

OFFICIAL

Lower Limestone Coast subregional model: Province 2 of the Border Designated Area

Department for Environment and Water
September, 2024

DEW Technical report 2024/15



Government
of South Australia

Department for
Environment and Water

OFFICIAL

This page fulfils document classification and authorisation requirements.

1. Document classification

Ensure appropriate classification is contained in header (see here for guidance):

<https://data.sa.gov.au/sites/default/files/Toolkit/Data-Classification-Marking-Decision-Diagram.pdf>

2. Release authorisation

Ensure intended release authorities are recorded in Table 1 below as per Section 2B of document preparation, review and publishing process.

Table 1. Release authority nominations: Name of person with authority to release each type of document

None	n/a
Internal review	Victor Waclawik
External review	Veronica Riches
Public comment	Peter Baker
External publication	Peter Baker
Internal release only	Peter Baker

Table 2. Document version, type and Release Date: This table records the date that authority was granted to release the recorded version. No date indicates it has not been approved for release

Document location	iShare: Science, Monitoring and Knowledge Delivery Program > SE > 2022-23_Lower_Limestone_Coast
Version	9.1
Release type	Public
Release authority	Peter Baker
Release date	12 September 2024

All hard copies of this document are uncontrolled.
Refer to the file held in iShare for the authorised version.

September 2024

Disclaimer

The Department for Environment and Water and its employees do not warrant or make any representation regarding the use, or results of the use, of the information contained herein as regards to its correctness, accuracy, reliability, currency or otherwise. The Department for Environment and Water and its employees expressly disclaims all liability or responsibility to any person using the information or advice. Information contained in this document is correct at the time of writing.



With the exception of the Piping Shrike emblem, other material or devices protected by Aboriginal rights or a trademark, and subject to review by the Government of South Australia at all times, the content of this document is licensed under the Creative Commons Attribution 4.0 Licence. All other rights are reserved.

© Crown in right of the State of South Australia, through the Department for Environment and Water 2024

Preferred way to cite this publication

Waclawik, V & Wood, C (2024) Lower Limestone Coast subregional model: Province 2 of the Border Designated Area, DEW Technical report 2024/15, Government of South Australia, Department for Environment and Water, Adelaide.

Download this document at

https://www.waterconnect.sa.gov.au/Content/Publications/DEW/DEW_TR2024_15.pdf>

Foreword

The Department for Environment and Water (DEW) is responsible for the management of the state's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Landscape Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

Ben Bruce
CHIEF EXECUTIVE
DEPARTMENT FOR ENVIRONMENT AND WATER

Acknowledgements

Internal review of the report was provided by the project hydrogeology lead Virginia Riches, Manager Groundwater Planning and Modelling, DEW; and the project groundwater modelling technical lead Michael Teubner Principal Groundwater Modeller, DEW.

External review of the report was provided by Hugh Middlemis Principal Groundwater Engineer, HydroGeoLogic Pty, Ltd.

Simon Baker OAM, Senior Hydrogeologist at the Victorian Department of Environment, Land, Water and Planning: for the provision of water use data from Victoria.

Contents

Foreword	ii
Acknowledgements	iii
Summary	viii
1 Introduction	1
1.1 Background	1
1.2 Objectives and Scope of Work	1
1.3 Location and physical setting	1
1.4 Administrative Framework	2
2 Conceptual Groundwater Model	4
2.1 Climate	4
2.2 Soil and Land Use	7
2.3 Geology	10
2.4 Hydrogeology	13
2.5 Groundwater Flows and Water Level Trends	16
2.6 Groundwater Salinity	21
2.7 Aquifer Properties	23
2.8 Recharge	26
2.9 Evapotranspiration	28
2.10 Groundwater Extraction	28
2.11 Surface Water – Groundwater Interactions	29
2.12 Conceptual Modelling Summary	29
2.12.1 Inflows	30
2.12.2 Outflows	30
3 Model Construction	31
3.1 Previous Modelling Studies	31
3.2 Code selection and modelling approach	31
3.3 Model domain and grid	31
3.4 Layer Elevations	32
3.5 Boundary Conditions	32
3.5.1 Regional Flow	32
3.6 Recharge	35
3.7 Evapotranspiration	35
3.8 Extraction	35
3.9 Hydraulic Parameters	38
3.10 Initial conditions and stress periods	41
4 Model Calibration	42
4.1 Calibration methodology	42
4.2 Transient calibration	46

4.3	Calibration Performance	47
4.4	Modelled Groundwater Levels	51
4.4.1	BGA Zone 5a	51
4.4.2	BGA Zone 6a (Frances)	51
4.4.3	BGA Zones 5b and 6b	52
4.4.4	Hynam East	52
5	Parameter Sensitivity and Predictive Uncertainty	57
5.1	Parameter sensitivity	57
5.2	Predictive uncertainty	58
5.3	Assumptions and Limitations	62
6	Scenarios	65
6.1	Background	65
6.2	Climate change impacts on groundwater recharge	65
6.3	Groundwater extraction assumptions	66
6.4	Boundary condition assumptions	68
6.5	Scenario Modelled Groundwater Levels	68
6.6	Scenario Potentiometric Surfaces	73
6.7	Scenario Change in Water Level	76
7	Conclusions and Recommendations	79
7.1	Conclusions	79
7.2	Recommendations	79
8	Appendices	80
A.	Modelled Hydrographs	81
B.	Scenario Hydrographs	82
	Units of measurement	83
	Units of measurement commonly used (SI and non-SI Australian legal)	84
9	Glossary	85
10	References	88

List of figures

Figure 1.1.	Study location map and administrative boundaries.	3
Figure 2.1.	Average Maximum and Minimum Monthly Temperatures (1965-1994) recorded at Kybybolite in the south central region of the study area (BoM 2022).	4
Figure 2.2.	Average annual rainfall (BoM 2022).	5
Figure 2.3.	Rainfall records for selected locations (BoM 2022).	6
Figure 2.4.	Soil clay content.	8
Figure 2.5.	Land Use.	9
Figure 2.6.	Simplified stratigraphic sequence.	11
Figure 2.7.	Surficial geology.	12
Figure 2.8.	Conceptual model schematic (not to scale). Note: The Kanawinka Fault gradually diminishes in displacement to the Northwest and eventually disappears.	14
Figure 2.9.	Extent of overlying confining beds.	15
Figure 2.10.	Reduced Standing Water Levels September 1975.	17
Figure 2.11.	Reduced Standing Water Levels March–May 2022.	18
Figure 2.12.	Representative hydrographs within the study area.	19
Figure 2.13.	Location of representative hydrographs.	20
Figure 2.14.	Groundwater Salinity.	22
Figure 2.15.	Base of Murray Group showing aquifer test results for hydraulic conductivity.	24
Figure 2.16.	Base of Murray Group showing aquifer test results for specific yield.	25
Figure 2.17.	Groundwater extraction: South Australia.	29
Figure 2.18.	Groundwater extraction: Victoria.	29
Figure 3.1.	Modelled layer elevations.	33
Figure 3.2.	General Head Boundaries.	34
Figure 3.3.	Recharge zones.	36
Figure 3.4.	Modelled groundwater extraction well and observation well locations.	37
Figure 3.5.	Initial Steady-State horizontal hydraulic conductivity zones.	39
Figure 3.6.	PEST parameter estimation of horizontal hydraulic conductivity.	40
Figure 4.1.	Steady-State modelling final calibration result.	44
Figure 4.2.	Steady-State modelling observed and modelled potentiometric surfaces 1975.	45
Figure 4.3.	Transient modelling final calibration result.	47
Figure 4.4.	Transient modelling observed and modelled potentiometric surfaces April 2022.	48
Figure 4.5.	Modelled total water balance.	49
Figure 4.6.	Modelled Storage water balance.	50
Figure 4.7.	Modelled Recharge and Evapotranspiration water balance.	50
Figure 4.8.	Modelled total groundwater extraction.	51
Figure 4.9.	Hydrographs BGA Zone 5A (Hydrograph vertical scale range= 10m).	53
Figure 4.10.	Hydrographs BGA Zone 6A (Hydrograph vertical scale range= 10m).	54
Figure 4.11.	Hydrographs BGA Zones 5B & 6B (Hydrograph vertical scale range= 10m).	55
Figure 4.12.	Hydrographs Hynam East (Hydrograph vertical scale range= 10m).	56
Figure 5.1.	Parameter sensitivity: horizontal hydraulic conductivity.	57
Figure 5.2.	Parameter sensitivity: Specific Yield.	58
Figure 5.3.	Ensemble iterations plotted against the objective function (ϕ) showing ensemble collapse around Iteration #4.	59
Figure 5.4.	Objective function density for Iteration #2, Iteration #3 and Iteration #4 demonstrating the development of "calibration" through the iterative process.	60
Figure 5.5.	Representative hydrographs displaying modelled versus observed heads for the base case and all Realisations from Iteration #3.	61
Figure 5.6.	Spatial distribution of the range of horizontal hydraulic conductivity for Iteration #3.	63
Figure 6.1.	South Australian Groundwater Management Area extraction volume for Scenario 1 and Scenario 2.	67

Figure 6.2.	Scenario Hydrographs BGA Zone 5a showing predicted declines in groundwater levels for Scenario 1 (green) and Scenario 2 (red) (Hydrograph vertical scale range= 10m).	69
Figure 6.3.	Scenario Hydrographs BGA Zone 6a showing predicted declines in groundwater levels for Scenario 1 (green) and Scenario 2 (red) (Hydrograph vertical scale range= 10m).	70
Figure 6.4.	Scenario Hydrographs BGA Zones 5b & 6b showing predicted declines in groundwater levels for Scenario 1 (green) and Scenario 2 (red) (Hydrograph vertical scale range= 10m).	71
Figure 6.5.	Scenario Hydrographs Hynam East showing predicted declines in groundwater levels for Scenario 1 (green) and Scenario 2 (red) (Hydrograph vertical scale range= 10m).	72
Figure 6.6.	Scenario 1 Potentiometric Surface in 2050 compared with the 2022 measured potentiometric surface.	74
Figure 6.7.	Scenario 2 potentiometric surface in 2050 compared with the 2022 measured potentiometric surface.	75
Figure 6.8.	Change in water level for Scenario 1.	77
Figure 6.9.	Change in water levels for Scenario 2.	78

List of tables

Table 2.1.	Summary of recharge investigations in the study area	26
Table 3.1.	Recharge Summary Statistics.	35
Table 3.2.	Modelling Phases.	41

Summary

The review of the Lower Limestone Coast Water Allocation Plan (LLC WAP) in 2023 involves a comprehensive approach to risk assessment and planning. The Limestone Coast Landscape Board has partnered with the Department for Environment and Water (DEW) to develop sub-regional models for the Lower Limestone Coast Prescribed Wells Area.

A numerical groundwater model has been established, consistent with best practice guidelines, covering management areas in the northeast of the Lower Limestone Coast, extending into Victoria and encompassing a significant portion of Border Groundwater Agreement (BGA) Province 2. The focus is on BGA Zones 5A, 5B, 6A, and 6B, as well as the South Australian Groundwater Management Areas of Frances and Hynam East. The model has been history-matched ('calibrated') to historic groundwater levels and potentiometric surfaces, and is deemed suitable for evaluating the effects of policy decisions in the LLC WAP on the modelled areas.

Two scenarios have been examined to represent the base cases for predicted conditions. Scenario 1 maintains current conditions, with groundwater extraction volumes at current levels and no change in climate. Scenario 2 envisions increased groundwater extraction up to the maximum allocation while anticipating a significant reduction in groundwater recharge due to climate change.

Results from Scenario 1 indicate a continued decline in groundwater levels (3 m to 4 m), consistent with current groundwater level trends. In Scenario 2, a more rapid and deeper decline in groundwater levels (7 m to 8 m) is observed, corresponding to higher extraction volumes and significantly reduced recharge. Notably, the water table distribution reveals a regional decline associated with areas of concentrated groundwater extraction.

Given that scenarios 1 and 2 represent large differences in extraction volumes and outcomes, it is foreseen that additional scenarios will be required to thoroughly assess the impacts of policies outlined in the LLC WAP. Collaboration with water planners is essential to provide specific details for these additional scenarios, ensuring a comprehensive evaluation of potential outcomes and effective decision-making for sustainable water management.

1 Introduction

1.1 Background

In 2018, the Government of South Australia commissioned an independent review of the science underpinning the Lower Limestone Coast Water Allocation Plan (LLCWAP), in relation to groundwater allocation reductions. The review was conducted by an independent panel through the Goyder Institute for Water Research and made several key recommendations for future work (Simmons et al., 2019).

The review recommended “that groundwater modelling of the LLC PWA is updated to include a suite of subregional models that can answer specific questions at an appropriate range of spatial and temporal scales” (Simmons et al., 2019).

In consultation with the Limestone Coast Landscape Board, DEW has been working on a series of subregional models across the Lower Limestone Coast (LLC) Prescribed Wells Area (PWA) to assist with risk assessment and planning in the lead up to the review of the LLC Water Allocation Plan (WAP) in 2023. This report covers the development of a subregional model covering management areas in the north-east of the LLC PWA including Hynam East, Zone 5A and Frances (Figure 1.1). The model extends east to capture groundwater inflow processes from Victoria, including the Zone 5B and Zone 6B management zones in the Border Designated Area.

1.2 Objectives and Scope of Work

This modelling investigation focuses on the regionally unconfined Tertiary Limestone Aquifer (TLA) to help assess risks and opportunities related to groundwater resource development and climate change within the area of interest.

The objectives of this project are to:

- Investigate resource development within Hynam East, and Zones 5A/5B & 6A/6B of the Border Groundwaters Agreement through numerical groundwater flow modelling;
- Develop the capacity to interrogate future resource development and climate change that may impact groundwater within the study area; and,
- Provide recommendations to help inform water planning in the Lower Limestone Coast Water Allocation Plan, as well as communicating results to the Border Groundwater Agreement Committee.

1.3 Location and physical setting

The project area is located along the border between South Australia and Victoria and extends from near Bordertown in the north to Naracoorte in the south. It encompasses areas on both sides of the border including part of the Limestone Coast region in South Australia and part of the West Wimmera region on the Victorian side of the border (Figure 1.1). The area of interest incorporates the towns of Neuarpuur, Apsley and Edenhope in Victoria and Frances, Naracoorte and Padthaway in South Australia.

The region incorporates highlands and ranges in the east and lowland areas in the south and west, with a clear demarcation between highland and lowland areas created by the Naracoorte Ranges. The west of the study area incorporates coastal plains, dunes and interdunal flats. The area has an extensive network of drains established predominantly in the lowland areas (DEW 2021).

1.4 Administrative Framework

Along the South Australian-Victorian border, the groundwater resource is managed cooperatively between both states under the Border Groundwaters Agreement (2005). This agreement acknowledges that the available groundwater shall be shared equitably between the two states. It covers an area that extends 20 kilometres either side of the border, from the coast in the south to the Murray River in the north. This area is known as the Border Designated Area and is divided into 22 management zones with 11 zones in each state. The area of interest investigated in this report contains Zones 5A, 5B, 6A and 6B as well as sections of 4A, 4B, 7A and 7B (DELWP 2020) (Figure 1.1).

Groundwater on the South Australian side of the border is managed through Water Allocation Plans (WAPs) and on the Victorian side of the border via Water Management Plans (WMPs). Under both systems, groundwater is managed by capping allocations and managing licensed use to protect the resource and environmental values.

In South Australia the area of interest incorporates elements of the Padthaway Prescribed Wells Area (PWA), the Lower Limestone Coast PWA and the Tatiara PWA. These areas are managed by the Limestone Coast Landscape Board (DEW 2021). In Victoria, groundwater is governed under the West Wimmera Groundwater Management Area (GMA) which is managed by Grampians Wimmera Mallee Water.

Groundwater is the main water resource in the region and is used for irrigation, industrial, stock and domestic and town water supplies. Morambro Creek is the only prescribed surface water resource in the region (DEW 2021). Other significant surface waterways include Nalang Creek in the north and Naracoorte Creek in the south (Figure 1.1).

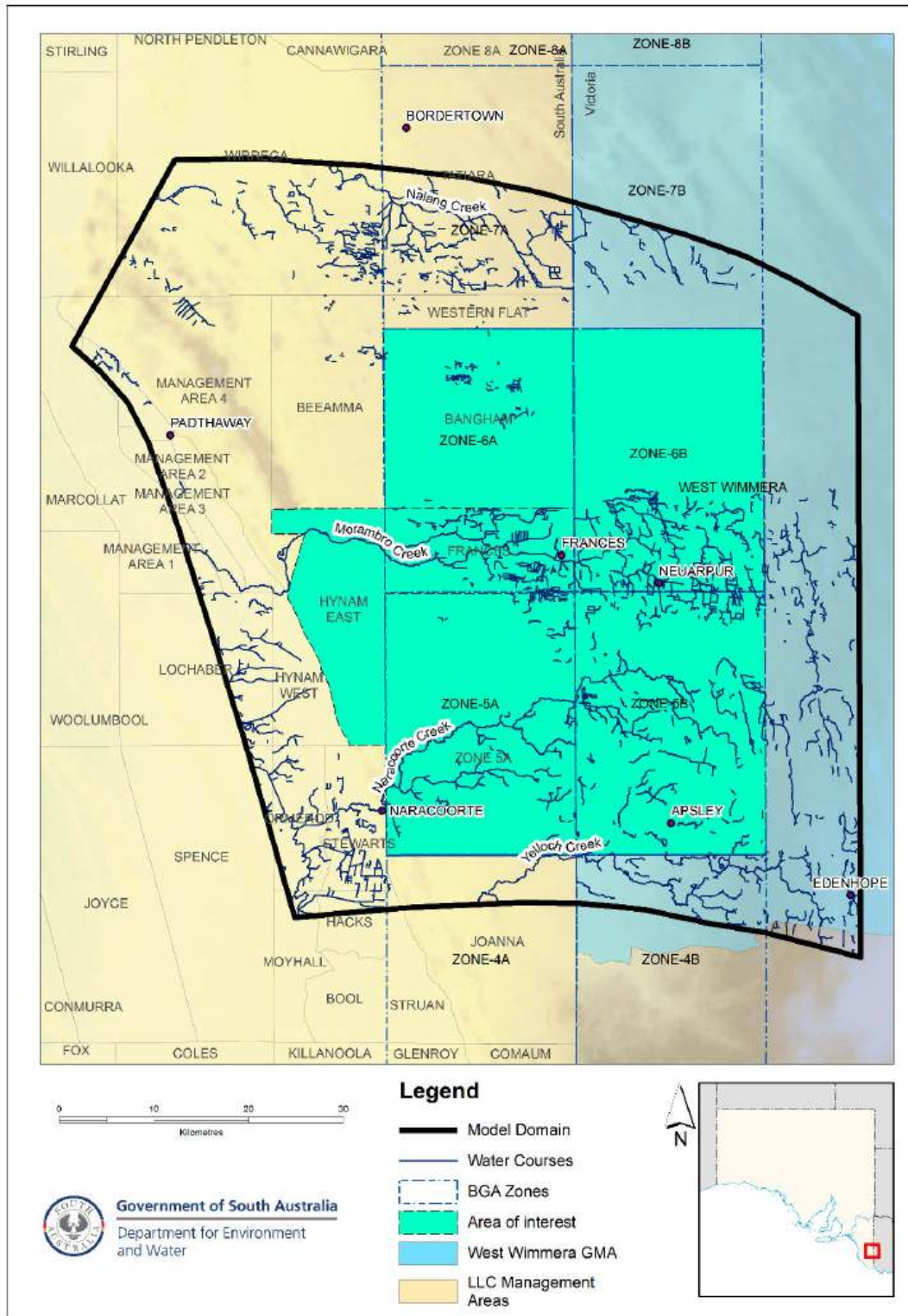


Figure 1.1. Study location map and administrative boundaries.

2 Conceptual Groundwater Model

2.1 Climate

The climate is characterized by hot, dry summers and cool, wet winters. Average temperatures range from about 30°C in summer to about 5°C in winter (Figure 2.1).

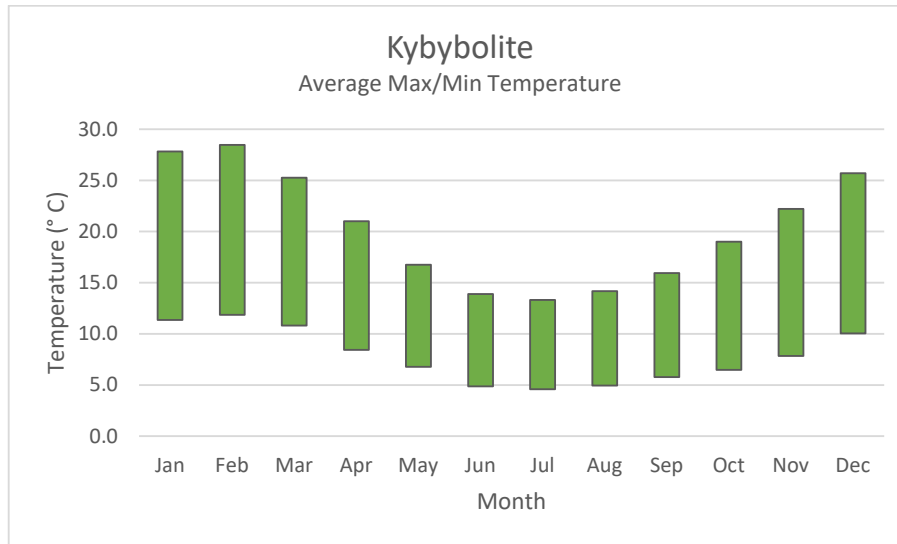


Figure 2.1. Average Maximum and Minimum Monthly Temperatures (1965-1994) recorded at Kybybolite in the south central region of the study area (BoM 2022).

Mean annual rainfall measured at Frances, in the center of the study area, is 517 mm/y (BoM station 26007, records 1890 to 2021). Approximately 75% of annual rainfall falls between April and October, which is typically when groundwater recharge occurs (Barnett et al. 2015). BoM Mean Annual Rainfall Isoheyt data is shown in Figure 2.2 and Mean Annual Rainfall records for selected sites on Figure 2.3. There is a moderate rainfall gradient from north to south. Average annual rainfall is approximately 450 mm/y in the north and increases to approximately 550 mm/y in the south.

Comparing rainfall at each station across the study area indicates that throughout the 20th Century there was a protracted increase in rainfall until approximately 1995. Climatic conditions in the 28 years since 1995 demonstrate a protracted decrease in average annual rainfall. This trend is evident in the Cumulative Deviation From Mean (CDFM) Rainfall. This impacts both groundwater extraction and recharge as irrigators use greater volumes of water to irrigate due to the drier conditions, while at the same time, there is less water available as diffuse rainfall recharge.

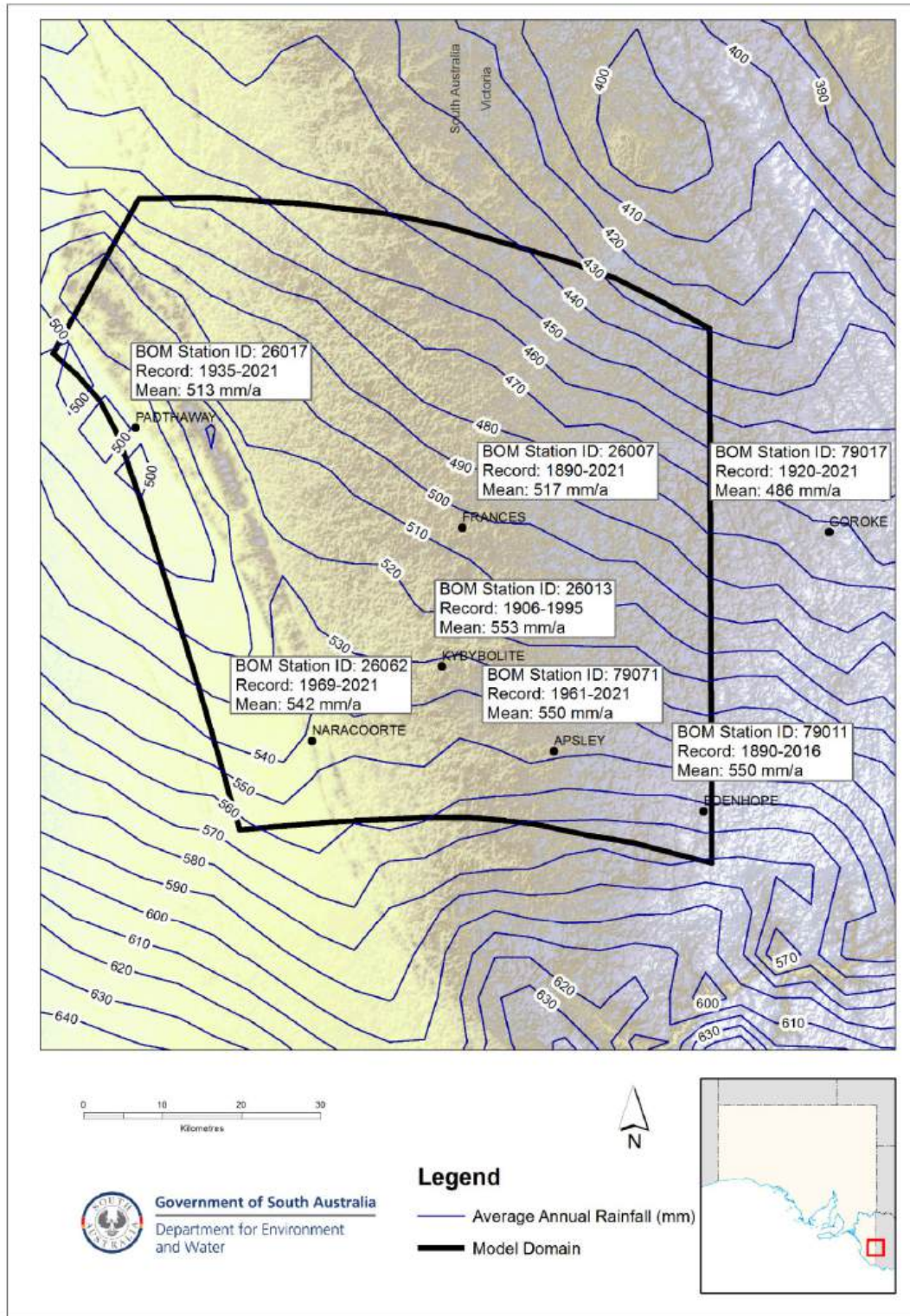


Figure 2.2. Average annual rainfall (BoM 2022).



Figure 2.3. Rainfall records for selected locations (BoM 2022).

2.2 Soil and Land Use

The Soil and Landscape Grid of Australia (Malone & Searle, 2022) was examined to identify factors that may influence recharge in the study area. Figure 2.4 shows the modelled clay content for soils in the region at a depth of 60 to 100 cm. There is a strip of deep sand (blue) that extends across the upper half of the study area. Kennett-Smith et al. (1994) identified a relationship between drainage rates and the clay content of the soil in the top two metres of the soil profile. Where there is a significant percentage of clay, drainage through the soil profile is anticipated to be retarded. This leads to recharge to the water table also being reduced.

Land use (Figure 2.5) is dominated by pastures and grasslands used for animal grazing and there are significant areas of native woody cover associated with Little Desert National Park and various other smaller state parks and conservation reserves. Irrigated areas are distributed throughout the region with significant concentrations of irrigation near Padthaway and Neuarpuir. Land use classifications in Figure 2.5 are based on compiled 2014 and 2016 surveys from South Australian and Victorian sources (DEW 2020a; DJPR, 2018).

Some land use change has been documented in the study area, with Harrington et al. (2015) showing areas of 'Conservation and Natural Environment' being converted to 'Grazing modified pastures' between 1969 and 2008 in the areas of Bangham, Beeamma, Hynam East and the Padthaway Ranges. However, the exact timing of land use change in these areas is not known. Within the past 30 years, land use has not changed significantly throughout most of the region; however, in some localised regions of the study area there have been significant changes. There has been an increase in irrigated vineyards in the Padthaway region and increased horticultural irrigation and irrigated vineyards in Zone 5a and the Hundred of Joanna (Willoughby et al. 2018).

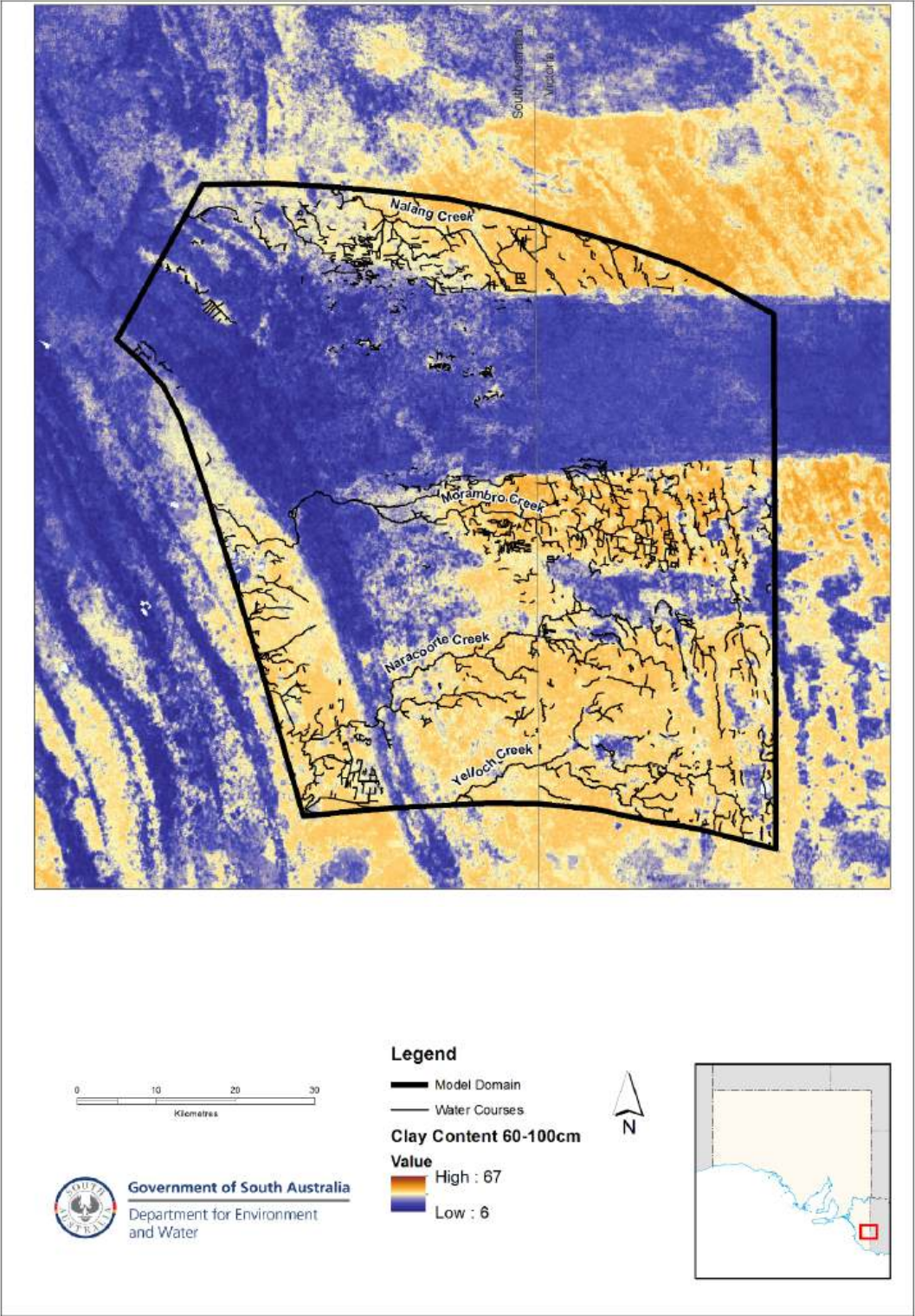


Figure 2.4. Soil clay content.

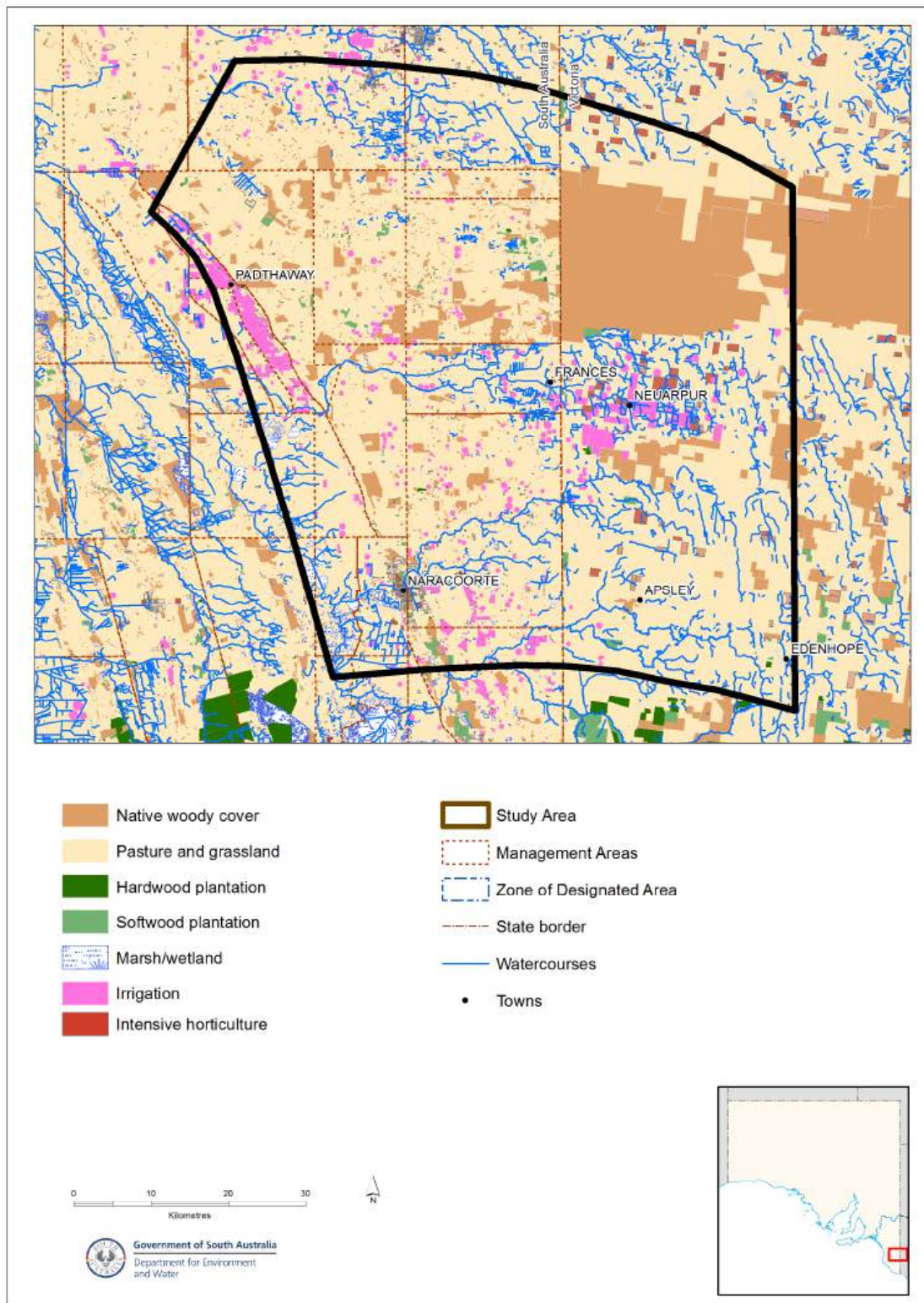


Figure 2.5. Land Use.

2.3 Geology

The study area is located within the southwest portion of the Murray Basin. It is bounded by the Proterozoic and Paleozoic fold belt rocks of the Grampians to the east, the Dundas Plateau to the southeast, and it abuts the Tertiary Gambier Sub-Basin of the Otway Basin to the south and west (Morgan et al. 2015). The Murray Basin and Gambier Sub-Basin are separated in the north by the Padthaway Ridge and in the southwest by the Kanawinka Fault and associated monocline that drapes the fault zone (Cobb & Barnett 1994). The Kanawinka Fault trends northwest with the throw to the southwest. The stratigraphy of the two basins is considered equivalent.

Within the Murray Basin, the stratigraphic sequence begins during the Late Paleocene to Middle Eocene with the deposition of the fluvio-lacustrine sediments of the Renmark Group. During the Early Oligocene to Late Miocene the Ettrick Formation and Geera Clay were deposited in shallow to marginal marine environments. From the late Oligocene the Murray Group Limestone was deposited in shallow marine environments (Brown 1989). During the Pliocene a series of marine transgressions and regressions resulted in the deposition of the Loxton-Parilla Sands and Bookpurnong Beds in a marginal marine to fluvial depositional environment (McLennan 2016).

The Quaternary aeolian dunes of the Woorinen Formation were formed by reworking the Loxton-Parilla Sands during arid glacial periods in the Pleistocene (Cupper et al. 2003).

Eustatic sea level rise during the Early Pleistocene resulted in several marine transgressions that extended inland to the Kanawinka Fault and caused major reworking of Tertiary sedimentary units, depositing the marine sands and sandstones of the Coomandook Formation and the coastal aeolianite of the Bridgewater Formation. The Bridgewater Formation is composed of fossiliferous sand dunes formed in strand lines sub-parallel to the coastline, with the shallow marine limestone of the Padthaway Formation being deposited in inter-dunal areas. These units, where present, overly the karstic Gambier Limestone and form part of the regional unconfined aquifer (Morgan et al. 2015).

During a period related to the last glacial aridity about 22,000-18,000 years ago, erosion of Loxton-Parilla Sands from prominent points in the landscape led to the deposition of the predominantly quartz dunes of the Molineaux/Lowan Sand (Pell et al. 2001).

The temporal and spatial distribution of geological units are presented in Figure 2.6 and Figure 2.7.

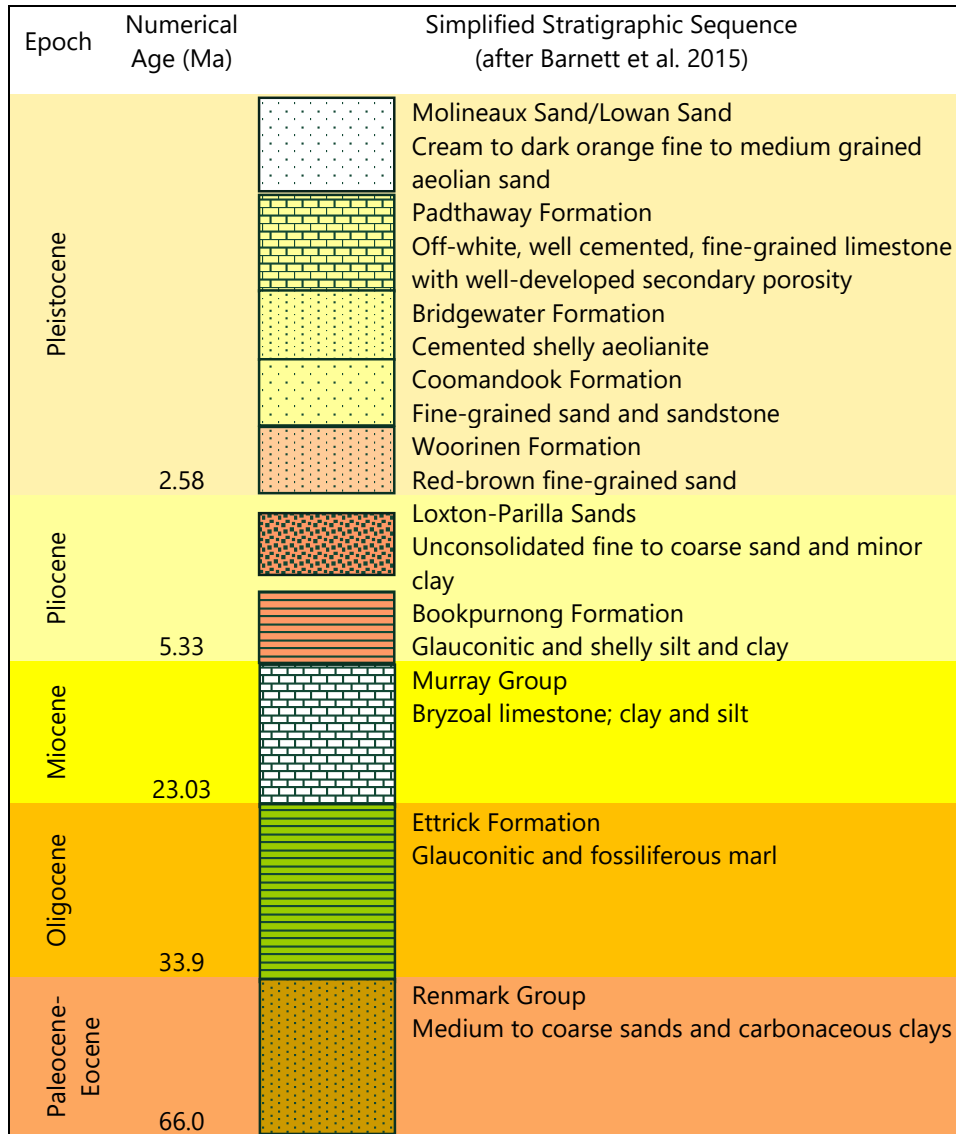


Figure 2.6. Simplified stratigraphic sequence.

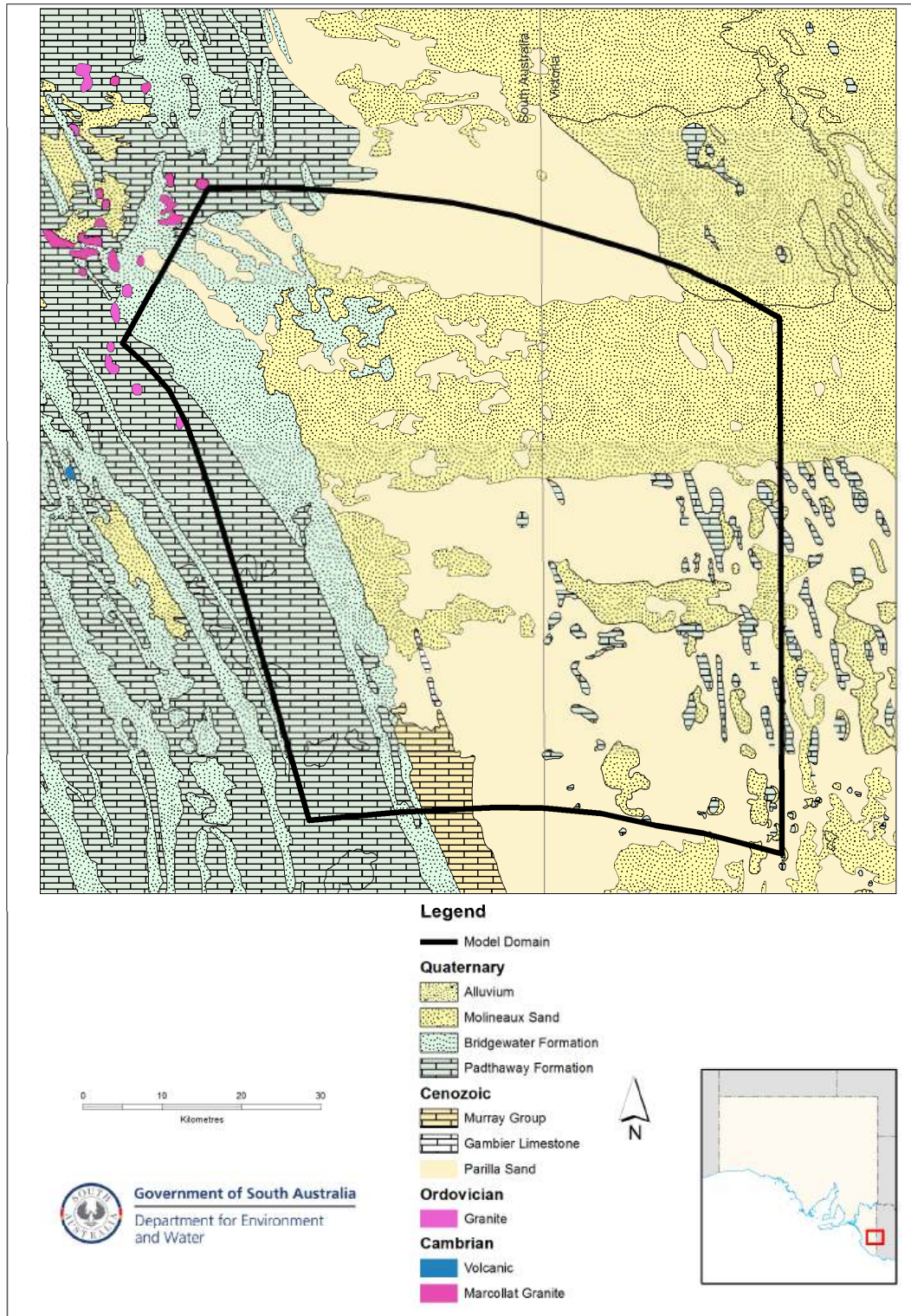


Figure 2.7. Surficial geology.

2.4 Hydrogeology

This study is concerned with the water resources of the Tertiary Limestone Aquifer (TLA). The TLA is composed of multiple geological units across the Murray Basin and within the study area; these include the Tertiary Duddo Limestone, Murray Group Limestone and Gambier Limestone and, in terms of hydrostratigraphy, the Quaternary Coomandook Formation, Padthaway Formation and Bridgewater Formation. These formations are considered to be in direct hydraulic connection across the study area (Figure 2.8).

Underlying the TLA is the Lower Tertiary Aquitard composed of the clays and marls of the Geera Clay and Ettrick Formation. Below that, the Tertiary Confined Sands Aquifer (TCSA) consists mainly of interbedded quartz sand, finer grained sediments and clay horizons of the Renmark Group and includes the Warina Sands, the Buccleuch Beds and the Olney Formation. There is some evidence of downward leakage from the TLA to the TCSA in areas to the south of Province 2 (Brown et al. 2001, Mustafa and Lawson 2011). There is no evidence of downwards leakage within the study area, and no significant extraction from the TCSA. Hence it is not included in the model.

Overlying the TLA in the east are the clays of the Bookpurnong Beds. These act as a confining layer to the TLA; however, the Bookpurnong Beds transition laterally, inter-fingering with Loxton-Parilla Sands to the west. The Bookpurnong Beds thin and pinch out near the eastern margin of the study area. Across this zone the water table transitions from east to west. In the east the TLA is confined by the Bookpurnong Beds. In the central area, where the Loxton-Parilla Sands aquifer is saturated, unconfined conditions are encountered. In the west of the study area the water table is unconfined and resides wholly within the TLA (Figure 2.9).

The water table in the TLA slopes gently towards the coast, but where it crosses the Kanawinka Fault it slopes more steeply towards the southwest (White & Webb 2015). The steeper water table slope suggests that, across the fault zone, a combination of features acts as a partial barrier to flow. It is unclear if the fault itself acts as a barrier or the juxtaposition of different units with differing hydraulic conductivities is responsible for the steepening gradients (Figure 2.10 and Figure 2.11).

Groundwater salinity is commonly less than 1800 mg/L (DEWNR/GWMW/SRW 2014).

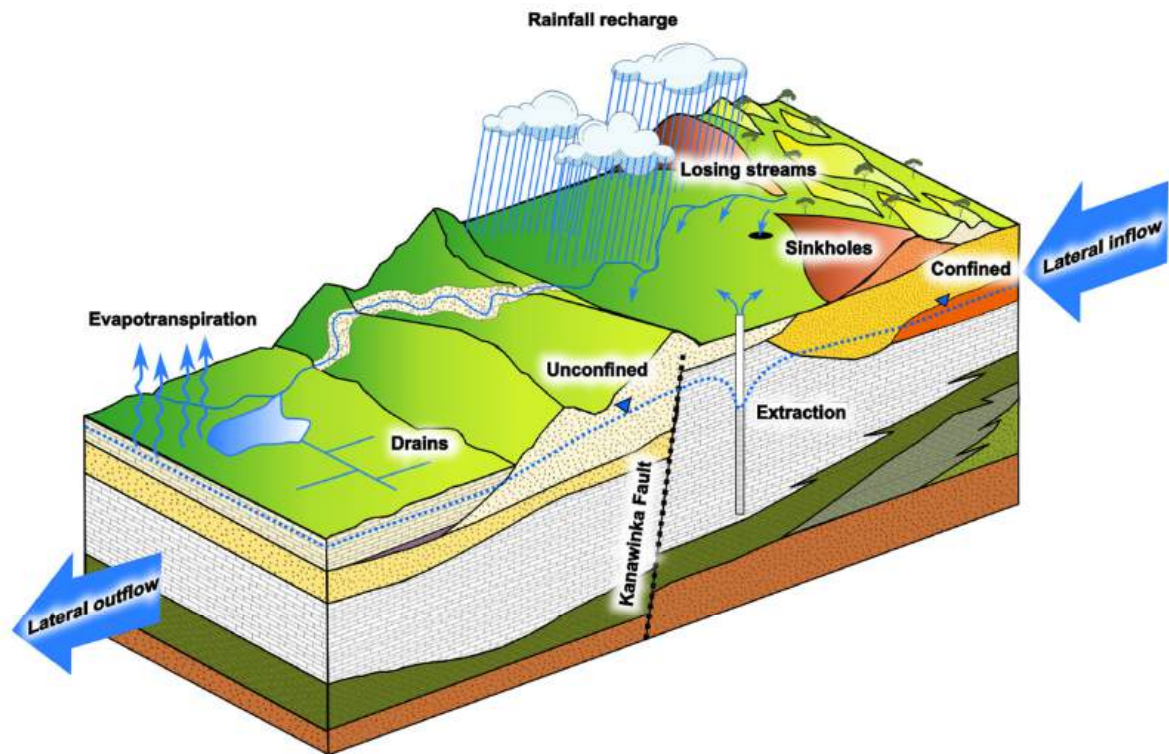


Figure 2.8. Conceptual model schematic (not to scale). Note: The Kanawinka Fault gradually diminishes in displacement to the Northwest and eventually disappears.

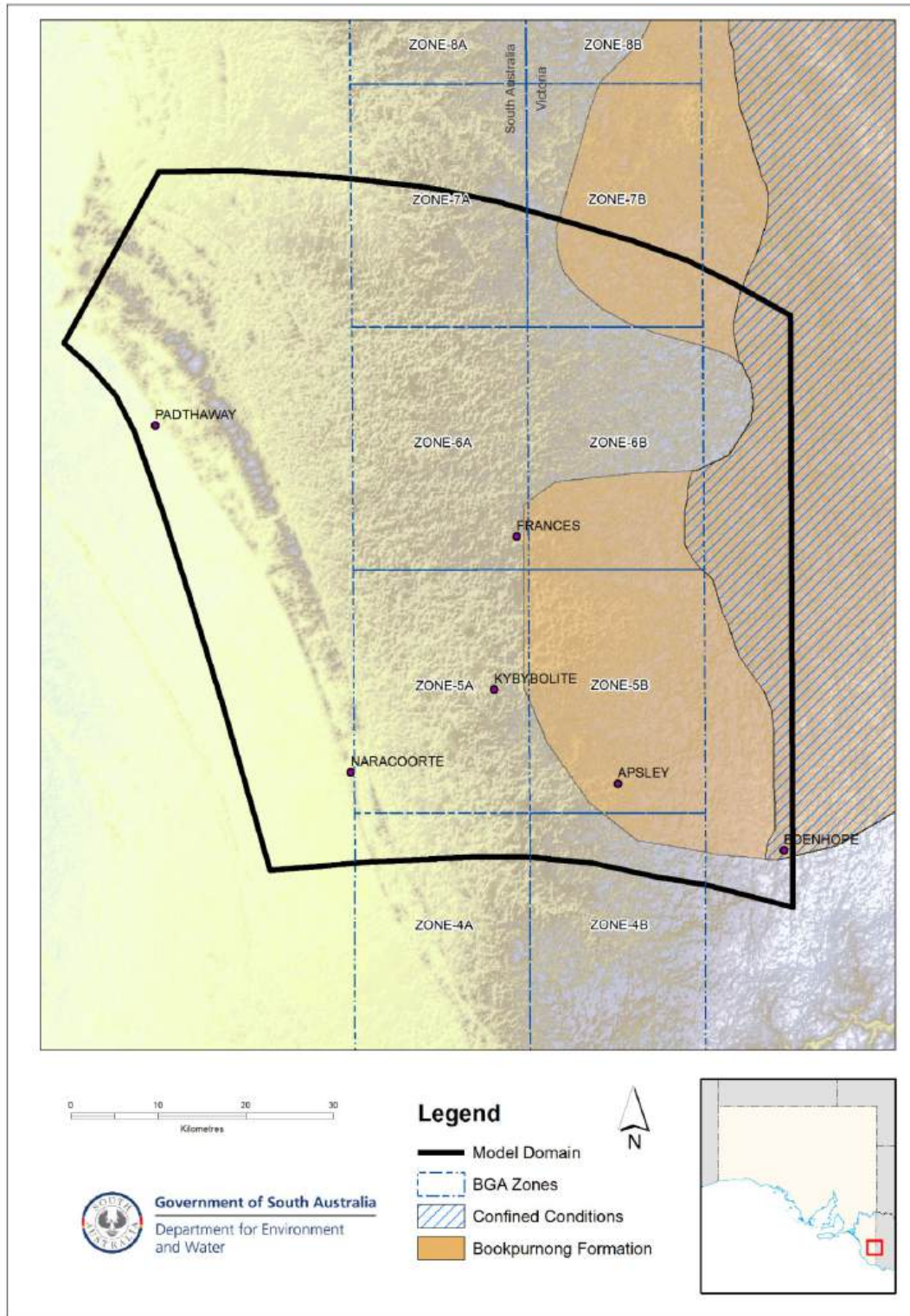


Figure 2.9. Extent of overlying confining beds.

2.5 Groundwater Flows and Water Level Trends

Within the study region, records of groundwater levels extend back to 1949; however, regular monitoring of groundwater levels did not start until the early 1970s in SA. In Victoria, water levels were sparsely monitored throughout the 1970s with regular data collection beginning in 1986. In order to develop preliminary potentiometric surface maps, South Australian data from September 1975 was used to create a potentiometric surface for SA. To this was added Victorian data for September ranging from 1970 to 1989. The use of data points with widely differing sample times is justified on the basis that there is an absence of data within the Victorian portion of the model area throughout this period. It is necessary to incorporate this range of times to identify sufficient data points to constrain the potentiometric surface in the eastern half of the study region.

Data was contoured using Surfer® 12 (Golden Software, LLC, 2015) utilizing the Minimum Curvature method. This dataset originally included several anomalous readings interpreted as pumping wells. These have been filtered out to produce a regional water table equivalent to a “pre-development scenario” circa 1975 (Figure 2.10).

The potentiometric surface was also contoured for the March-April-May quarter of 2022 to display the contemporary distribution of the water table (Figure 2.11). It is evident from the 2022 dataset that cones of depression are present in the potentiometric surface, owing to the data being taken just after the summer irrigation season, and prior to seasonal rainfall and recharge.

In the TLA, groundwater flows generally from east to west, perpendicular to the plotted potentiometric surface contours, from Victoria to South Australia across the state border (Figure 2.11).

A series of representative hydrographs are shown in Figure 2.12 for key areas within the study region. Hydrograph locations are shown in Figure 2.13. It is evident from these plots that there is a dominant downward trend in groundwater levels throughout the region since the mid to late 1990s, consistent with the downward trend in rainfall (Figure 2.3).

Observation well HYN007 displays trends attributed to a delayed recharge response due to land clearing consistent with the study of Wohling et al. (2005). Up to 1980, groundwater levels fluctuate but display no obvious trend. The increase in groundwater levels seen from about 1980 to 1995 is attributed to increased recharge as a consequence of clearing native vegetation for pasture. From 1995 to the present, there is a marked fall in groundwater levels that corresponds to a decrease in recharge as a result of a decrease in rainfall. As discussed in section 2.1, lower rainfall typically correlates with an increase in groundwater extraction, hence changes in rainfall and extraction are likely to have contributed to groundwater level decline. Similar trends can be seen to varying degrees in observation wells GGL009, BIN024 and BIN005.

Observation well 60436 represents a region surrounded by native vegetation where recharge is considered very low. This hydrograph shows a slight fall in water levels commencing in approximately 1995 and trending downwards to the present. This well is located in a National Park and the groundwater response reflects the decline in rainfall (Figure 2.3).

Water levels throughout this region are declining over time, with many wells currently displaying the lowest levels on record (DEW, 2023b).

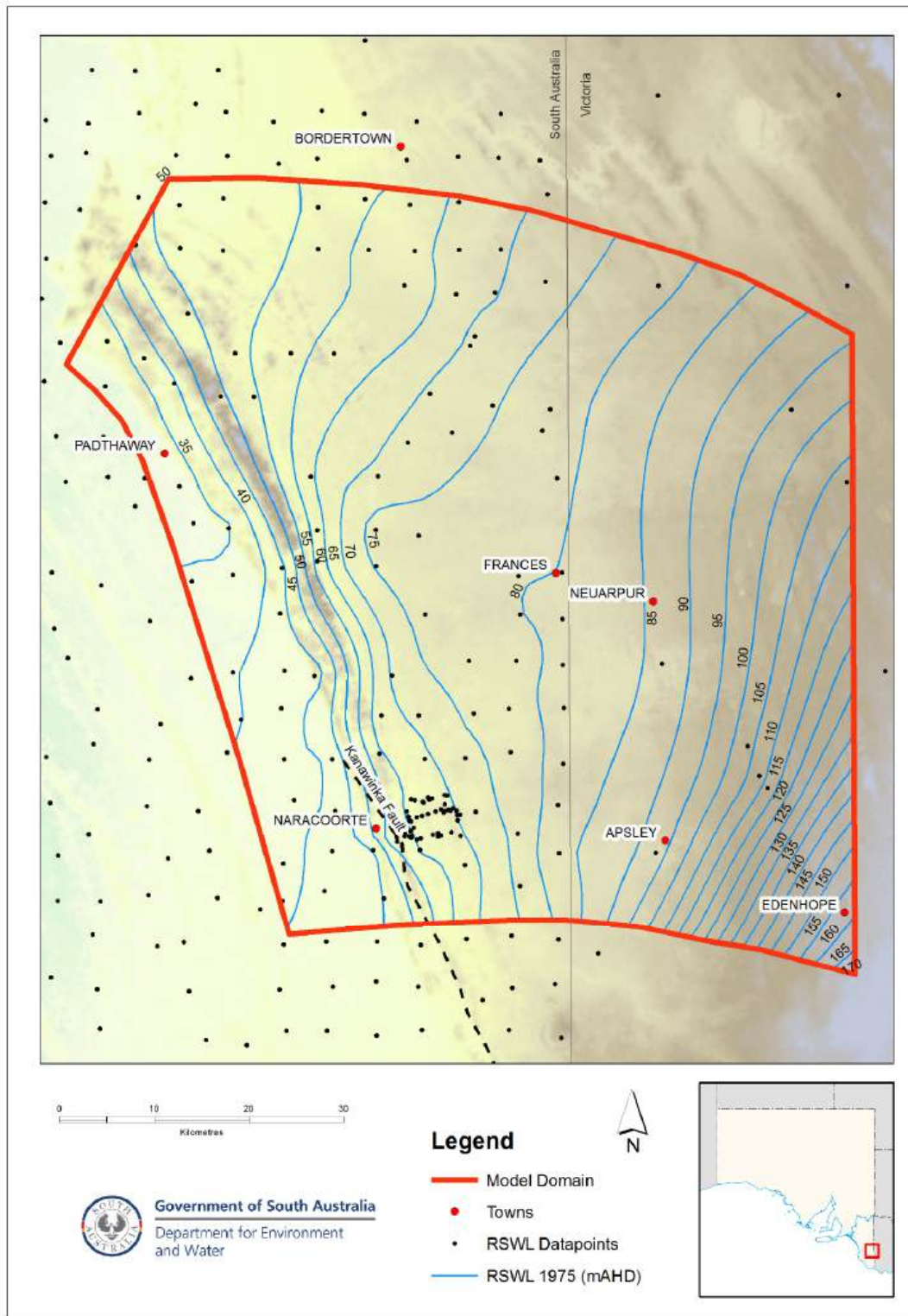


Figure 2.10. Reduced Standing Water Levels September 1975.

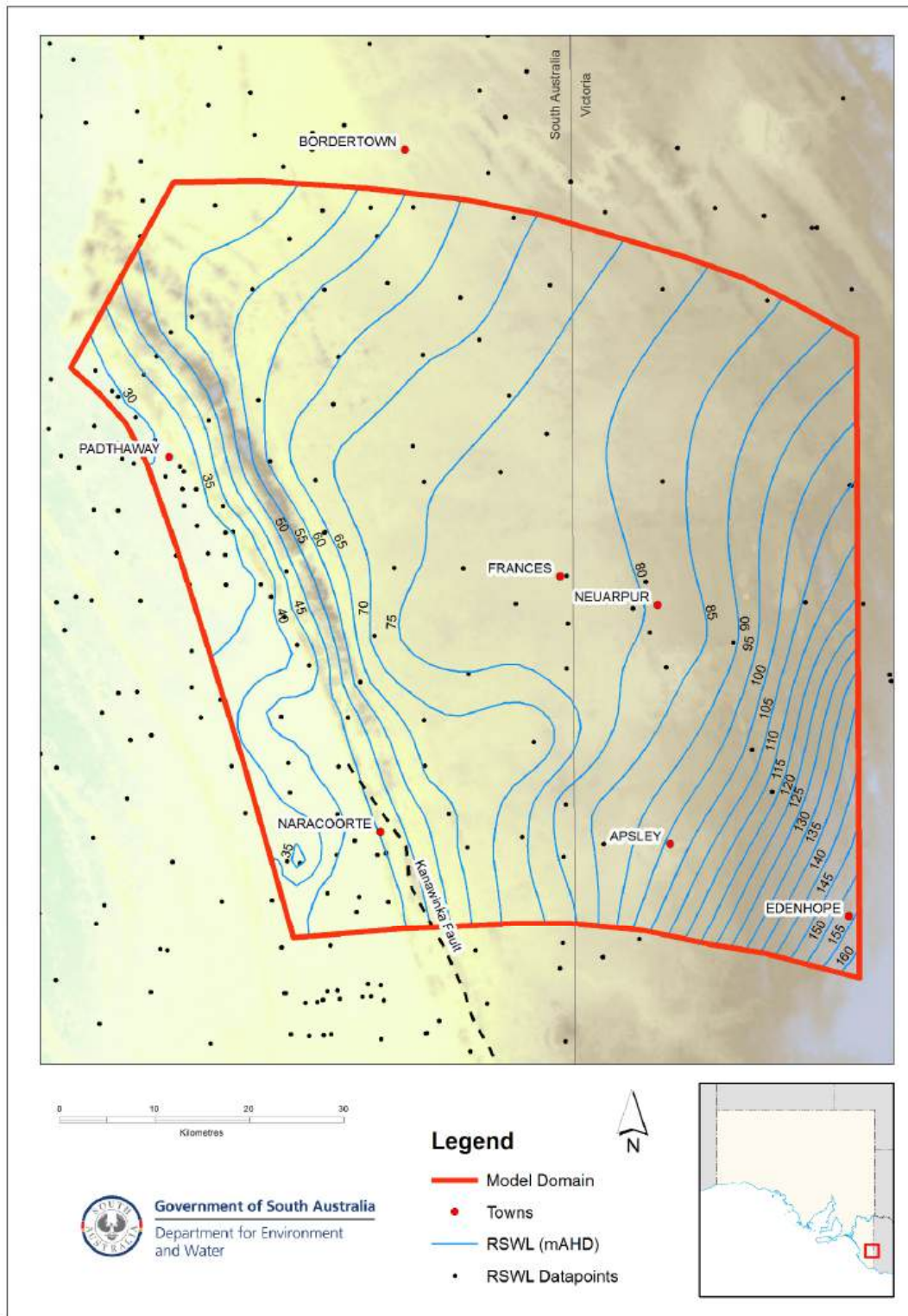


Figure 2.11. Reduced Standing Water Levels March–May 2022.

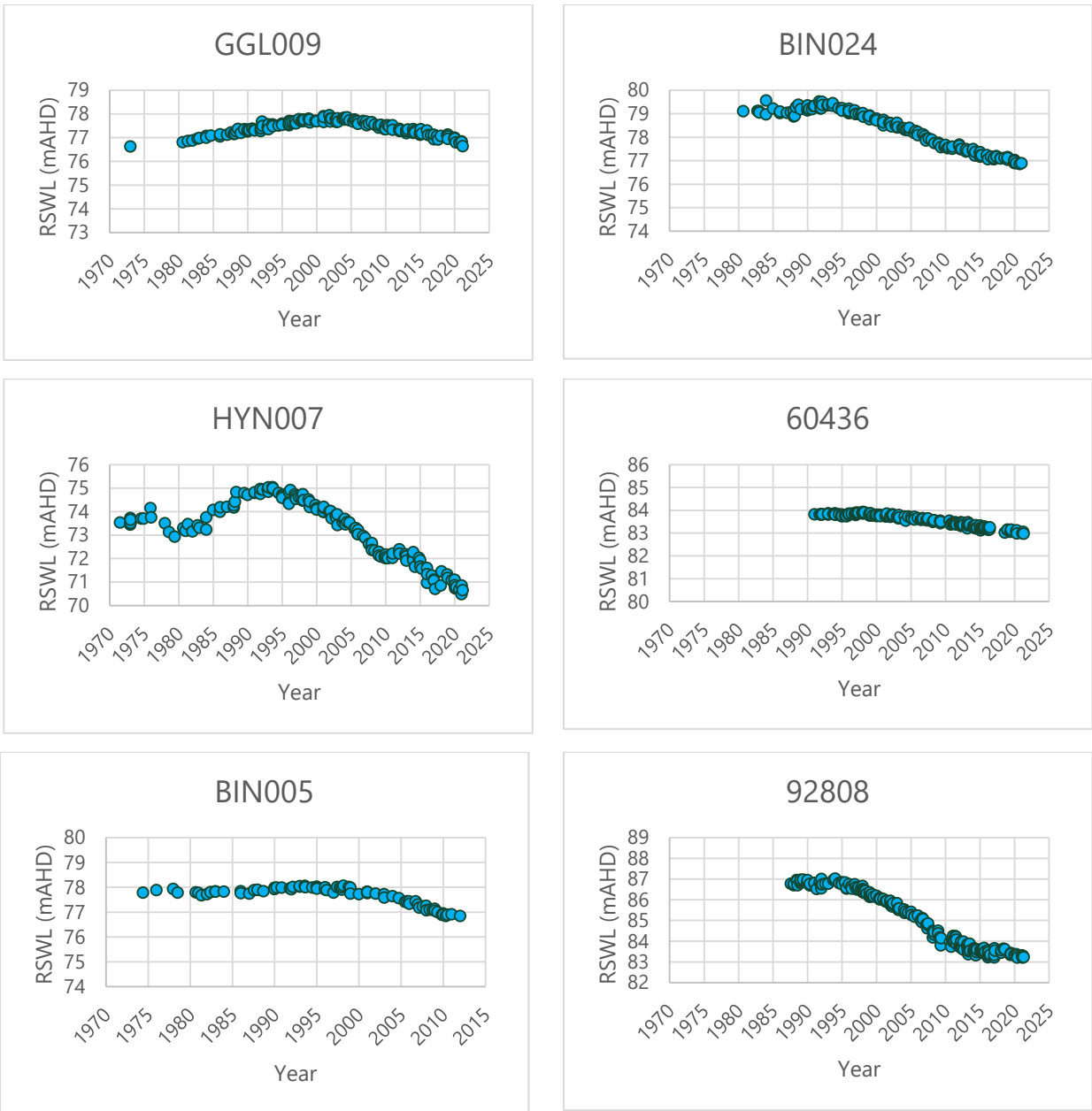


Figure 2.12. Representative hydrographs within the study area.

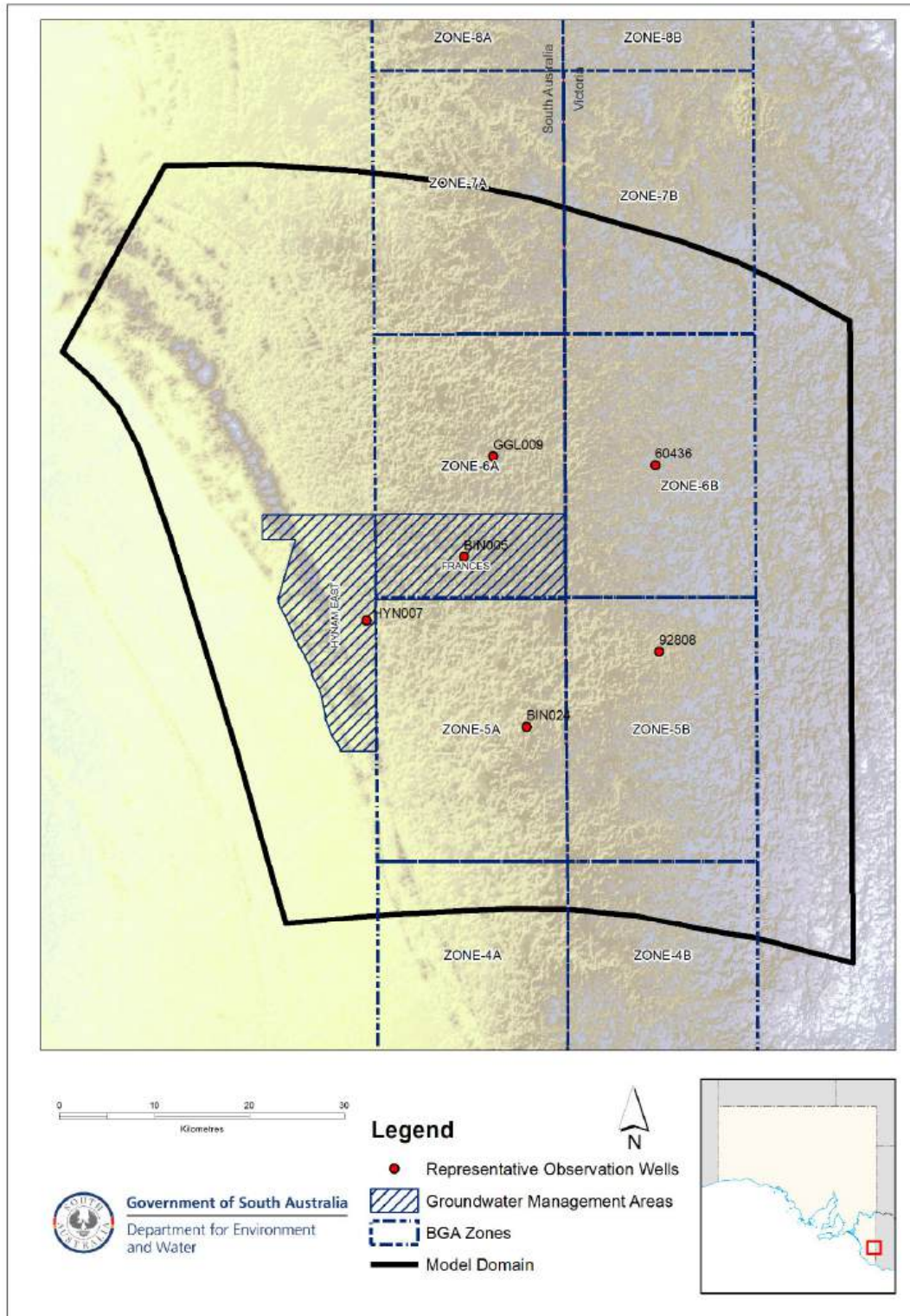


Figure 2.13. Location of representative hydrographs.

2.6 Groundwater Salinity

Groundwater salinity varies widely in the study area (Figure 2.14), influenced by recharge, evapotranspiration and land use. Salinity is greater in areas where water tables are shallow, largely to the west of the study area, suggesting evapotranspiration plays a significant role in concentrating salts in these lowland areas. Within highland areas, salinity is relatively low except in areas adjacent to water courses. It is unclear why this is the case, but one possible mechanism is shallower water tables in the vicinity of water ways being impacted by evapotranspiration.

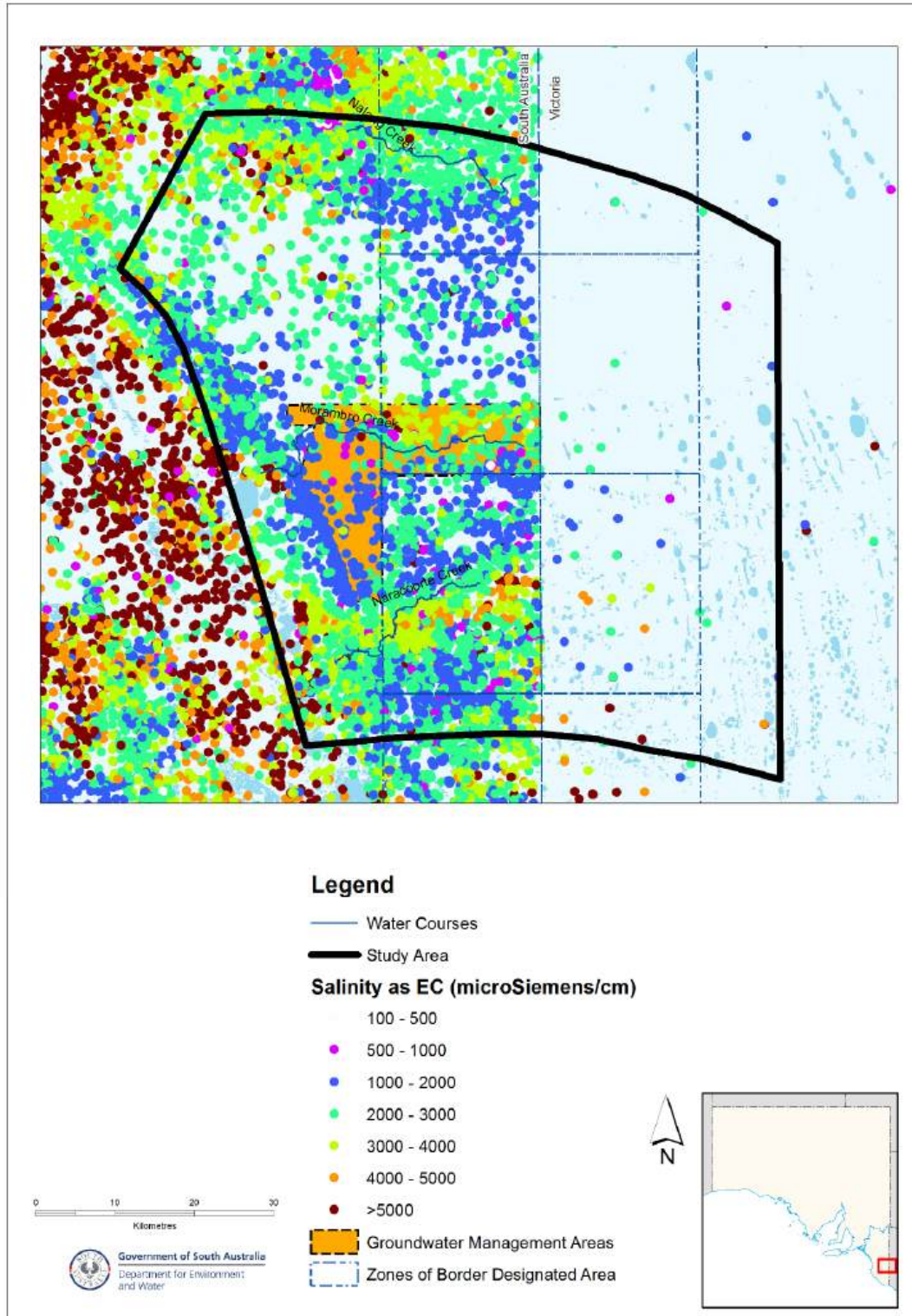


Figure 2.14. Groundwater Salinity.

2.7 Aquifer Properties

Multiple aquifer tests have been conducted within the study area. Consequently, there is a fair to good degree of information regarding aquifer properties. Horizontal hydraulic conductivity values for the Tertiary Limestone Aquifer range from 0.18 m/d to 3,500 m/d. Lower values are associated with the Murray Group Limestone while higher values are associated with the Bridgewater Formation. Values can be high and adjacent points may vary significantly but these values are not considered unreasonable when high permeability formations and karstic features in the landscape are accounted for. Specific yield ranges from 0.01 to 0.27.

Figure 2.15 and Figure 2.16 both display the bottom elevation of the TLA. Higher transmissivity values occur in the middle of the study area where the aquifer is thickest and are generally low where the aquifer is thin, such as in the southeastern quadrant. Specific yield is also greater within the thicker sequences of the aquifer.

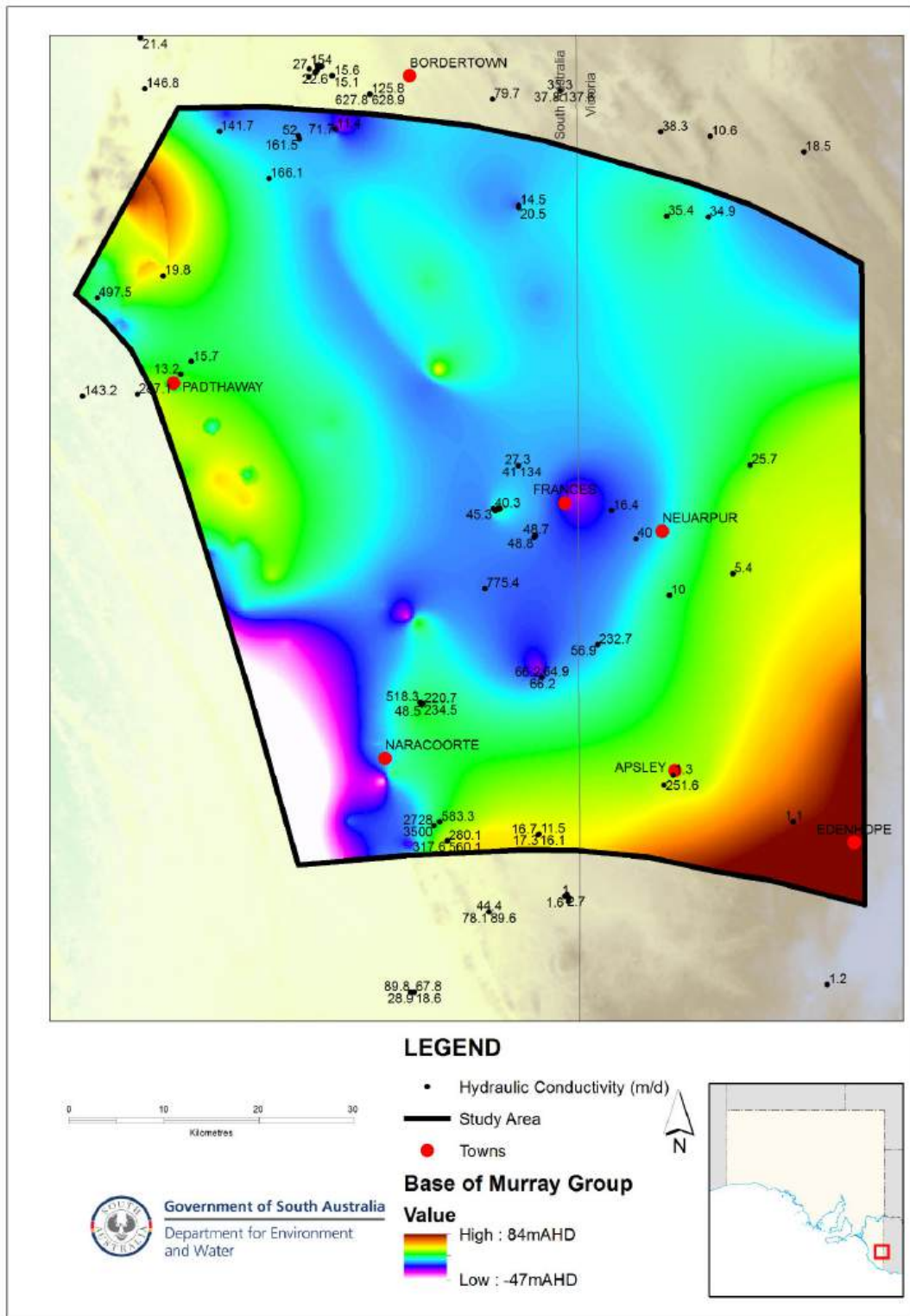


Figure 2.15. Base of Murray Group showing aquifer test results for hydraulic conductivity.

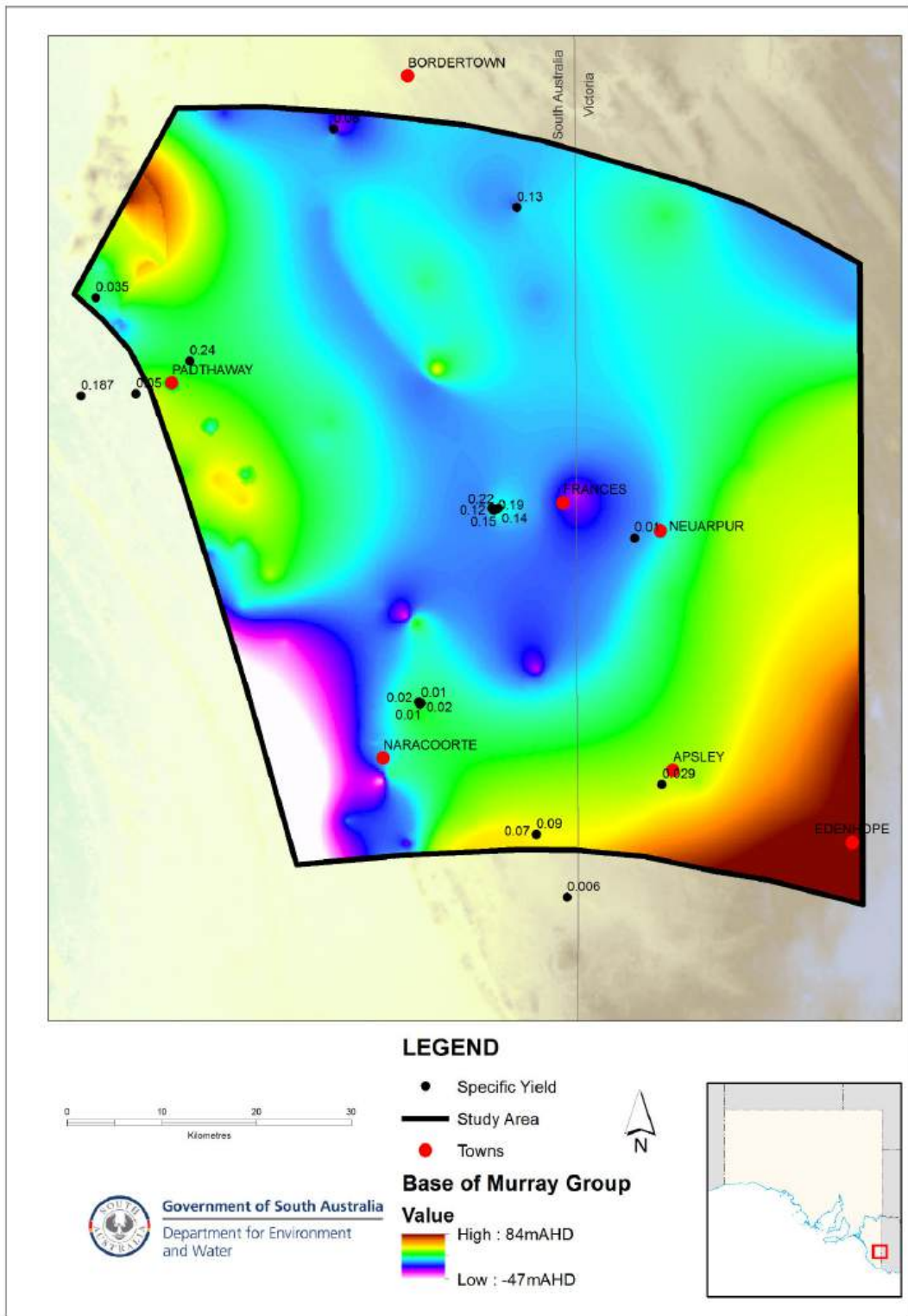


Figure 2.16. Base of Murray Group showing aquifer test results for specific yield.

2.8 Recharge

Various authors have investigated recharge within the region (Bradley et al., 1989 Wohling, 2008, Wood, 2011, Cheng 2019). These studies have found recharge rates varying from 2 – 132 mm/y, but most studies have resulted in estimates <70 mm/y in the study area. The range in rates is influenced by depth to water, soil type and rainfall. Land use also influences recharge, with lower estimates 0.9–6.6 mm/y under native vegetation (Table 2.1).

Table 2.1. Summary of recharge investigations in the study area

Study	Location	Land use	Recharge rate	Method
Bradley et al., 1995	Zone 5A	Pasture	12 – 70 mm/y	Water table fluctuation method
Bradley et al., 1995	Zone 6A	Pasture	2 – 35 mm/y	Water table fluctuation method
Wohling 2008	Zone 5A	Pasture	4.7 – 39 mm/y	Chloride, CFC and 1D modelling
Wohling 2008	Zone 5A	Native vegetation	0.9 – 6.6 mm/y	Chloride mass balance and chloride front displacement
Wohling 2008	Zone 6A	Pasture	2.9 – 26 mm/y	Chloride, CFC and 1D modelling
Wohling 2008	Zone 6A	Native vegetation	0.5 – 6 mm/y	Chloride methods
Wohling 2008	Zone 6A	Irrigation	8.1 - 51 mm/y	Chloride methods
Wood 2011	Zone 6A (Bangham management area)	Pasture	5 – 30 mm/y	Chloride front displacement and CFC analysis
Cheng 2019	Zone 5B/6B (Neuarpur)	Pasture and irrigation	5.6 – 63.1 mm/y (mean) 0.1 – 132 mm/y (range)	HydroSight modelling at 14 sites

Studies in the Padthaway PWA investigated recharge in the Padthaway Ranges (Wohling et al., 2005), which are included in the model domain. These studies found that historic native vegetation clearance resulted in a lagged increase in recharge occurring over the decades following land clearance. The lagged response to recharge is caused by the depth to groundwater in the Padthaway Ranges – up to 38 m – and the time it takes for the unsaturated zone to be flushed following native vegetation clearance. Wohling et al (2005) found point estimates of 2.5 to >49 mm/y, based on profiles of soil water chloride in the unsaturated zone. A relationship between soil type and drainage was then used to spatially map changes in recharge from 1970–2010, with recharge increasing over time as a result of land use clearance. This information was used successfully in the Padthaway groundwater flow model to simulate groundwater levels in the Padthaway Ranges which rise from 1970 to 2005, in contrast to trends in rainfall and declines in groundwater level elsewhere (Aquaterra 2008). These types of trends are also observed in Zone 6A and in the Bangham area. Harrington *et al.* (2015) noted that these areas are likely to have also undergone changes in land use from native vegetation to pasture from 1969 onwards, similar to the Padthaway Ranges.

Studies in the Limestone Coast region have used the Water Table Fluctuation (WTF) method to estimate recharge, such as Brown, Harrington & Lawson (2006) and Fu et al. (2018). The WTF methodology as used by these authors excludes bores with a depth to water greater than 10 m. This limit is applied because the recharge from a rainfall event is attenuated through the unsaturated profile. Within the study area, water tables are generally much deeper

than 10 m, particularly in the highland areas that form the eastern portion of the model. However, the benefit of the WTF approach is that it may provide a temporal record of recharge rates for use in the model. Consequently, the WTF method was applied to hydrograph data in the study area. The resulting recharge rates range from 0.2 mm/y to 388 mm/y.

The mean WTF recharge is calculated as 48 mm/y, a value that is likely skewed by large point-source recharge values in some locations. It should be noted that the application of the WTF method is designed to incorporate point source recharge, and high recharge values are expected where measurements are near karstic features or drainage bores, such as occur in the region.

The median WTF recharge value is calculated as 26 mm/y. This is high when compared to recharge studies utilizing chloride methods but is within the range of studies utilizing the WTF method or Hydrosight modelling (Cheng 2019).

Recharge in highland areas is relatively low in comparison to recharge in lowland areas. Recharge also tends to increase towards the south in line with increased rainfall and decreased evapotranspiration rates.

2.9 Evapotranspiration

Evapotranspiration from groundwater in the Limestone Coast region has been conceptualised to occur generally where the depth to water is less than 2 m (Li and Cranswick, 2017; DEW, 2020b). The depth to groundwater is >2 m over the majority of the domain, and evapotranspiration is not considered to be a large part of the water balance.

Evapotranspiration is likely to occur west of the Kanawinka lineament where water tables are shallow. Evapotranspiration rates from shallow water tables in the Padthaway region were measured at several CSIRO flux stations as part of a study into Salt Accessions. The total actual evapotranspiration in 2004 was measured at 499 mm/y (Aquaterra 2008, DWLBC 2005).

2.10 Groundwater Extraction

South Australian groundwater extraction data are based on estimated use prior to 2009 and metered groundwater extraction data after that date. Estimated use is based on the dataset compiled by Harrington & Li (2015), who applied average metered extraction from 2009/10 to 2013 to each licence in past years, back to the construction date for the extraction well associated with each licence. This produces a trend in the total groundwater extraction volume that gradually increases over time (Figure 2.17).

Victorian groundwater extraction data was accessed through the Department of Energy, Environment and Climate Action. Data are based on estimated use prior to 2009 and metered groundwater extraction data after that date. Estimated use is based on a similar method to Harrington & Li (2015), where median metered extraction from 2009-2019 was applied in past years, back to the construction date for the extraction well associated with each licence (Figure 2.18). There are 97 extraction wells in the Victorian dataset that have no construction date recorded. These wells have been included starting from 2009.

Metered data shows extraction for the entire study area varies over time since 2007. In South Australia there is a general trend of higher extraction in lower rainfall years and, conversely, lower extraction in higher rainfall years (Figure 2.17), as would be expected. It should be noted that extraction data is reported for the financial year (July to June), whereas annual rainfall in Figure 2.3 represents rainfall recorded for the calendar year. Rainfall does vary across the study area and, as such, a perfect correlation between rainfall and extraction is not expected. Errors in reported metered extraction data are probable; however, the fluctuating trends in line with rainfall observed in Figure 2.17 give confidence in the data being used.

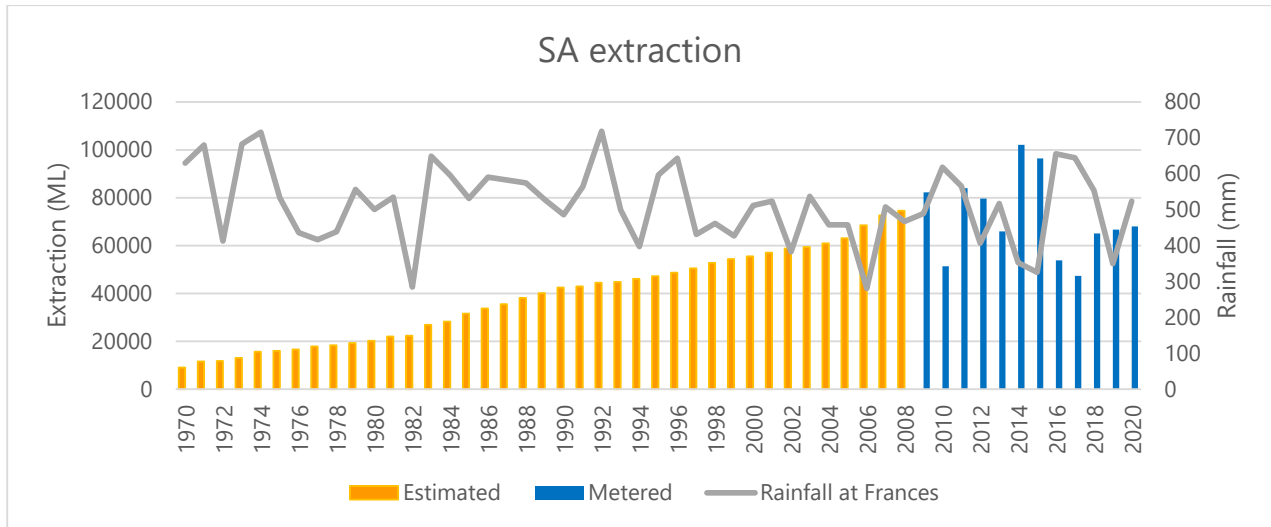


Figure 2.17. Groundwater extraction: South Australia.

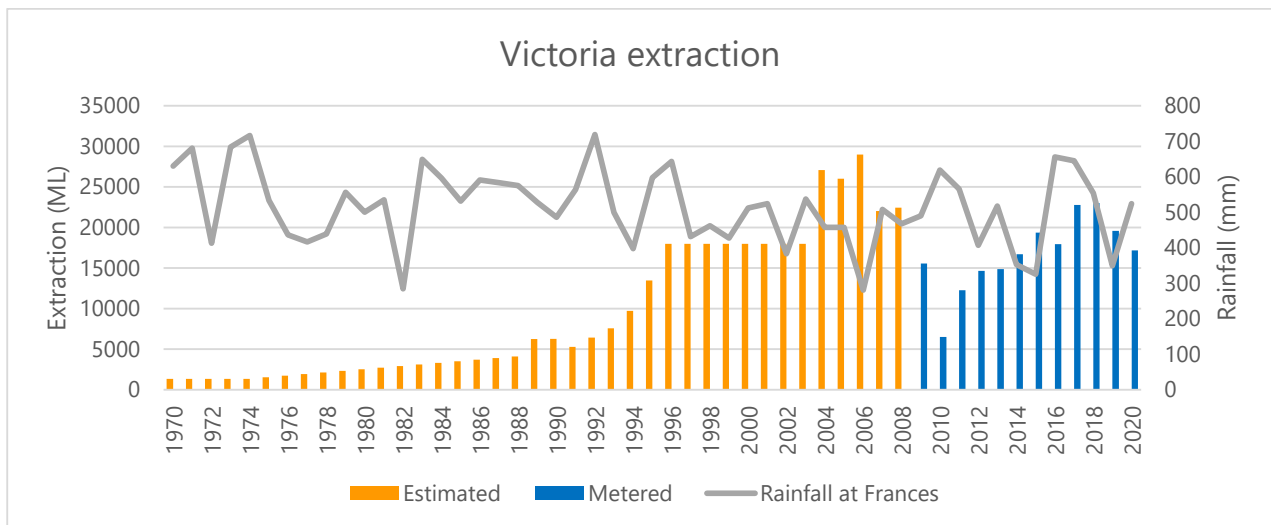


Figure 2.18. Groundwater extraction: Victoria.

2.11 Surface Water – Groundwater Interactions

Several creeks cross the area from east to west: namely Naracoorte Creek, Morambro Creek and Nalang Creek. (Figure 2.4). These creeks lie at an elevation of more than 5 m above the watertable. They are likely to be predominantly losing streams and are not believed to receive significant groundwater discharge (SENRM 2019).

An extensive system of drains exists to the west of the Naracoorte Ranges. These drains were constructed mainly between 1949 and 1972 to remove water from the landscape to create productive land (SENRM/SEWCDB 2019).

2.12 Conceptual Modelling Summary

The study area may be separated into two zones: the broadly distributed highland zone to the east of the Naracoorte Ranges, and the lowland zone to the west of the ranges. The highland zone consists of the Murray

Group limestone aquifer that has large storage volumes and receives relatively low recharge rates through a thick unsaturated zone (Cheng, 2019). The lowland zone consists of the Padthaway Formation and Bridgewater Formation that together form the highly permeable Quaternary limestone aquifer. Groundwater flows from east to west-northwest from the highland areas to the lowland areas.

2.12.1 Inflows

Inflows to the area are dominated by diffuse rainfall recharge, with median estimated rates around 25 mm/y (Table 2.1).

Point source recharge via karstic features has been identified as a significant recharge process. Herczeg and Leaney (1993) determined that the influence of point-source recharge was local and estimate that recharge via karstic features makes up approximately 10% of total recharge, which indicates that such local scale features are likely not critical to the sub-regional modelling.

Groundwater inflow also occurs as lateral flow from the east of the study area and is estimated via Darcy's Law to be in the order of 150,000 m³/d.

2.12.2 Outflows

There are several outflows from the study area. Natural outflows include groundwater flow to the west and evapotranspiration from shallow water tables. However, evapotranspiration of groundwater is only likely to occur west of the Kanawinka lineament, in a relatively small part of the study area. Additional outflows include pumping for irrigation and discharge to drains.

3 Model Construction

3.1 Previous Modelling Studies

Previous modelling studies conducted in the study area and surrounds include:

- Frances – Neuarpuur model (SKM 2003)
- South East Regional Water Balance Project (Morgan et al. 2015)
- Tatiara PWA model (Li & Cranswick 2017)
- Technical Review of Groundwater Resources Province 2 (CDM Smith 2017)
- Padthaway model (Aquaterra 2008/DEW 2020b)
- GISERA model (Doble et al. 2020)
- Lower Limestone Coast sub-regional modelling: Mid-South East (DEW 2023)

The documentation for each of these models was reviewed and data was used where relevant. This includes groundwater extraction records, recharge data and methodology, aquifer parameter data and interpreted distributions, and modelled aquifer layer elevations.

3.2 Code selection and modelling approach

The Province 2 groundwater modelling has been designed and executed consistent with best practice guidelines (Barnett et al. 2012). The modelling used MODFLOW-2005 (Harbaugh 2005) as the solver and Groundwater Vistas Version 8 (ESI 2020) as the modelling GUI.

Groundwater flow within the model was assumed to flow through an equivalent porous medium. Although this may poorly simulate small-scale conditions where karst features occur, these features are limited and have only a small effect on groundwater movement. This method can adequately represent the behavior of the regional flow system (Anderson & Woessner 1992).

3.3 Model domain and grid

The area of interest encompasses the management areas of Hynam East, Zone 5A and Frances within the Lower Limestone Coast Prescribed Wells Area, as well as Zones 5B, 6A and 6B in the Border Designated Area (Figure 1.1). The model domain incorporates portions of the Tatiara, Padthaway and Lower Limestone Coast Prescribed Wells Areas in South Australia and the West Wimmera Groundwater Management Area in Victoria.

The grid is oriented north-south and east-west composed of a regular model grid divided into 450 rows and 450 columns with a uniform cell size of 200 x 200 m. The model is a single layer covering 5333 km² and consisting of 133,313 active cells.

The lateral model domain boundary extents were chosen to encompass Hynam East and BGA Zones 5A, 5B, 6A and 6B with sufficient distance to reduce boundary effects on the modelling results. Boundaries to the north and south are approximately perpendicular to the groundwater contours. The eastern boundary is located 10 km east of the Border Designated Area boundary in Victoria, a distance considered sufficient to minimize boundary effects while largely excluding areas to the east of the model where the aquifer is confined by the clays of the

Bookpurnong Beds and the Shepparton Formation (See Section 2.4 and Figure 2.9). By excluding these areas, the model complexity is reduced and the TLA can be simulated as a single, unconfined layer. In the southwest the model domain is located west of the Naracoorte Ranges a sufficient distance to incorporate the highland regions and transition zones such as Hynam East. In the northwest the model has been truncated to exclude several basement inliers.

3.4 Layer Elevations

The model consists of a single layer (Layer 1) whose elevations are derived from a Digital Elevation Model (DEM) and from digitized drillhole data that provides subsurface information on the layer thickness and geometry.

The top elevation of layer 1 (Figure 3.1) represents the ground surface. It is sourced from the Digital Elevation Model (DEM) 5 Metre Grid of Australia derived from LiDAR surveys (Geoscience Australia 2015). The DEM was imported into the model where the elevations were averaged for each 200 x 200 m model cell.

The bottom elevation of layer 1 (Figure 3.1) is derived from data developed by Barnett et al. (2015). The resultant dataset is gridded at 200 x 200 m. This was imported into the model and defines the base of the TLA.

3.5 Boundary Conditions

3.5.1 Regional Flow

The potentiometric surface shows that the regional flow direction is generally from east to west, with southeast to northwest trends in some areas (Figure 3.2). General Head Boundaries (GHB) have been implemented as head-dependent flow boundaries along the east, west, and part of the north-west, to represent regional inflow and outflow (Figure 3.2). The remainder of the northern and southern model domain boundaries have been set approximately parallel to the groundwater regional flow direction and are assigned as no-flow boundaries (Figure 3.2)

In the northwest corner of the model, groundwater extraction in the adjacent Tatiara PWA results in a decline in the potentiometric surface across the model boundary. This decline has been accommodated by setting transient GHBs along a portion of the northern edge of the model.

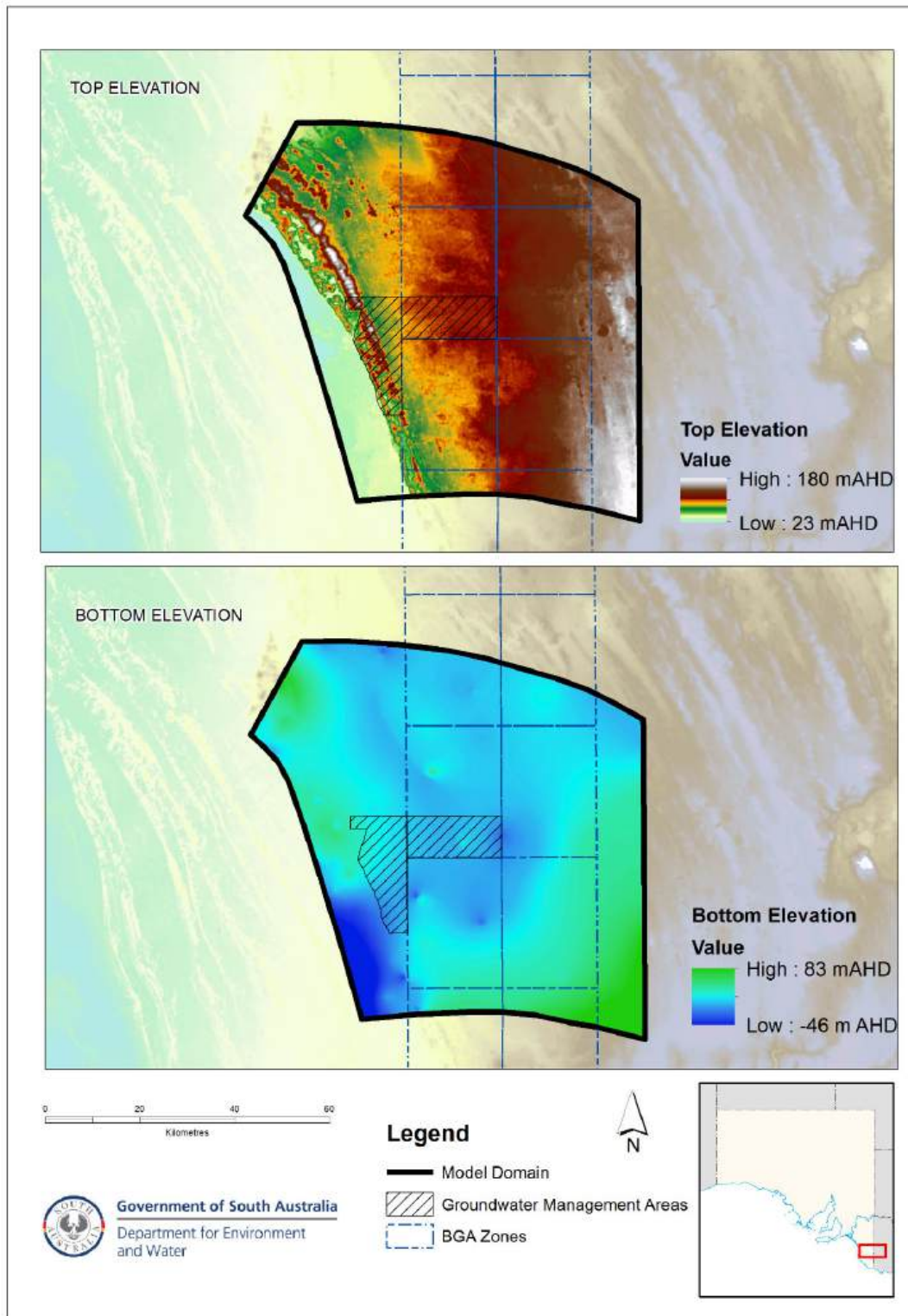


Figure 3.1. Modelled layer elevations.

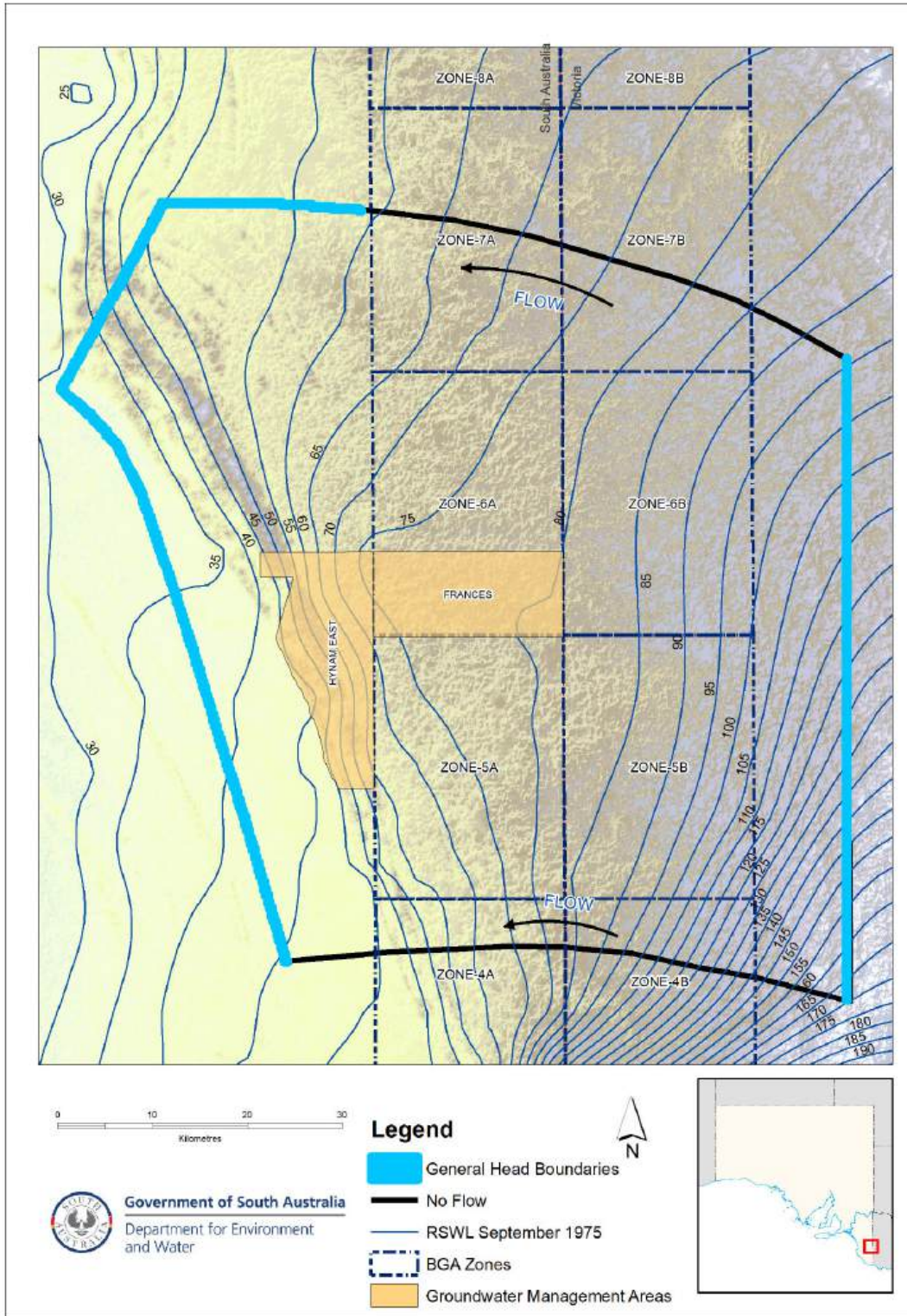


Figure 3.2. General Head Boundaries.

3.6 Recharge

As discussed in Section 2.8, the Watertable Fluctuation Method (WTF) was used to derive recharge estimates at bores across the study area, following the method described in Fu et al. (2018). An initial estimate of WTF recharge in each well was plotted spatially and contoured to create zones of recharge for the steady state modelling.

Hydrograph trends were examined to determine regions that displayed similar hydrograph fluctuations. Similar hydrograph trends were grouped together into cohesive spatial zones. Other features such as surficial geology, soil type and topography were then used in conjunction with the grouped hydrographs to delineate new recharge zones replacing the initial zones identified (Table 3.1). Zones were added to account for native vegetation and the effects on recharge attributed to the impacts of native vegetation clearance in the Molineaux Sand/Lowan Sand areas. Recharge rates were varied through time within each zone (Figure 3.3).

Table 3.1. Recharge Summary Statistics.

Statistic (mm/y)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11	Zone 12
Max.	19.2	0.0015	10.1	27.4	27.4	27.4	137.3	93.2	21.3	21.3	50.6	24.2
Min.	0.0015	0.0015	10.1	7.2	1.4	1.4	7.5	7.5	1.1	1.1	0.1	0.0012
Range	19.2	0	0	20.2	26.0	26.0	129.8	85.6	20.2	20.2	50.5	24.2
Mean	7.5	0.0015	10.1	13.7	10.0	9.9	53.3	48.7	13.3	12.8	27.3	13.5
Median	6.8	0.0015	10.1	12.3	9.0	9.0	53.6	52.7	11.3	11.3	21.8	10.4
Mode	4.6	0.0015	10.1	12.3	2.2	2.2	137.3	15.3	21.3	21.3	50.6	24.2
Standard Deviation	4.4	0	0	3.9	6.3	6.4	24.7	19.4	6.7	7.2	19.1	8.8

3.7 Evapotranspiration

An evapotranspiration (ET) rate of 500 mm/y was applied based on CSIRO measurements (Aquaterra 2008). An extinction depth of 2 m was set as the depth limit, such that evapotranspiration generally only occurs in shallow water table areas west of the Kanawinka lineament. These areas lie outside the zone of interest and any inaccuracies or complexity arising from evapotranspiration from shallow water tables will not have a significant effect on the primary modelling outcomes.

3.8 Extraction

Groundwater extraction datasets have been developed for the model domain using a combination of estimated and metered groundwater extraction data as described in Section 2.10 (Figure 3.4). The location of observation wells has also been included in Figure 3.4.

Pumping activity is low around the edges of the model and reconstruction of historic potentiometric surfaces suggests that the hydraulic heads in this area have not been significantly affected by pumping. Consequently, based on the potentiometric surfaces, the northern and southern boundaries of the model have been treated as no-flow boundaries.

However, there is an exception in the northwest corner of the model where pumping rates from outside the model create a cone of depression that extends into the model domain. To account for this external influence time-varying General Head Boundaries have been used to simulate this drawdown (Figure 3.2).

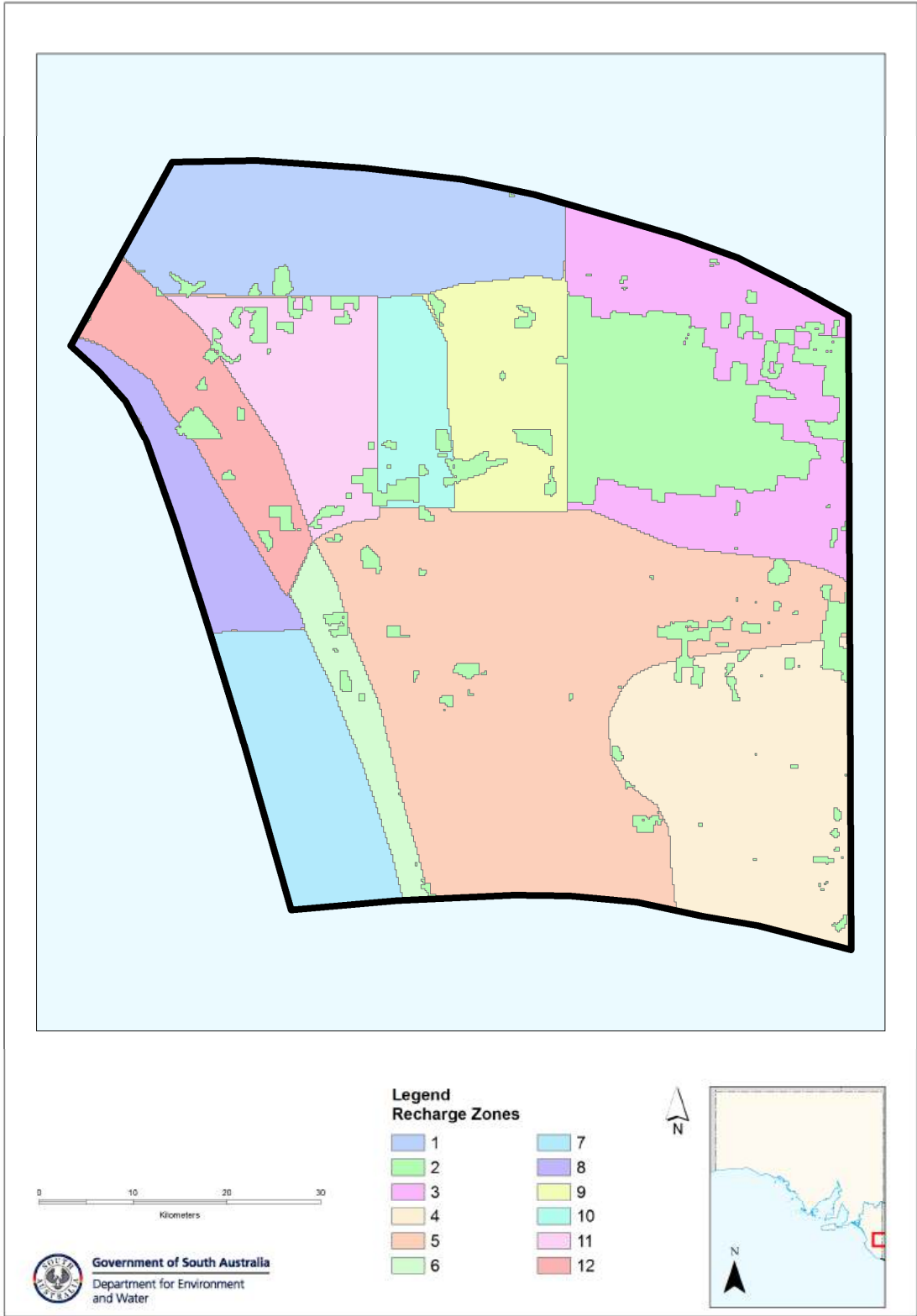


Figure 3.3. Recharge zones.

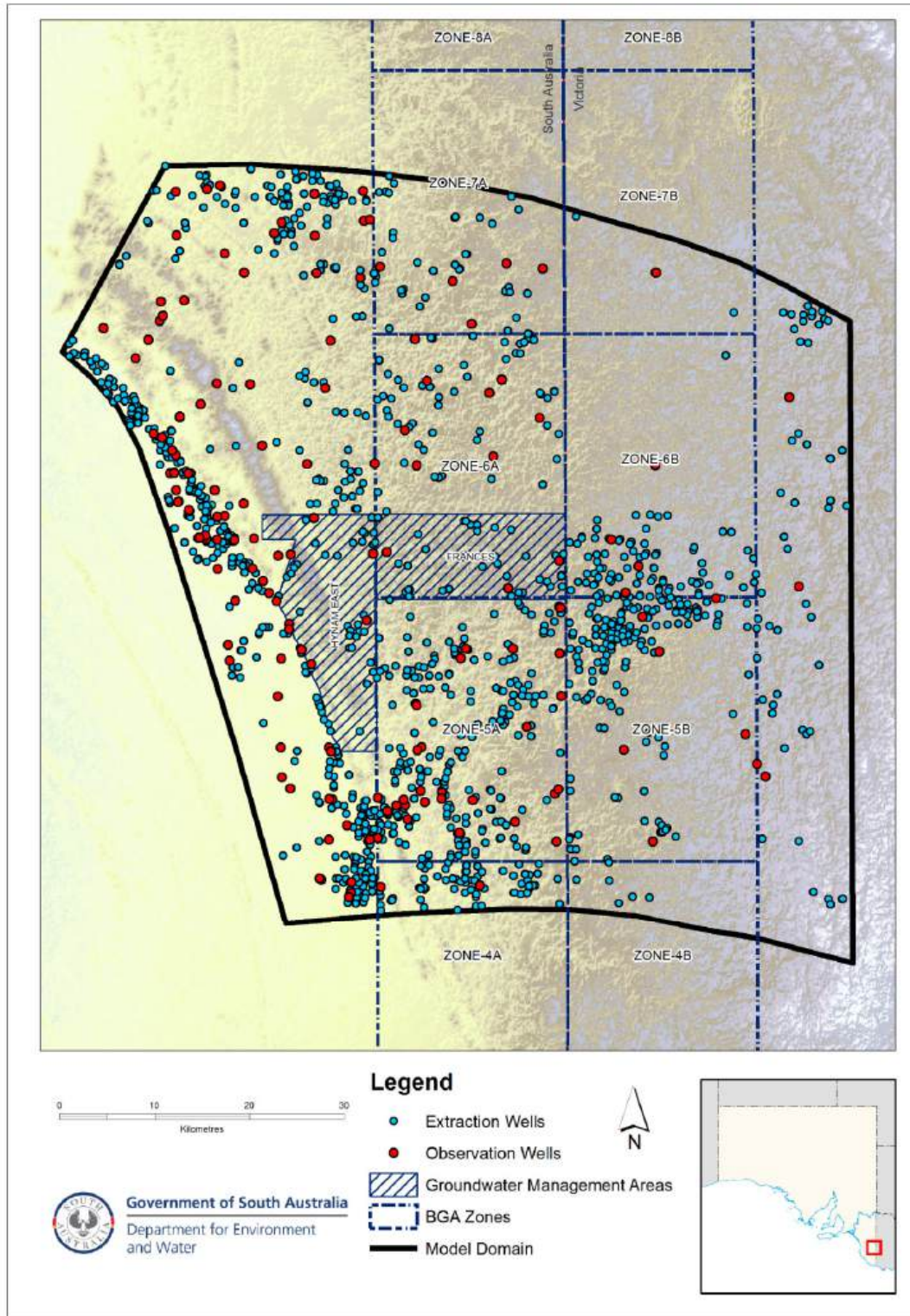


Figure 3.4. Modelled groundwater extraction well and observation well locations.

3.9 Hydraulic Parameters

Initial values for hydraulic conductivity were designated into zones based on surface geology and the distribution of the groundwater potentiometric surface, along with aquifer test data and information from previous studies (Li & Cranswick (2017), DEW (2020)). These initial parameters were plotted in regions (Figure 3.5) and then varied through a manual trial and error history match ('calibration') process using steady-state modelling to produce parameter values that achieve a reasonable match to the measured groundwater levels and potentiometric surfaces. Further parameter estimation was undertaken via PEST (WNC 2018) utilising 537 distributed Pilot Points to determine a matrix of Hydraulic Conductivity (Figure 3.6).

Modelled hydraulic conductivity exhibits a very wide range, from 0.67 m/d to 1,200 m/d across the model domain, with the maximum hydraulic conductivity capped at 1,200 m/d for PEST analysis. This upper bound is based on the measured hydraulic conductivities presented in Figure 2.15 excluding extreme outliers in the Naracoorte area. These areas of very high conductivity are associated with outcrops of Murray Group Limestone containing karstic features located near Naracoorte.

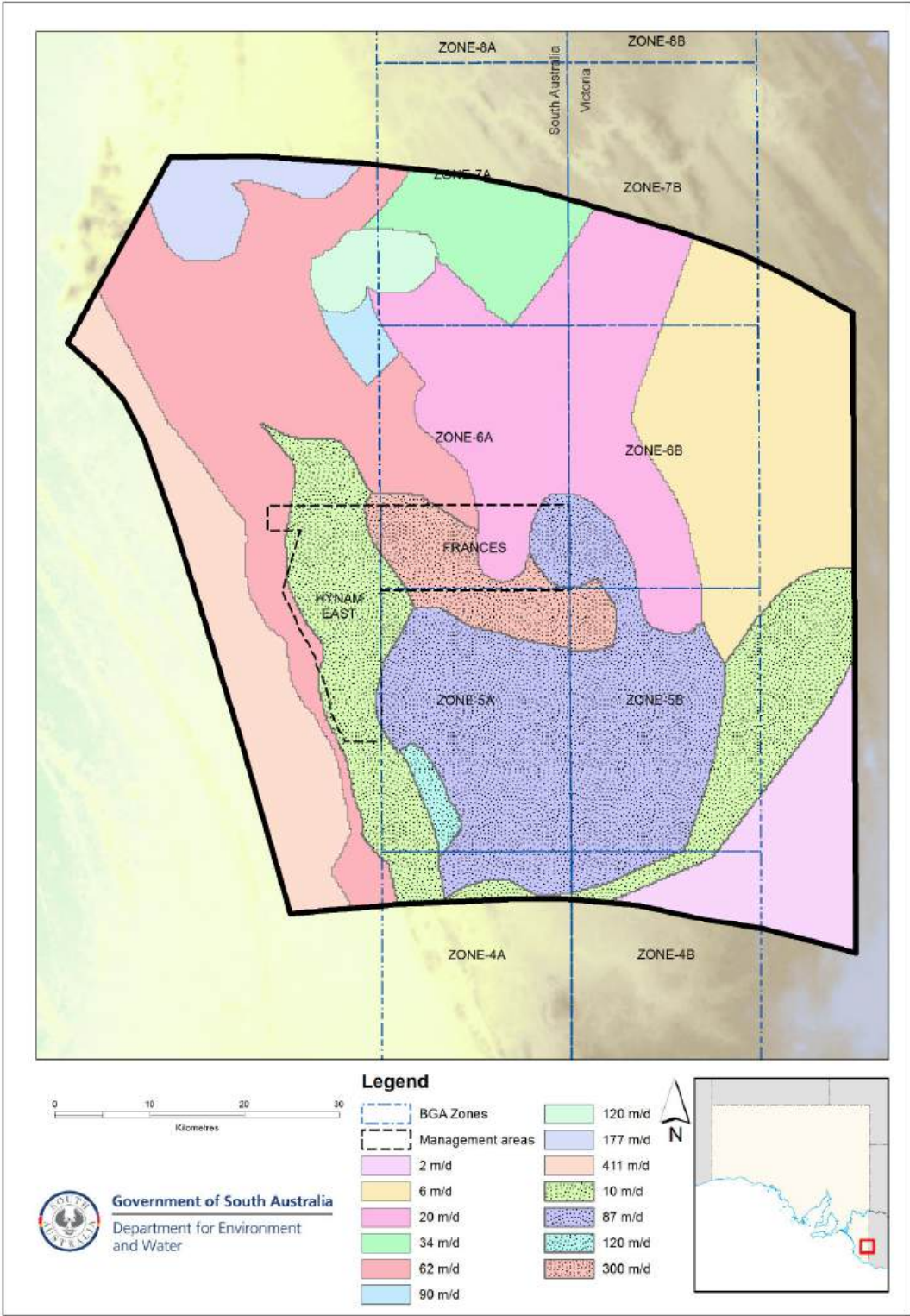


Figure 3.5. Initial Steady-State horizontal hydraulic conductivity zones.

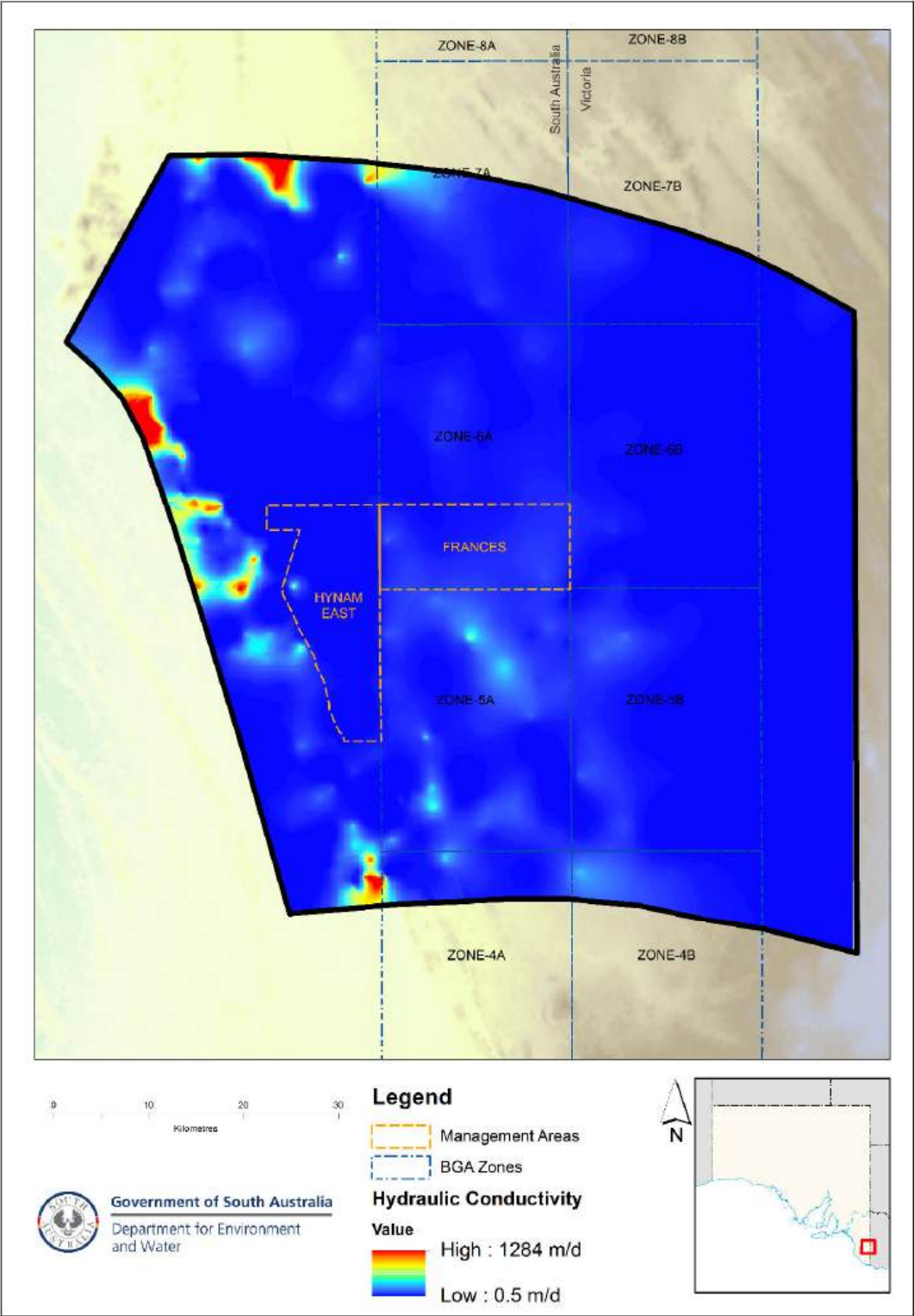


Figure 3.6. PEST parameter estimation of horizontal hydraulic conductivity.

3.10 Initial conditions and stress periods

Initial heads in the steady state model were modified iteratively through the trial and error calibration process. The results from the steady state modelling were then used as the initial conditions for the transient modelling.

Time discretization is summarised in Table 3.2.

The transient modelling is discretised into 104 stress periods. The initial stress period is a steady state stress period that effectively generates the starting heads for the transient modelling. Transient stress periods represent bi-annual seasons. The wet winter season is 212 days long and the dry summer season is 153 days long. Leap years have been accounted for by adding an extra day to the summer stress period every four years.

The model simulations have a start date set as 30 September 1970 with history matching starting on 1 October 1975, and ending on 30 April 2022.

Scenario modelling starts on 1 May 2022 and continues for 29 years finishing at the end of the final stress period on 29 September 2051.

Table 3.2. Modelling Phases.

Model Phase	Stress Period	Start Date
Steady-State	1	30 September 1970
Warm-up	2-11	1 October 1970
History Matching	12-104	1 October 1975
Scenario	105-162	1 May 2022

4 Model History Matching ('Calibration')

4.1 History matching methodology

History matching ('calibration') was conducted as an iterative process. A steady-state model was constructed to provide initial parameter values and starting heads to the transient model, and to explore broad conceptualisation issues. History matching of the steady-state model was conducted against the 1975 potentiometric surface (Figure 2.10). History matching of the transient model was conducted against the observation well data from 1970–2022 (Figure 2.11) with calibration targets sourced from the DEW Obswell Network in SA (DEW 2023b) and the DELWP State Observation Bore Network in Victoria (DELWP 2023).

Initial history matching was conducted on an iterative trial-and-error basis, adjusting recharge and hydraulic conductivity manually to achieve acceptable steady state modelling matches to measured data. Further parameter estimation for the steady-state model was then conducted using PEST++ (White et al. 2020) with pilot points.

Steady state conditioning ('calibration') resulted in very satisfactory results producing a gridded hydraulic conductivity matrix with good matches to target observations. Results are presented in Figure 4.1 and



Figure 4.2Figure 4.2. The root mean squared error (RMSE) is 4.28 m while the scaled RMSE is 5.4%.

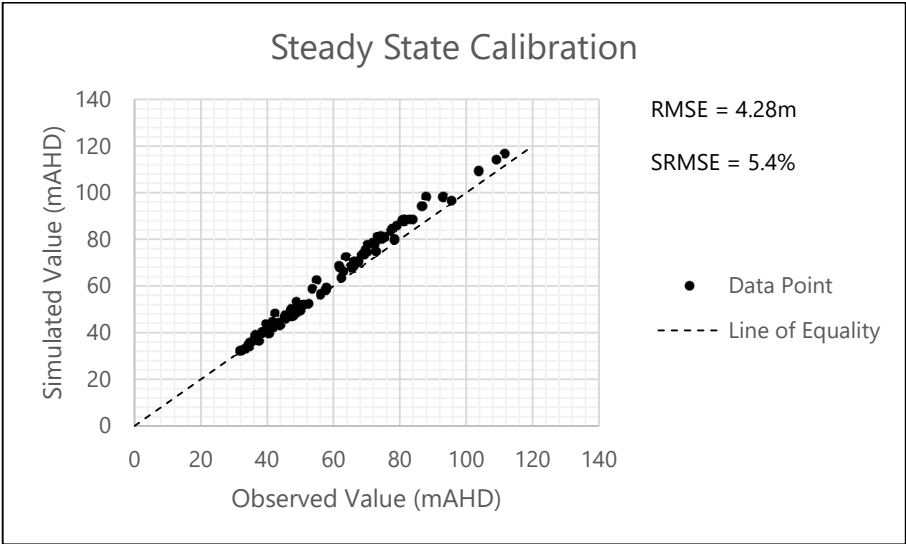


Figure 4.1. Steady-State modelling final calibration result.

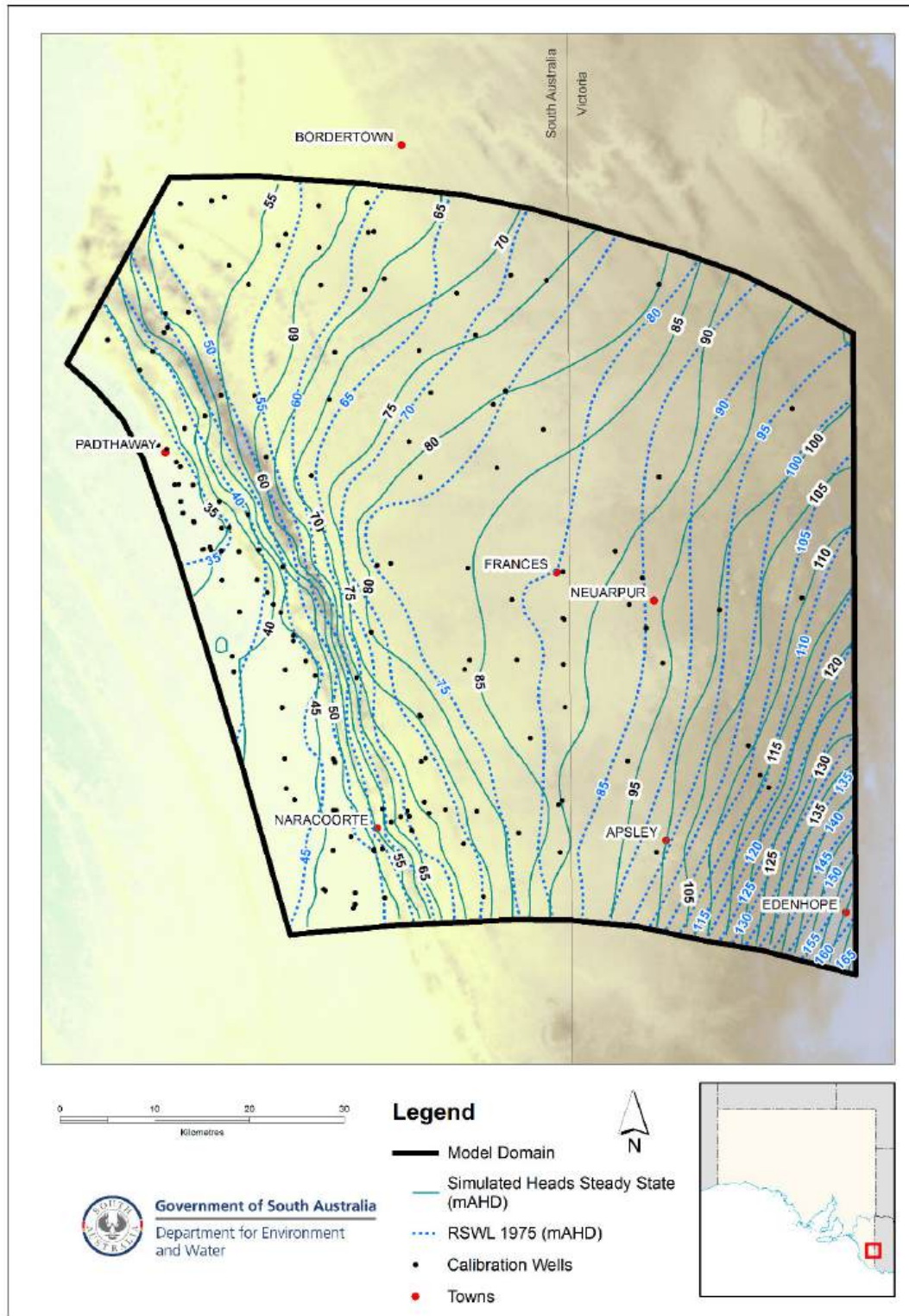


Figure 4.2. Steady-State modelling observed and modelled potentiometric surfaces 1975.

4.2 Transient history match

Transient history matching was largely focused on manual adjustment of recharge zones and rates. Initial runs using recharge derived from the water table fluctuation estimates showed generally good agreement between recharge variation and hydrograph trends. However, there were areas of the modelling where further work on recharge was required. The following sections describe these areas (see also Section 2.8).

During the process, a correlation was identified between the shape of certain hydrographs across the center of the model and the distribution of the Molineaux/Lowan Sands. Based on the shape of hydrographs presented in Wohling et al (2005) these hydrographs are most likely influenced by increased recharge following land use clearance. The observation wells displaying these hydrographs were grouped and converted into several recharge zones. Recharge was adjusted manually within each zone to match the hydrographs in each zone. Including these zones improved the qualitative and quantitative history match performance.

4.3 History Match Performance

Figure 4.3 presents the data observations plotted against the simulated results for the transient modelling. There are 160 observation wells with 17,113 observations. Observations span from September 1970 to March 2022. The modelling results display a very strong correlation between the observed and simulated water levels indicating that the modelling can reproduce the observed results very well. The results demonstrate a good fit to observed groundwater levels with an overall root mean squared (RMS) error of 0.5 m and a scaled root mean squared (SRMS) error of 0.6%.

A comparison between the simulated and observed potentiometric surface from April 2022 (Figure 4.4) indicates a broad agreement between the distribution of the two surfaces with general trends and line spacing simulated approximately by the modelling.

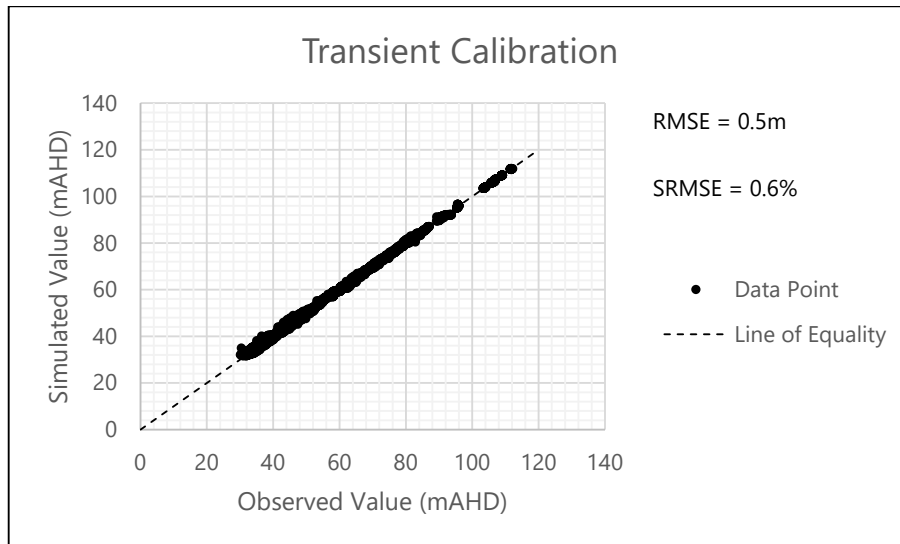


Figure 4.3. Transient modelling final calibration result.

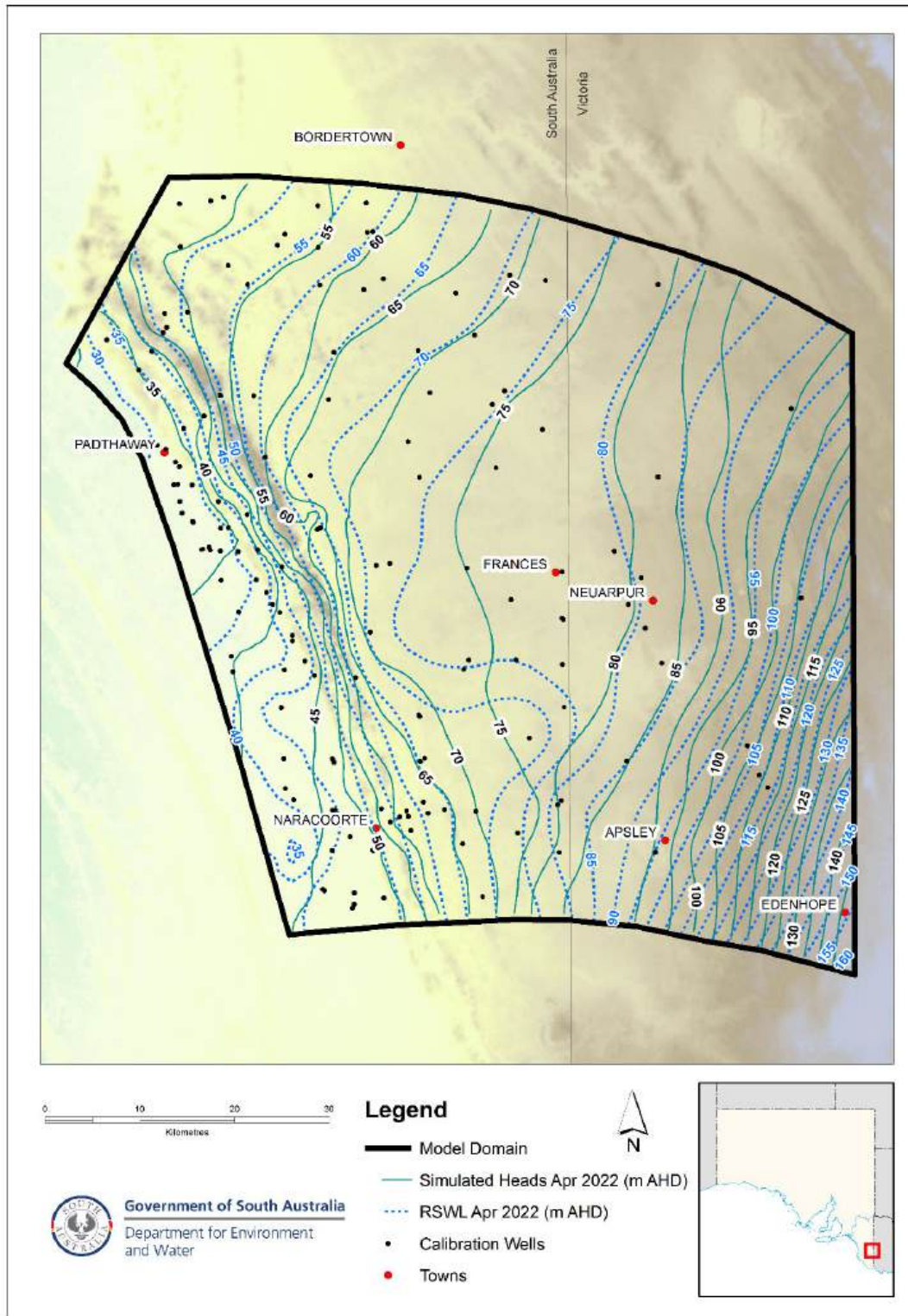


Figure 4.4. Transient modelling observed and modelled potentiometric surfaces April 2022.

The total mass balance for the modelling is presented in Figure 4.5. This shows the total volume of water leaving the model compared to the total volume of water entering the model.

When converted to a percentage of total volume, the percent discrepancy for the modelled water budget is less than 1% for every stress period. This indicates that the modelling reliably processes inputs and outputs and there are no structural errors.

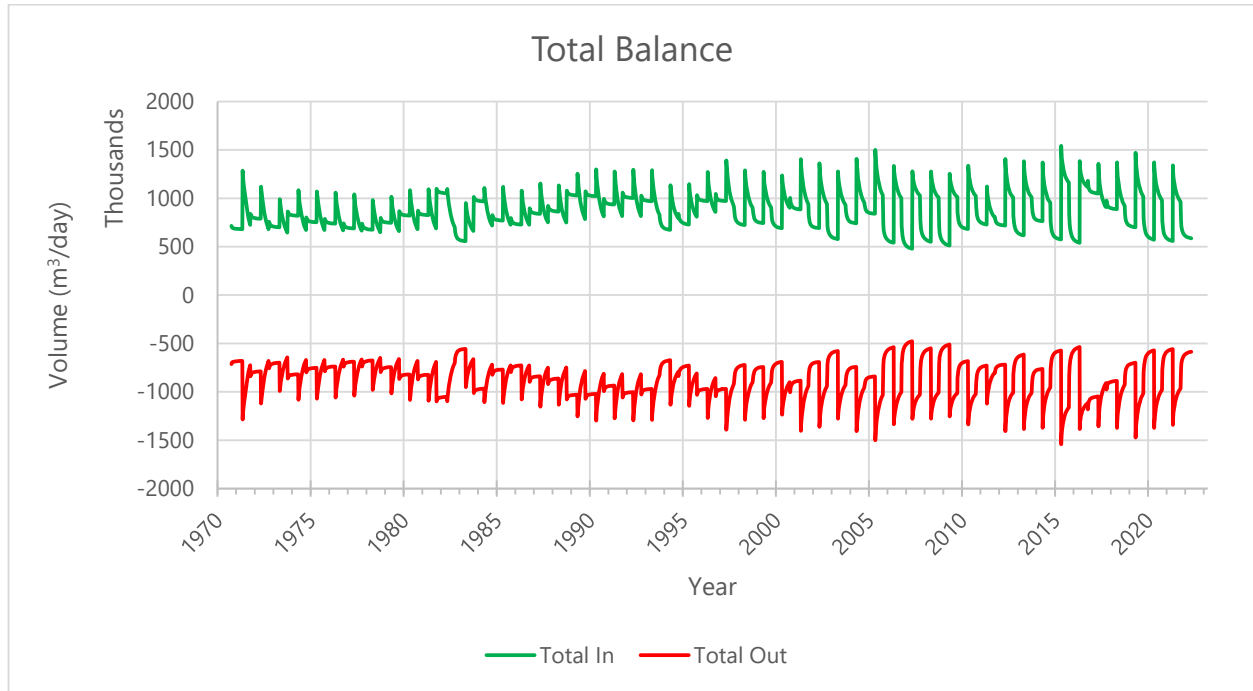


Figure 4.5. Modelled total water balance.

Figure 4.6 shows the comparative volumes going in and out of Storage and Figure 4.7 and Figure 4.8 show the recharge, evapotranspiration and extraction components of the water balance. Comparing across the different plots it is evident that recharge entering the system is largely going to storage as expected. There is some decline in recharge over time, consistent with changes in rainfall, and a corresponding increase in extraction, which results in reduced water tables and thus a decline in depth-dependent evapotranspiration (below the evapotranspiration extinction depth in some areas).

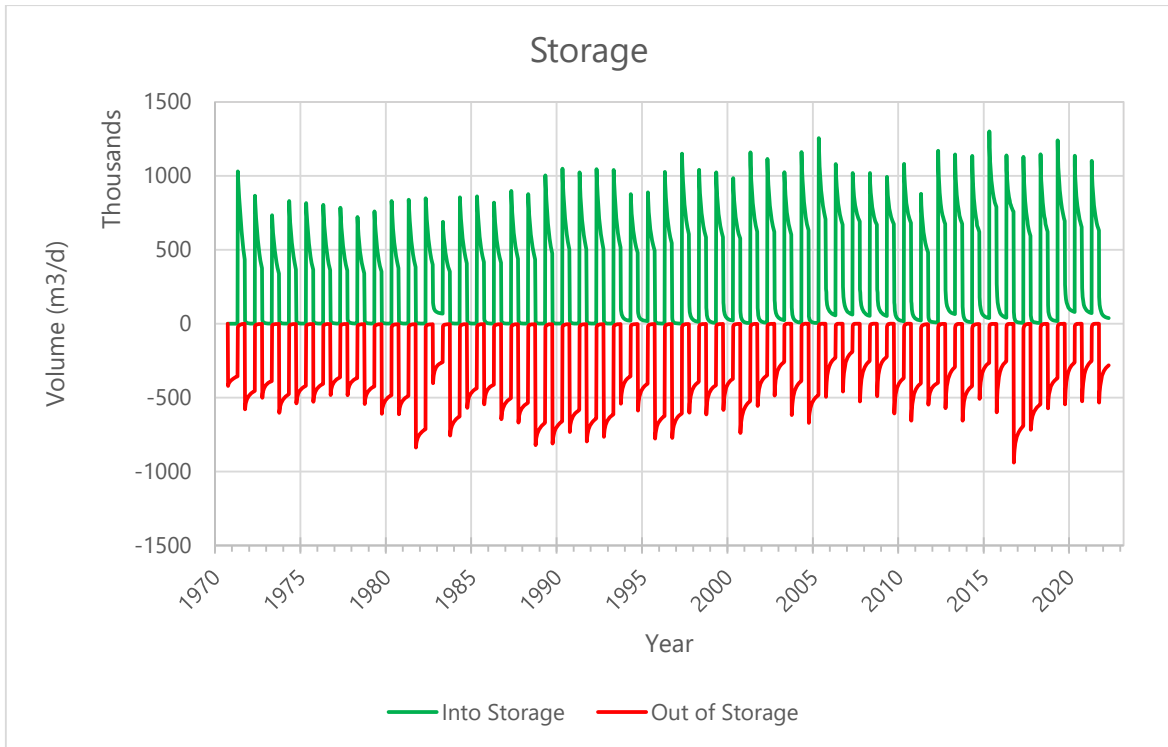


Figure 4.6. Modelled Storage water balance.

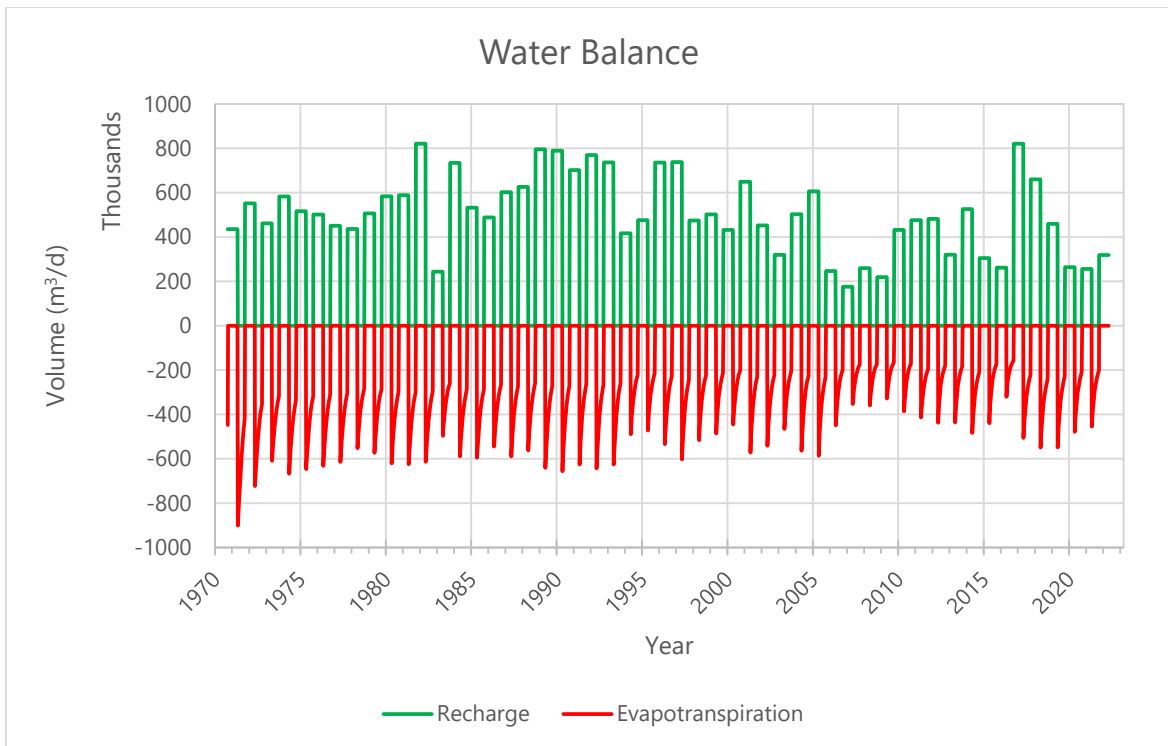


Figure 4.7. Modelled Recharge and Evapotranspiration water balance.

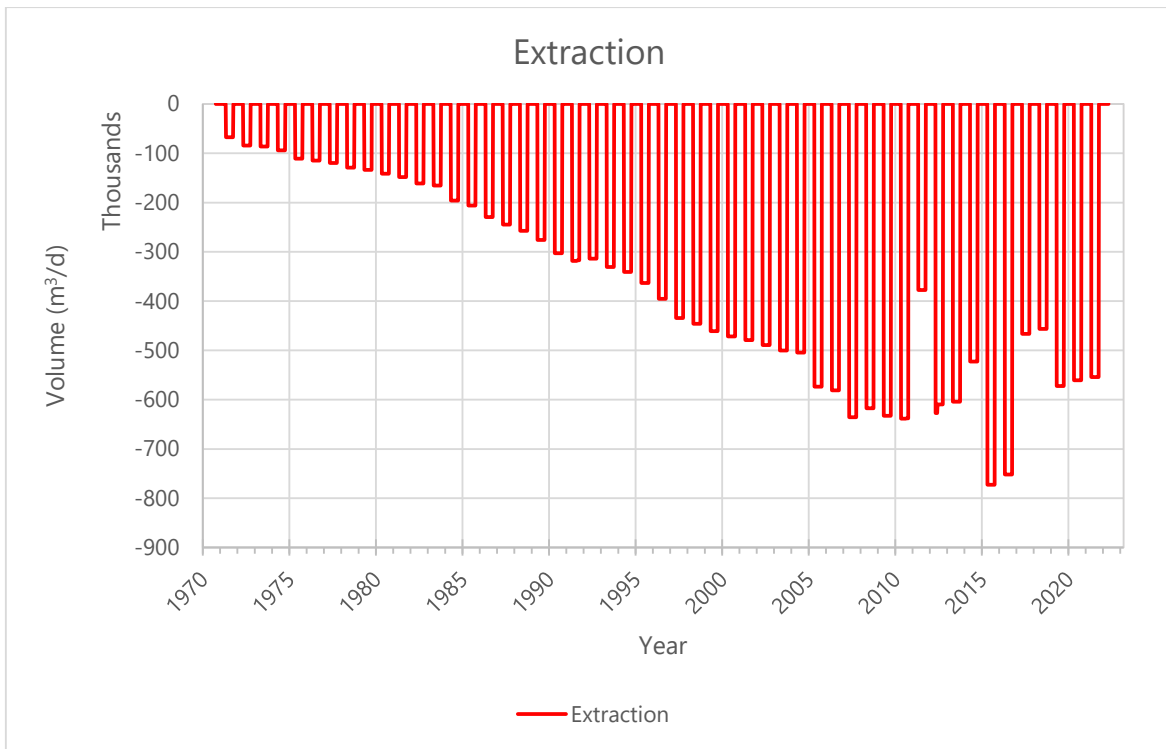


Figure 4.8. Modelled total groundwater extraction.

4.4 Modelled Groundwater Levels

Measured and modelled hydrographs at locations where there is long term data show a good fit to both level and trend in most cases. A complete set of measured and modelled hydrographs can be found in Appendix A. Figure 4.9, Figure 4.10, Figure 4.11 and Figure 4.12 show a generally good fit to groundwater levels in key areas where robust model performance is needed.

4.4.1 BGA Zone 5A

Figure 4.9 indicates that there is an overall downward trend of groundwater levels in Zone 5A over the length of the record. In most of the hydrographs there is also an increase in groundwater levels observed between the late 1980s and the mid-1990s. This brief increase in water levels is attributed to climatic conditions with wetter than average years during this period (Figure 2.3). Observed water levels then resume their downward trend.

Modelled groundwater trends closely match observed trends for the majority of observation wells in this zone.

4.4.2 BGA Zone 6A (Frances)

Figure 4.10 indicates that observed water levels in Zone 6A display a marked rising and falling trend throughout the modelling timeframe. This rise and fall are not consistently timed, and it is associated with the distribution of the Molineaux/Lowan Sand. This observed groundwater response is attributed to clearing of native vegetation beginning in the 1960's that resulted in a lagged increase in recharge (Wohling et al. (2005), Harrington et al. (2015)). Observed water levels indicate that, once the new recharge equilibrium is reached, the trend continues the downward tendency observed throughout the study area. Most observation bores display a close match between modelled and observed data.

4.4.3 BGA Zones 5B and 6B

Observed water level trends along the South Australian – Victorian border (Figure 4.11) display a similar downward trend to that seen in Zone 5A.

In the lower quadrant of Zone 5B there are observation bores (51844, 51845 and 51846) that display a more horizontal and cyclic trend. It is noted that these water level responses are less than 1 m in magnitude; nevertheless, the modelled data does a very good job of matching the observed data.

4.4.4 Hynam East

There are no observation bores with long term data in the center of Hynam East Management Area (Figure 4.12). Hynam East has previously been identified as an area with an insufficient coverage of monitoring wells (Simmons et al. 2019) and five new monitoring wells were installed in early 2021. However, there is currently insufficient data from these new wells to constrain the model in this region.

Bores located around the edge of the management area show varying trends associated with different landforms.

In the highland areas, along the northern and eastern boundary of the management area, observed water levels show a lagged response to clearing. The modelled response matches this (e.g. HYN007).

In lowland areas, along the western boundary, modelled water levels match observed water levels well for the majority of the hydrograph. There are issues with the model over-estimating water levels during the early stress periods. This may be attributed to initial conditions that over-estimate water levels in this zone. Superimposed on this is the increase in recharge associated with vegetation clearing along the ranges. The precise timing of vegetation clearing is unknown and may vary locally resulting in significant differences in timing with the upward trend in water levels observed in this location.

Those wells displaying more recent data indicate that the model underestimates water levels at some locations. This is likely to be related to underestimating recharge at these local data points.

The fluctuation in these lowland observation bores is driven by seasonal evapotranspiration from shallow water tables. The magnitude of the seasonal fluctuation is well replicated (HYN005, HYN018 and HYN034).

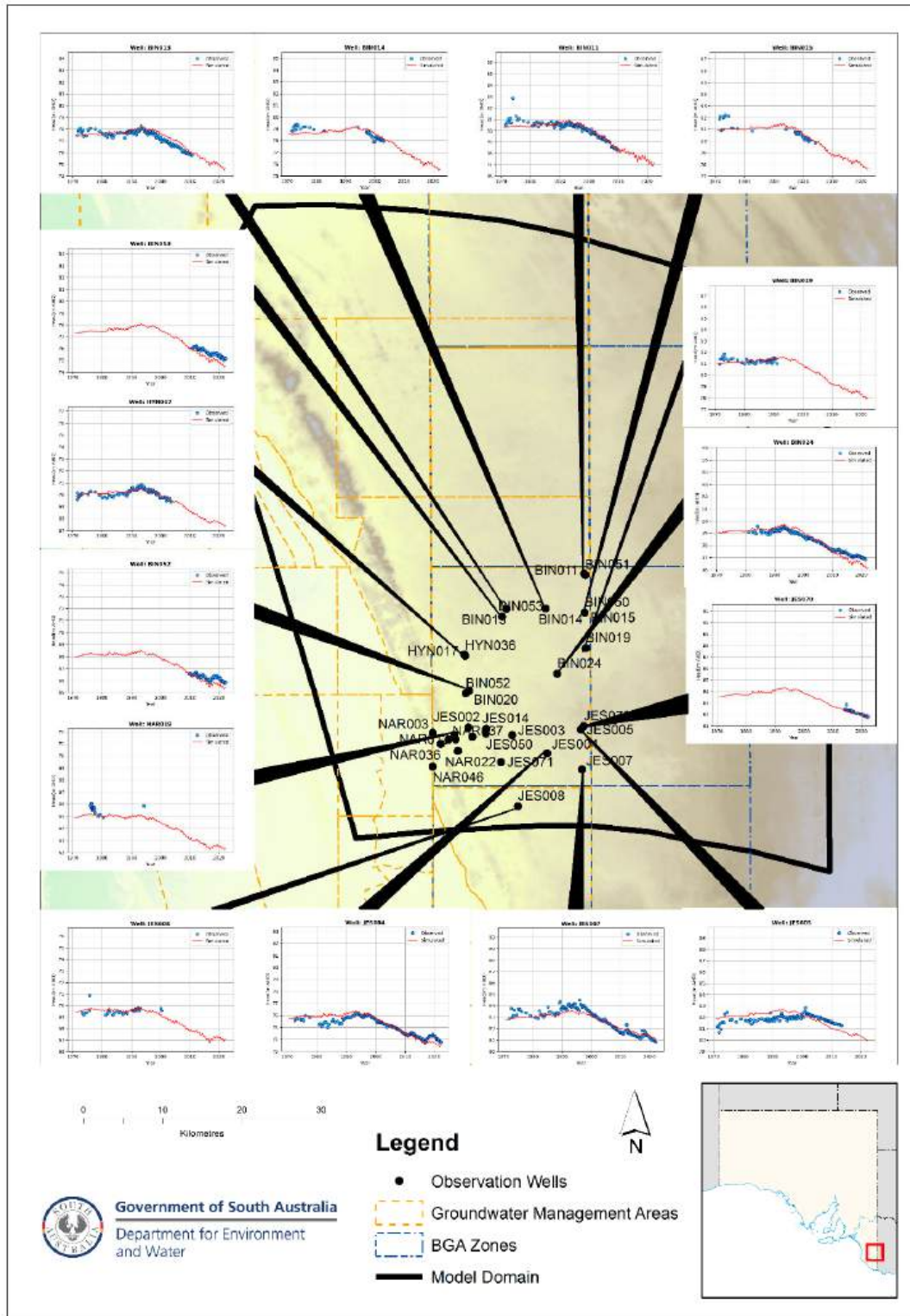


Figure 4.9. Hydrographs BGA Zone 5A (Hydrograph vertical scale range= 10m).

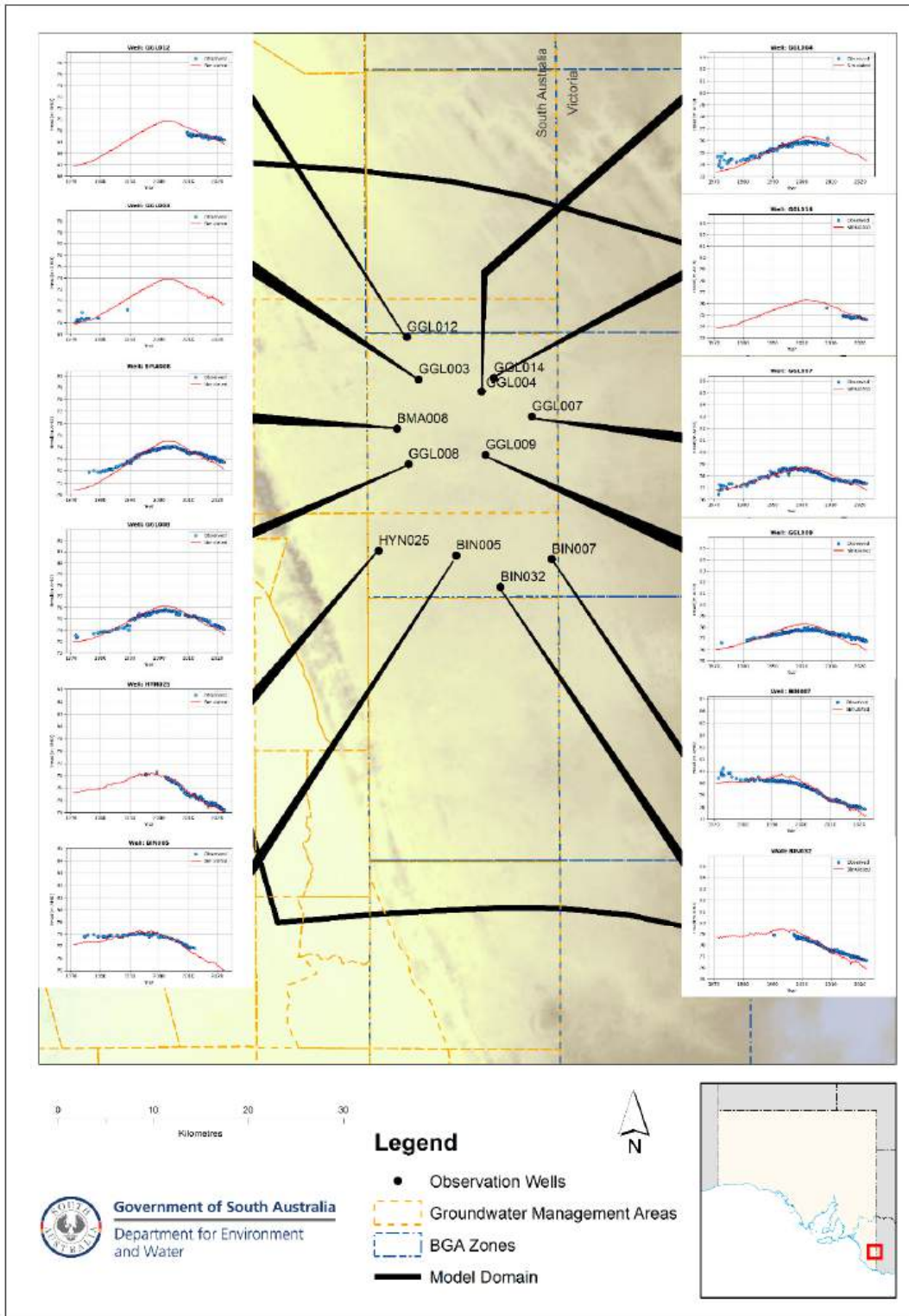


Figure 4.10. Hydrographs BGA Zone 6A (Hydrograph vertical scale range= 10m).

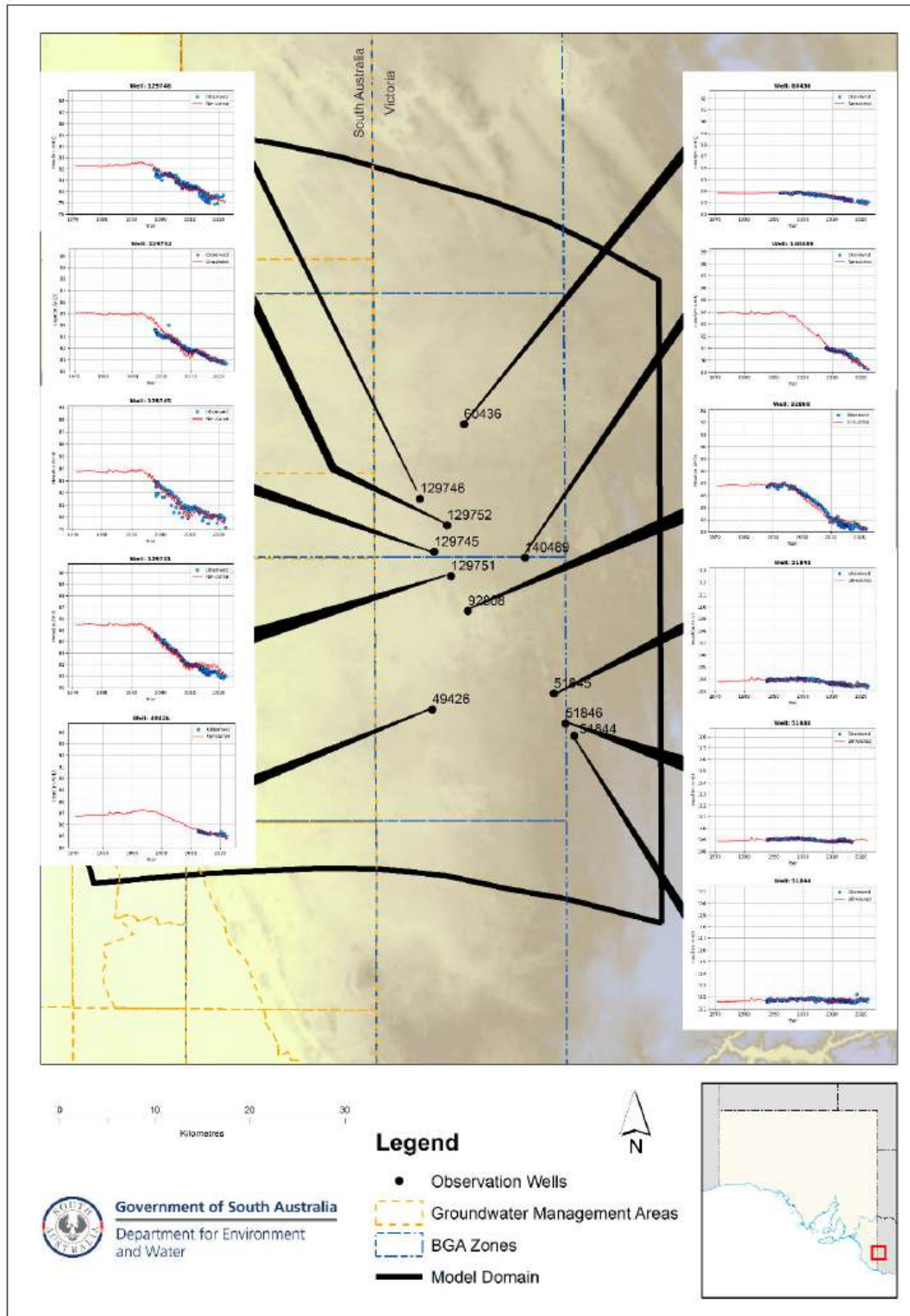


Figure 4.11. Hydrographs BGA Zones 5B & 6B (Hydrograph vertical scale range= 10m).

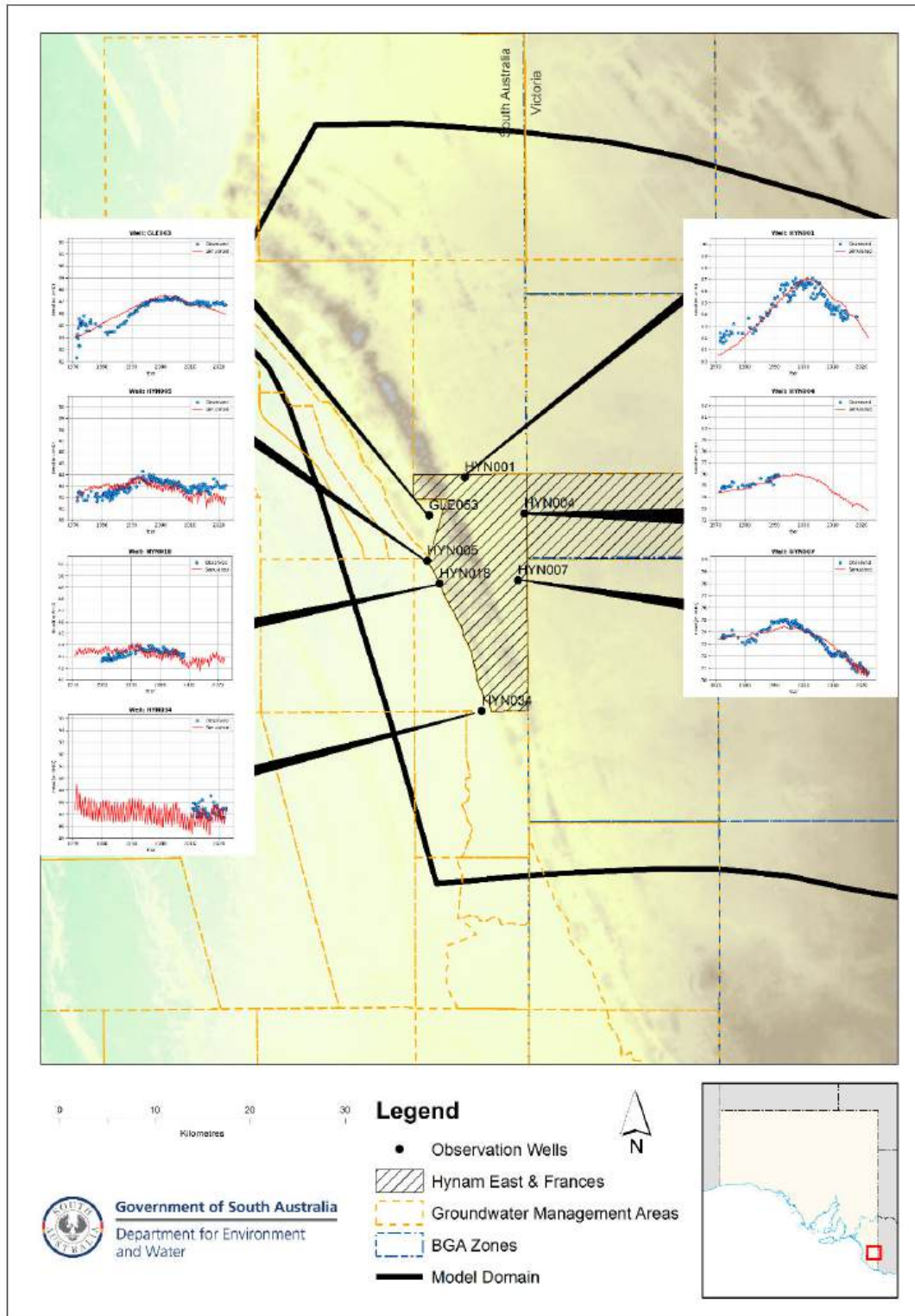


Figure 4.12. Hydrographs Hynam East (Hydrograph vertical scale range= 10m).

5 Parameter Sensitivity and Uncertainty

5.1 Parameter sensitivity

Parameter sensitivity was assessed using the GWV8 auto-sensitivity function. This function works by varying a selected model parameter by a given multiplier over a series of runs and investigating the degree to which the variation changes the modelling outcome.

Parameters chosen for investigation were the horizontal hydraulic conductivity and specific yield. From the base case, the parameters were increased globally by 10% each for five runs and decreased globally by 10% each for five more runs, resulting in a total of 11 runs with varying parameters. The degree to which varying the parameter affects the RMS error is plotted as Figure 5.1 and Figure 5.2.

When the GWV8 auto-sensitivity function is applied to horizontal hydraulic conductivity this causes the residuals to increase regardless of whether the parameter is increased or decreased (Figure 5.1). The base case resides at the bottom of the curve giving confidence that, with respect to hydraulic conductivity, the model is well conditioned ('calibrated') to the available data.

When the auto-sensitivity function is applied to specific yield the residuals increase in a similar fashion to the hydraulic conductivity (Figure 5.2).

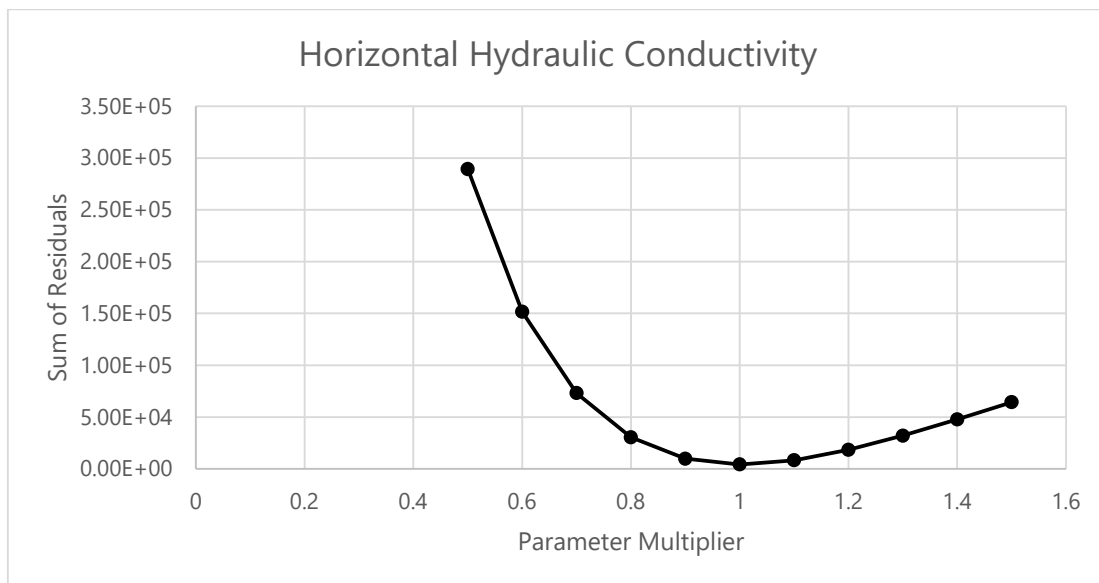


Figure 5.1. Parameter sensitivity: horizontal hydraulic conductivity.

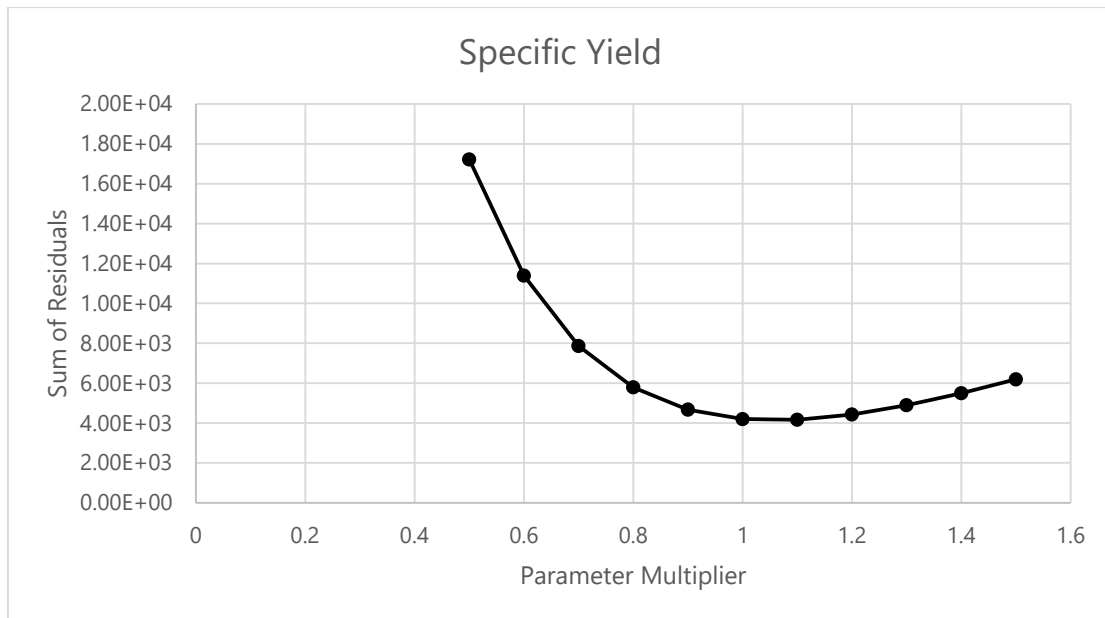


Figure 5.2. Parameter sensitivity: Specific Yield.

5.2 Parameter uncertainty

Traditionally the quality of the calibration (history matching) and an examination of parameter sensitivity were regarded as sufficient to declare a model suitable for predictive scenario modelling. The introduction of automated parameter estimation processes exemplified by PEST (WNC 2018) has led to a contemporary shift in perspective that seeks a more thorough evaluation of predictive uncertainty (Peeters and Middlemis 2023). To this end an analysis of parameter uncertainty was conducted utilising PESTPP-IES.

The number of realisations was assigned as 20% of the number of parameters to be determined. There is no universally accepted rule for choosing the number of realisations for a PESTPP-IES analysis and 20% of parameter numbers is considered reasonable (White et al. 2020). In this case, 877 parameters were to be determined resulting in 175 realisations.

The maximum optimisation Iterations was set at 20 and PESTPP-IES achieved optimisation in 9 Iterations. "ensemble collapse" was observed around Iteration 4 (Figure 5.3). Ensemble collapse refers to a situation where the ensemble of parameter values loses diversity. The parameter adjustment process should lead to an ensemble where the parameter values converge towards the optimal values, but still maintain some variation to reflect the inherent uncertainty. Ensemble collapse occurs when this variation is lost and all the parameter values in the ensemble become very similar.

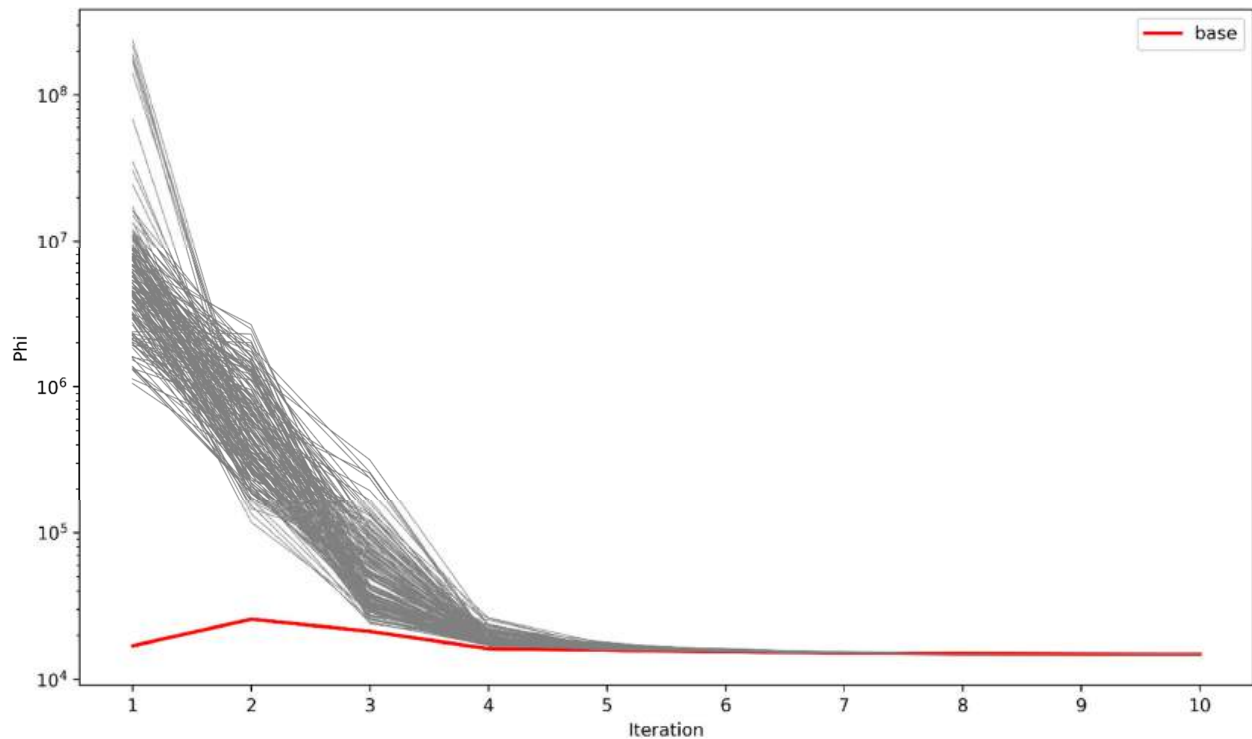


Figure 5.3. Ensemble iterations plotted against the objective function (ϕ) showing ensemble collapse around Iteration #4.

An examination of the density of the objective function (ϕ) for each iteration (Figure 5.4) was conducted to determine the optimal iteration to use in order to analyse uncertainty. This was identified as iteration #3.

Iteration #2 displays a very broad range of values for the objective function (ϕ) suggesting that the majority of models within this iteration are “uncalibrated” and would not match the observed data well.

Iteration #4 displays a very narrow range of values for the objective function (ϕ) suggesting that the majority of models within this iteration are “calibrated” and would generate very good matches for the observed data.

Iteration #3 displays an intermediate range of values for the objective function (ϕ). The majority of models in Iteration #3 have their objective function within 20% of the base calibration. This represents a value for the objective function (ϕ) where it is deemed that the model is able to replicate the observed data sufficiently well. A small number of model realisations exceeded the base model objective function (ϕ) by more than 20%, however the visual fit to hydrographs was judged to be sufficient for a majority of relevant hydrographs.

The degree of variability in the objective function (ϕ) for iteration #3 is considered appropriate to capture the range of uncertainty within the models of each realisation. Any of these models might be considered adequate to use as predictive tools and each model has a range of different parameters. The problem of non-uniqueness is addressed by choosing the model with the lowest objective function (ϕ). The base case (by design) represents the minimum error variance model and possesses the lowest objective function (ϕ).

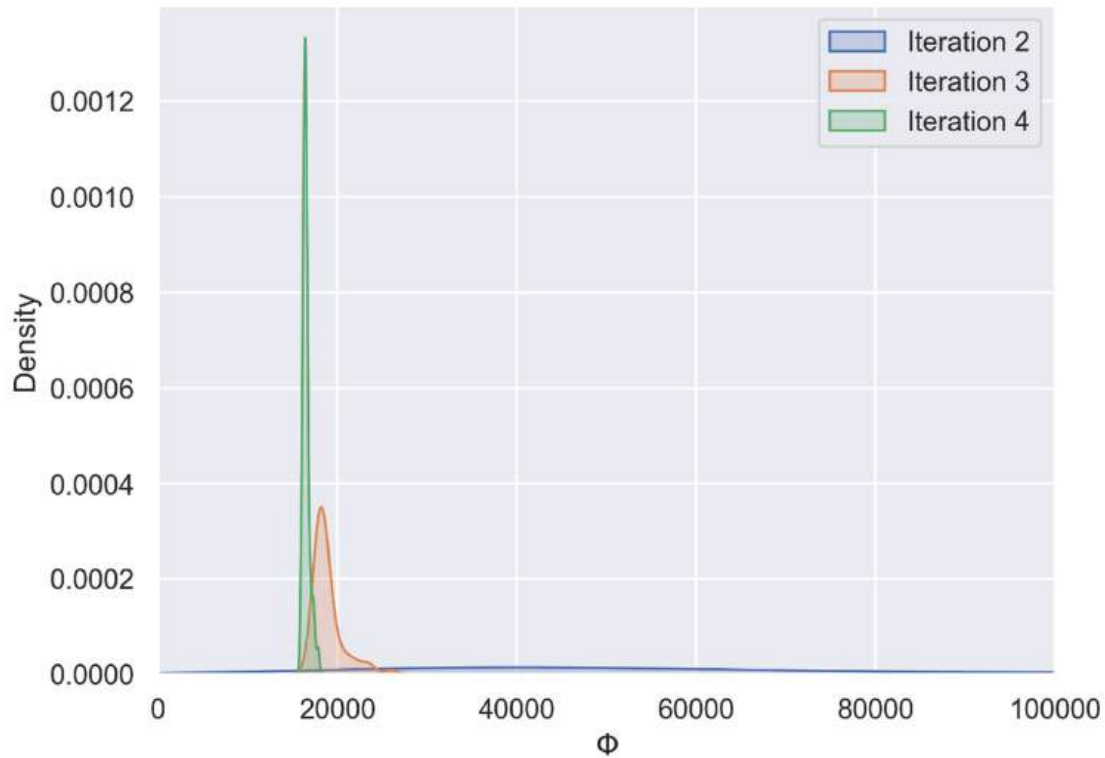


Figure 5.4. Objective function density for Iteration #2, Iteration #3 and Iteration #4 demonstrating the development of “calibration” through the iterative process.

Representative hydrographs displaying the base model (“calibrated model”) compared to all realisations from iteration #3 are shown in Figure 5.5 and plots for all hydrographs are presented in Appendix B.

The distribution of heads for all realisations forms an envelope of uncertainty encompassing the base case “calibrated” model. In all of the representative hydrographs this range is in the order of 1m.

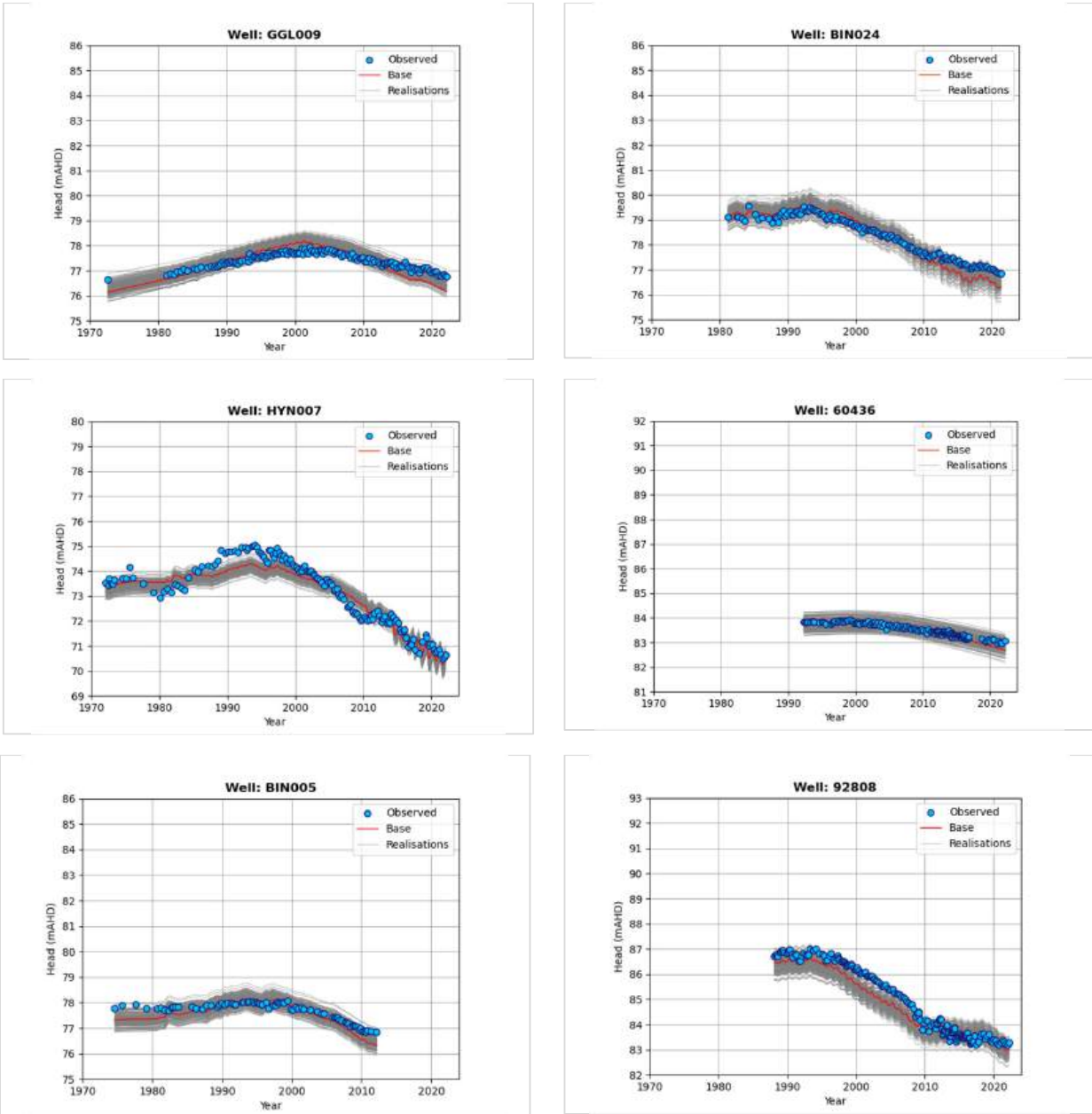


Figure 5.5. Representative hydrographs displaying modelled versus observed heads for the base case and all Realisations from Iteration #3.

In addition to the output heads and hydrographs an examination was made of the uncertainty surrounding the parameters that were adjusted during history matching “calibration”. In this instance the parameters for horizontal hydraulic conductivity (k_h) were assessed.

Utilizing the parameters from Iteration #3, the maximum and minimum values for each pilot point were determined across each realisation of Iteration #3. The ratio $k_{h \text{ max}}/k_{h \text{ min}}$ was plotted spatially to examine the degree of variability of horizontal hydraulic conductivity across these realisations (Figure 5.6). This plot represents the range of horizontal hydraulic conductivity values at each pilot point for Iteration #3. There is some clipping around the edges of the model domain as a result of the interpolation procedure.

Throughout the model domain the range of horizontal hydraulic conductivity is generally less than an order of magnitude. Larger ranges are seen near Edenhope and in the northeast corner of the model.

Within the eastern portion of the model there is less observation data to constrain the model inversion process and the underlying parameter has a greater degree of freedom and consequently a greater range.

Of the key areas to be examined Zone 6B displays the greatest range of uncertainty for horizontal hydraulic conductivity. This occurs in an area of national park where there are no observation bores. The remainder of Zone 6B displays a much lower range of horizontal hydraulic conductivity values.

In summary, both the observation well hydrographs (Figure 5.5) and the ratio of horizontal hydraulic conductivity (Figure 5.6) indicate that there is a relatively small range in the results as an outcome of the uncertainty analysis. Where there is less data, such as in the Victorian portion of the model domain, there is greater uncertainty regarding the ability of the model to accurately predict hydraulic head. However, for the majority of the model, and in particular the areas of interest, the uncertainty analysis provides confidence that the base model gives an accurate representation of hydraulic heads.

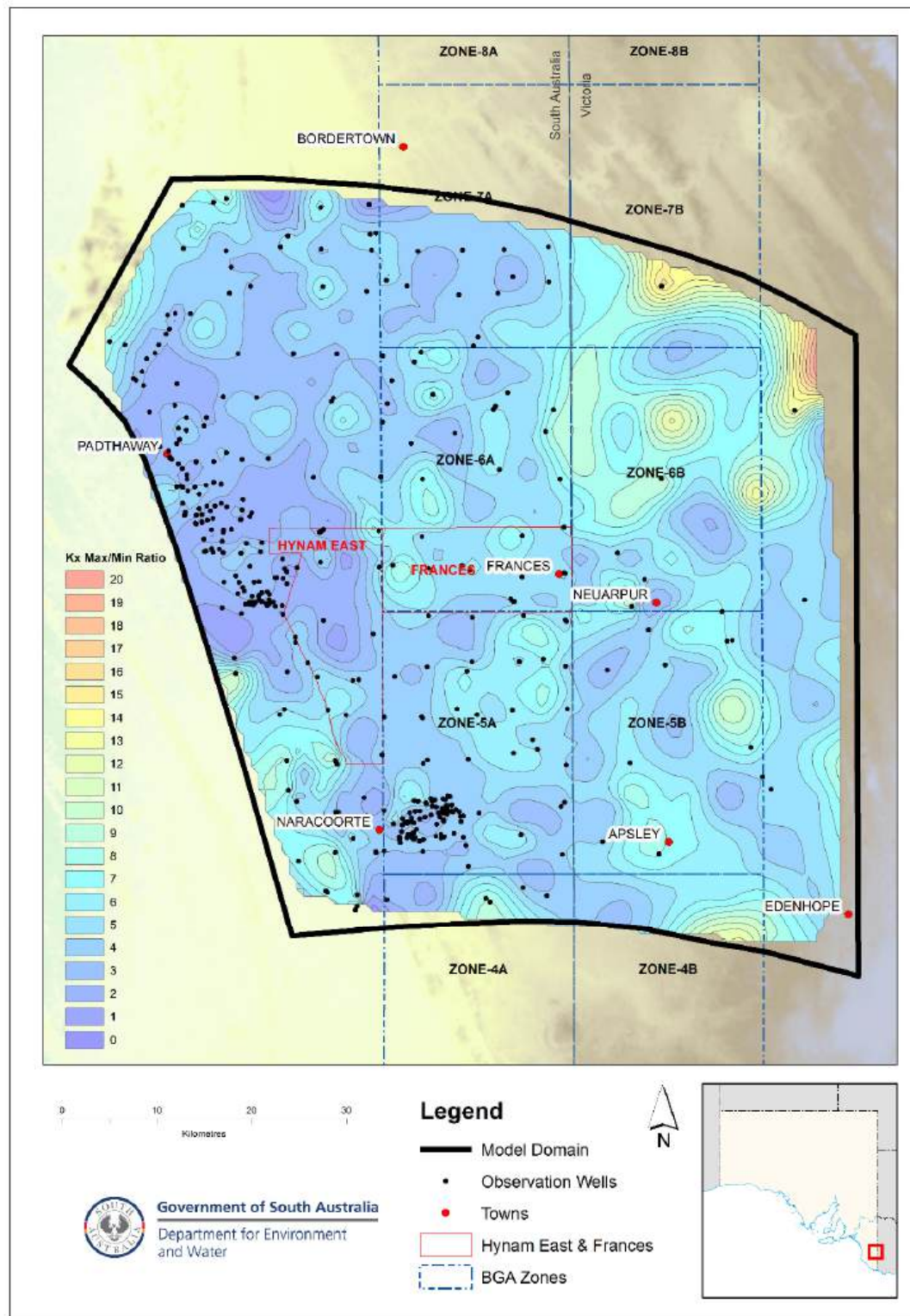


Figure 5.6. Spatial distribution of the range of horizontal hydraulic conductivity for Iteration #3.

5.3 Assumptions and Limitations

As with all modelling projects assumptions have been made in developing the model and there are certain limitations on the use of the modelling outputs.

- Simplification of the model into a single layer: This assumption overlooks several known hydrogeological factors, specifically the occurrence of confining layers in the far east of the model and the presence of the water table in the Loxton-Parilla Sands aquifer in the east of the model. If confined or partially confined conditions do have an impact along the eastern edge of the model it is likely that the modelling will over-estimate heads in these areas.
- Historical pumping rates are estimated prior to the installation of meters, based on available information on irrigation well development. The methods applied here provide sufficient data to history match water levels. The lack of historical records of groundwater extraction is acknowledged as a limitation within the modelling.
- The modelled area is known for point-source recharge via karstic features or drainage bores. The methods used to estimate recharge (the WTF method) and hydraulic conductivity (equivalent porous media) do account for point-source recharge; however, the actual volume of point-source recharge is an unknown quantity.
- The modelling history match demonstrates a sound emulation of the response of the water table in BGA Zones 5A, 5B, 6A and 6B, as well as Frances and Hynam East GMAs. The model is not designed to be used outside of these areas. Any application of the model outside of the study area but inside the model domain should be used with caution.

6 Scenarios

6.1 Background

The scope for modelling scenarios described in this report is limited, and it is expected that further scenario work, including predictive uncertainty analysis, will be required during the review of the Lower Limestone Coast Water Allocation Plan. This work will involve collaboration with the Limestone Coast Landscape Board and DEW policy staff, and consultation with stakeholders. Hence the scenarios described here provide an initial baseline and demonstration of the application of the modelling to assess the impact of pumping and climate scenarios. Further scenarios, uncertainty analysis and definition of resource condition limits can build on this work.

The Lower Limestone Coast Water Allocation Plan review commenced in 2023, and a new Water Allocation Plan will likely be in place for 10 years. As a proof of concept task suitable for this stage of the investigation, scenarios are run without uncertainty analysis from 2022 to 2050 and simulate the impact of various recharge and extraction conditions. The timescale is selected to extend beyond the anticipated span of the new Lower Limestone Coast WAP.

Two scenarios are considered here, which simulate continued current average conditions (business as usual), and increased extraction with reduced recharge (a conservative scenario to overestimate potential impacts):

- Scenario 1 simulates extraction and rainfall as used in the modelling from 2011–21 continuing into the future.
- Scenario 2 simulates an increase in extraction up to full allocation levels, while recharge reduces, consistent with climate change projections.

6.2 Climate change impacts on groundwater recharge

Climate change impacts can be seen in the protracted decrease in average annual rainfall since 1995 (Figure 2.3). The practical effect of this reduction in rainfall is that irrigators use greater volumes of water to irrigate due to the drier conditions, while at the same time, there is less water available as diffuse rainfall recharge. A warming climate is likely to exacerbate these trends into the future.

Green and Pannell (2020) provide guidelines for selecting climate projections for risk assessment. In this study, modelling scenarios are run to 2050, to assess potential impacts beyond the span of a revised Lower Limestone Coast Water Allocation Plan. Green and Pannell advise that where assessments occur before 2050, a single future emissions scenario may be sufficient to assess impacts of climate change and help simplify the assessment process. In doing so, the authors recommend using a high future emissions scenario.

Representative concentration pathways (RCP) have been developed by the International Panel on Climate Change (IPCC) to represent plausible future trends in emissions and greenhouse gas concentrations in the atmosphere. The RCP8.5 emission scenario represents a 'high' emissions scenario, which Green and Pannell (2020) cite as suitable for the following reasons:

- Greenhouse gas emissions continue to rise globally and measured temperature changes in Australia track towards the higher end of simulated temperature changes.
- The differences between temperature changes to 2050 for different RCPs (e.g. the difference between medium and high emission scenarios) are relatively minor.

- Assuming a high concentration pathway provides a precautionary approach to assessing potential climate change impacts.

Climate change impacts on recharge are based on rainfall projections provided by Charles and Fu (2015). As summarised by Green and Pannell (2020), an RCP8.5 emission scenario leads to a 6% decline in mean annual rainfall by 2050 for the nearest RCP site, Keith.

In order to convert the decline in rainfall into a decline in recharge a scaling factor has been applied. The scaling factor approach is based on previous work simulating the impact of downscaled climate change scenarios on recharge using unsaturated zone models. This approach has been applied extensively in groundwater modelling exercises in the Barossa Valley (Li and Cranswick 2016), Eyre Peninsula (DEW 2020c) and the South East (DEW 2020b).

Projected changes in rainfall are translated to changes in recharge using a scaling factor of 3 (Green and Pannell 2020). A 6% decline in rainfall results in an 18% decline in recharge.

Changes in recharge are applied incrementally from the first year of scenario runs, such that recharge declines by 18% by 2050.

It should be recognised that this approach to simulating the potential impacts of climate change on groundwater recharge is a simplified approach. Further work is recommended to assess potential impacts of changes in seasonality of rainfall on groundwater recharge and consider a wider set of climate change projections.

6.3 Groundwater extraction assumptions

In scenario 1, future groundwater extraction is based on conditions for the years 2011–21, repeated in a 10-year cycle to the end of the modelling period.

In scenario 2, groundwater extraction increases to full levels of allocation (Figure 6.1). In the South Australian portion of the model, allocation volumes described in the current Lower Limestone Coast Water Allocation Plan are used. These volumes are higher than Permissible Annual Volumes (PAV) described in the Border Groundwater Agreement. In the Victorian portion of the model however, full allocation volumes are based on Permissible Annual Volumes in the Border Groundwater Agreement. Allocation is significantly higher than extraction in most of the areas; hence, a rapid increase is not considered a realistic scenario. Nevertheless, it is necessary to test the potential impact of allocations being activated up to full levels. As discussed earlier, these scenarios represent initial benchmarks to test modelling performance, demonstrate outputs and inform consultation. It is recommended that further scenarios be run, including with uncertainty analysis, to test additional land use and extraction assumptions in consultation with stakeholders.

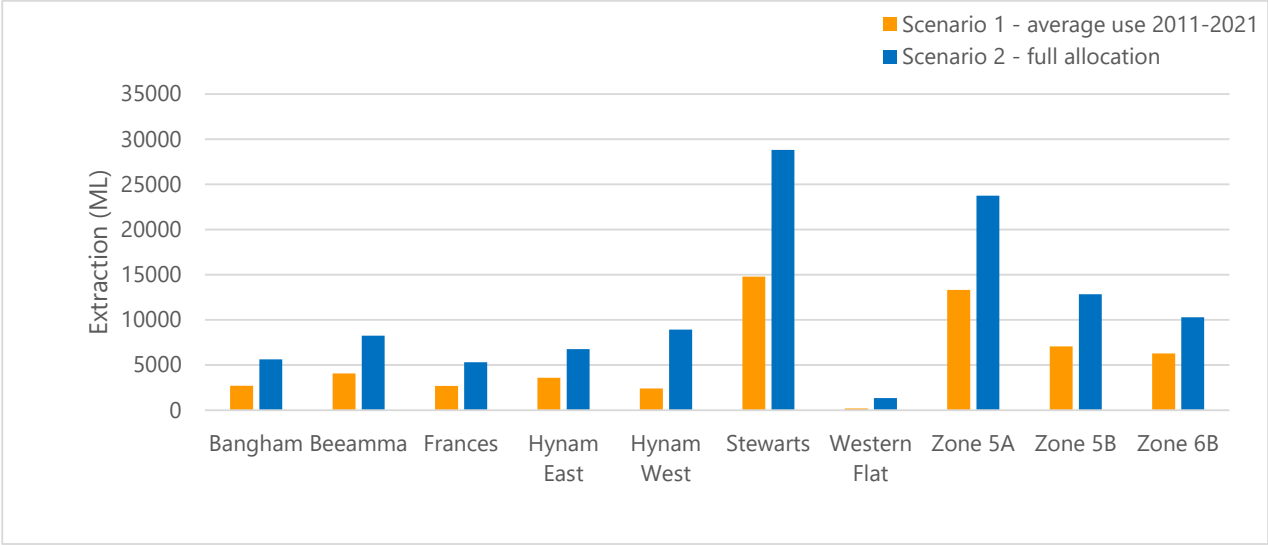


Figure 6.1. South Australian Groundwater Management Area extraction volume for Scenario 1 and Scenario 2.

6.4 Boundary condition assumptions

Both scenarios are modelled on the basis that boundary conditions do not change. Reduced recharge as a result of climate change modelled in Scenario 2 would affect a broader area than the model domain and reflect a regional decrease in both recharge and groundwater levels. The degree to which groundwater levels may or may not fall regionally is unknown, and as such, maintaining boundary conditions at 2022 levels is considered justified.

6.5 Scenario Modelled Groundwater Levels

Figures 6.2 to 6.5 display the results of the scenario modelling on predicted groundwater levels. In all cases groundwater levels are predicted to fall.

For Scenario 1, current trends in groundwater levels continue and there is a consistent rate of decline. Falls in groundwater head are generally in the order of 1 to 2 metres by 2050. Examining the results for Scenario 2, modelled groundwater trends decline at an accelerated rate, resulting in greater declines in groundwater head by 2050. Falls in groundwater head are generally in the order of 5 to 6 metres by 2050. These results are in line with expectations given the extraction and recharge parameters applied to each scenario.

The hydrographs displayed in Hynam East (Figure 6.5) display relatively large seasonal changes in head for observation wells HYN005, HYN007, HYN018 and HYN034 in Scenario 2. This response shows rapid recovery in winter from high pumping rates during the summer irrigation season and occurs where there are shallow water tables closer to the coastal plain area. Recharge is also higher in these areas, which may influence some of the seasonal recovery, however the overall trend is declining.

Plots for all hydrographs are presented in Appendix C

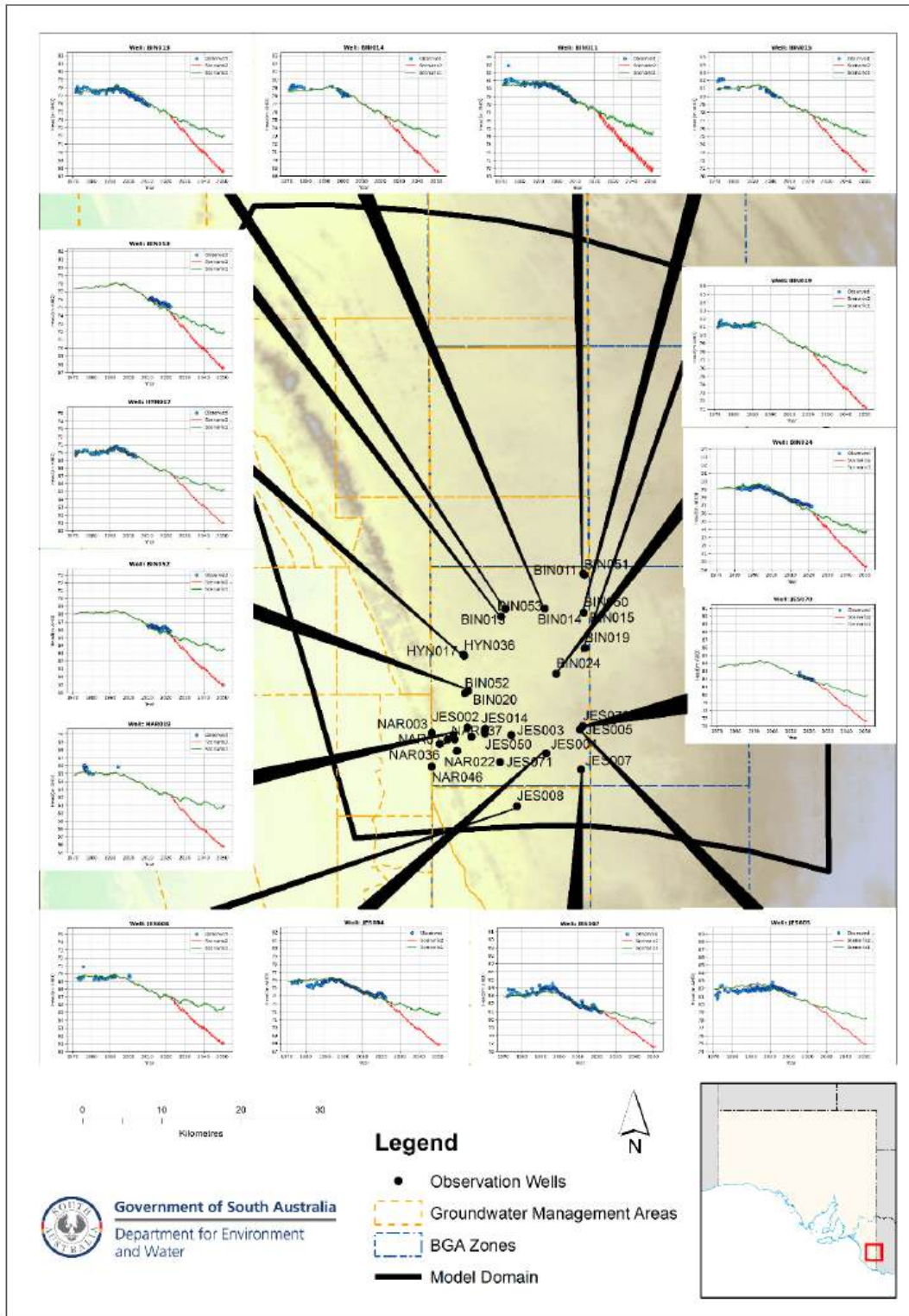


Figure 6.2. Scenario Hydrographs BGA Zone 5a showing predicted declines in groundwater levels for Scenario 1 (green) and Scenario 2 (red) (Hydrograph vertical scale range= 10m).

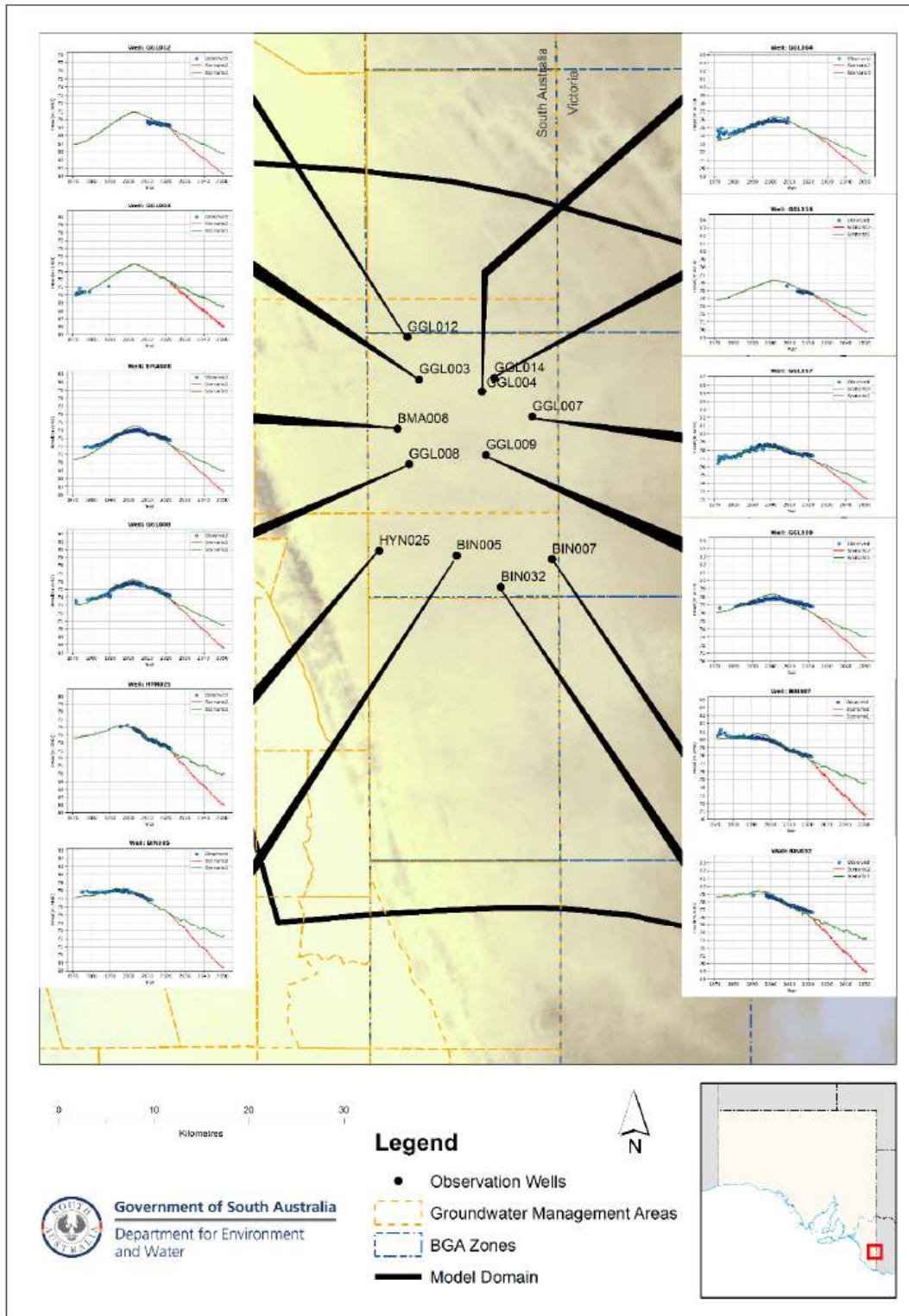


Figure 6.3. Scenario Hydrographs BGA Zone 6a showing predicted declines in groundwater levels for Scenario 1 (green) and Scenario 2 (red) (Hydrograph vertical scale range= 10m).

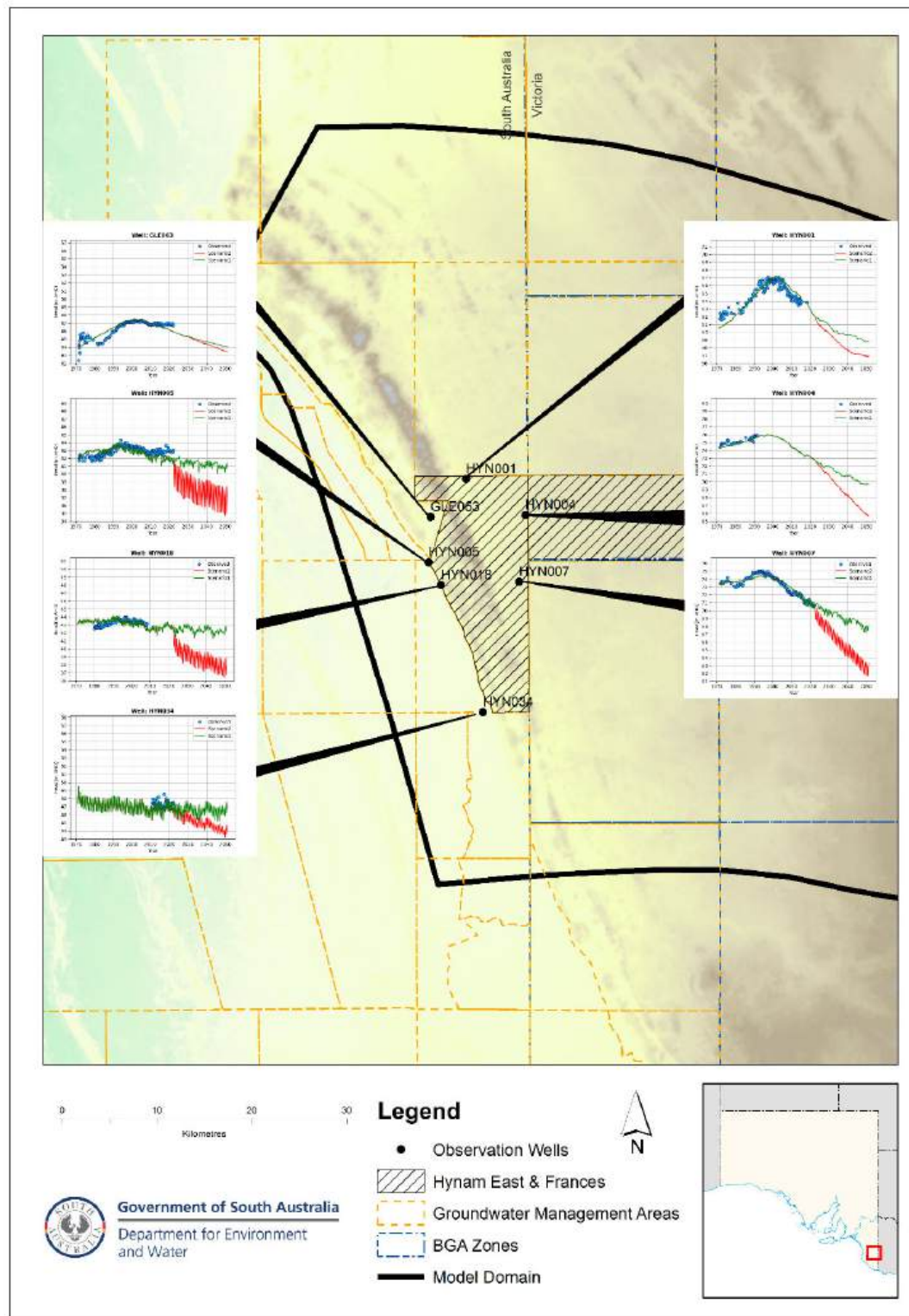


Figure 6.5. Scenario Hydrographs Hynam East showing predicted declines in groundwater levels for Scenario 1 (green) and Scenario 2 (red) (Hydrograph vertical scale range= 10m).

6.6 Scenario Potentiometric Surfaces

Figure 6.6 and Figure 6.7 display the potentiometric surfaces between 2022 and 2050.

For Scenario 1 there are declines in groundwater levels largely in the South Australian portion of the model (Figure 6.6). Declines in groundwater level of 1 to 2 m occur across much of the model domain, consistent with current trends in groundwater level. The exception is groundwater levels on the western margin of the domain, where the water table is shallow.

For Scenario 2 the declines in groundwater levels across the entire domain are more pronounced (Figure 6.7) as a result of changes in climate and increases in pumping.

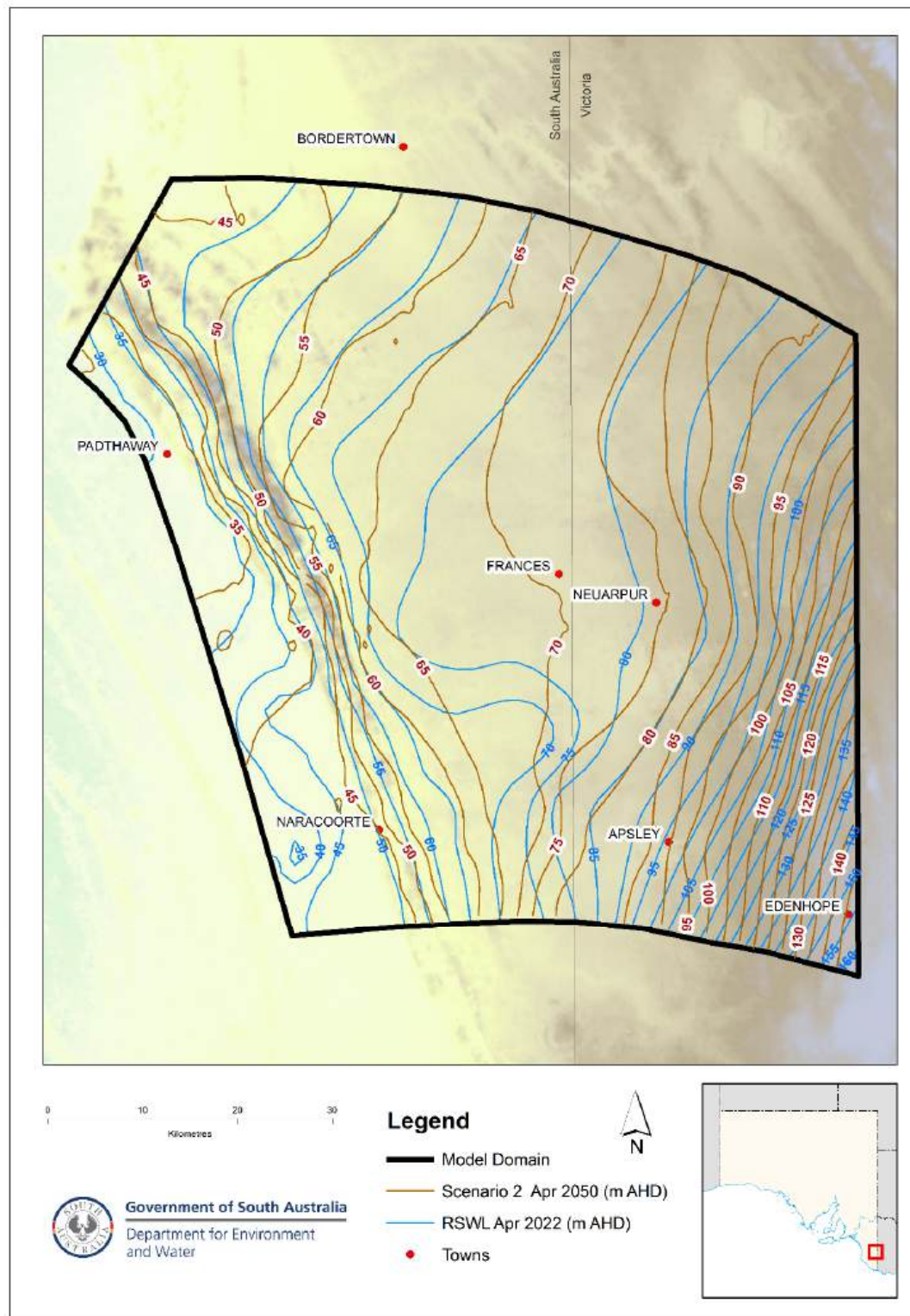


Figure 6.7. Scenario 2 potentiometric surface in 2050 compared with the 2022 measured potentiometric surface.

6.7 Scenario Change in Water Level

To visualize alterations in the potentiometric surface, difference maps provide a clear representation. Figure 6.8 and Figure 6.9 illustrate the comparison between the modelled heads at the end of the history match modelling (April 2022) and those at the end of each Scenario run (April 2050). The eastern and western boundaries exhibit regions of minimal to no change due to constant water levels enforced by boundary conditions. In the northwest corner, boundary conditions reflecting declining water levels outside the model domain contribute to a decrease in water levels in that area.

In Scenario 2 (Figure 6.9), indicative of groundwater extraction pumped at the maximum allocation under RCP 8.5 climatic conditions, significant groundwater level decreases up to 7 m are anticipated within the study area, particularly around the Frances-Neuapurr region, Zone 5A and Stewarts management areas and in various locations in and around the management area of Hynam East. Groundwater levels throughout the rest of the model area decrease to a lesser extent, but maximum allocation usage under RCP 8.5 is predicted to have a significant effect throughout large sections of the model area.

Scenario 1 (Figure 6.8) displays similar trends to Scenario 2 (Figure 6.9) but the impacts are notably subdued in comparison. Groundwater declines occur in similar locations (Neuapurr, Frances and around Hynam East) but the magnitude is lower.

The eastern margin of the model represents a region where confined conditions due to the presence of the Bookpurnong Beds have been ignored. Areas of increased water level in this area of the model are likely due to the absence of confined conditions in the model.

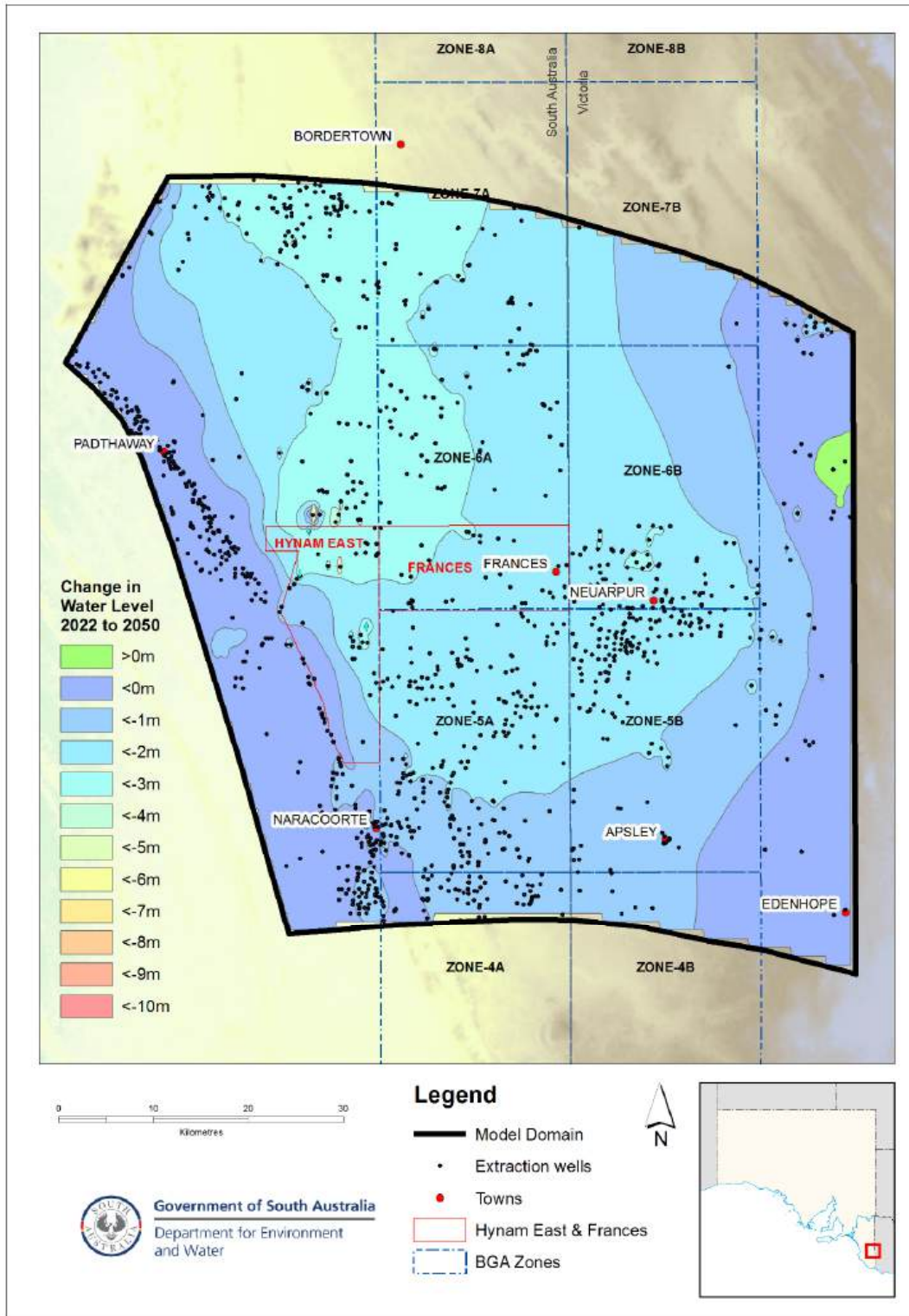


Figure 6.8. Change in water level for Scenario 1.

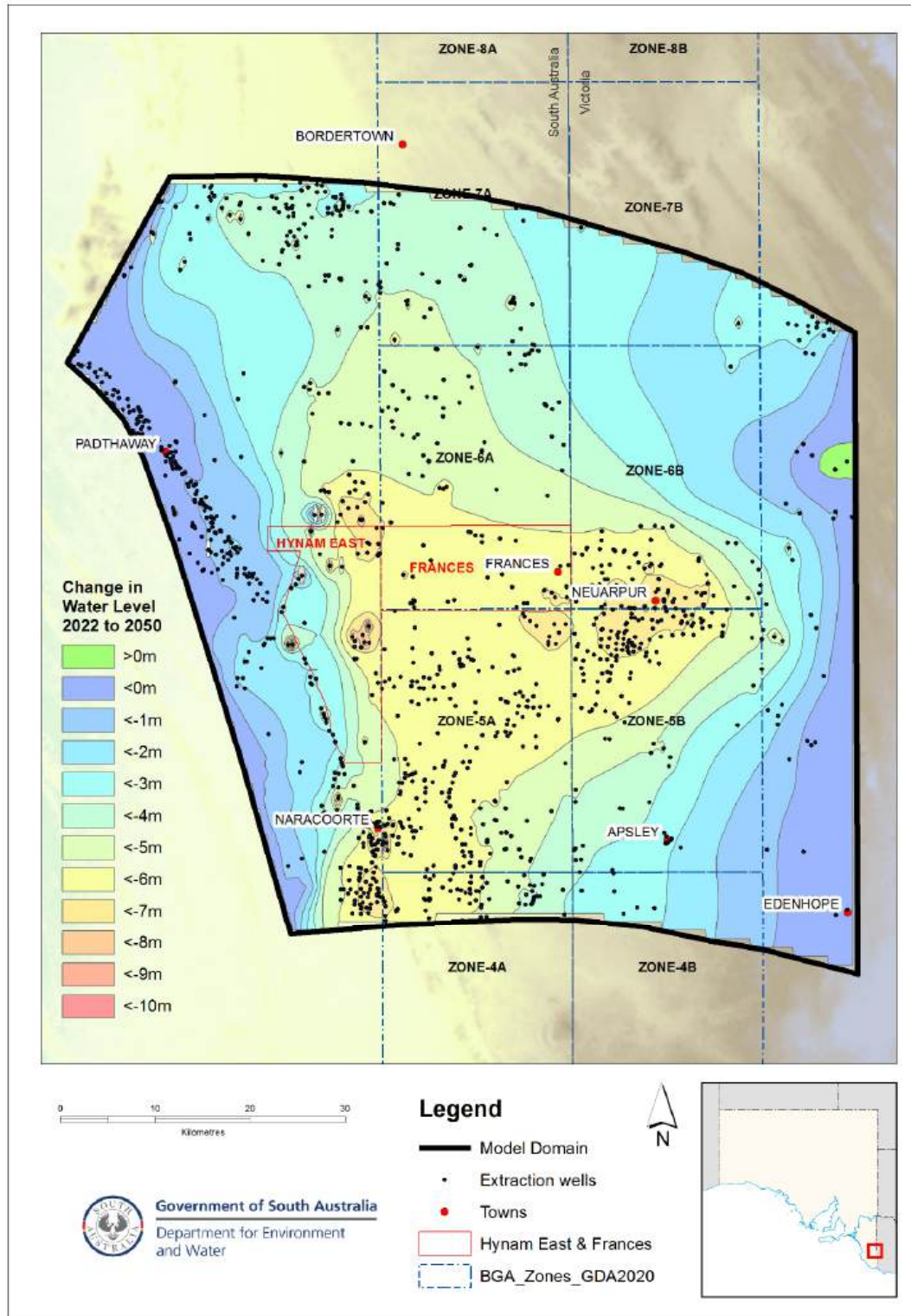


Figure 6.9. Change in water levels for Scenario 2.

7 Conclusions and Recommendations

7.1 Conclusions

A numerical groundwater model has been developed for the region encompassing Border Groundwater Agreement Zones 5A, 5B, 6A and 6B and the Groundwater Management Areas of Frances and Hynam East. This model has been history matched ('calibrated') to acceptable tolerance and has been used to run predictive scenarios.

Two scenarios were examined:

1. Groundwater extraction and recharge held at current levels from the end of the history match period (2022) up to 2050, and;
2. Groundwater extraction set at full allocation and recharge declining in line with climate change projections from 2022 to 2050.

The two scenarios modelled both display a continuation of the current trend of declining groundwater levels. Scenario 1, representing a continuation of current conditions, displays falls that are less than Scenario 2, which represents declining recharge and pumping at full allocation.

The modelling suggests that the magnitude of the impact for Scenario 1 is in the order of a 3 m to 4 m fall over 30 years in the northwest of the model. For Scenario 2 the magnitude of impact is in the order of a 6 m to 7 m decline over 30 years centered around the Frances and Neuapurr, Zone 5a and Stewarts management areas and in various locations in and around the management area of Hynam East.

Climate change impacts on recharge have been modelled via decreasing recharge over time. This accounts for recharge that occurs within the model domain but does not account for the decrease of recharge outside the model domain. The modelling has not accounted for reduced lateral flow resulting from a regional decrease in recharge. However, recharge is likely to be relatively low to the east of the model domain.

7.2 Recommendations

This modelling has been designed as a tool for estimating the potential impacts of decisions made in the process of reviewing the LLC WAP. The Scenarios run to date represent two scenarios within which possible policy decisions could be examined. It is recommended that the current modelling results serve as a basis for consultation with water planners and stakeholders to discuss management implications, and design further scenarios for testing management options.

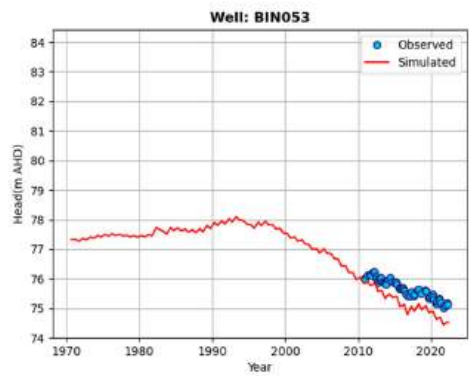
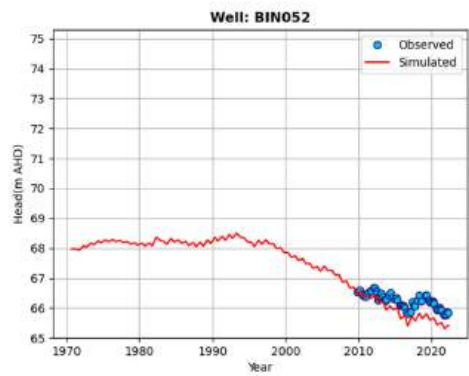
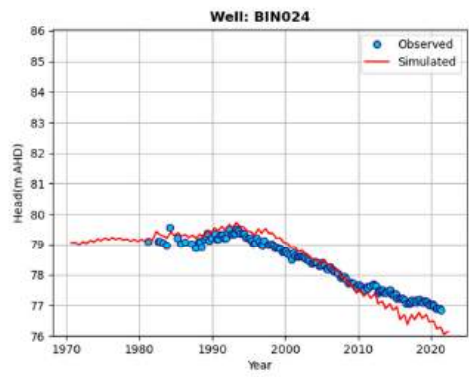
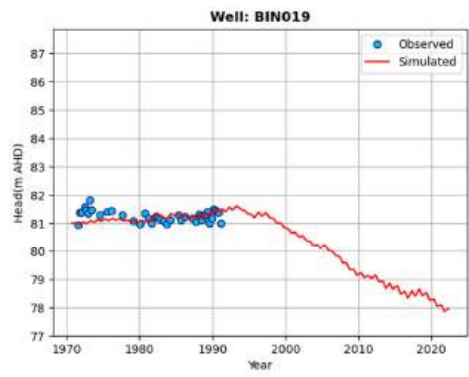
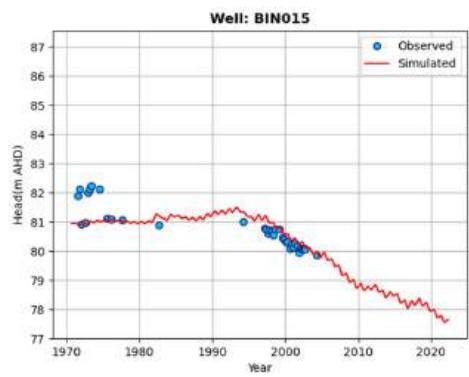
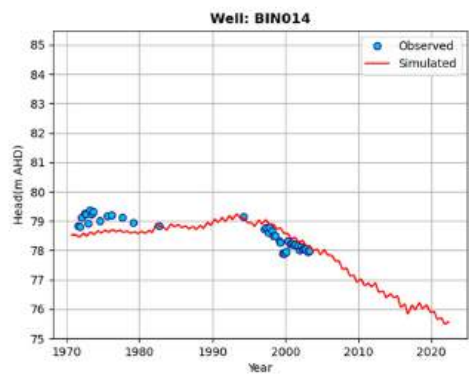
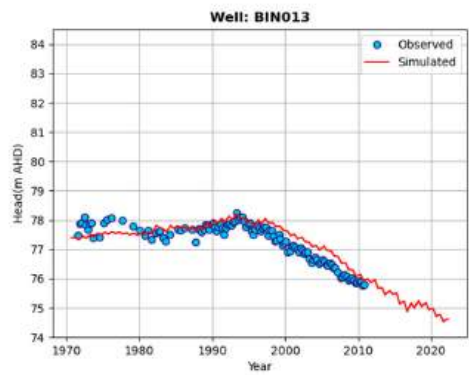
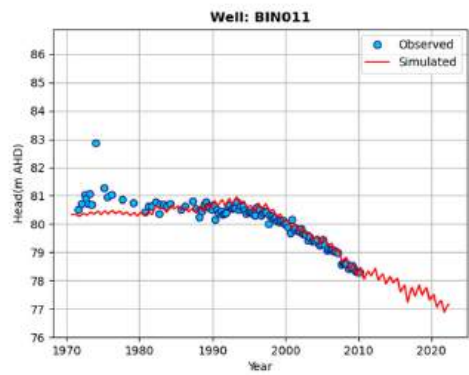
The model has been history matched from 1970 to 2022 based on the best available data. However, some areas are relatively data poor. It is recommended that, in Victoria, the number of observation wells is increased to fill gaps in the spatial distribution of the monitoring network. More broadly, it is recommended that groundwater level measuring should occur at least quarterly and preferably monthly to resolve seasonal variations.

It is recommended that future scenario modelling tasks be conducted using uncertainty analysis methods (Peeters and Middlemis 2023), to provide improved support for decision making in relation the upcoming review of the Lower Limestone Coast Water Allocation Plan.

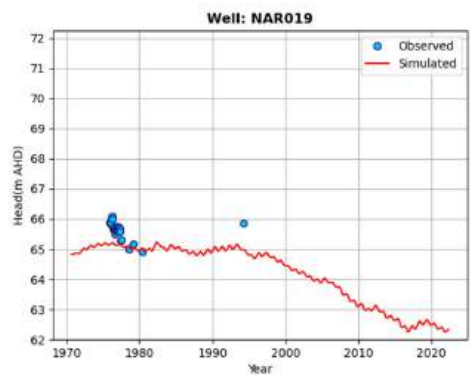
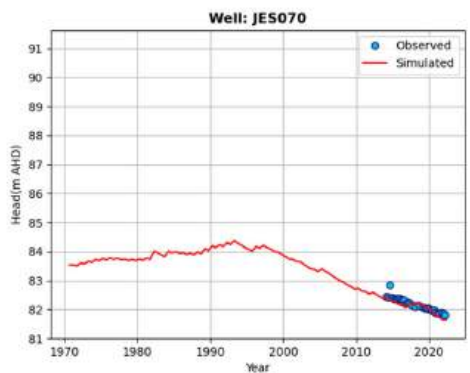
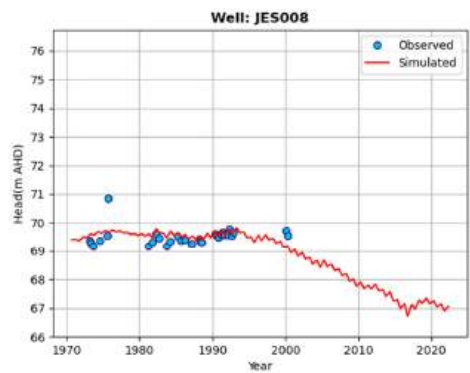
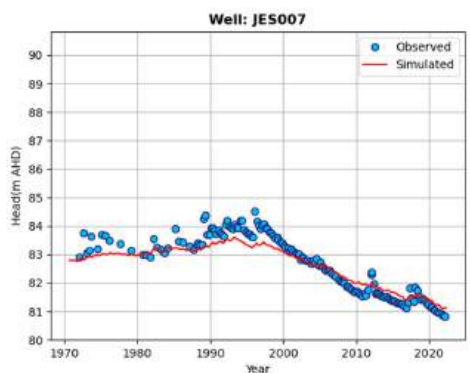
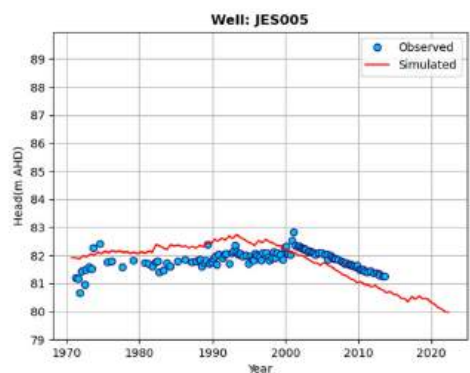
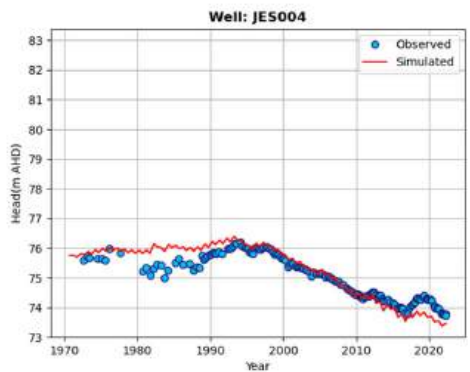
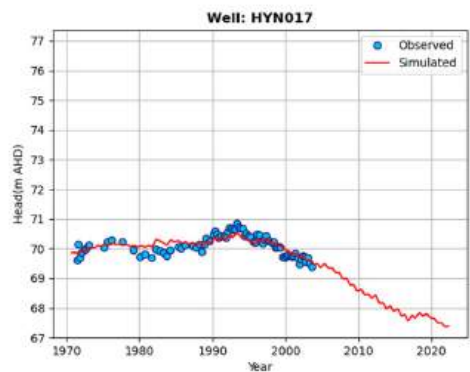
8 Appendices

A. Modelled Hydrographs

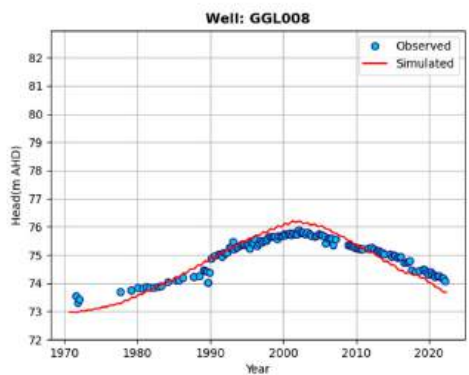
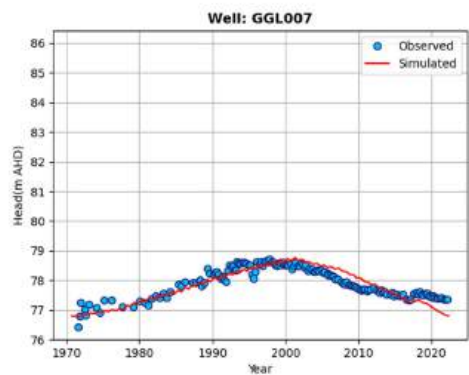
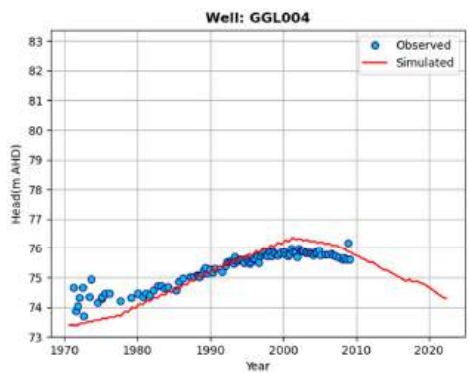
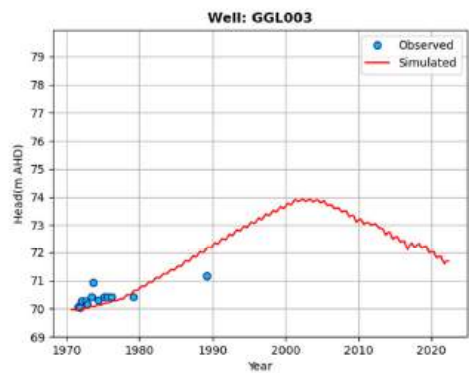
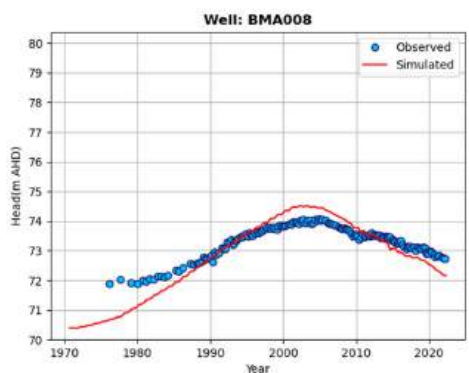
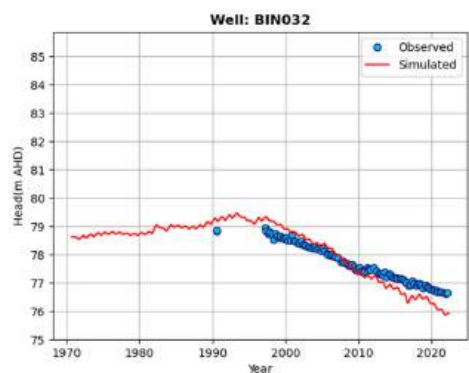
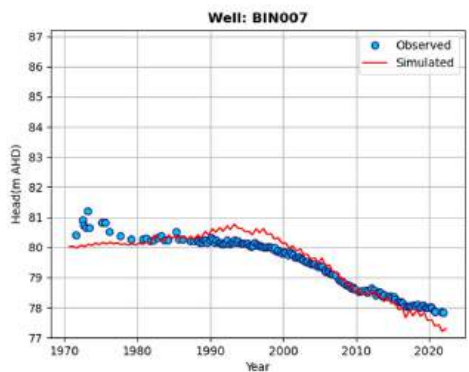
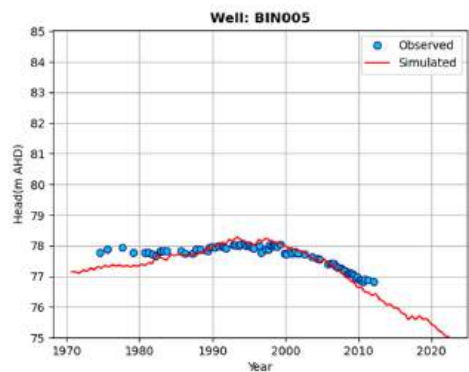
ZONE 5a



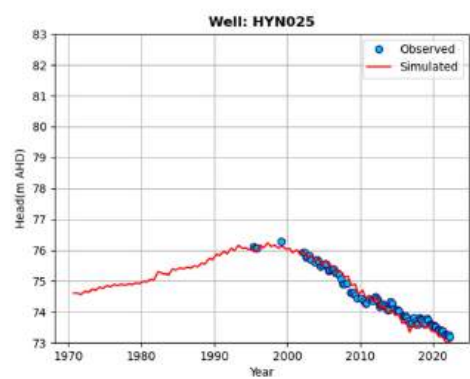
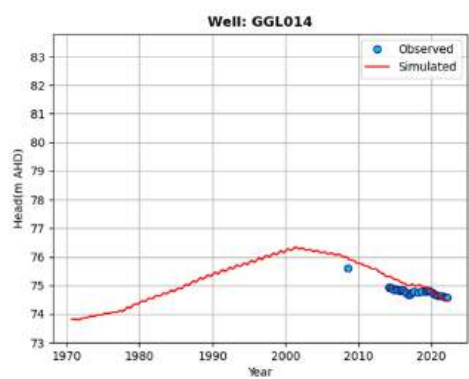
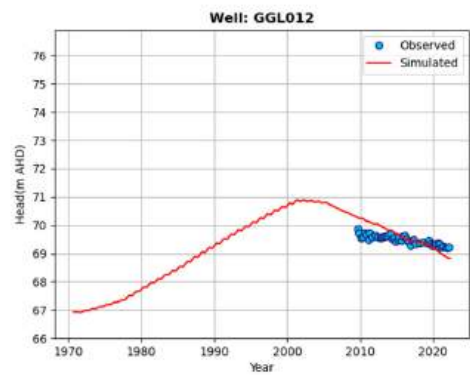
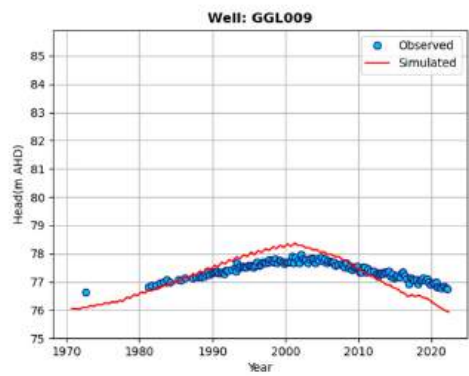
ZONE 5a



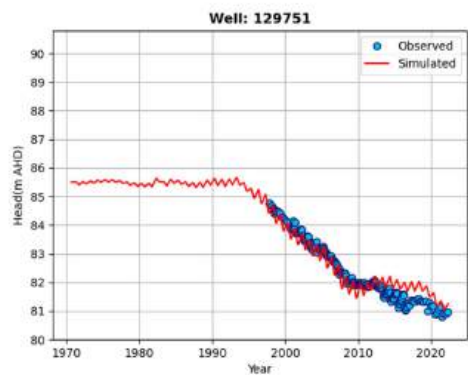
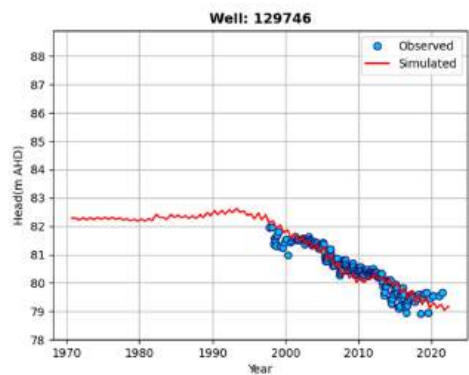
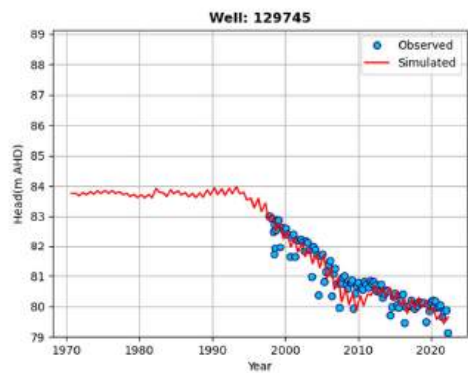
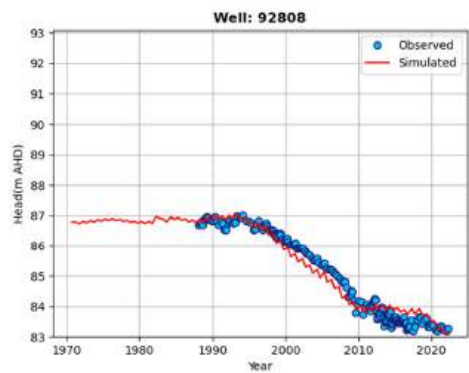
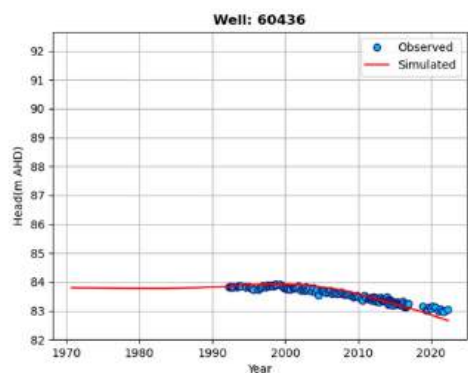
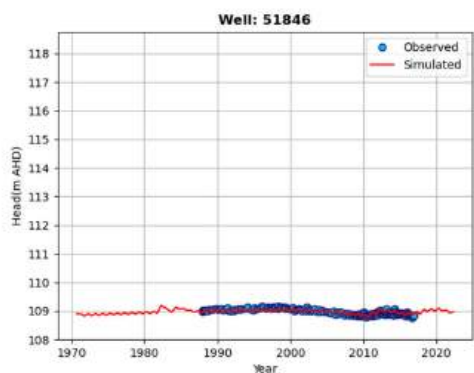
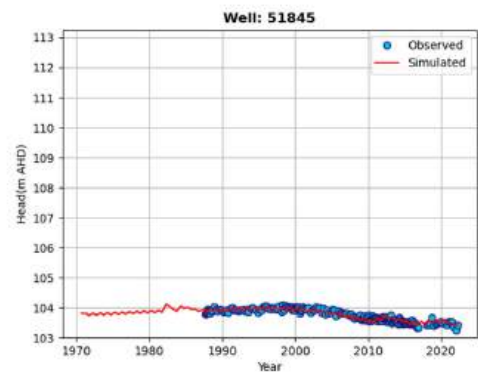
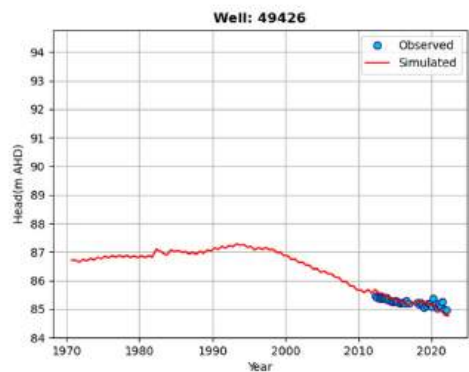
ZONE 6a



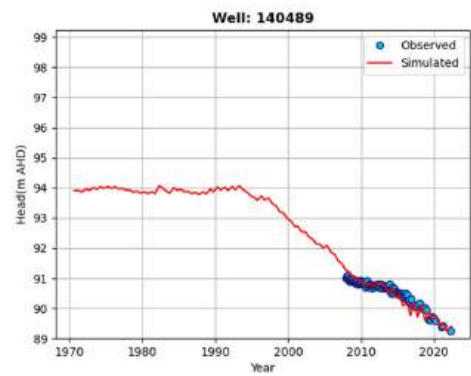
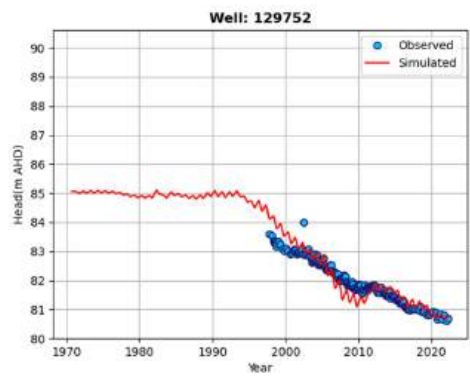
ZONE 6a



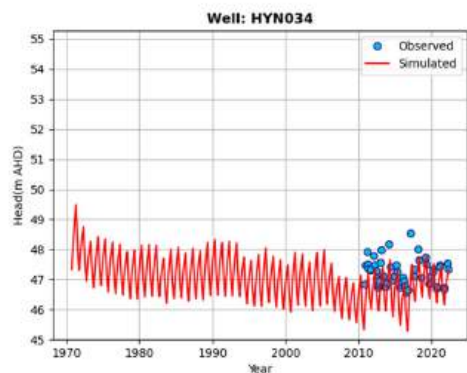
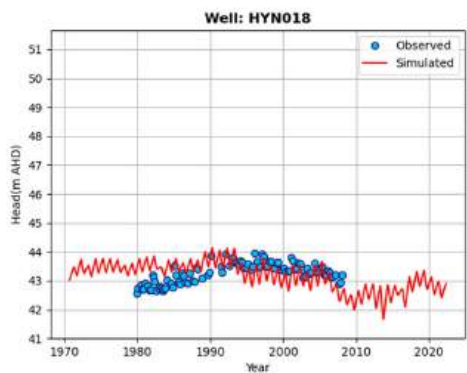
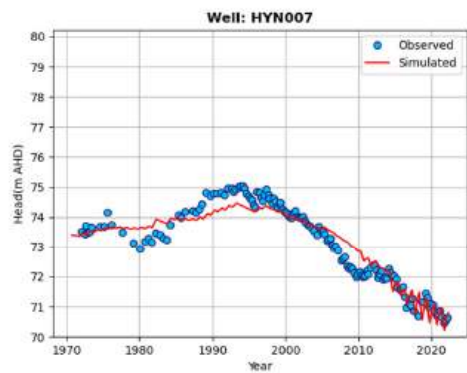
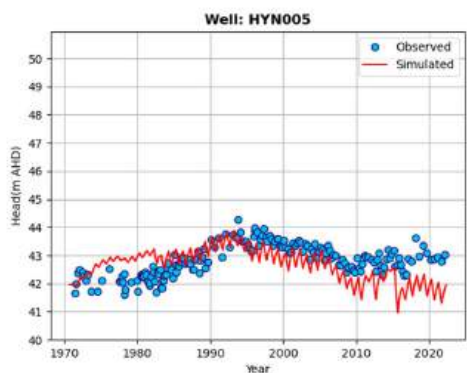
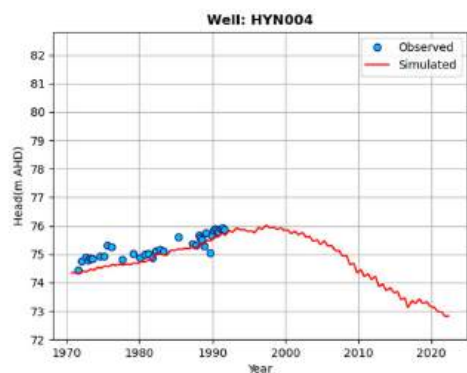
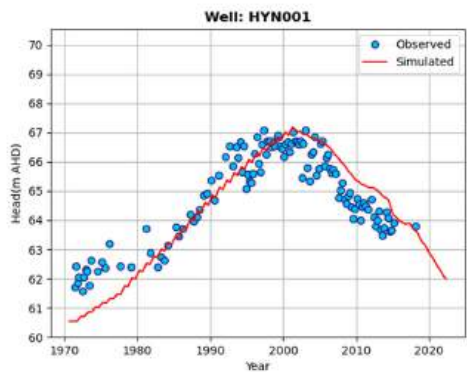
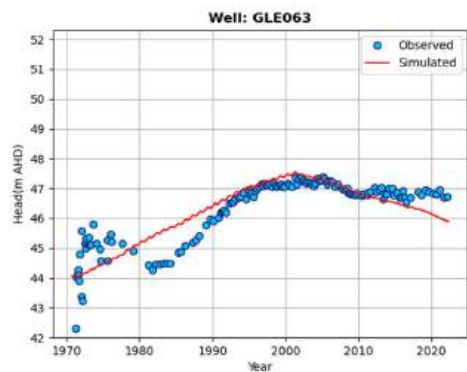
ZONE 5b & 6b



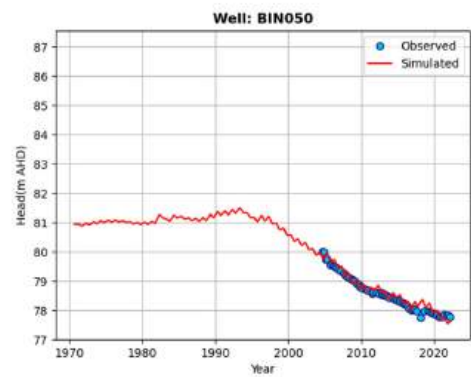
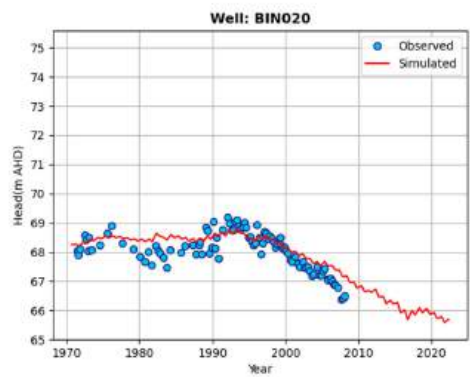
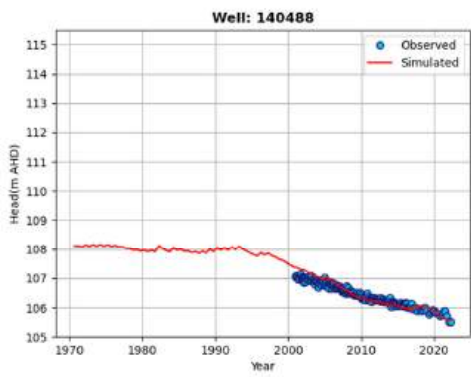
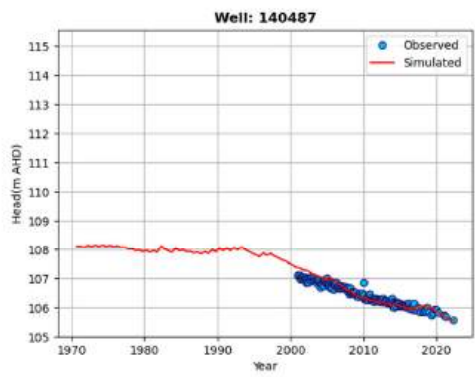
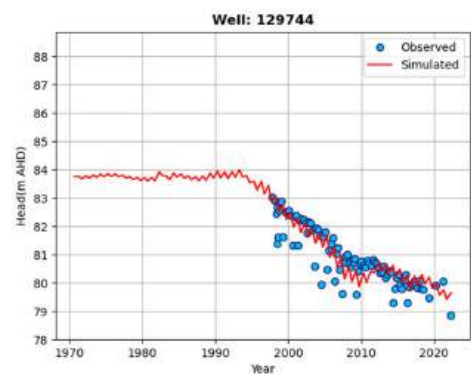
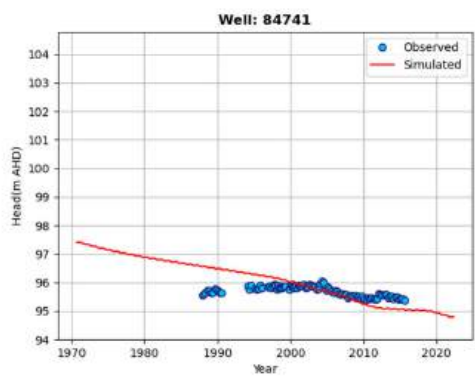
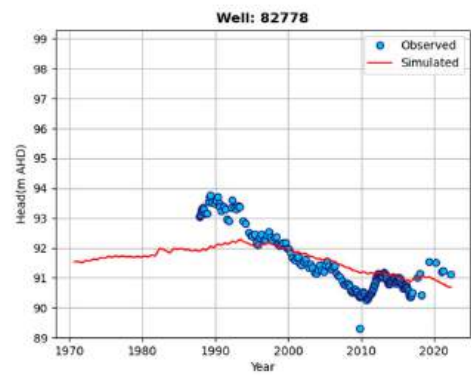
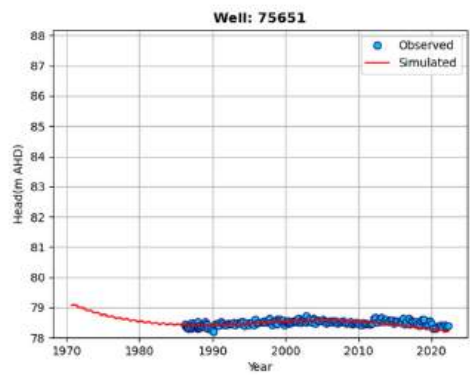
ZONE 5b & 6b

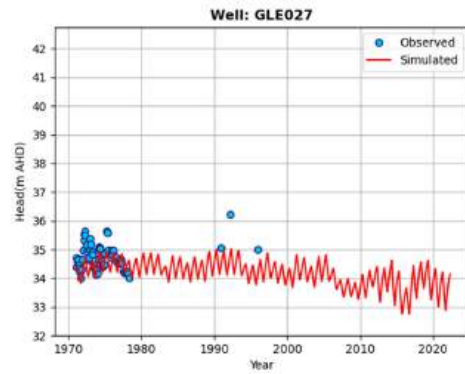
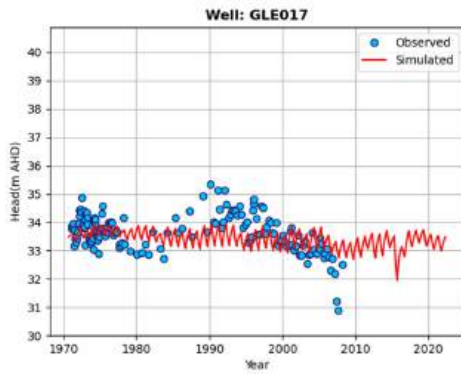
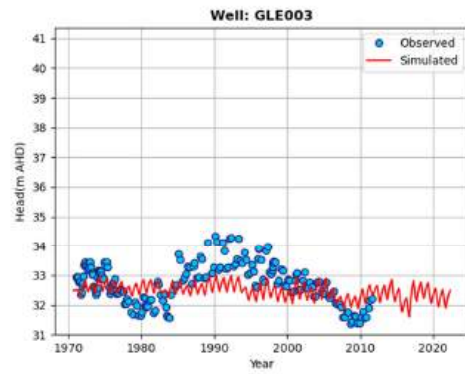
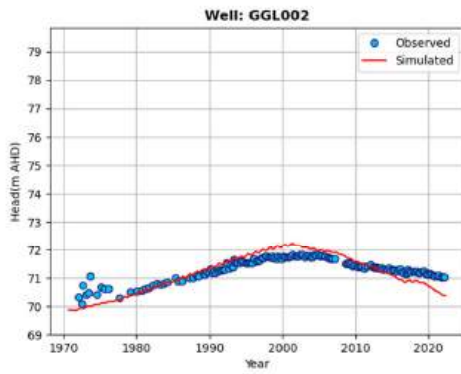
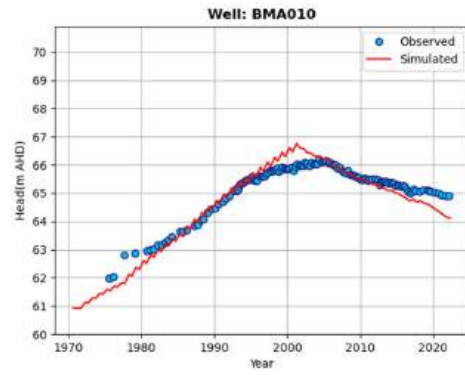
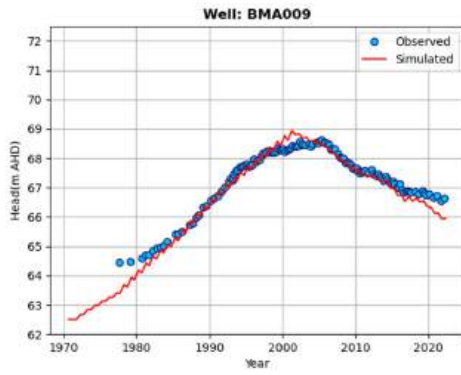
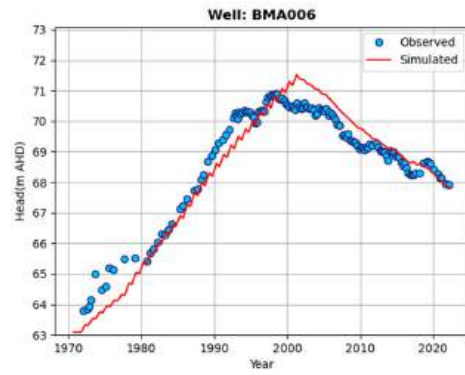
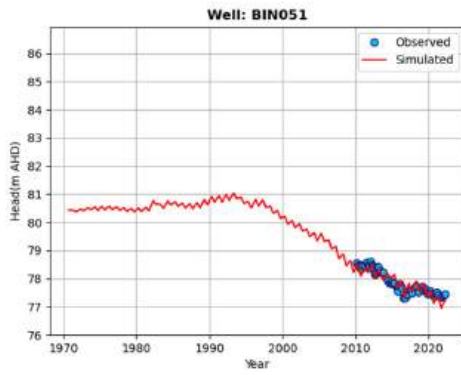


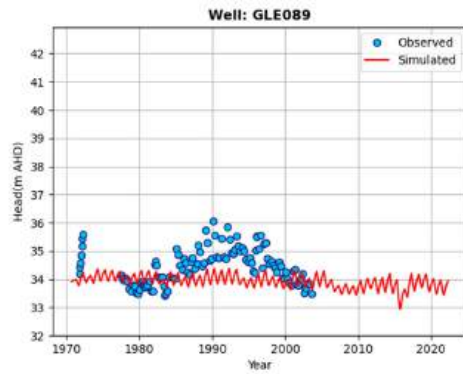
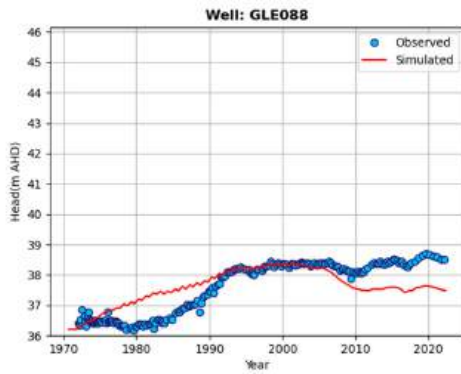
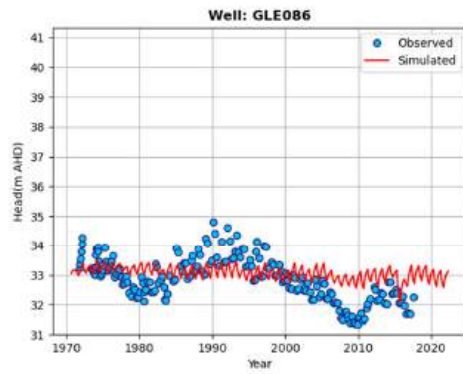
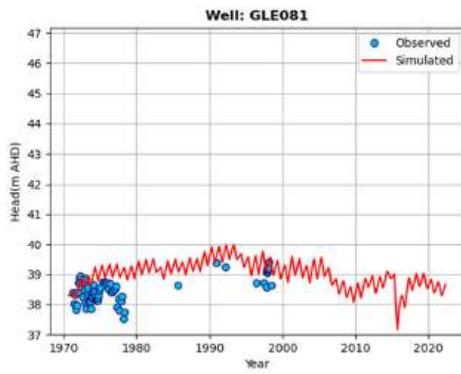
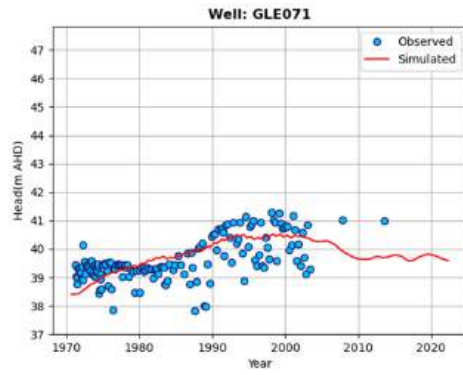
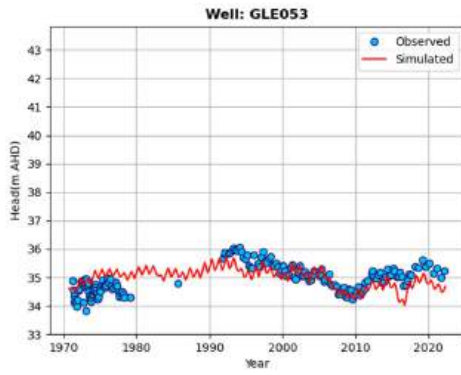
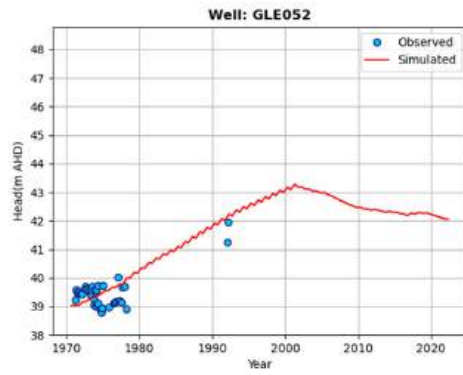
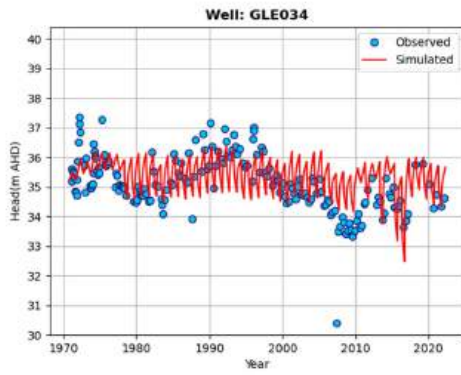
Hynam East

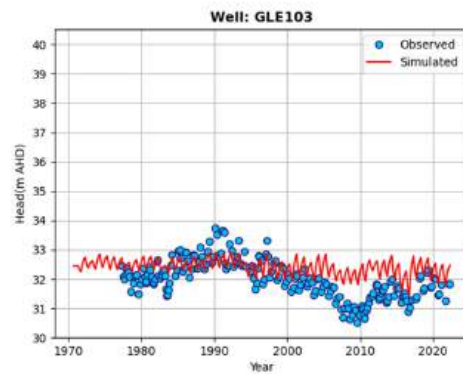
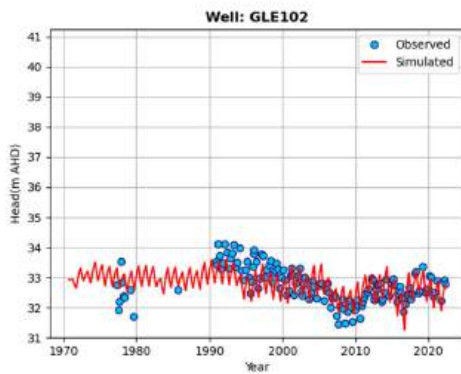
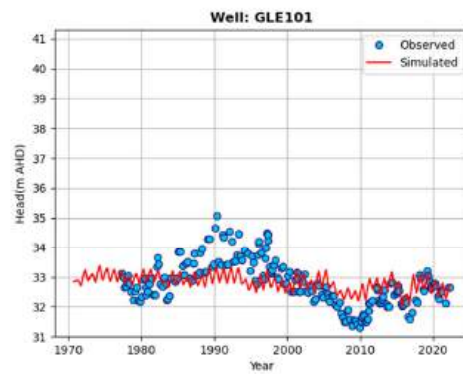
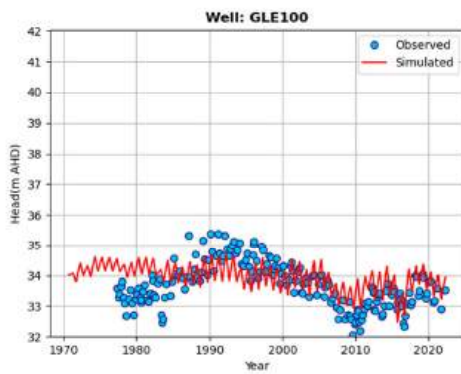
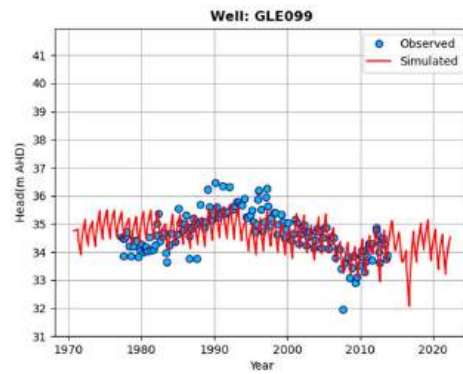
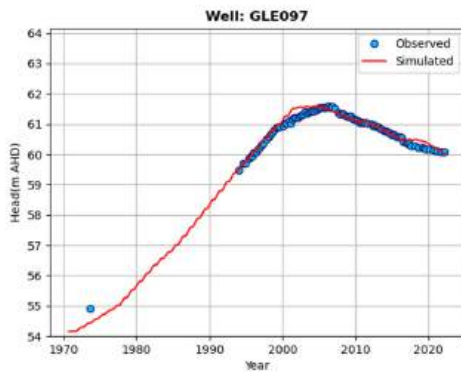
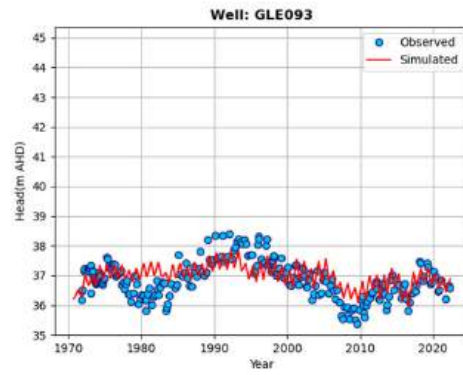
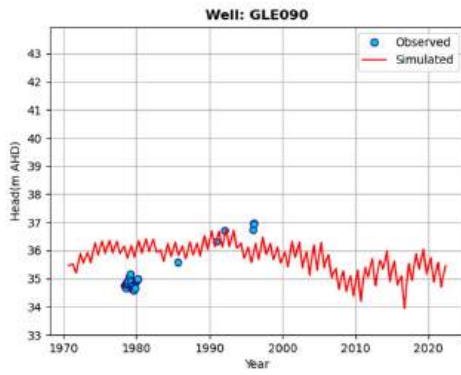


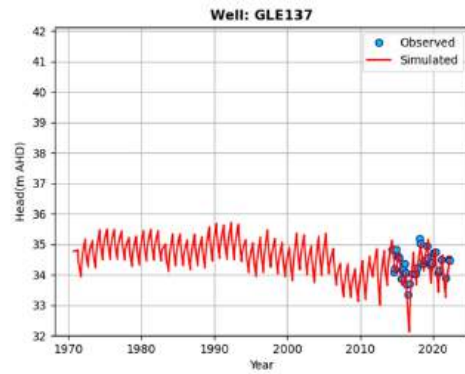
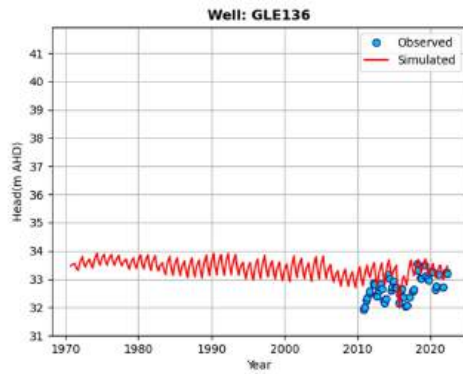
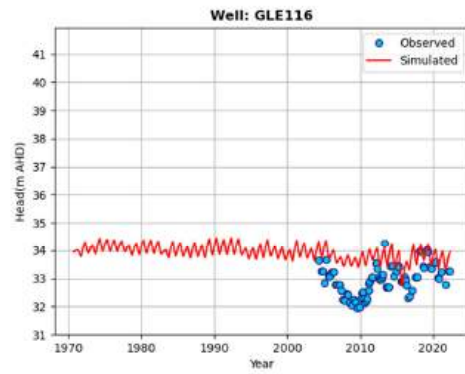
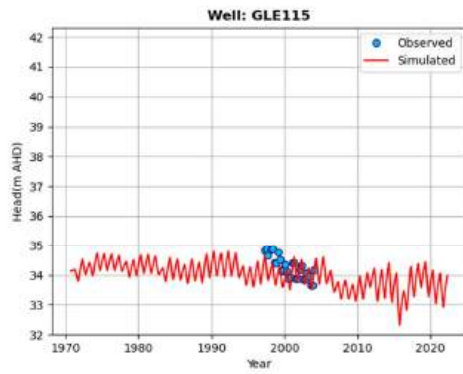
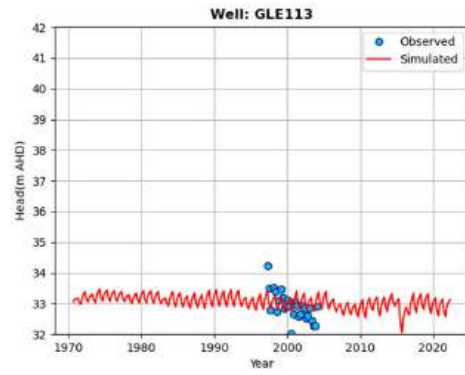
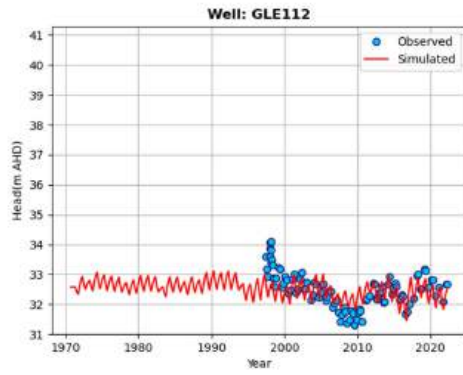
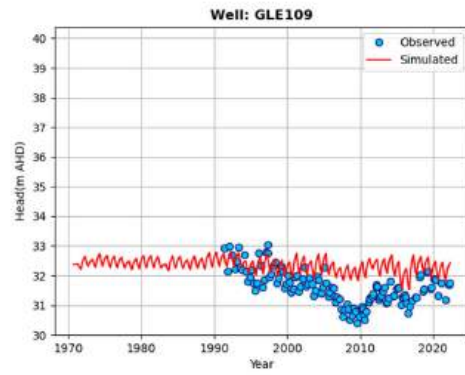
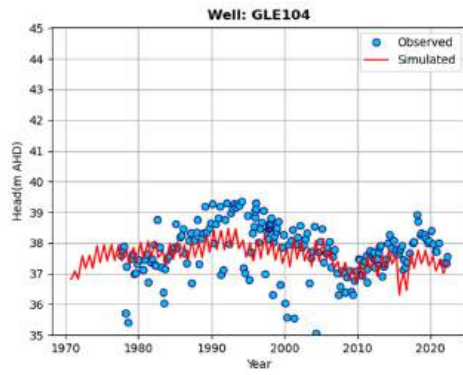
Miscellaneous

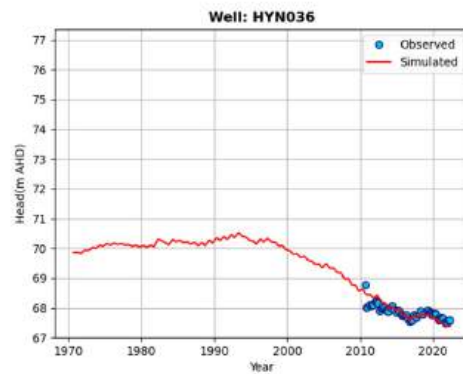
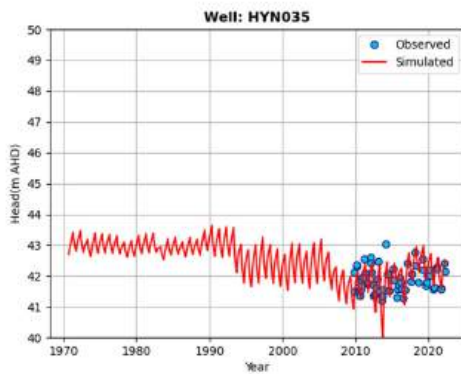
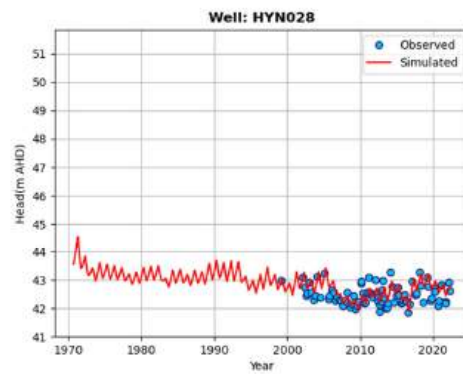
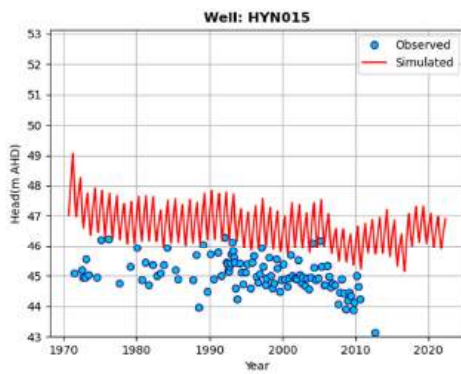
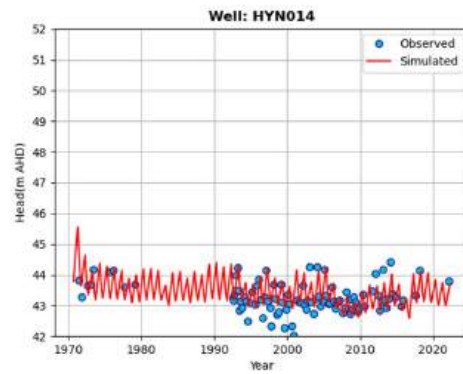
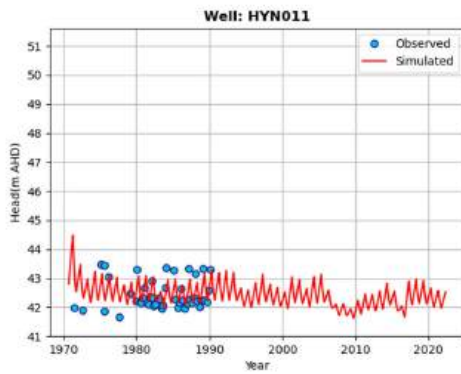
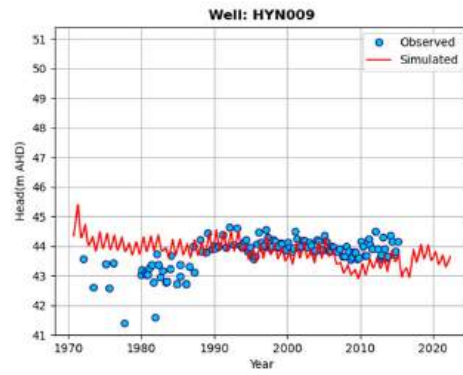
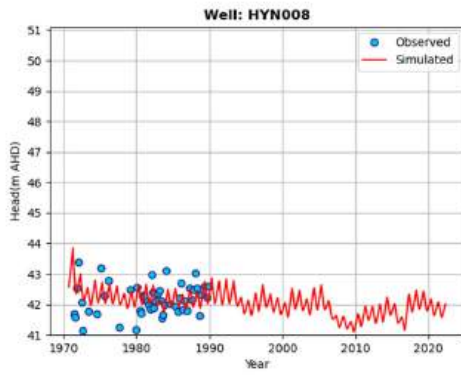


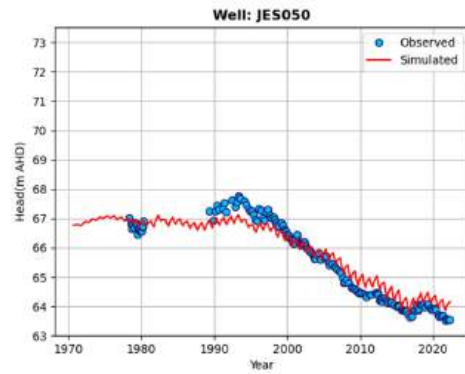
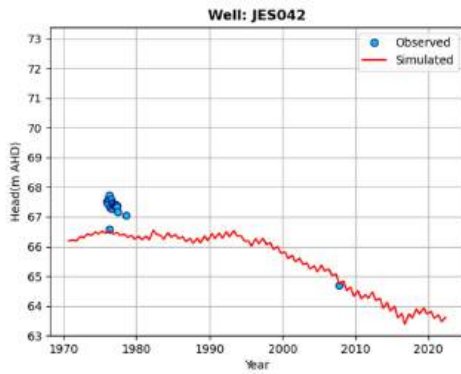
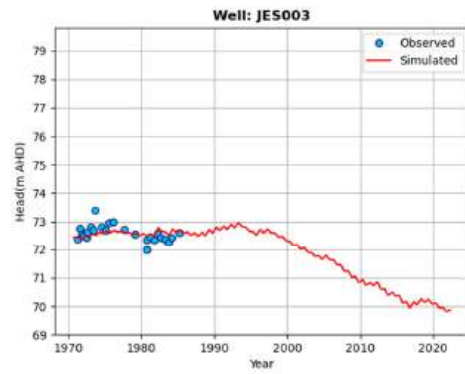
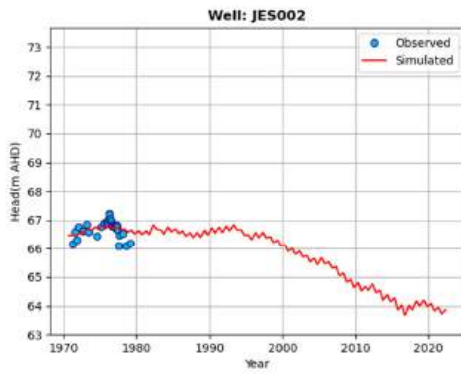
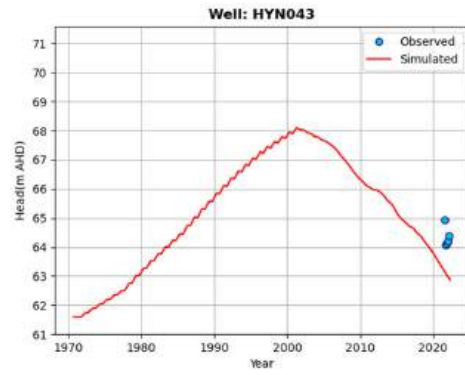
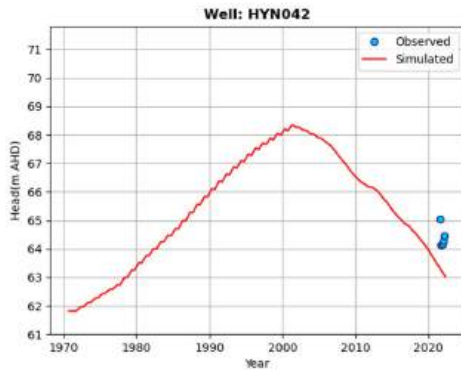
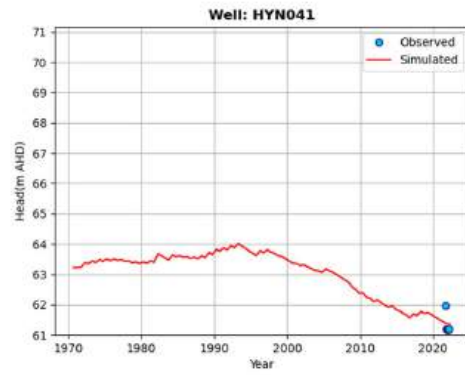
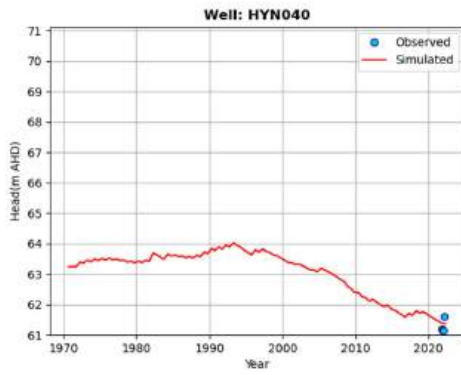


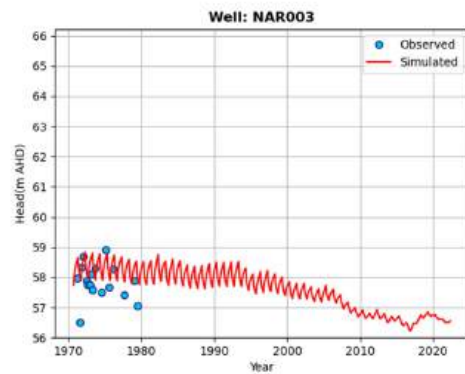
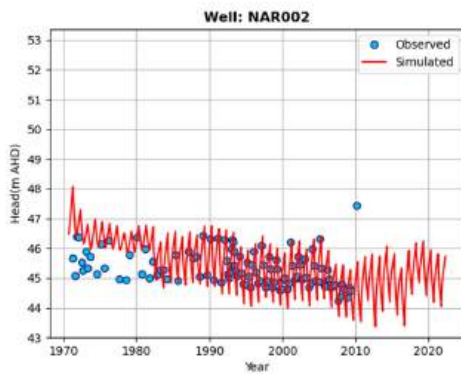
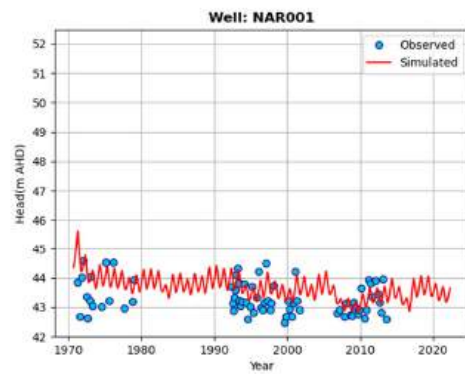
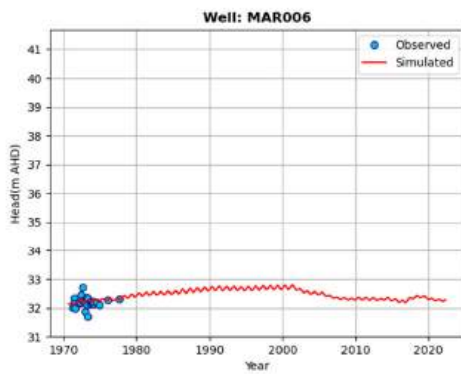
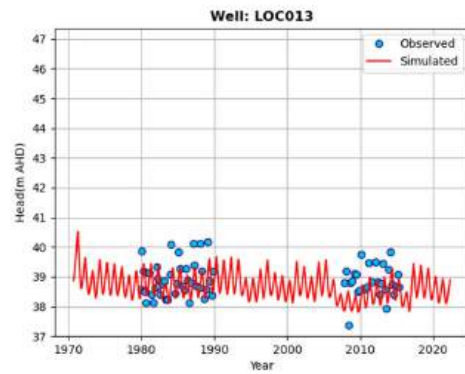
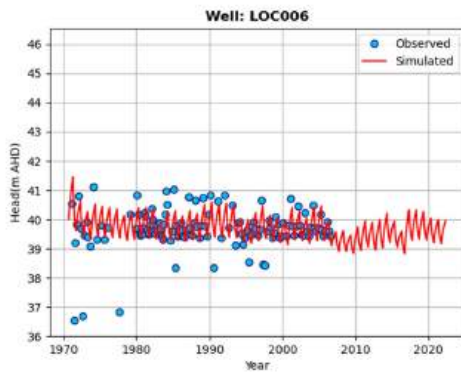
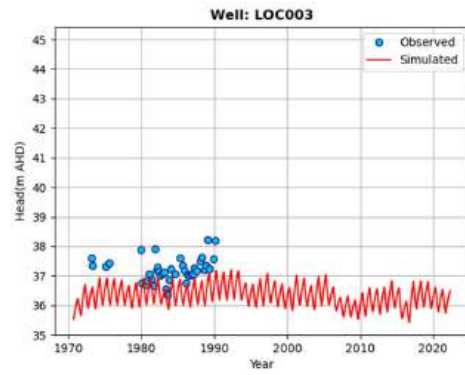
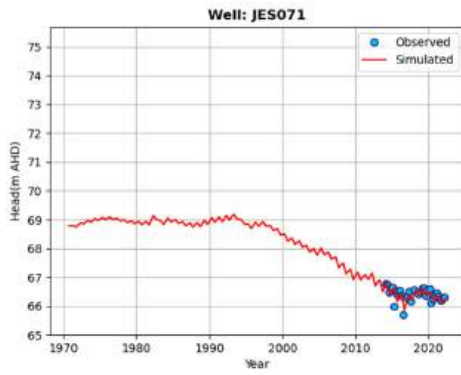


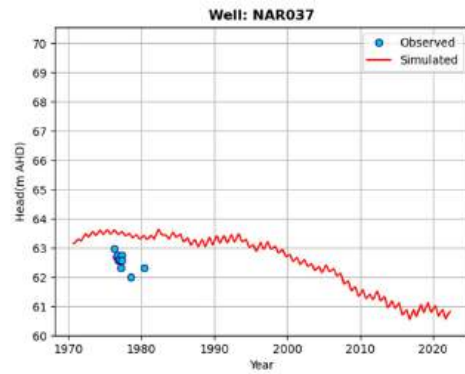
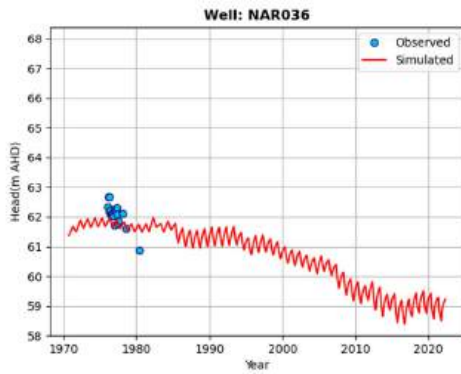
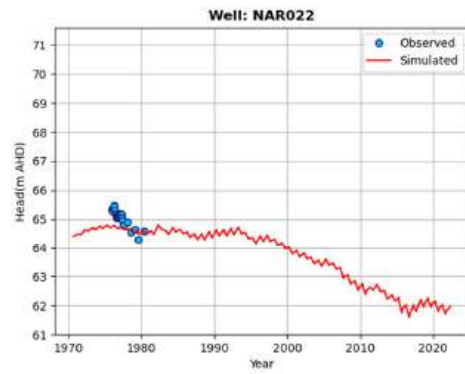
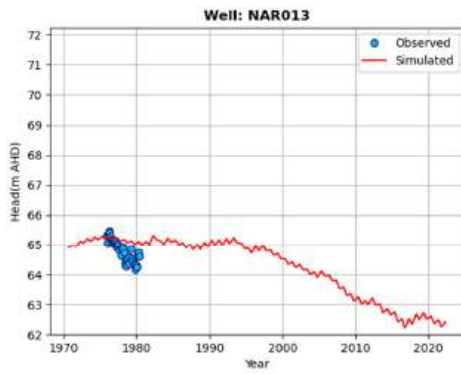
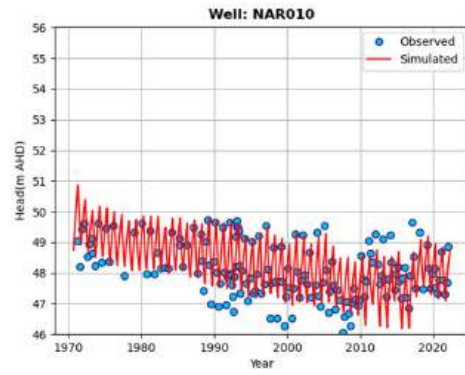
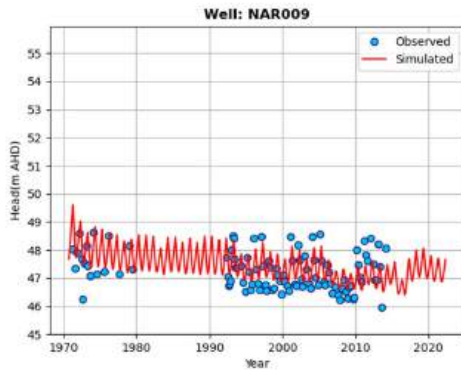
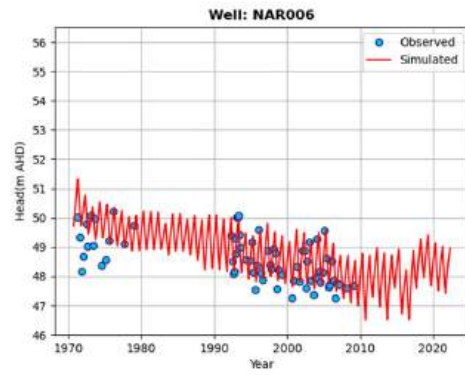
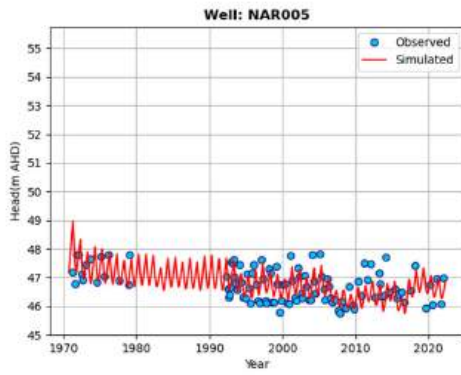


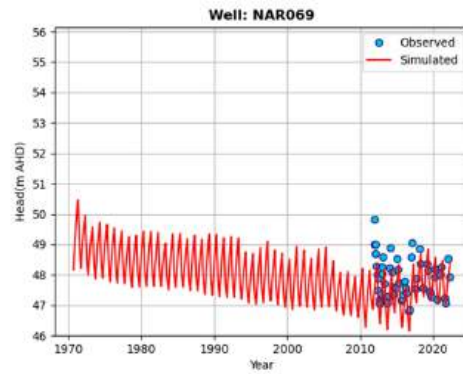
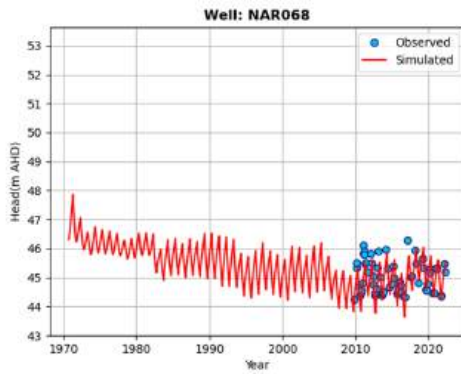
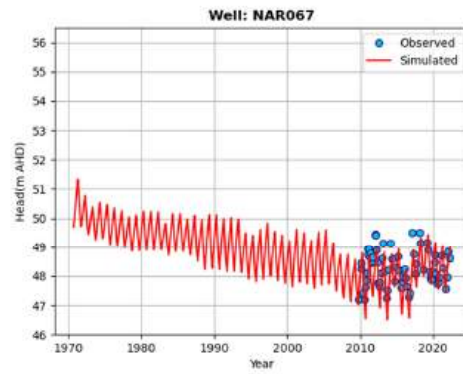
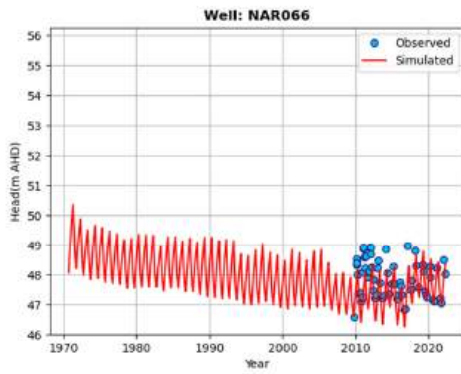
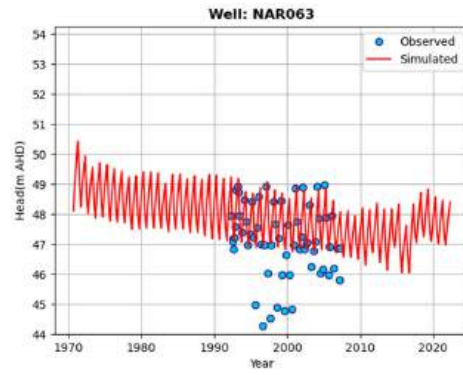
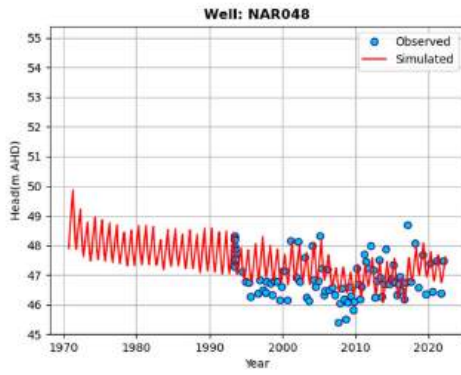
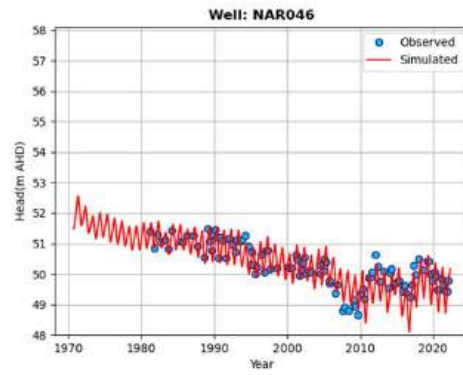
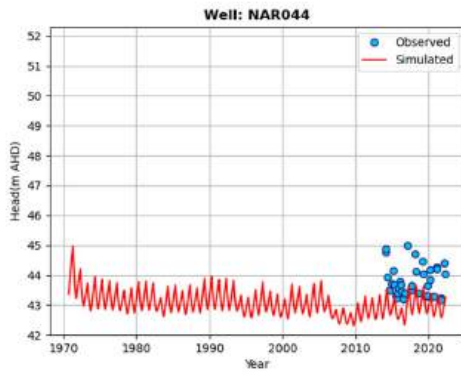


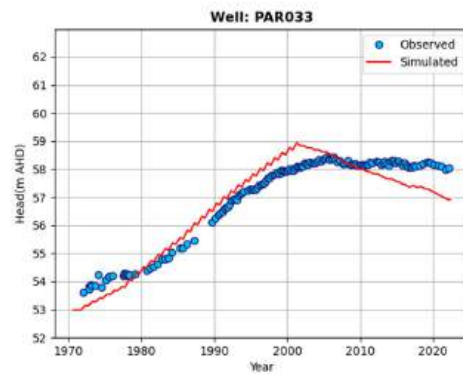
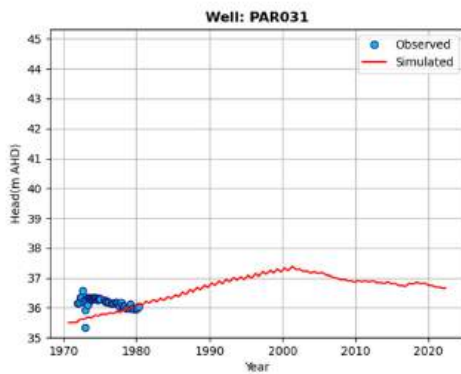
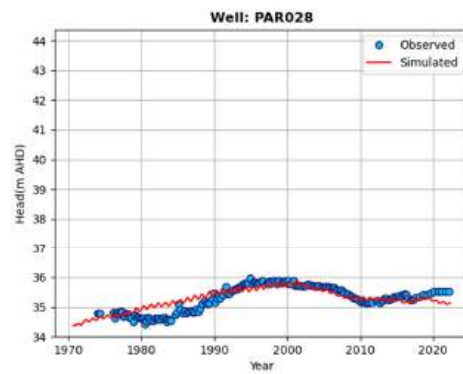
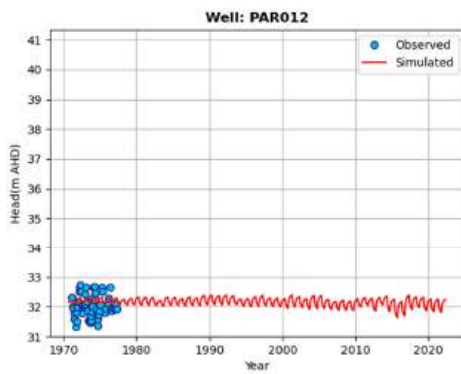
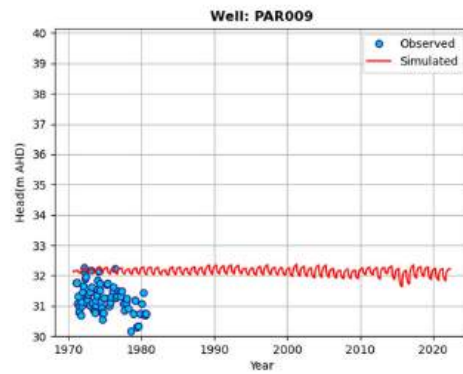
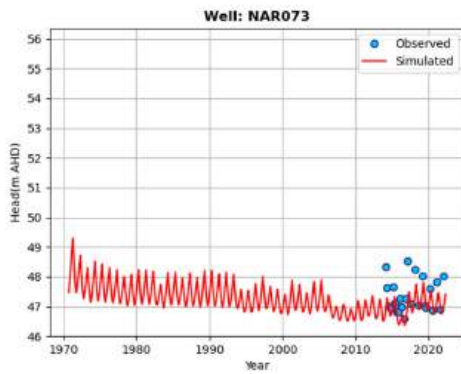
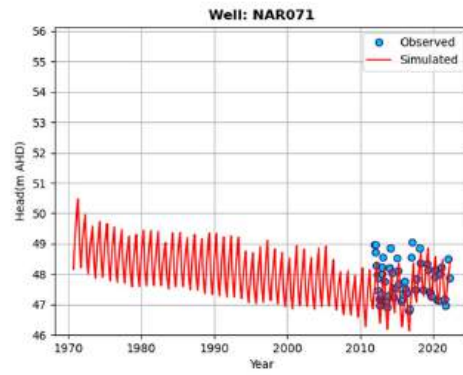
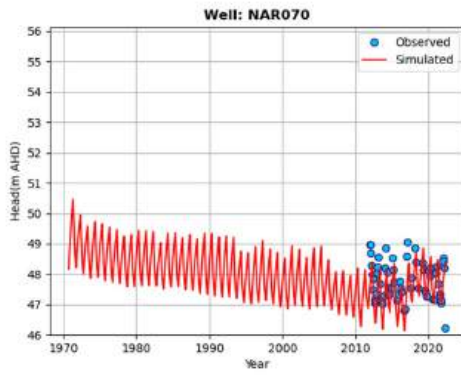


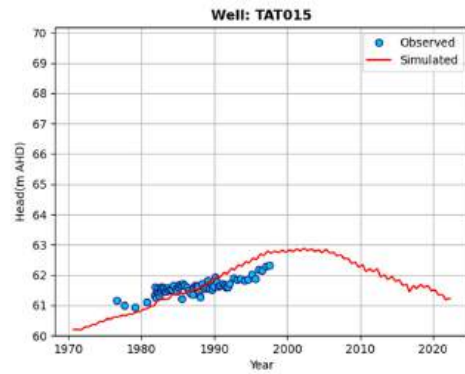
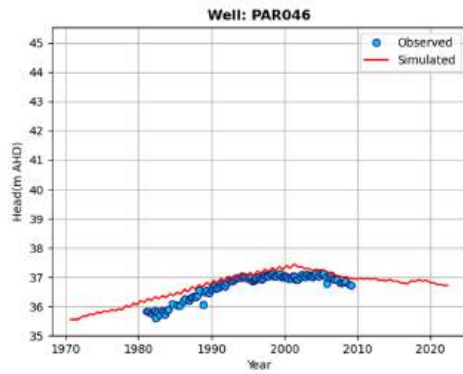
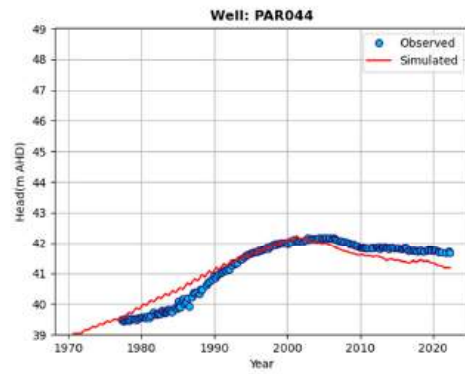
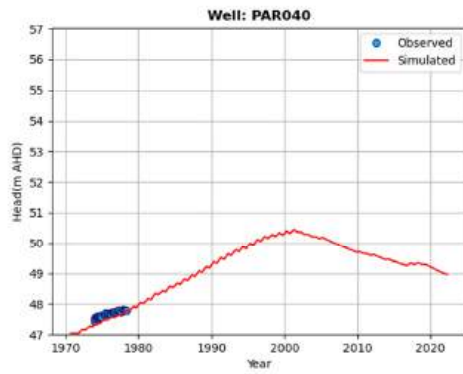
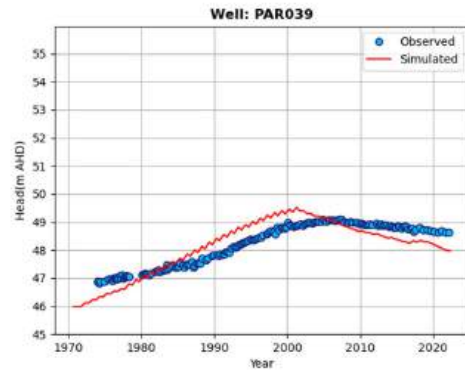
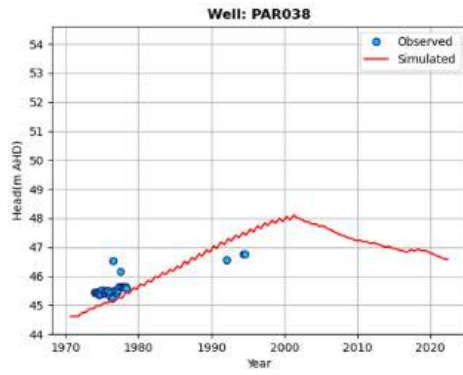
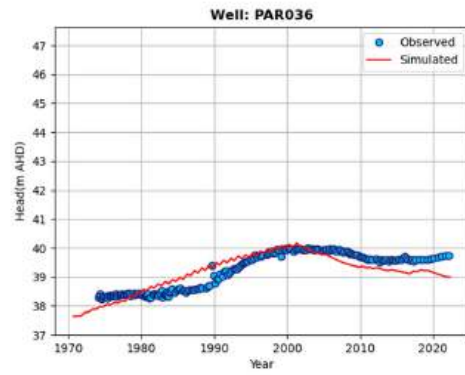
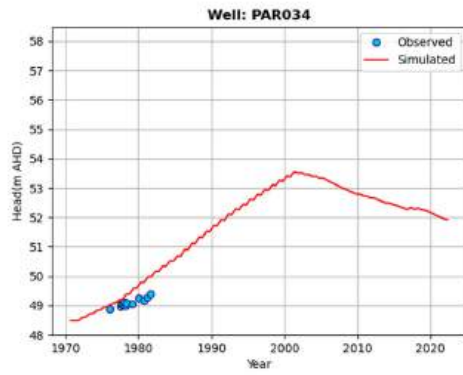


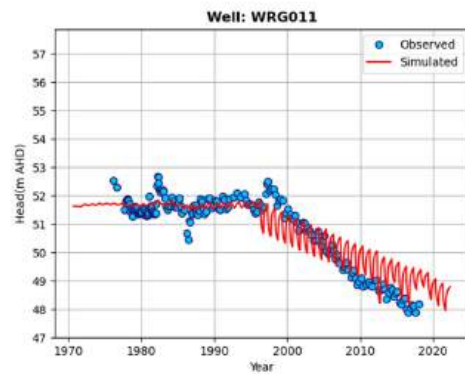
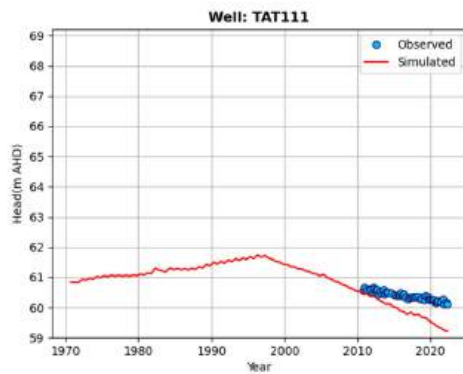
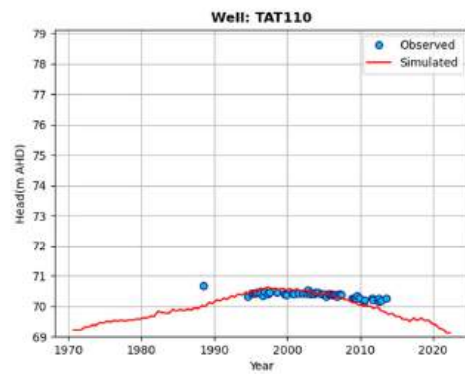
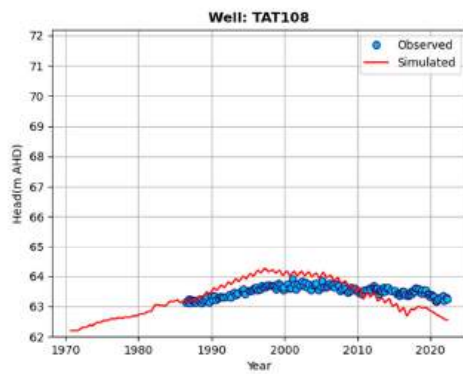
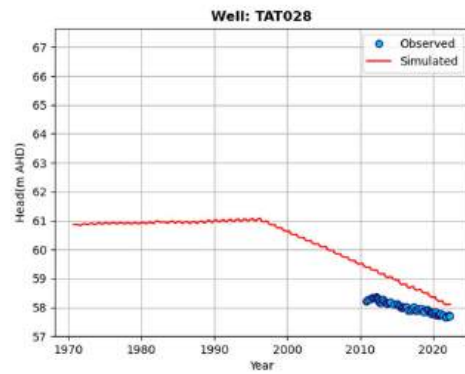
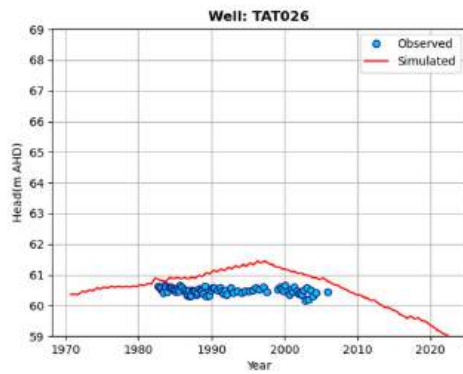
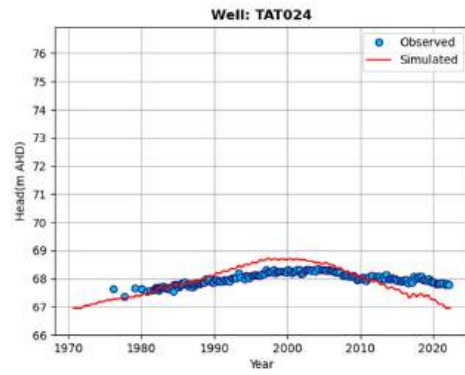
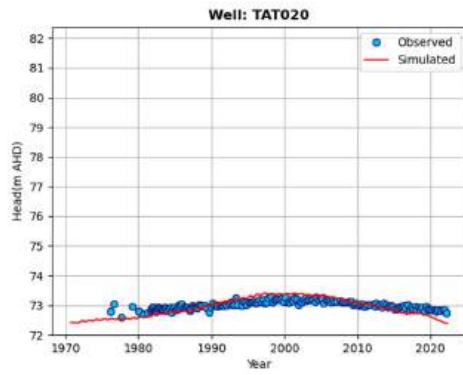


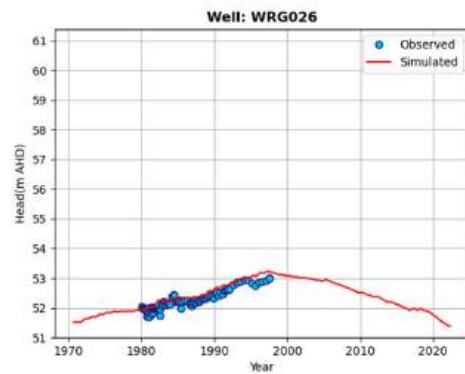
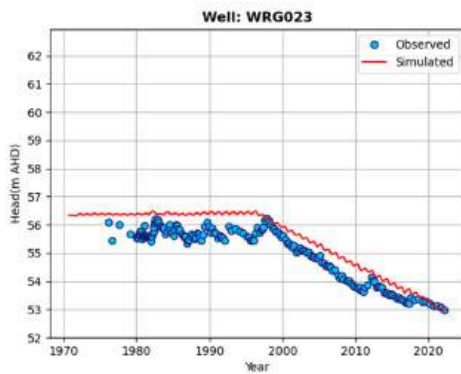
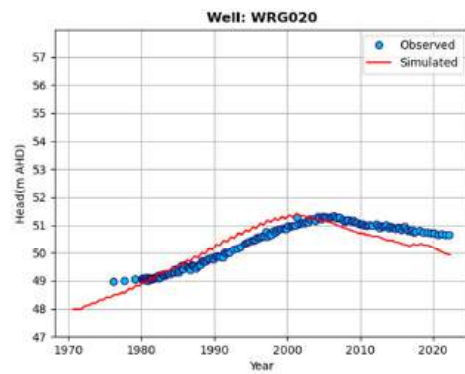
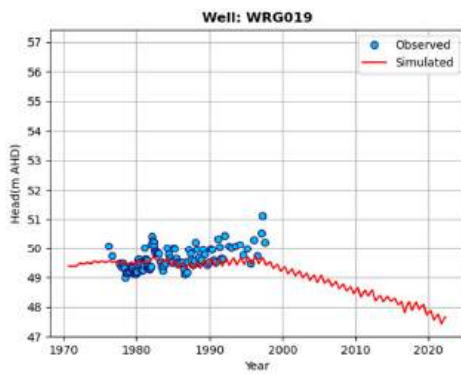
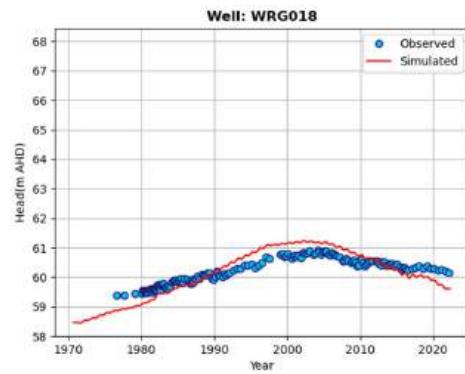
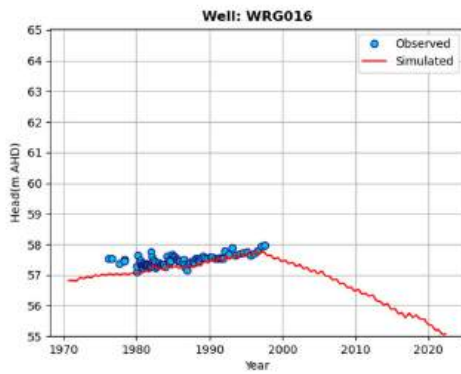
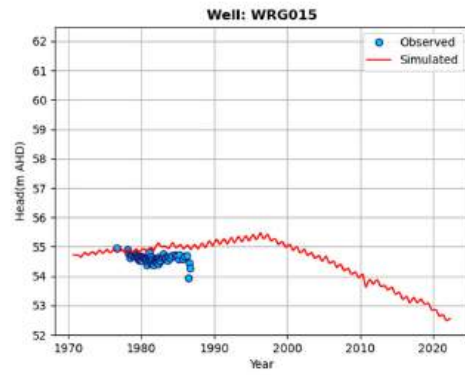
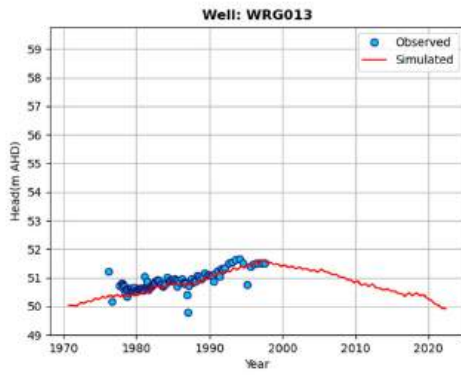


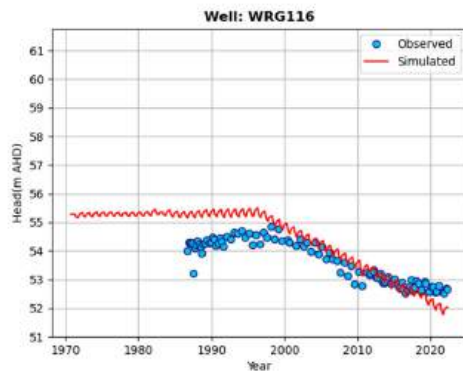
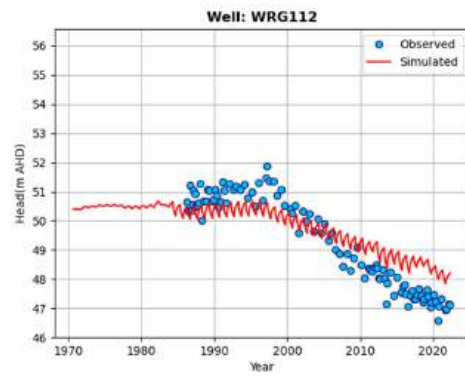
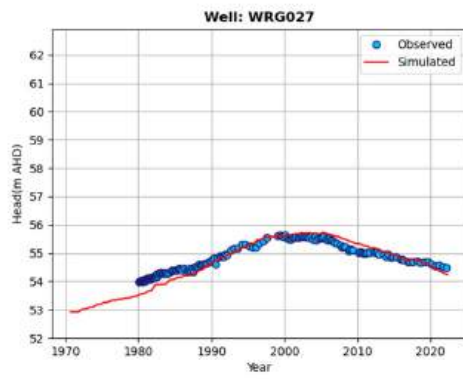






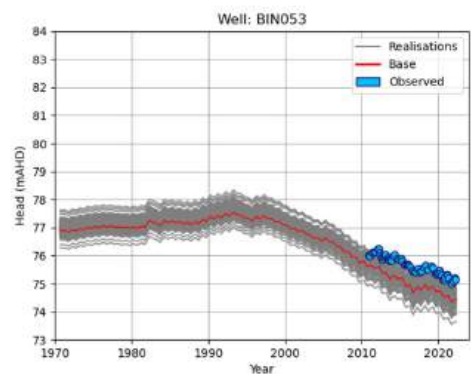
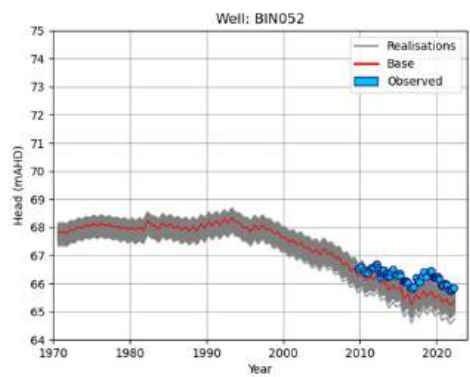
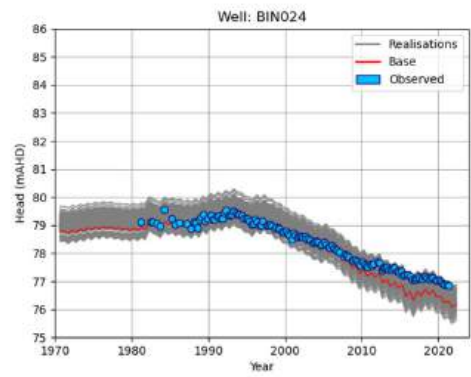
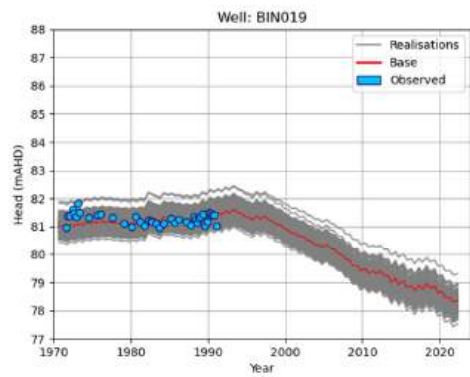
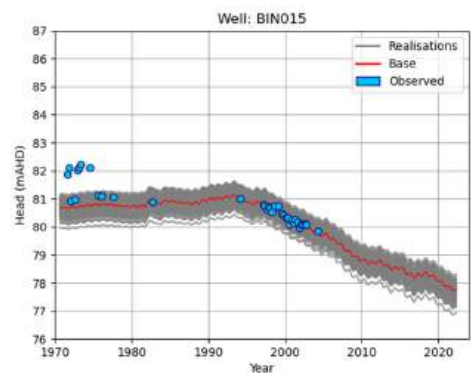
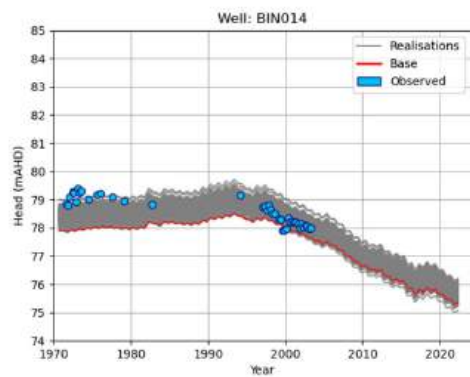
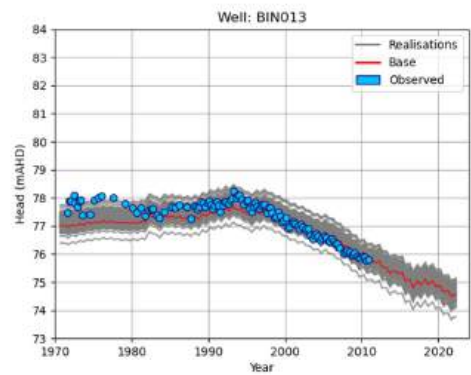
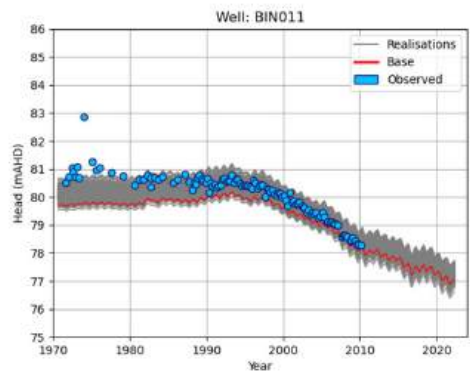




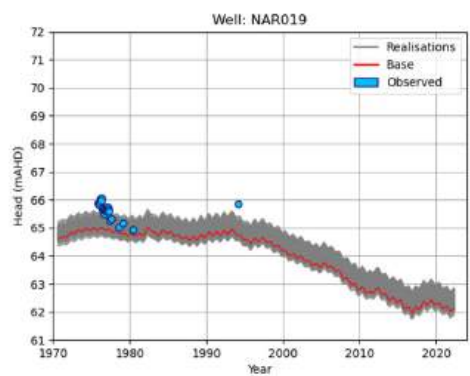
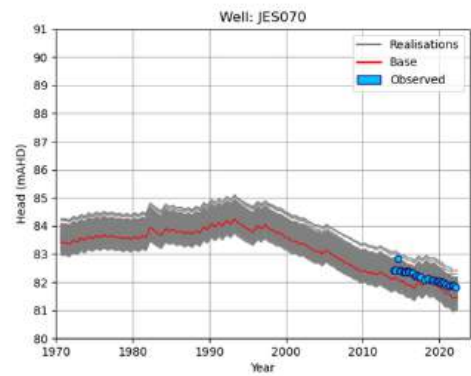
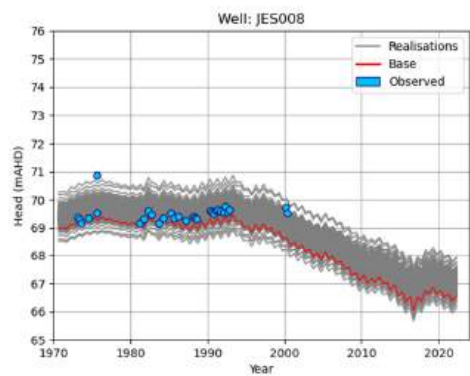
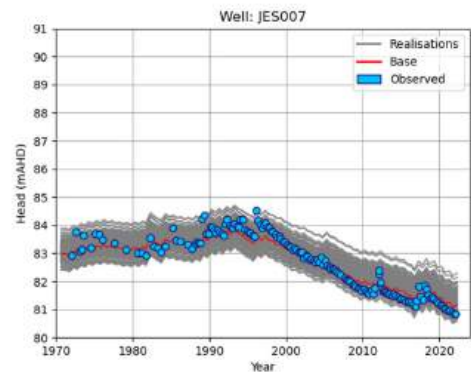
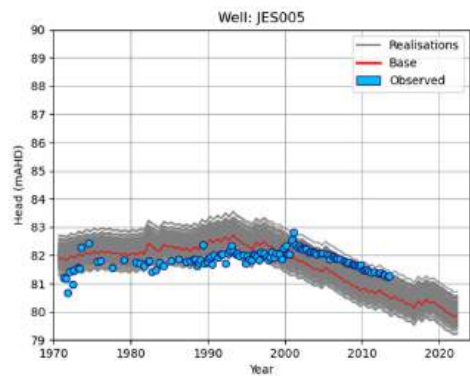
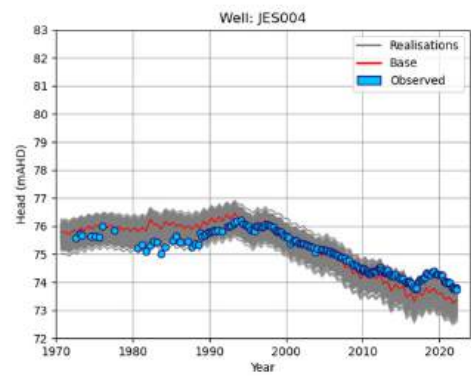
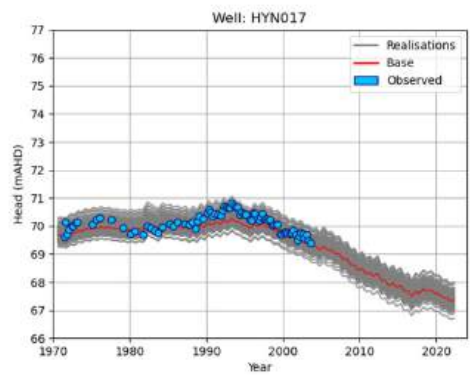


B. Hydrograph Uncertainty Analysis

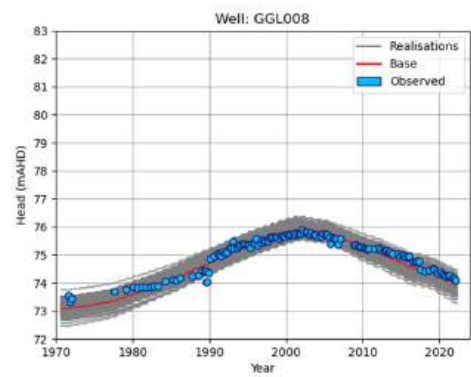
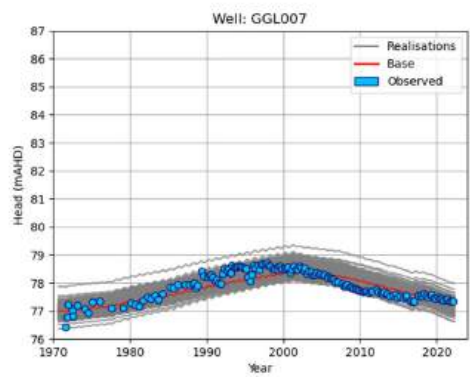
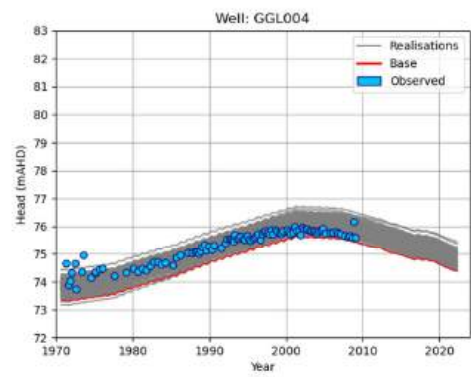
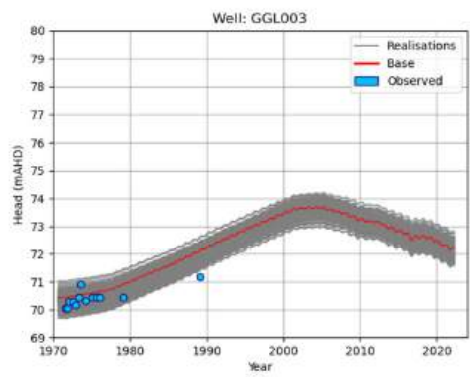
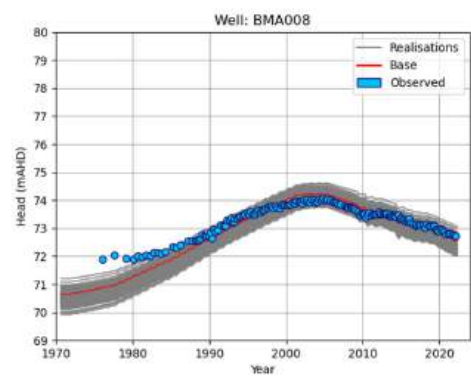
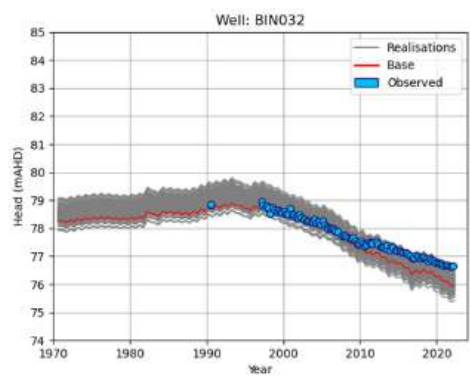
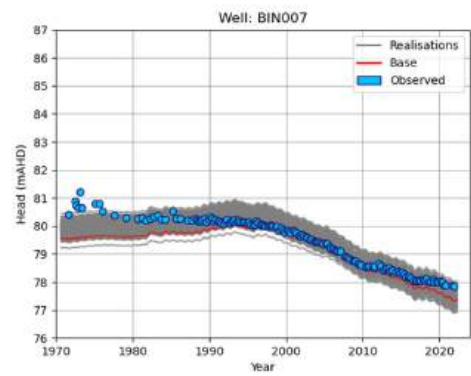
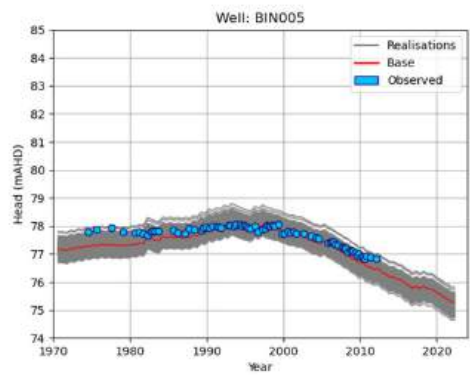
ZONE 5a



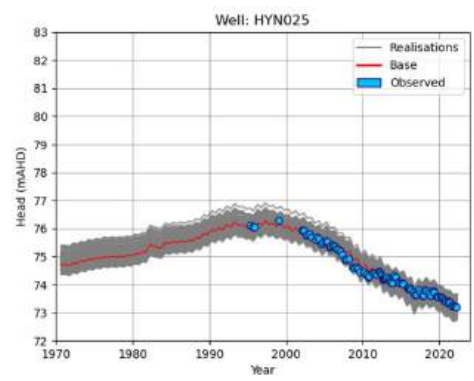
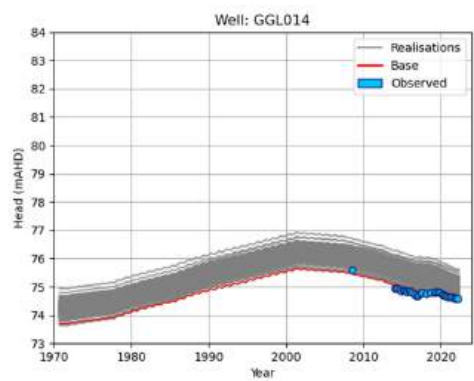
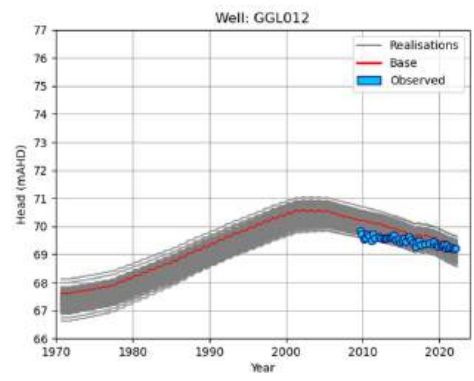
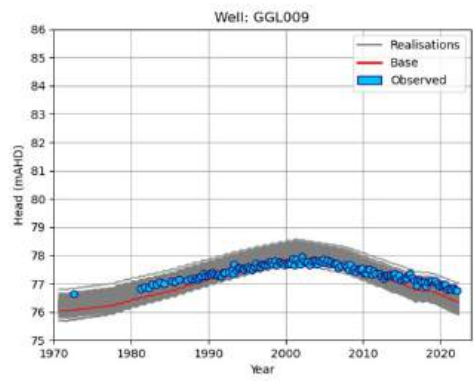
ZONE 5a



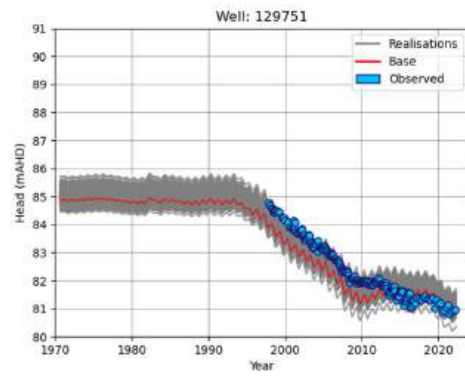
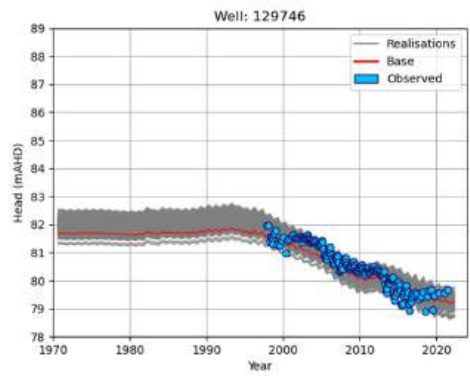
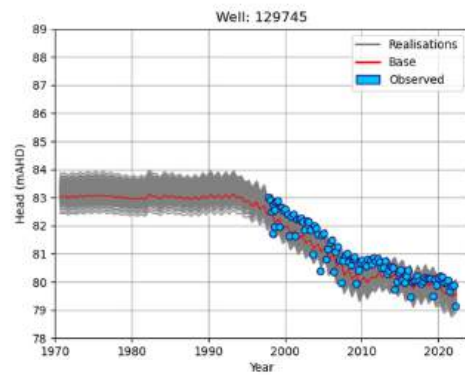
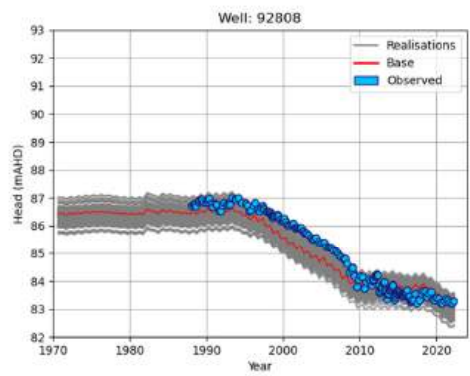
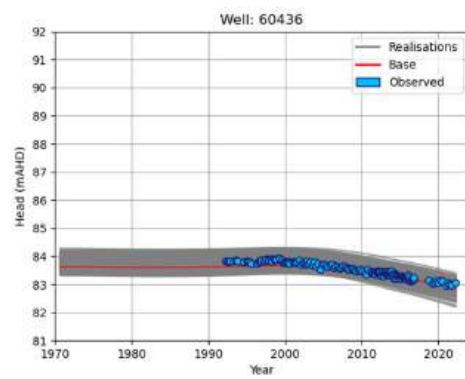
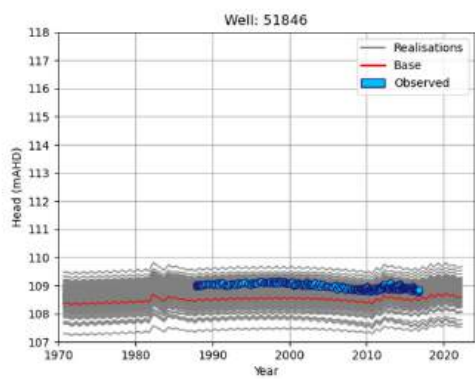
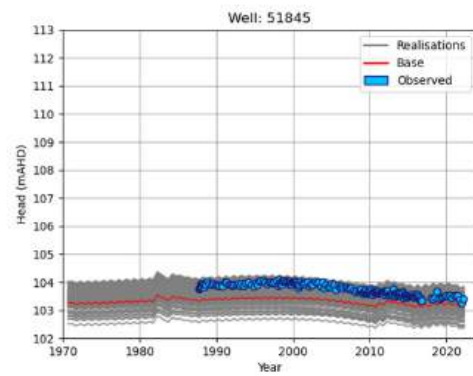
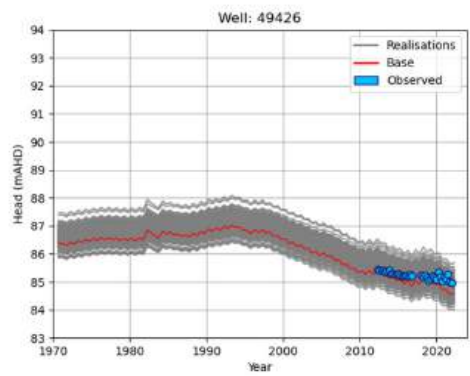
ZONE 6a



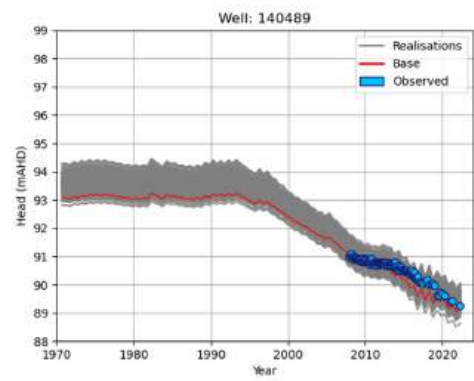
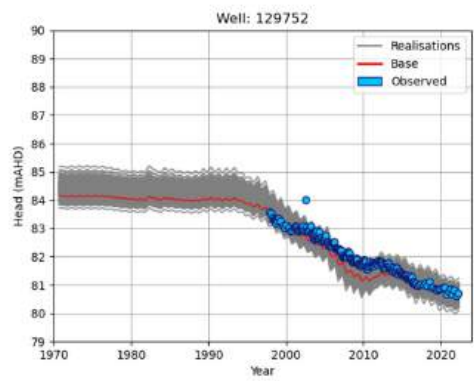
ZONE 6a



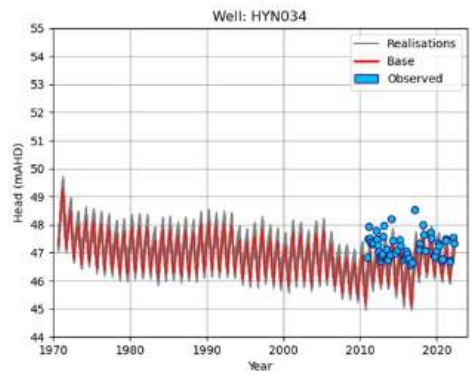
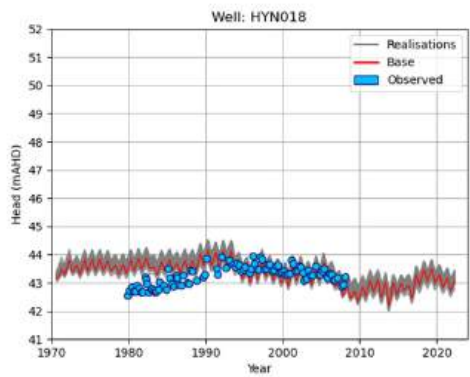
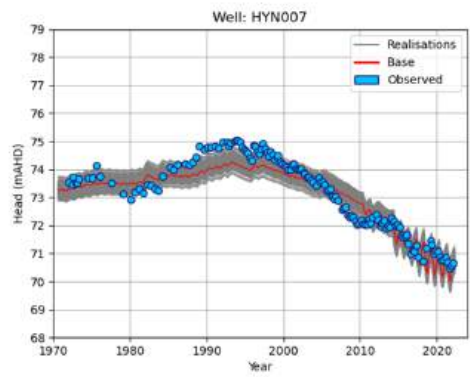
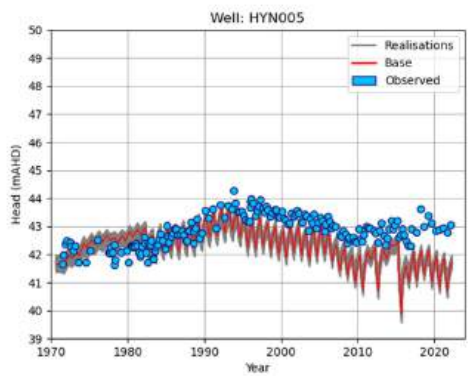
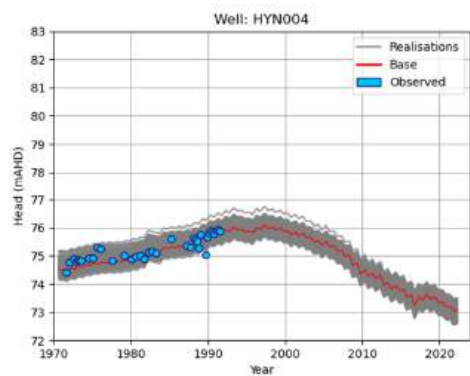
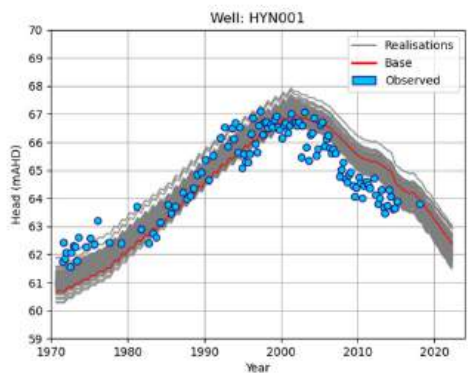
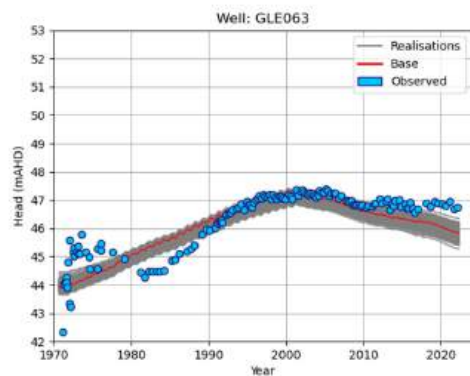
ZONE 5b & 6b



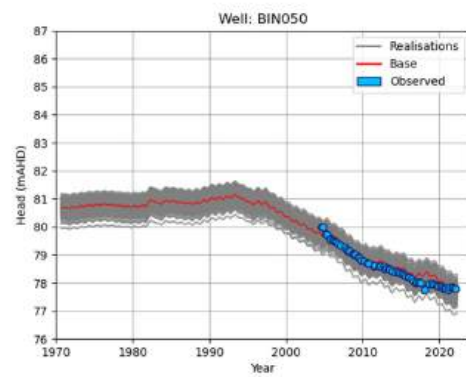
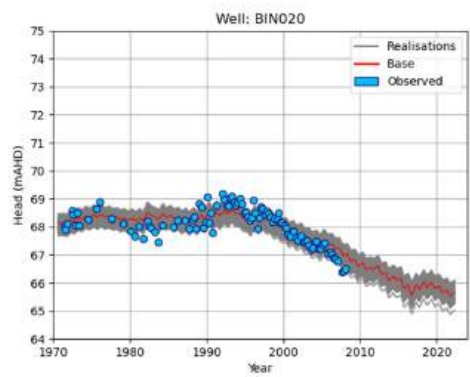
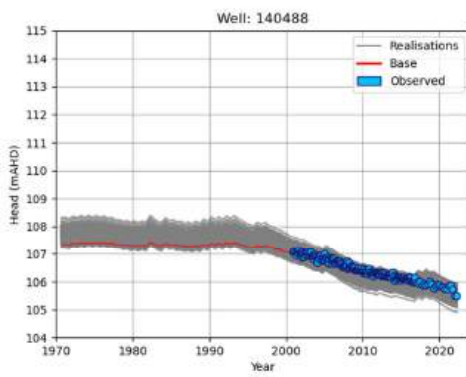
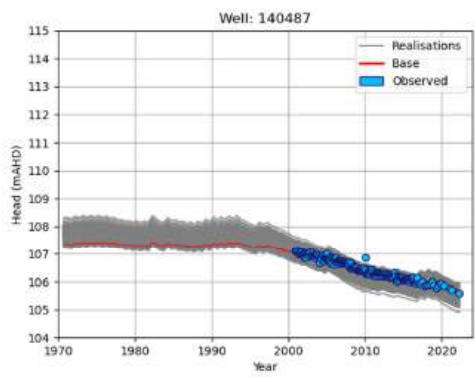
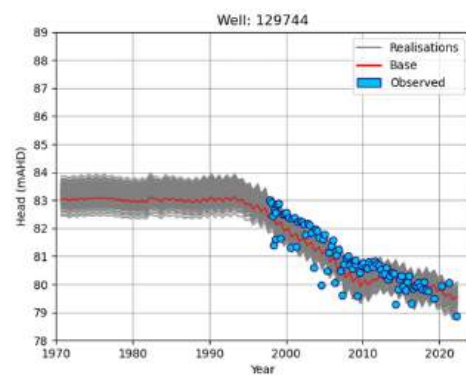
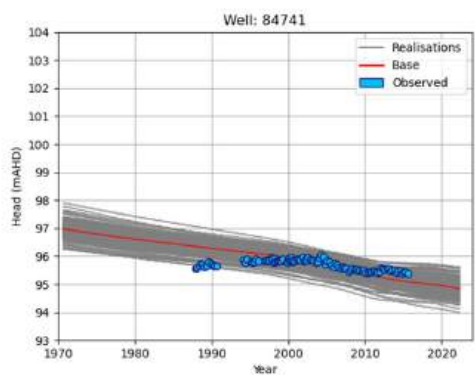
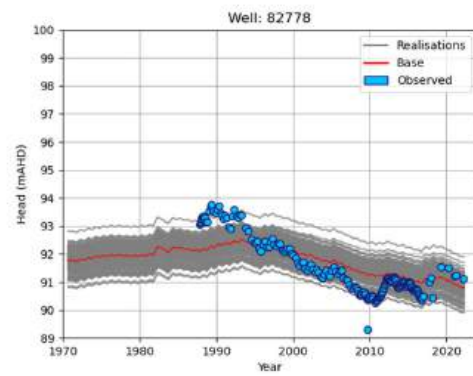
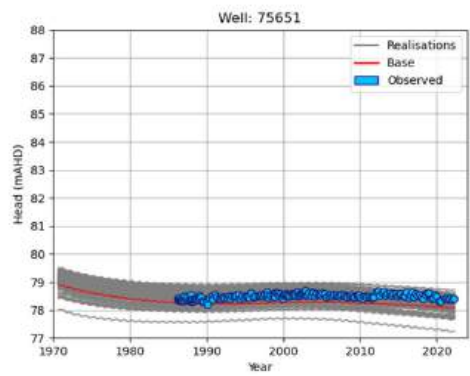
ZONE 5b & 6b

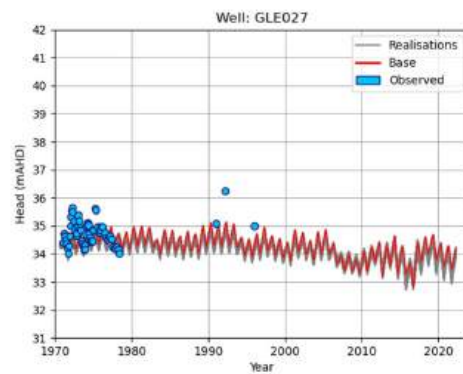
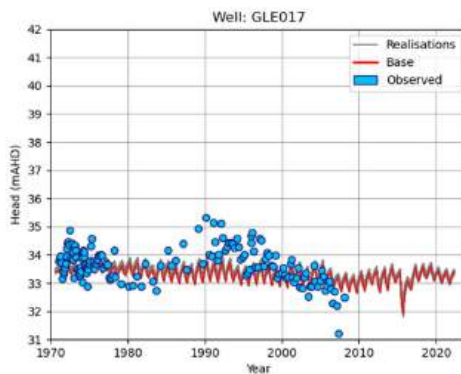
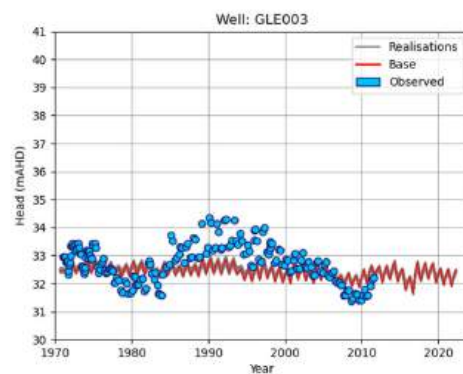
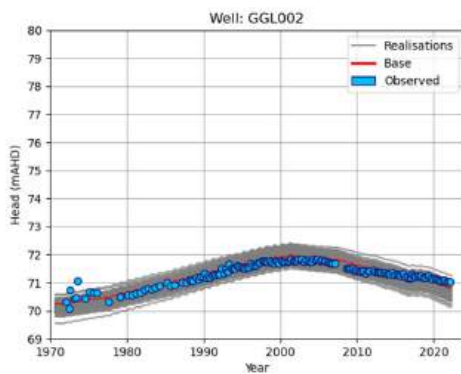
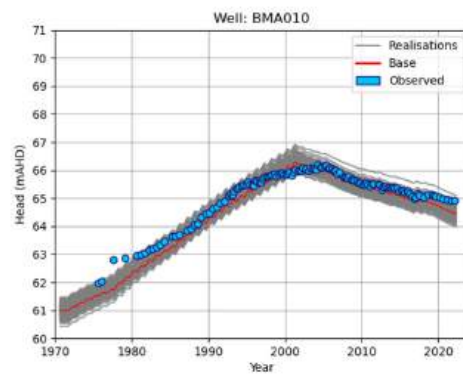
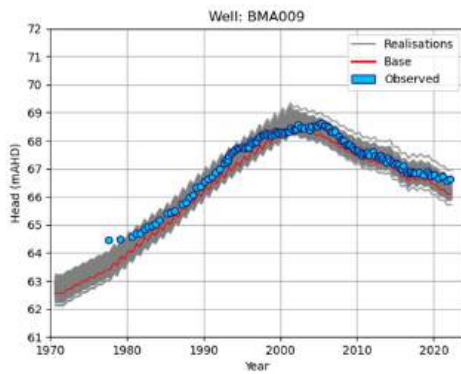
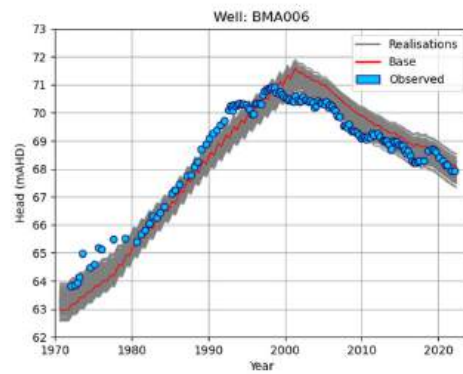
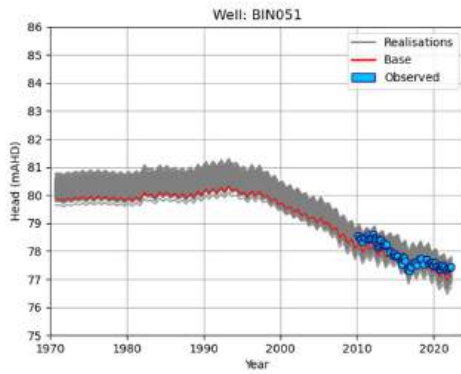


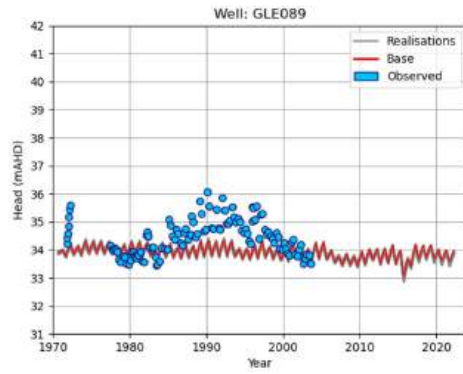
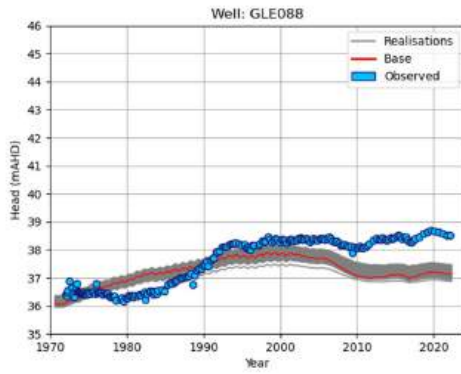
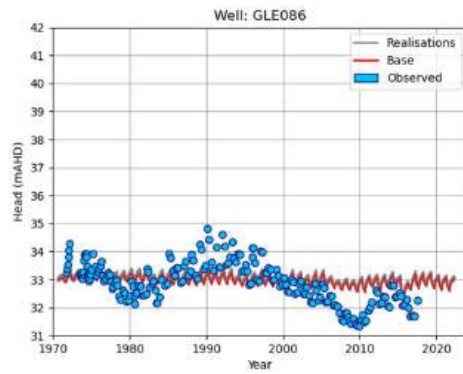
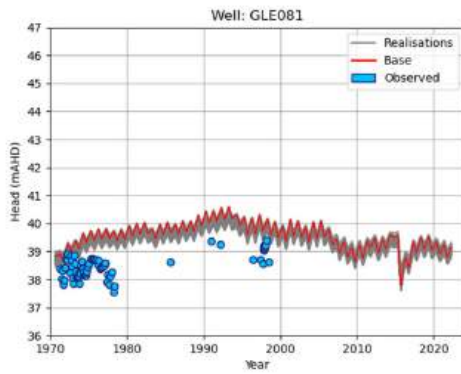
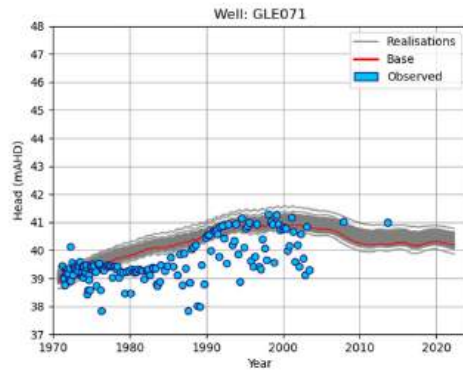
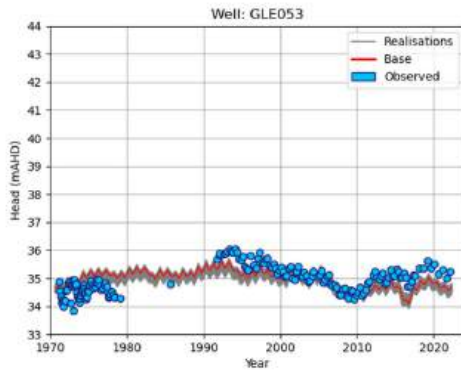
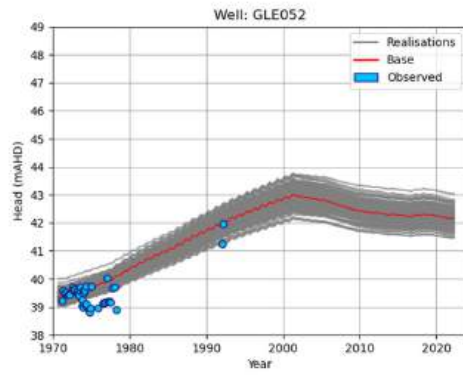
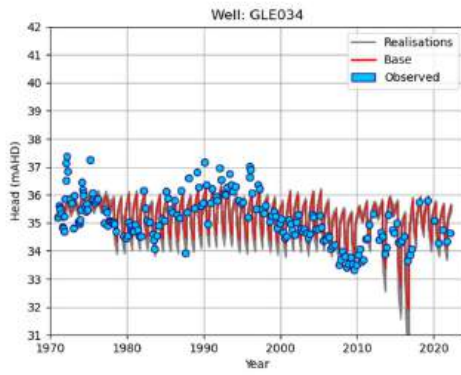
Hynam East

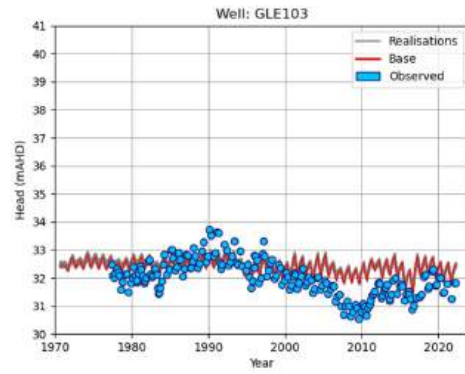
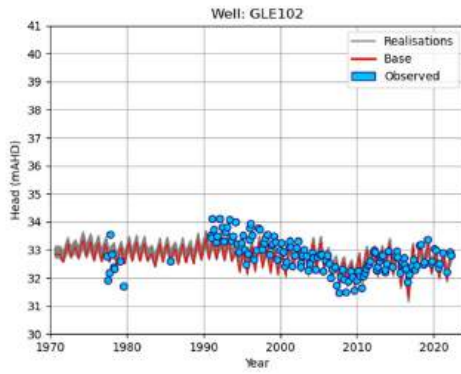
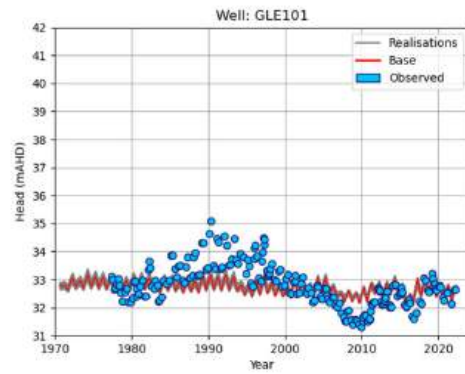
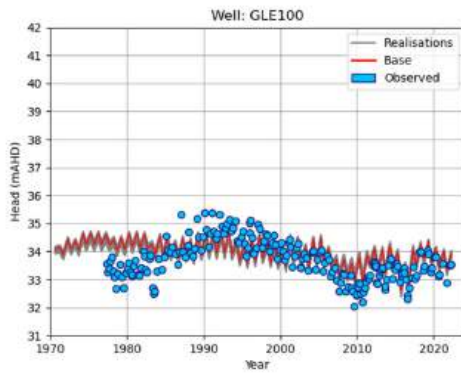
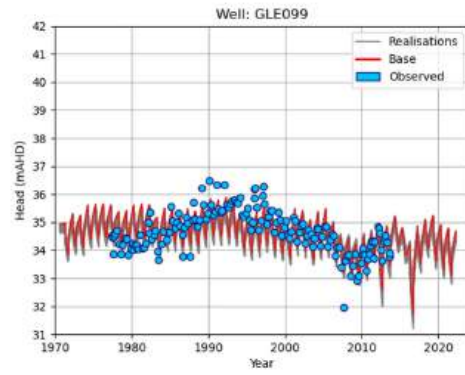
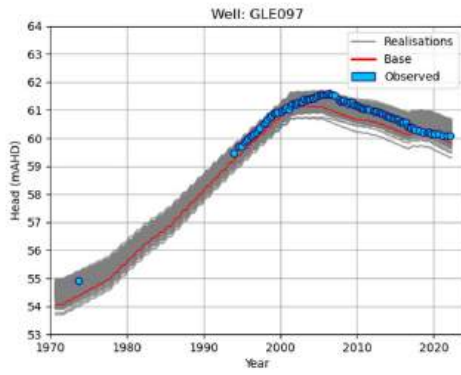
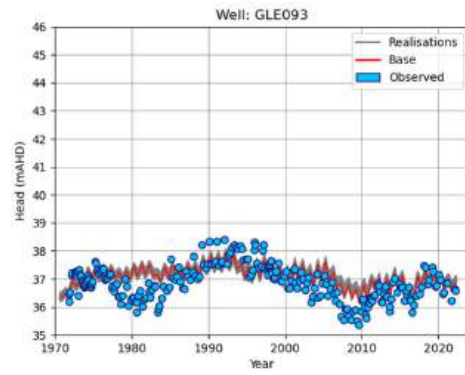
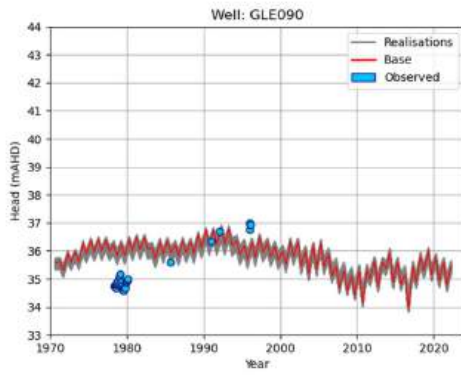


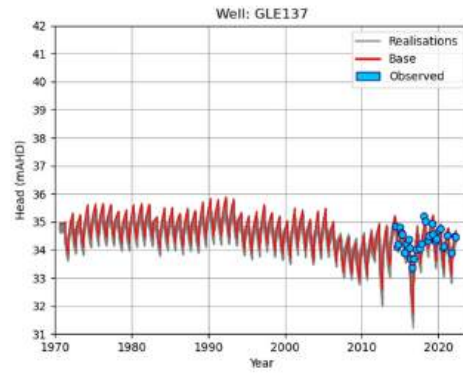
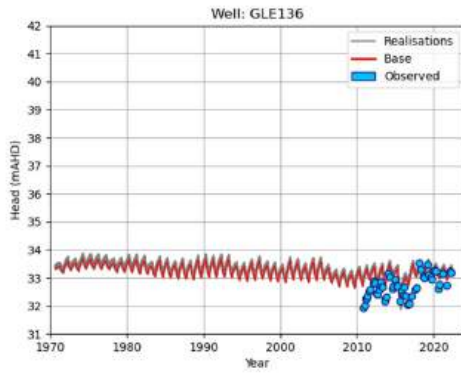
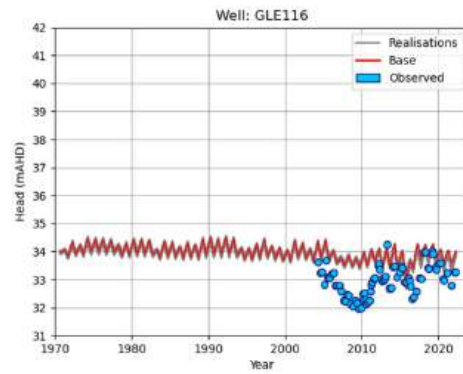
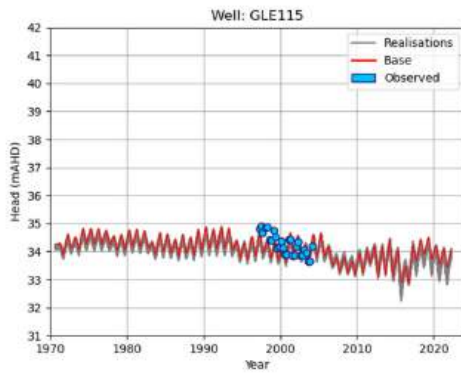
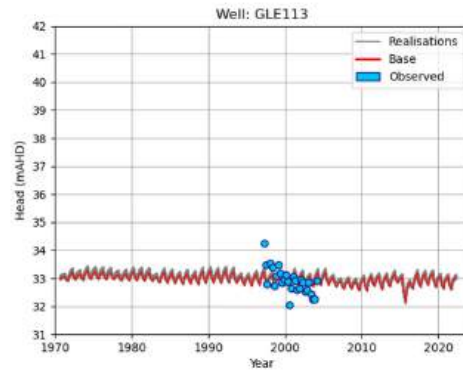
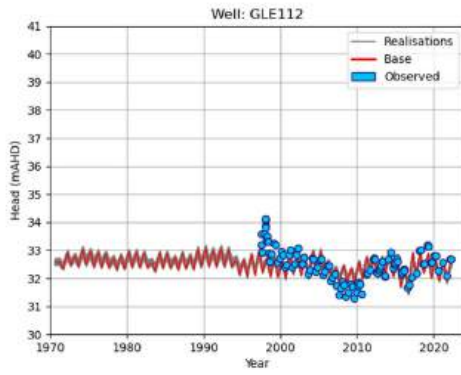
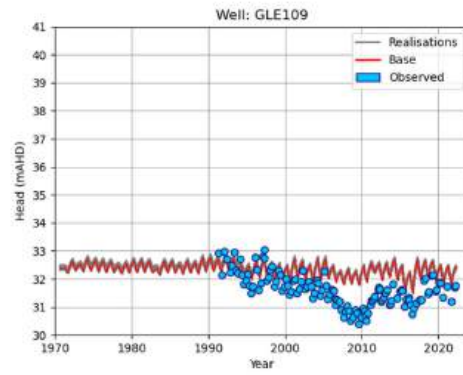
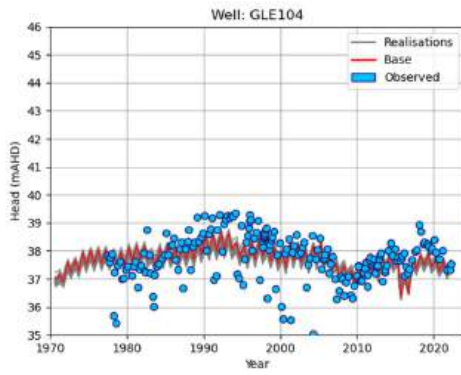
Miscellaneous

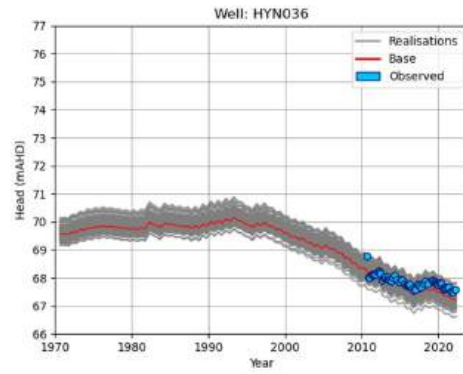
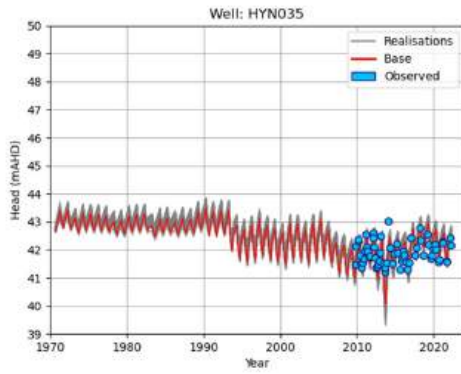
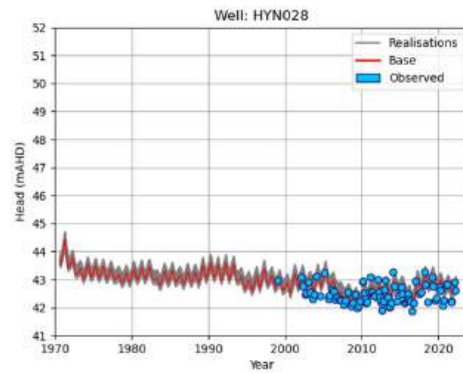
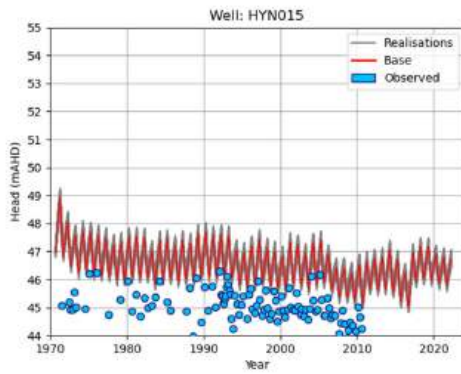
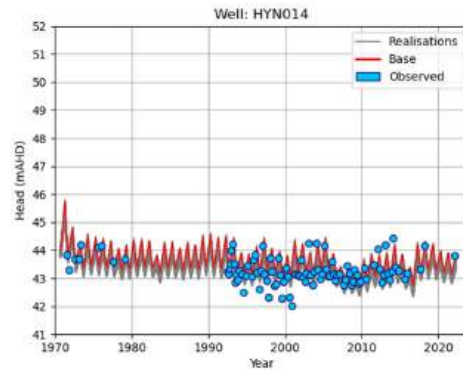
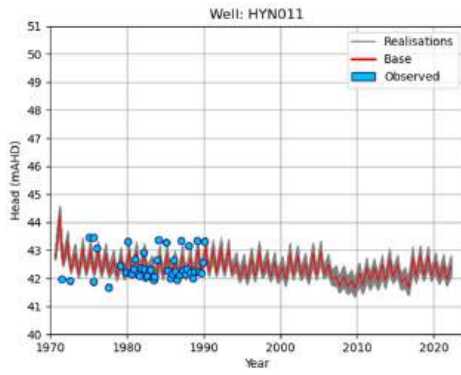
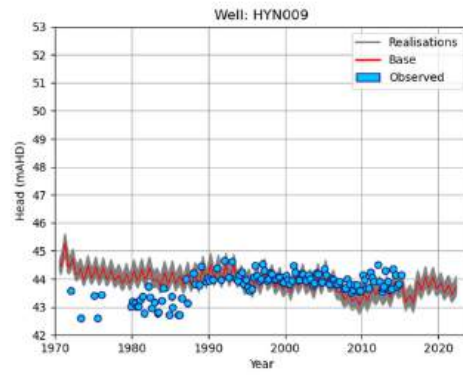
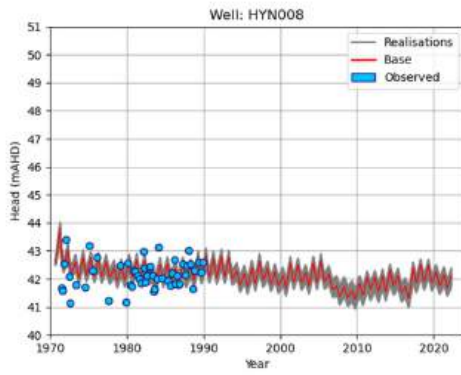


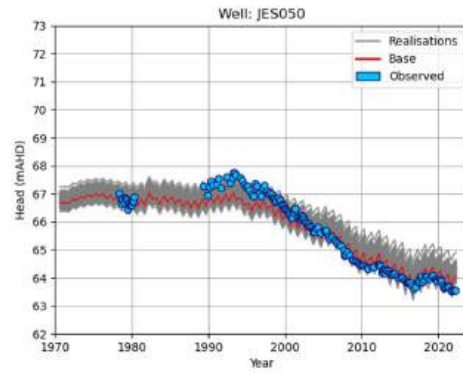
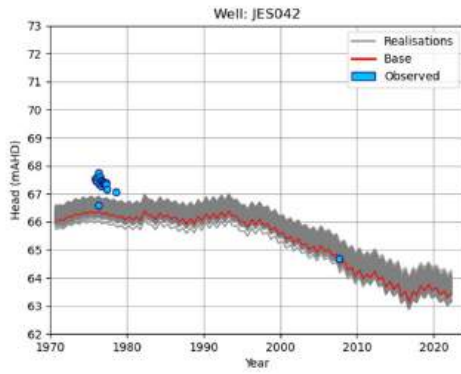
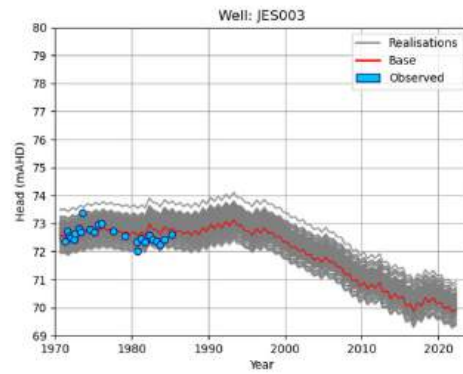
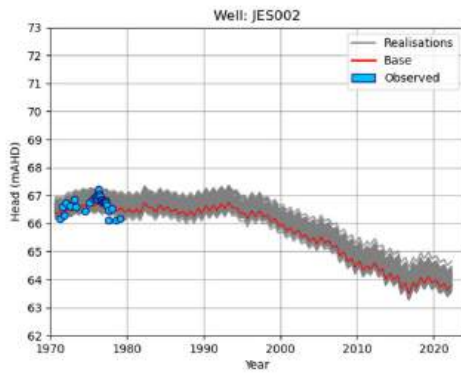
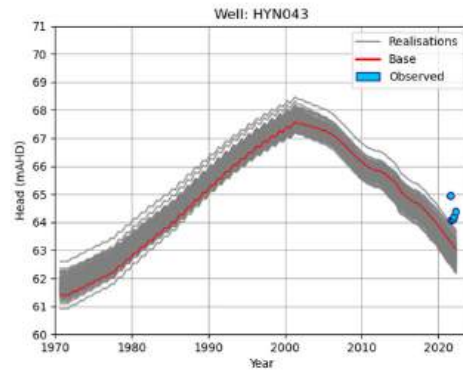
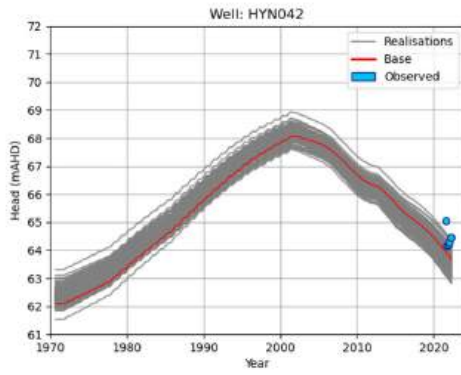
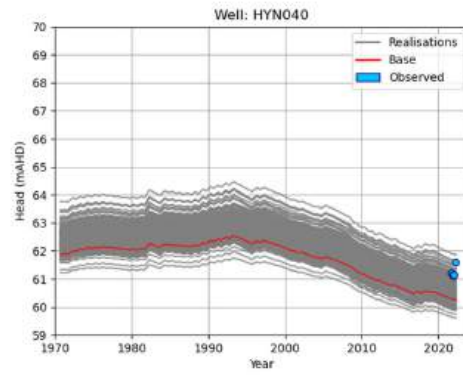
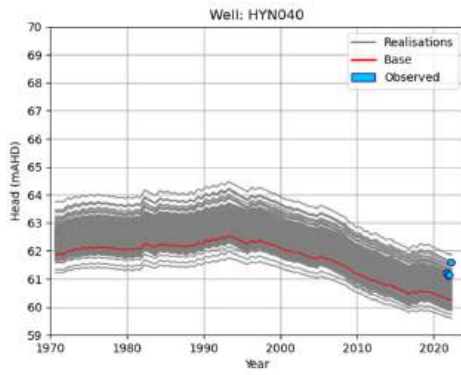


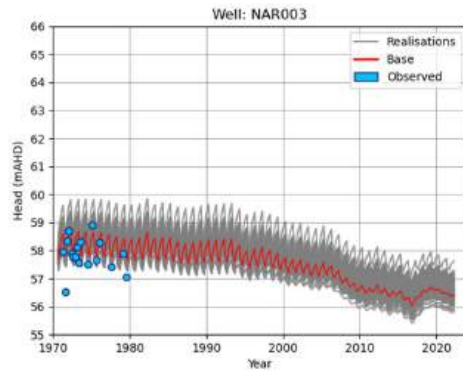
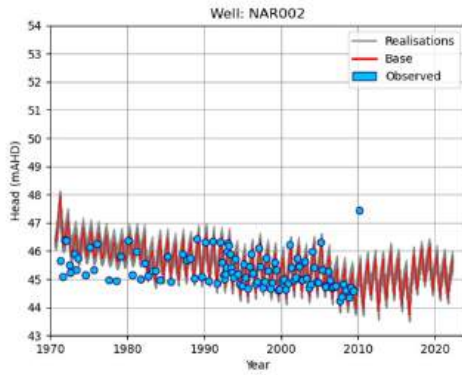
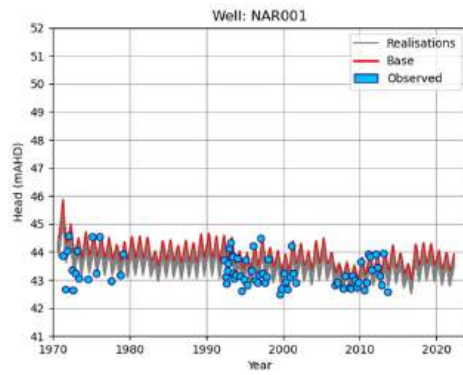
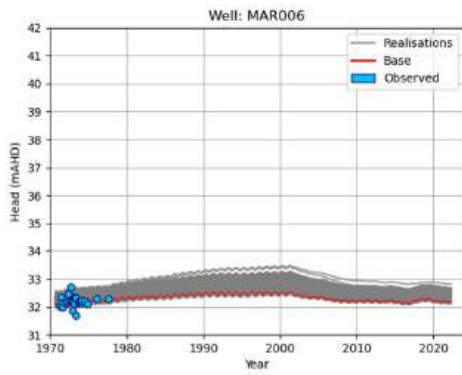
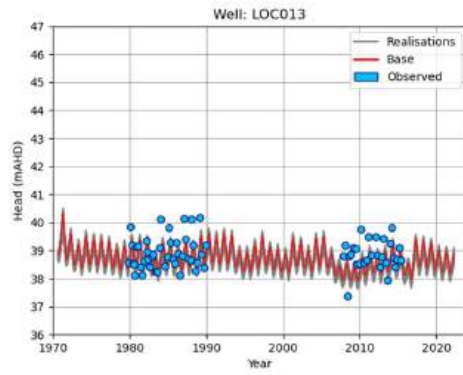
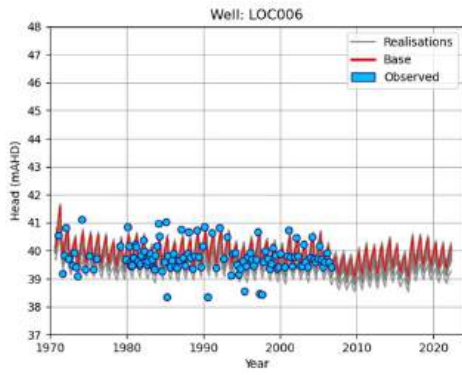
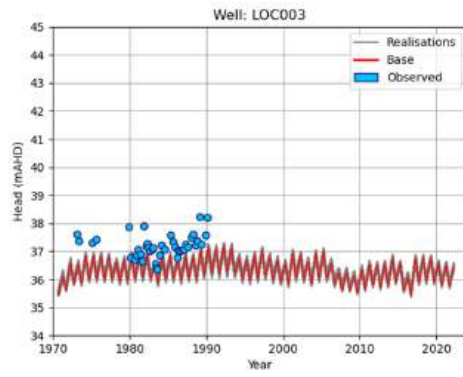
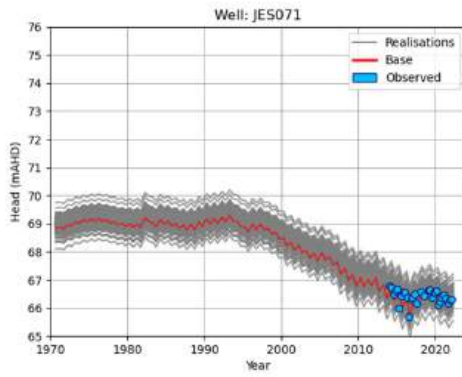


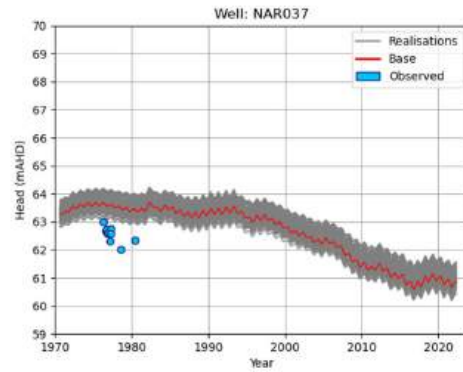
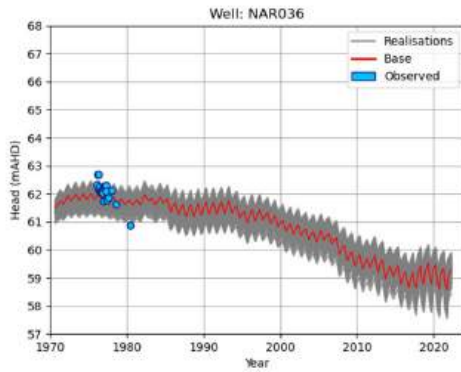
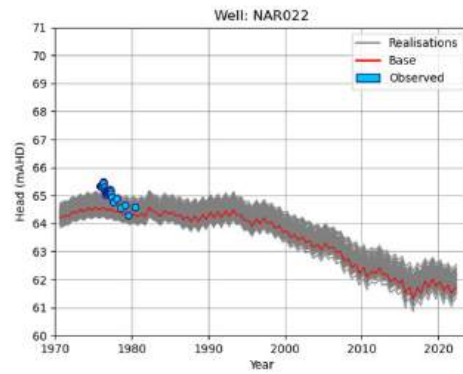
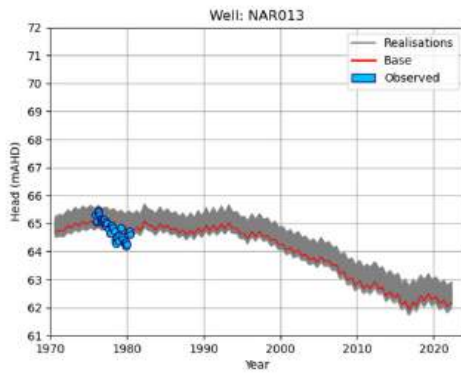
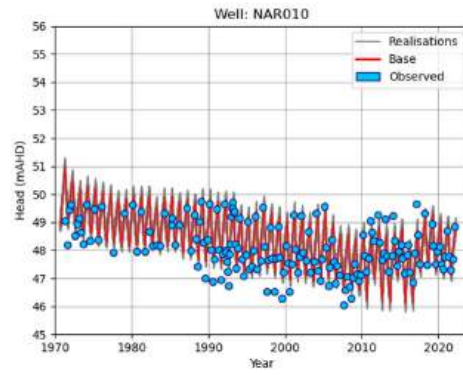
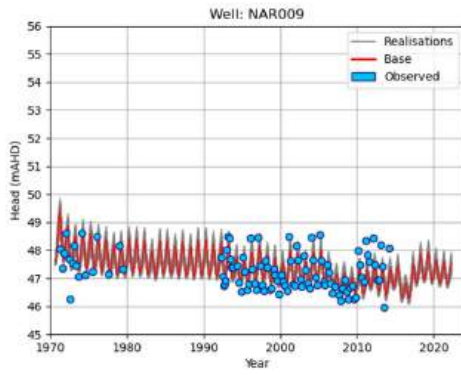
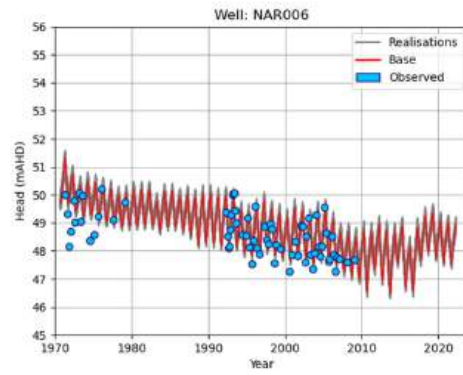
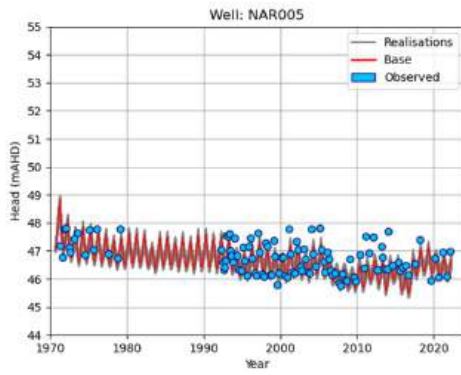


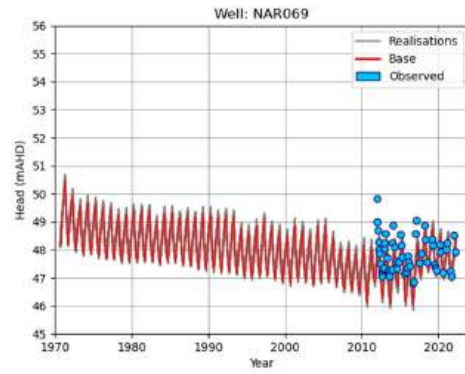
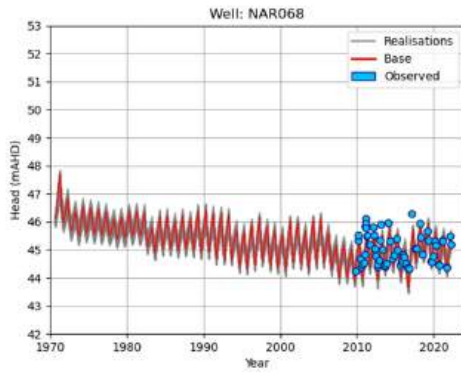
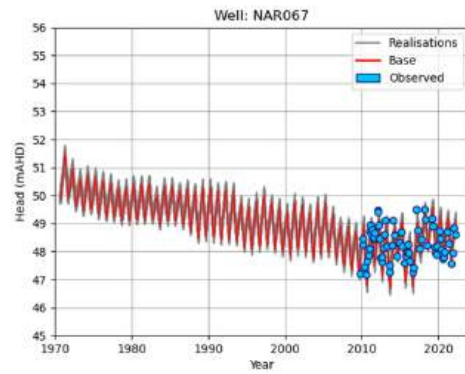
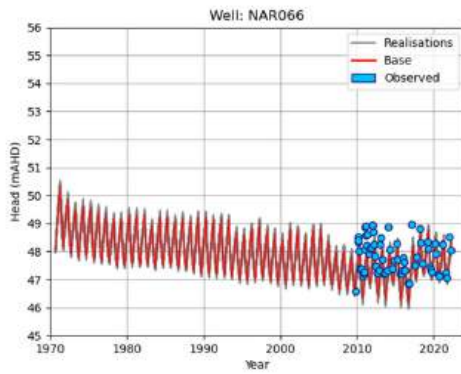
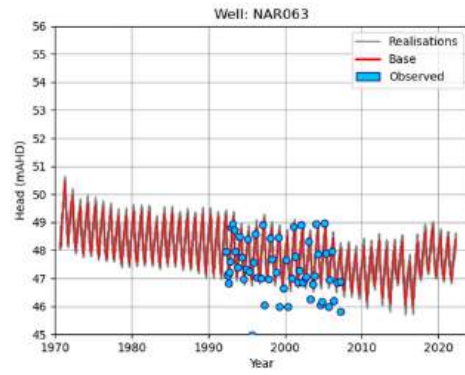
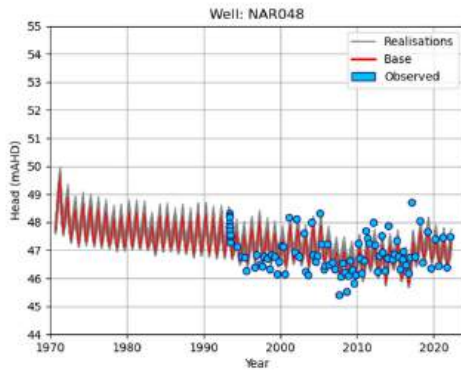
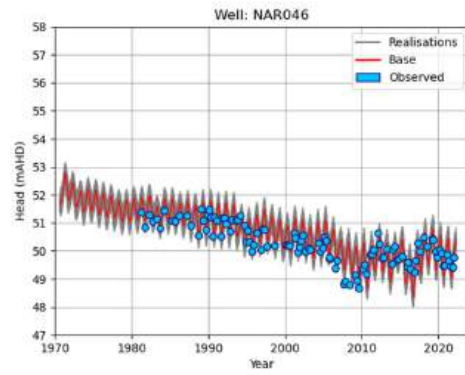
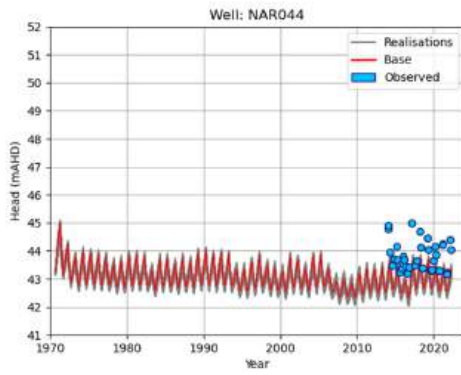


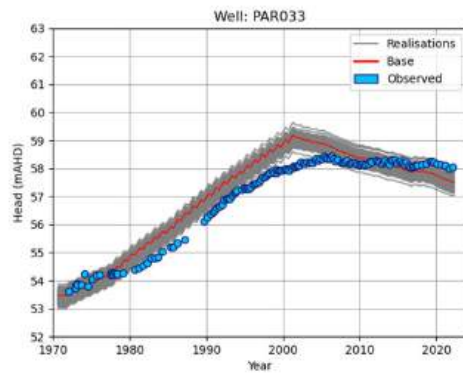
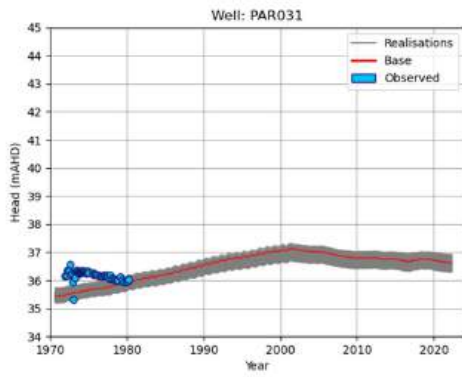
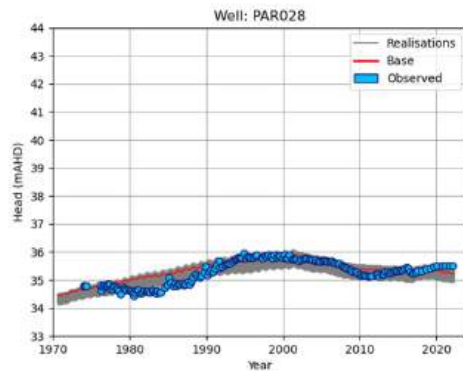
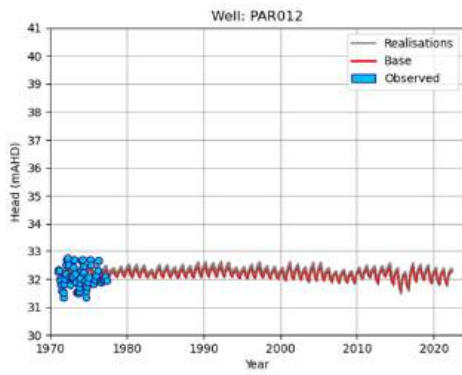
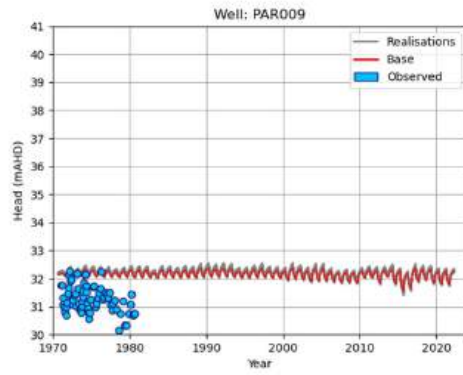
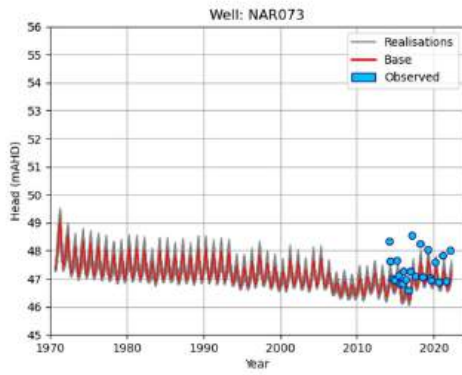
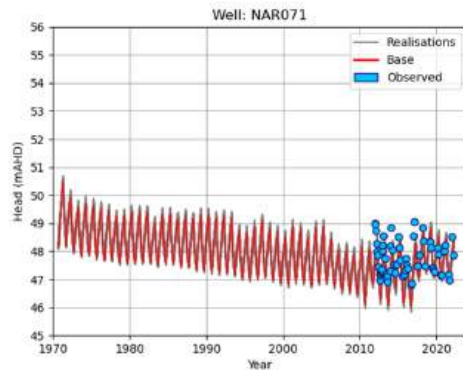
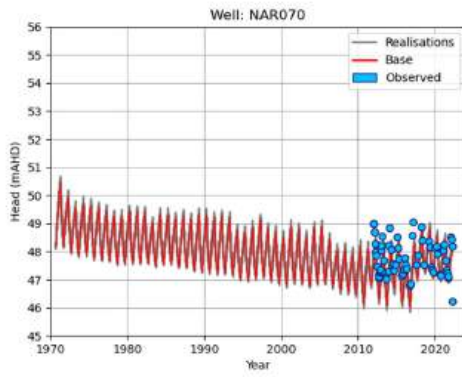


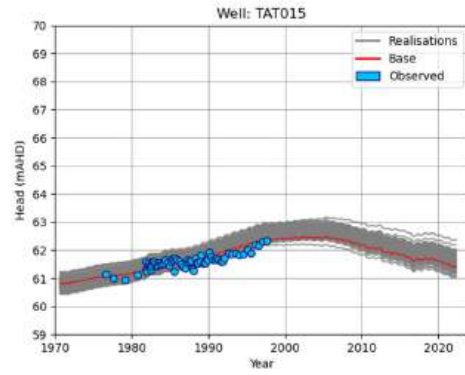
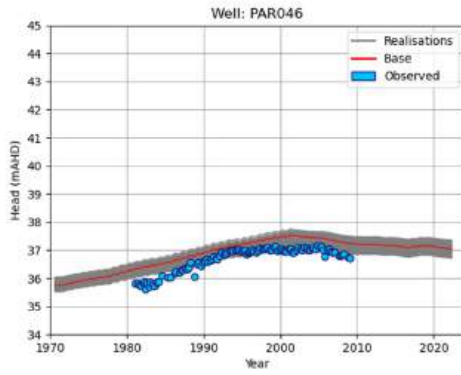
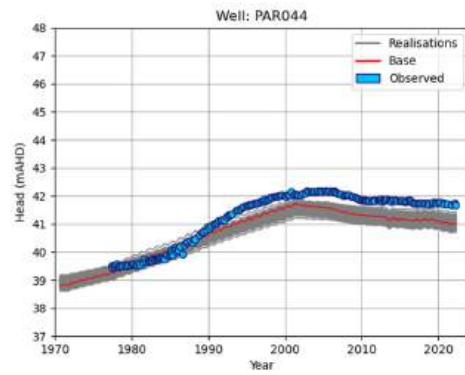
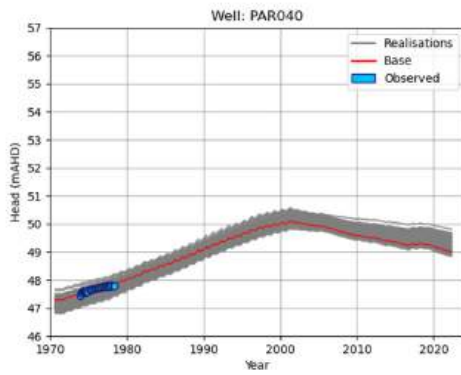
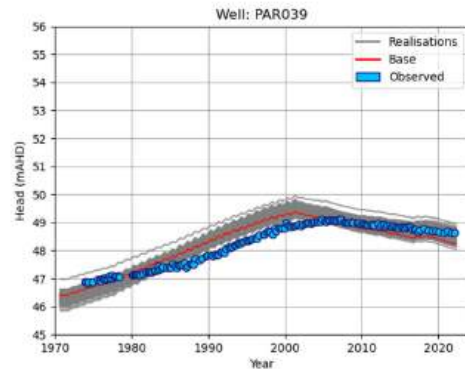
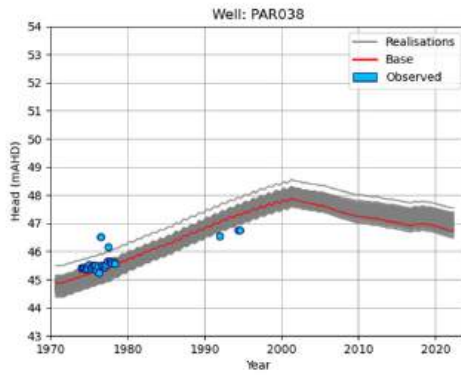
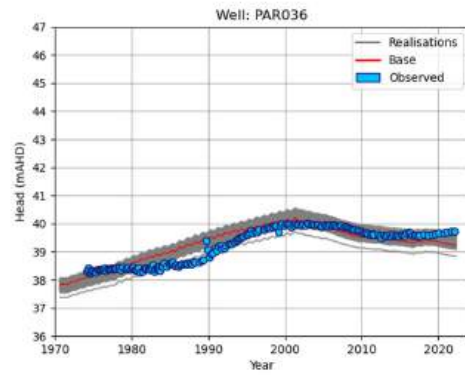
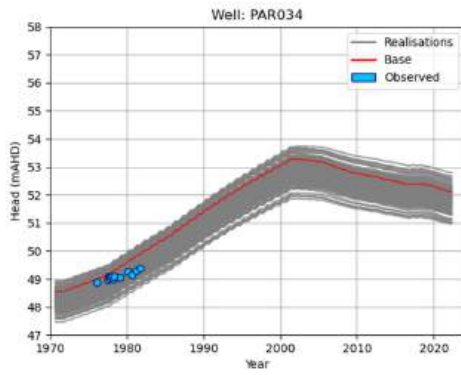


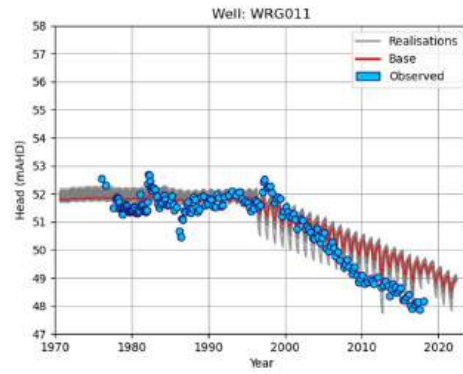
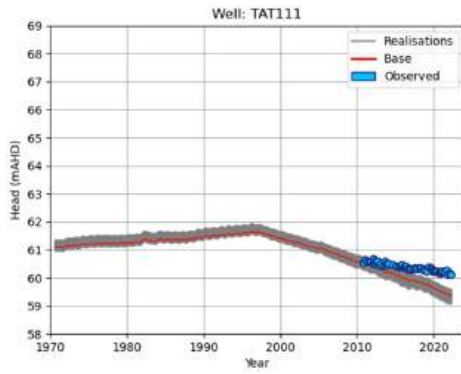
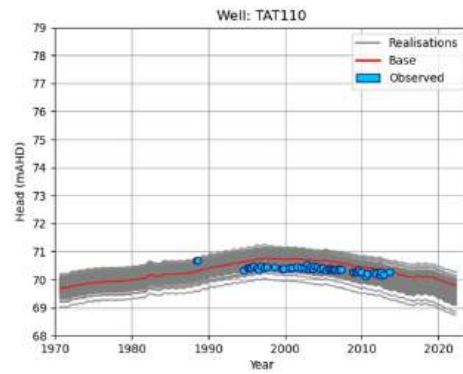
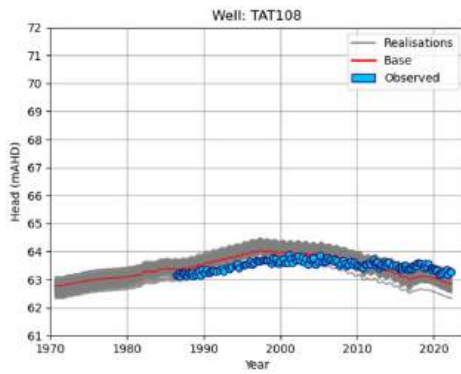
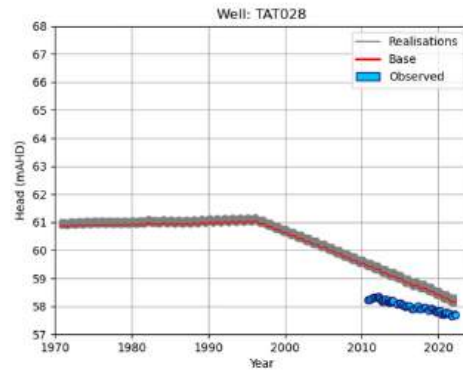
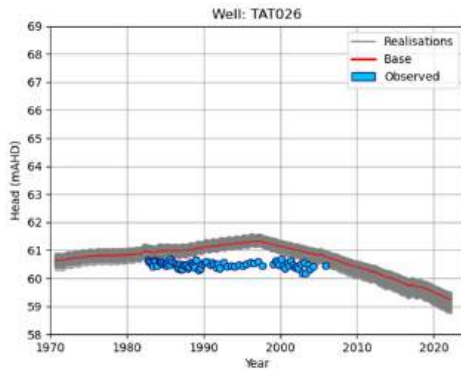
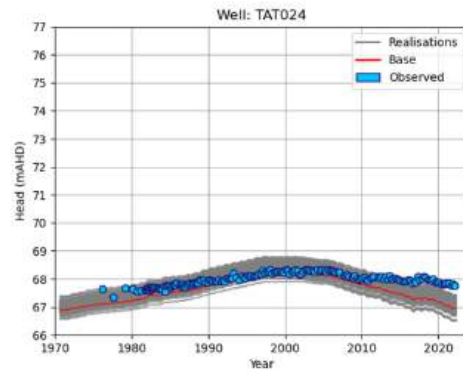
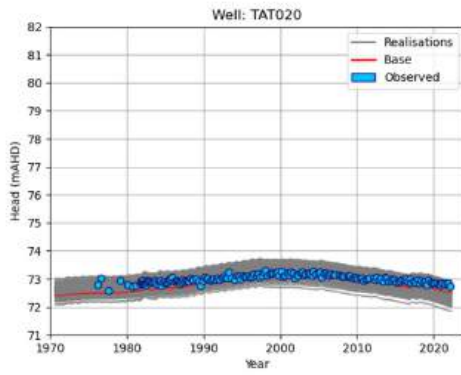


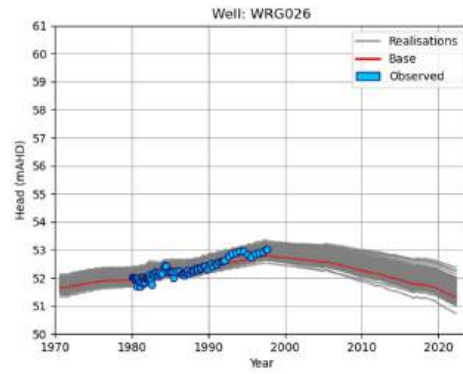
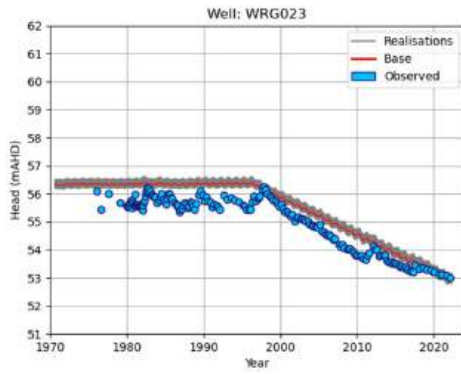
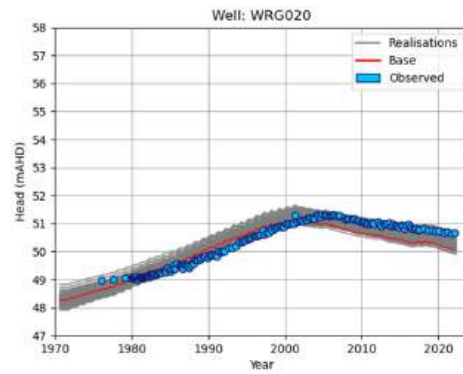
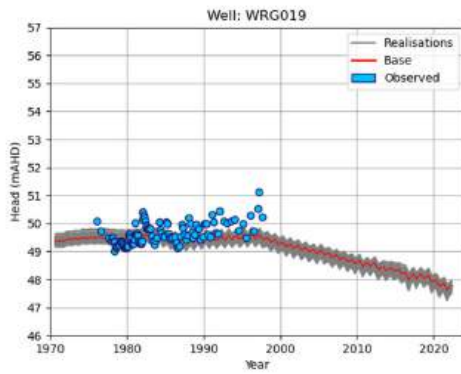
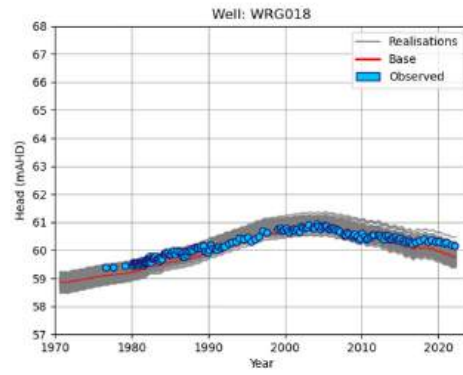
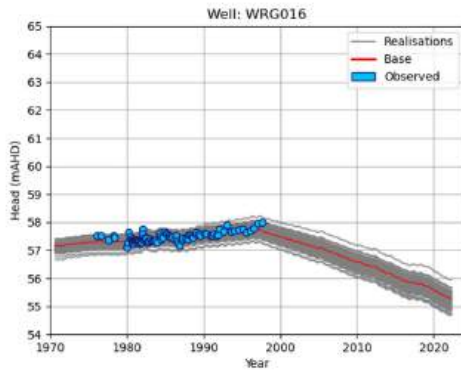
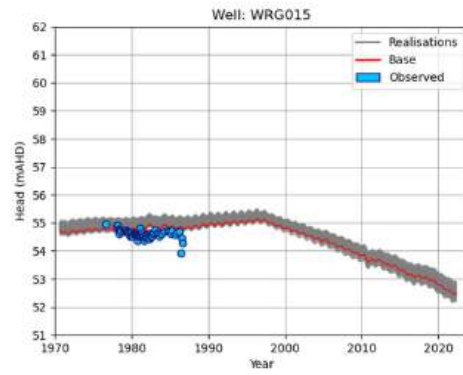
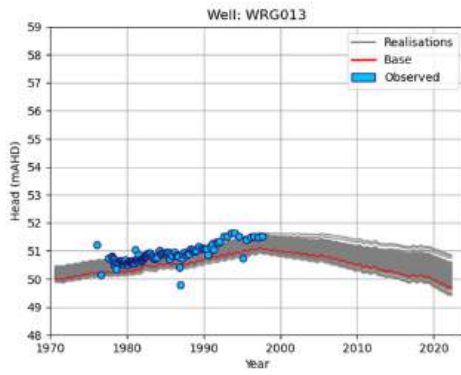


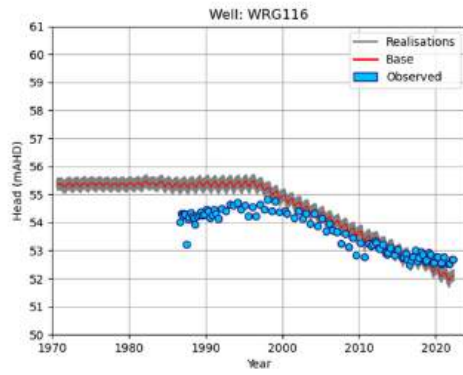
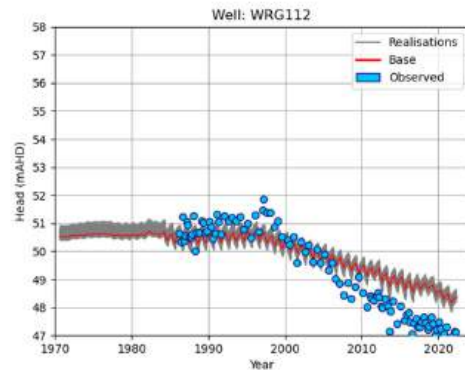
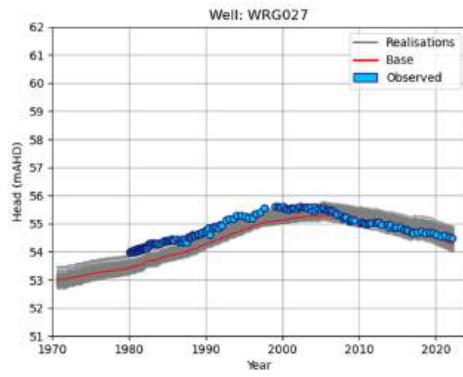






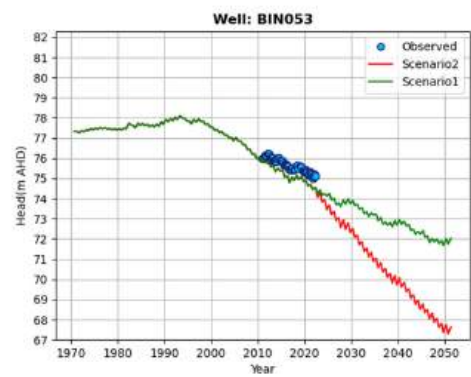
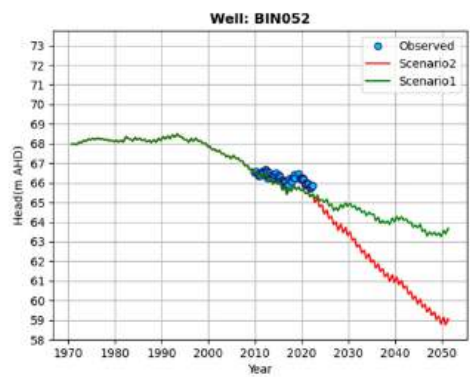
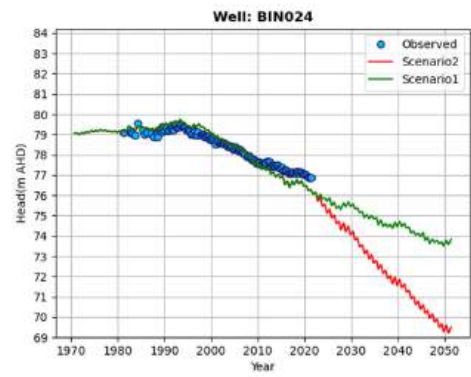
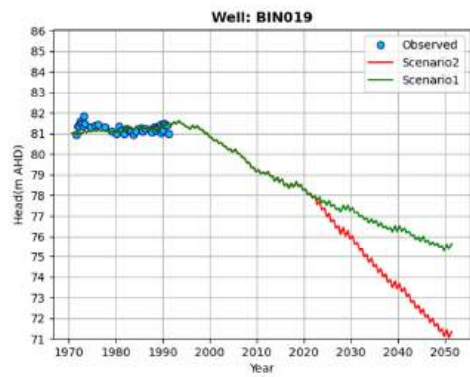
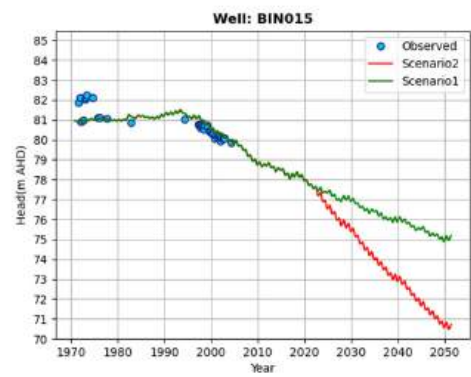
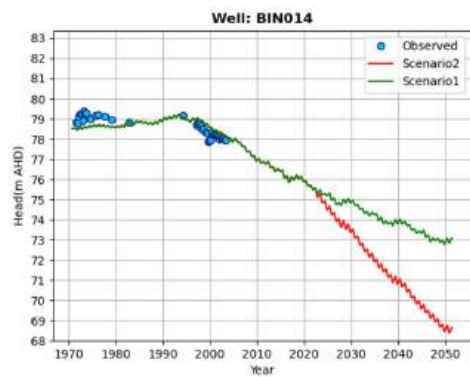
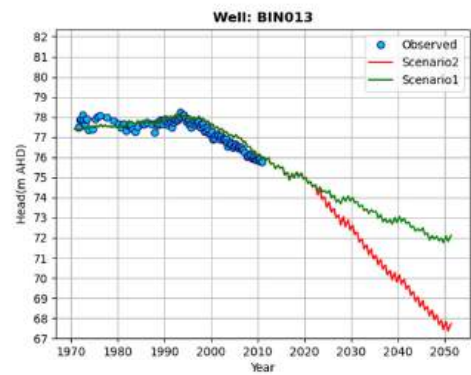
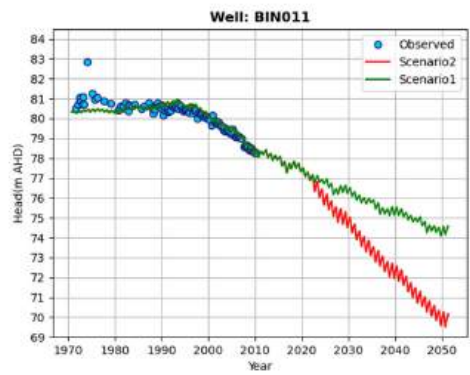




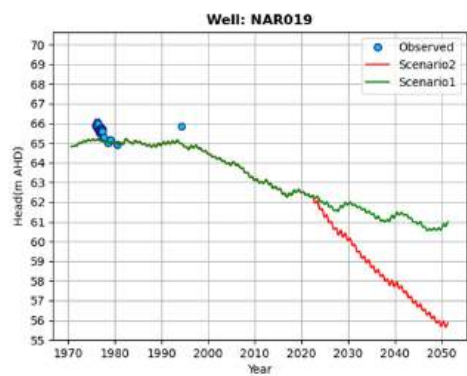
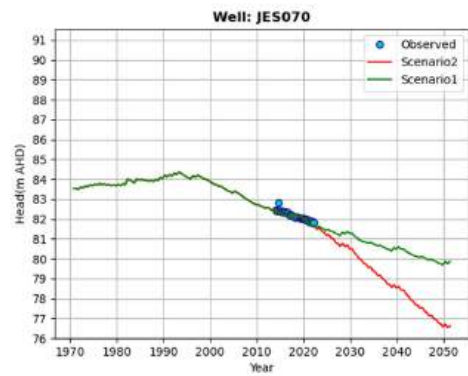
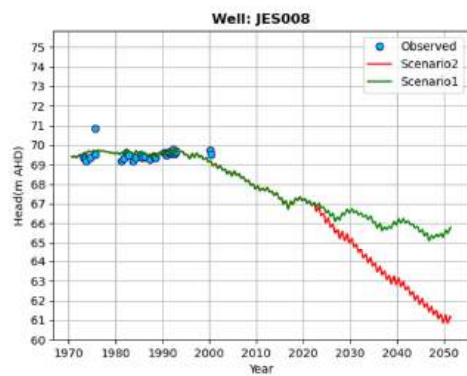
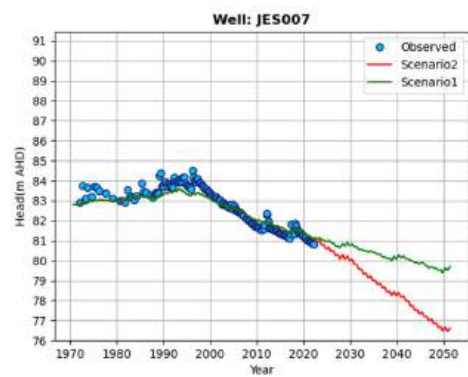
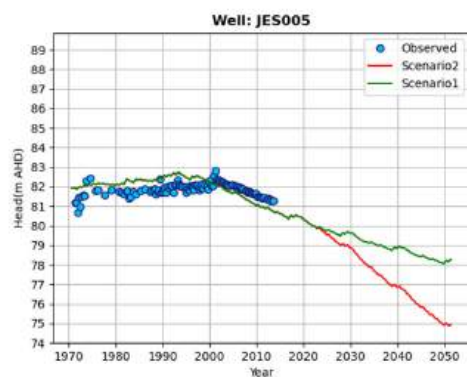
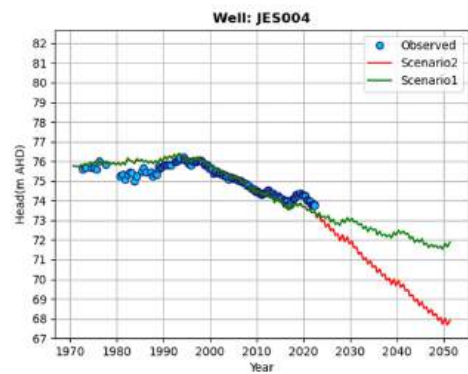
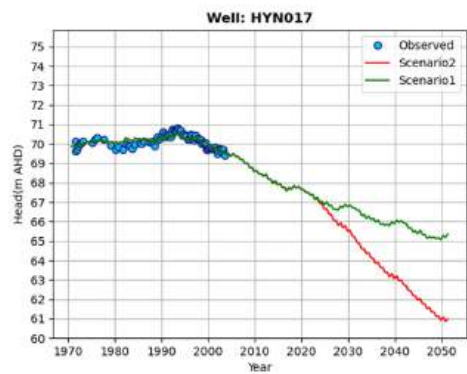


C. Scenario Hydrographs

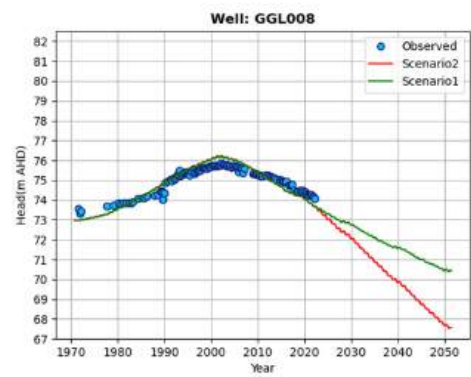
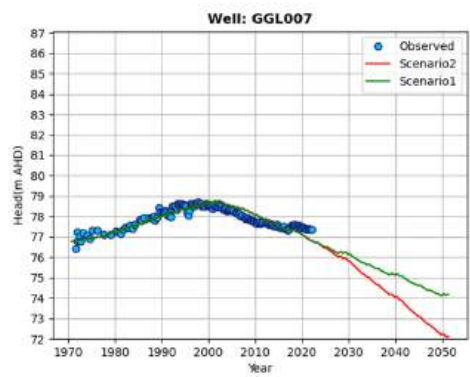
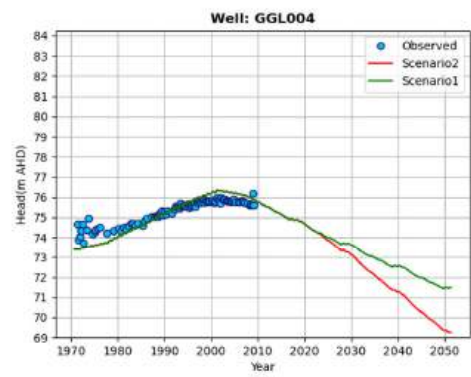
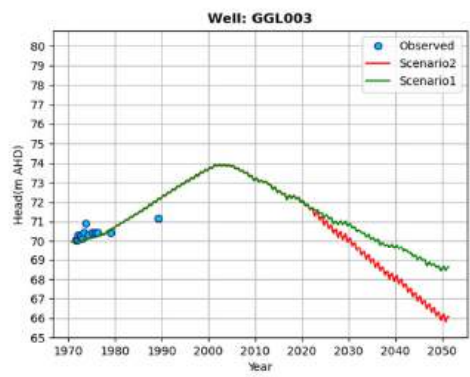
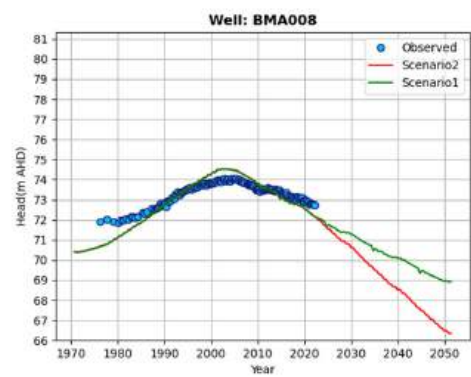
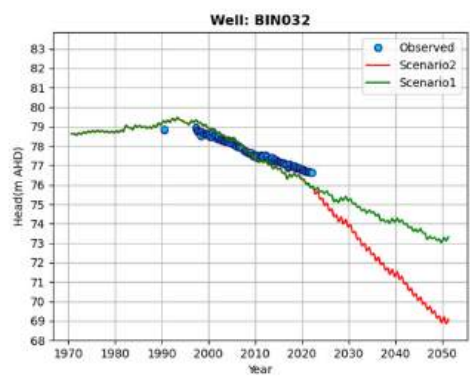
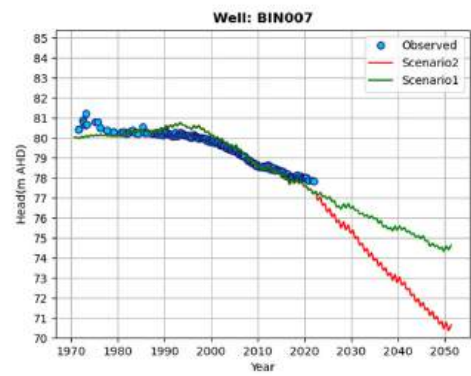
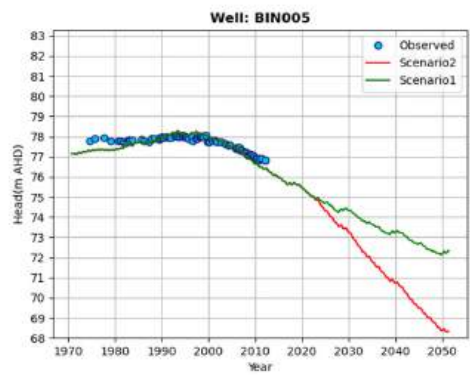
ZONE 5a



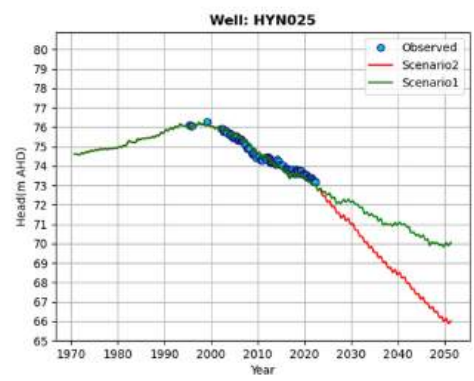
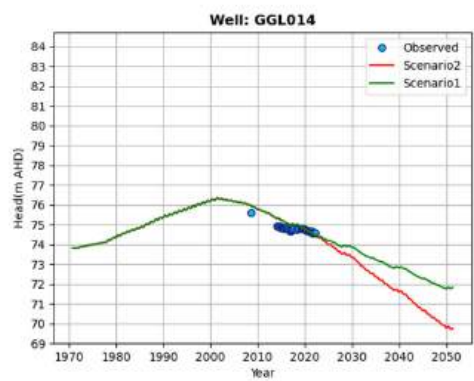
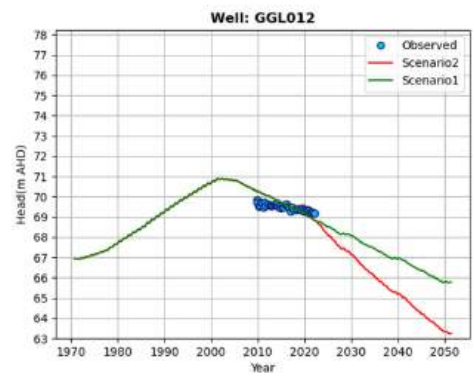
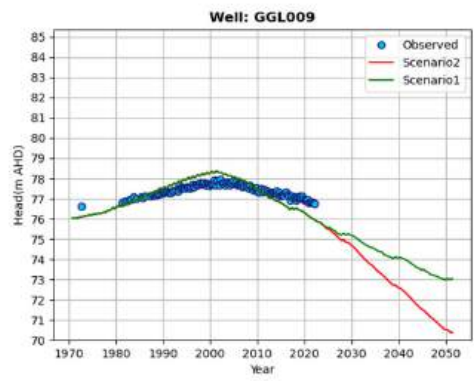
ZONE 5a



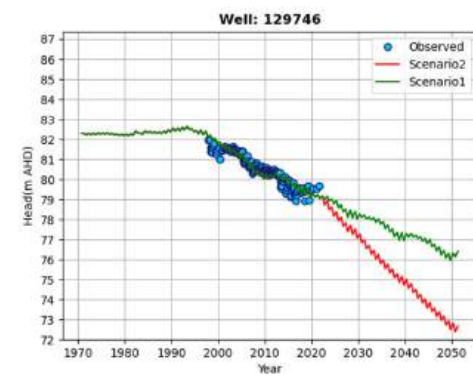
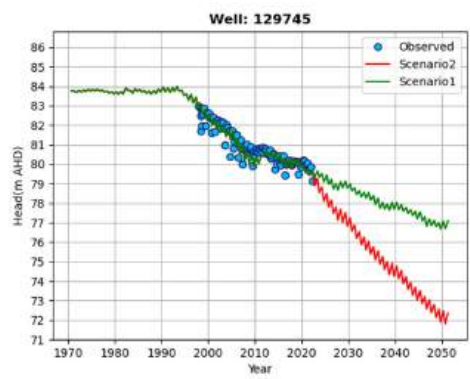
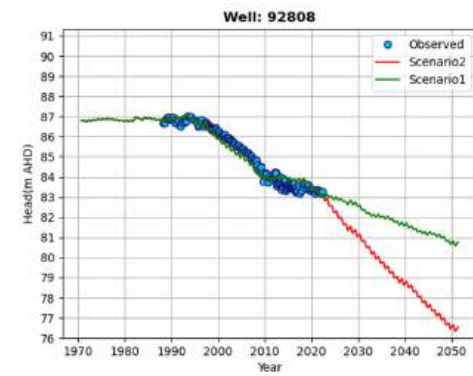
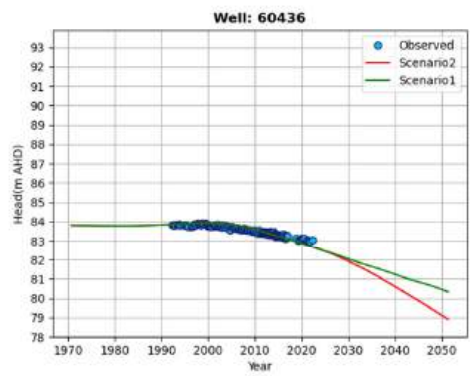
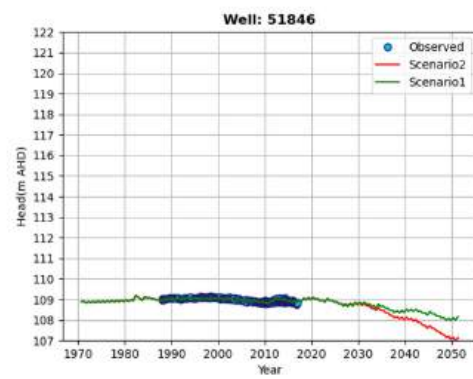
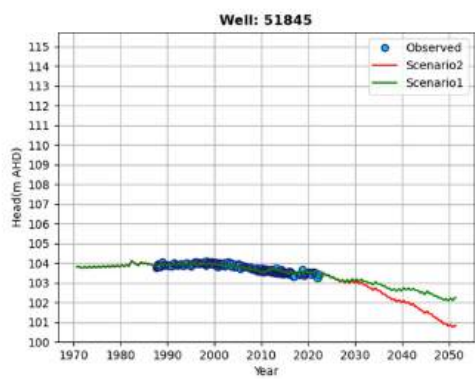
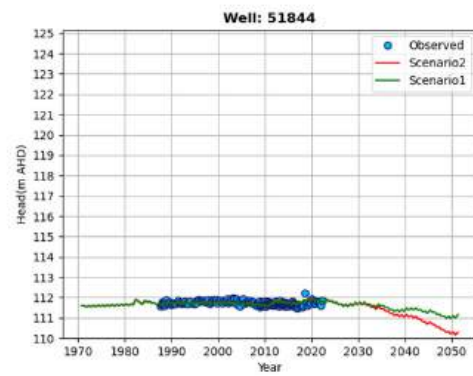
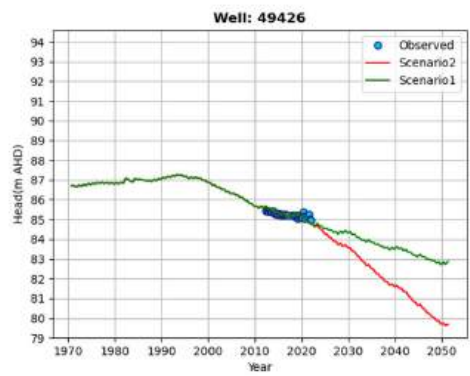
ZONE 6a



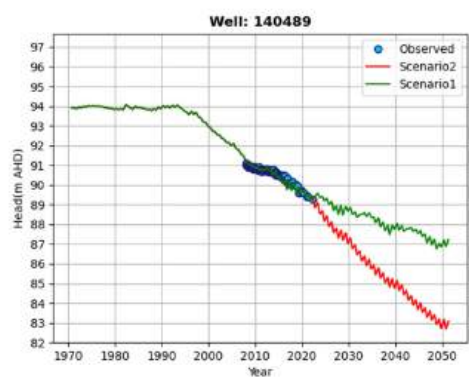
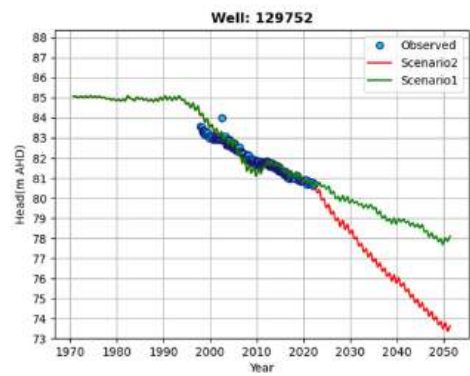
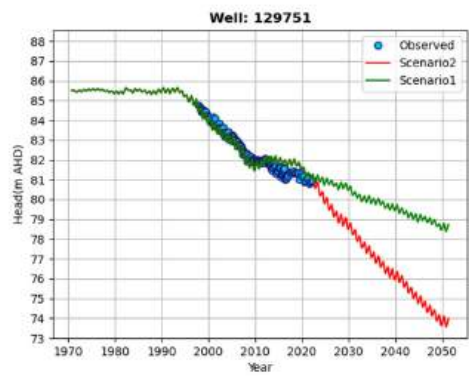
ZONE 6a



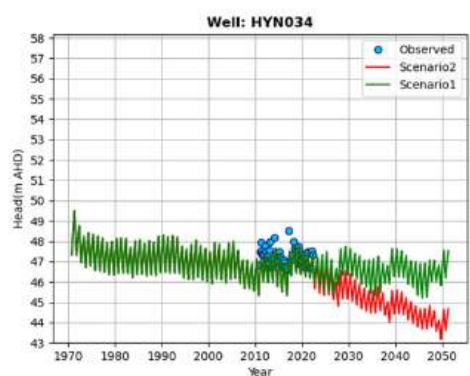
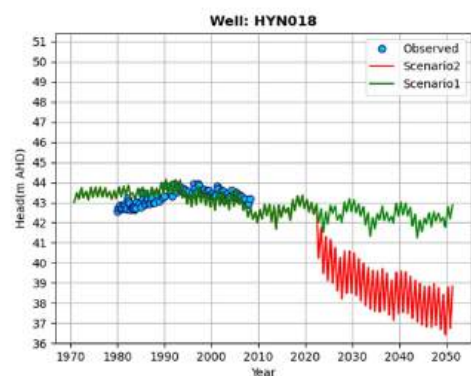
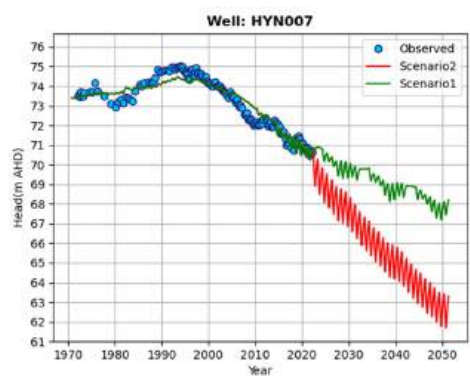
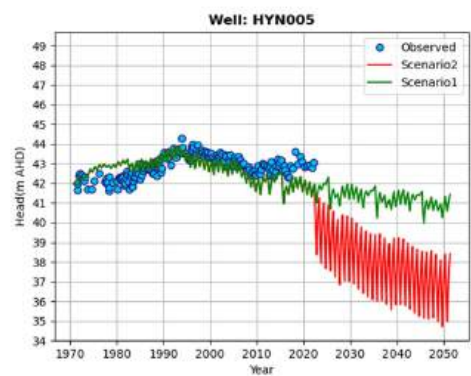
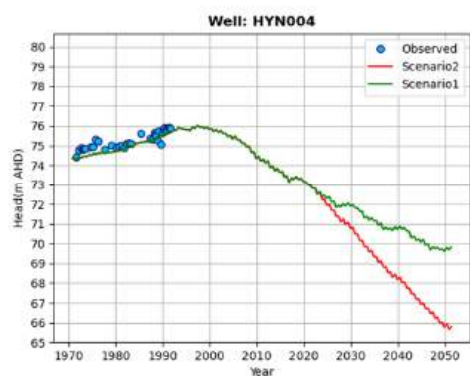
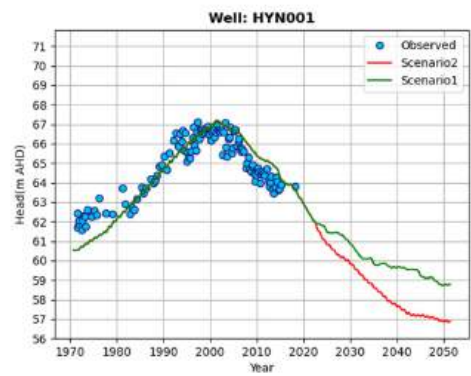
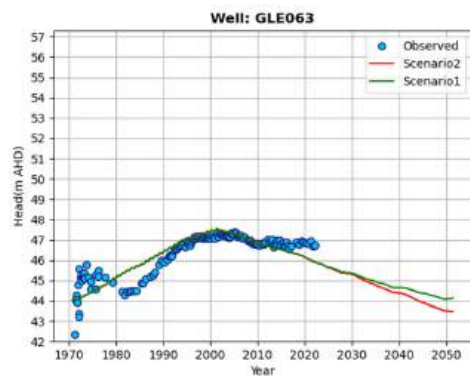
ZONE 5b & 6b



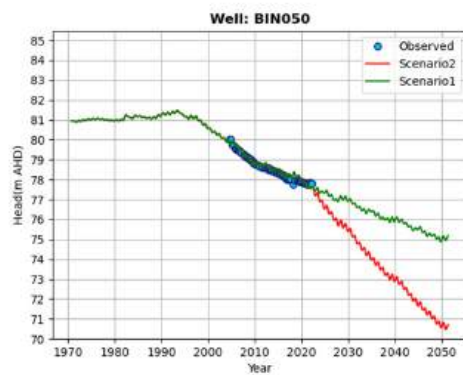
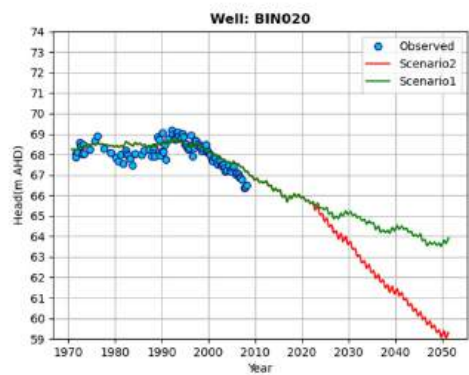
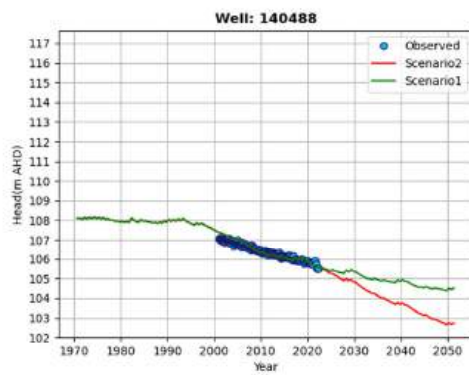
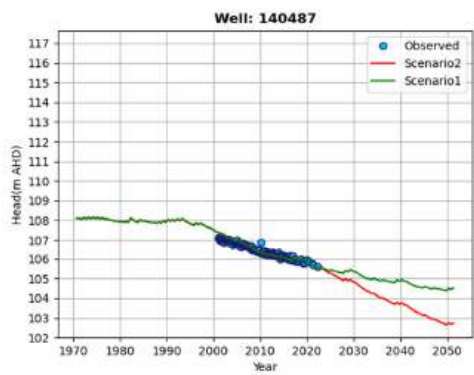
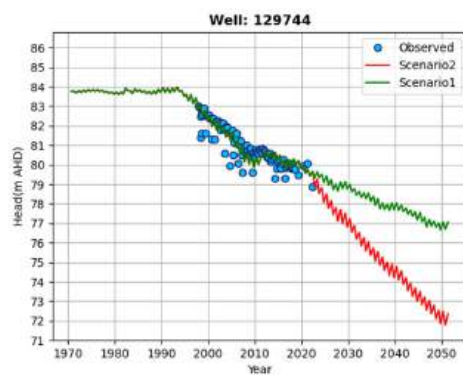
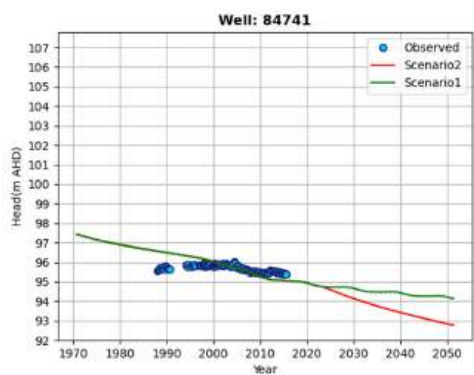
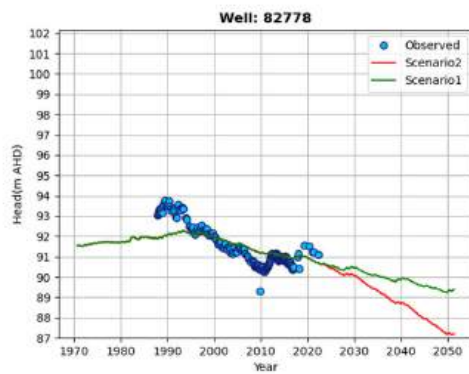
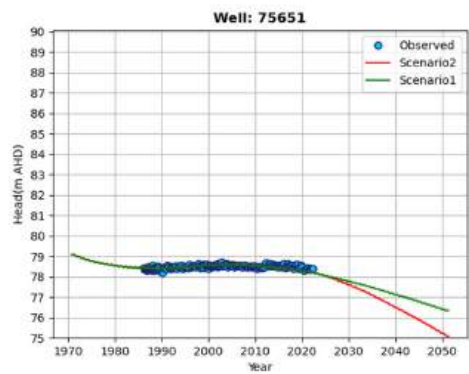
ZONE 5b & 6b

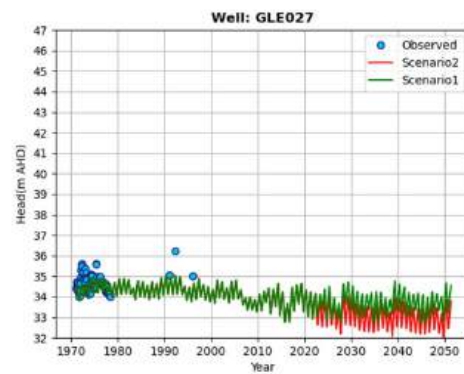
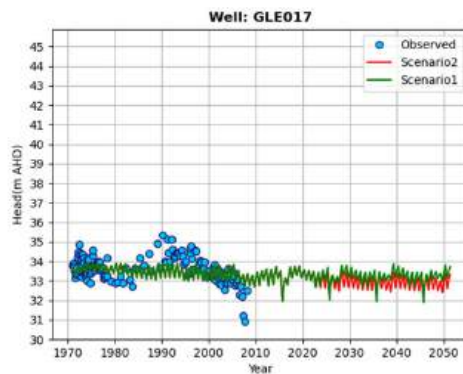
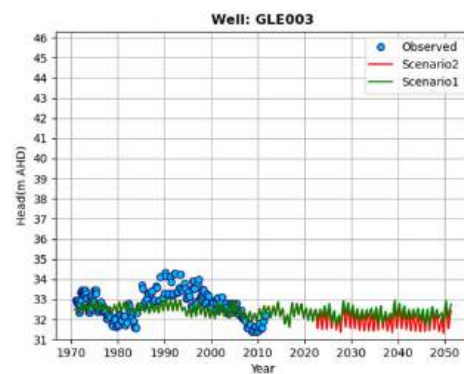
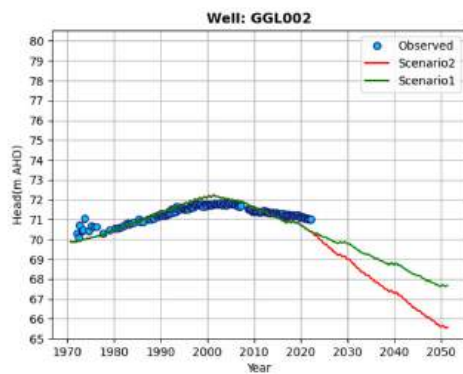
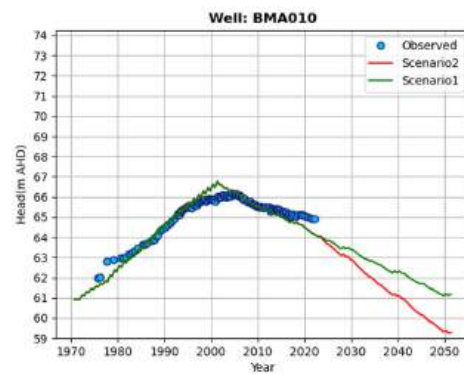
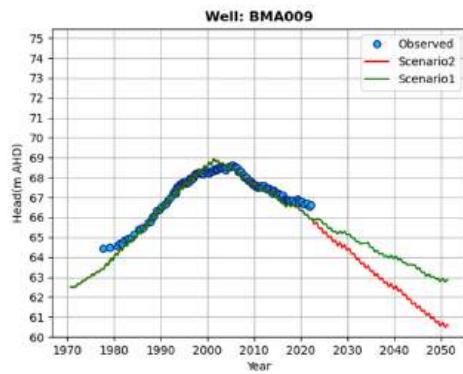
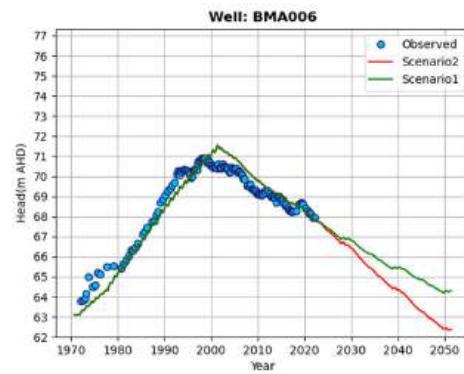
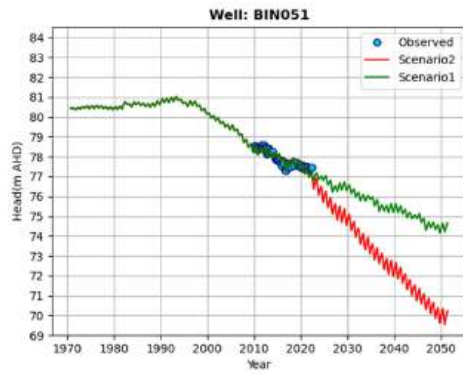


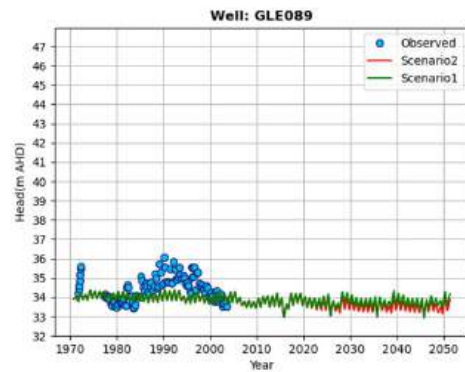
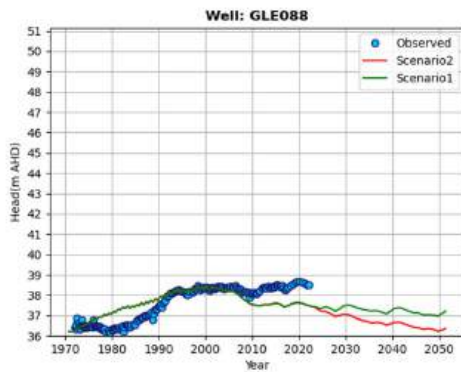
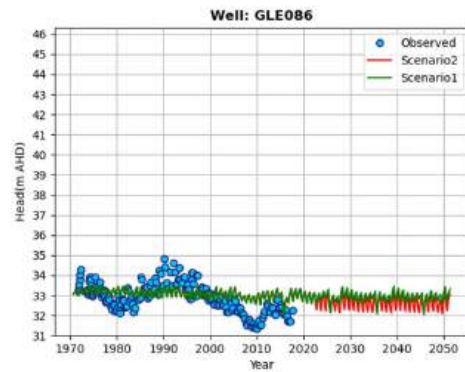
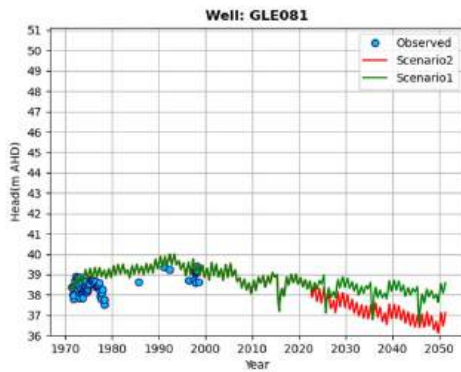
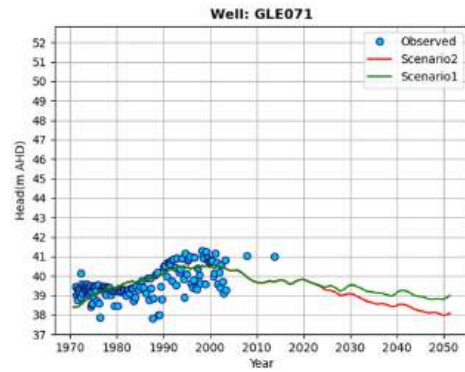
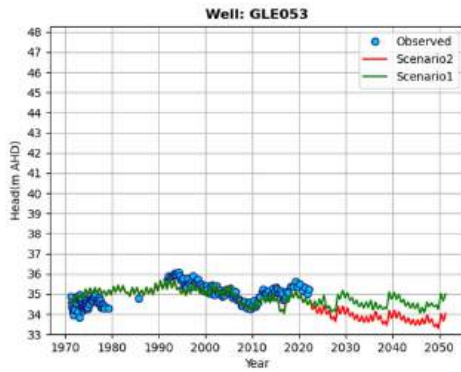
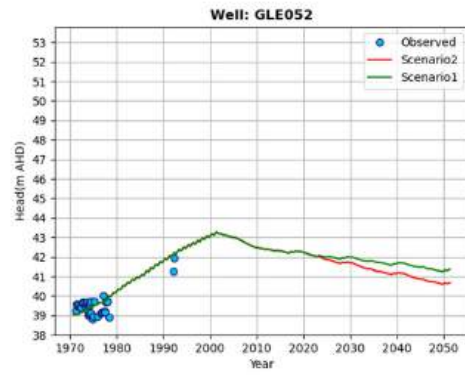
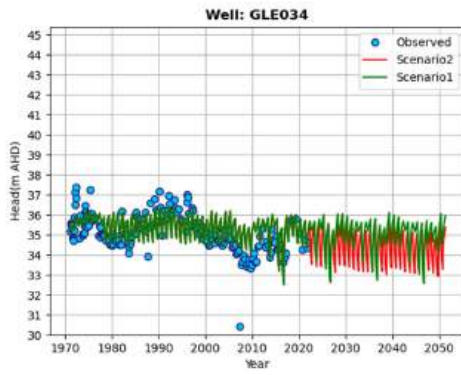
Hynam East

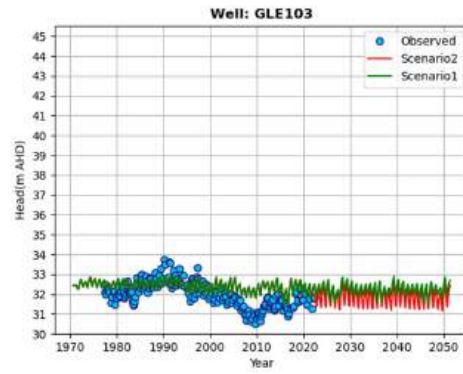
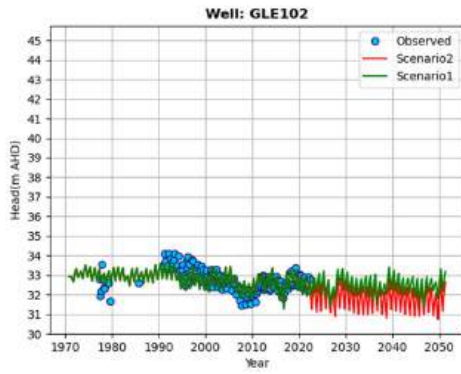
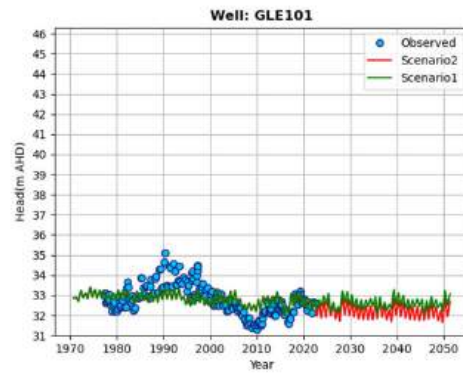
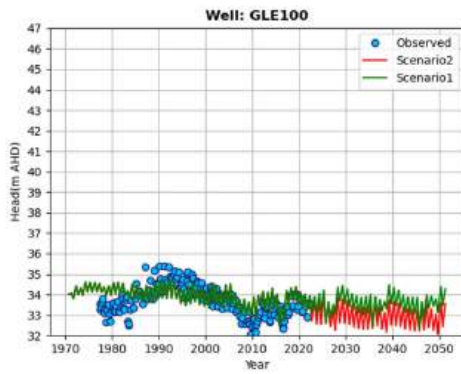
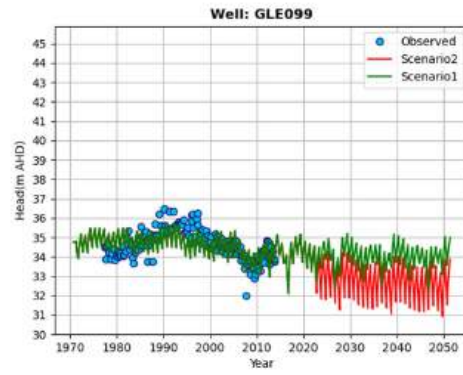
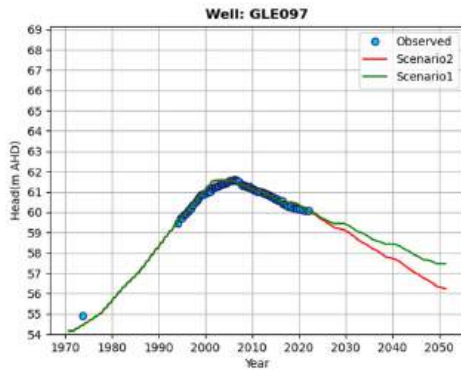
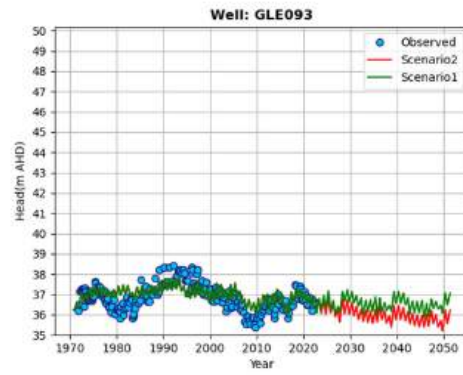
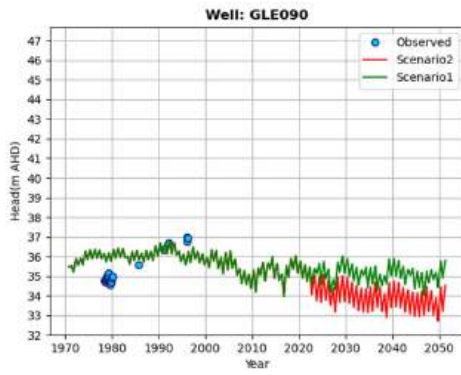


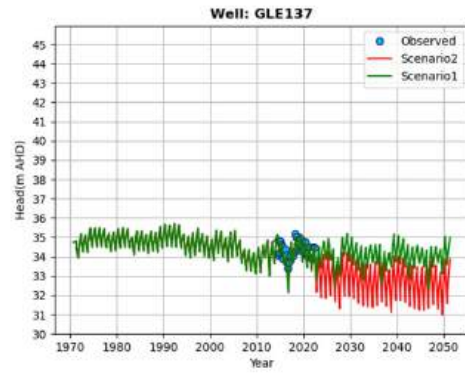
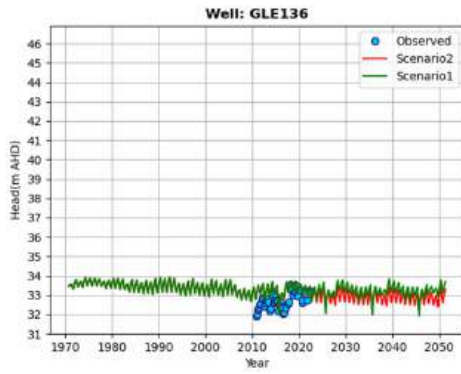
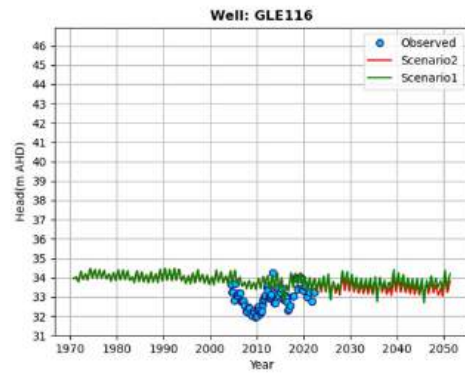
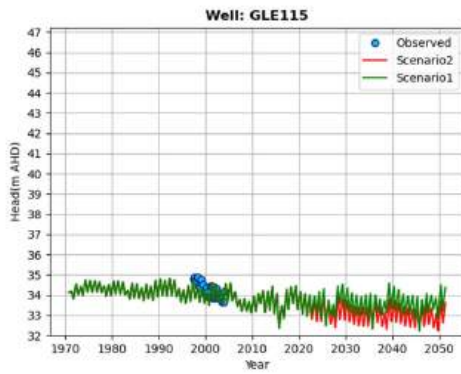
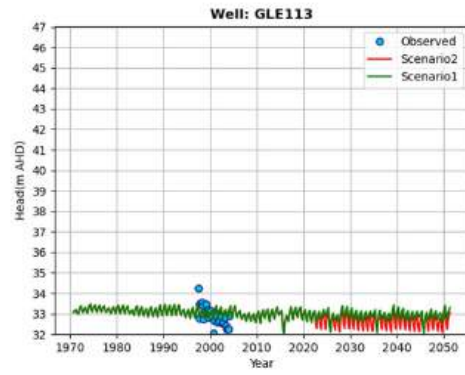
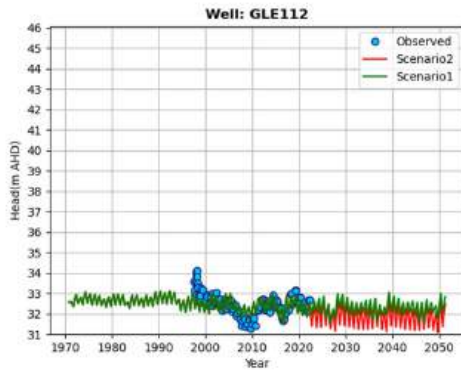
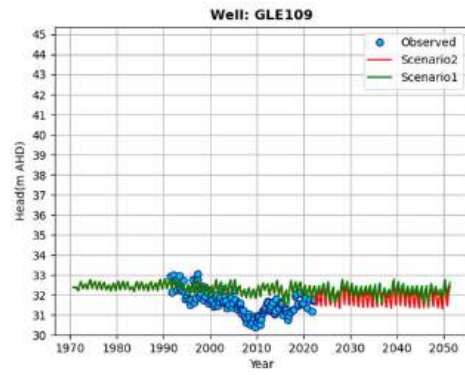
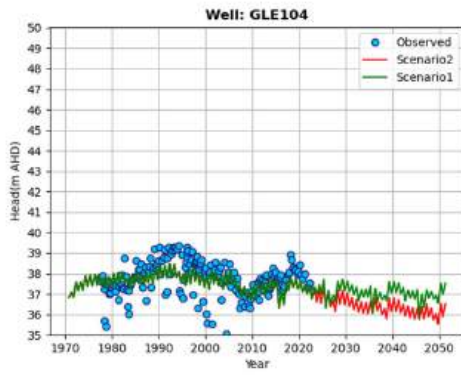
Miscellaneous

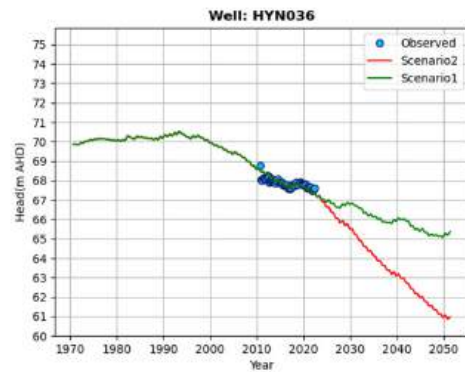
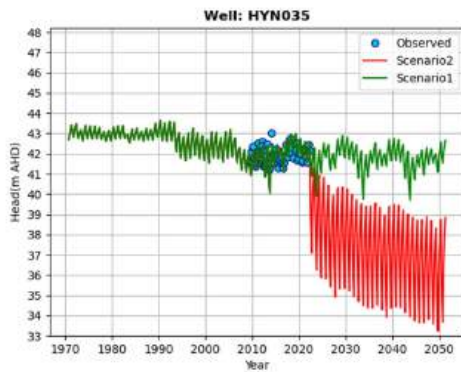
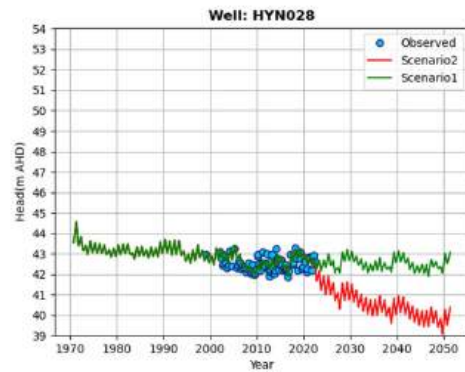
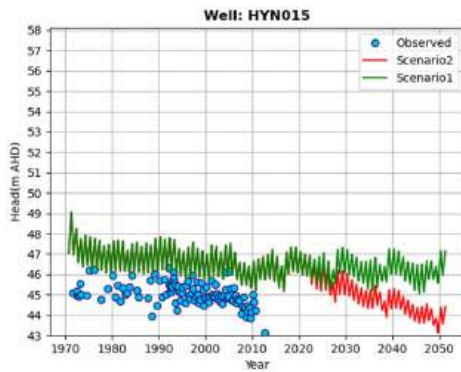
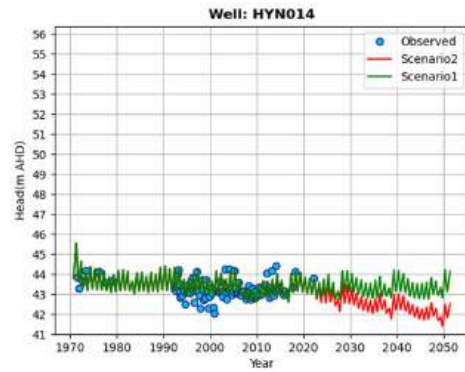
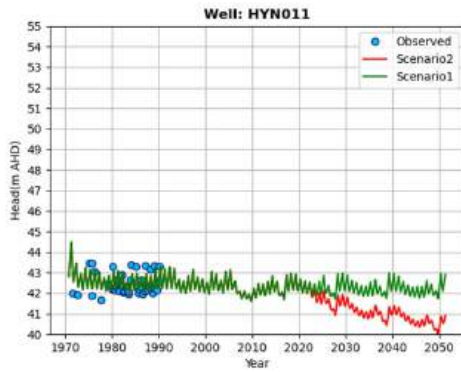
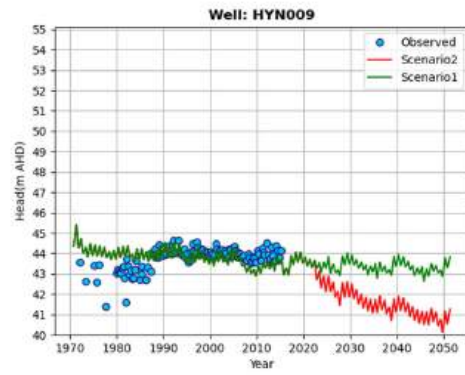
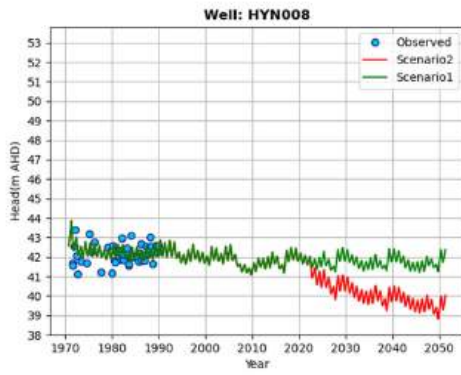


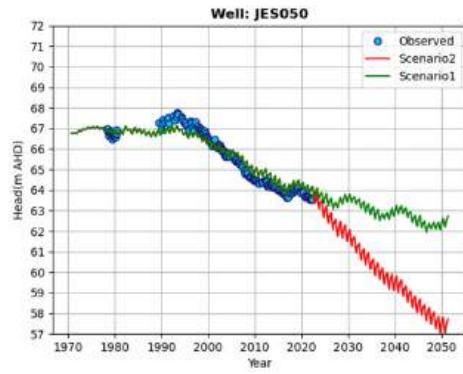
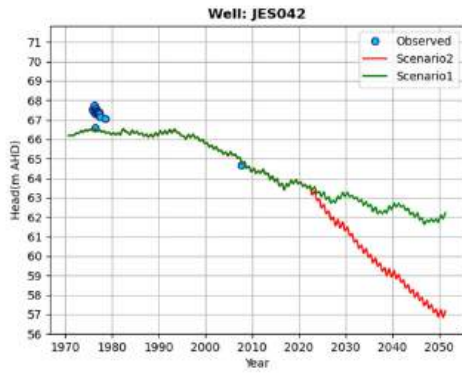
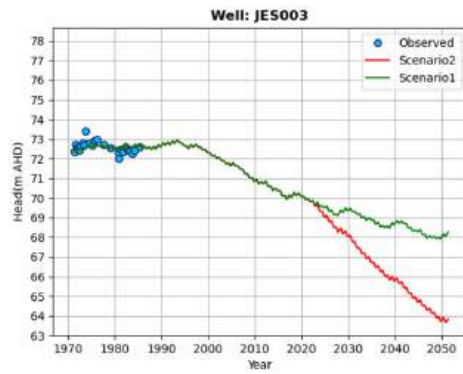
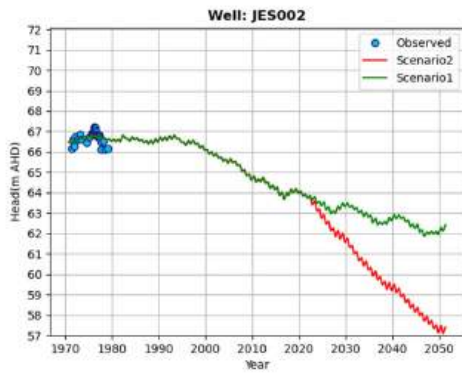
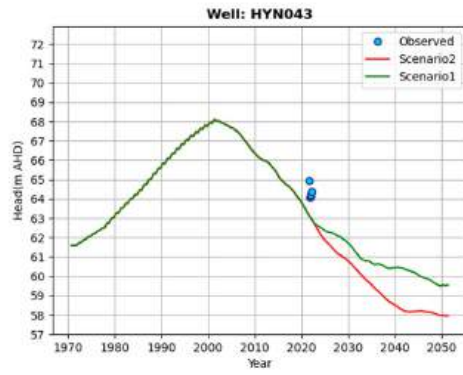
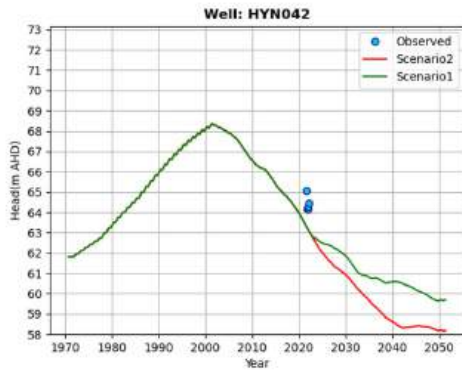
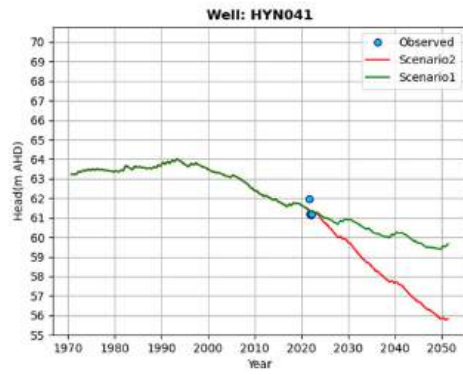
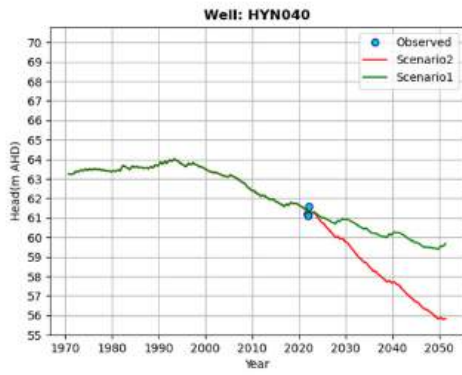


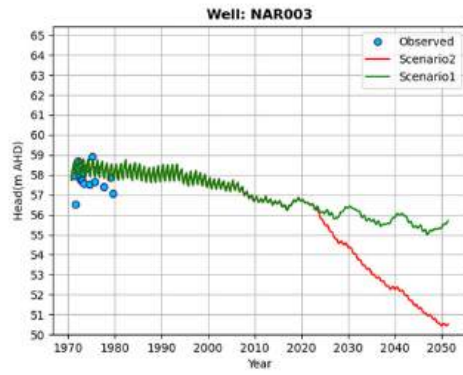
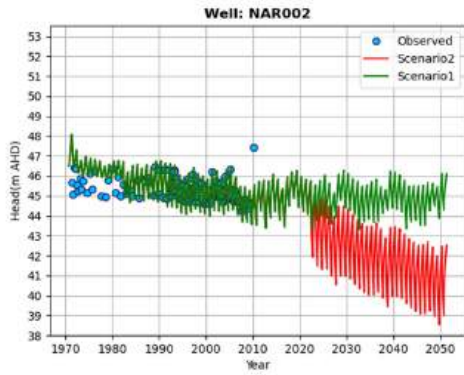
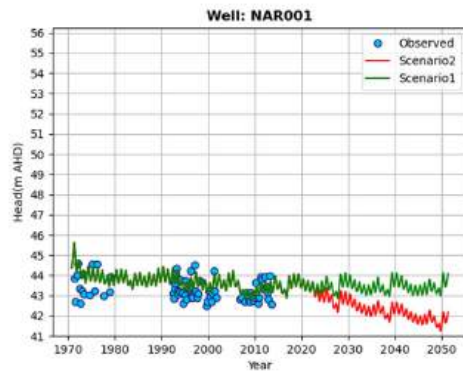
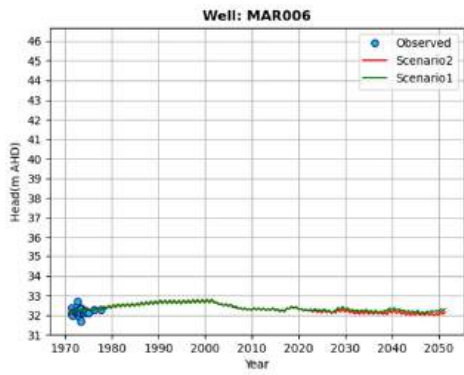
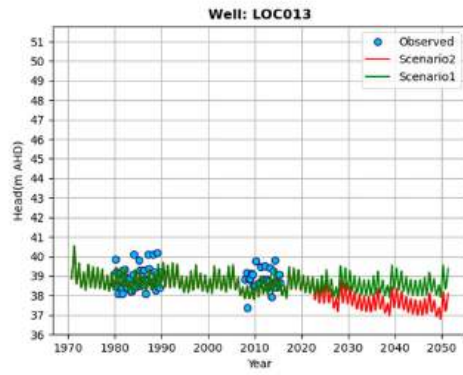
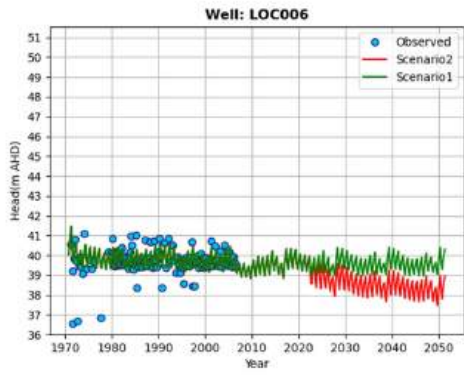
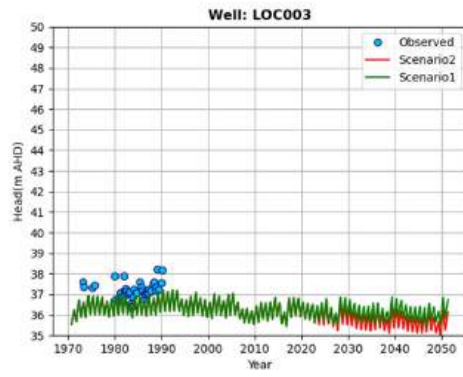
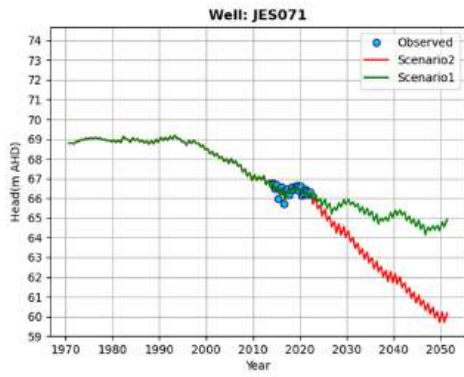


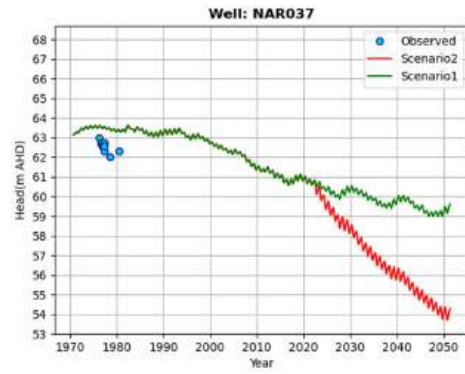
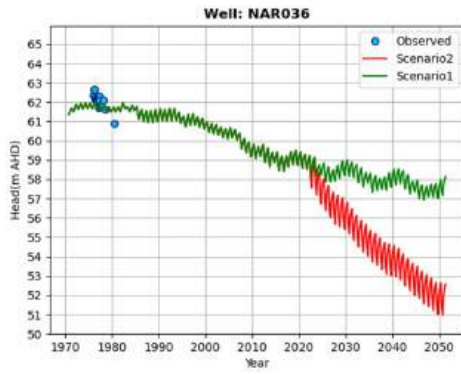
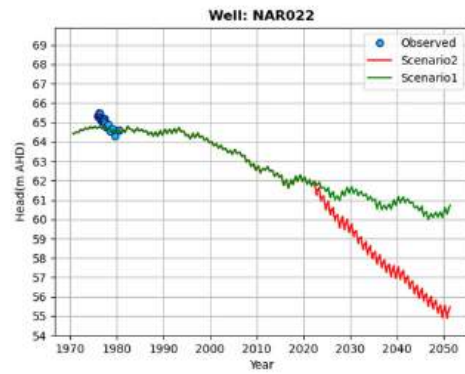
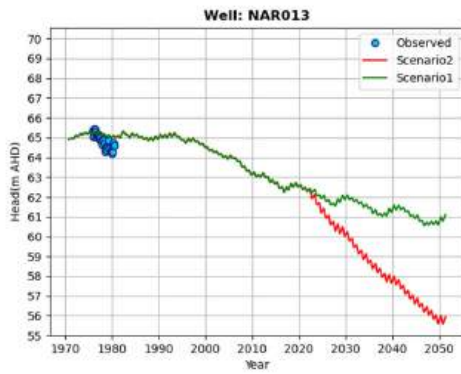
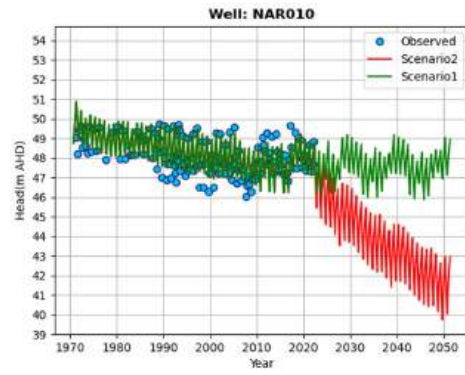
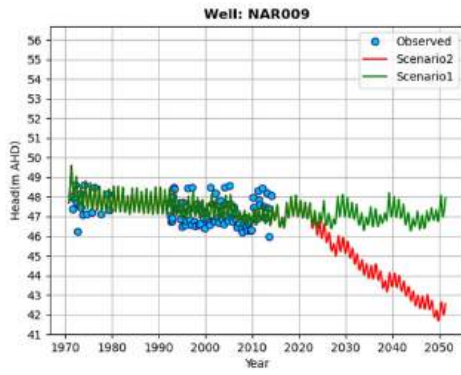
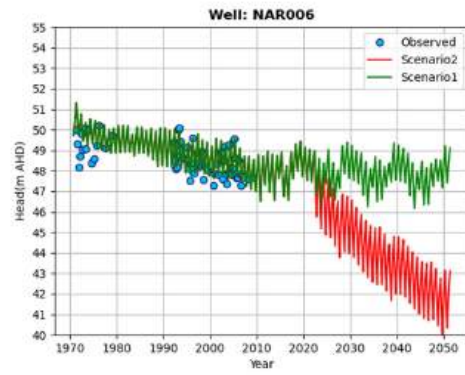
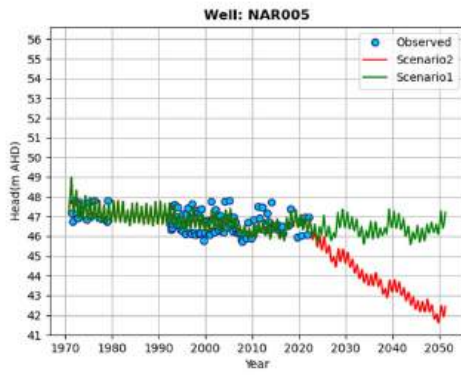


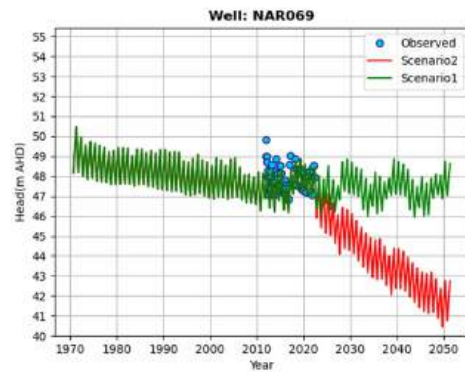
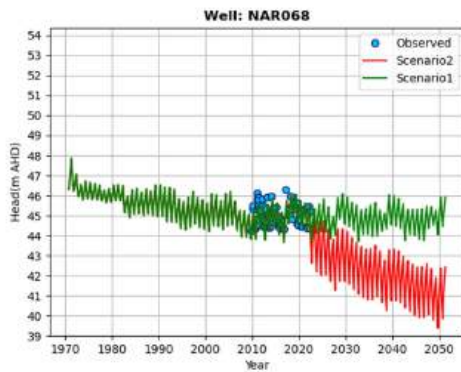
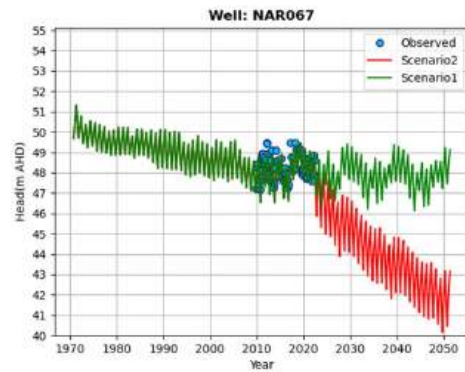
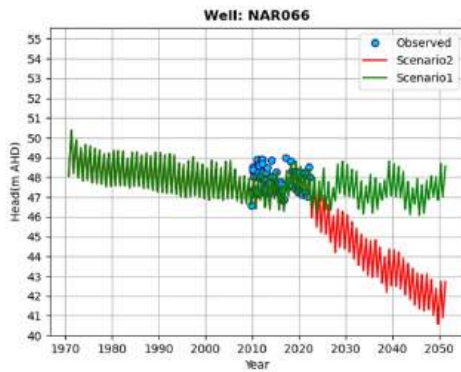
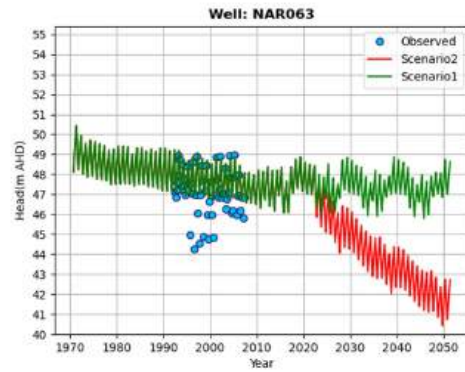
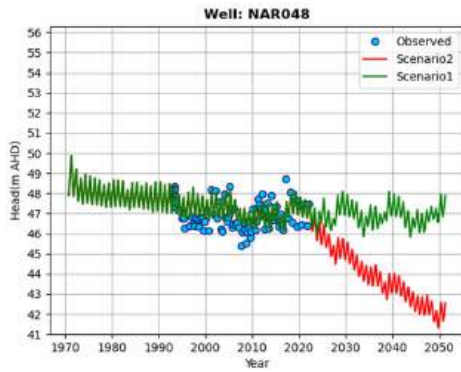
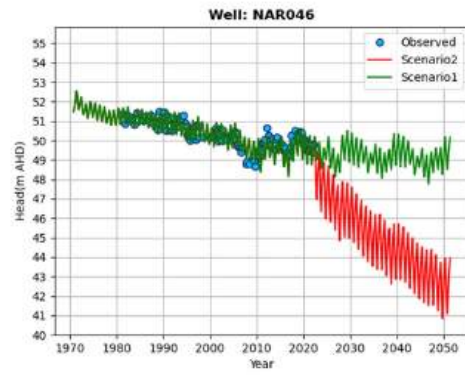
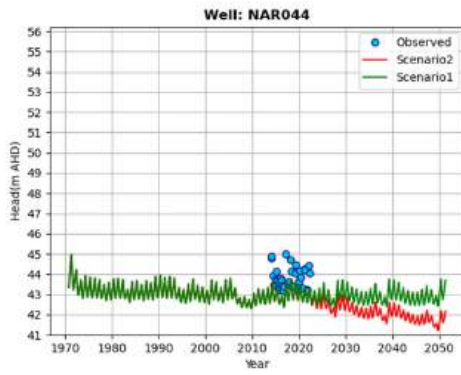


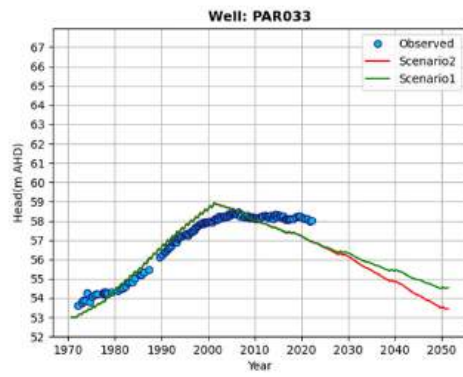
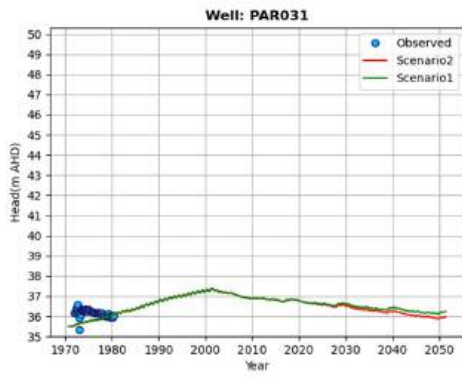
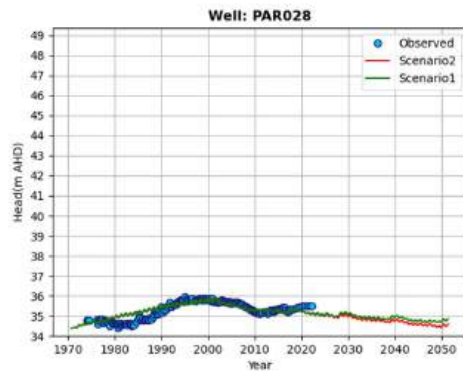
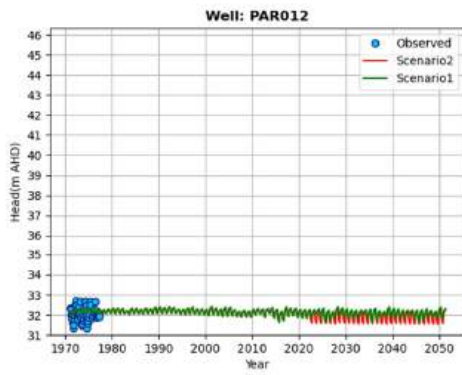
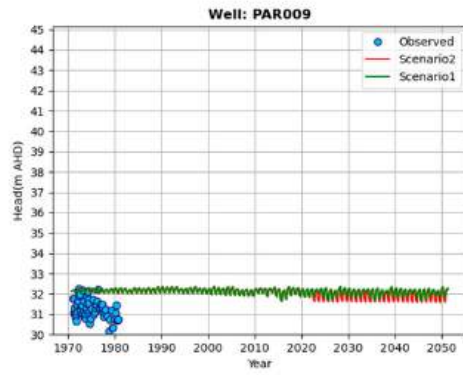
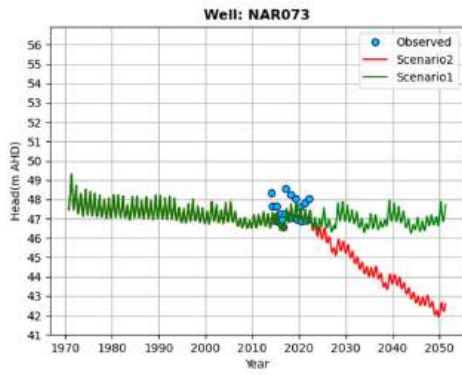
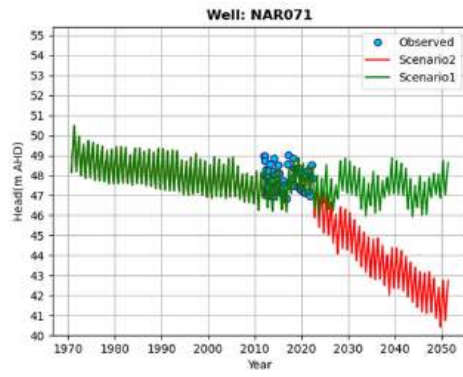
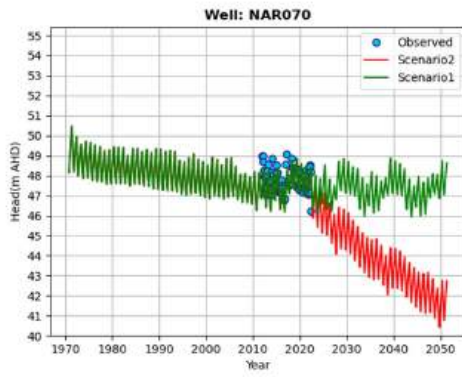


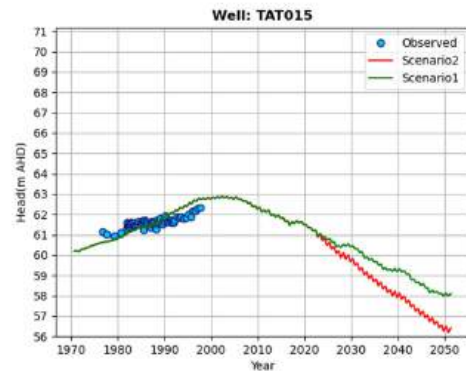
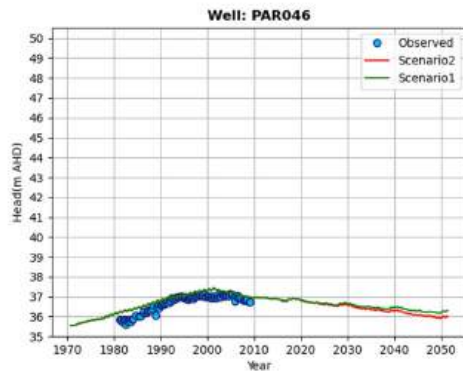
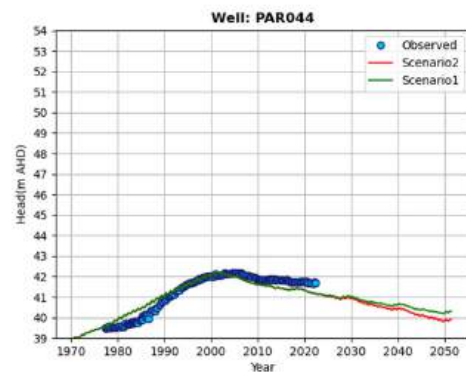
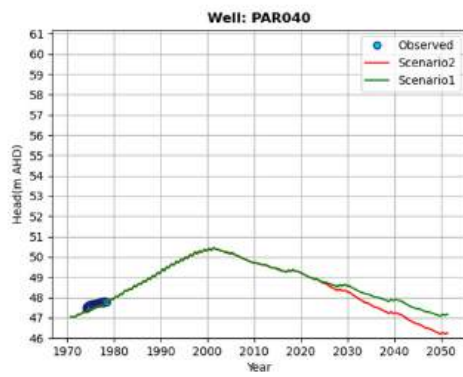
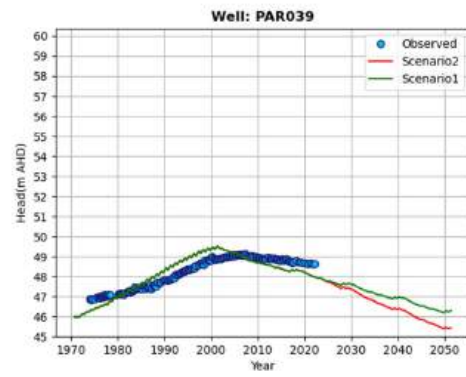
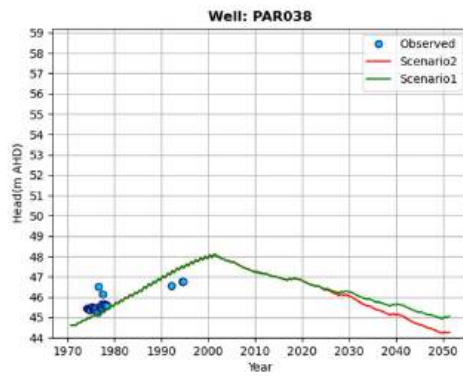
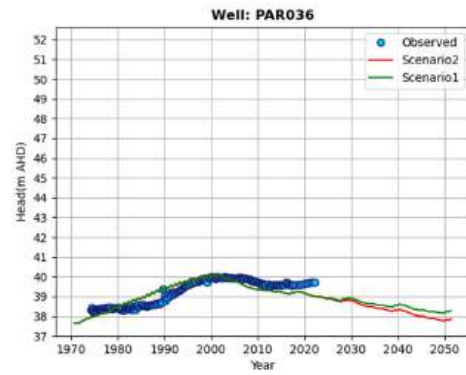
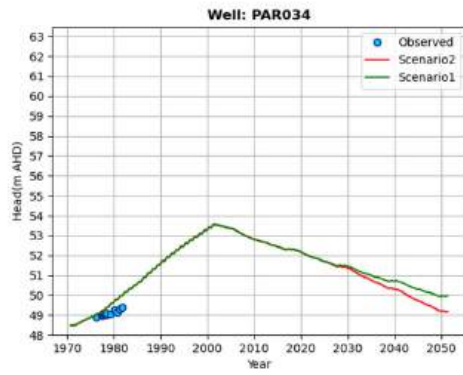


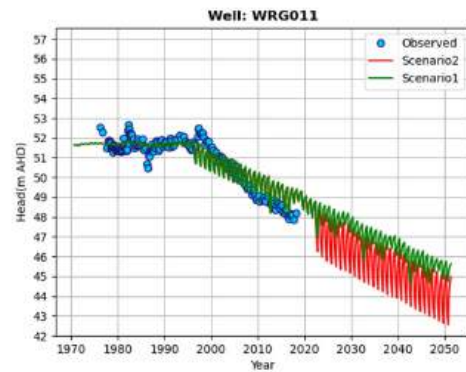
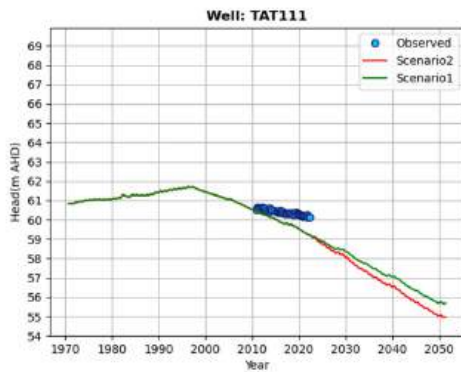
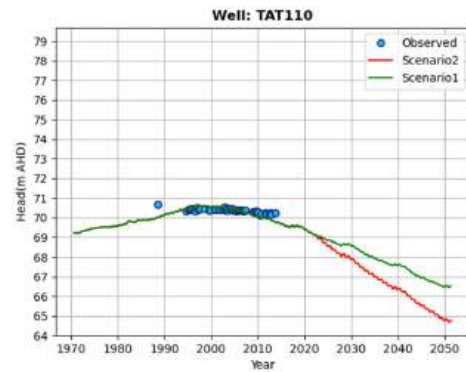
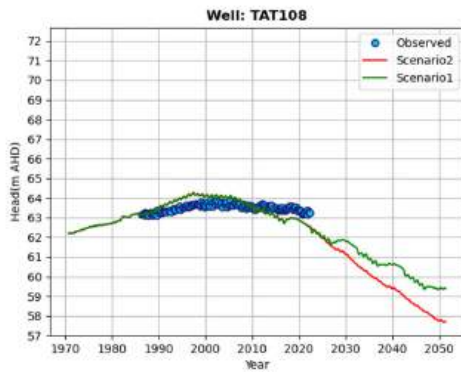
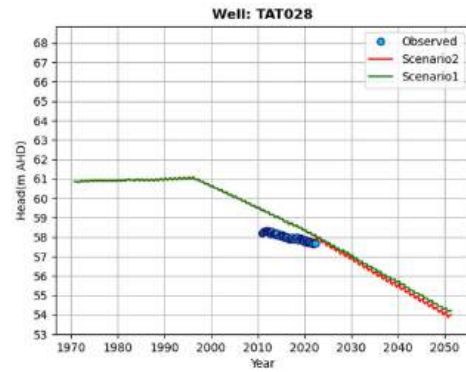
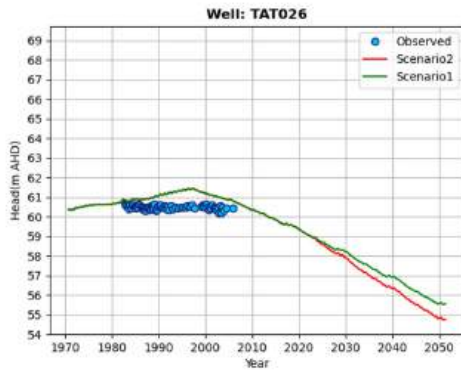
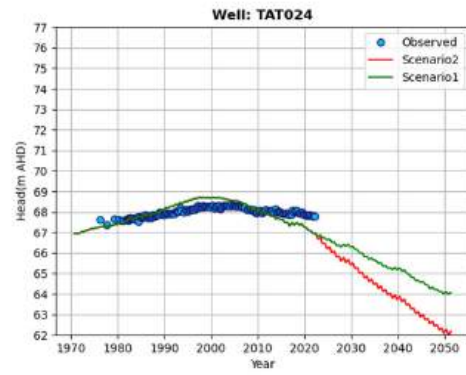
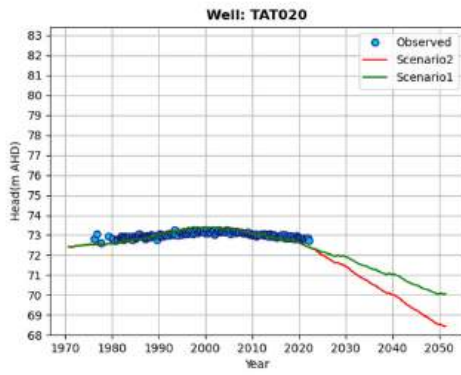


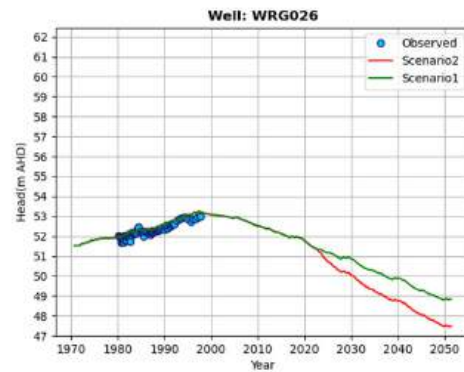
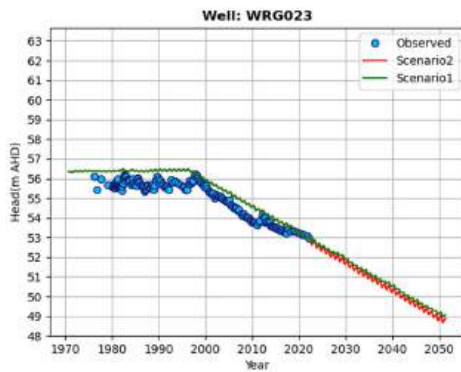
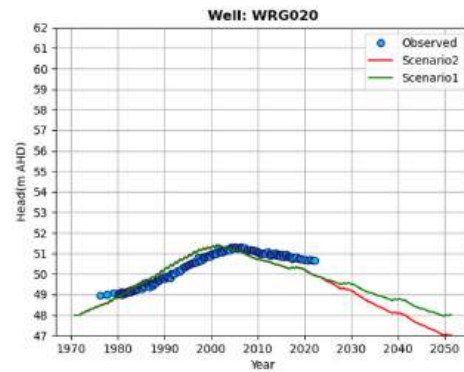
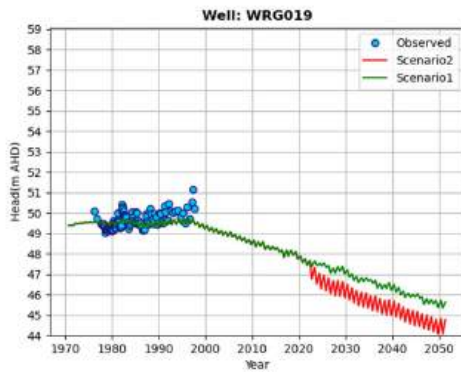
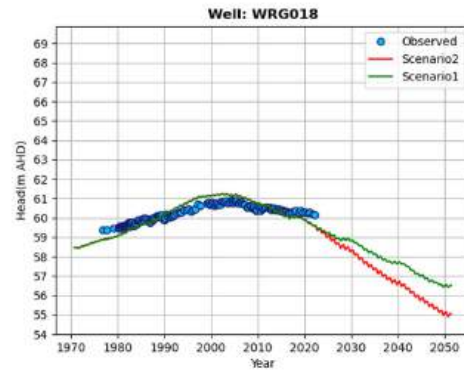
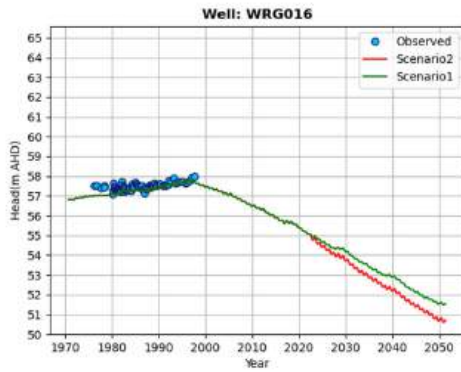
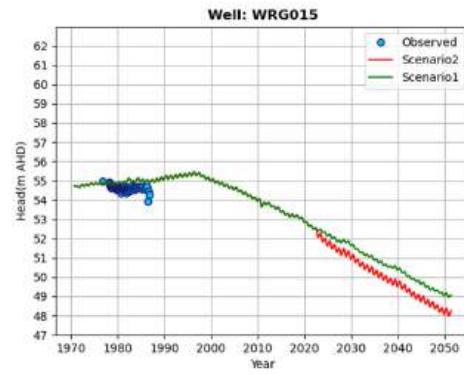
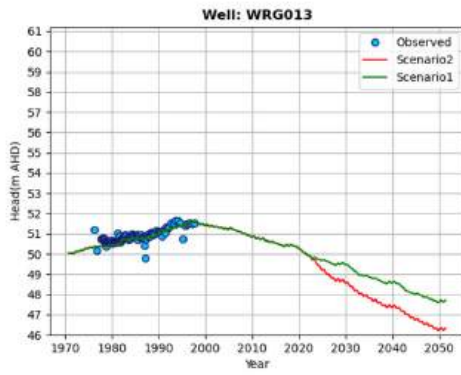


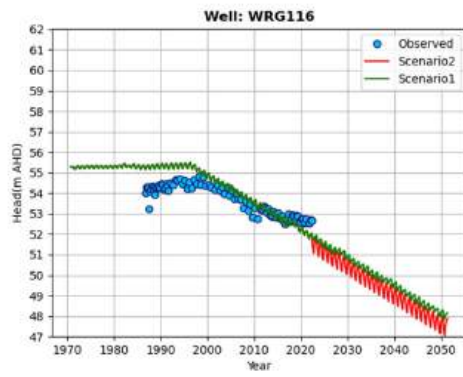
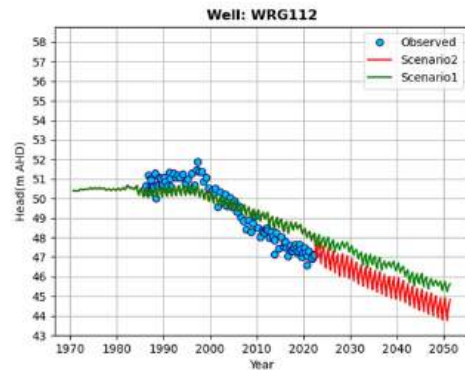
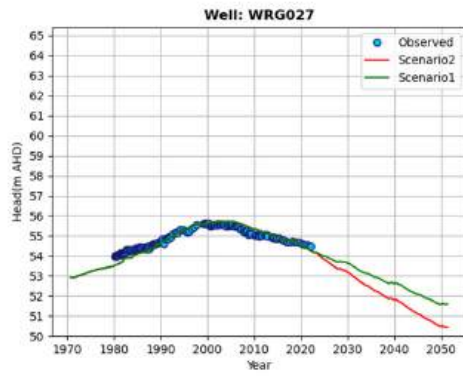












9 Units of measurement

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

10 Glossary

Aquiclude — In hydrologic terms, a formation that contains water but cannot transmit it rapidly enough to furnish a significant supply to a well or spring

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'

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

Geomorphic — Related to the physical properties of the rock, soil and water in and around a stream

Geomorphology — The scientific study of the landforms on the Earth's surface and of the processes that have fashioned them

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

Greenhouse effect — The balance of incoming and outgoing solar radiation which regulates our climate. Changes to the composition of the atmosphere, such as the addition of carbon dioxide through human activities, have the potential to alter the radiation balance and to effect changes to the climate. Scientists suggest that changes would include global warming, a rise in sea level and shifts in rainfall patterns.

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

Groundwater Data — Interactive map and search tool for viewing information about South Australia's wells with access to well details including, graphs showing water salinity and water level. It provides a variety of search methods, including filtering the results. [waterconnect.sa.gov.au/Systems/GD/]

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'

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

Impact — A change in the chemical, physical, or biological quality or condition of a water body caused by external sources

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’

Licensee — A person who holds a water licence

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

Mallee — Region of southern Australia where current landscape (or past landscape) is mallee woodland; often referred to as Mallee region or Mallee zone. Areas of the Mallee have been extensively cleared for agriculture.

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 runoff, assessing the impacts of dams or predicting ecological response to environmental change

MODFLOW — A three-dimensional, finite difference code developed by the USGS to simulate groundwater flow

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

Percentile — A way of describing sets of data by ranking the dataset and establishing the value for each percentage of the total number of data records. The 90th percentile of the distribution is the value such that 90% of the observations fall at or below it.

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m²/d

Porosity — The ratio of an unconsolidated material that contains pores or voids, commonly expressed as a volume

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 water resource — A water resource declared by the Governor to be prescribed under the Act, and includes underground water to which access is obtained by prescribed wells. Prescription of a water resource requires that future management of the resource be regulated via a licensing system.

Python — A high-level, object oriented computer programming language that is the language of choice for scripting in ESRI ArcGIS (ArcPy).

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

Runoff — Water that runs off, as rain that flows off the land into streams.

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

Salinity — The concentration of dissolved salts in water or soil, expressed in terms of concentration (mg/L) or electrical conductivity (EC)

Specific storage (S_s) — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; measured in m⁻¹

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

Sub-catchment — The area of land determined by topographical features within which rainfall will contribute to runoff at a particular point

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

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 (taken perpendicular to the direction of flow), measured in m^2/d

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 (e.g. kilolitres) to be used over a specified period of time, usually per water use year (as distinct from any other sort of allocation)

Water affecting activities — Activities referred to in Part 4, Division 1, s. 9 of the Act

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

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

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 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, water allocation plans and local water management plans prepared under Part 7 of the Act

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

Wetlands — Defined by the Act as a swamp or marsh and includes any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance. This describes wetlands as areas of permanent or periodic to intermittent inundation, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six metres.

11 References

- Anderson MP & Woessner WW (1992). Applied Groundwater Modelling. Academic Press. San Diego.
- Aquaterra (2008). Padthaway Groundwater Flow and Solute Transport Model (PadMod1), Report A47\011f, Aquaterra Consulting Pty Ltd, Adelaide.
- Aquaterra (2010). Modelling Forestry Effects on Groundwater Resources in the South East of SA. Consultant report A115/R001c, prepared for Department of Water, Land and Biodiversity Conservation. Adelaide.
- Barnett B, Townley L, Post V, Evans R, Hunt R, Peeters L, Richardson S, Werner A, Knapton A, Boronkay A (2012). Australian Groundwater Modelling Guidelines. National Water Commission.
<https://webarchive.nla.gov.au/awa/20160615064846/http://archive.nwc.gov.au/library/waterlines/82>
- Barnett S, Lawson J, Li C, Skewes M, Harrington N, Woods J, & Plush B (2015). A Hydrostratigraphic Model for the Shallow Aquifer Systems of the Western Otway Basin and South Western Murray Basin. Goyder Institute for Water Research.
- Brown, CM (1989). Structural and stratigraphic framework of groundwater occurrence and surface discharge in the Murray Basin, southeastern Australia. BMR Journal of Australian Geology & Geophysics, 11, 127-146.
- Brown K, Harrington G, and Lawson J (2006). Review of groundwater resource condition and management principles for the Tertiary Limestone Aquifer in the South East of South Australia. South Australia. Department of Water, Land and Biodiversity Conservation. DWLBC Report 2006/2.
- Brown KG, Love AJ & Harrington GA (2001). Vertical groundwater recharge to the Tertiary confined sand aquifer, South East, South Australia, DWR Report 2001/002, Government of South Australia, Department for Water Resources, Adelaide.
- Bureau of Meteorology (2022). <http://www.bom.gov.au/>
- CDM Smith (2017). Technical Review of Groundwater Resources Province 2 - Groundwater Modelling, report prepared for Department of Environment, Land, Water & Planning, Victoria.
- Charles SP & Fu G (2015). Statistically Downscaled Projections for South Australia, Goyder Institute for Water Research Technical Report Series No. 15/1, Adelaide, South Australia
- Cheng X (2019). Hydrosight case study: estimation of aquifer properties and recharge in Neuarpur. Report prepared for Agriculture Victoria. Department of Jobs, Precincts and Regions, Melbourne. Retrieved July 6, 2023, from <http://nla.gov.au/nla.obj-2527017374>
- Cobb MA & Barnett SR (1994). Naracoorte Hydrogeological Map (1:250 000 scale). Australian Geological Survey Organisation.
- Copper ML, Quilford-White S & Neilson, J (2003). Quaternary: ice ages – environments of change. In: Geology of Victoria (pp 337-360). Edition 3. Chapter 11. Geological Society of Australia. Ed. Birch, WD.
- DELWP (2020). South Australian-Victorian Border Groundwaters Agreement Review Committee. Thirty-Fifth Annual Report. State Government of Victoria, Department of Environment, Land, Water and Planning, Adelaide and Melbourne.
- DELWP (2023). Water Measurement Information System. <https://data.water.vic.gov.au/> . Website accessed September 2022. State Government of Victoria, Department of Environment, Land, Water and Planning, Melbourne.

- DJPR (2018). The Victorian Land Use Information System (VLUIS) 2016 dataset, <https://discover.data.vic.gov.au/dataset/victorian-land-use-information-system-2016> . Website accessed November 2022. State Government of Victoria, Department of Jobs, Precincts and Regions, Melbourne.
- DEW (2020a). Land Use (ACLUMP) data set, <https://data.sa.gov.au/data/dataset/land-use-aclump> website accessed November 2022. Government of South Australia, Department for Environment and Water, Adelaide.
- DEW (2020b). Padthaway Water Allocation Plan review 2019–20: Groundwater science support, DEW Technical report 2020/38, Government of South Australia, Department for Environment and Water, Adelaide
- DEW (2020c). Uley South groundwater model, DEW Technical report 2020/37, Government of South Australia, Department for Environment and Water, Adelaide.
- DEW (2021). Prescribed areas of the Limestone Coast 2019-20 water resources assessment. DEW Technical Note 2021/10. Government of South Australia, Department for Environment and Water, Adelaide.
- DEW (2023). Lower Limestone Coast subregional modelling: mid-South East. DEW Technical Report 2022. Government of South Australia, Department for Environment and Water.
- DEW (2023a). Limestone Coast Prescribed Areas, 2020–21 water resources assessment, DEW Technical Note 2022/13, Government of South Australia, Department for Environment and Water, Adelaide.
- DEW (2023b). WaterConnect: Groundwater Data. www.waterconnect.sa.gov.au. Website accessed September 2022. Government of South Australia, Department for Environment and Water, Adelaide.
- DENR/GWM/SRW (2014). The Tertiary Limestone Aquifer: Information sheet 2 of 4. Pamphlet prepared for the Borders Groundwater Agreement. Department of Environment and Natural Resources/Grampians Wimmera Mallee Water/Southern Rural Water.
- Doble R, Pickett T, Janardhanan S, Crosbie R, Gonzalez D (2020) Potential impacts on groundwater resources from conventional gas in the South East of SA, CSIRO Land and Water.
- DWLBC (2005). Padthaway Salt Accession Study. Volume Two: Results. Government of South Australia, Department of Water, Land, Biodiversity and Conservation, Adelaide.
- ESI (2020). Groundwater Vistas Version 8. Environmental Simulations Incorporated, Pennsylvania, USA.
- Fu G, Crosbie RS, Barron O, Charles SP, Dawes W, Shi X, Van Niel T, Li C (2018). Attributing variations of temporal and spatial groundwater recharge: a statistical analysis of climatic and non-climatic factors, Journal of Hydrology 568, pp 816-834.
- GA (2015). Digital Elevation Model (DEM) of Australia derived from LiDAR 5 Metre Grid. Geoscience Australia, Canberra.
- Golden Software, LLC. (2015). Surfer® 12 from Golden Software. www.goldensoftware.com. Golden, Colorado, USA.
- Green G, Gibbs M & Wood C (2011). Impacts of Climate Change on Water Resources, Phase 3 Volume 1: Northern and Yorke Natural Resources Management Region, DFW Technical Report 2011/03, Government of South Australia, Department for Water, Adelaide.
- Green G, Gibbs M, Alcoe D & Wood C (2012). Impacts of Climate Change on Water Resources Phase 3 Volume 2 Eyre Peninsula Natural Resources Management Region, DFW Technical Report 2012/04, Government of South Australia, Department for Water, Adelaide
- Green G and Pannell A (2020). Guide to Climate Projections for Risk Assessment and Planning in South Australia, Government of South Australia, Department for Environment and Water, Adelaide.

- Harbaugh AW (2005). MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model – the Ground Water Flow Process. U.S. Geological Survey Techniques and Methods 6-A16
- Harrington N. & Li C. (2015). Development of a Groundwater Extraction Dataset for the South East of SA: 1970 – 2013, Goyder Institute for Water Research Technical Report Series No. 13/14
- Harrington N, Millington A, Sodahlan ME and Phillips D. (2015). Development of Preliminary 1969 and 1983 Land Use Maps for the South East of SA, Goyder Institute for Water Research Technical Report Series No. 15/16.
- Herczeg AL & Leaney FWJ (1993). Estimates of Regional Recharge to a Karst Aquifer: Naracoorte Ranges, SA. CSIRO Centre for Groundwater Studies. Report No. 53.
- Herrera PA, Marazuela MA, Formentin G and Hofmann T (2022) Towards an effective application of parameter estimation and uncertainty analysis to mathematical groundwater models. SN Applied Sciences (2022) 4:213. <https://doi.org/10.1007/s42452-022-05086-w>
- Kennett-Smith A, Cook, PG, Walker, GR. (1994). Factors affecting groundwater recharge following clearing in the southwestern Murray Basin. Journal of Hydrology 154(1-4), 85-105.
- Li C & Cranswick R (2016). Barossa PWA Groundwater Resource Capacity: Report 2 – Numerical Groundwater Flow Modelling, DEWNR Technical report 2016/05 (unpublished), Government of South Australia, Department for Environment, Water and Natural Resources, Adelaide.
- Li C and Cranswick RH (2017). *Tatiara PWA numerical groundwater flow model and scenario projections: Volume 1*. DEWNR Technical report 2017/17, Government of South Australia, Department of Environment, Water and Natural Resources, Adelaide.
- Malone B and Searle R (2022). Soil and Landscape Grid National Soil Attribute Maps - Clay (3" resolution) - Release 2. v4. CSIRO. Data Collection. <https://doi.org/10.25919/hc4s-3130>
- McLennan SM (2016). Sedimentation and geochemistry of the Loxton-Parilla Sands in the Murray Basin, southeastern Australia. PhD Thesis. Department of Geology and Geophysics, University of Adelaide.
- Morgan LK, Harrington N, Werner AD, Huston JL, Woods J, Knowling MJ (2015). South East Regional Water Balance Project – Phase 2. Development of a Regional Groundwater Flow Model, Goyder Institute for Water Research Technical Report Series No.15/38.
- Mustafa S. and Lawson J. (2011). South Australia-Victoria Border Zone groundwater investigation: Results of the pumping test program. DfW Technical Report 2011/23, Department for Water, Adelaide.
- Pell SD, Chivas AR & Williams IS (2001). The Mallee Dunefields: development and sand provenance. Journal of Arid Environments vol. 48 pp: 149-170.
- Peeters LJM and Middlemis H. (2023). Information Guidelines Explanatory Note - Uncertainty Analysis for Groundwater Modelling. Prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of Climate Change, Energy, the Environment and Water, Commonwealth of Australia, 2023. www.iesc.environment.gov.au/publications/information-guidelines-explanatory-note-uncertainty-analysis
- QGIS Development Team (2023). QGIS Geographic Information System. Open Source Geospatial Foundation Project. <http://qgis.osgeo.org>
- SENRM/SEWCDB (2019). South East Drainage and Wetland Strategy, South East Natural Resource Management Board/South East Water Conservation and Drainage Board, Government of South Australia.

SENMB (2019). Water Allocation Plan for the Lower Limestone Coast Prescribed Wells Area, South East Natural Resource Management Board, Government of South Australia.

Simmons C, Cook P, Boulton AJ, Zhang L (2019). Independent review of science underpinning reductions to licensed water allocation volumes in the Lower Limestone Coast water allocation plan. Goyder Institute for Water Research Technical Report Series No. 19/01.

SKM (2003) SA/Vic Border Groundwater Agreement. Neuarpuur/Francis Regional Groundwater Model. Sinclair-Knight-Merz. Report for the Victorian Department of Natural Resources and Environment.

Walton WC (1991). Principles of Groundwater Engineering. CRC Press. Boca Raton, Florida, pp. 546.

WNC (2018). PEST Model Independent Parameter Estimation User Manual Part I: PEST, SENSAN, and Global Optimisers. 7th Edition. Watermark Numerical Computing.

White S & Webb JA (2015). The influence of tectonics on flank margin cave formation on a passive continental margin: Naracoorte, Southeastern Australia. *Geomorphology* v229 pp.58-72.

White JT, Hunt RJ, Fienen MN, and Doherty JE (2020). Approaches to Highly Parameterized Inversion: PEST++ Version 5, a Software Suite for Parameter Estimation, Uncertainty Analysis, Management Optimization and Sensitivity Analysis: U.S. Geological Survey Techniques and Methods 7C26, 51 p

Willoughby N, Thompson D, Royal M, Miles M (2018). South Australian Land Cover Layers: an introduction and summary statistics. DEW Technical report 2018/01. Government of South Australia, Department of Environment and Water, Adelaide.

Wohling D, Leaney F, Davies P & Harrington N (2005). Groundwater Salinisation in the Naracoorte Ranges Portion of the Padthaway Prescribed Wells Area, Report DWLBC 2005/27, Government of South Australia, Department of Water, Land and Biodiversity Conservation, Adelaide.



**Government
of South Australia**

Department for
Environment and Water