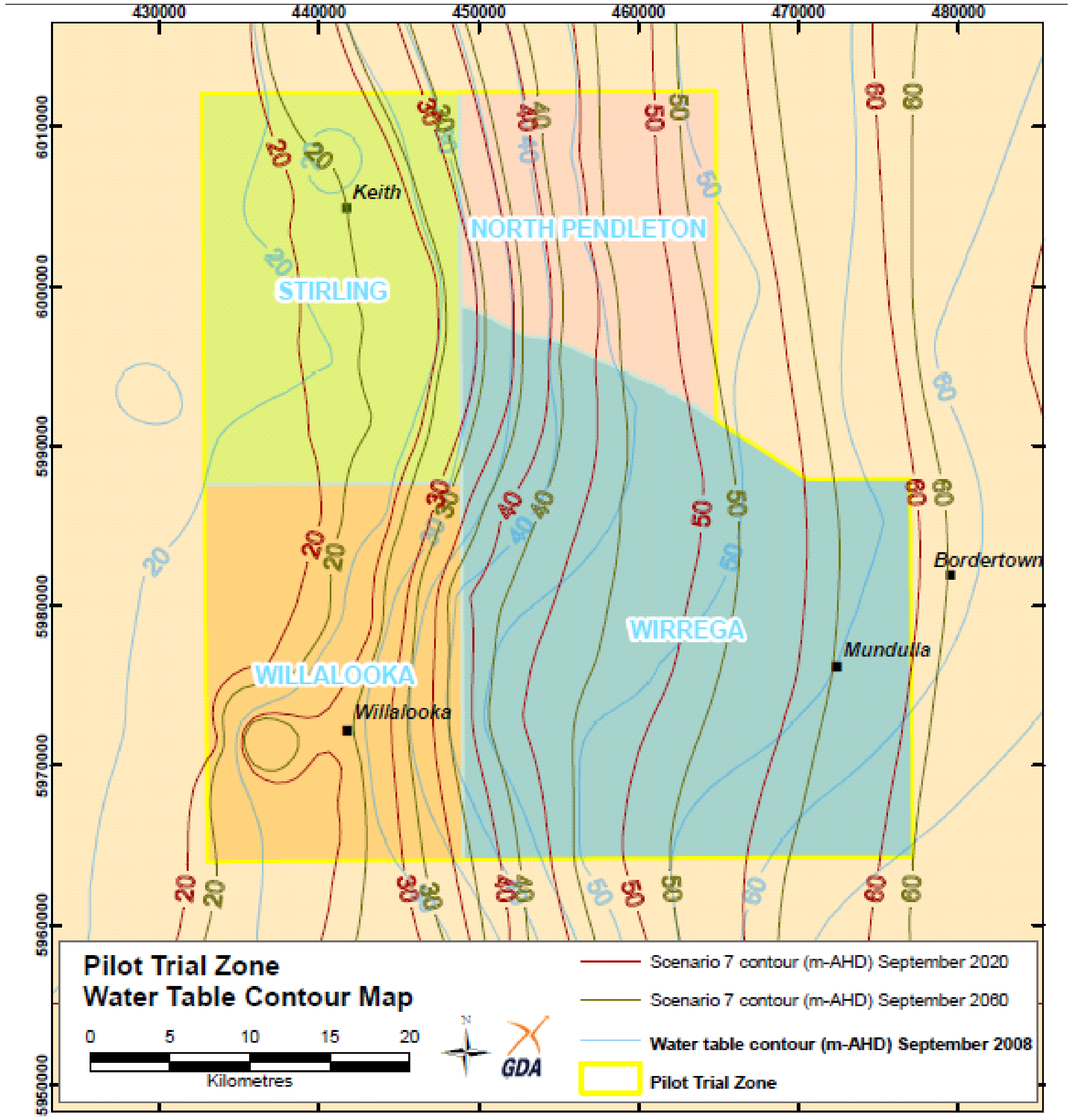
20
Kilometres
GDA
Scenario 6 contour (m-AHD) September 2020
Scenario 6 contour (m-AHD) September 2060
Water table contour (m-AHD) September 2008
Pilot Trial Zone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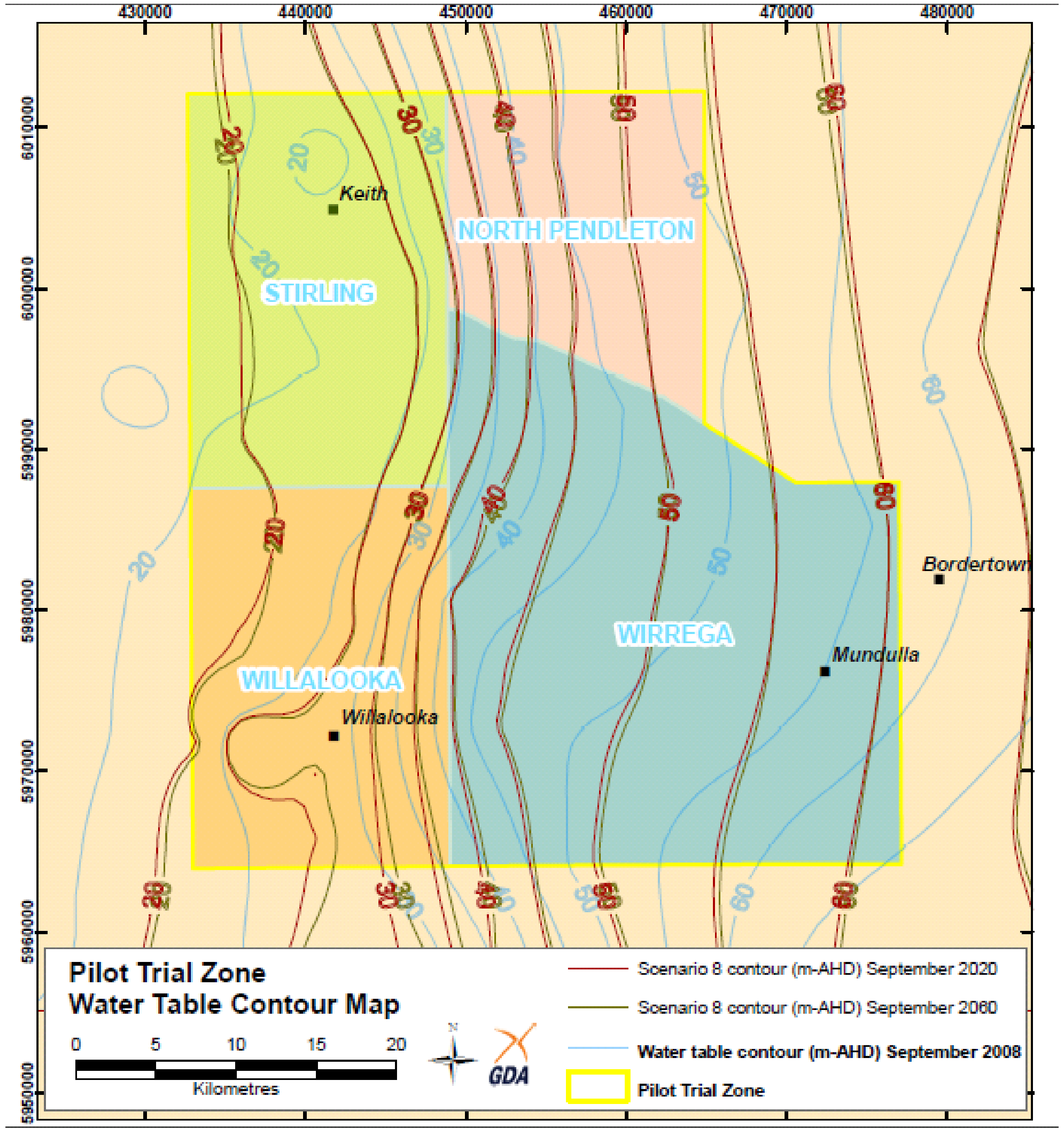
NORTH PENDLETON
WIRREGA
WILLALOOKA
Willalooka
Mundulla
Bordertown
Pilot Trial Zone
Water Table Contour Map
0 5 10 15 20
Kilometres
GDA
Scenario 7 contour (m-AHD) September 2020
Scenario 7 contour (m-AHD) September 2060
Water table contour (m-AHD) September 2008
Pilot Trial Zone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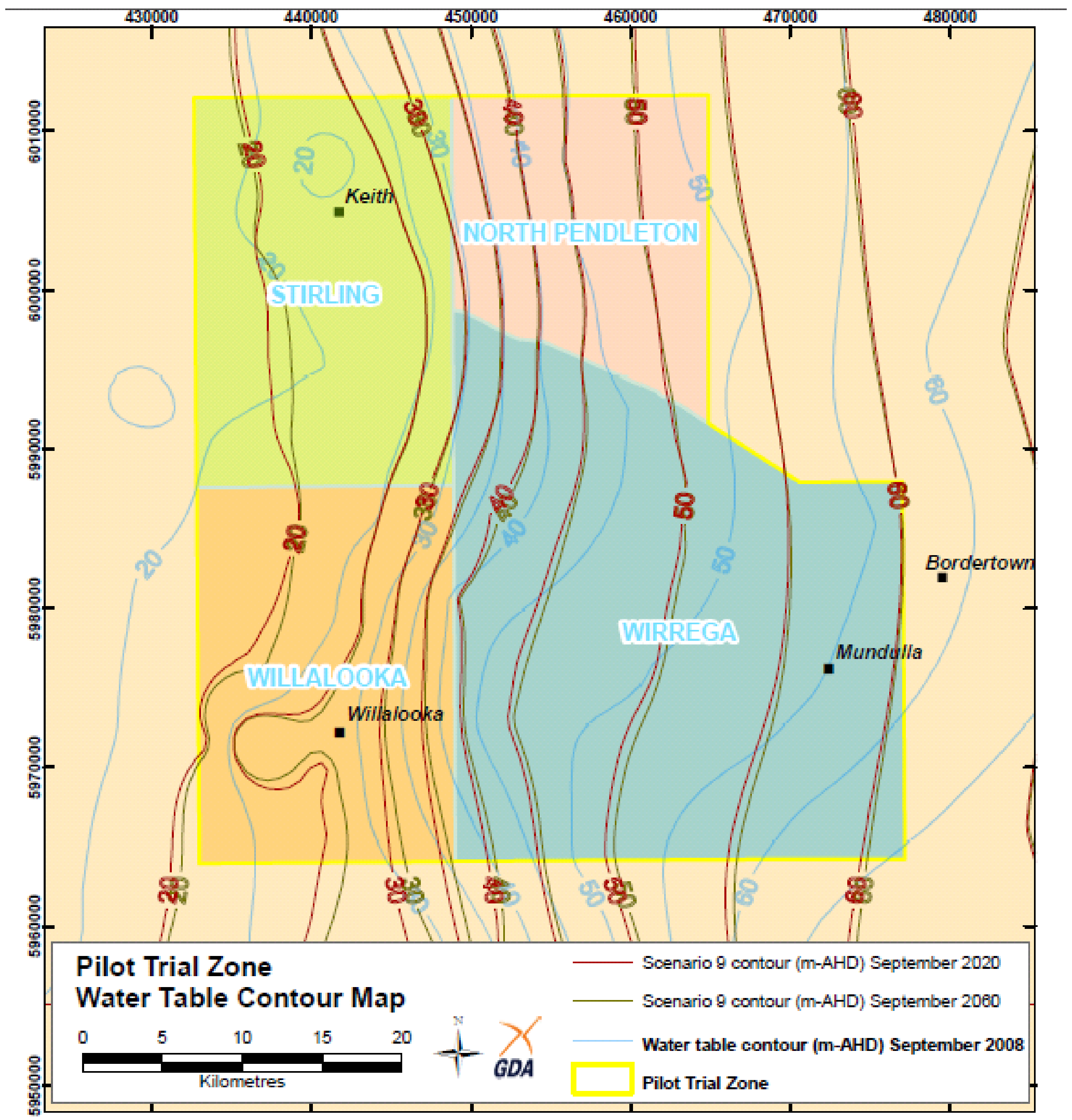
Keith
STIRLING
NORTH PENDLETON
WIRREGA
WILLALOOKA
Willalooka
Mundulla
Bordertown
Pilot Trial Zone
Water Table Contour Map
0 5 10 15 20
Kilometres
GDA
Scenario 8 contour (m-AHD) September 2020
Scenario 8 contour (m-AHD) September 2060
Water table contour (m-AHD) September 2008
Pilot Trial Zone



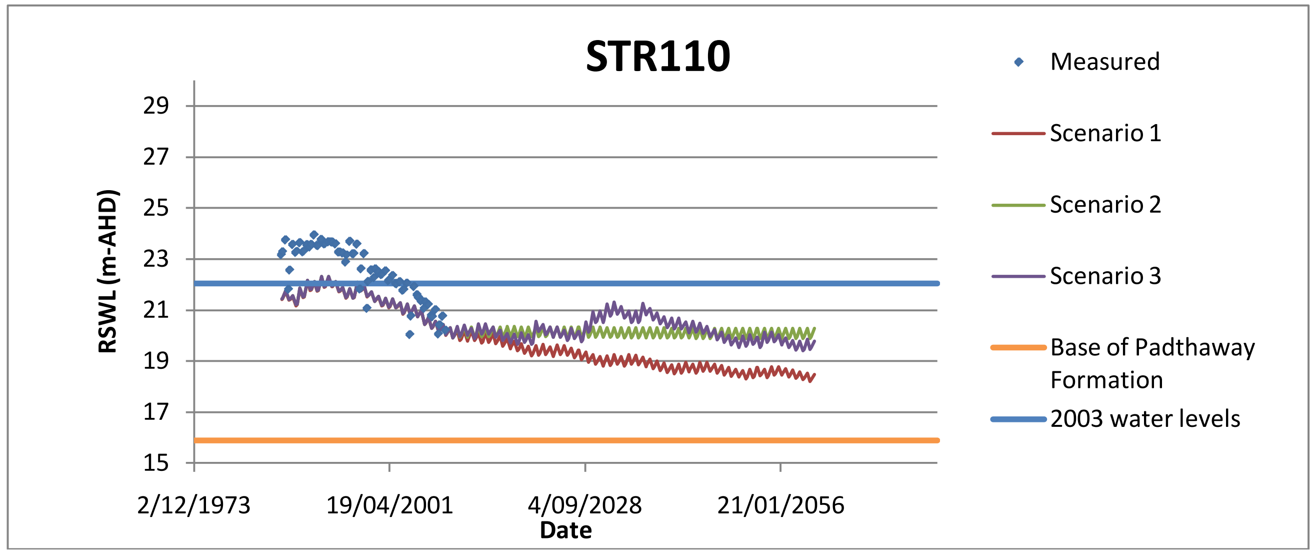
Pilot Trial Zone
Water Table Contour Map
Kilometres
GDA
Scenario 9 contour (m-AHD) September 2020
Scenario 9 contour (m-AHD) September 2060
Water table contour (m-AHD) September 2008
Pilot Trial Zone
NORTH PENDLETON
STIRLING
WILLALOOKA
WIRREGA
Keith
Willalooka
Mundulla
Bordertown

F. RESOURCE CONDITION LIMITS IN THE PILOT TRIAL ZONE

As part of the AM sub-program, a number of workshops were held in the PTZ between 2008 and 2010. Community members were invited to attend, as were key technical and policy staff from the region. Over the course of the workshops, the concept of AM was introduced, as was the idea of using RCLs to manage groundwater, rather than rates of change. The following table summarises the key RCLs developed in the workshops and our current ability to run model scenarios around them.

Resource Condition Limit	Feasibility
1. Maintain groundwater levels in the more productive layers of the aquifer in the western low-lying areas and prevent further decline in groundwater levels. Where possible, restore water levels to pre-2003 levels.	This is achievable given our current knowledge and can be tested in the groundwater model.
2. Manage salinity by maintaining an east to west gradient in the watertable.	This is possible—while we do not have as much information on salinity as we do on water levels and geology, we can still use the model to investigate changes in the watertable gradient and volumes of water flowing out of the western boundary of the model.
3. Manage salinity to tolerable thresholds for particular crop types.	This is an aspirational RCL as we do not currently have enough data on salinity processes in the area and cannot model them appropriately.

The following graphs show the levels specified in the first RCL and how some of the key observation wells performed against these RCLs in the various model scenarios.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RSWL (m-AHD)
29
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21
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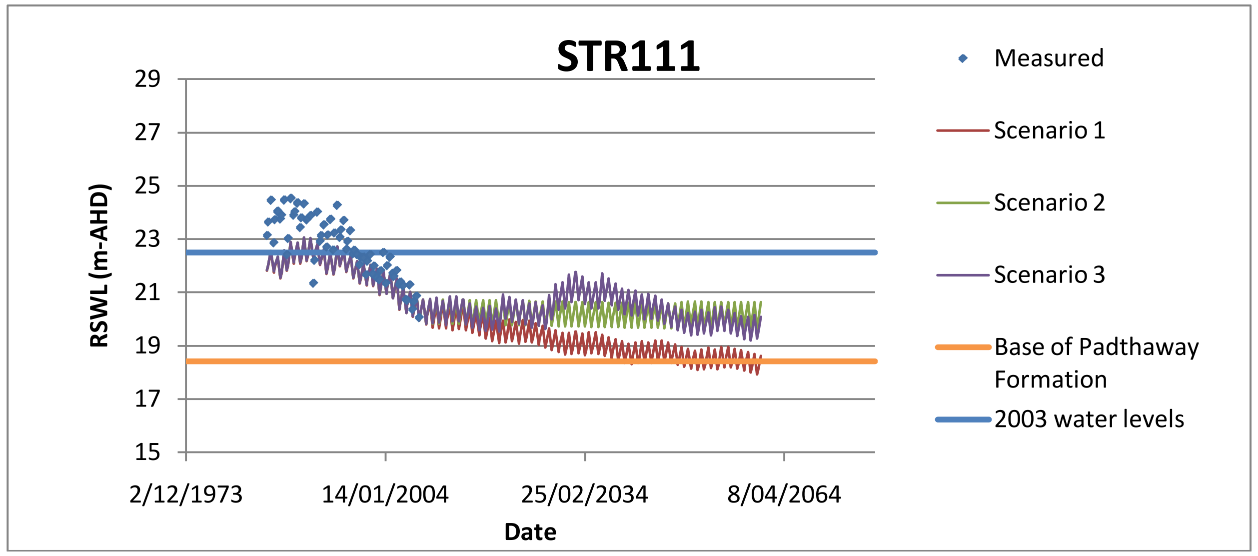
17
15
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Base of Padthaway Formation
2003 water levels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RSWL (m-AHD)
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2/12/1973
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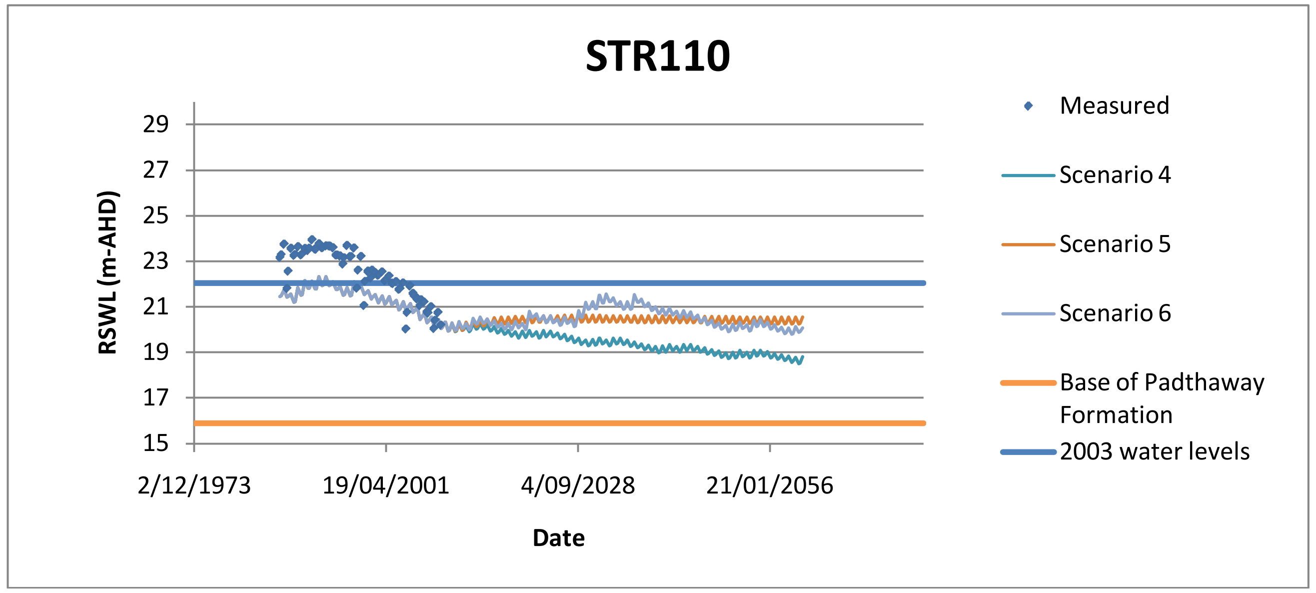
8/04/2064
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Base of Padthaway Formation
2003 water levels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RSWL (m-AHD)
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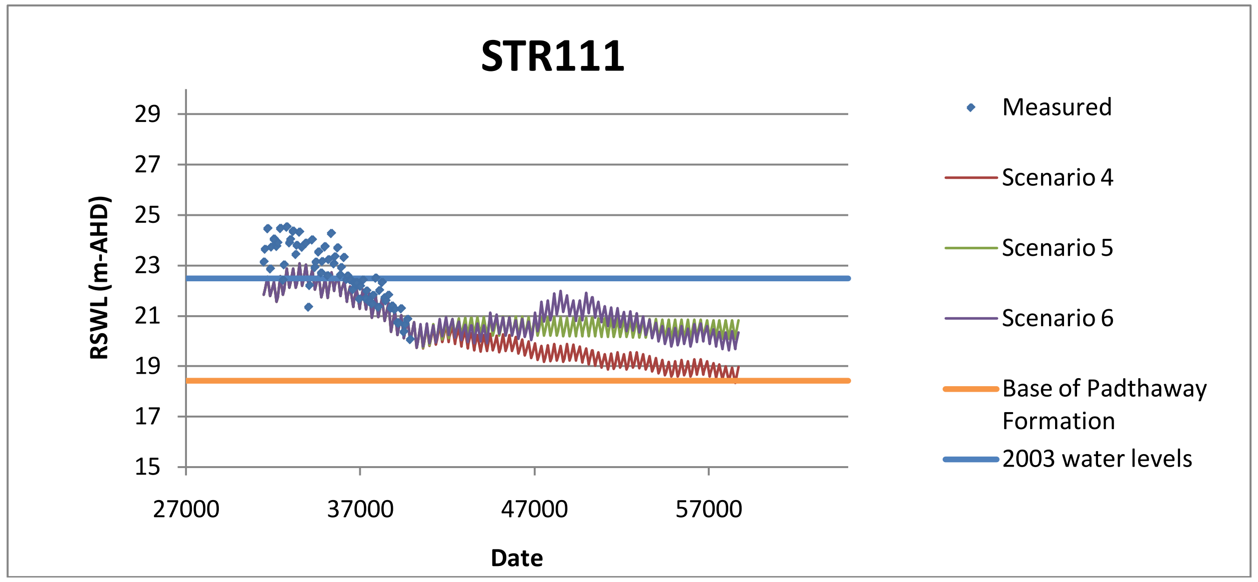
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 4
Scenario 5
Scenario 6
Base of Padthaway Formation
2003 water levels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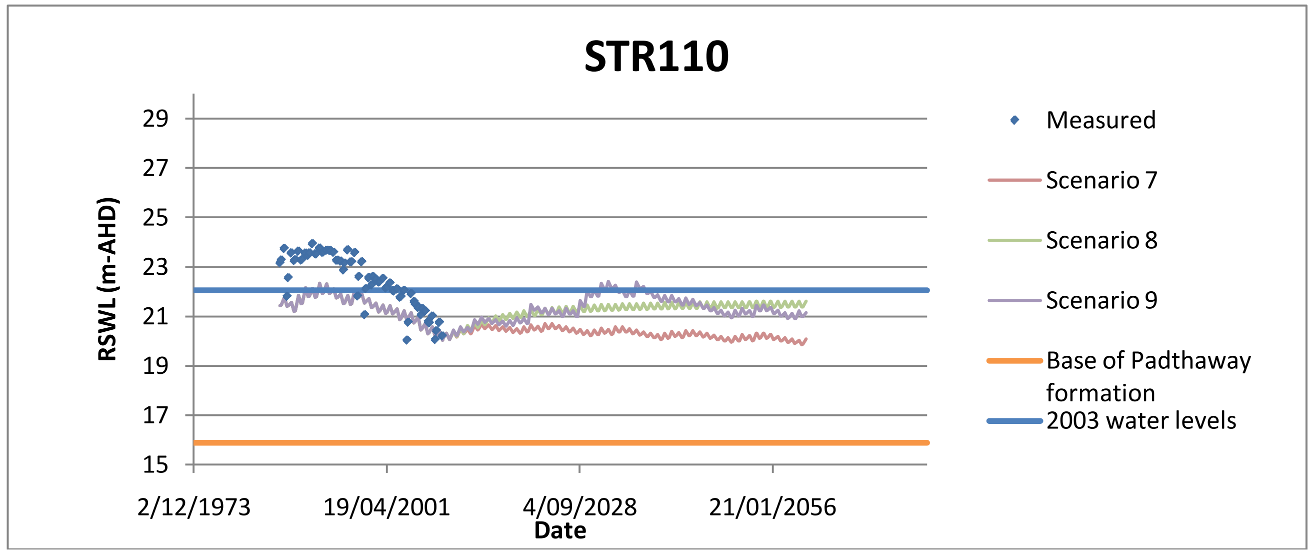
Date
Measured
Scenario 4
Scenario 5
Scenario 6
Base of Padthaway Formation
2003 water levels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RSWL (m-AHD)
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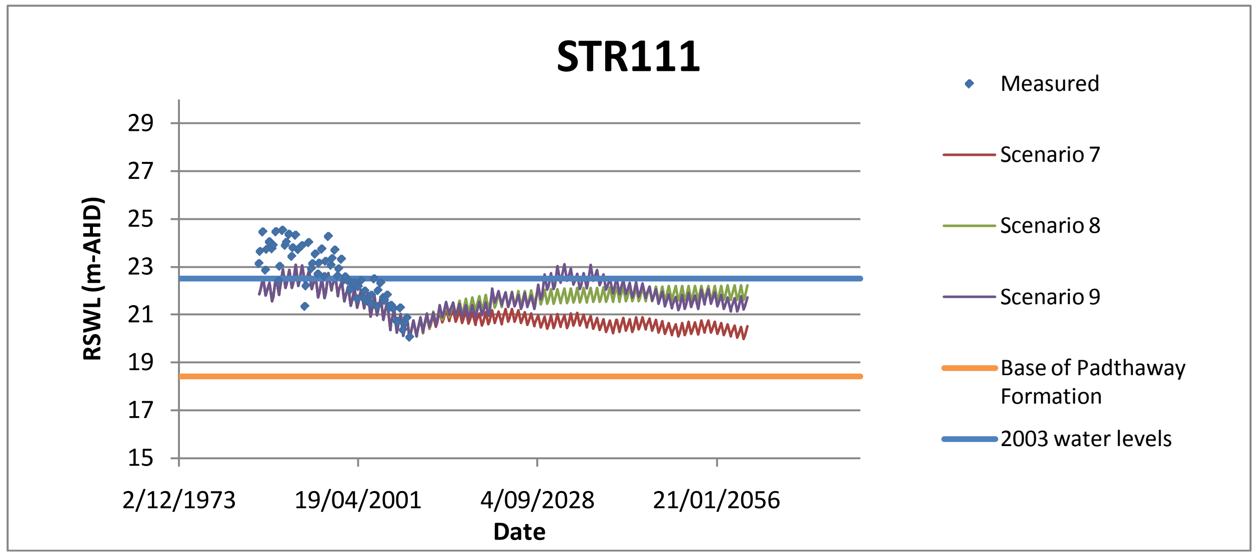
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 7
Scenario 8
Scenario 9
Base of Padthaway formation
2003 water levels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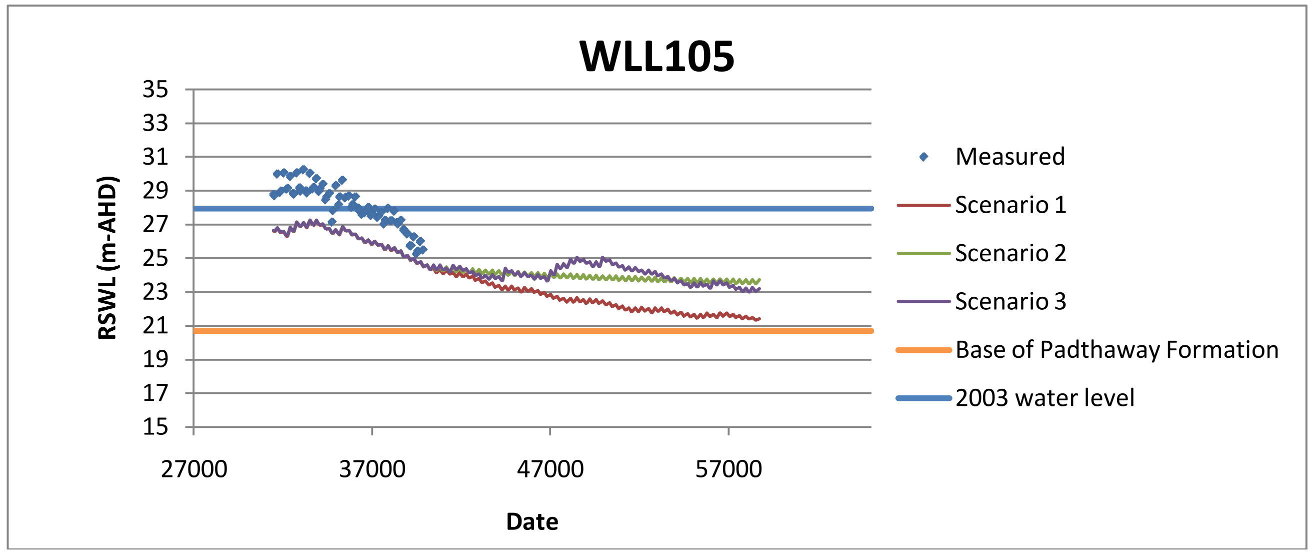
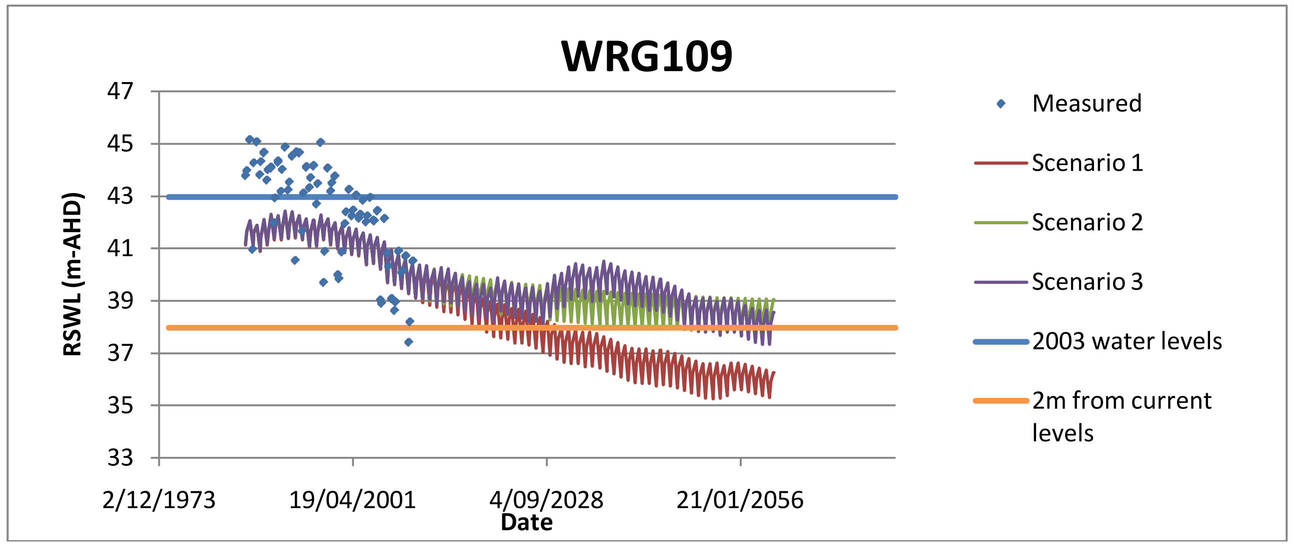
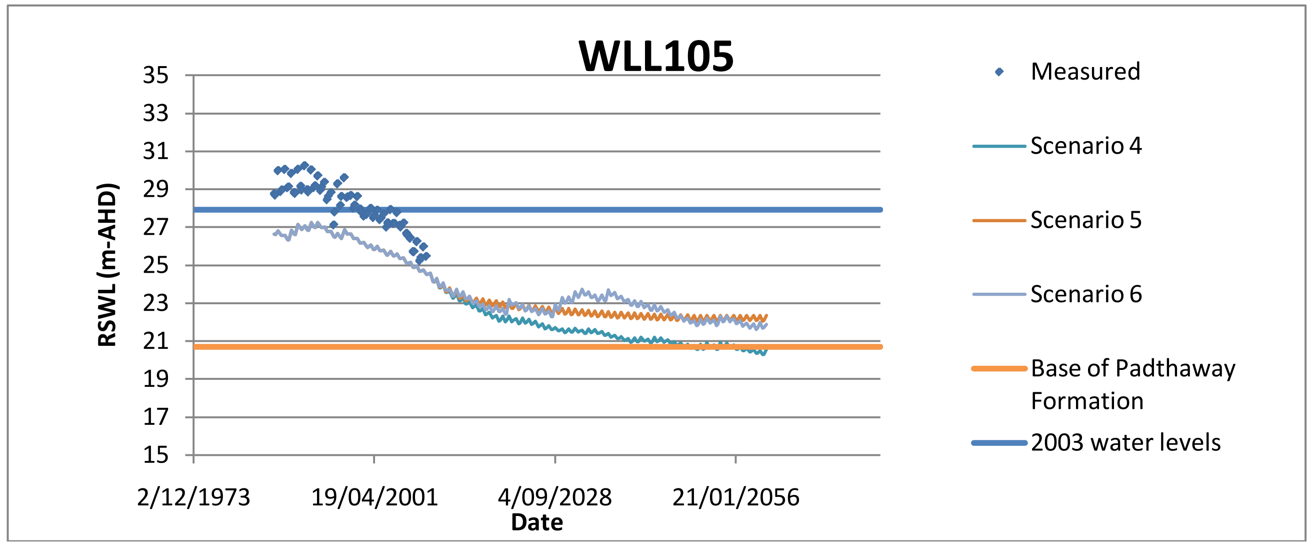
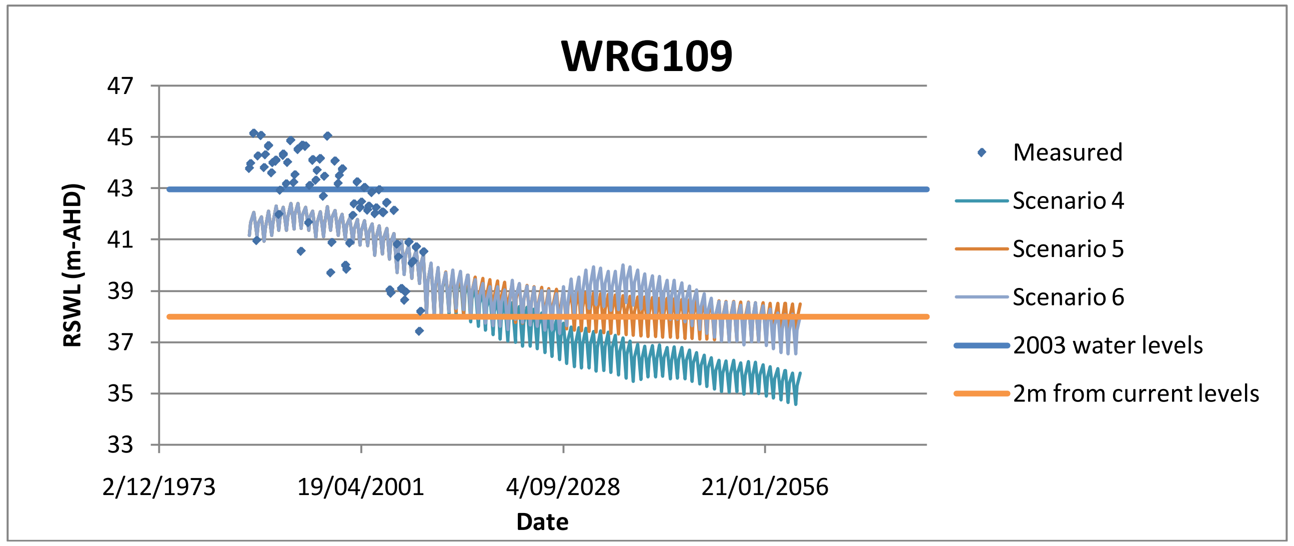
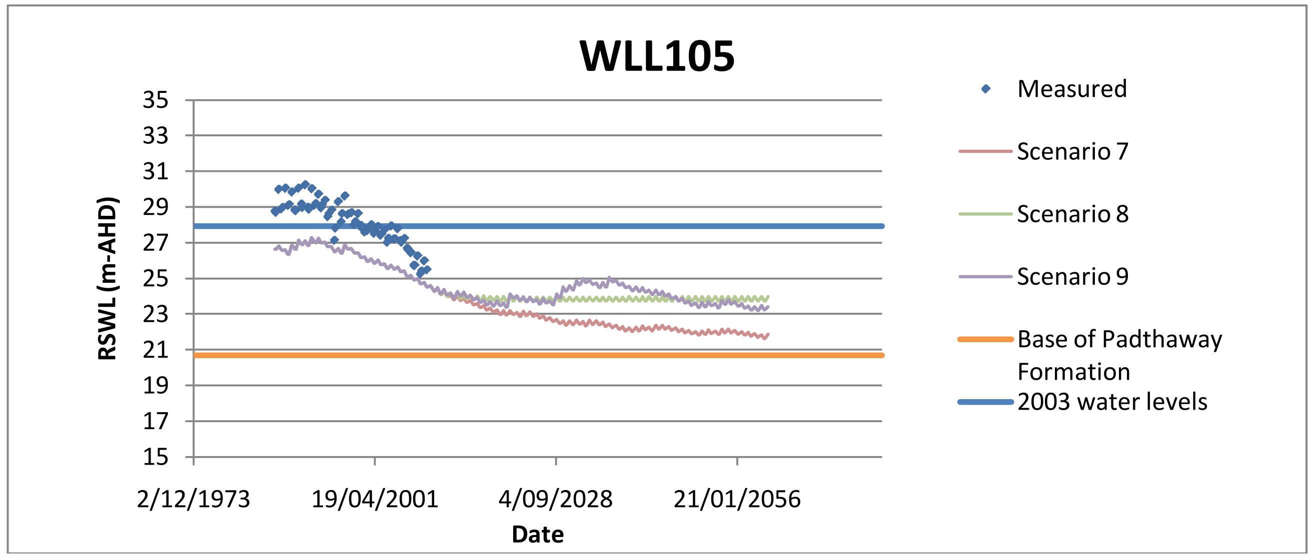
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 7
Scenario 8
Scenario 9
Base of Padthaway Formation
2003 water levels

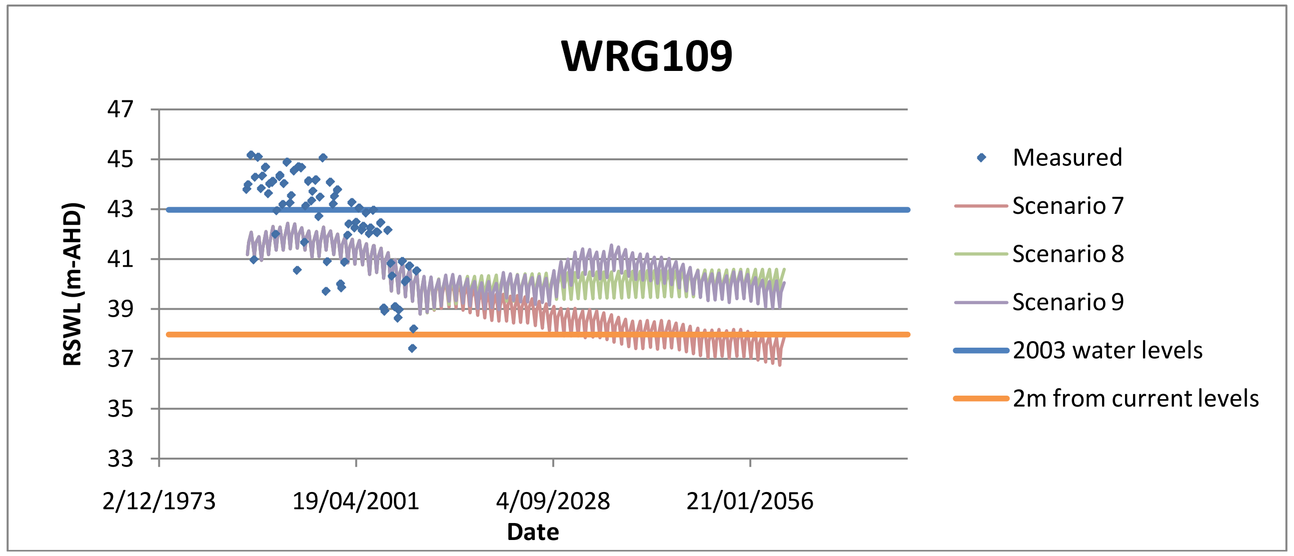

WLL105
RSWL (m-AHD)
35
33
31
29
27
25
23
21
19
17
15
27000
37000
47000
57000
Date
Measured
Scenario 1
Scenario 2
Scenario 3
Base of Padthaway Formation
2003 water level

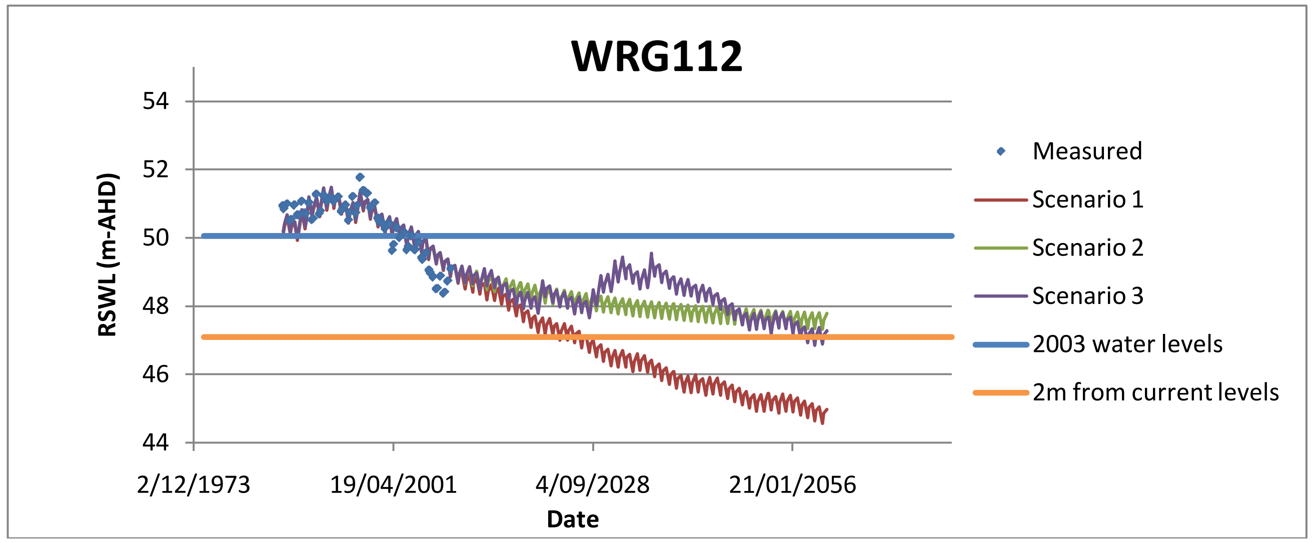

WRG109
RSWL (m-AHD)
47
45
43
41
39
37
35
33
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
2003 water levels
2m from current levels


WLL105
RSWL (m-AHD)
35
33
31
29
27
25
23
21
19
17
15
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 4
Scenario 5
Scenario 6
Base of Padthaway Formation
2003 water levels

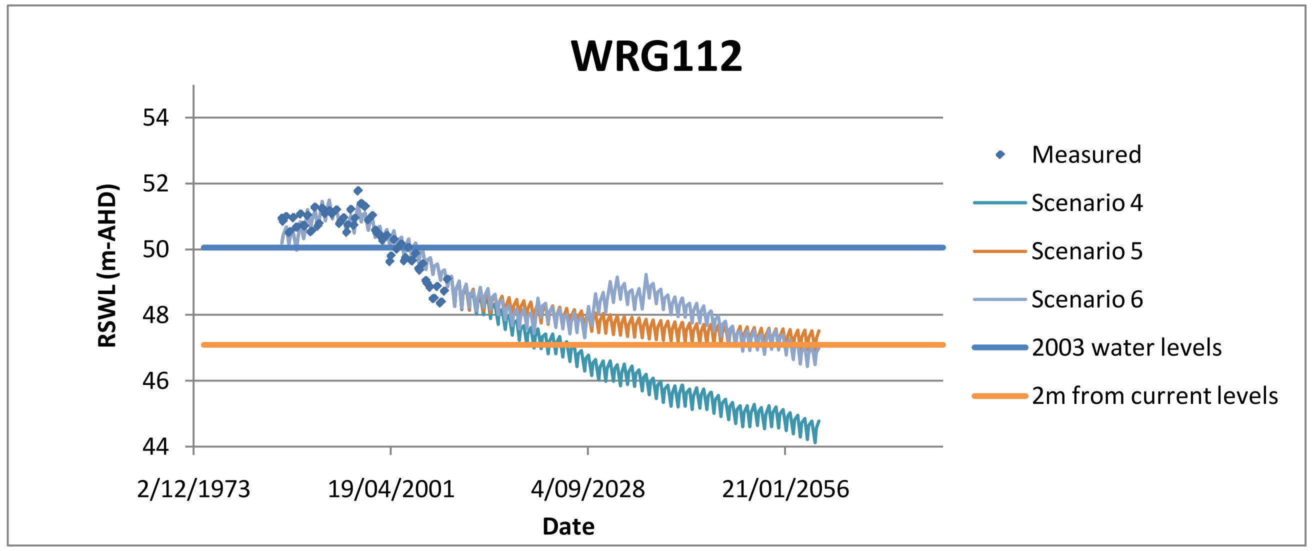

WRG109
RSWL (m-AHD)
47
45
43
41
39
37
35
33
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 4
Scenario 5
Scenario 6
2003 water levels
2m from current levels


WLL105
RSWL (m-AHD)
35
33
31
29
27
25
23
21
19
17
15
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 7
Scenario 8
Scenario 9
Base of Padthaway Formation
2003 water levels

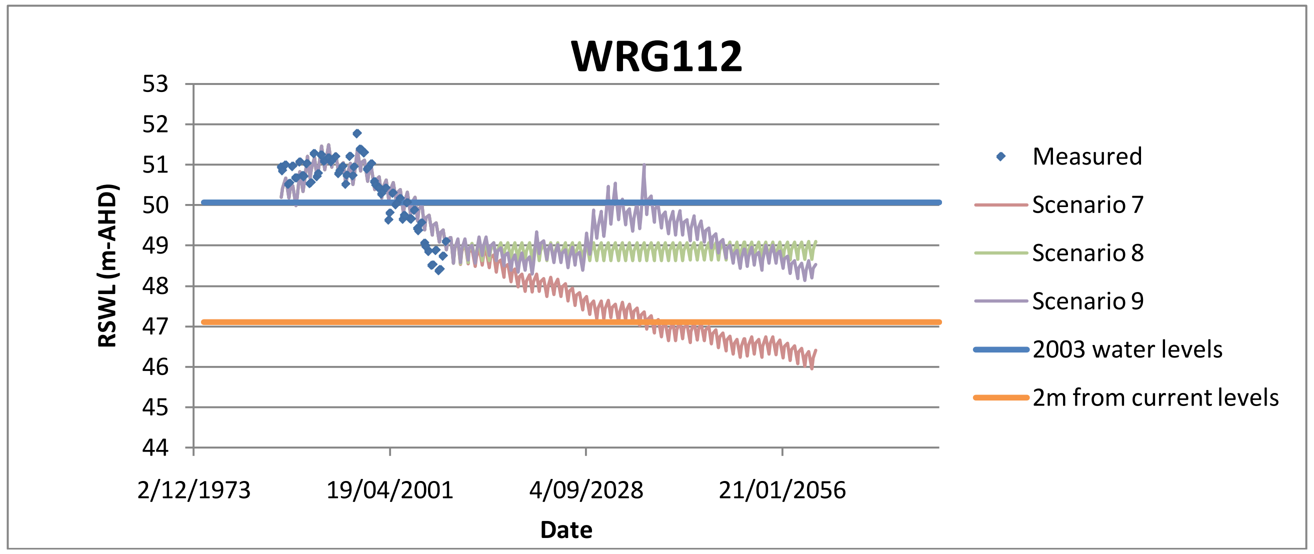

WRG109
RSWL (m-AHD)
47
45
43
41
39
37
35
33
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 7
Scenario 8
Scenario 9
2003 water levels
2m from current levels



WRG112
RSWL (m-AHD)
54
52
50
48
46
44
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 1
Scenario 2
Scenario 3
2003 water levels
2m from current levels



WRG112
RSWL (m-AHD)
54
52
50
48
46
44
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 4
Scenario 5
Scenario 6
2003 water levels
2m from current levels



WRG112
RSWL (m-AHD)
53
52
51
50
49
48
47
46
45
44
2/12/1973
19/04/2001
4/09/2028
21/01/2056
Date
Measured
Scenario 7
Scenario 8
Scenario 9
2003 water levels
2m from current levels

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

~	approximately equal to
bgs	below ground surface
EC	electrical conductivity (µS/cm)
K	hydraulic conductivity (m/d)
pH	acidity
pMC	percent of modern carbon
ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
w/v	weight in volume
w/w	weight in weight

GLOSSARY

Adaptive management — A management approach often used in natural resource management where there is little information and/or a lot of complexity, and there is a need to implement some management changes sooner rather than later. The approach is to use the best available information for the first actions, implement the changes, monitor the outcomes, investigate the assumptions, and regularly evaluate and review the actions required. Consideration must be given to the temporal and spatial scale of monitoring and the evaluation processes appropriate to the ecosystem being managed.

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

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

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

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

Aquitard — A layer in the geological profile that separates two aquifers and restricts the flow between them

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'

CSIRO — Commonwealth Scientific and Industrial Research Organisation

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

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

Irrigation season — The period in which major irrigation diversions occur, usually starting in August–September and ending in April–May

Licence — A licence to take water in accordance with the Act; see also 'water licence'

MDBC — Murray–Darling Basin Commission

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

Obswell — Observation Well Network

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

Prescribed well — A well declared to be a prescribed well under the Act

Production well — The pumped well in an aquifer test, as opposed to observation wells; a wide-hole well, fully developed and screened for water supply, drilled on the basis of previous exploration wells

PWA — Prescribed Wells Area

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

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

Stock use — The taking of water to provide drinking water for stock other than stock subject to intensive farming (as defined by the Act)

(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

Sustainability — The ability of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity over time

T — Transmissivity; a parameter indicating the ease of groundwater flow through a metre width of

TDS — Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity

Tertiary aquifer — A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago)

Transmissivity (T) — A parameter indicating the ease of groundwater flow through a metre width of aquifer section

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

Volumetric allocation — An allocation of water expressed on a water licence as a volume (eg. kilolitres) to be used over a specified period of time, usually per water use year (as distinct from any other sort of allocation)

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

Water allocation, area based — An allocation of water that entitles the licensee to irrigate a specified area of land for a specified period of time usually per water–use year

WAP — Water Allocation Plan; a plan prepared by a CWMB or water resources planning committee and adopted by the Minister in accordance with the Act

Water body — Includes watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse

Water-dependent ecosystems — Those parts of the environment, the species composition and natural ecological processes, that are determined by the permanent or temporary presence of flowing or standing water, above or below ground; the in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water-dependent ecosystems

Water licence — A licence granted under the Act entitling the holder to take water from a prescribed watercourse, lake or well or to take surface water from a surface water prescribed area; this grants the licensee a right to take an allocation of water specified on the licence, which may also include conditions on the taking and use of that water; a water licence confers a property right on the holder of the licence and this right is separate from land title

Water plans — The State Water Plan, catchment water management plans, water allocation plans and local water management plans prepared under Part 7 of the Act

Water resource monitoring — An integrated activity for evaluating the physical, chemical, and biological character of water resources, including (1) surface waters, groundwaters, estuaries, and near-coastal waters; and (2) associated aquatic communities and physical habitats, which include wetlands

Water resource quality — (1) The condition of water or some water-related resource as measured by biological surveys, habitat-quality assessments, chemical-specific analyses of pollutants in water bodies, and toxicity tests. (2) The condition of water or some water-related resource as measured by habitat quality, energy dynamics, chemical quality, hydrological regime, and biotic factors

Watertable – the saturated-unsaturated interface in an unconfined aquifer

Water-use year — The period between 1 July in any given calendar year and 30 June the following calendar year; also called a licensing year

WDE — Water dependent ecosystem

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

GLOSSARY

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