Lower Limestone Coast subregional model: coastal areas south of Mount Gambier

Department for Environment and Water
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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

The Department for Environment and Water wishes to thank the Limestone Coast Landscape Board staff for engagement on this project and discussions on the model results. Hugh Middlemis (Hydrogeologic Pty Ltd) is thanked for peer reviewing the report.

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Summary

This report documents the conceptualisation, construction and calibration of a numerical groundwater flow model covering the groundwater management areas of Donovans, MacDonnell and Kongorong in the Lower Limestone Coast Prescribed Wells Area (LLCPWA) in South Australia. These areas are located south of Mount Gambier and are bounded to the south by the Southern Ocean and to the east by the Glenelg River estuary in Victoria. The purpose of the model is to be used as a tool to assess the impact of future groundwater use and climate change scenarios on groundwater levels and coastal discharge in the area to assist in the review of the Lower Limestone Coast Water Allocation Plan (LLCWAP) which commenced in 2023. The development of the model for this purpose follows recommendations made by an independent review of the science informing groundwater management in the Limestone Coast (Simmons et al. 2019).

The model simulates groundwater flow in the regional Tertiary Limestone Aquifer (TLA) and is divided into three-layers each representing sub-units of the aquifer. The model is calibrated to groundwater level measurements from 1970–2022 in the study area. The model is also calibrated to measured discharge at three karst springs along the coast. The model uses the SeaWater Intrusion 2 (SWI2) package to simulated position and movement of the seawater interface. However, there is limited data related to the seawater interface with which to constrain these simulations and caution is advised in their interpretation. A major geophysical investigation into the coastal groundwater system was commissioned subsequent to the model being developed (Goyder 2022), and it is anticipated that this will help inform future review of seawater intrusion modelling by delineating a ‘start position’ for landward incursion.

Two model scenarios have been run projecting from 2022 to 2050. Scenario 1 simulates groundwater extraction and recharge over the period 2012–21, while scenario 2 simulates an increase in extraction to full allocation levels and a decrease in recharge due to decreased rainfall under climate change. Scenario 1 shows groundwater levels stabilising within year-to-year fluctuations, while scenario 2 shows ongoing declines that can be attributed to the highly conservative assumptions (high extraction and low recharge).

Assumptions and limitations identified with the model approach taken are documented and discussed, and recommendations for future work are presented. Given that the geophysical study being undertaken by Goyder (2022) will provide significantly more information related to the coastal seawater interface than was available during model construction, it is recommended model results be revisited and revised, if necessary, pending outcomes of the geophysical study. As the scenario presentation is limited, it is recommended that further consultation with the Limestone Coast Landscape Board is undertaken so that further scenario work and formats for data presentation can be developed as the LLCWAP is reviewed.

1 Introduction

1.1 Background

The coastal groundwater management areas south of Mount Gambier are home to multiple environmental, social and economic assets, all of which depend upon groundwater. The management areas (MAs) of Donovans, MacDonnell and Kongorong occupy a 65 km stretch of coast west of the South Australian-Victorian border (Figure 1.1). Within these areas are 9,200 hectares of commercial forest plantations, irrigated dairy agriculture with groundwater extraction ranging from 28 to 51 GL/y and the Ramsar listed Piccaninnie Ponds Karst Wetland (herein Piccaninnie Ponds). Several other karst springs and wetlands are present along the coastal strip with the region referred to as the 'Karst springs and associated alkaline fens of the Naracoorte Coastal Plain Bioregion,' and listed as critically endangered under the Commonwealth *Environment Protection Biodiversity Conservation Act 1999* (DAWE, 2020). Many of the karst springs are also important tourist destinations for the region.

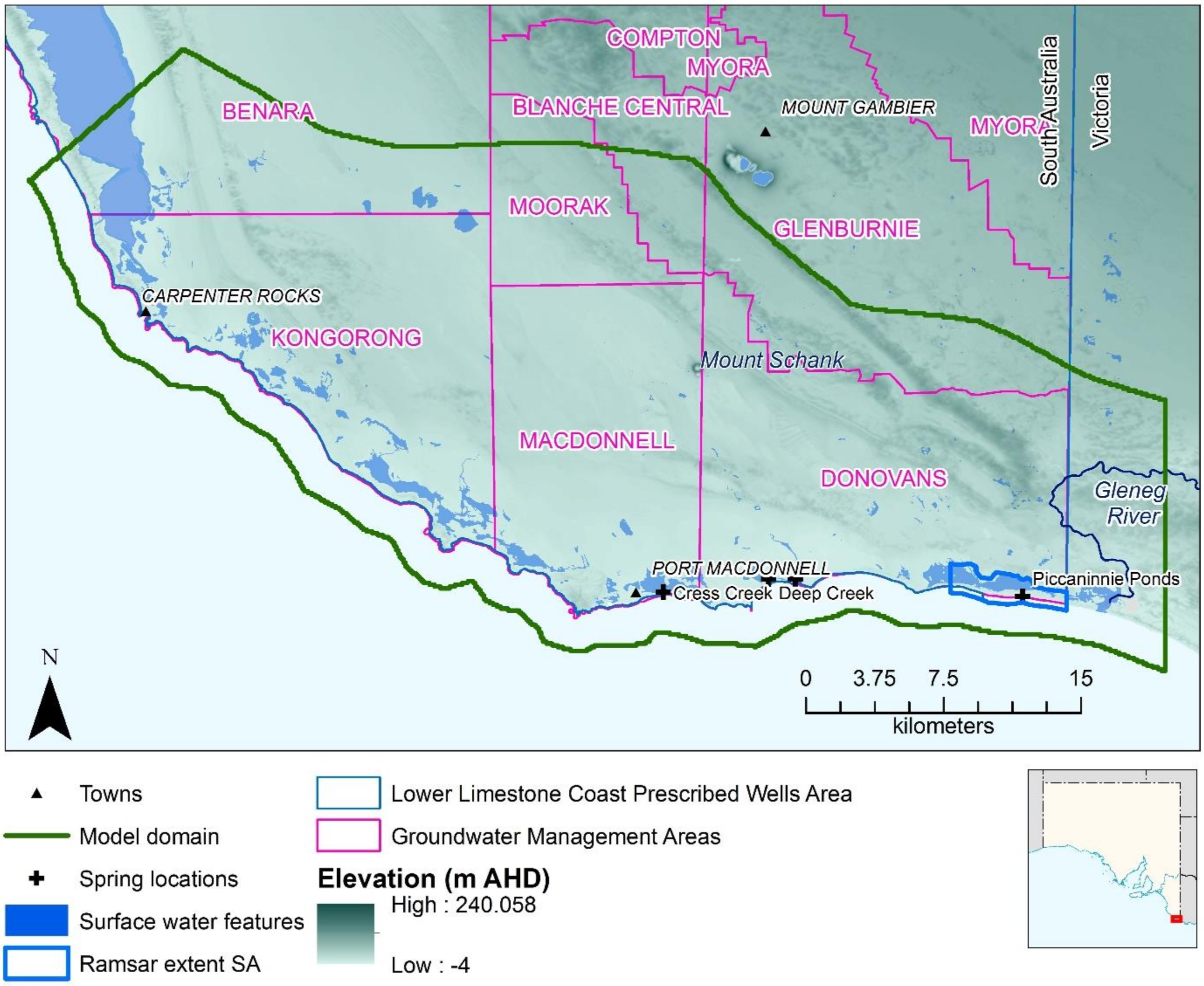


Figure 1.1. Study area and model domain

Groundwater is managed through the Lower Limestone Coast (LLC) Water Allocation Plan (WAP, SENRM 2013). The 2019 LLCWAP Risk Assessment found there was a high risk of adverse impacts to karst springs in the MacDonnell management area as a result of groundwater level declines and fluctuations caused by seasonal groundwater extraction (NRSE, 2019). At the same time, a review of the science supporting the LLCWAP recommended development of sub-regional models to assist in assessing risk to groundwater resource and the economic and environmental assets it supports (Simmons et al., 2019).

1.2 Objectives

The objectives of this study are to:

- summarise the conceptual background of the coastal area south of Mount Gambier;
- develop a groundwater flow model for the coastal management areas south of Mount Gambier capable of assessing the impact of climate and pumping on groundwater levels and discharge to key groundwater dependent ecosystems;
- run preliminary scenarios testing the impact of pumping and climate change on groundwater level and groundwater dependent ecosystems; and
- use the model to investigate the position and movement of the seawater interface.

It is acknowledged that the hydrogeology of the area and conceptual model of the seawater interface is likely to be developed further through research work being undertaken by the Goyder Institute (2022) due for completion in 2024. These investigation projects were commissioned after commencement of model construction; hence, the model provides a baseline for assessment of the coastal groundwater resource and an initial assessment of the seawater interface and associated uncertainties. Should this new data and information result in a significant change to the conceptualisation used in this model, if recommended, the model can be modified accordingly and scenarios 1 and 2 re-run.

2 Conceptual model

2.1 Conceptual model summary

The conceptual model for the study area was reviewed by DEW (2021). The regional unconfined Tertiary Limestone Aquifer (TLA) is the main source of water for irrigation supply and several important ecosystems including the Ramsar-listed Piccaninnie Ponds. The TLA consists of several sub-units of varying lithology which can be broadly categorised into three main units: the Green Point Member; the Camelback Member and the Greenways Member (White, 1996). These units are separated from the underlying Tertiary Confined Sand Aquifer (TCSA) by an aquitard (Table 2.1) which ranges in thickness from 5 – 50 m in the study area (Barnett et al. 2015). Groundwater flows from the northern part of the study area towards the coast with potentiometric contours approximately parallel to the coastline (Figure 2.2). Groundwater discharges at the coast through springs, beach seeps and via submarine groundwater discharge. There is limited groundwater use from the TCSA in the study area and no known interaction between the two aquifers in the study area; hence, it is not considered further in this study.

The seawater Interface has been detected in the aquifer at a few locations and occurs at depths of ~125 m below ground close to the coast (Waterhouse, 1977) and 154 m below ground 1.2 km inland based on data from drilling (Mustafa et al., 2012; Figure 2.3). The occurrence at 154 m depth 1.2 km inland correlates with findings of an earlier geophysical survey (King and Dodd, 2002). Resistivity contours based on modelled inversion of a land-based transient electromagnetic (TEM) survey in the Eight Mile Creek area are presented in Figure 2.3. The full inland spatial extent of the interface is not currently known and monitoring of any movement of the interface historically has been limited to long-screened wells which may not provide accurate information (Shalev et al. 2009). At the time of preparing this report, further investigations are underway to investigate seawater intrusion including installation of additional monitoring wells in the study area, geophysical surveys including an aerial electromagnetic (AEM) survey and additional modelling.

Groundwater level measurements are available since the early 1970s. Close to the coast groundwater levels have been generally stable, while further inland groundwater levels declined by up to 2 m from the mid-1990s to the mid-2000s (Figure 2.1). The decline in groundwater levels during this period corresponds with declining rainfall and an increase in the density of irrigation through the study area as exemplified in the hydrograph for MAC046 (Figure 2.1). Associated with declining groundwater levels are an increase in the seasonal magnitude of groundwater level fluctuations in parts of the study area (Figure 2.1) associated with increased groundwater extraction over summer. Some of these changes can be seen in the potentiometric surfaces in Figure 2.2; however, changes in the potentiometric surface may also reflect changes in the location of monitoring wells over time.

Table 2.1. Summary of stratigraphy in the study area

Period	Epoch	Formation name	Aquifer code	Description	Hydrostratigraphic unit	Model layer
Quaternary	Holocene	Quaternary volcanics	Qhv	Basaltic pyroclastics		1
	Pleistocene	Padthaway Formation	Qpl	Lagoonal fine-grained dolomite and clay	Tertiary Limestone Aquifer (TLA)	
		Bridgewater Formation	Qpbc	Sandy limestone		
Tertiary	Late Oligocene to middle Miocene	Gambier Limestone: Green Point Member	Thgr(U1)	Cream to light-grey bryozoal limestone, may contain chert		
			Thgr(U2)	Grey marl with abundant chert		
			Thgr(U3)	Cream to light-grey bryozoal limestone, may contain chert		
			Thgr(U4)	Grey marl with abundant chert		
	Early Oligocene to early Miocene	Gambier Limestone: Camelback Member	Thgc	Orange/pink dolomite, typically fractured at the top of the unit (high transmissivity in this zone)		2
	Eocene to early Oligocene	Gambier Limestone: Greenways Member	Thgg	Grey marl with frequent chert bands, often glauconitic near base		3
	Eocene	*Narrawaturk Marl*	*Tnn*	*Green to brown marl and limestone, very glauconitic with limonite pellets*	*Tertiary Aquitard*	*Not modelled*
		Mepunga Formation	*Tnm*	*Sparsely fossiliferous, brownish quartz grit*		*Not modelled*
	Palaeocene	*Dilwyn Formation*	*Twd*	*Interbedded sequence of fluvial/deltaic sand and clay, sand units are aquifers. An upper clay unit of the Dilwyn Formation can form part of the regional aquitard.*	*Tertiary Confined Sand Aquifer (TCSA)*	*Not modelled*

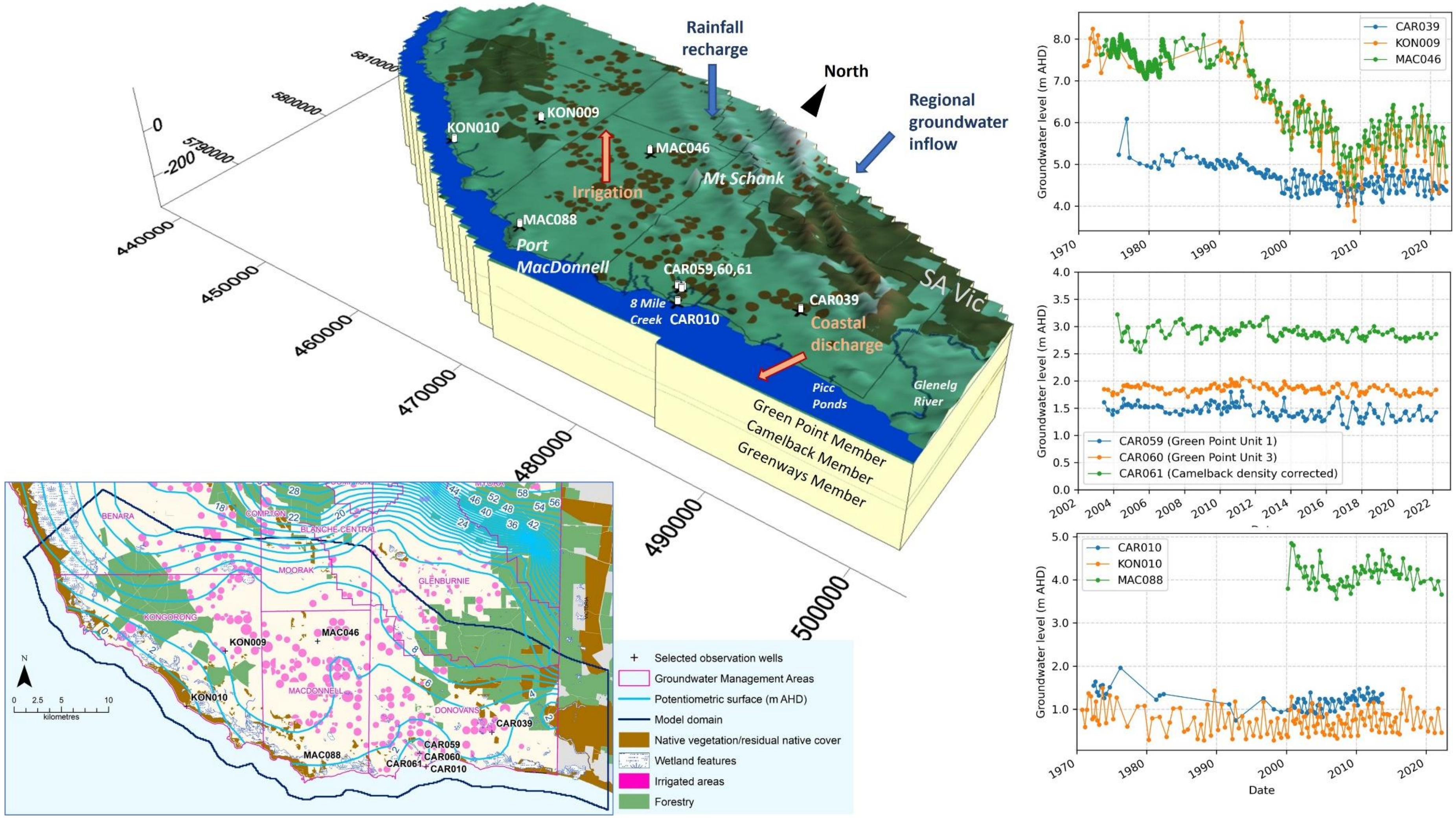


Figure 2.1. Conceptual model of main groundwater inflow and outflow processes in the study area

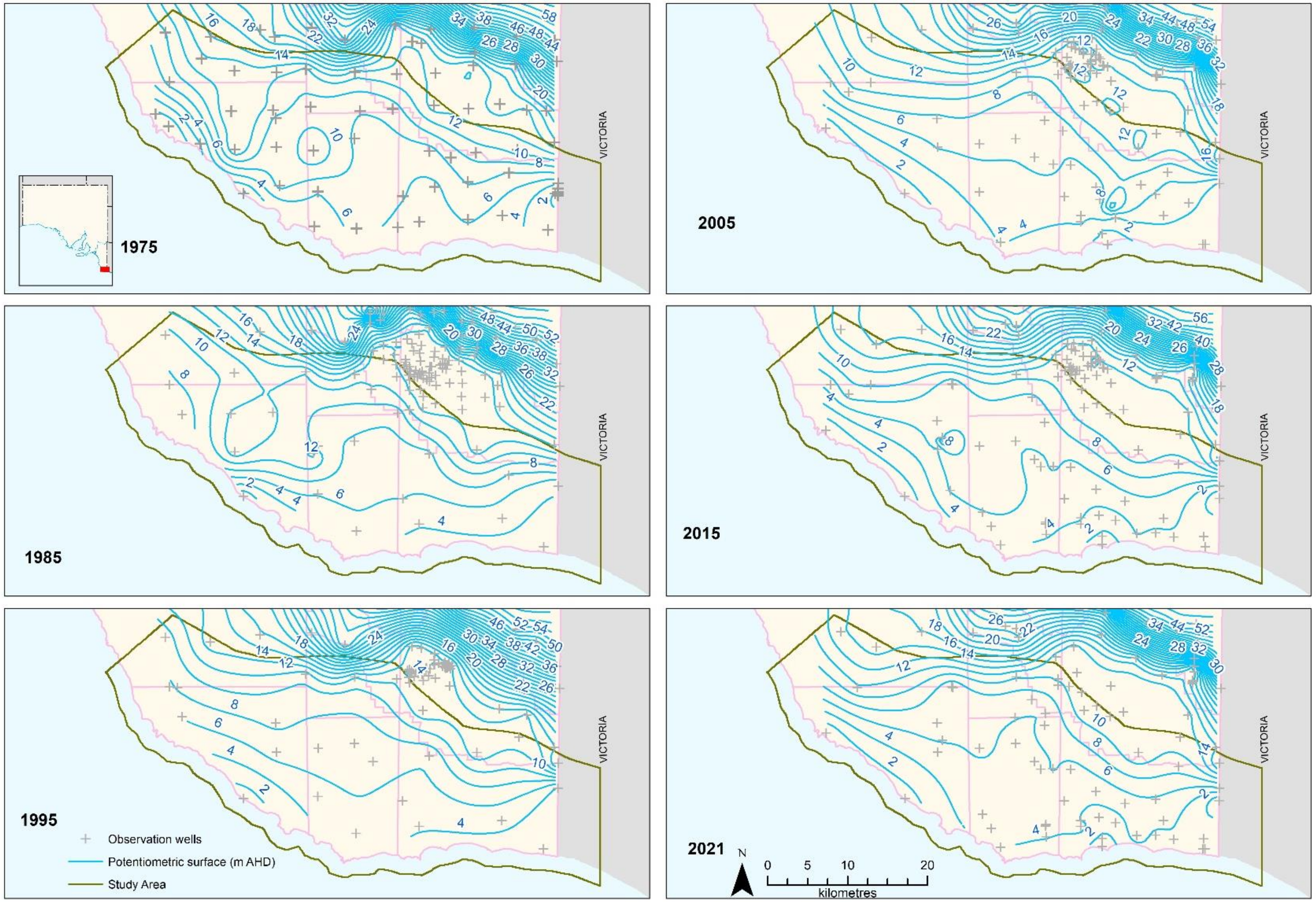


Figure 2.2. Potentiometric surfaces based on observation data

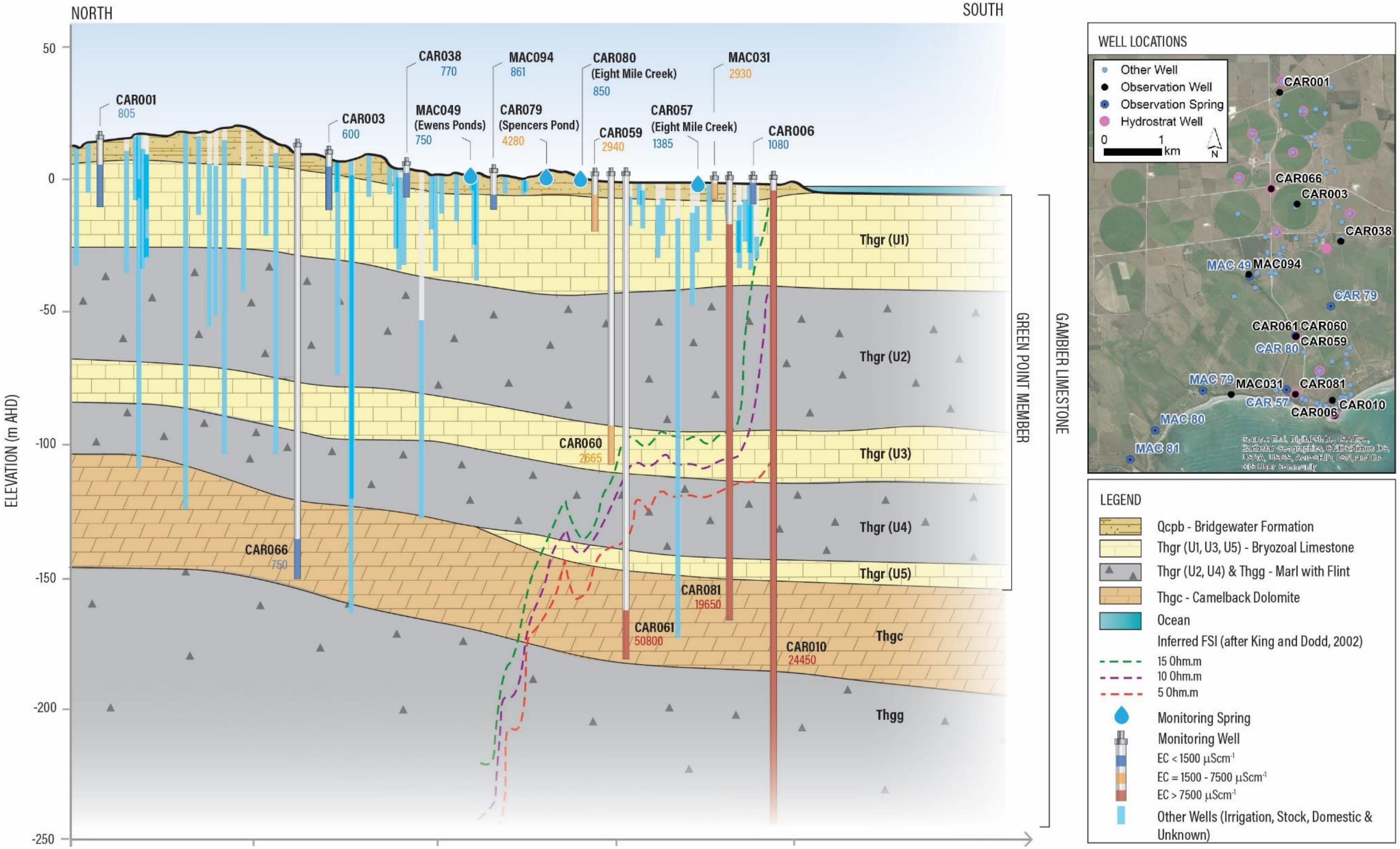


Figure 2.3. Conceptual model of aquifer and resistivity contours in the Eight Mile Creek area (DEW 2021)

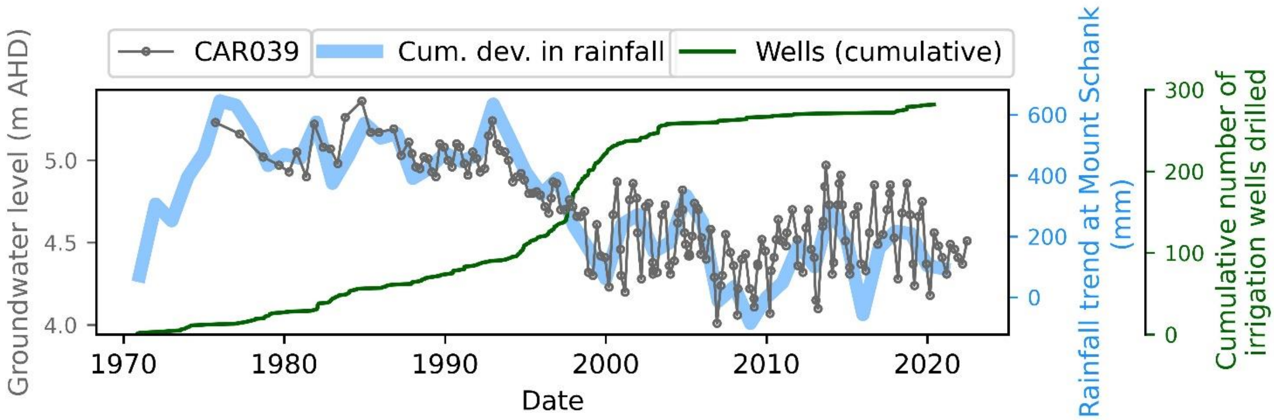


Figure 2.4. Groundwater level at MAC046, cumulative deviation in mean annual rainfall, and cumulative increase in irrigation wells in the study area

2.1.1 Inflows

A summary of the water balance developed in DEW (2021) is presented in Table 2.2. The main groundwater inflows are regional flow from the north and diffuse rainfall recharge within the study area. Groundwater levels north of the study area have declined over time; nevertheless, modelling by Stadter and Yan (2000) showed it to be a significant inflow volume. Diffuse rainfall recharge varies with land use and soil type with generally lower rates under plantation forest and clay soils (which are typically mutually exclusive) and higher rates under thin and skeletal soils where there is not significant, deep-rooted vegetation cover. Recharge varies from year to year with rainfall and has varied over time. For example, estimates from field studies were higher in the 1970s (up to 250 mm/y, Allison and Hughes (1978)) than more recent studies (Bradley et al. (1995), Wood (2011)). Fu et al. (2019) have shown that declines in recharge from 1970–2012 in the area correspond with declines in April–October rainfall. These variations are reflected in the wide range of values shown in Table 2.2.

2.1.2 Outflows

The main groundwater outflows are discharge to the coast, groundwater extraction for irrigation and evapotranspiration. Discharge at the coast occurs via multiple pathways including discharge through springs such as Ewens Ponds and Piccaninnie Ponds. Discharge from these springs is typically channeled towards the sea through drains. Flow from Piccaninnie Ponds, Eight Mile Creek (fed by Ewens Ponds), Deep Creek and Cress Creek is gauged periodically. Discharge has declined since the 1970s following declining groundwater levels and the average annual flow is ~94 GL/y (Figure 2.5). Piccaninnie Ponds is up to 110 m deep in parts and previous work has shown it to have some connection to the transition zone between seawater and freshwater (Wood and Harrington, 2015). The raising of surface water levels in the Ponds following wetland restoration work (Bachmann 2016) resulted in declining salinity, thought to be a result of lowering of the seawater-freshwater interface (Figure 2.6).

Table 2.2. Summary water balance for the study area (from DEW 2021)

Inflows	**Volume (ML/y)**
Recharge	35,409–101,644*
Regional inflow from the north	149,568**
Outflows	**Volume (ML/y)**
Coastal discharge as SGD	37,000–145,000***
Coastal discharge from springs	94,000^
Groundwater extraction	28,130–51,489^^
Evapotranspiration	4932**
Discharge to the Glenelg River	17,053**
Total inflows:	184,977–251,212
Total outflows:	181,115–312,474

* From upscaled recharge volumes from current and previous WAPs.

** From Stadter and Yan (2000).

*** From Lamontagne et al (2015) for a 25 km transect from the coast to Port MacDonnell, noting that Stadter and Yan (2000) modelled the flux as 58,000 ML/y along a 58 km stretch of coast.

^ Based on measured flow from four spring fed drains in Figure 2.5.

^^ Metered extraction data for the management areas of Donovans, MacDonnell and Kongorong.

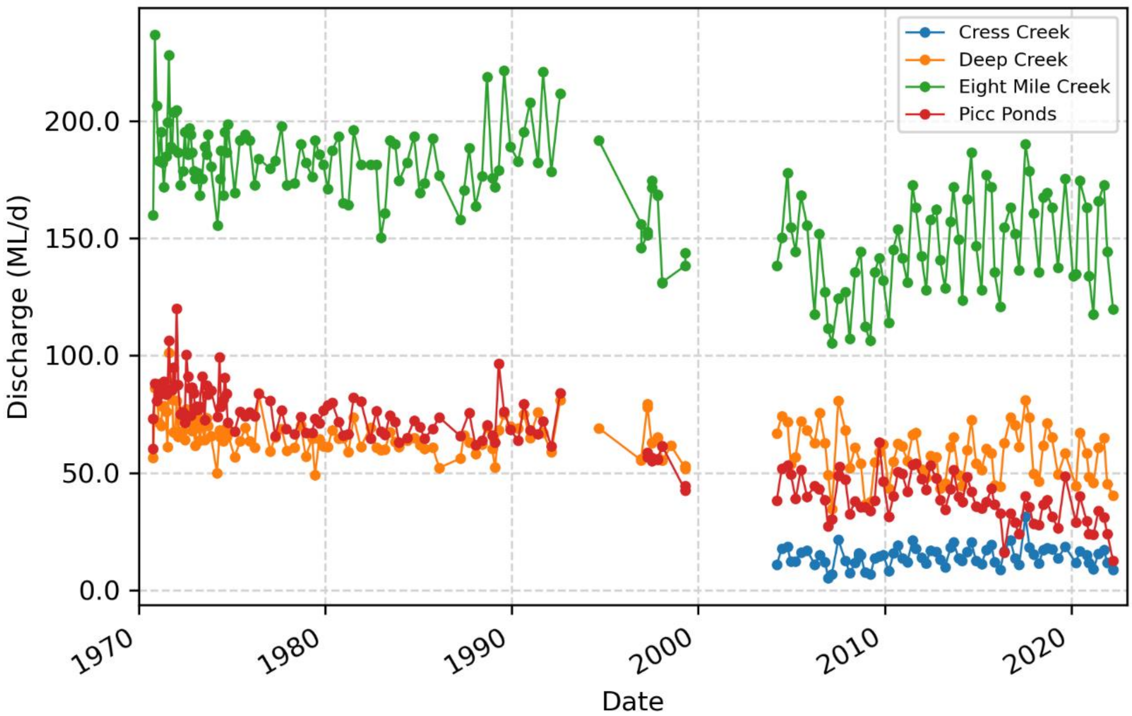


Figure 2.5. Gauged flows in the major spring-fed drains in the study area

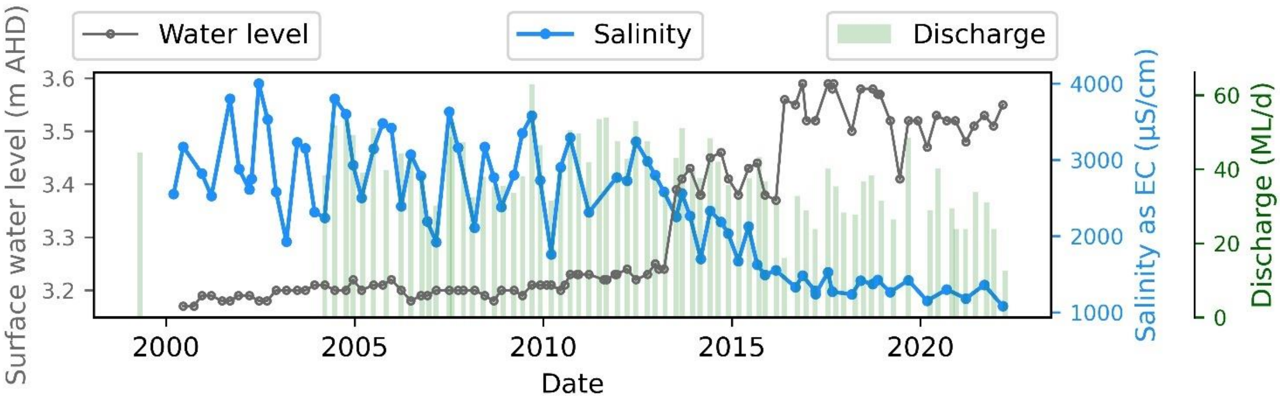


Figure 2.6. Changes in surface water level, salinity and discharge in Piccaninnie Ponds

Discharge also occurs through beach seeps and submarine groundwater discharge. Discharge from submarine groundwater discharge has been estimated by CSIRO along a 25 km stretch of coast from the border to Port MacDonnell. Based on coastal radium and salinity sampling, Lamontagne et al. (2015) estimate groundwater discharge to the coast to be approximately equal to the volume measured from spring discharge (~94 GL/y). Lamontagne et al., also estimated additional discharge from ungauged beach seeps to be no more than 50% of gauged spring discharge (i.e., no more than 47 GL/y). Some discharge to the Glenelg River is also likely to occur with the previously modelled estimates of ~17 GL/y (Stadter and Yan 2000).

Metered groundwater extraction data collected since 2008 indicates extraction ranges from 28–51 GL/y and shows an inverse relationship with rainfall, with higher extraction in low rainfall years and vice versa. Prior to metering of groundwater extraction, groundwater use is based on estimates derived from records of irrigation well constructions (Harrington and Li, 2015). There was a significant increase in construction of irrigation wells from the mid-1990s to the mid-2000s (Figure 2.4), consistent with land use maps which show an increase in areas under irrigation through this time period (DEW, 2021). Previous groundwater modelling for the area (Stadter and Yan, 2000) estimated evapotranspiration to be a relatively minor component of the water balance and there is currently interpreted to be limited groundwater use by plantation forests likely to be occurring as these typically overlie deeper (>6 m below ground) water tables in the study area. However, groundwater use by plantation forests may occur from depths greater than 6 m.

2.1.3 Water balance summary

In summary, there is large temporal variability in the key inflow and outflow processes (Table 2.2). It should be noted that some of these fluxes are not estimated at the scale of the current model area – for example, coastal discharge from springs is based on measurement from four spring-fed drains only. In general, groundwater levels in inland areas have declined since the 1970s corresponding to a decline in recharge and an increase in extraction. Closer to the coast groundwater levels have been relatively stable. However, a decline in discharge from springs along the coast has been observed since the 1970s. It is not known whether this has impacted submarine groundwater discharge over this period.

3 Model construction

3.1 Model approach, domain and grid

The model is constructed with MODFLOW-2005 to permit use of the SWI2 package for simulating the seawater interface. The Groundwater Vistas software package is used as the modelling interface. Though the study area contains significant karst features, no attempt is made to simulate conduit flow and the model has been considered an equivalent-porous media (EPM) model. Such models have been shown to be suitable for simulating flow and spring discharge in karst aquifers at the monthly or seasonal time scale (Kuniansky, 2016) which is the aim with this study.

The domain is set to cover the management areas of Donovans, MacDonnell and Kongorong, which are the coastal management areas with the highest volume of groundwater use in the Lower Limestone Coast. The southern boundary is set 2 km offshore to facilitate use of the SWI2 package, while the northern boundary is based on the boundary used by Stadter and Yan (2000). The eastern boundary extends 5 km into Victoria into part of Zone 1B of the Border Designated Area. This is an area of limited groundwater use within Victoria; hence, the model does not extend further into Victoria and should not be used to assess groundwater resource conditions and potential impacts in Zone 1B. Furthermore, while there is insufficient groundwater level data in the Glenelg River estuary area to constrain model results, the Glenelg River itself is included using the MODFLOW Drain package, discussed in section 3.8. The western boundary is set perpendicular to potentiometric contours. The model is divided into cells 100m by 100m, giving a total of 357,456 active cells over its three layers.

3.2 Boundary conditions

The northern boundary is set as a general head boundary to simulate regional groundwater flow into the study area. In the western part of the domain, the boundary head is constant with time as groundwater levels in the Benara area have been relatively constant since the 1970s. Across the rest of the boundary, groundwater levels have declined over the past 50 years (Figure 3.1). Consequently, the northern boundary condition for the rest of the domain is a time varying boundary with groundwater levels declining since the 1970s following the trends observed. This is the same approach used by Stadter and Yan (2000).

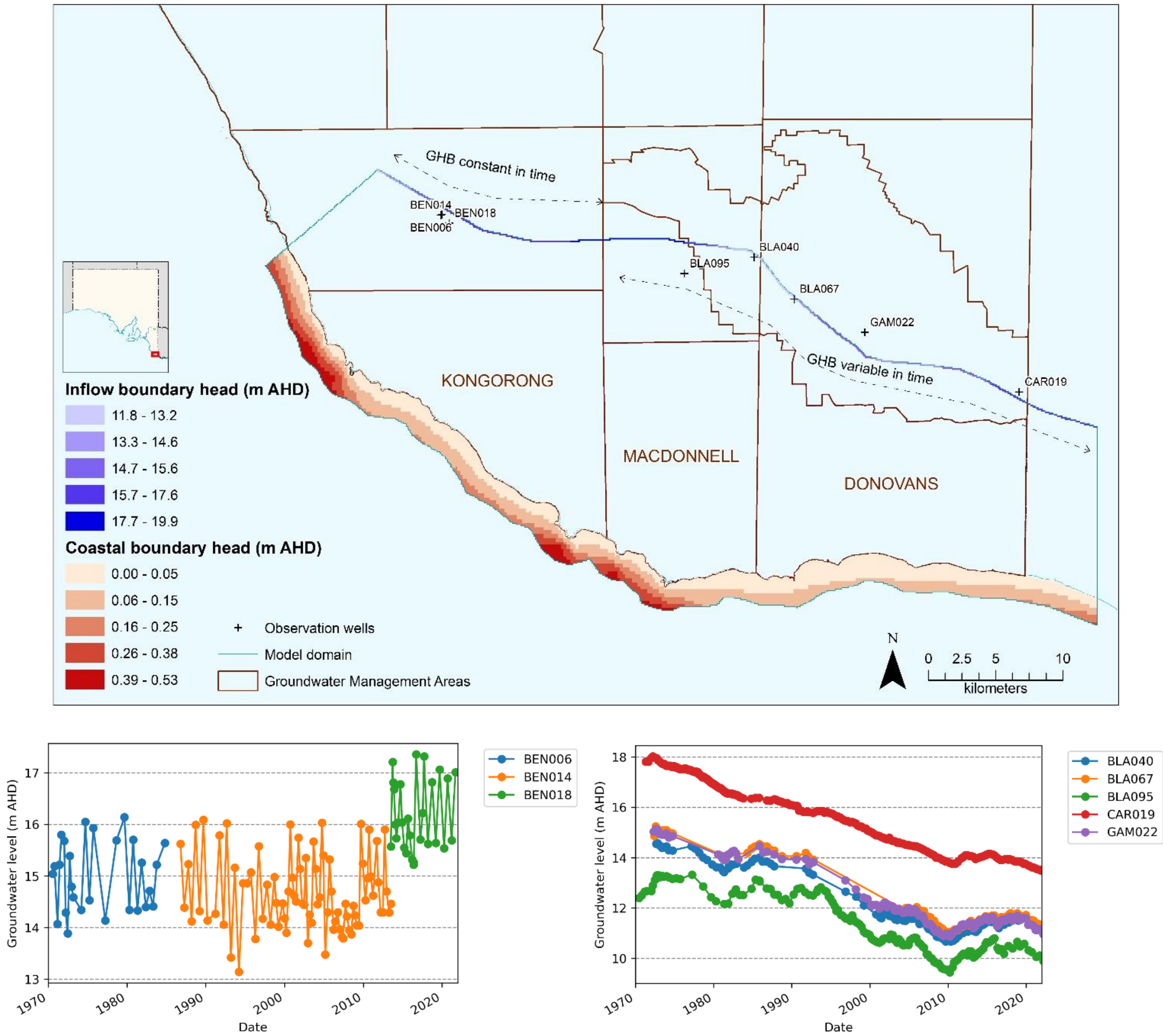


Figure 3.1. General head boundary values and groundwater level trends along inflow boundary

The southern coastal boundary is simulated with a general head boundary which is required for use of the SWI2 package to simulate the seawater interface. SWI2 has been used in many regional scale modelling studies (Hughes and White, 2016; Izuku, Rotzoll and Nishikawa, 2021) including recent work in the Eyre Peninsula, South Australia (DEW 2020a). It is acknowledged that simulating the seawater interface in this model does not provide definitive information on the extent of seawater intrusion. Rather, it provides preliminary information which will need to be assessed against observations. It should also be noted that a research project to investigate seawater intrusion through aerial geophysics and modelling has been established during model construction and calibration (Goyder Institute 2022). Should this new data and information result in a significant change to the conceptualisation used in this model, if recommended, the model can be modified accordingly and scenarios re-run.

Implementation of the SWI2 package follows recommendations in Bakker et al (2013). The domain is extended 2 km offshore so that the upper tip of the interface is not at the edge of the model domain. Coastal boundary cells are set as general head boundaries in the offshore zone. The head values in these cells represent equivalent freshwater head values at the ocean bottom following the equation:

$$\Delta h = \Delta\rho \frac{C_i}{C_{max}}(h_i - z_i)$$

where Δh is the is the correction applied to head boundary values, $\Delta\rho$ is the fractional increase in density from fresh water to sea water of 0.025, C_i and C_{max} are the concentrations at the cell and max seawater concentrations (assumed to be 35 g/L), h_i is the boundary head at the cell (assumed to be 0 m AHD) and z_i is the surface elevation at the cell. The values are constant in time. In doing so, sea level is assumed to be at 0 m AHD and tidal and seasonal sea level variations are not simulated. Densities for freshwater and seawater are set at dimensionless values of 0 and 0.025 respectively, with 0.025 applied as the concentration in the coastal GHB cells. With these parameters applied the simulated interface approximates the 50% freshwater-seawater contour.

The SWI2 package also requires parameters related to the maximum slope of the seawater interface at the tip and toe locations where the tip and toe are the locations where the interface intersects the top and bottom of an aquifer layer respectively. A maximum slope for the tip and toe of 0.2 is used, based on interpretation of geophysical data related to conductivity contours and likely position of the interface collected by King and Dodd (2002) in the Eight Mile Creek (Figure 2.3) area.

3.3 Layer elevations and layer types

The model consists of three layers, with all layers representing the Tertiary Limestone Aquifer (TLA, Table 2.1). The top of layer 1 is based on a digital elevation model developed using LiDAR (DEW 2020b) onshore. Offshore elevation for the seafloor was taken from Geoscience Australia Australian Bathymetry and Topography Grid (Whiteway, 2009). The remaining layer elevations are based on lithological interpretation from drilling logs, as described in previous studies for the area (Harrington, Chambers and Lawson (2007); Lawson (2013) and DEW (2021)). The use of multiple layers for the TLA is supported by groundwater levels in key areas of interest close to the coast. For example, in the Eight Mile Creek area, differences in aquifer lithology with depth appear to have influence on groundwater level and position of the seawater interface (Figure 2.3).

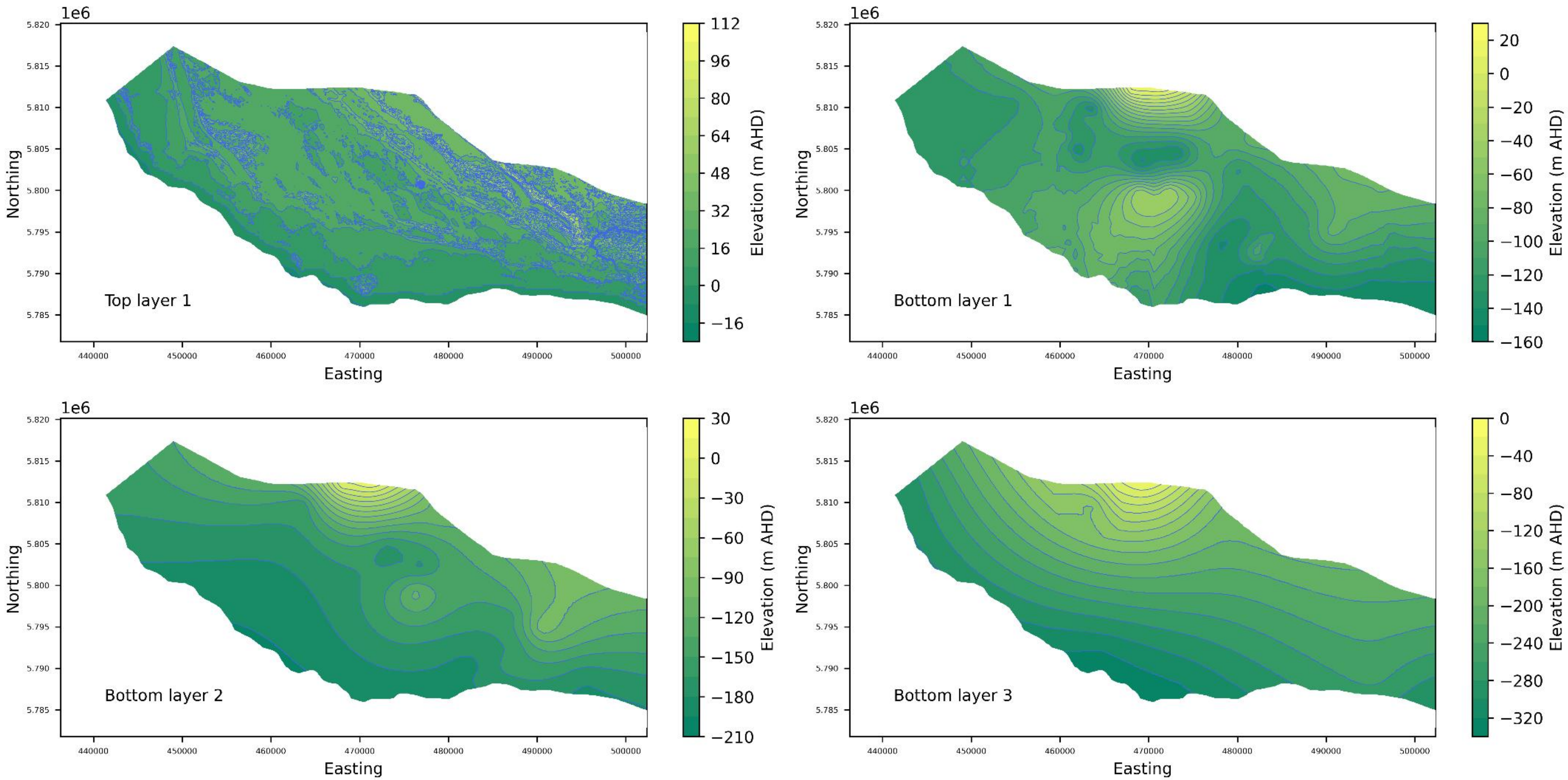


Figure 3.2. Model layer elevations

3.4 Time discretisation

Quarterly stress periods are used to approximate seasonal variability in rainfall and pumping. The model commences in August 1970 and stress periods commence on the first days of November, February, May and August. The base model consisted of 206 stress periods, simulating conditions to February 2022. Rainfall recharge is simulated through the May-October period, while irrigation pumping is simulated through the November–April period. As in DEW 2022, it is acknowledged that quarterly stress periods are coarse but given that groundwater level data is typically only available quarterly, and extraction data only available annually quarterly stress periods do not impact on the model results.

3.5 Recharge

Recharge rates are shown in Figure 3.3 and zones in Figure 3.4. Recharge rates in pasture areas are based on estimates from the water table fluctuation method, following the approach presented by Crosbie and Davies (2013) and Fu et al (2019), with wells considered to be too close to pumping wells removed from the analysis. Recharge in areas of plantation forest were set to 17% of the pasture recharge rate. This reflects the influence of plantation forests on reducing recharge (Benyon and Doody, 2004) and is consistent with assumptions applied in the LLC WAP where application of forest water accounting models results in recharge in softwood plantations being 83% less than surrounding pasture over the life of a plantation. Recharge was set to zero in areas of native vegetation, based on previous studies and following assumptions in the Lower Limestone Coast Water Allocation Plan (SENRM, 2013).

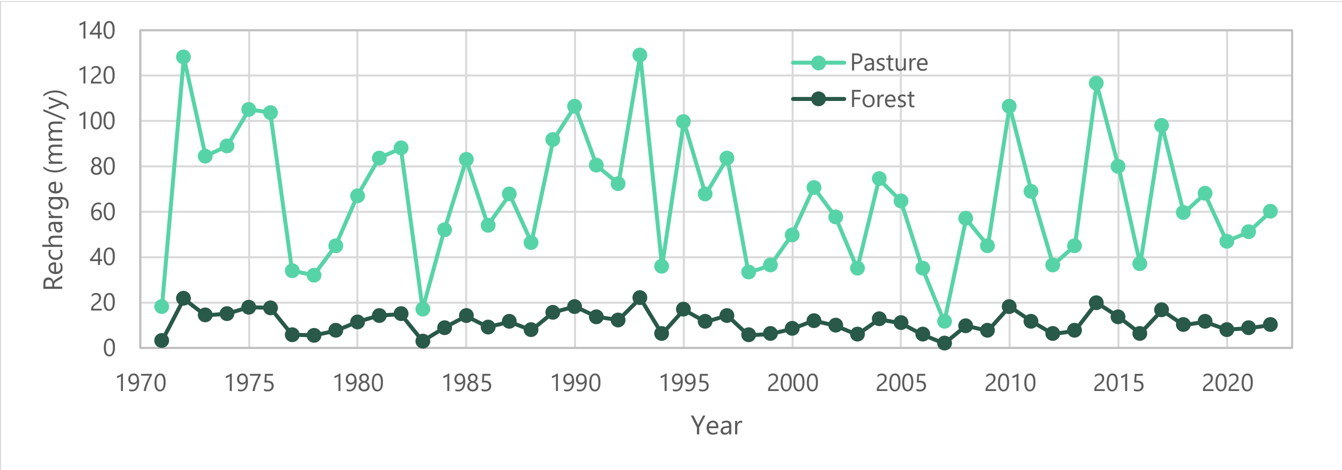


Figure 3.3. Recharge rates in the model

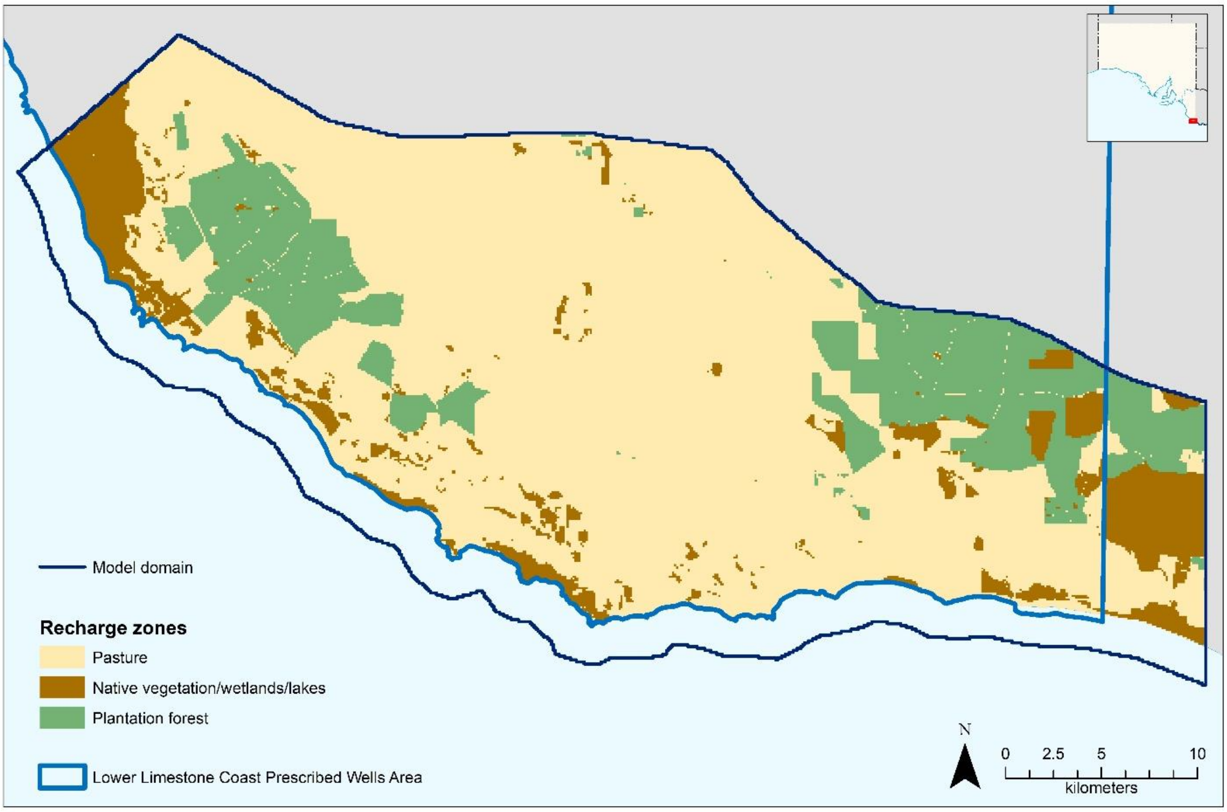


Figure 3.4. Recharge zones in the model

3.6 Evapotranspiration

Evapotranspiration (ET) for the majority of the model domain (pasture areas) is set at 450 mm/y with an extinction depth of 2 m, based on Wood (2017). ET from plantation forests is assumed to be 0 mm/y as groundwater levels are typically >6 m below ground level under plantations in the study area though some ET from plantation forests is likely.

3.7 Extraction

Extraction is based on metered data from 2007 and estimated data reported in Harrington and Li (2015) prior to 2007 (Figure 3.5). In most cases, extraction data was tied to well unit numbers. Consequently, irrigation extraction points could be tied to a well location (Figure 3.6) and depth through SA Geodata and an elevation for point extraction assigned with extraction assigned to specific layers within the model. Note this may not be the most realistic representation of extraction as extraction wells typically have shallow surface casing and thereafter are open to all sub-units of the TLA through which they are drilled. A number of extraction wells are present in the Glenburnie management area both north and south of the model domain with the time varying boundary simulating declines which may be influenced by pumping north of the domain.

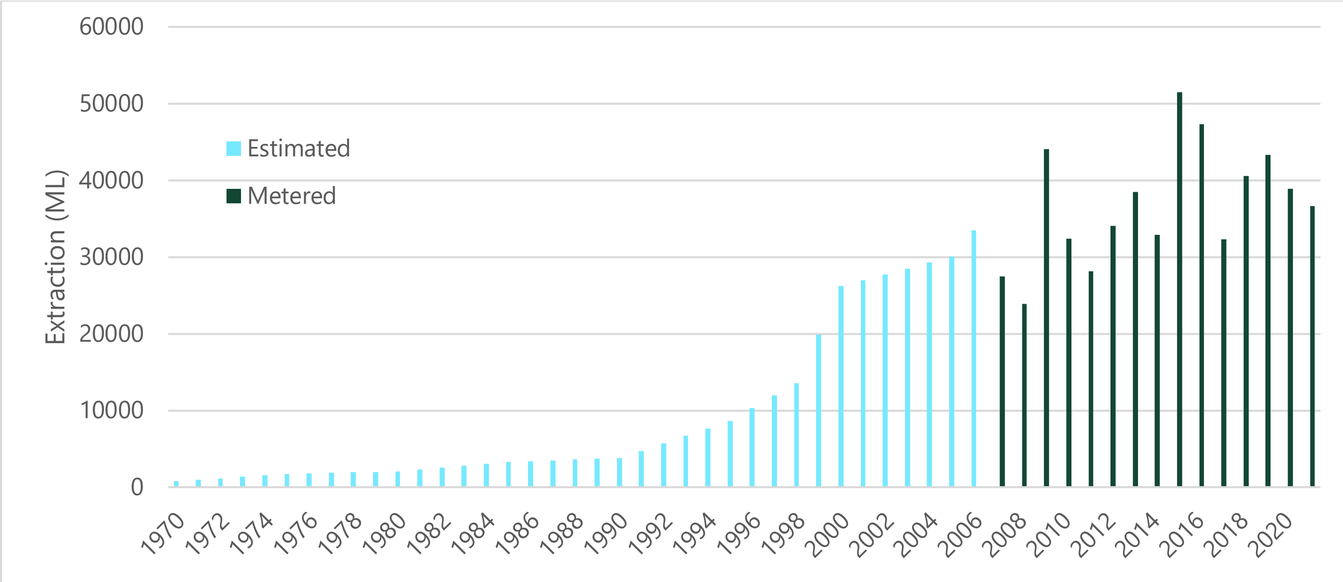


Figure 3.5. Extraction data used in the model

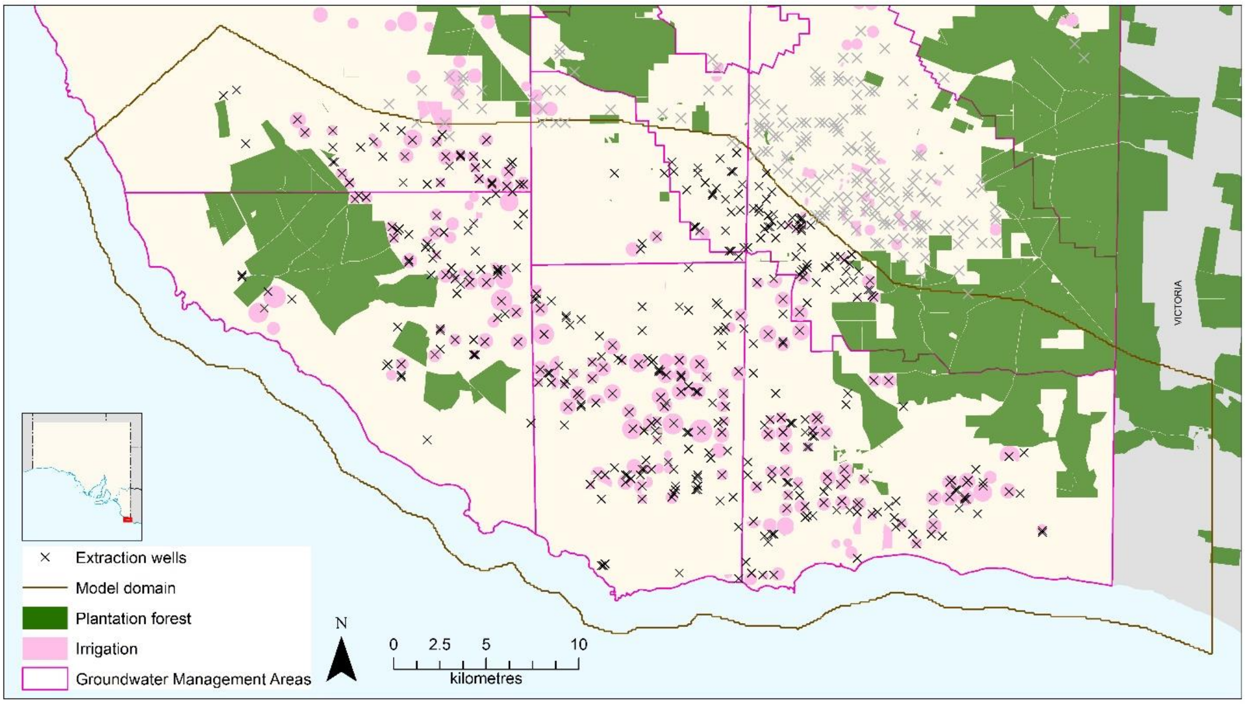


Figure 3.6. Location of extraction wells in the model domain

3.8 Springs and drains

Springs, constructed drains and the Glenelg River are represented with the MODFLOW Drains package. Drain elevations are set 1 m below the ground surface of drain cells and levels are constant in time. The exceptions are the drain cells at the location of springs, where measurements of spring water level are available, and these are used. Conductance parameters are very high for sites such as Piccaninnie Ponds (100,755 m^2/d), reflecting the way in which the springs are simulated as drains. Piccaninnie Ponds is up to 120 m deep with groundwater discharge occurring at all depths of open limestone. However, implementing Piccaninnie Ponds as a drain cell with a bottom elevation of -120 m below ground level yielded erroneous groundwater levels in the vicinity of the ponds regardless of the conductance used.

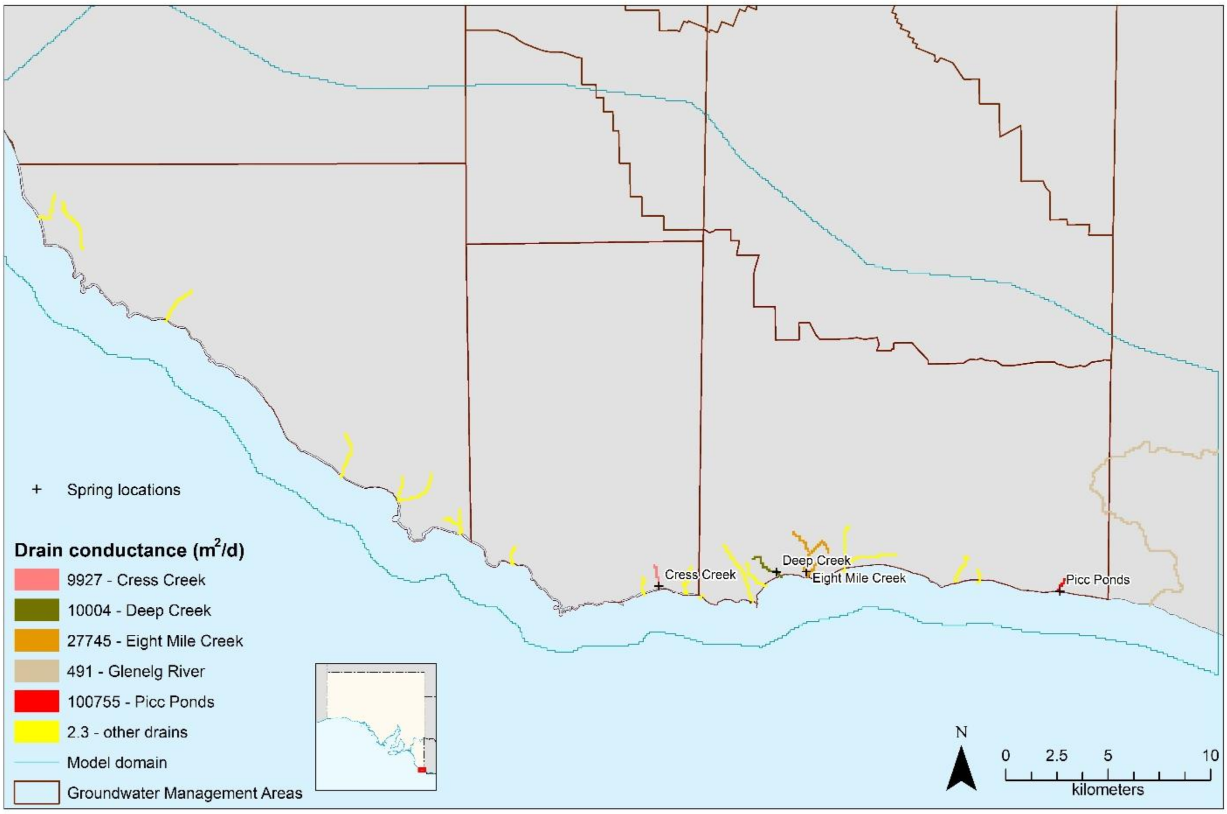


Figure 3.7. Drain locations and conductance values

3.9 Aquifer properties

Within the model domain area, there are 35 reported values for hydraulic conductivity, based on aquifer tests conducted at 16 locations (DEW, 2021). That is, multiple tests and interpreted values are available at some locations. Values range from 0.1 to 10,780 m/d where the wide variance in results reflects the heterogeneity of the area but also potentially the different types of tests applied. For example, some pump tests reported are for wells with open intervals up to 299 m for relatively short test durations (Cobb, 1979). Consequently, some test results show relatively low values, such as 0.1 m/d in wells adjacent to major karst springs, where discharge may be more than 100–200 ML/d which would indicate relatively high hydraulic conductivity. Likewise, the highest values recorded are for a more recent pump test of a well in the very north of the model domain where the results are influenced by significant fracturing encountered during drilling (Lawson and Howles, 2017). The geometric mean for pump test values in the study area is 11.6 m/d while for the whole Limestone Coast region (n=374) the geometric mean is 22.7 m/d.

Hydraulic conductivity in the model was initially implemented using zones then refined with the implementation of pilot points (Doherty, Fienen and Hunt, 2010). Spatial distribution of points was implemented using a combination of gridded pilot points and infilling at, and between, observation wells using the target triangulation feature in Groundwater Vistas with lower and upper bounds from 0.1 to 1000 m/d. Where pilot points reached the maximum bound in initial PEST runs the maximum was increased to 1400 m/d, while the maximum from any pump test value was 5000 m/d. Given that the majority of the observation wells are in layers 1 and 2, these layers contain the most pilot point values. The distributions resulting from calibration are shown in Figure 3.8 where the geometric mean values for pilot points are 34.5 m/d, 19.5 m/d and 10.5 m/d in layers 1, 2 and 3 respectively, which are in reasonable agreement with the values from measured data.

Initial attempts to include vertical conductivity (Kz) pilot points that were not tied to horizontal conductivity (Kx) pilot points resulted in unrealistic Kx:Kz ratios. Consequently, an alternative approach to calibrating Kz was implemented where pilot point values were used to determine the Kx:Kz in Groundwater Vistas. Ratio upper and lower bounds of 2 and 10,000 were used, based on Anderson, Woessner and Hunt (2015), who cite examples where values range from 2 to 20,000. OGIA (2019) describe a groundwater modelling study in which vertical anisotropy ratios were calibrated with pilot points in PEST with upper bounds up to 38,994 for sandstone layers.

Storage parameters are likewise based on pilot point calibration with initial values based on literature values. The resulting distributions are shown in Figure 3.10 with specific yield in layer 1 showing a geometric mean of 0.102, which is close to the commonly adopted value of 0.1 for the Tertiary Limestone Aquifer (Fu et al. 2019). Layers 2 and 3 are treated as confined in the model with geometric mean storativity values of 9.2×10^{-6} and 1.5×10^{-6} respectively.

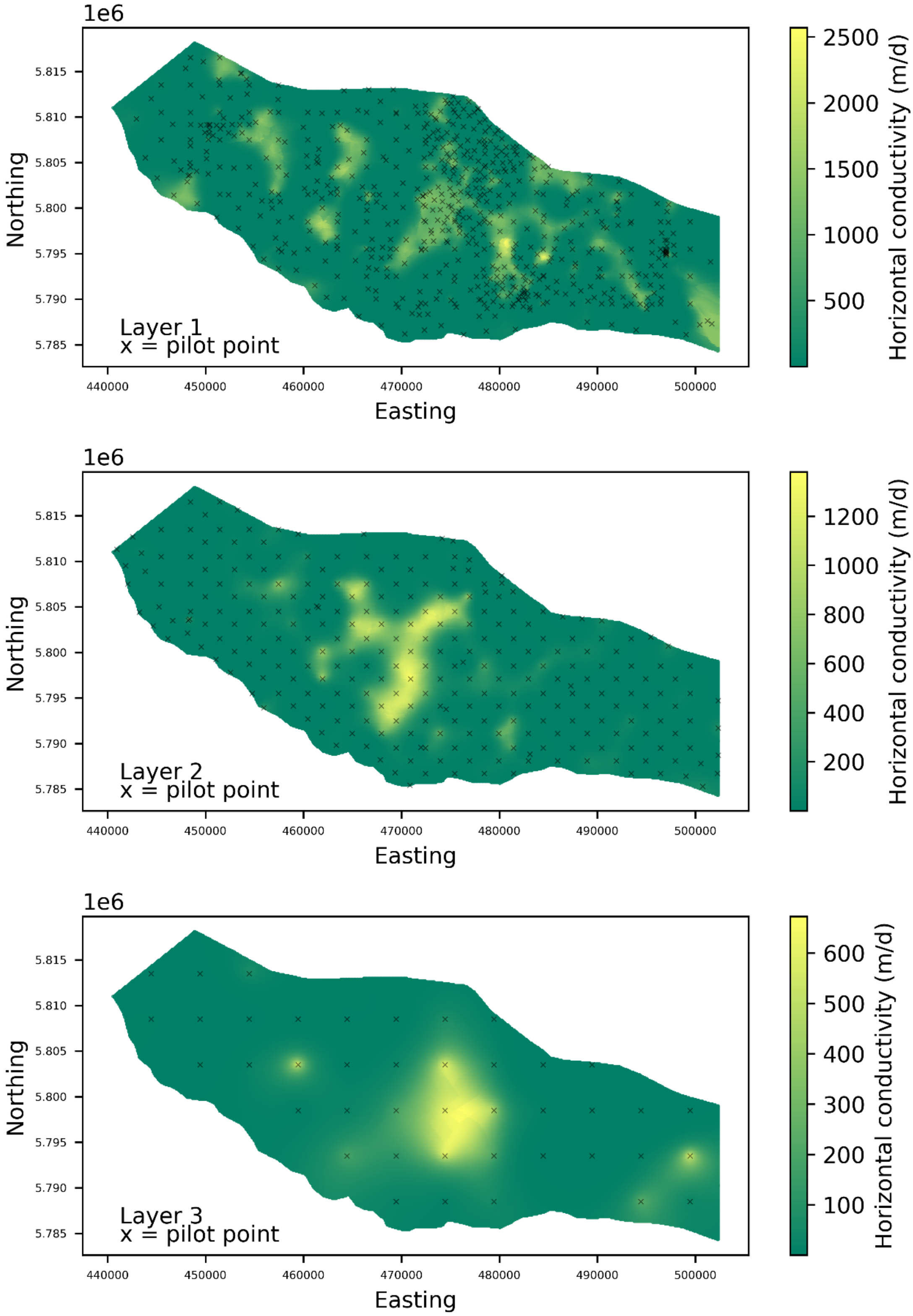


Figure 3.8. Horizontal hydraulic conductivity in the three model layers

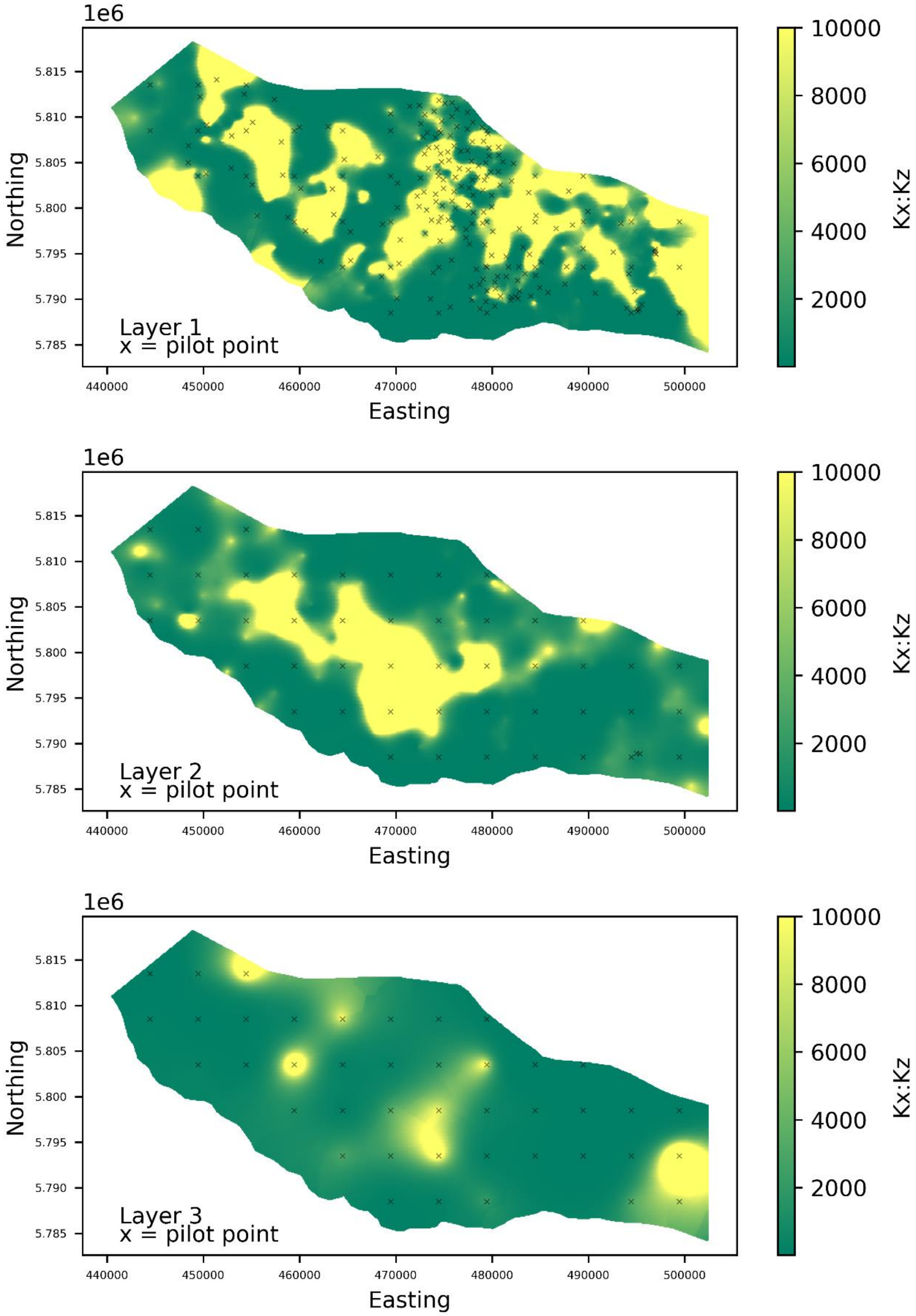


Figure 3.9. Kx:Kz values (ratio of horizontal to vertical conductivity) in the three model layers

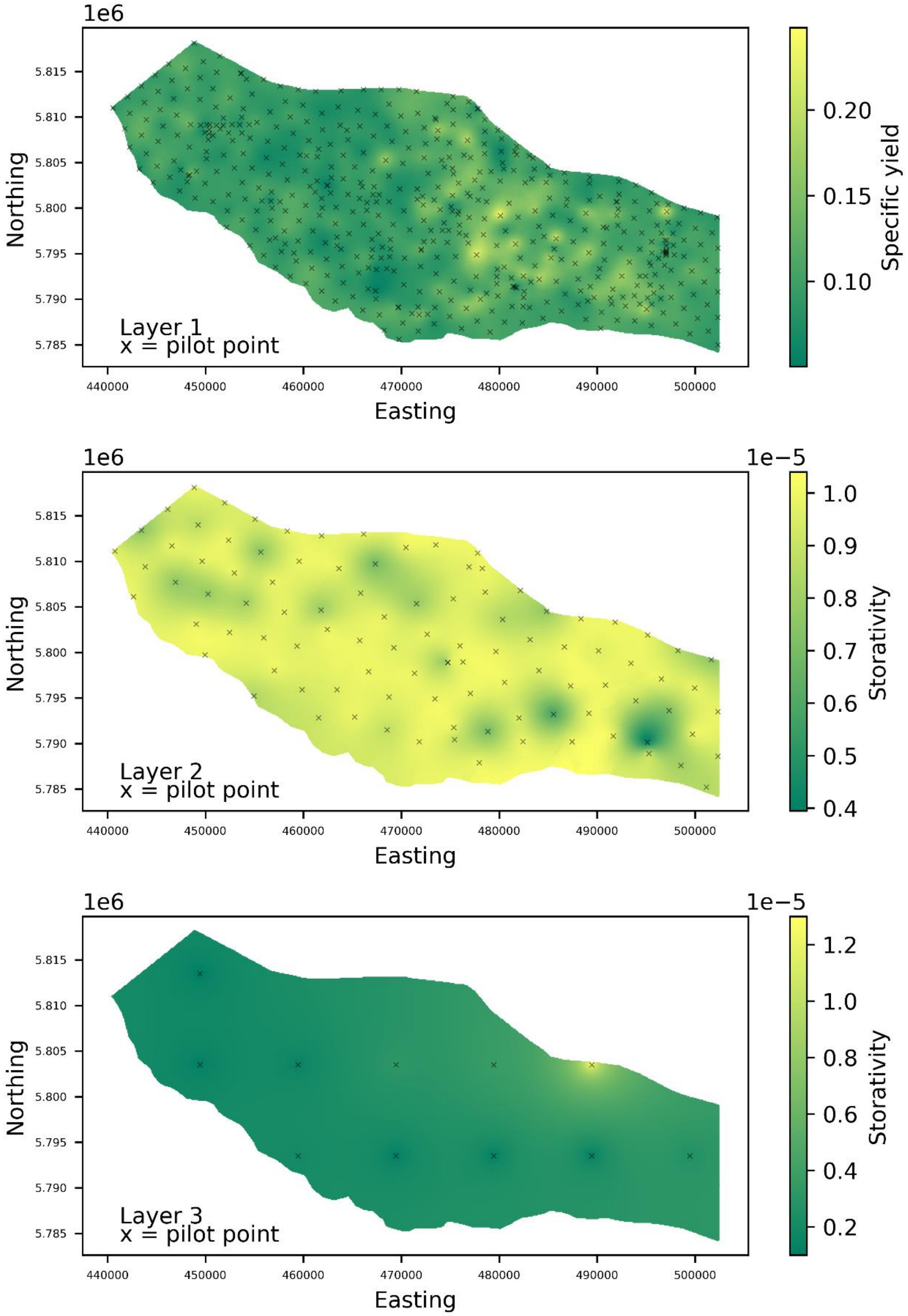


Figure 3.10. Storage properties in the three model layers

4 Model calibration

4.1 Calibration approach

The model was calibrated using an iterative manual and automated approach. Manual work included refinement of recharge and boundary values, as well as initial testing of hydraulic conductivity values, while automated calibration involved the use of PEST++ on pilot points of aquifer properties, the setup of which is described in Section 3.9. A steady state model was developed to generate initial heads and properties for the transient model and to test conceptual model questions and modelling approaches. The steady state model also served to generate initial conditions for the transient model and SWI2 simulation. Following the approach in DEW (2020a) for developing initial conditions for the SWI2 package, the steady state model was run for 10 years in transient mode but with constant fluxes over time and no groundwater extraction simulated. In this way it is best described as a quasi-steady state model. Note that no groundwater level observations prior to extraction are available so the steady state model purpose is largely to generate initial conditions for the transient model. Calibration targets for the steady state model were average groundwater levels from the period 1970–73. 1017 horizontal hydraulic conductivity (Kx) pilot points and 517 vertical hydraulic conductivity (Kz) pilot points were used in the initial steady state calibration.

The main focus of calibration was the transient model which was calibrated to measurements of groundwater level and gauged spring discharge across the model domain from 1970-2021. Preliminary calibration was undertaken using 11,054 manual measurements of groundwater level. This was supplemented with 66,184 logger measurements of daily groundwater level in later stages of calibration and uncertainty analysis. An additional 599 manual measurements of spring discharge were used in all stages of calibration with the fluxes assigned to drain reaches for the observation locations shown in Figure 3.7. Parameters allowed to vary in the PEST calibration included 946 pilot points for horizontal hydraulic conductivity (Kx), 514 pilot points for specific yield (Sy) in layer 1 and confined storage (S) in layers 2 and 3. Pilot points for Kz were not used explicitly in the transient calibration. Instead, pilot points for the ratio Kx:Kz were used. In this way, bounds on the ratio of vertical anisotropy could be maintained. There are no measurements of vertical hydraulic conductivity in sub-units of the TLA in the study area; hence, upper bounds for pilot points were set with maximum values of 10,000. The upper bound is based on limited examples in the literature of values exceeding 10,000 in sedimentary aquifers (Anderson, Hunt and Woessner, 2015; OGIA 2019). Following calibration of the transient model, the steady state model was re-run with parameters derived from transient calibration and new initial conditions were generated and applied to the final transient calibration scenario.

4.2 Groundwater levels

The fit to measured groundwater levels from the steady state model is shown in Figure 4.1 where final parameters from the transient model have been used. The root mean squared (RMS) error here is 0.85 m and scaled (SRMS) over the range in groundwater level measurements (13.7 m) is 6.2%.

For the transient model groundwater levels presented in Figure 4.2, there is some scatter, with modelled levels generally converging around a 1:1 line (Figure 4.2). The root mean squared error is 0.69 m, and the scaled root mean square error is 3.25%. These statistics are based on the 11054 manual measurements of groundwater level. Including the significant number of logger data (66,184 measurements) gives RMS of 0.49 m and SRMS of 2.3%. A cluster of outliers where the model underestimates level in Figure 4.2 relates to wells CAR002, MAC010 and MAC037. CAR002 and MAC010 show anomalous water level increases which cannot be explained by model processes and were given a low weight (0.2) in the final PEST calibration. MAC037 has a limited set of observations, and is located 500 m from MAC056 which has a longer term trend and is fit well in the model. A complete set of measured and modelled hydrographs can be found in Appendix A.

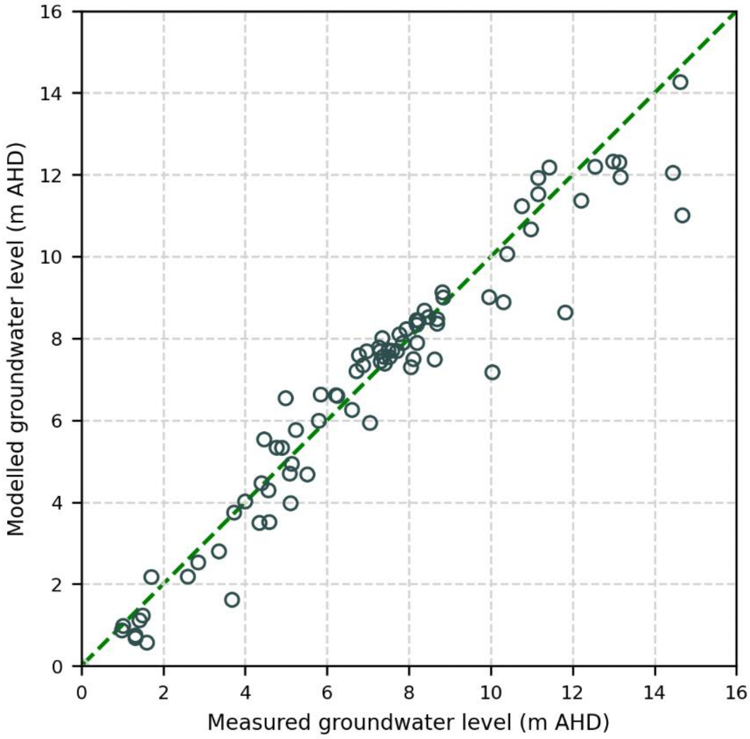


Figure 4.1. Measured and modelled groundwater levels in steady state model

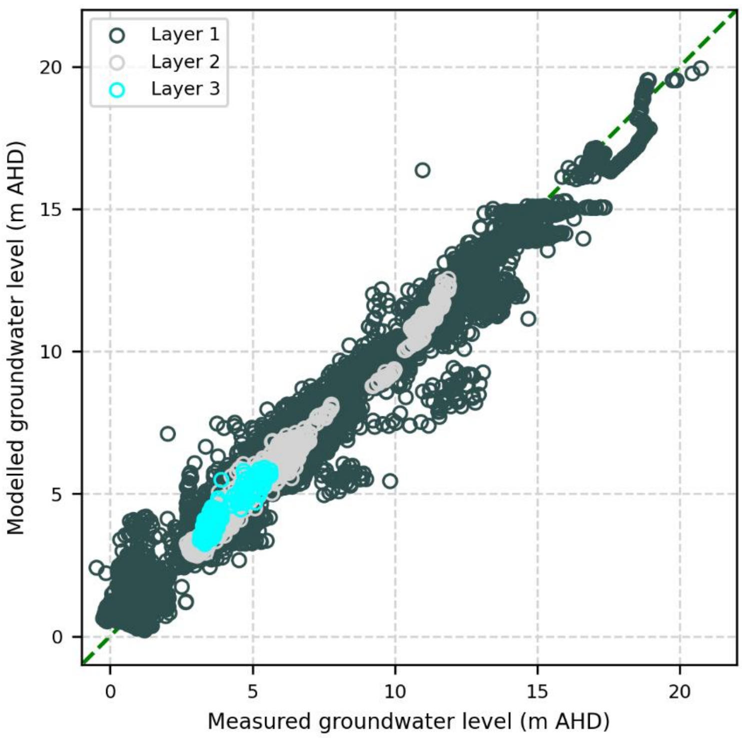


Figure 4.2. Measured and modelled groundwater levels in transient model

Groundwater levels at locations with long term data are generally well matched with the model reproducing long-term trends. Hydrographs of measured and modelled groundwater levels for all observation wells with more than

30 measurements can be found in Appendix A. In the Donovans management area (Figure 4.3) there is a generally good fit to longer term declines in wells such as MAC019, MAC047 and CAR039, with the model slightly overestimating groundwater levels. Long-term observations close to the coast are limited. CAR011 shows groundwater levels overestimated historically; however, there is a good match to recent trends following the raising of water levels in Piccaninnie Ponds. This is simulated with the stage of the Drain cells in Piccaninnie Ponds being raised. Measured groundwater levels for CAR061 are density corrected (DEW, 2021) and the model simulates these well – noting that observation well CAR061 is in layer 2 of the model.

In the MacDonnell management area, the long-term trend is also well matched (Figure 4.4); however, under and over estimation is noted variously across the management area. The same is apparent for the Kongorong management area (Figure 4.5), where some interesting trends emerge. For example, groundwater levels in KON014 were not initially density corrected as the most recent salinity results record 'fresh' groundwater. However, this well was drilled into the seawater interface in 1975 with salinity of 23,000 mg/L recorded at 40 m below ground. The SWI2 simulation shows the interface present in this model cell at 20 to 23 m below ground. Therefore, groundwater levels were subsequently density corrected and show a good fit to model results (corrected and uncorrected levels are presented in Figure 4.5 for comparison). Observation well KON010 on the other hand is only drilled to a relatively shallow depth and no higher salinity readings are recorded; hence, the groundwater level is not density corrected. However, model results show the seawater interface could be present at this location and modelled groundwater levels are higher than those measured. Other points to note include modelled groundwater levels at KON033 which do not match seasonal high-water levels observed. However, KON033 is completed at ground level in a roadside verge and monitoring records note the presence of surface water from rainfall in the verge surrounding the well which may explain some of the seasonal high readings.

The modelled potentiometric surface (Figure 4.6) approximately matches the measured surface, noting the location and density of observation points. The biggest discrepancy relates to the 6 m contour line which crosses the central part of the domain where measurement data is sparse. Some observations closer to the coast show groundwater levels above 6 m AHD such as KON033; however, as mentioned above, these data may be influenced by roadside flooding and are not included in the potentiometric surface in Figure 4.6.

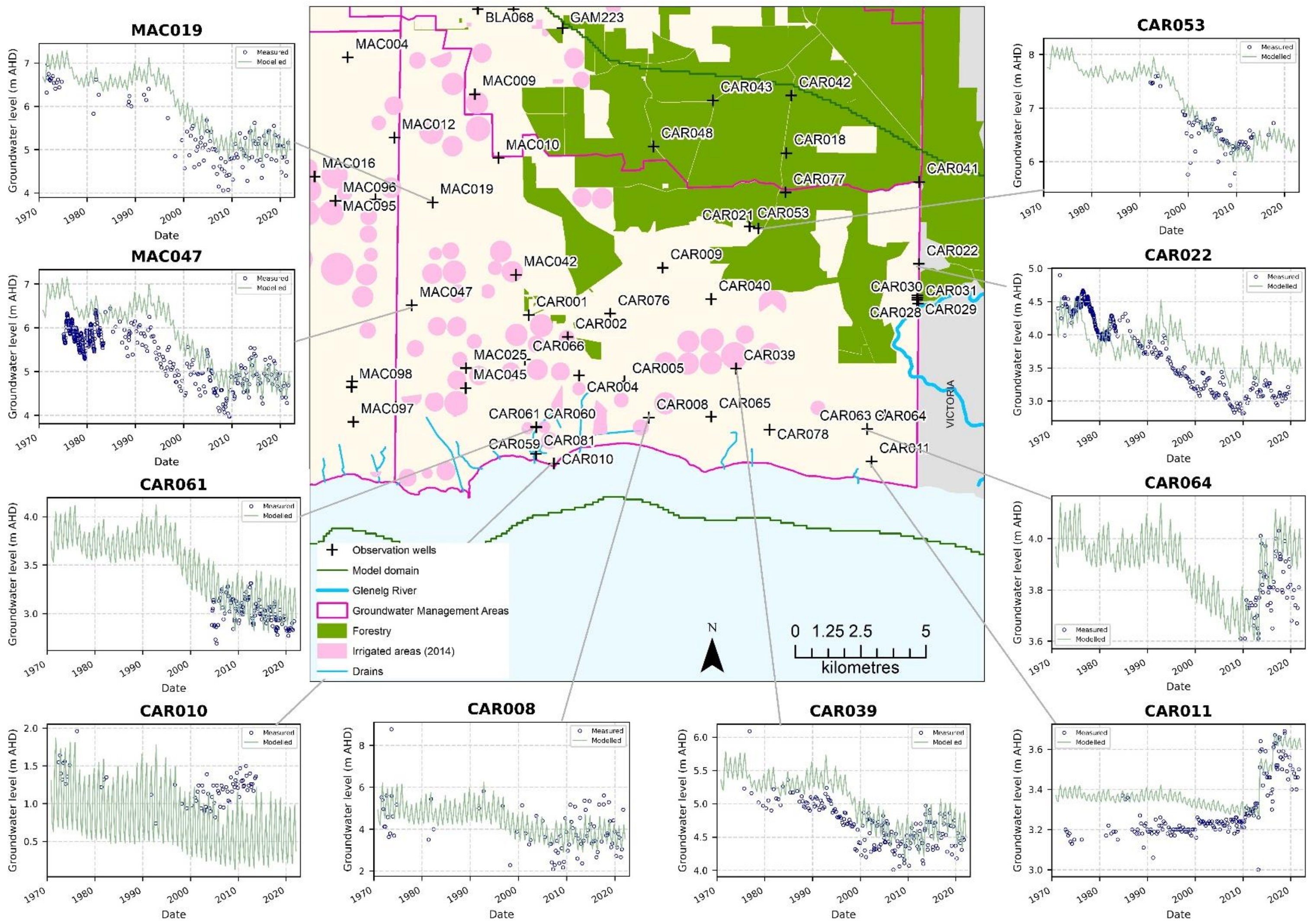


Figure 4.3. Time series of measured and modelled groundwater levels in and around the Donovans management area

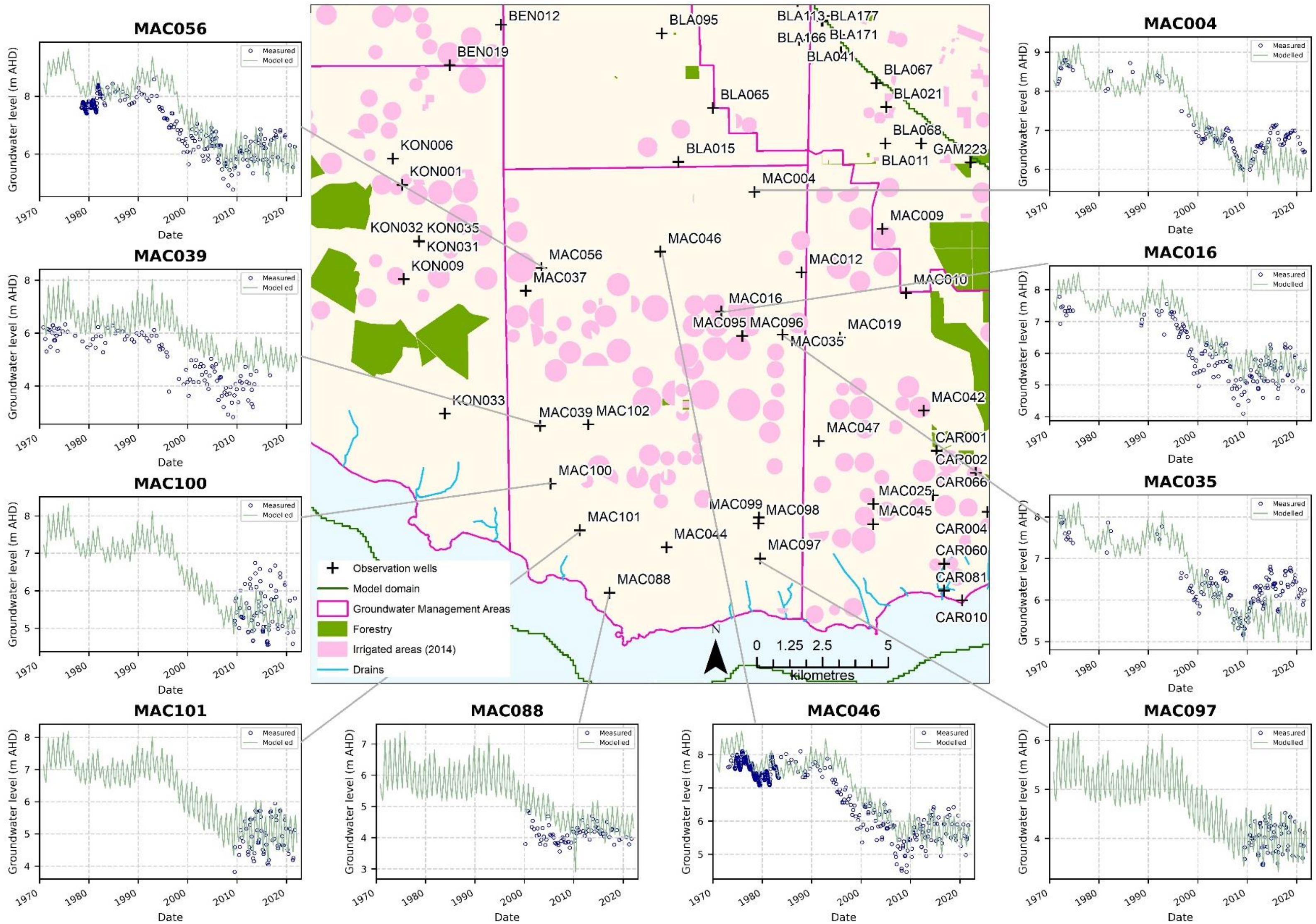


Figure 4.4. Time series of measured and modelled groundwater levels in the MacDonnell management area

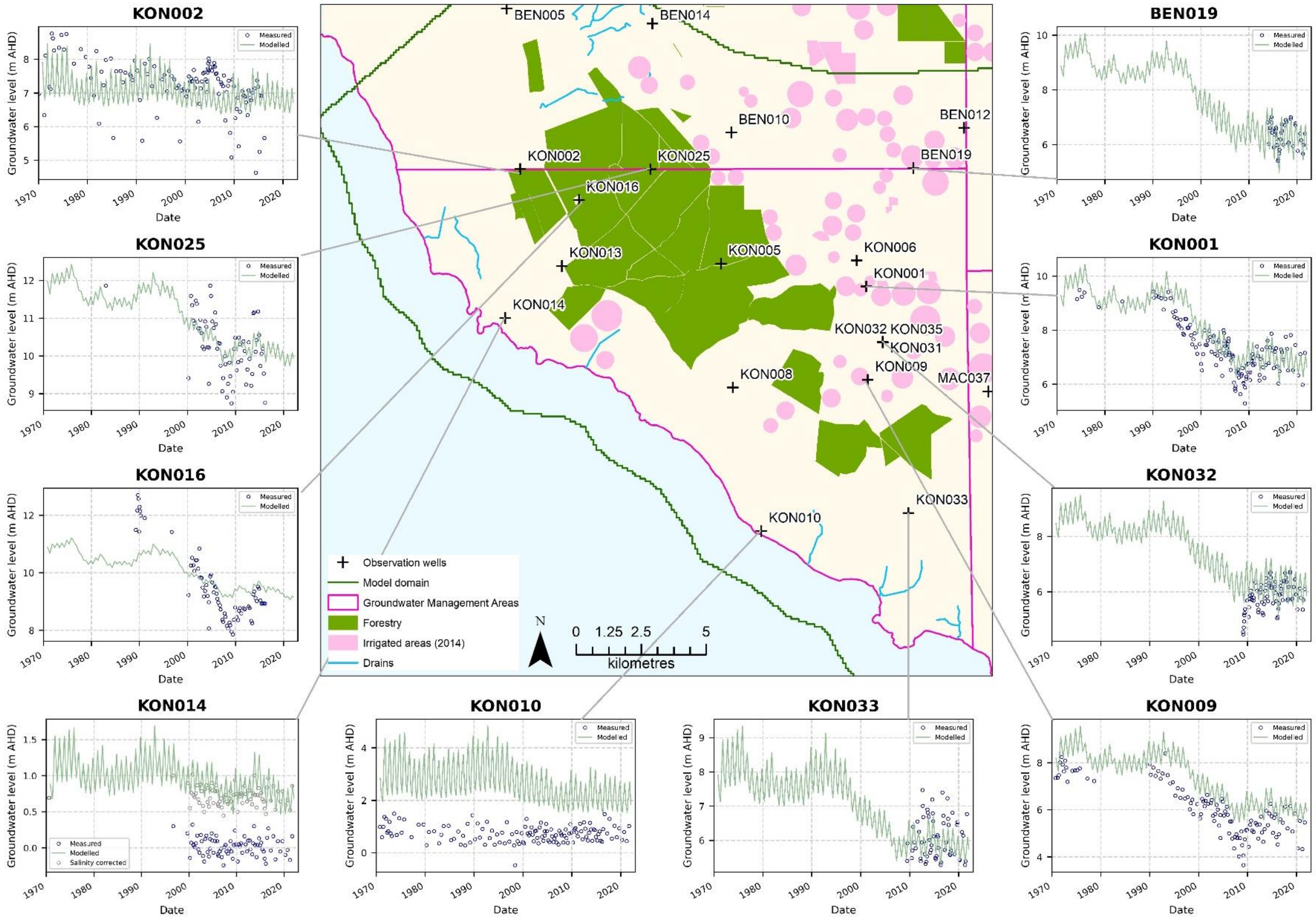


Figure 4.5. Time series of measured and modelled groundwater levels in the Kongorong management area

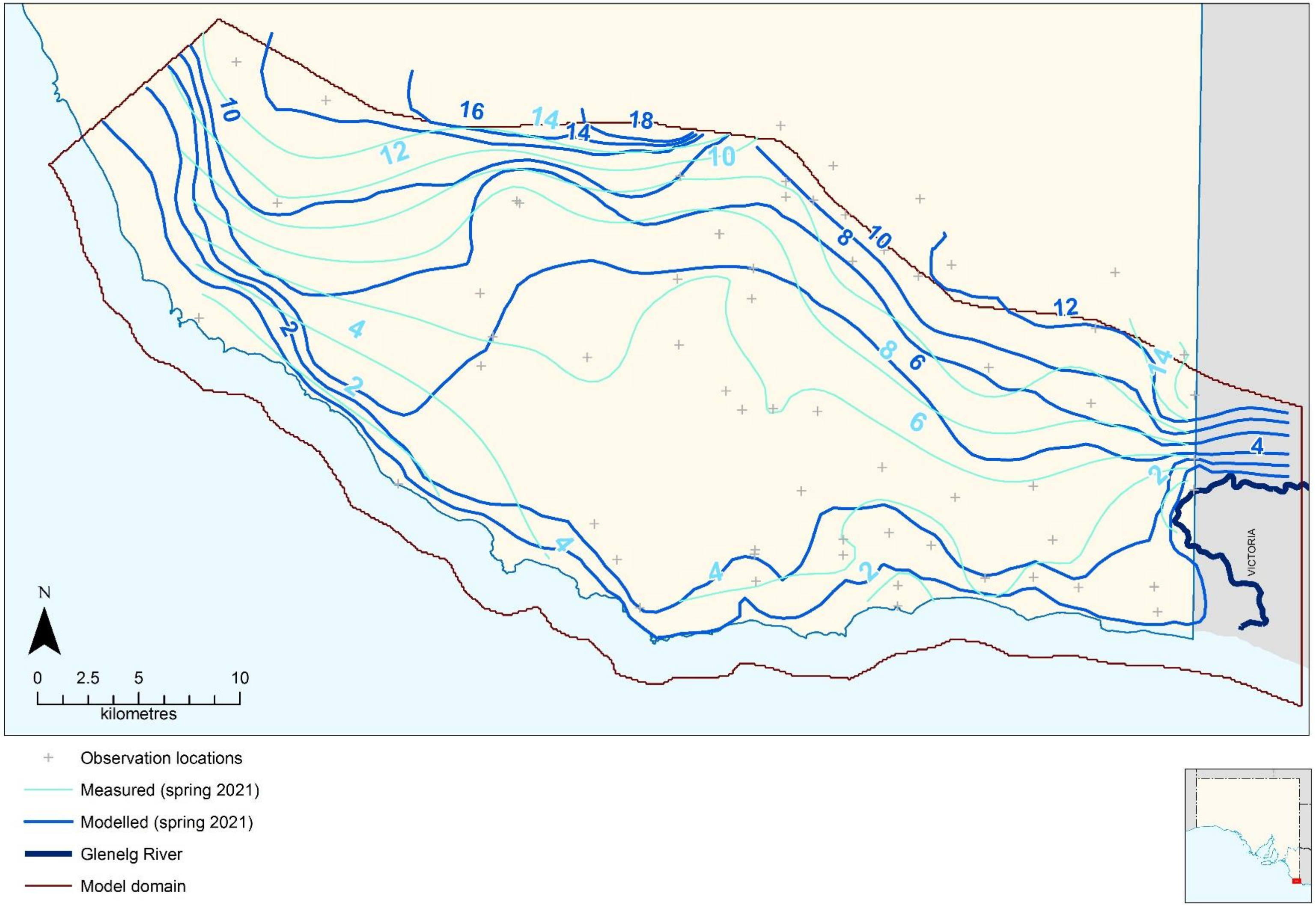


Figure 4.6. Measured and modelled potentiometric surfaces

4.3 Karst spring discharge

Measurements of groundwater discharge from gauged spring-fed drains were included in model calibration. Discharge volumes were assigned to drain cells for the reaches labelled in Figure 3.7. Modelled discharges broadly correlate with measurements (Figure 4.7) with a SRMS of 6.55%. Trends in groundwater discharge also match what has been observed historically with overall declines in discharge between the 1970s and the present (Figure 4.8).

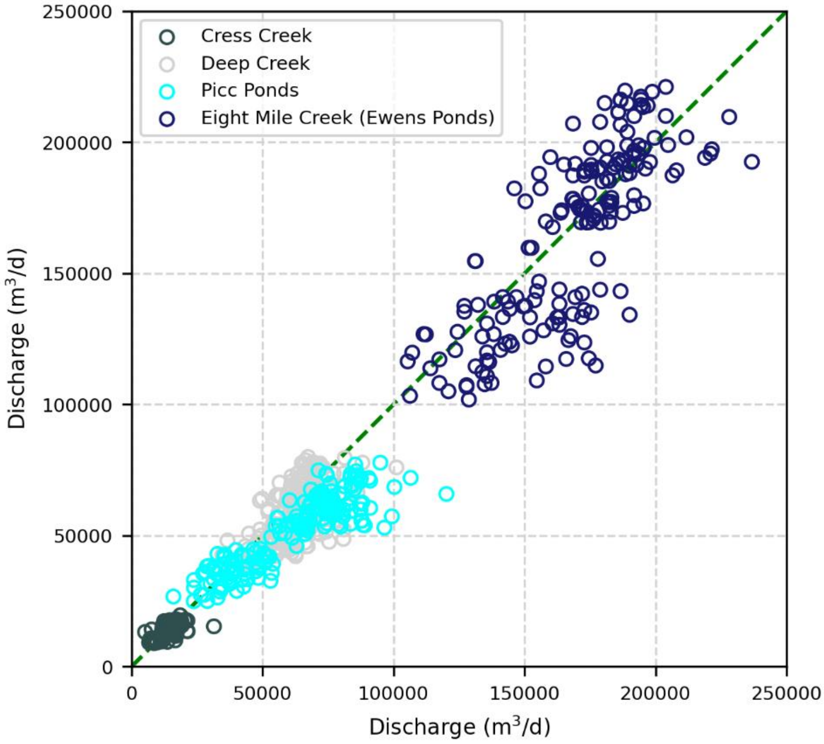


Figure 4.7. Measured and modelled spring discharge rates in transient model

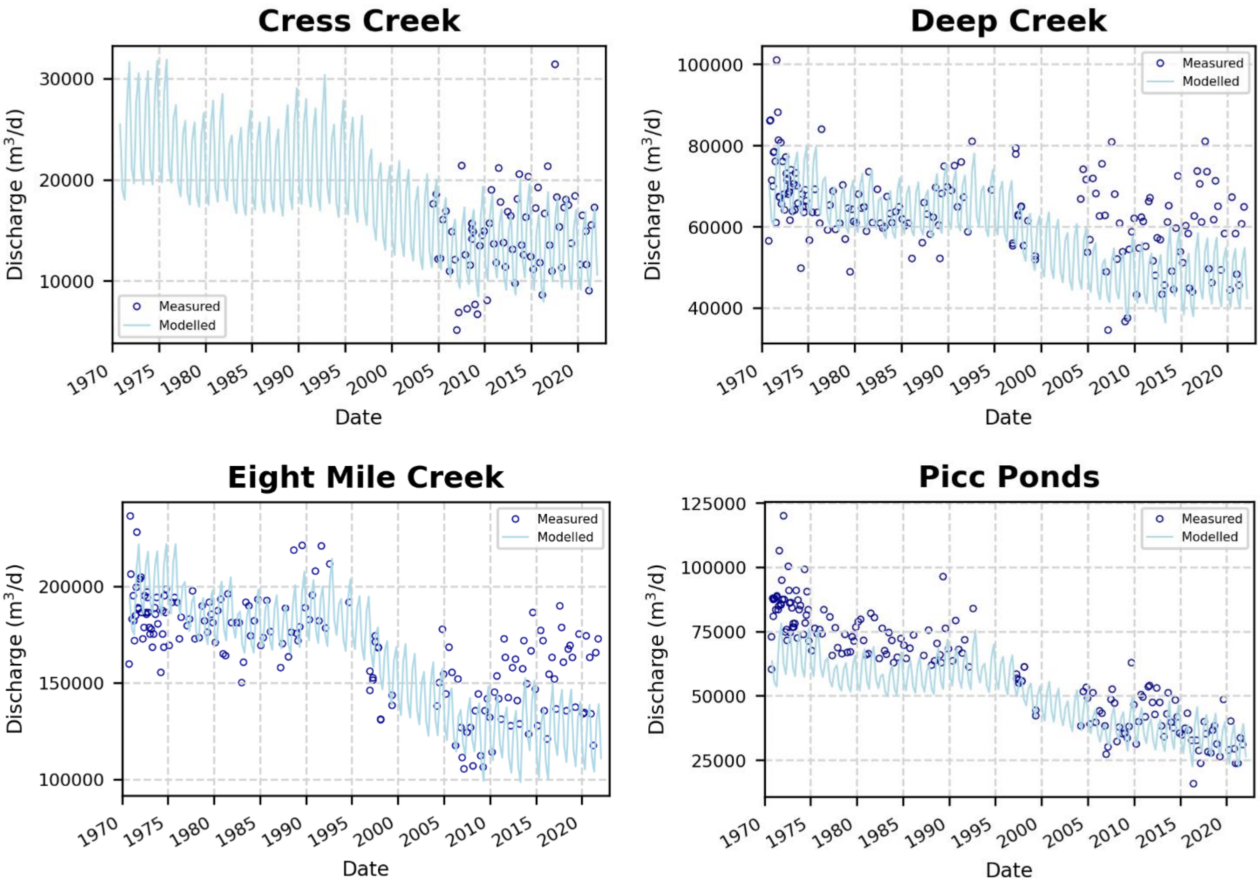


Figure 4.8. Time series of measured and modelled spring discharge rates in the transient model

4.4 Water balance

The mass balance shows that in the early parts of the simulation, discharge is dominated by flux from the drain cells (Fig 4.6). Note this includes flux from all springs and drains and Glenelg River in the domain. The simulated flux from drains reduces significantly from 1970 to 2022 with the flux from drains becoming equal to coastal discharge at the head boundary (discharge to the ocean) from approximately 2005 onwards. Conceptually this agrees with Lamontagne et al. (2015), who estimated that terrestrial groundwater discharge to a 25 km stretch of the coast was approximately equal to measured discharge from four coastal springs.

Simulated evapotranspiration is higher than that reported by Stadter and Yan (2000) which is possibly due to the difference in modelling approach. For example, modelled groundwater ET is most likely to occur in areas where the water table is shallowest, generally closer to the coast. Stadter and Yan simulated discharge to springs using general head boundaries and modified elevation of the underlying Tertiary aquitard to replicate the seawater interface, thus driving flux towards springs. This approach may have resulted in different modelled groundwater elevations close to the coast, where the water table is shallowest; however, there was less groundwater level data available close to the coast to constrain this at the time of the model by Stadter and Yan. In the current study the seawater interface was being simulated explicitly with the SWI2 package and there was more groundwater data close to the coast available to constrain model results; hence, the modelled evapotranspiration is expected to be different.

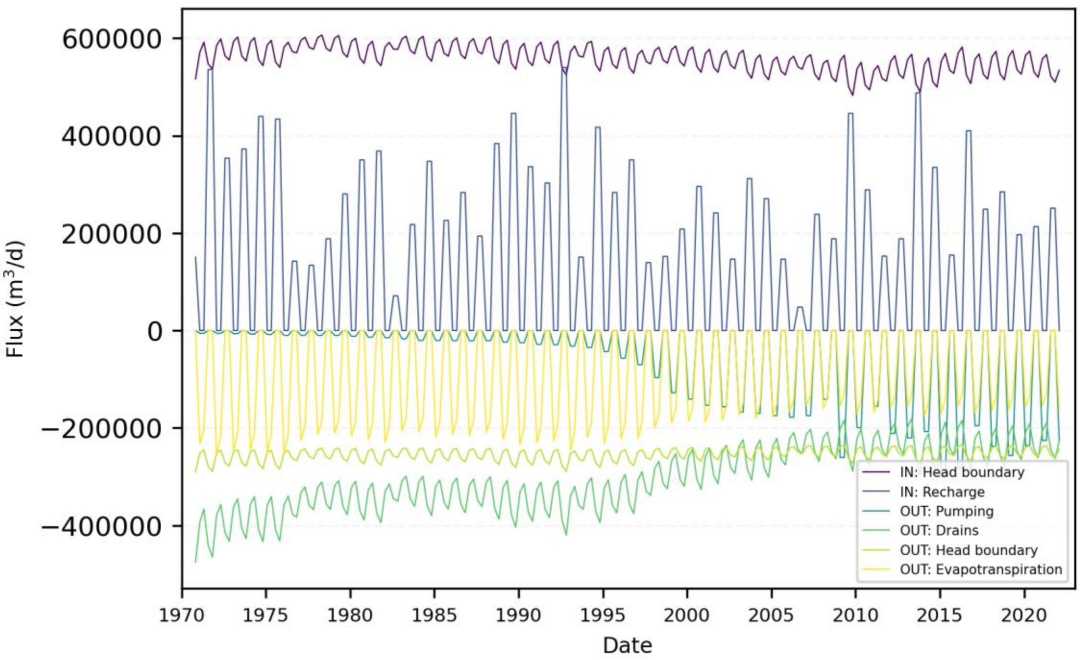


Figure 4.9. Transient mass balance from the model

As described in section 3.7, pumping data is imported and assigned to layers based on total depths of wells. This may not be the most accurate representation where extraction wells typically have shallow surface casing and are thereafter open to all formations they penetrate. However, it provides a conservative approach for assessing seawater intrusion risk. Following this approach, groundwater extraction is apportioned relatively evenly between layers 1 and 2 (Figure 4.10). In the early parts of the simulation, extraction is predominantly from layer 1 as most irrigation wells from this time would have been relatively shallow. However, extraction from layer 2 becomes greater from 2000 onwards as more and deeper wells are drilled in the region. From 2000 onwards extraction from layers 1 and 2 is generally of a similar magnitude; however, extraction from layer 2 does exceed that from layer 1 by up to 48,000 m^3/d in 2016 (Figure 4.10).

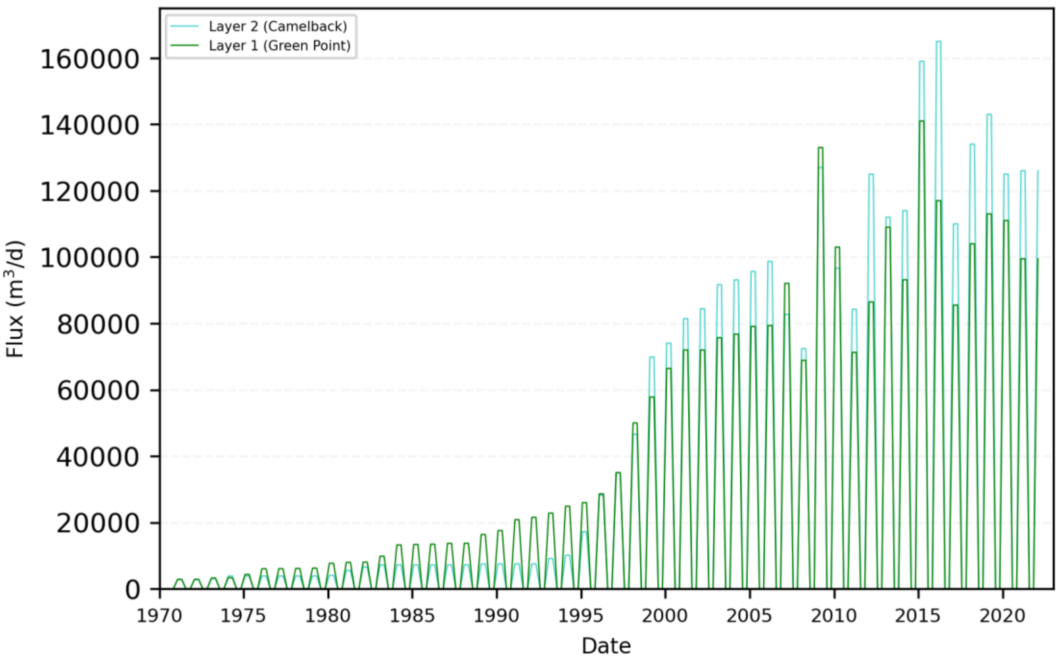


Figure 4.10. Simulated pumping from model layers

4.5 Seawater interface

The modelled position of the interface varies within each layer with some results showing agreement with observations and some results showing the modelled position of the interface does not match observations. Note the interface as presented in SWI2 results represents the 50% isohaline between freshwater and seawater. Figure 4.11 shows the simulated position of the interface toe in each layer at the end of the model simulation (January 2022). The interface toe is the point at which the 50% isohaline intersects the bottom of the model layer. Also shown are all recorded measurements of groundwater salinity in the TLA in the study area that are greater than 5000 µS/cm. Modelled inland positions of the interface toe generally correspond with observations of higher groundwater salinity in coastal wells. It should be reiterated here that information on the depth, inland extent, and movement of the seawater interface is limited in the study area.

The furthest inland extent of the interface occurs in layer 1 in relation to the Glenelg River. This result is not unexpected as the Glenelg River drain cells have elevations close to 0 m AHD and the Glenelg River at 7 km inland at the SA-Vic border has historically shown salinity ranging from 18,500 to 44,000 µS/cm. Butcher et al (2017) describe the Glenelg River estuary as the longest estuary system in Victoria at 75 km with salinity in the upper parts of the estuary sometimes matching that of seawater. Groundwater salinity data in the vicinity of the river is limited; however, some wells have recorded higher salinity in the past. The exact configuration of salinity within the aquifer in the vicinity of the Glenelg River is not known; hence, the results are difficult to assess in greater detail. This inland extent in the Glenelg River estuary is not reflected in the underlying layers which may be influenced by low vertical conductance.

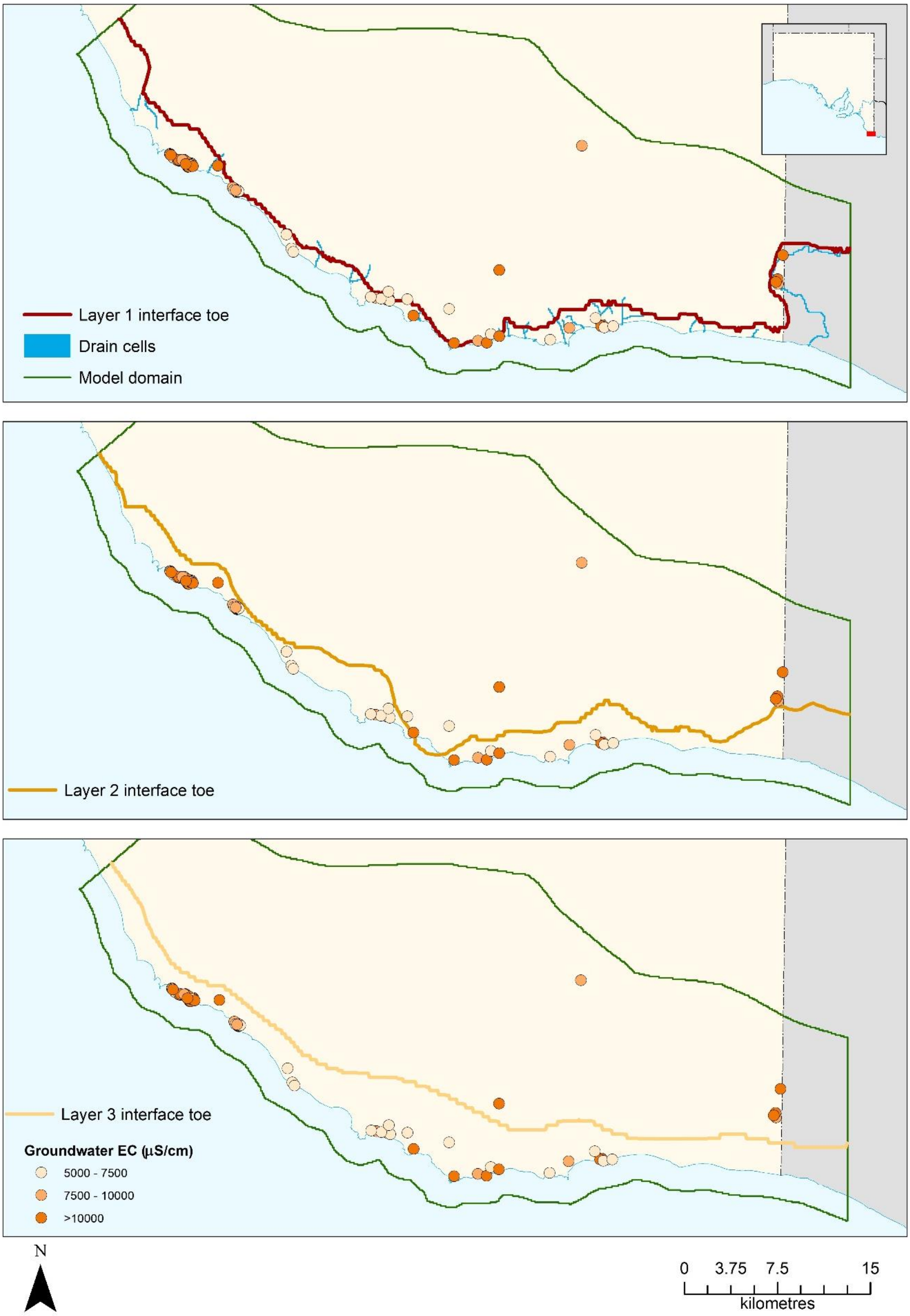


Figure 4.11. Simulated position of the seawater interface

5 Model uncertainty and limitations

5.1 Assumptions and limitations

The model makes several assumptions in parameterising and simulating processes in the study area. The following assumptions and limitations have been identified with the current model, along with a discussion of potential future work to make improvements.

- While the SWI2 package has been used to simulate the position and movement of the seawater interface there is limited data with which to compare results. Consequently, the model should not be used to make absolute determinations related to potential future movement of the interface. Work is currently underway to investigate the position of the seawater interface in greater detail using airborne electromagnetic (AEM) surveys and modelling (Goyder Institute, 2022). It is anticipated that this work will provide improved understanding which may be used in future to improve results from this model.
- Extraction wells in the model are assigned to the model layer in which the maximum depth of the well is located. Consequently, extraction is split approximately equally between layer 1 and layer 2 (Figure 4.10). In reality, extraction wells are typically only cased to shallow depths and remain open to the formation – that is completed without casing or screens – for the remaining depth. Hence a 150 m deep well with a pump set at shallow depth may occur in layer 2 in the model while in reality drawing water from layer 1 and 2, or potentially layer 1 entirely if zones of higher conductivity are encountered. While running model scenarios, an additional scenario was tested in which all groundwater extraction occurs from layer 1 rather than split between layer 1 and 2. This yielded only minor differences in groundwater level in a small number of wells and no significant difference in modelled spring discharge. Nevertheless, further testing of the sensitivity of model results to assumptions regarding depth of groundwater extraction could be considered in future.
- Recharge is zoned in a simplified way that suits the conceptual model of the study area. Preliminary model work that considered more detailed recharge zonation to match changes in soil type, similar to the work of Allison and Hughes (1978), did not yield suitable results. Alternative and more detailed approaches to simulating recharge could be considered in future, for example, unsaturated zone modelling such as in Morgan et al. (2015). However, recharge rates derived in this way would need to be validated in detail against field estimates to ensure they provide appropriate inputs.
- Forest plantations are assumed not to be extracting groundwater, consistent with assumptions in the Lower Limestone Coast WAP (SENRMB, 2013). Furthermore, recharge interception by plantation forests is implemented in a simplified way, as discussed in section 3.5. Further work assessing groundwater model results against other data sets, such as the field-corrected satellite derived data sets of evapotranspiration described by Doody, Benyon and Gao (2023), is recommended.
- The model approach to using Kx:Kz to simulate vertical conductivity was implemented to ensure unrealistic vertical anisotropy ratios did not arise. However, the impact of high values of vertical anisotropy on SWI2 results is unclear. Further sensitivity testing is recommended to assess sensitivity of SWI2 results to vertical anisotropy. Alternative approaches to simulating position and movement of the interface, such as including low permeability layers explicitly, may also need to be assessed.
- Tidal or seasonal movement of seawater interface is not simulated, despite studies showing it may influence movement of the seawater interface (Wood and Harrington, 2015). Additionally, potential sea level rise in future scenarios has not been assessed and could be considered in future work.
- A formal parameter uncertainty analysis was not undertaken as part of this study. Instead, it is recommended that a conceptual uncertainty analysis be undertaken pending the outcomes of the current investigation into the position of the seawater interface using airborne geophysics (Goyder Institute,

2022). New understanding generated from these data may have implications for the conceptualisation of the coastal groundwater system presented here and consequently implications for model results. A conceptual uncertainty analysis could include simulations using alternative initial positions of the seawater interface derived from geophysics results or variations in hydraulic parameters.

6 Scenarios

6.1 Background

Two scenarios are considered here which simulate continued current average conditions and increased extraction with reduced recharge (Table 6.1). Scenario 1 simulates extraction and rainfall as used in the model from 2010–20 continuing into the future. Scenario 2 simulates an increase in extraction up to full allocation levels while recharge reduces following climate change projections. Assumptions related to groundwater extraction and recharge in these scenarios is presented below.

Table 6.1. Model scenarios

Scenario	Recharge	Extraction
1	Recharge based on 2011–21 conditions	Extraction based on 2011–21 extraction
2	Declining recharge based on climate change projections	Full allocation extraction

6.2 Climate change impacts on groundwater recharge

Climate change impacts for this study are assessed against projections made using RCP 8.5 to 2050 following recommendations in DEW (2022) 'Guide to Climate Projections for Risk Assessment and Planning in South Australia'. The projected change in mean annual rainfall for the Limestone Coast at 2050 for RCP 8.5 is a 6% decline. This is similar to the projection of a 6.6% decline made previously by Charles and Fu (2015).

Impacts of climate change on groundwater are made using a scaling factor approach to convert changes in rainfall to changes in recharge. This approach has been used widely in groundwater modelling studies by DEW (Li and Cranswick (2016); DEW 2020a, 2020b) and is based on previous modelling of climate change impacts on recharge using unsaturated zone models (Green, Gibbs and Wood, 2011; Green et al. 2012). Based on these studies and previous modelling approaches by DEW, a scaling factor of 3 is used here, such that a 6% decline in rainfall leads to an 18% decline in recharge. Changes in recharge in scenario 2 are applied incrementally to recharge in scenario 1, such that by 2050 recharge has declined by 18%.

6.3 Groundwater extraction assumptions

In scenario 1, groundwater extraction is based on rates of extraction from 2011-2021. In scenario 2, groundwater extraction is increased to full allocation levels. Based on 2021 extraction volumes, extraction in the management areas of Donovans, Kongorong and MacDonnell increases from 36,642 ML/y to 62,785 ML/y (Figure 6.1). The surrounding management areas of Moorak, Blanche Central, Benara and Glenburnie are not entirely represented in the model domain. Hence, in these areas in scenario 2, groundwater extraction increases to full allocation volumes for the licensed extraction wells in the domain but not to the total full allocation volume for the management area.

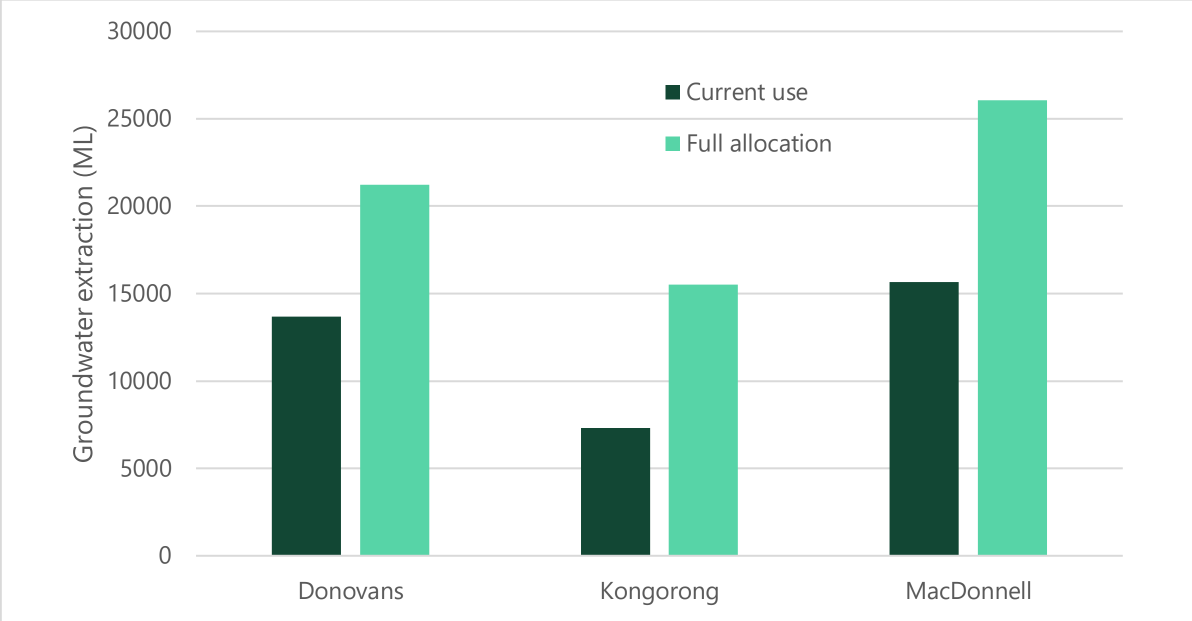


Figure 6.1. Volumes of current groundwater use (2021) and full allocation

6.4 Northern boundary inflow assumptions

The northern general head boundary of the groundwater model simulates constant upgradient groundwater levels in the Benara area and transient upgradient groundwater levels for the rest of the boundary length (Figure 3.1). The simulated groundwater level plots an overall decline from 1970-2021, consistent with groundwater levels, with some periods of stabilisation and recovery. As scenario 1 simulates recharge repeating values used for the last 10 years of the model simulation (2011-2021), scenario 1 uses boundary head levels that likewise repeat values from 2011-2021 cyclically (Figure 6.2).

The impact of changes in rainfall and recharge on boundary inflow are difficult to estimate. However, given the declining groundwater levels on the inflow boundary observed in the past, declines are likely to be expected from climate change. In scenario 2, the transient general head boundary values are based on those from 2011-2021 but declining incrementally to 2050. This is acknowledged as a coarse (but not unreasonable) assumption in implementing climate change impacts on boundary inflow.

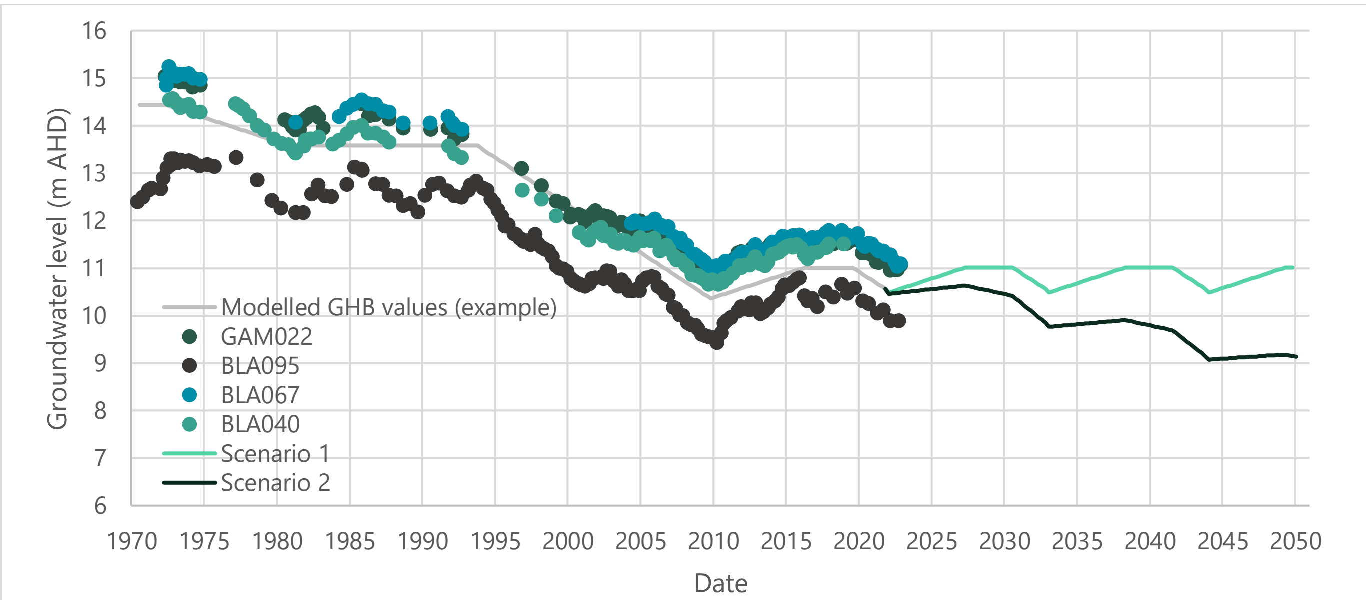


Figure 6.2. Example transient groundwater level trends for general head boundary in scenarios

6.5 Results

Scenario 1 simulates extraction and recharge from the last 10 years continuing into the future with groundwater levels and spring discharge predicted to generally stabilise, albeit with year to year fluctuations (Figure 6.3, Figure 6.5). In scenario 2; however, groundwater levels are predicted to decline by 0.01 to 2.6 m more than in scenario 1 by 2050. In some locations declines are predicted to occur from the start of the scenario run due to the impact of increased pumping (e.g., MAC046 in Figure 6.3). However, in other locations predicted declines are more gradual and result from assumptions about reduced recharge attributed to climate change (e.g., CAR039 in Figure 6.3). Thus, the projected changes in groundwater level are dependent upon assumptions regarding the location of increases in extraction. Figure 6.4 plots the spatial location of these differences where the value indicates the difference between groundwater levels in scenario 2 and 1 at 2050. The largest differences are observed close to the northern boundary, most likely influenced by the choice of boundary condition values in scenario 2 (Figure 6.2). Declines are also observed throughout the areas of irrigation extraction in MacDonnell and Kongorong. Differences are smaller in the Donovans management area as the difference between current extraction and full allocation extraction is smaller. It is assumed that extraction of full allocation occurs at the locations where licences are currently using groundwater.

Scenario 2 shows spring discharges are predicted to decline by 31% at Deep Creek, 43% at Eight Mile Creek and 56% at Cress Creek and Piccaninnie Ponds compared to scenario 1 (Fig 6.5). Although Donovans shows smaller differences in predicted groundwater level decline, the predicted decline in spring discharge at Piccaninnie Ponds is large; thus, the impacts of increased extraction and reduced rainfall from climate change may be amplified in spring discharge.

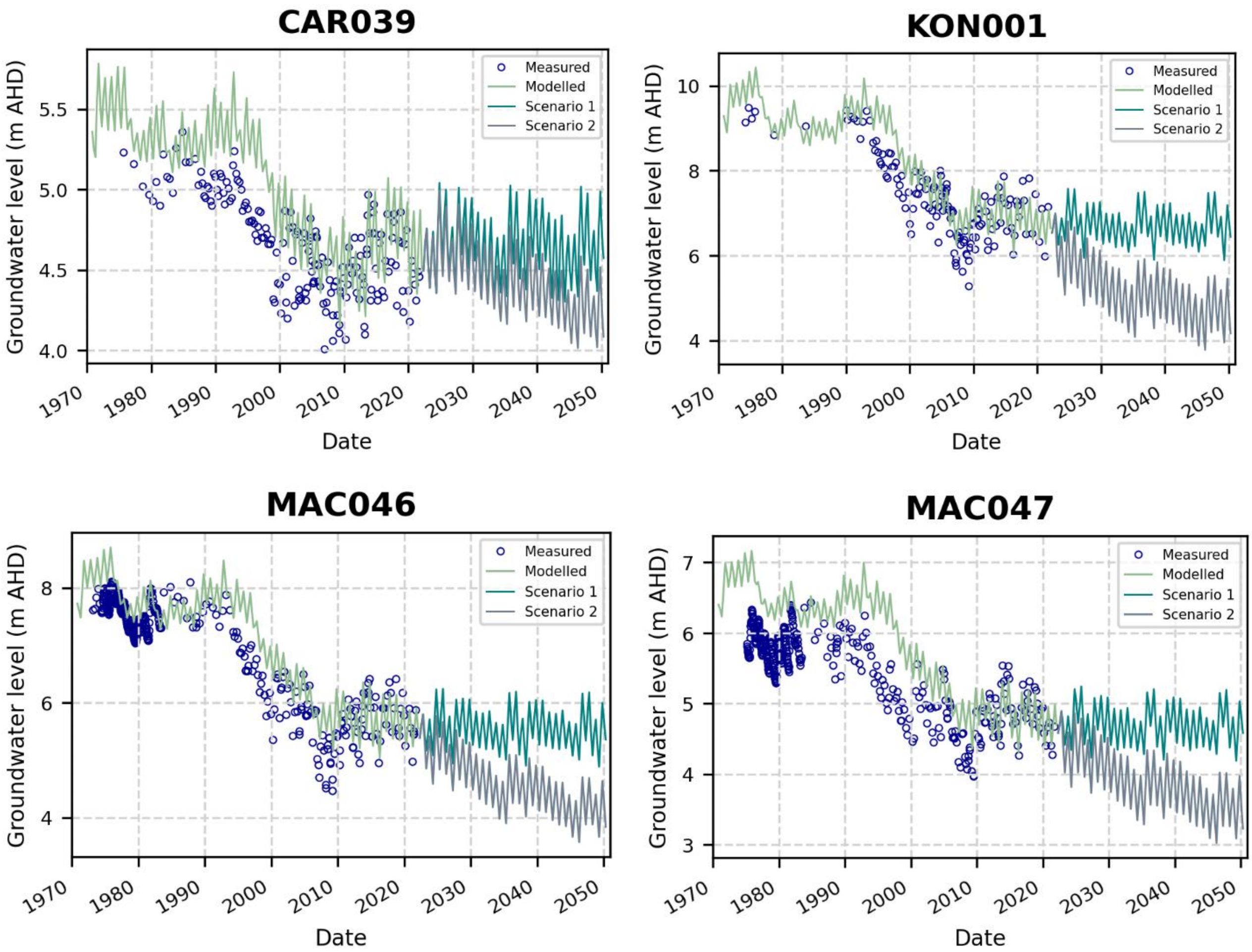


Figure 6.3. Groundwater level responses to scenarios in the study area

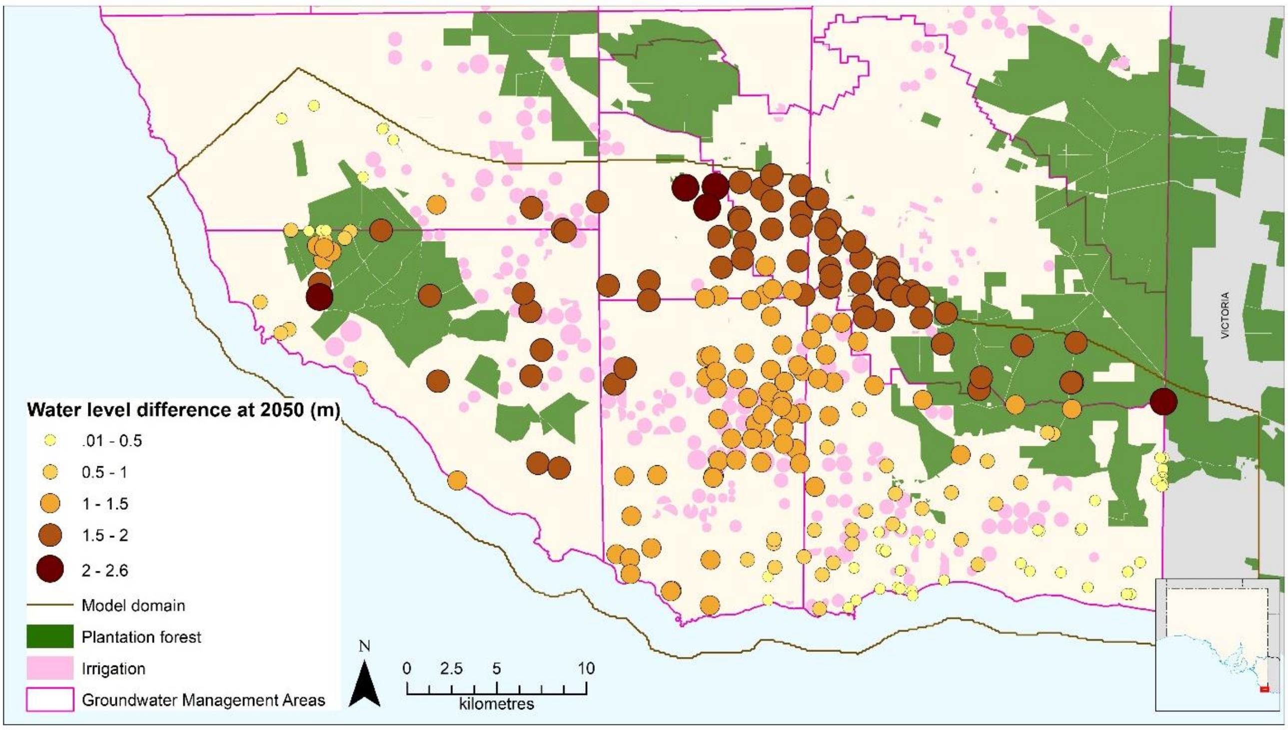


Figure 6.4. Difference in groundwater levels between scenario 1 and scenario 2 at 2050

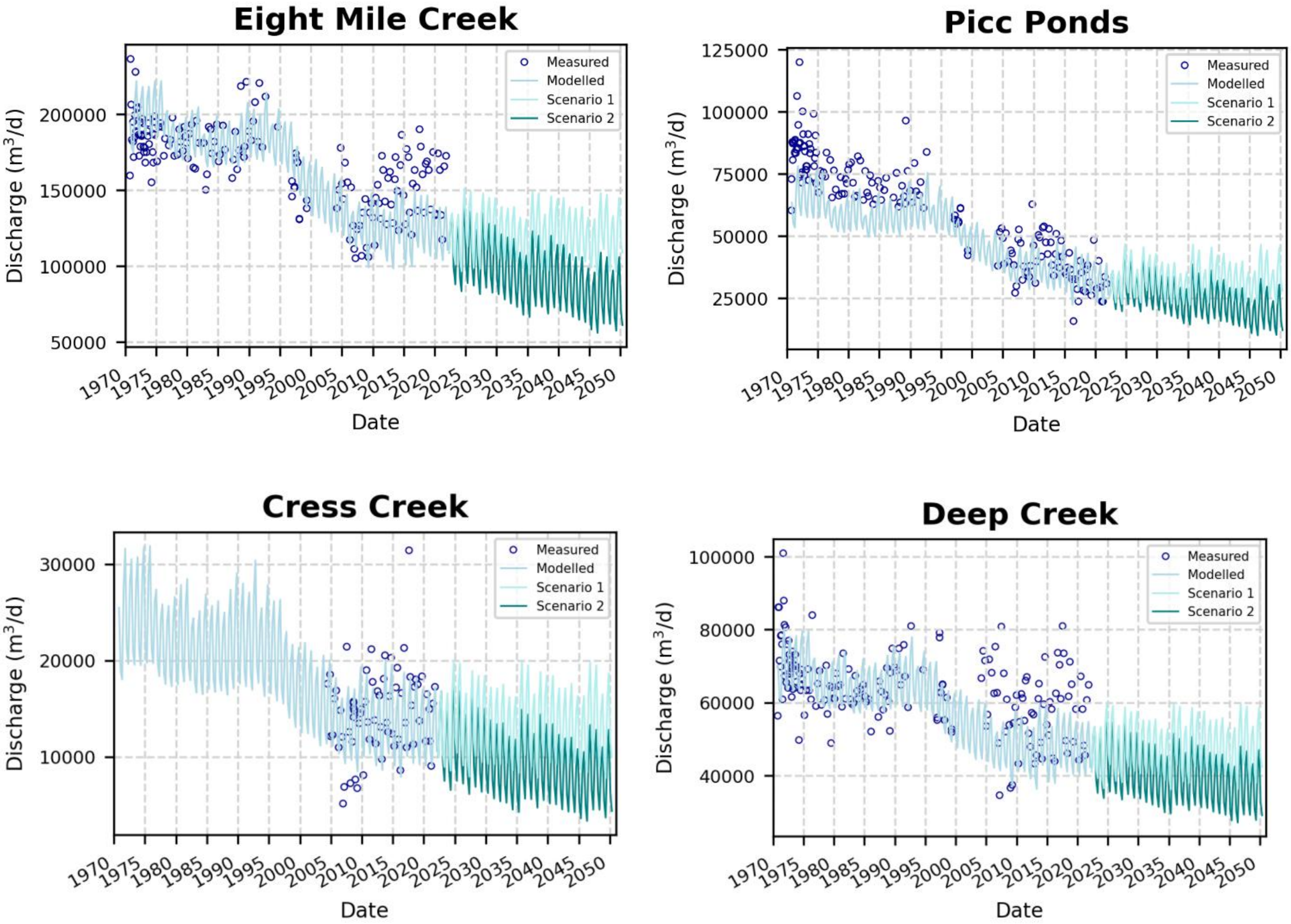


Figure 6.5. Spring discharge response to scenarios

As discussed in section 4.5, data on the position and movement of the seawater interface is limited; hence, results from the SWI2 simulation should be interpreted with care. Model results for the position of the interface will need to be revisited when more information is available from geophysical surveys and associated modelling (Goyder, 2022). Consequently, SWI2 results from scenarios are not presented in this report.

7 Conclusions and recommendations

7.1 Conclusions

A transient groundwater flow model has been developed for the Lower Limestone Coast management areas of Donovans, MacDonnell and Kongorong, south of Mount Gambier. While being a new model, the model adopts a domain area similar to that developed by Stadter and Yan (2000). The model simulates changes in groundwater level from 1970 to 2021 and fits measured groundwater levels and trends generally well across the study area. The model also provides a reasonable fit to measured discharge at groundwater fed karst springs. The SWI2 package is used for the coastal boundary to simulate the seawater-freshwater interface. While the simulated position of the interface provides some correlation with measurements, data for benchmarking is lacking. Hence, model results regarding position and movement of the seawater interface should be interpreted with caution.

Two model scenarios have been run to 2050 to provide a baseline for further scenario development. These scenarios consider (1) continuation of extraction and climate conditions observed over the past 10 years and (2) increases in extraction to full allocation and decreases in groundwater recharge from climate change. Results from scenario 1 show that predicted groundwater levels and spring discharges stabilise at current levels with year-to-year variations driven by variability in pumping and recharge. Scenario 2 shows that predicted groundwater levels decline by 0.01 to 2.6 m and spring discharge declines by 30 – 56% into the future.

7.2 Recommendations

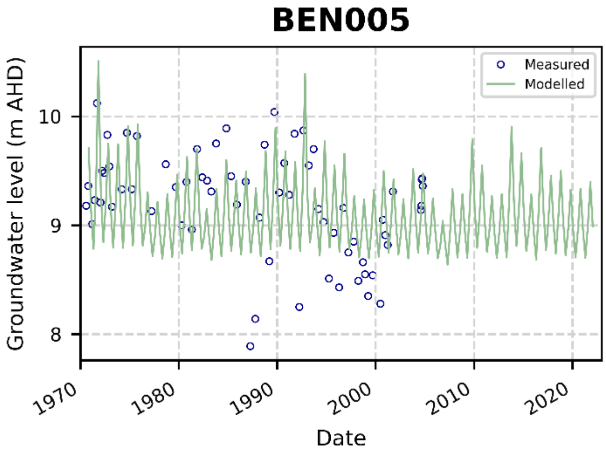
The purpose of this report is to document development of a groundwater model for the coastal areas south of Mount Gambier to assist in review of the Lower Limestone Coast Water Allocation Plan. Several recommendations can be made based on this work, some of which may be able to be addressed through further work in supporting the review of the LLCWAP.

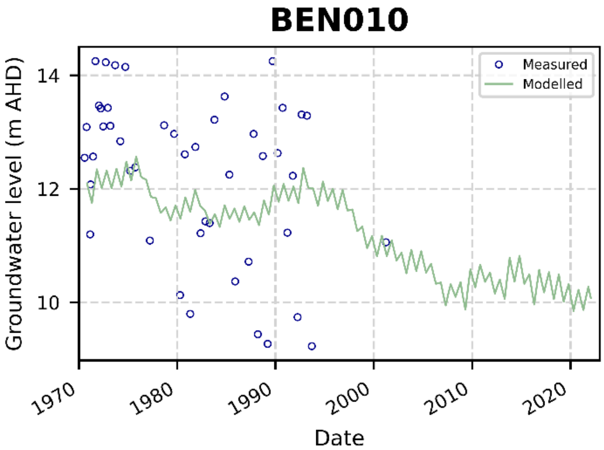
- Simulations on the position and movement of the seawater interface with the SWI2 package should be considered as preliminary results. Geophysical work currently being undertaken investigating the position of the interface should provide significantly more data than is currently available (Goyder, 2022). It is recommended that results of the SWI2 simulation be revisited as these data become available and options considered to revise the model if it is found to be inadequate.
- It is recommended that further parameter uncertainty work is conducted and carried into future scenario work.
- Model layering in this study is informed by conceptual understanding of differences in lithology in the Tertiary Limestone Aquifer and their measured impact on groundwater levels. However, further work could be conducted to better inform understanding of differences in TLA lithology with depth. Such work could include geophysical logging with nuclear magnetic resonance (NMR) on existing observation wells in the study area. Such work may help constrain conceptual understanding by providing additional data on changes in aquifer properties with depth.
- Scenarios described in this report are simple and serve to provide a baseline for further scenario development during the LLCWAP review process. Such scenarios should consider more dynamic changes in extraction and recharge into the future. For example, scenario 2 simulates extraction of full allocation volumes which is considered realistic in MacDonnell and Donovans given extraction in past years has approached these volumes. Nevertheless, extraction typically follows rainfall with higher extraction in lower rainfall years and vice versa. Further scenarios should consider this relationship especially when factoring in potential changes in rainfall and recharge from climate change.

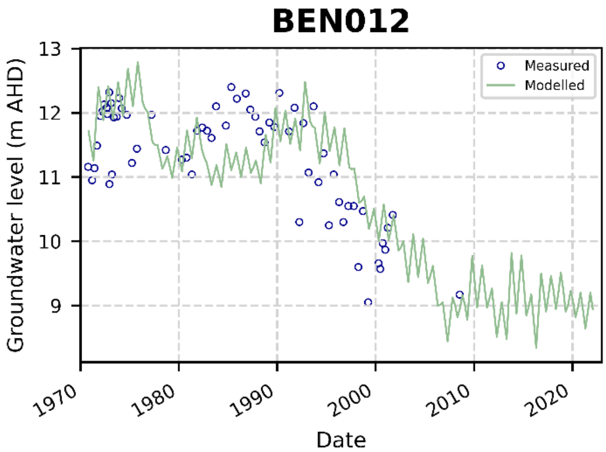
- Given uncertainty in modelled position and movement of the seawater interface scenario results on the seawater interface are not reported. Furthermore, scenarios do not investigate the potential influence of sea level rise on the seawater interface. Further work assessing the potential impacts of sea level rise are recommended following the results of the Goyder Institute (2022) studies.

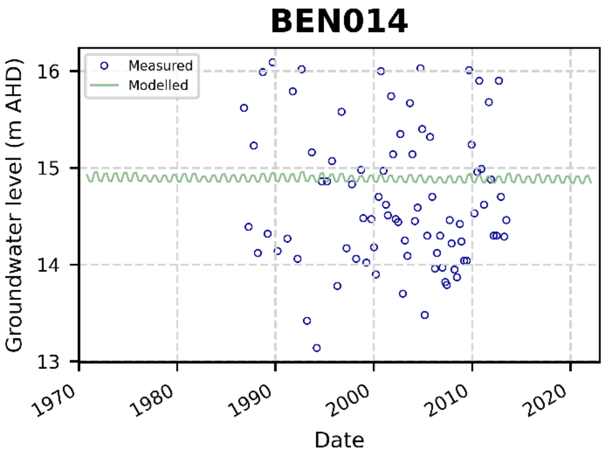
8 Appendices

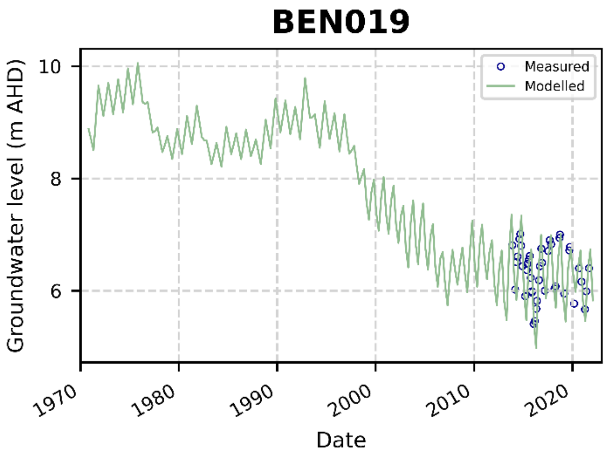
A. Measured and modelled groundwater levels

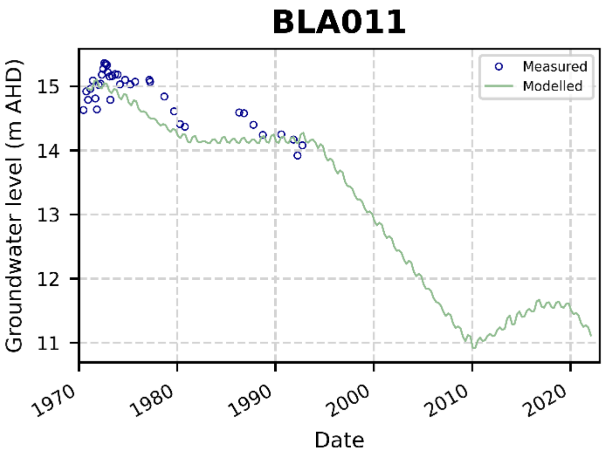


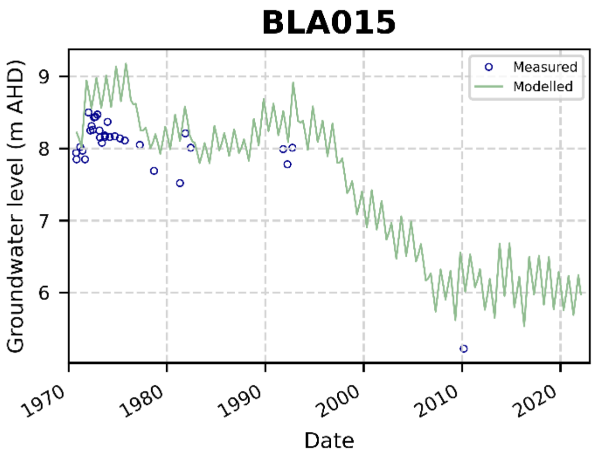


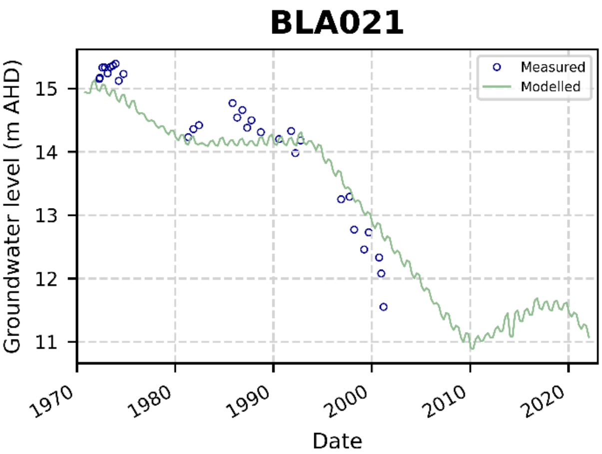


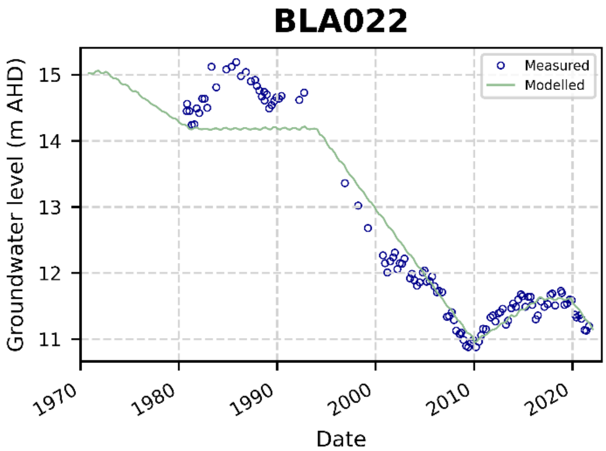







BLA015
Measured
Modelled
Groundwater level (m AHD)
9
8
7
6
1970
1980
1990
2000
2010
2020
Date


BLA021
Measured
Modelled
Groundwater level (m AHD)
15
14
13
12
11
1970
1980
1990
2000
2010
2020
Date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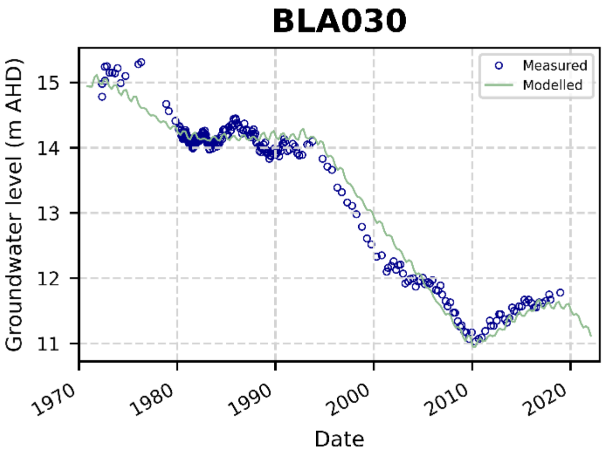
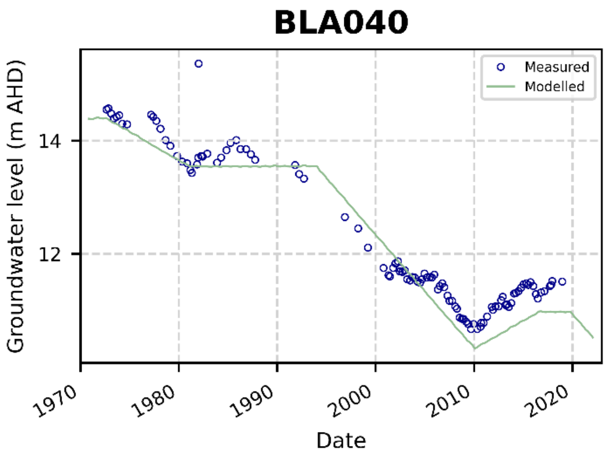
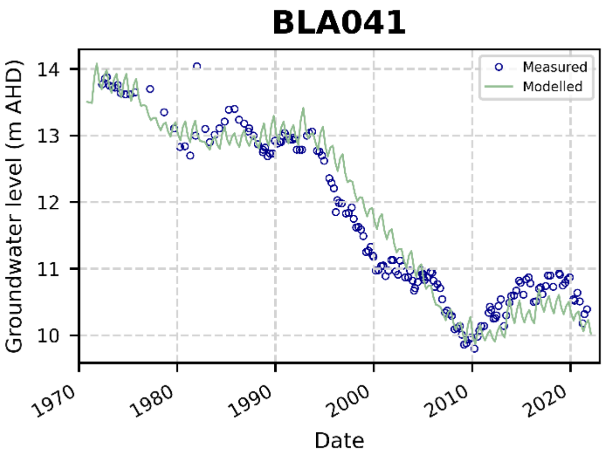
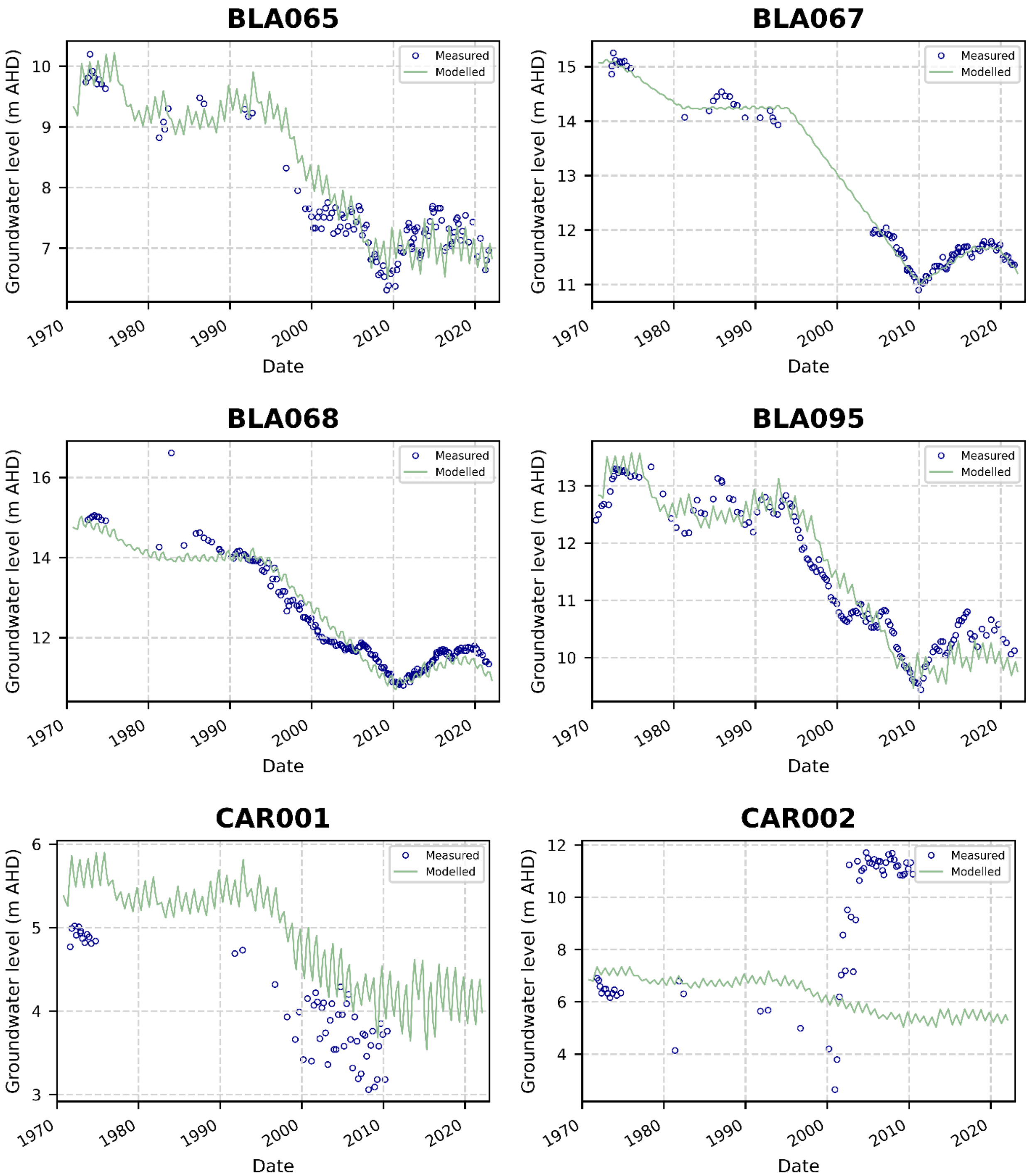
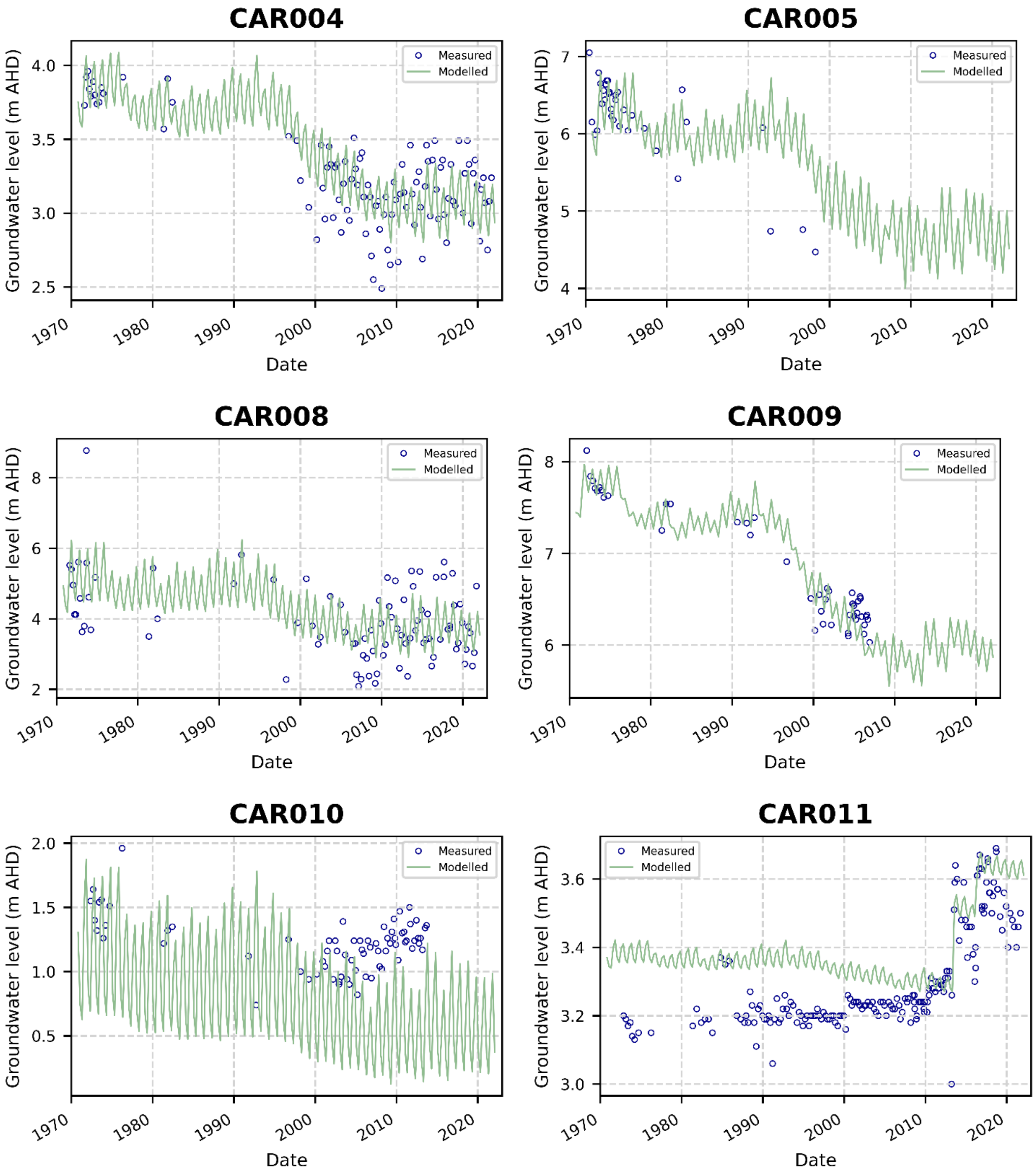
Measured
Modelled
Groundwater level (m AHD)
15
14
13
12
11
1970
1980
1990
2000
2010
2020
Date

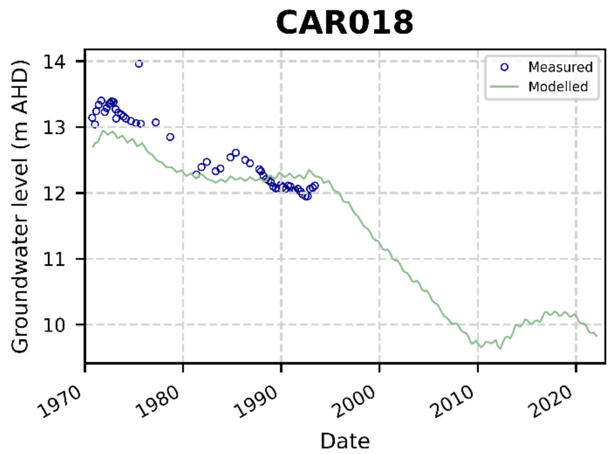

BLA030
Measured
Modelled
Groundwater level (m AHD)
15
14
13
12
11
1970
1980
1990
2000
2010
2020
Date


BLA040
Measured
Modelled
Groundwater level (m AHD)
14
12
1970
1980
1990
2000
2010
2020
Date


BLA041
Measured
Modelled
Groundwater level (m AHD)
14
13
12
11
10
1970
1980
1990
2000
2010
2020
Date


BLA065
BLA067
BLA068
BLA095
CAR001
CAR002
Measured
Modelled
Groundwater level (m AHD)
Date


CAR004
Measured
Modelled
Groundwater level (m AHD)
Date
CAR005
CAR008
CAR009
CAR010
CAR011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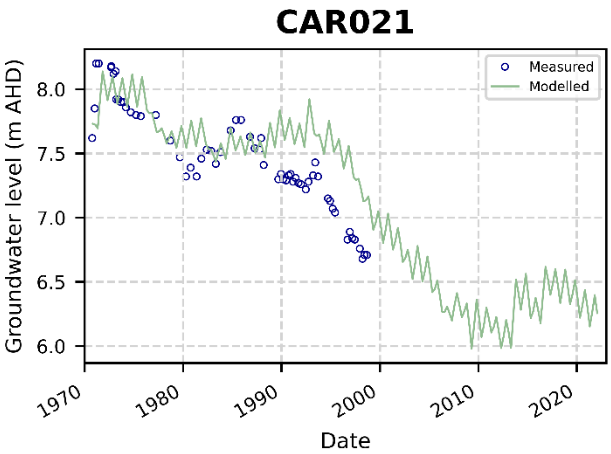
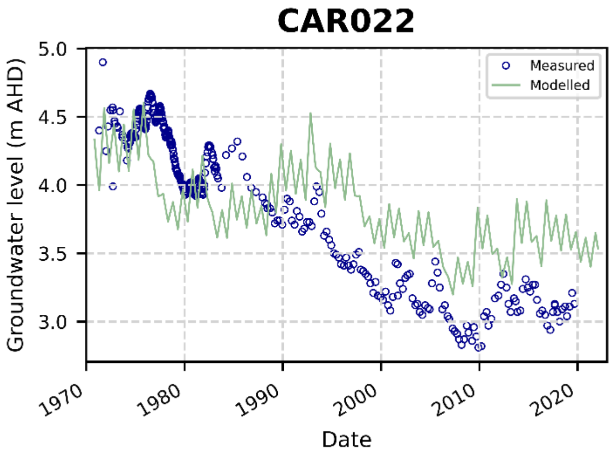
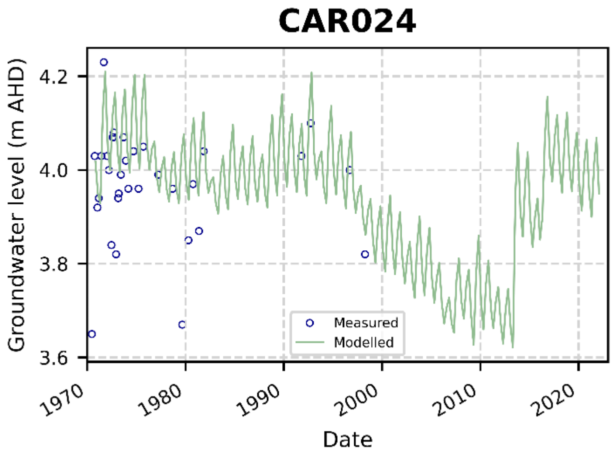
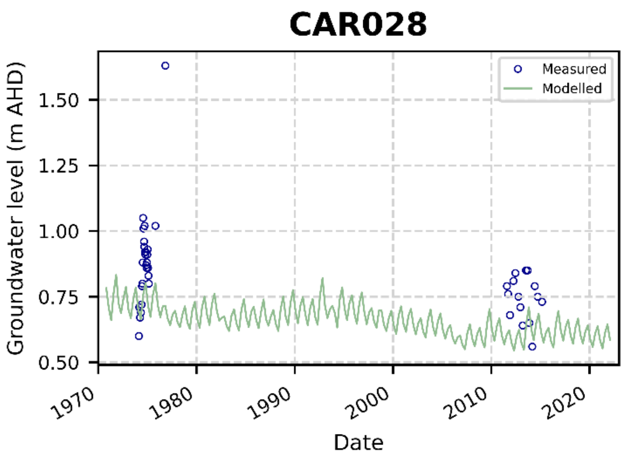
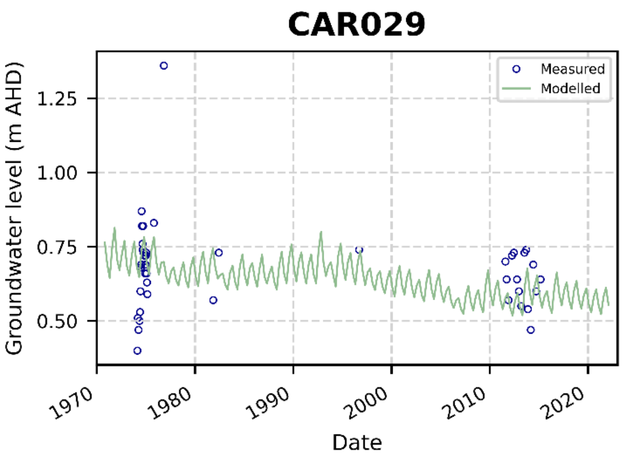
Groundwater level (m AHD)
14
13
12
11
10
Measured
Modelled
1970
1980
1990
2000
2010
2020
Date

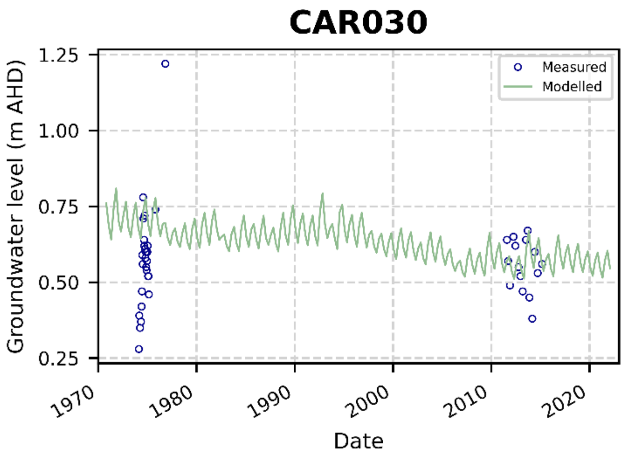

CAR021
Groundwater level (m AHD)
8.0
7.5
7.0
6.5
6.0
Measured
Modelled
1970
1980
1990
2000
2010
2020
Date

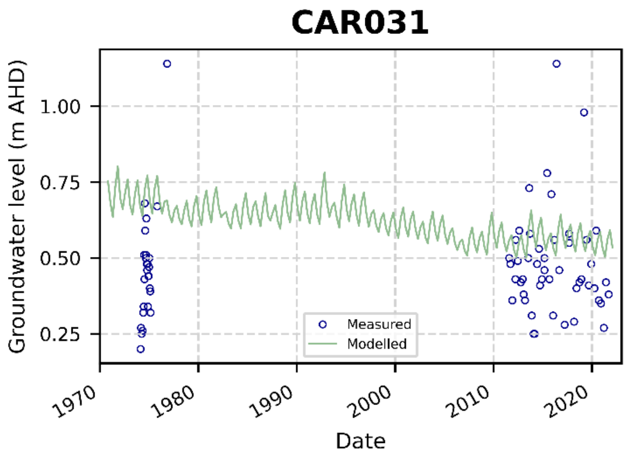

CAR022
Groundwater level (m AHD)
5.0
4.5
4.0
3.5
3.0
Measured
Modelled
1970
1980
1990
2000
2010
2020
Date


CAR024
Groundwater level (m AHD)
4.2
4.0
3.8
3.6
Measured
Modelled
1970
1980
1990
2000
2010
2020
Date


CAR028
Groundwater level (m AHD)
1.50
1.25
1.00
0.75
0.50
Measured
Modelled
1970
1980
1990
2000
2010
2020
Date


CAR029
Groundwater level (m AHD)
1.25
1.00
0.75
0.50
Measured
Modelled
1970
1980
1990
2000
2010
2020
Date


CAR030
Measured
Modelled
Groundwater level (m AHD)
Date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Modelled
Groundwater level (m AHD)
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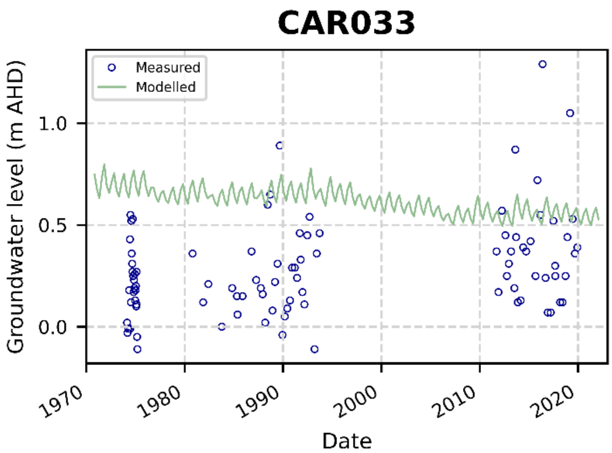
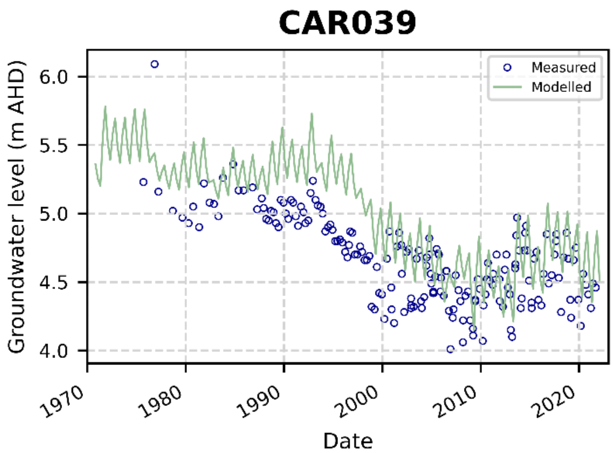

CAR033
Measured
Modelled
Groundwater level (m AHD)
Date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Groundwater level (m AHD)
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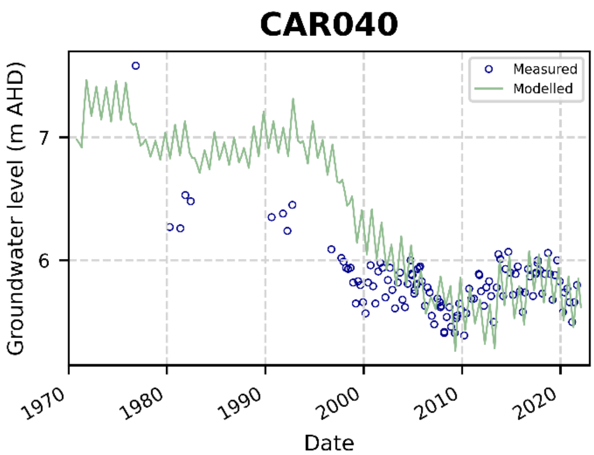
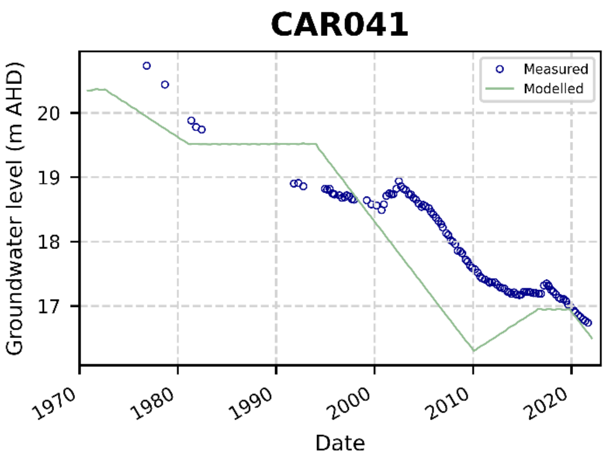

CAR040
Measured
Modelled
Groundwater level (m AHD)
Date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Measured
Modelled
Groundwater level (m AHD)
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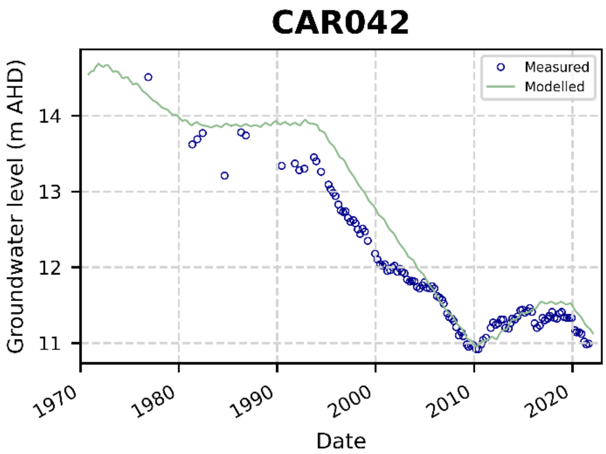
CAR042
Measured
Modelled
Groundwater level (m AHD)
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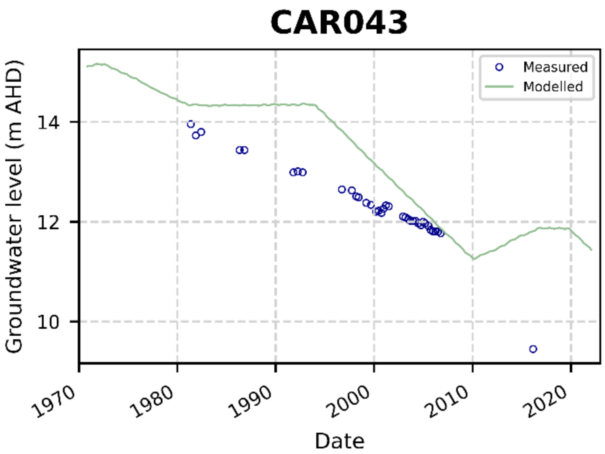
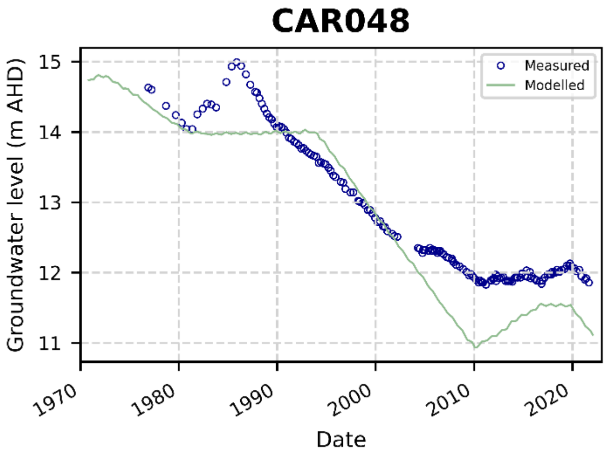
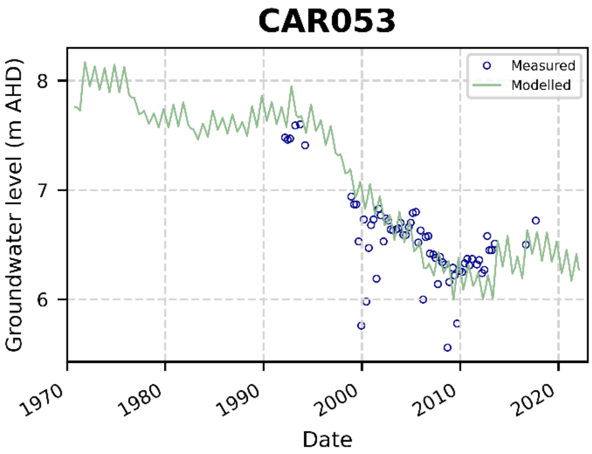
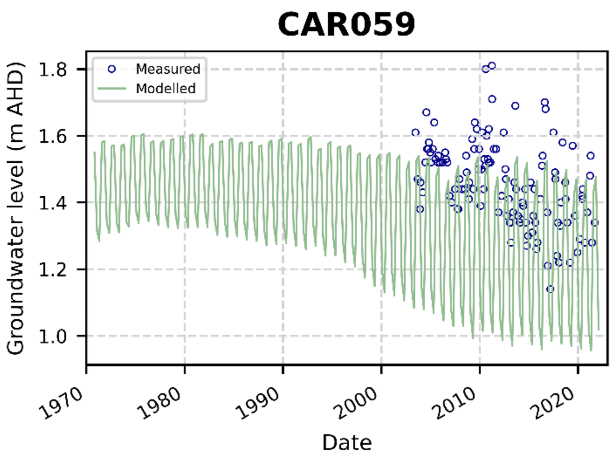
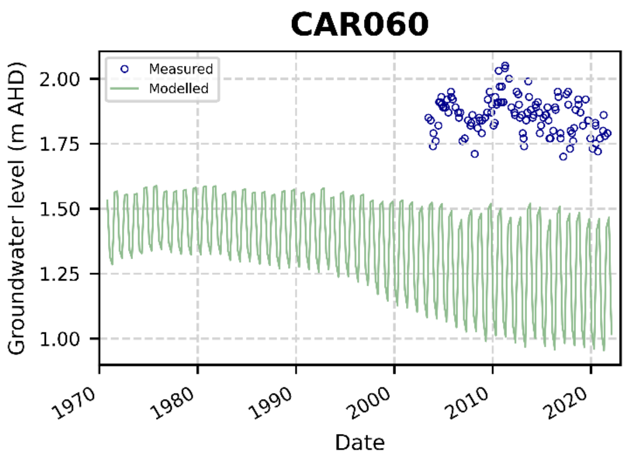

CAR043
Measured
Modelled
Groundwater level (m AHD)
Date


CAR048
Measured
Modelled
Groundwater level (m AHD)
Date


CAR053
Measured
Modelled
Groundwater level (m AHD)
Date


CAR059
Measured
Modelled
Groundwater level (m AHD)
Date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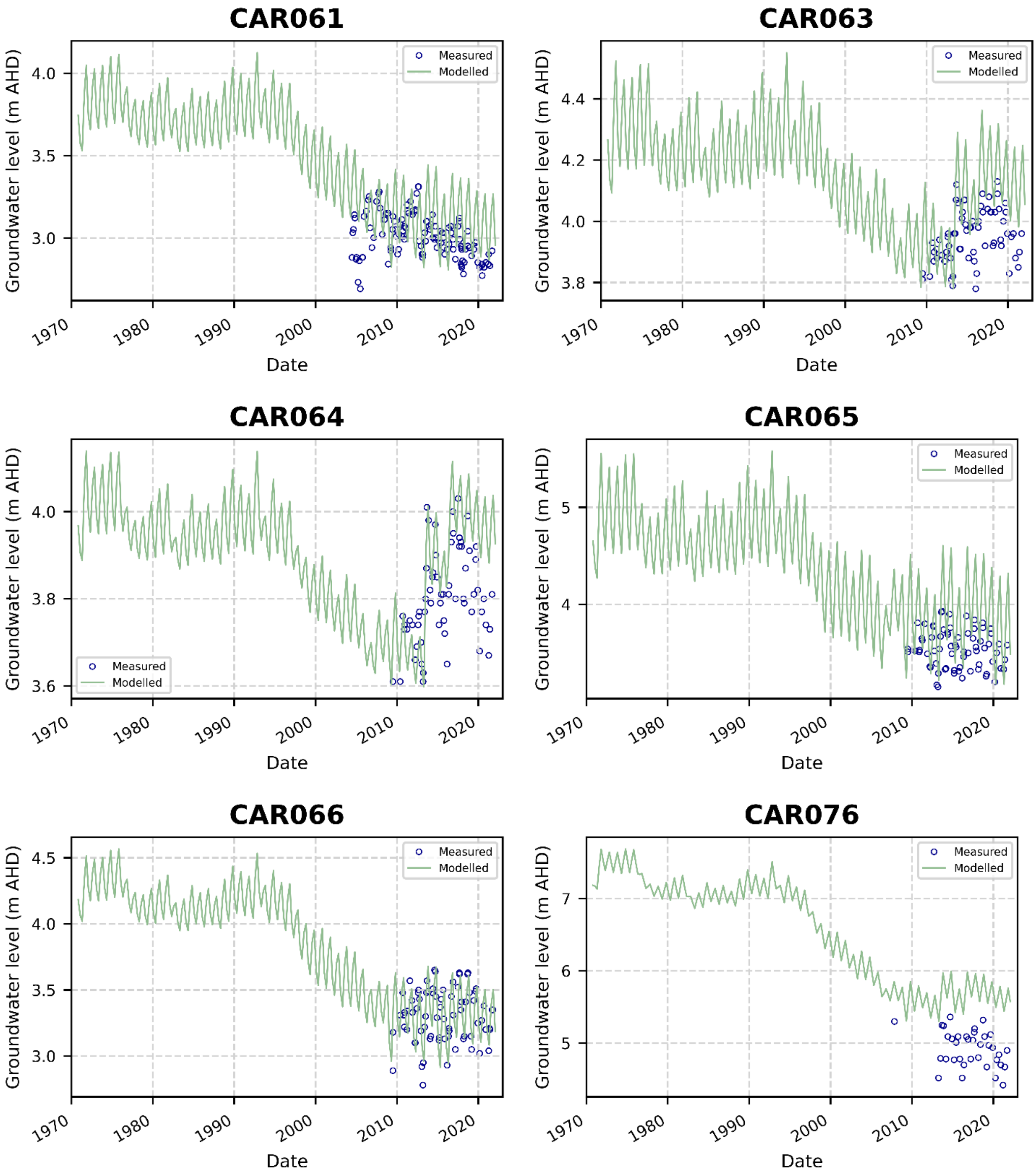
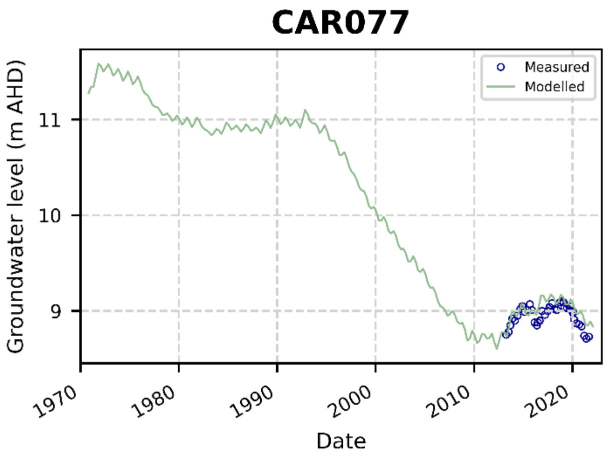
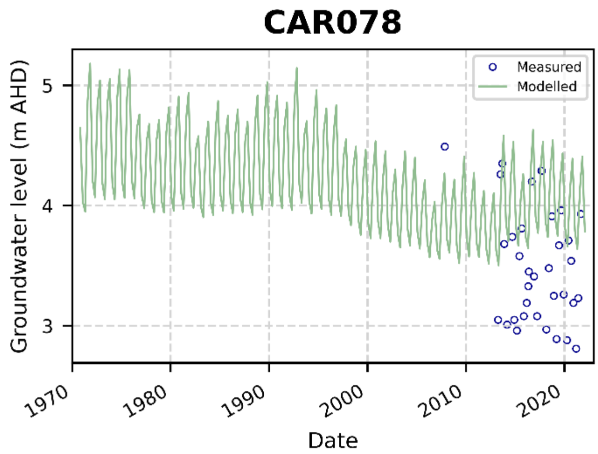
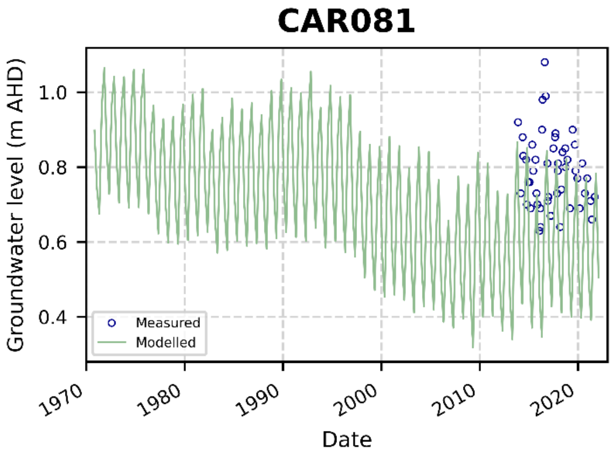
Measured
Modelled
Groundwater level (m AHD)
Date



CAR061
CAR063
CAR064
CAR065
CAR066
CAR076
Measured
Modelled
Groundwater level (m AHD)
Date
1970
1980
1990
2000
2010
2020


CAR077
Measured
Modelled
Groundwater level (m AHD)
11
10
9
1970
1980
1990
2000
2010
2020
Date


CAR078
Measured
Modelled
Groundwater level (m AHD)
5
4
3
1970
1980
1990
2000
2010
2020
Date


CAR081
Measured
Modelled
Groundwater level (m AHD)
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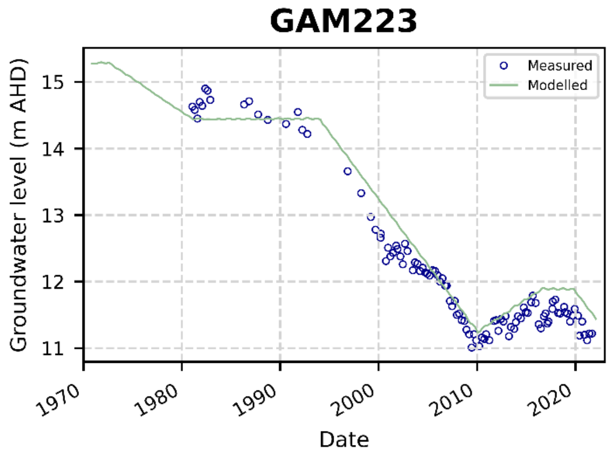
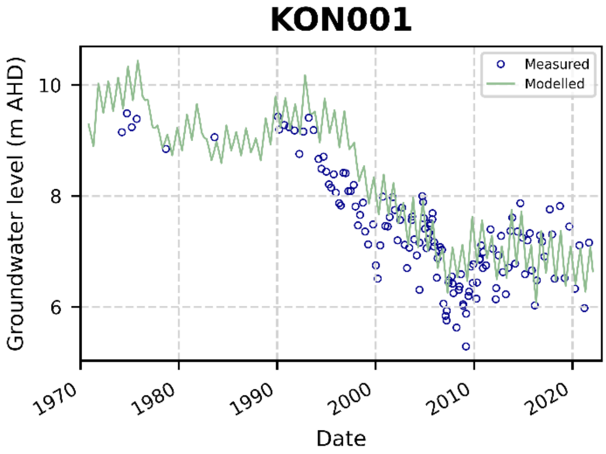
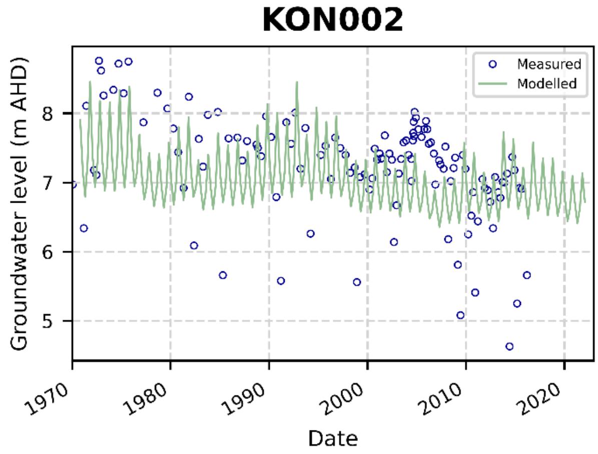
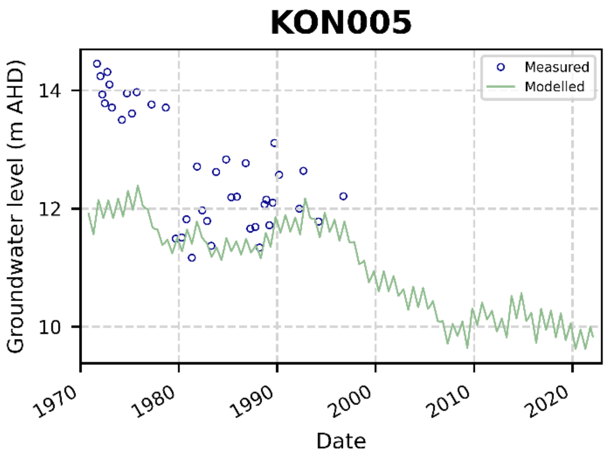
0.8
0.6
0.4
1970
1980
1990
2000
2010
2020
Date


GAM223
Measured
Modelled
Groundwater level (m AHD)
15
14
13
12
11
1970
1980
1990
2000
2010
2020
Date


KON001
Measured
Modelled
Groundwater level (m AHD)
10
8
6
1970
1980
1990
2000
2010
2020
Date


KON002
Measured
Modelled
Groundwater level (m AHD)
8
7
6
5
1970
1980
1990
2000
2010
2020
Date


KON005
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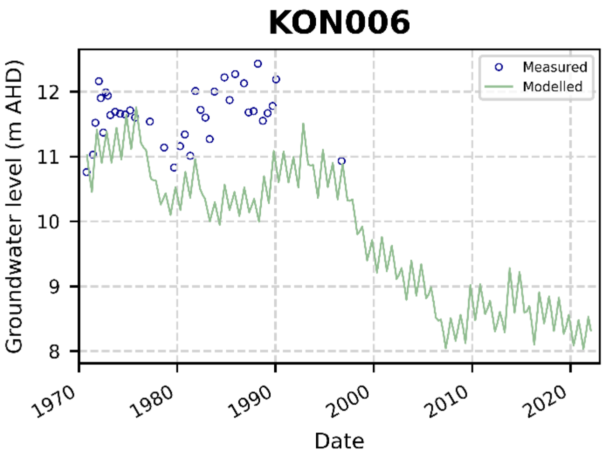
Groundwater level (m AHD)
Date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Groundwater level (m AHD)
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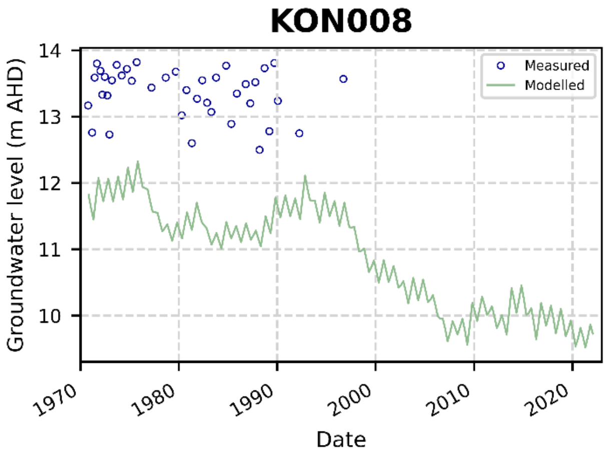
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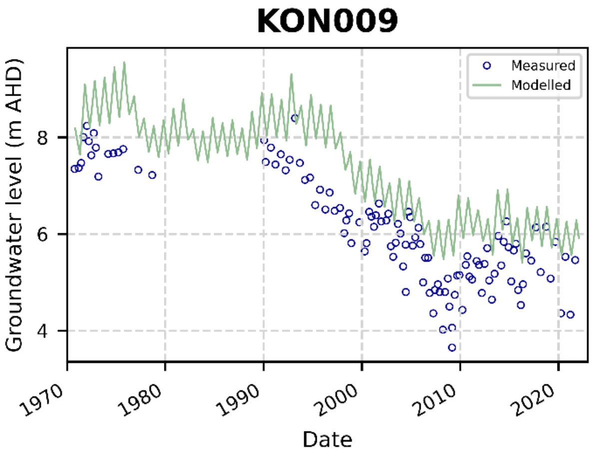
Measured
Modelled
Groundwater level (m AHD)
Date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Modelled
Groundwater level (m AHD)
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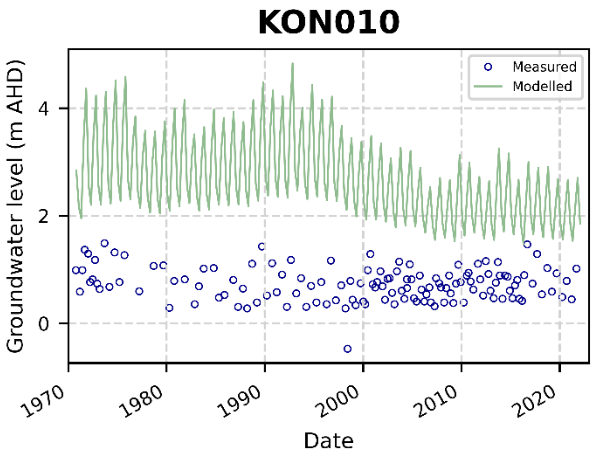
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Modelled
Groundwater level (m AHD)
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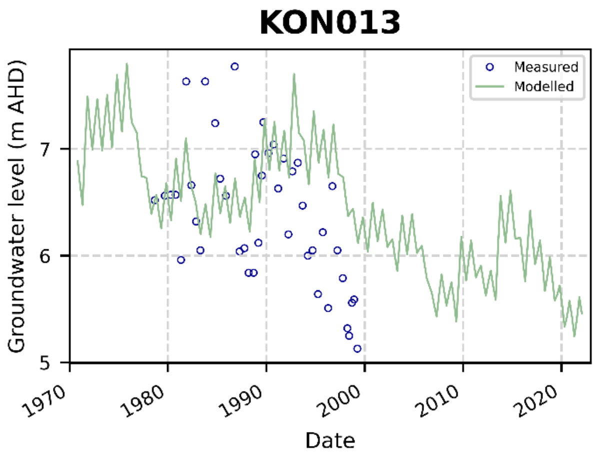
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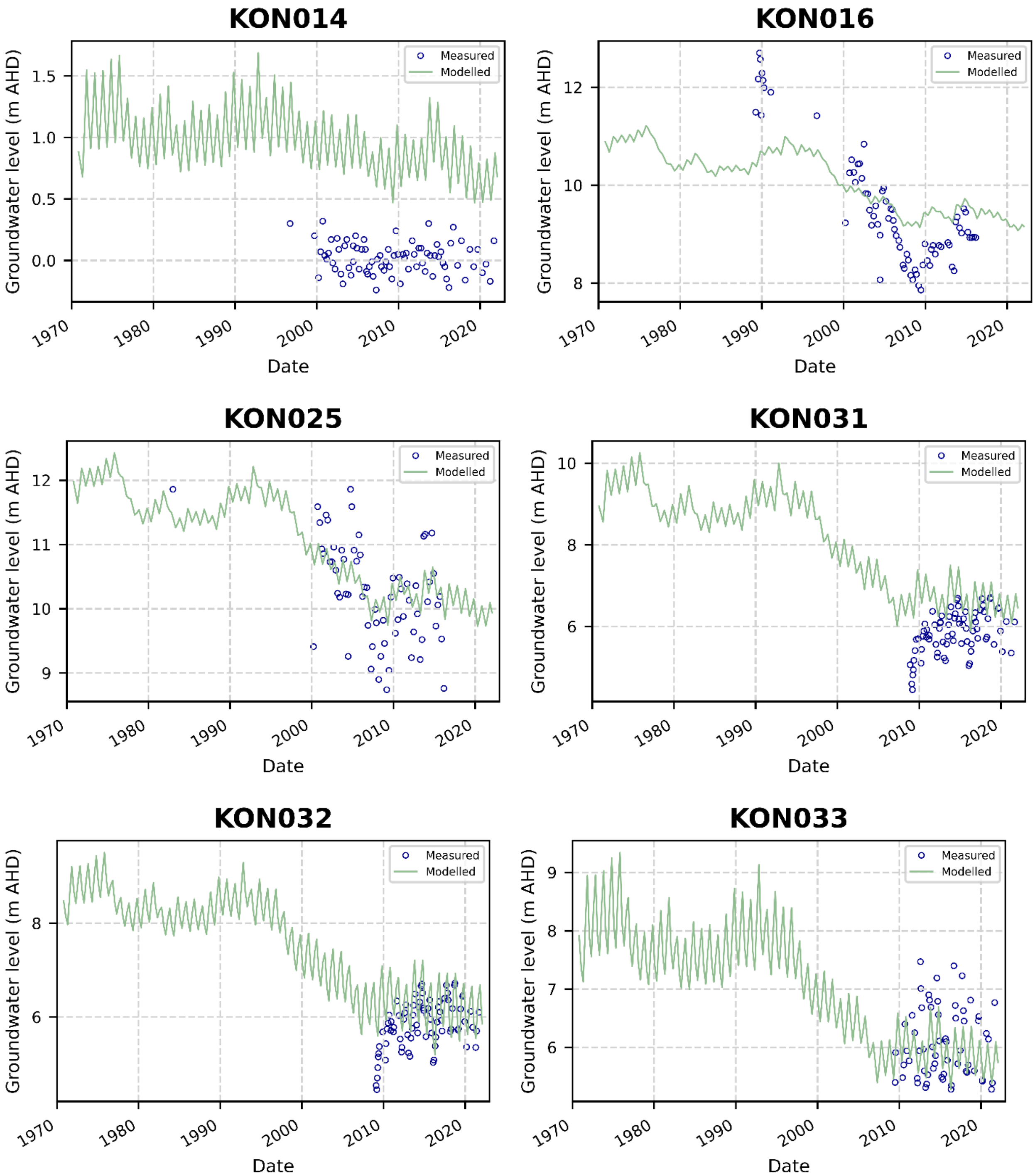
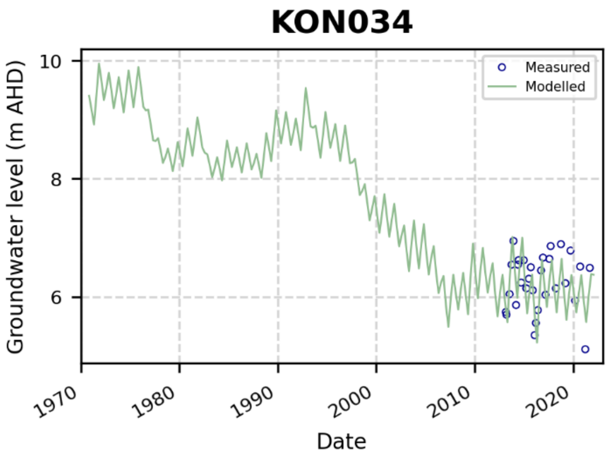
Groundwater level (m AHD)
Date


KON014
KON016
KON025
KON031
KON032
KON033
Groundwater level (m AHD)
Date
Measured
Modelled
1970
1980
1990
2000
2010
2020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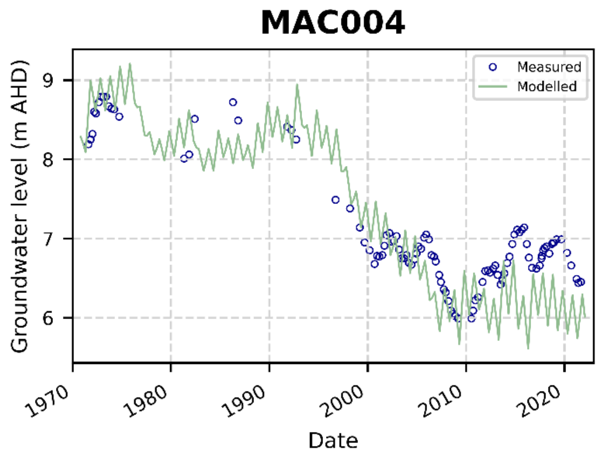
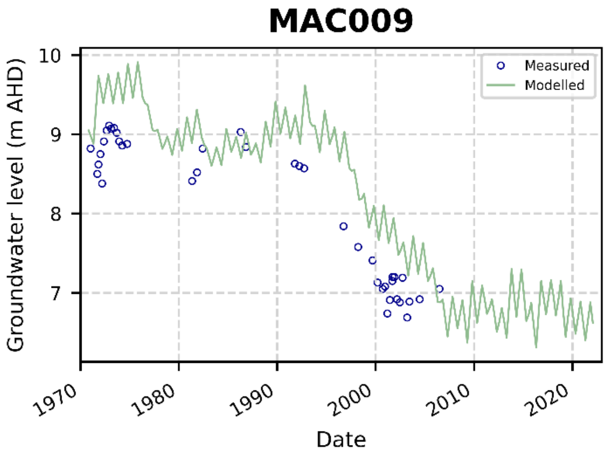
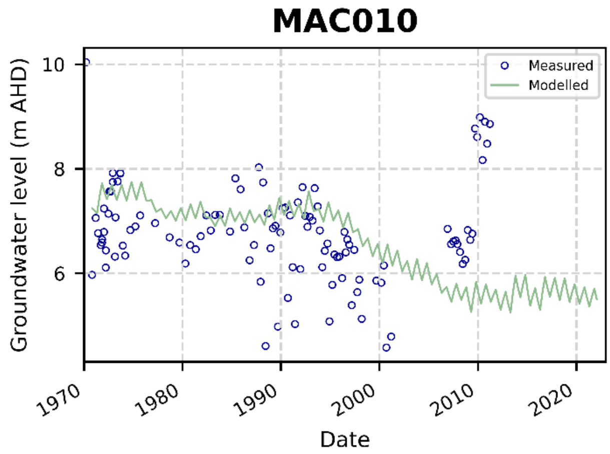
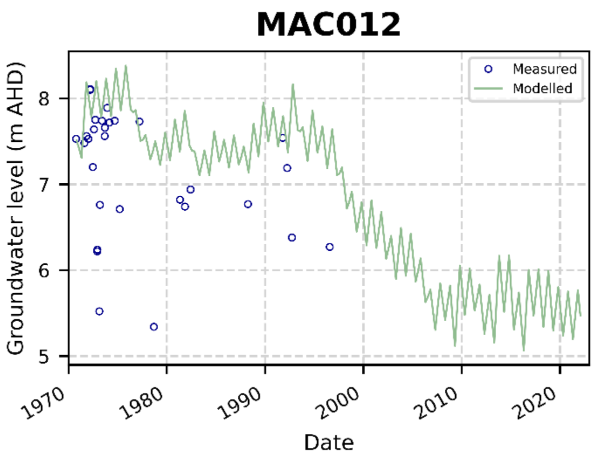
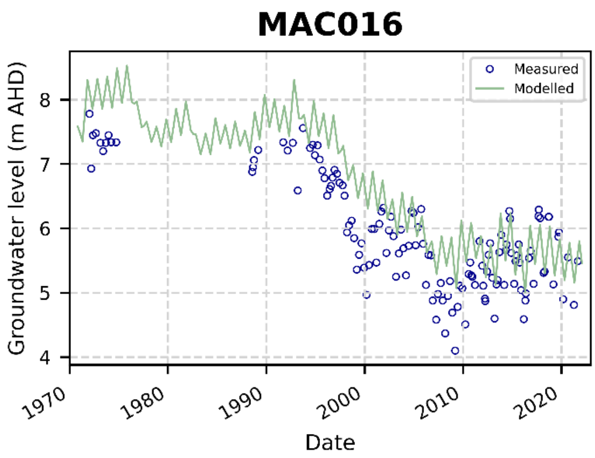
Groundwater level (m AHD)
Date
Measured
Modelled

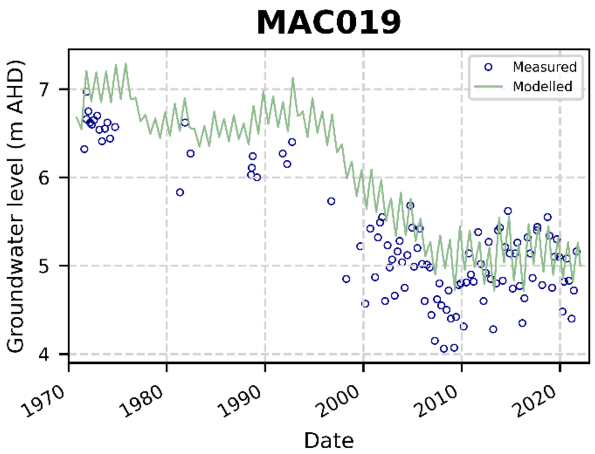

MAC004
Groundwater level (m AHD)
Date
Measured
Modelled

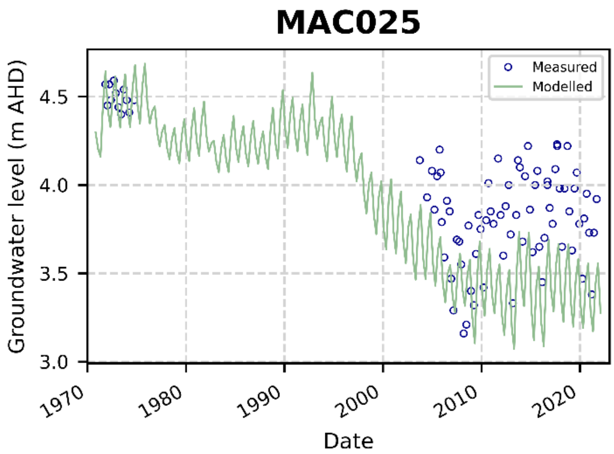

MAC009
Groundwater level (m AHD)
Date
Measured
Modelled

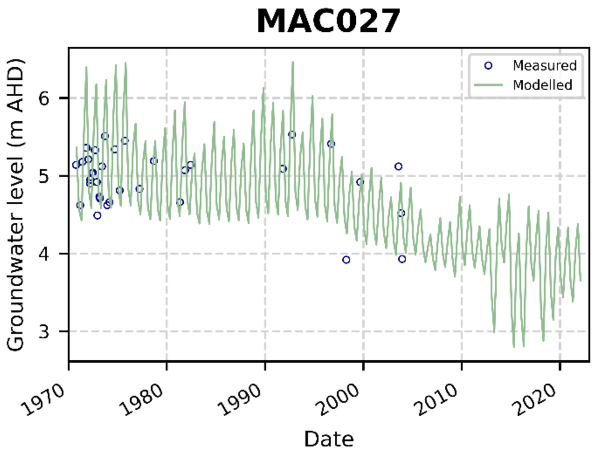

MAC010
Groundwater level (m AHD)
Date
Measured
Modelled

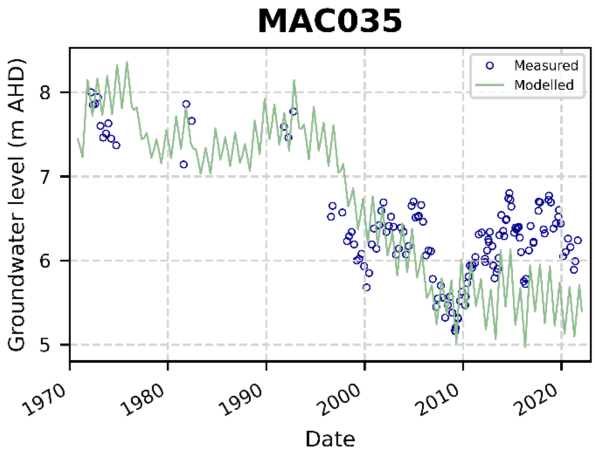

MAC012
Groundwater level (m AHD)
Date
Measured
Modelled

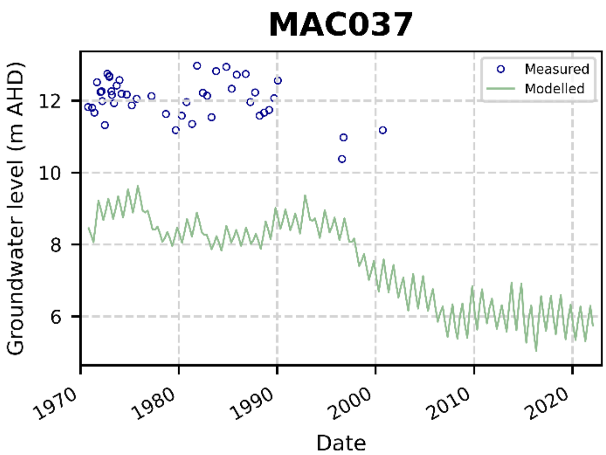

MAC016
Groundwater level (m AHD)
Date
Measured
Modelled

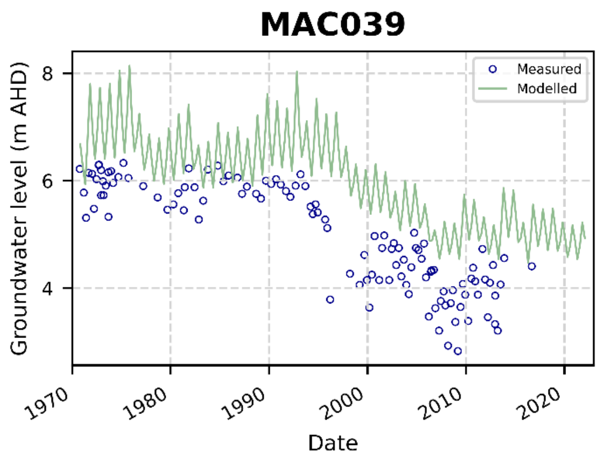

MAC019
Measured
Modelled
Groundwater level (m AHD)
Date

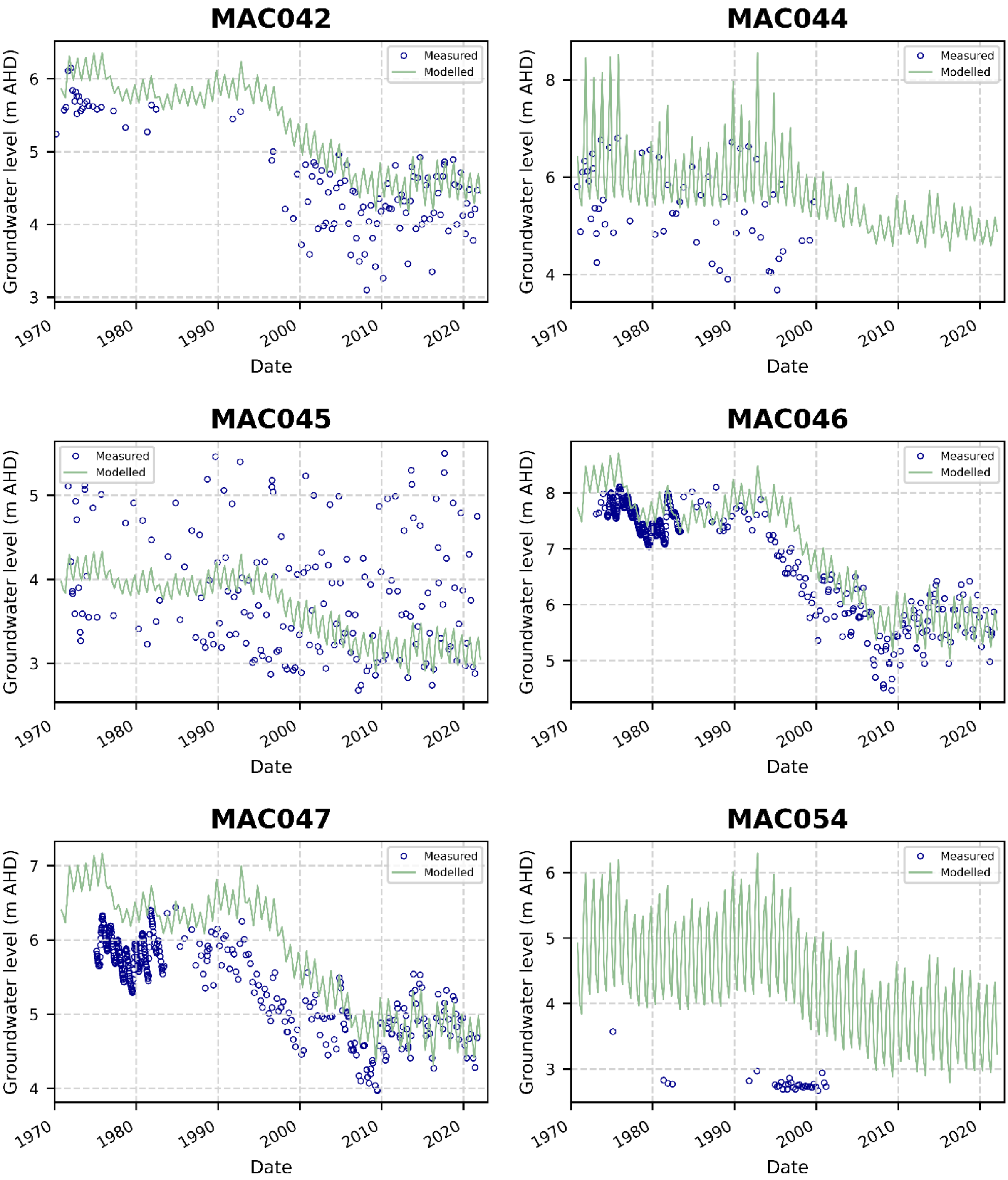

MAC025
Measured
Modelled
Groundwater level (m AHD)
Date

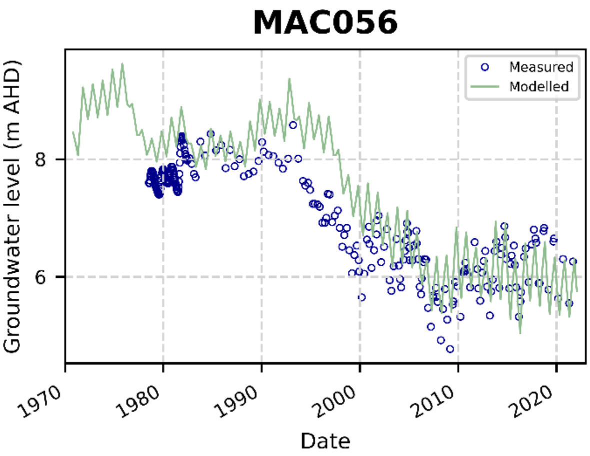

MAC027
Measured
Modelled
Groundwater level (m AHD)
Date

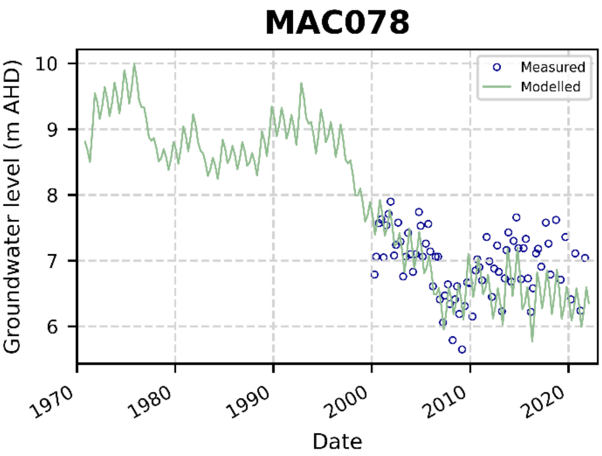

MAC035
Measured
Modelled
Groundwater level (m AHD)
Date

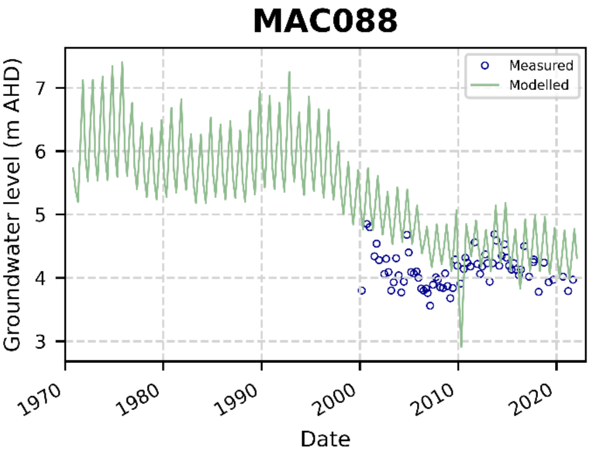

MAC037
Measured
Modelled
Groundwater level (m AHD)
Date

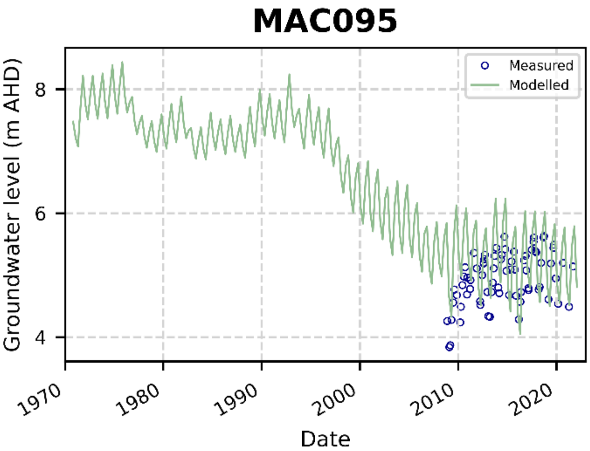

MAC039
Measured
Modelled
Groundwater level (m AHD)
Date

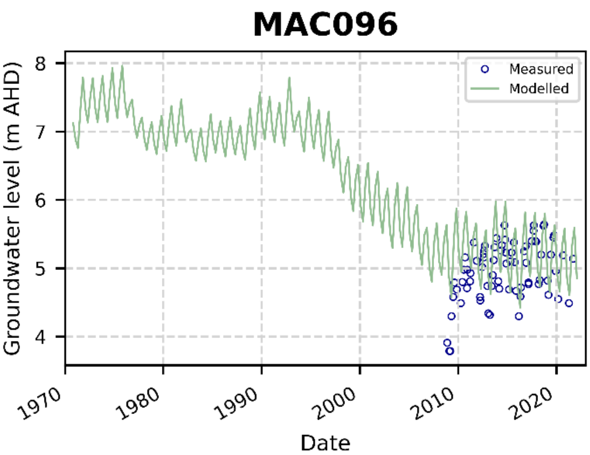

MAC042
MAC044
MAC045
MAC046
MAC047
MAC054
Measured
Modelled
Groundwater level (m AHD)
Date
1970
1980
1990
2000
2010
2020

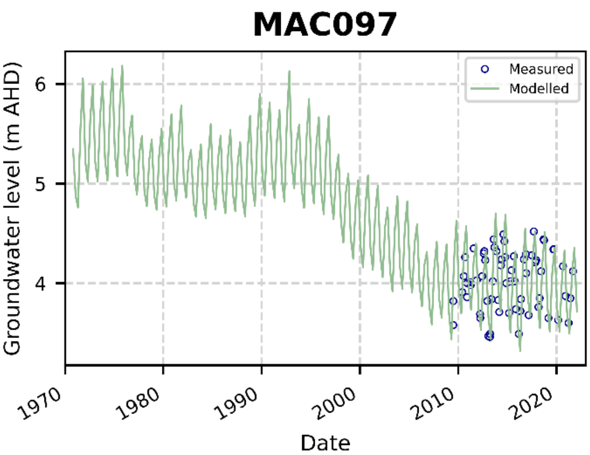

MAC056
Measured
Modelled
Groundwater level (m AHD)
6
8
1970
1980
1990
2000
2010
2020
Date

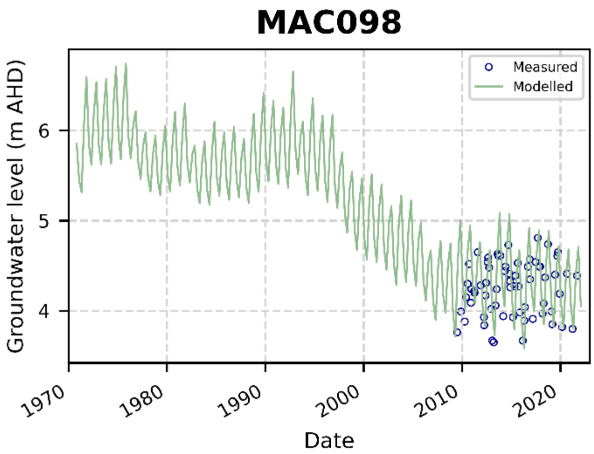

MAC078
Measured
Modelled
Groundwater level (m AHD)
6
7
8
9
10
1970
1980
1990
2000
2010
2020
Date

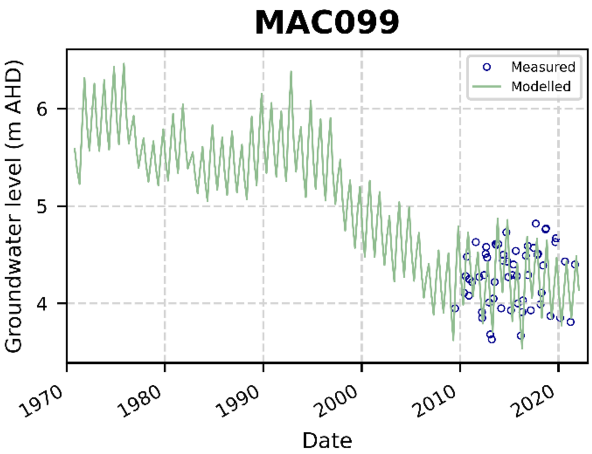

MAC088
Measured
Modelled
Groundwater level (m AHD)
3
4
5
6
7
1970
1980
1990
2000
2010
2020
Date

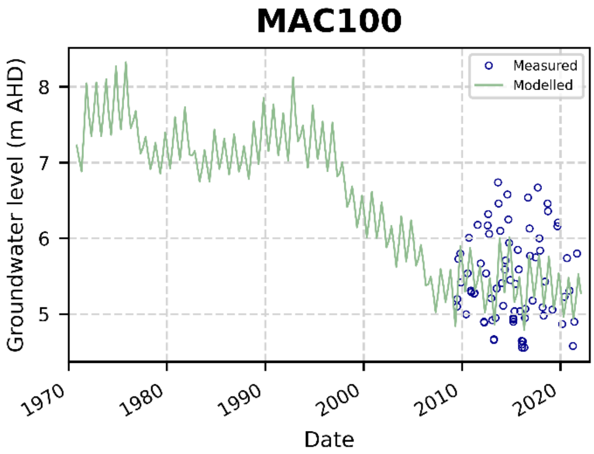

MAC095
Measured
Modelled
Groundwater level (m AHD)
4
6
8
1970
1980
1990
2000
2010
2020
Date

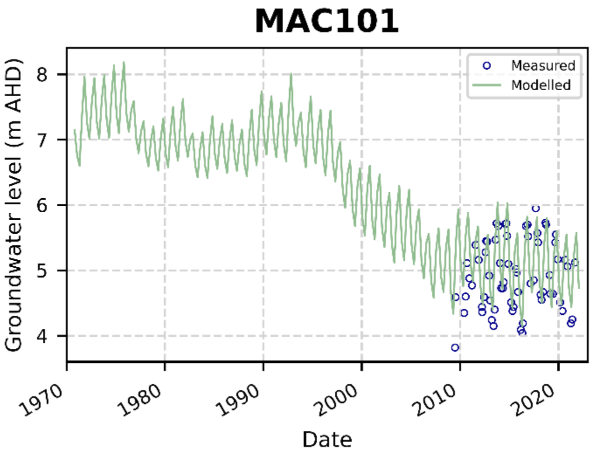

MAC096
Measured
Modelled
Groundwater level (m AHD)
4
5
6
7
8
1970
1980
1990
2000
2010
2020
Date


MAC097
Measured
Modelled
Groundwater level (m AHD)
4
5
6
1970
1980
1990
2000
2010
2020
Date

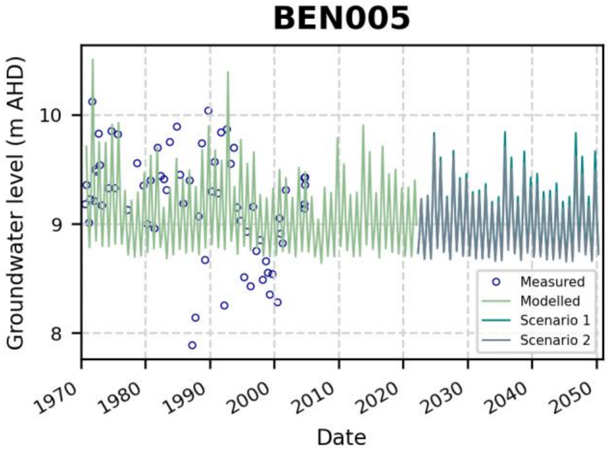

MAC098
Measured
Modelled
Groundwater level (m AHD)
4
5
6
1970
1980
1990
2000
2010
2020
Date

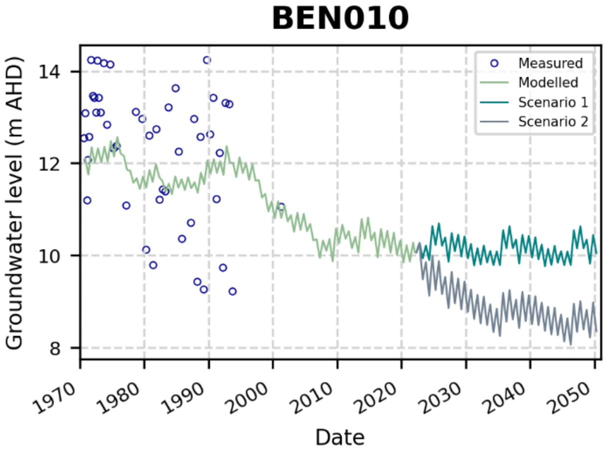

MAC099
Measured
Modelled
Groundwater level (m AHD)
4
5
6
1970
1980
1990
2000
2010
2020
Date

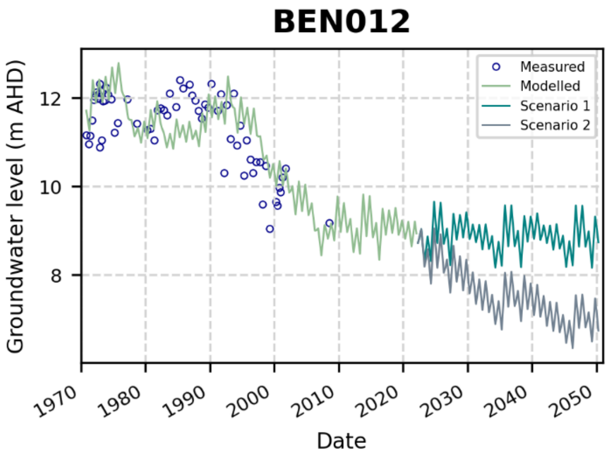

MAC100
Measured
Modelled
Groundwater level (m AHD)
5
6
7
8
1970
1980
1990
2000
2010
2020
Date

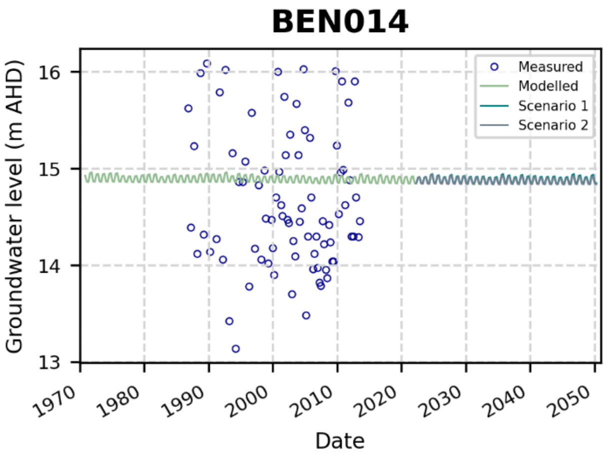

MAC101
Measured
Modelled
Groundwater level (m AHD)
4
5
6
7
8
1970
1980
1990
2000
2010
2020
Date

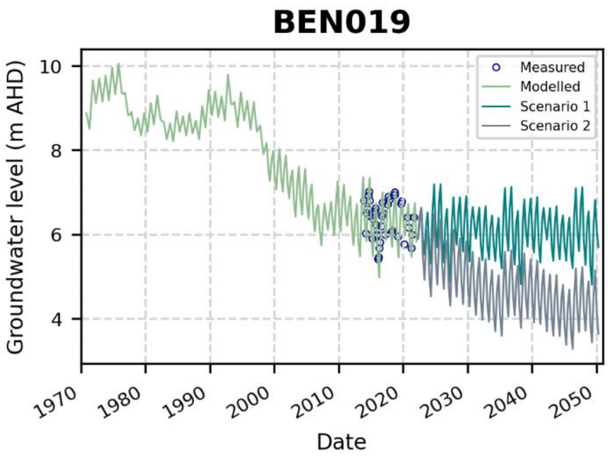
B. Scenario hydrographs

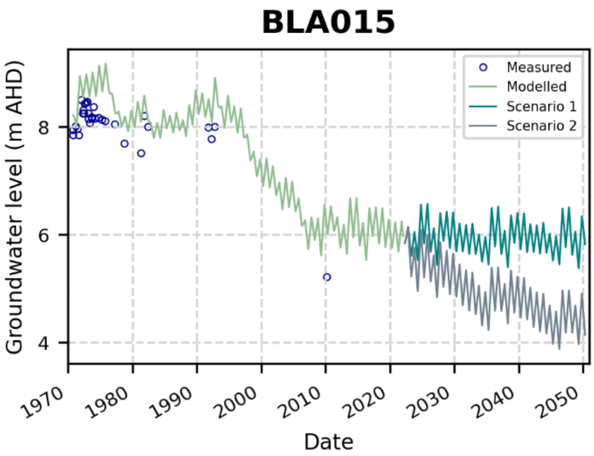


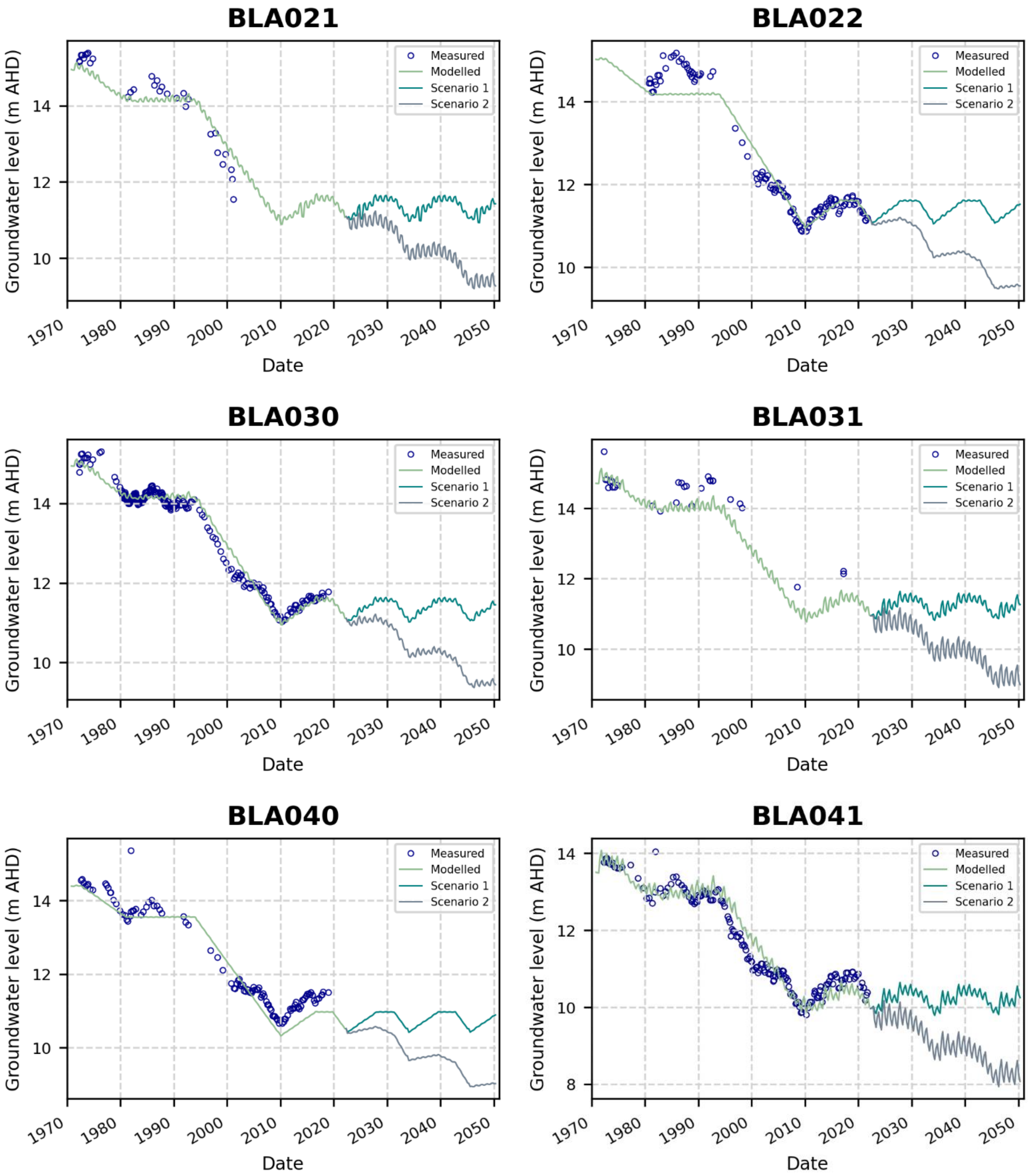


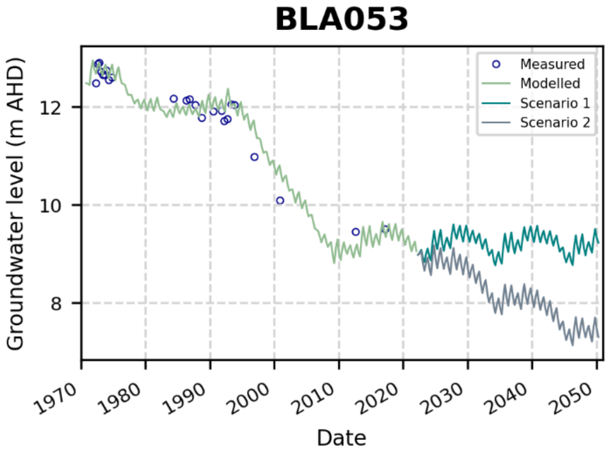


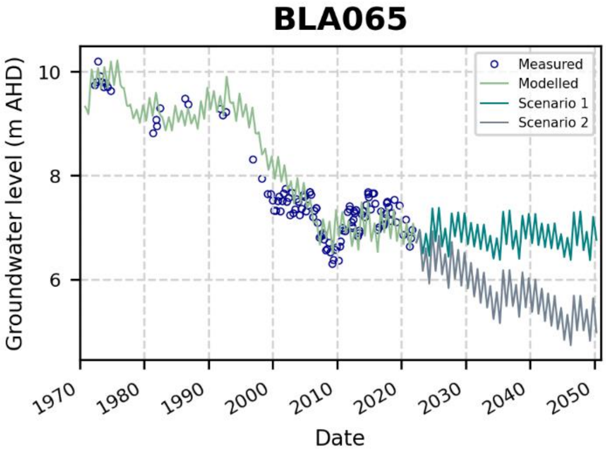


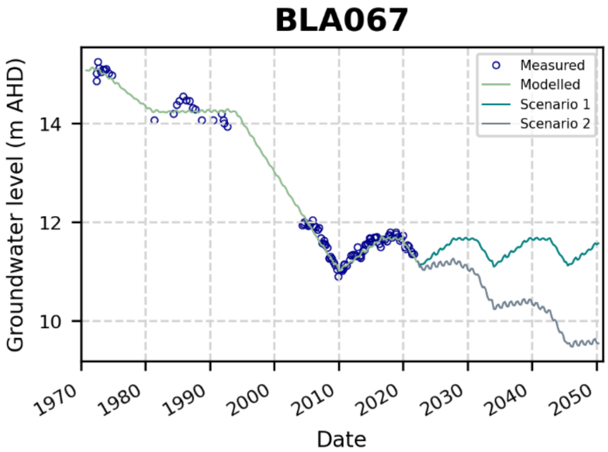


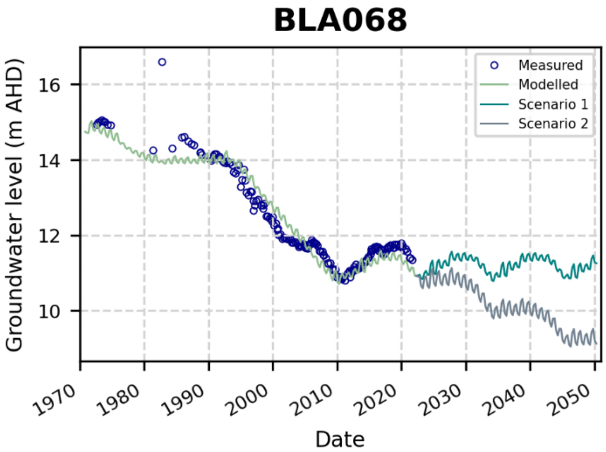


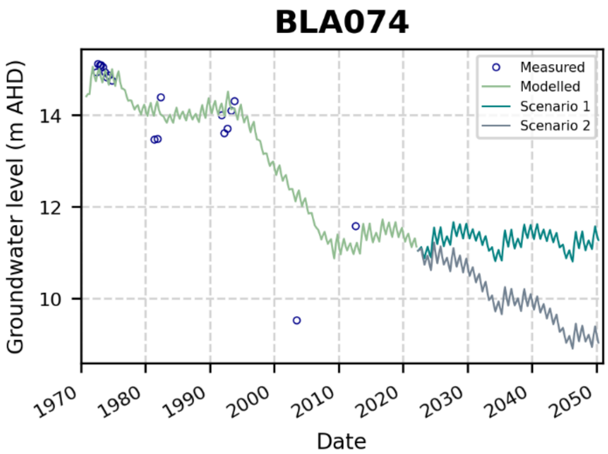

BLA021
BLA022
BLA030
BLA031
BLA040
BLA041
Measured
Modelled
Scenario 1
Scenario 2
Groundwater level (m AHD)
Date
1970
1980
1990
2000
2010
2020
2030
2040
2050

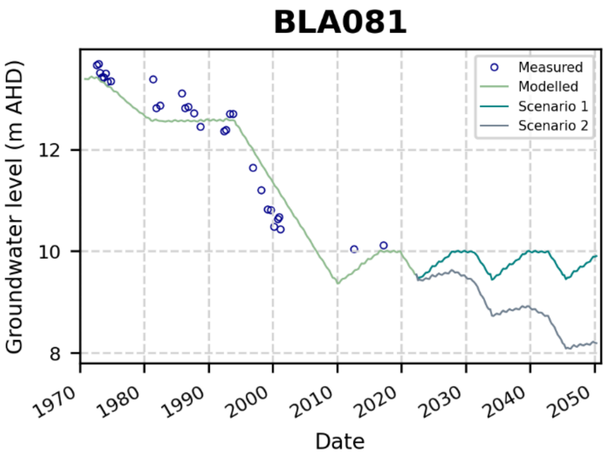

BLA053
Groundwater level (m AHD)
Measured
Modelled
Scenario 1
Scenario 2
Date

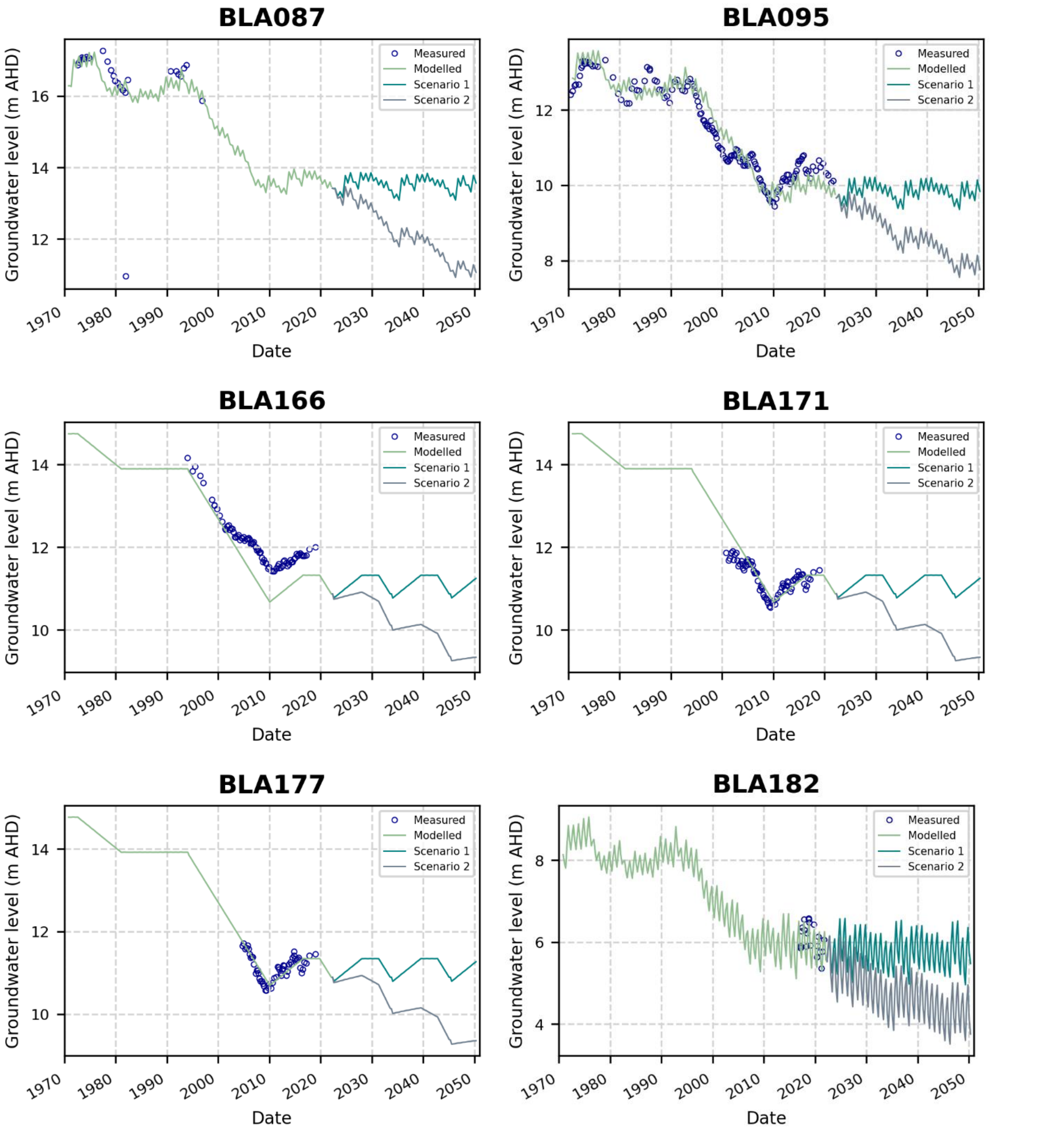

BLA065
Groundwater level (m AHD)
Measured
Modelled
Scenario 1
Scenario 2
Date

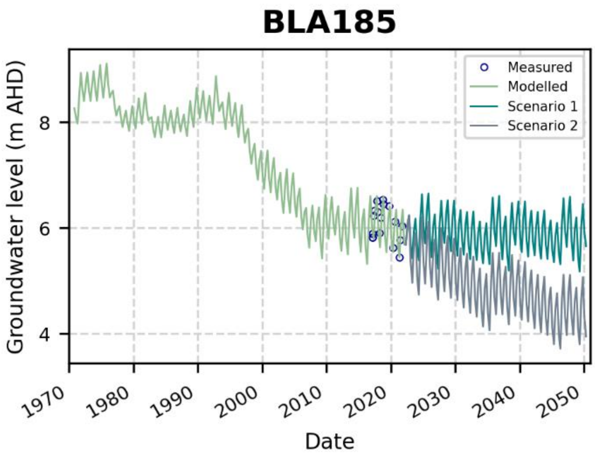

BLA067
Groundwater level (m AHD)
Measured
Modelled
Scenario 1
Scenario 2
Date

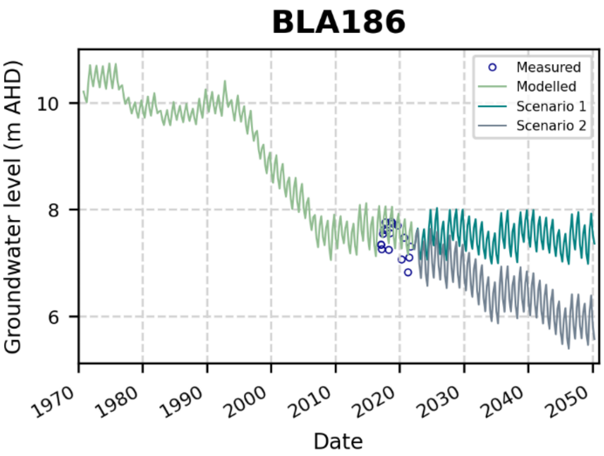

BLA068
Groundwater level (m AHD)
Measured
Modelled
Scenario 1
Scenario 2
Date

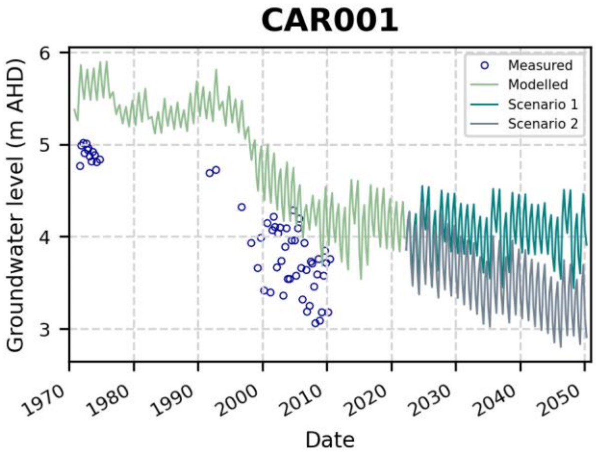

BLA074
Groundwater level (m AHD)
Measured
Modelled
Scenario 1
Scenario 2
Date

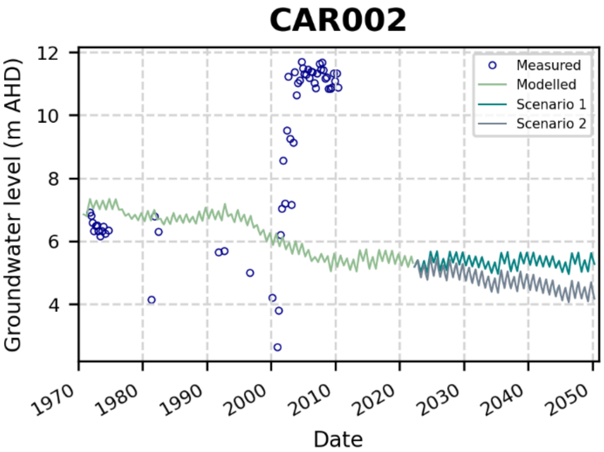

BLA081
Groundwater level (m AHD)
Measured
Modelled
Scenario 1
Scenario 2
Date

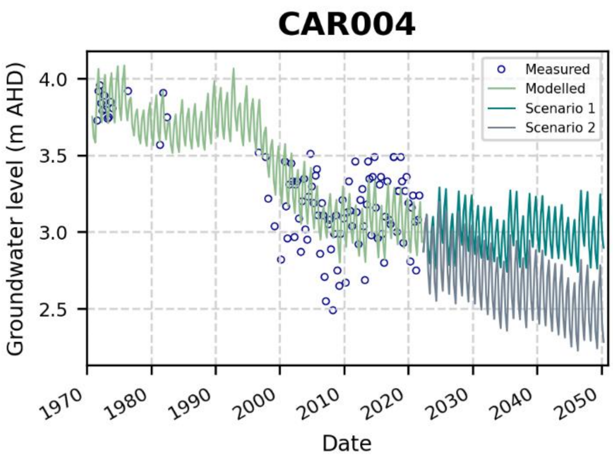

BLA087
BLA095
BLA166
BLA171
BLA177
BLA182
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2

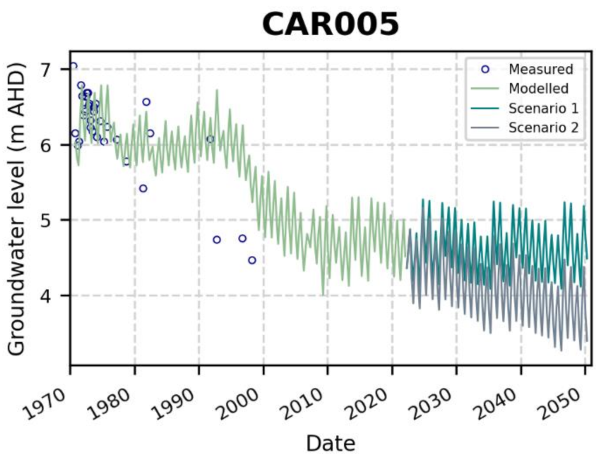

BLA185
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2

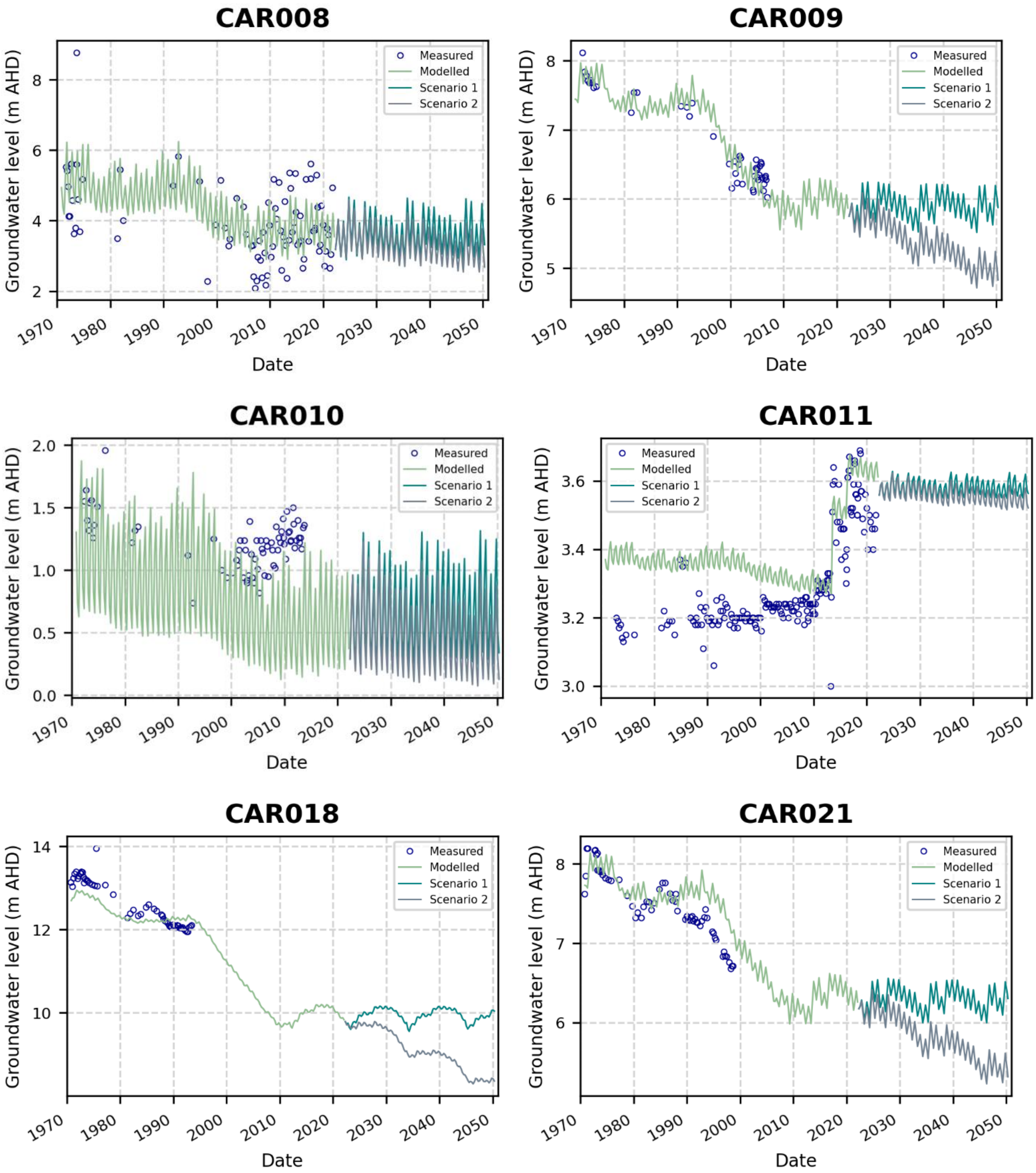

BLA186
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2


CAR001
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2

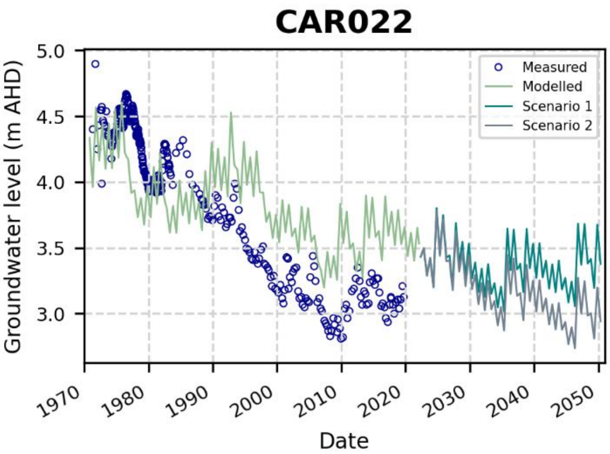

CAR002
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2

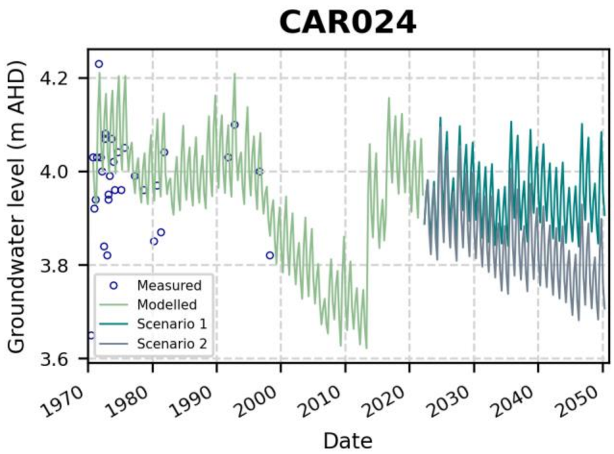

CAR004
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2

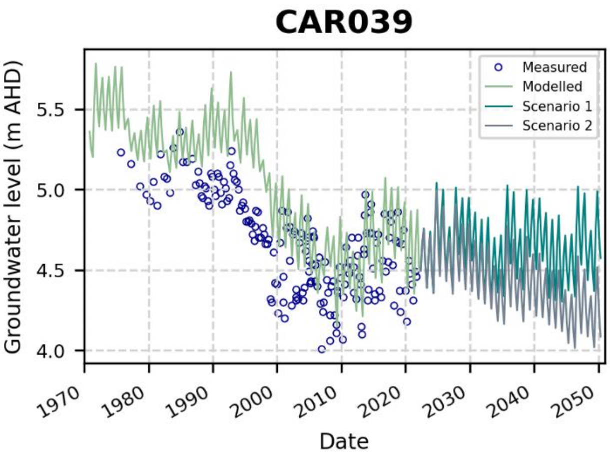

CAR005
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2

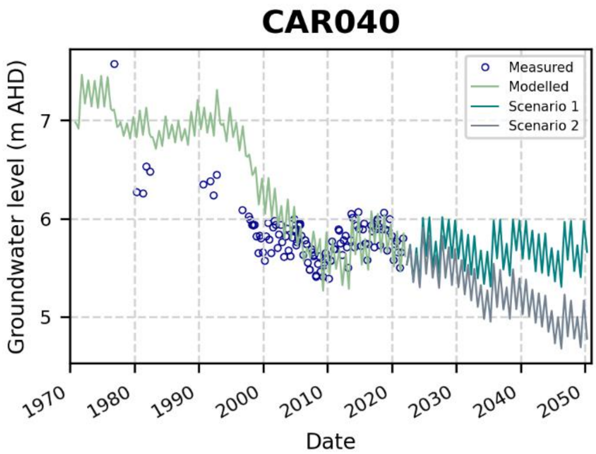


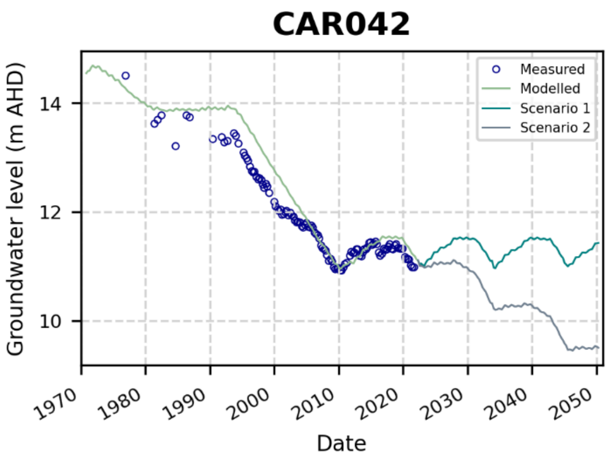
CAR008
CAR009
CAR010
CAR011
CAR018
CAR021
Measured
Modelled
Scenario 1
Scenario 2
Groundwater level (m AHD)
Date

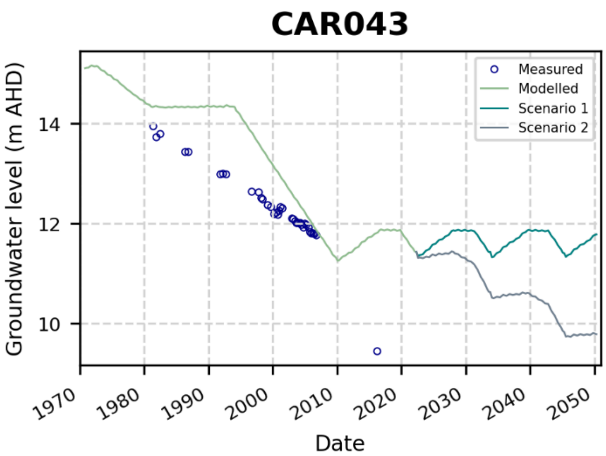

CAR022
Groundwater level (m AHD)
Date
5.0
4.5
4.0
3.5
3.0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Measured
Modelled
Scenario 1
Scenario 2

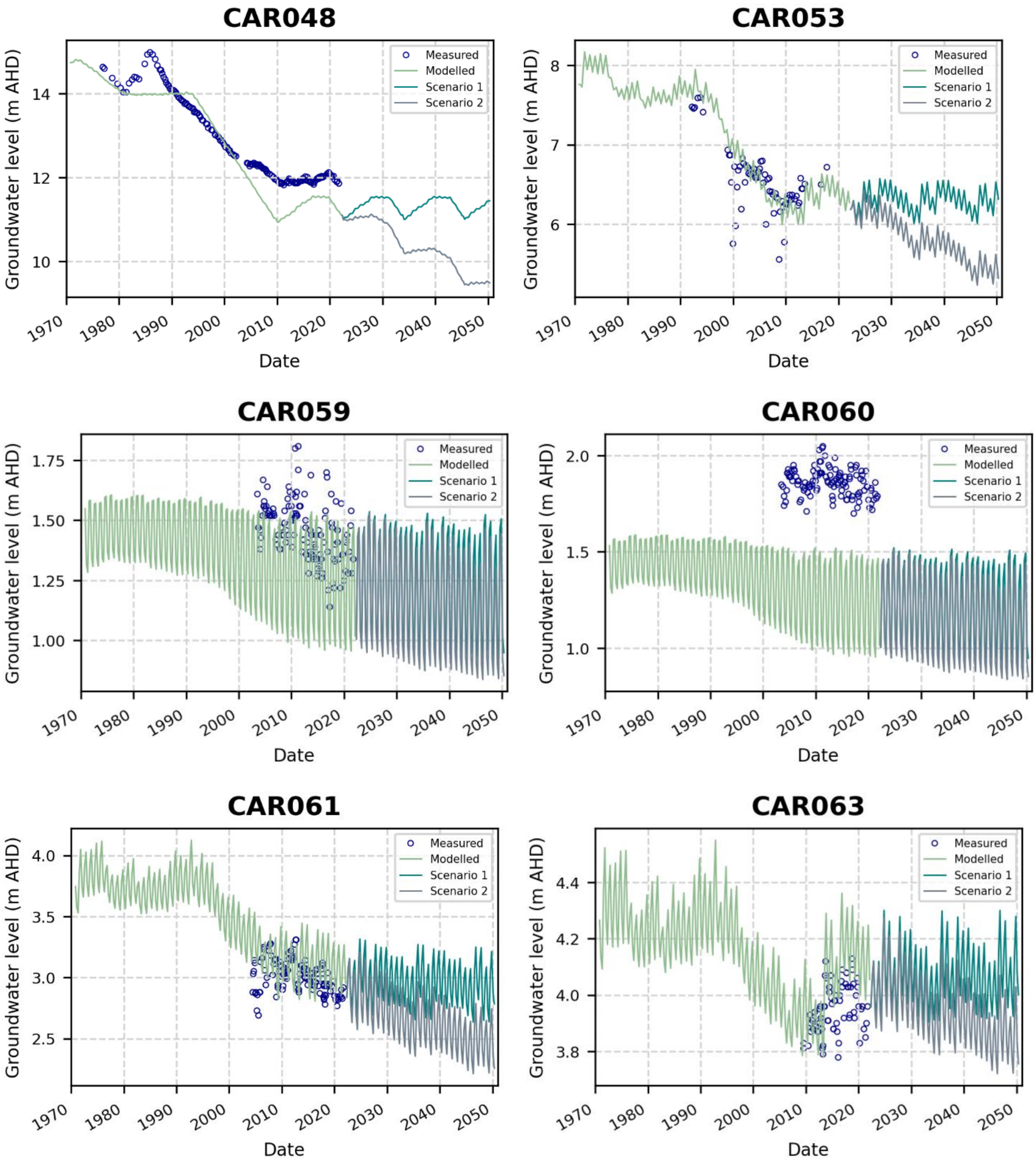

CAR024
Groundwater level (m AHD)
Date
4.2
4.0
3.8
3.6
1970
1980
1990
2000
2010
2020
2030
2040
2050
Measured
Modelled
Scenario 1
Scenario 2

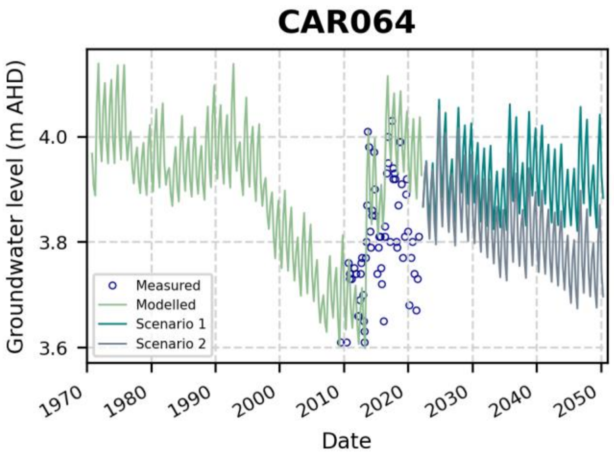

CAR039
Groundwater level (m AHD)
Date
5.5
5.0
4.5
4.0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Measured
Modelled
Scenario 1
Scenario 2

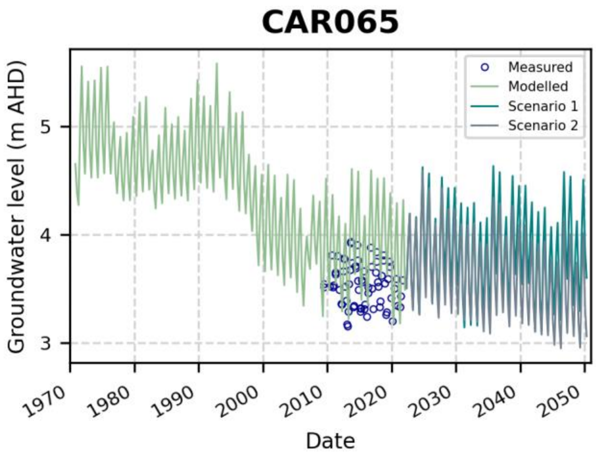

CAR040
Groundwater level (m AHD)
Date
7
6
5
1970
1980
1990
2000
2010
2020
2030
2040
2050
Measured
Modelled
Scenario 1
Scenario 2

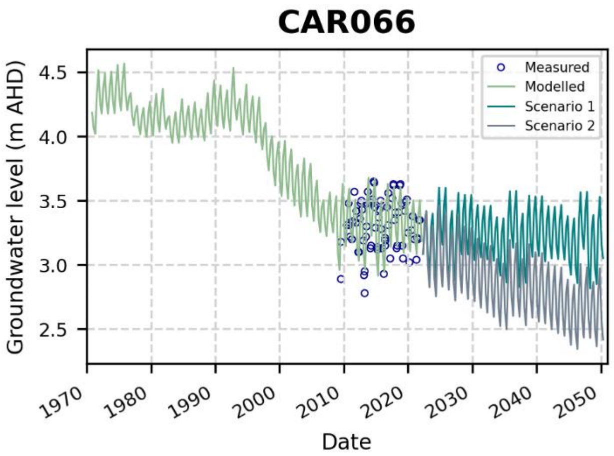

CAR042
Groundwater level (m AHD)
Date
14
12
10
1970
1980
1990
2000
2010
2020
2030
2040
2050
Measured
Modelled
Scenario 1
Scenario 2

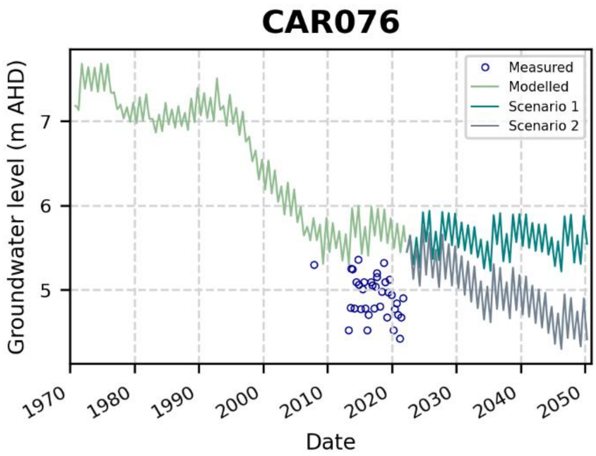

CAR043
Groundwater level (m AHD)
Date
14
12
10
1970
1980
1990
2000
2010
2020
2030
2040
2050
Measured
Modelled
Scenario 1
Scenario 2

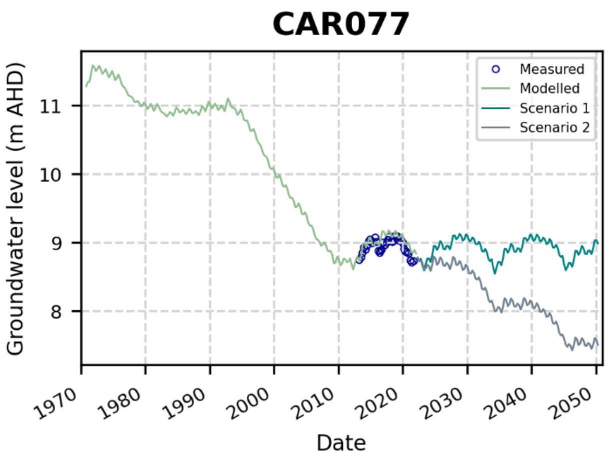

CAR048
CAR053
CAR059
CAR060
CAR061
CAR063
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2
1970
1980
1990
2000
2010
2020
2030
2040
2050

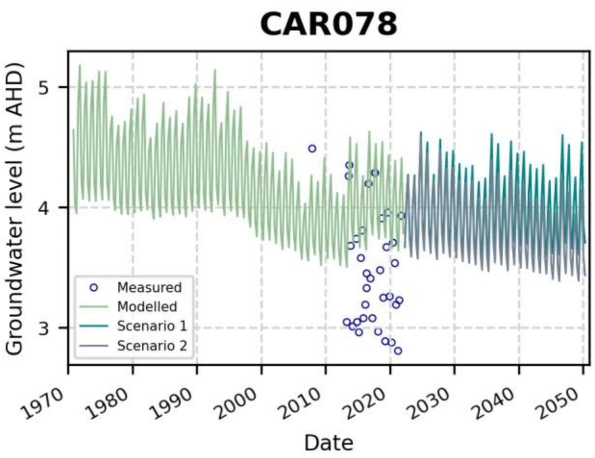

CAR064
Groundwater level (m AHD)
3.6
3.8
4.0
Date
1970 1980 1990 2000 2010 2020 2030 2040 2050
Measured
Modelled
Scenario 1
Scenario 2

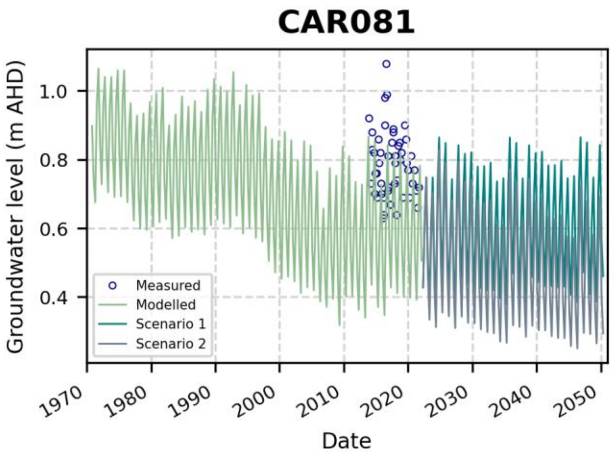

CAR065
Groundwater level (m AHD)
3
4
5
Date
1970 1980 1990 2000 2010 2020 2030 2040 2050
Measured
Modelled
Scenario 1
Scenario 2

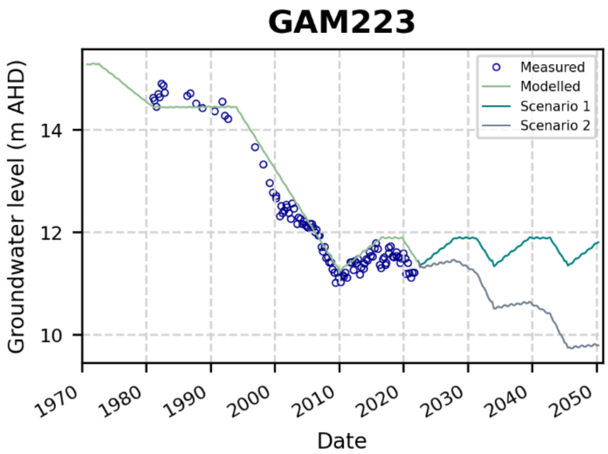

CAR066
Groundwater level (m AHD)
2.5
3.0
3.5
4.0
4.5
Date
1970 1980 1990 2000 2010 2020 2030 2040 2050
Measured
Modelled
Scenario 1
Scenario 2

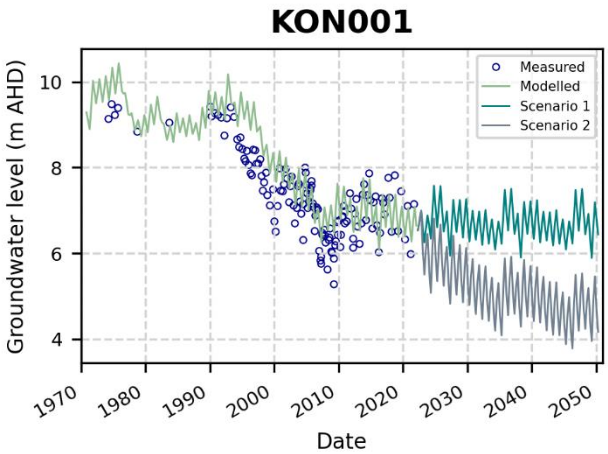

CAR076
Groundwater level (m AHD)
5
6
7
Date
1970 1980 1990 2000 2010 2020 2030 2040 2050
Measured
Modelled
Scenario 1
Scenario 2

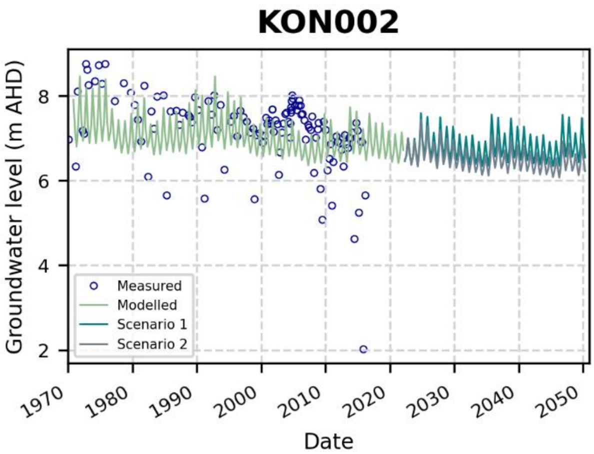

CAR077
Groundwater level (m AHD)
8
9
10
11
Date
1970 1980 1990 2000 2010 2020 2030 2040 2050
Measured
Modelled
Scenario 1
Scenario 2

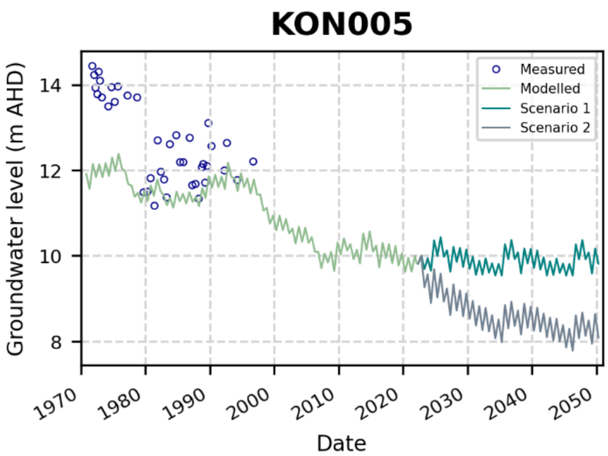

CAR078
Groundwater level (m AHD)
3
4
5
Date
1970 1980 1990 2000 2010 2020 2030 2040 2050
Measured
Modelled
Scenario 1
Scenario 2


CAR081
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2
0.4
0.6
0.8
1.0
1970
1980
1990
2000
2010
2020
2030
2040
2050


GAM223
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2
10
12
14
1970
1980
1990
2000
2010
2020
2030
2040
2050


KON001
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2
4
6
8
10
1970
1980
1990
2000
2010
2020
2030
2040
2050


KON002
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2
2
4
6
8
1970
1980
1990
2000
2010
2020
2030
2040
2050


KON005
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2
8
10
12
14
1970
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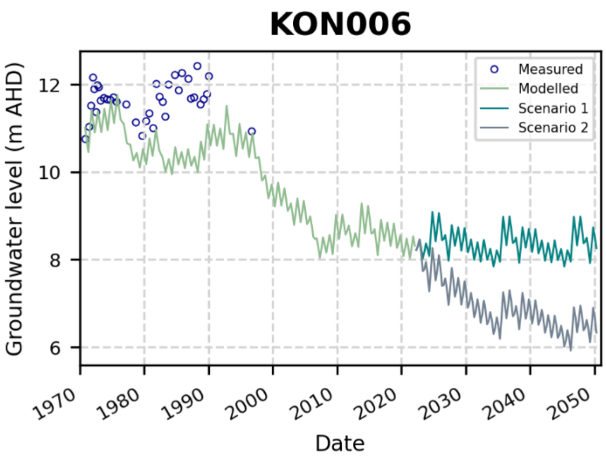
1990
2000
2010
2020
2030
2040
2050


KON006
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2
6
8
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12
1970
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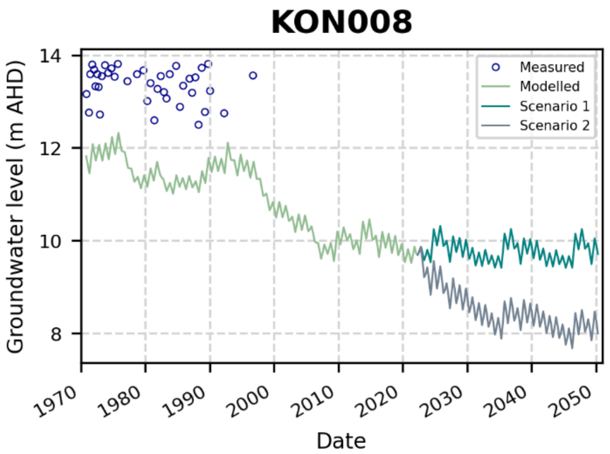
1990
2000
2010
2020
2030
2040
2050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Date
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Modelled
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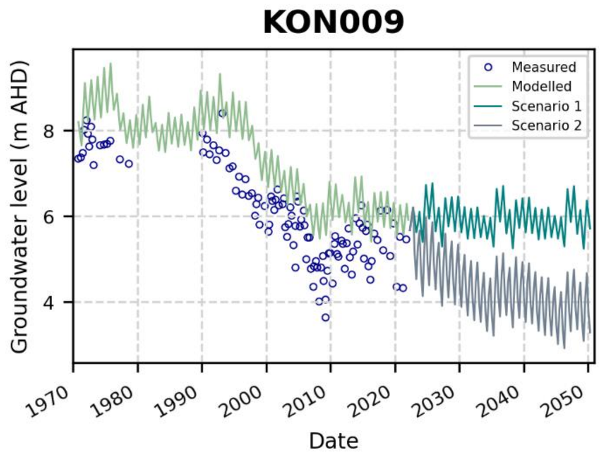
Scenario 2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Groundwater level (m AHD)
Date
Measured
Modelled
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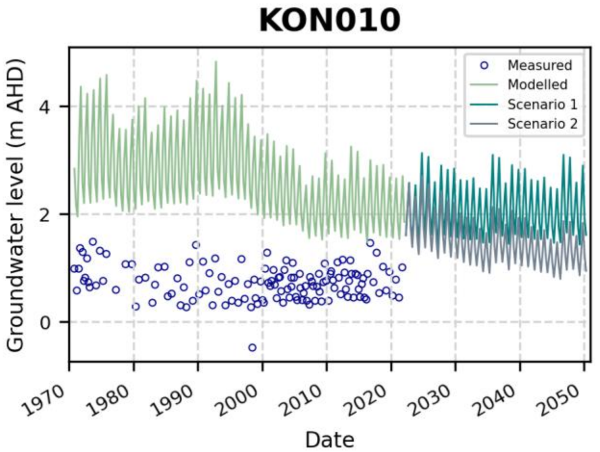
Scenario 2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Groundwater level (m AHD)
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Measured
Modelled
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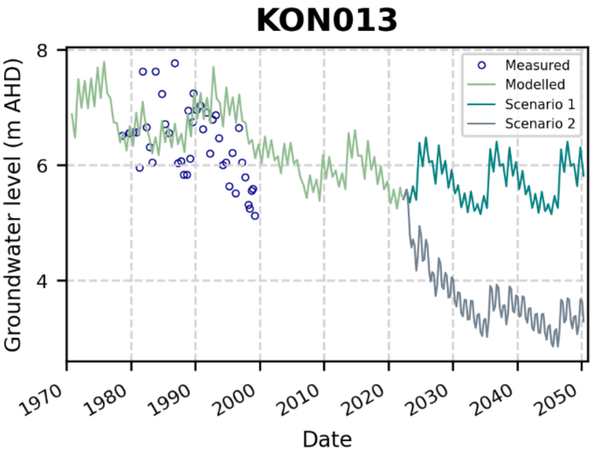
Scenario 2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Groundwater level (m AHD)
Date
Measured
Modelled
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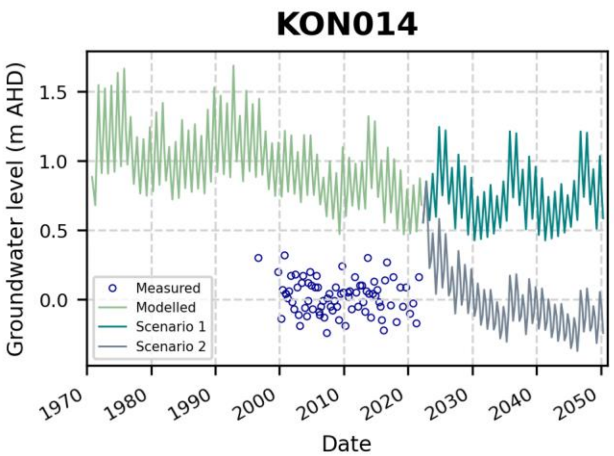
Scenario 2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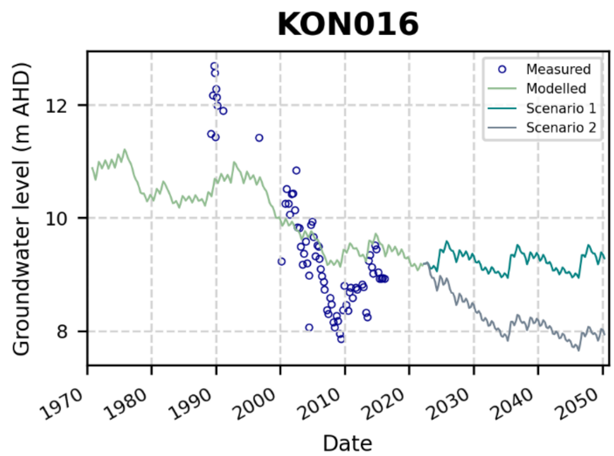
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Groundwater level (m AHD)
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Modelled
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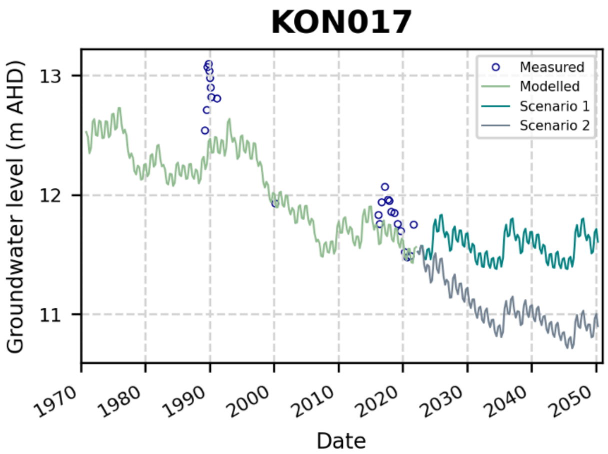
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Scenario 1
Scenario 2
Groundwater level (m AHD)
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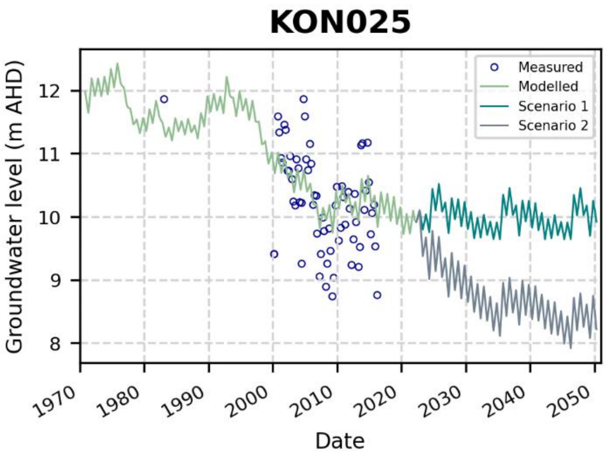
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Modelled
Scenario 1
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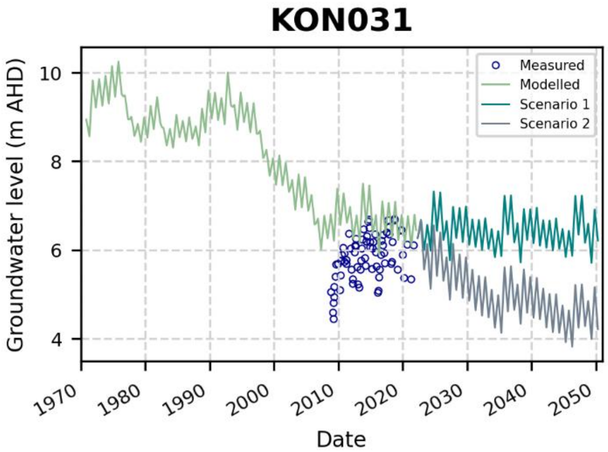
Groundwater level (m AHD)
Date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Groundwater level (m AHD)
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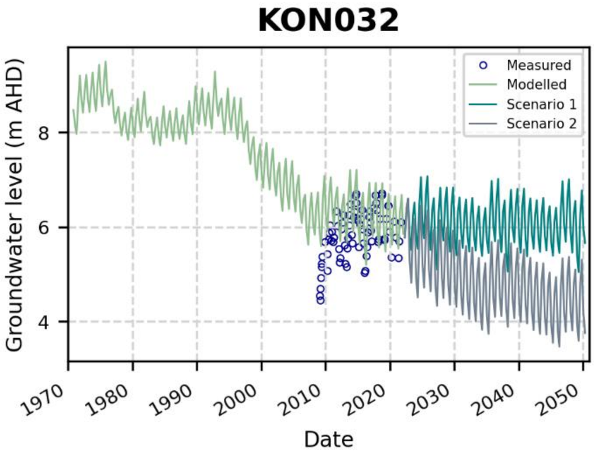
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Scenario 1
Scenario 2
Groundwater level (m AHD)
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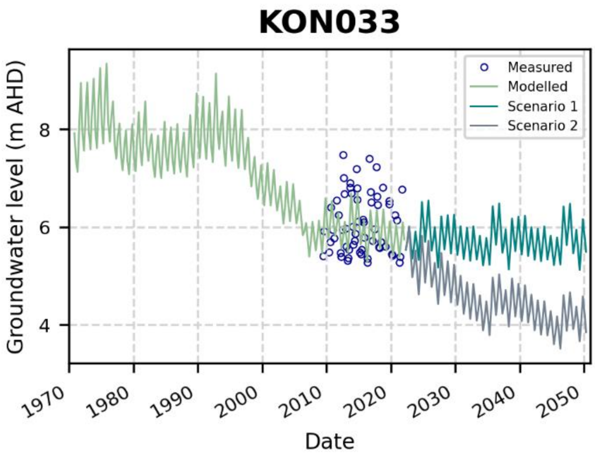
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Scenario 1
Scenario 2
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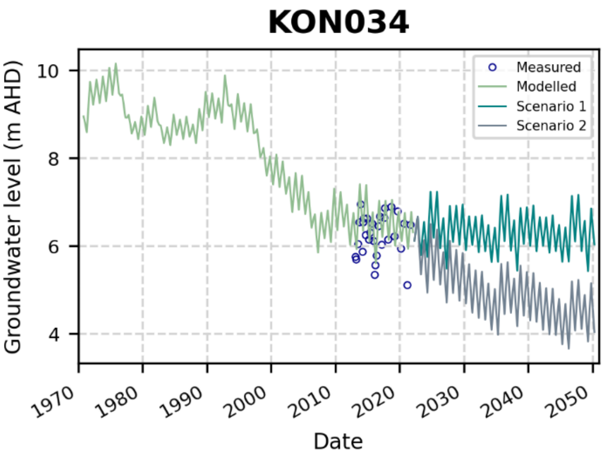
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Modelled
Scenario 1
Scenario 2
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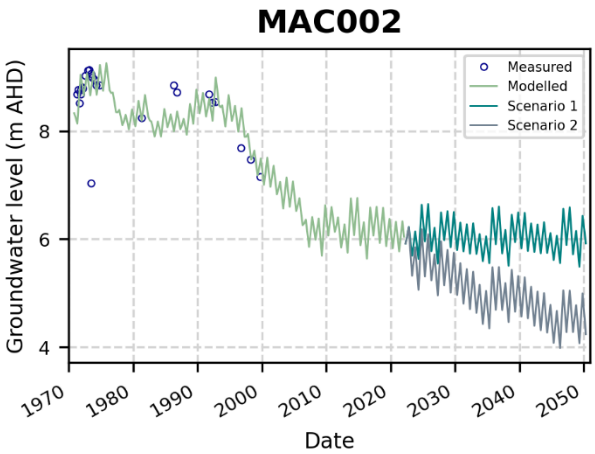
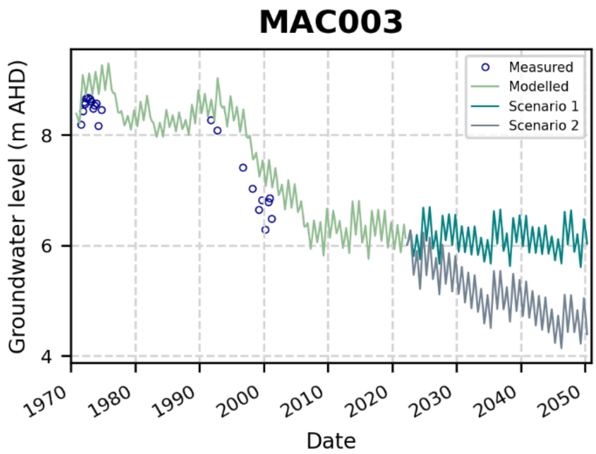
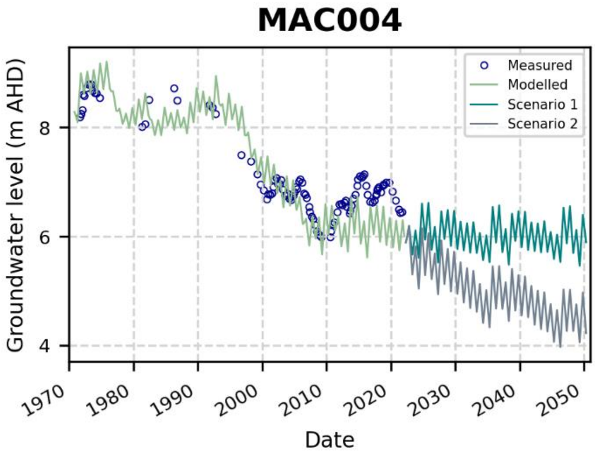
Date


MAC002
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC003
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC004
Groundwater level (m AHD)
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Measured
Modelled
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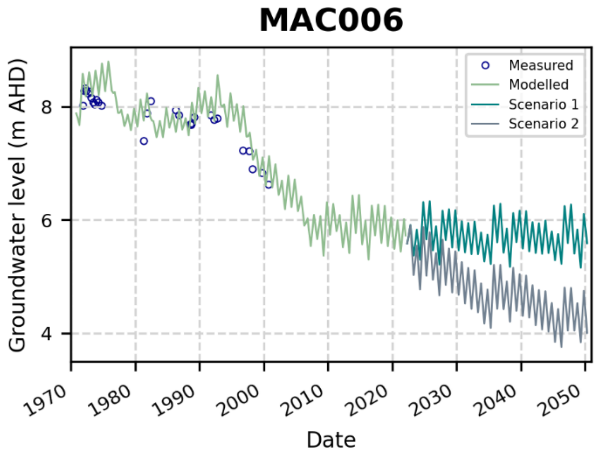
Scenario 2


MAC006
Groundwater level (m AHD)
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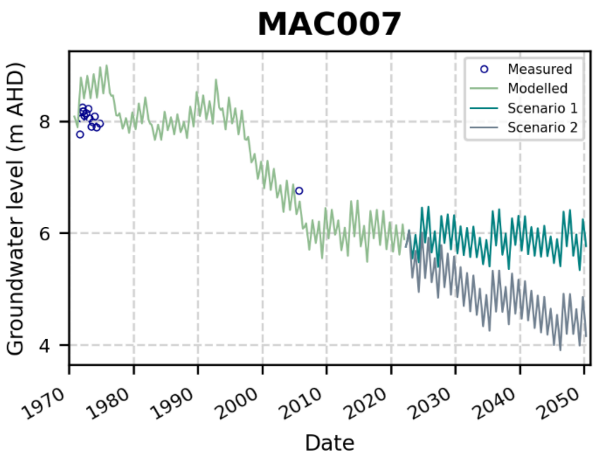
Scenario 2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Groundwater level (m AHD)
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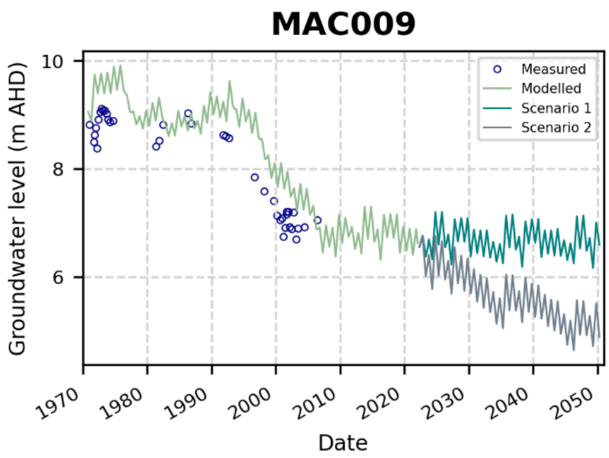
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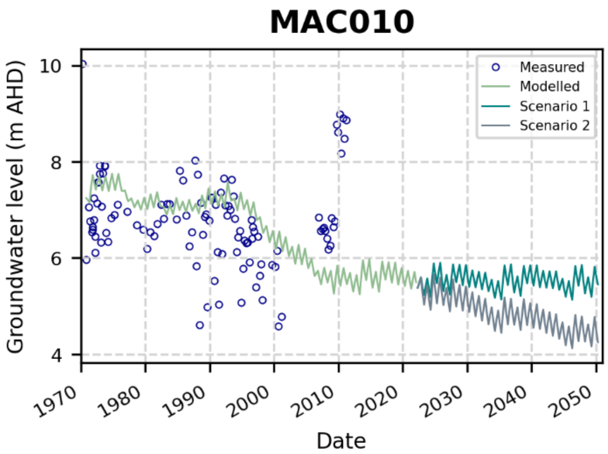
Scenario 2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Groundwater level (m AHD)
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Measured
Modelled
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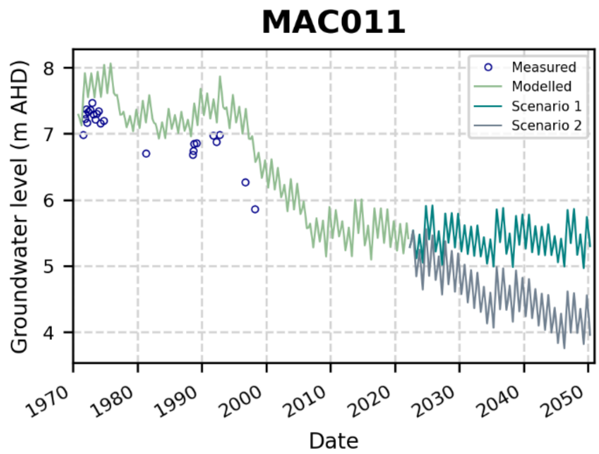
Scenario 2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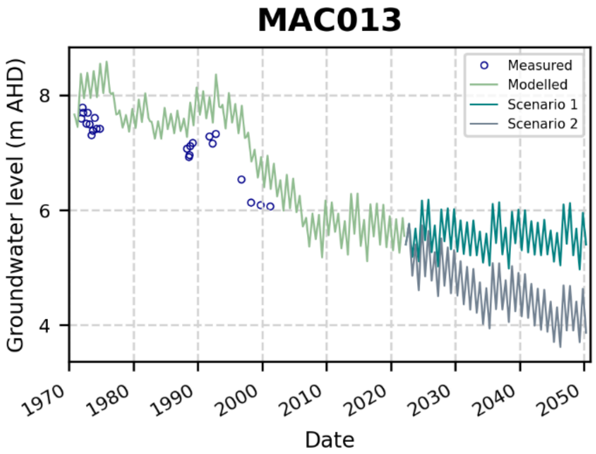
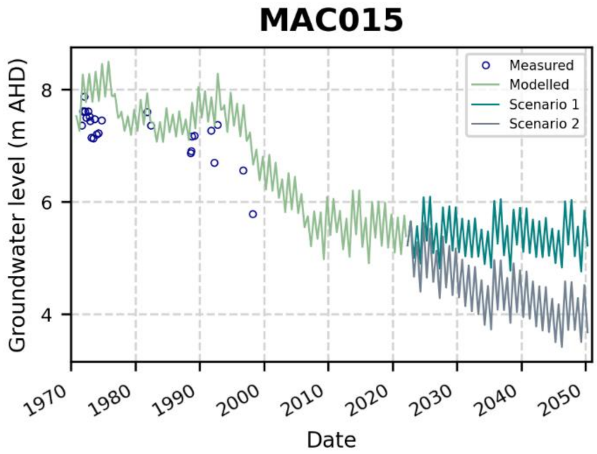
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC013
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2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Groundwater level (m AHD)
Date
Measured
Modelled
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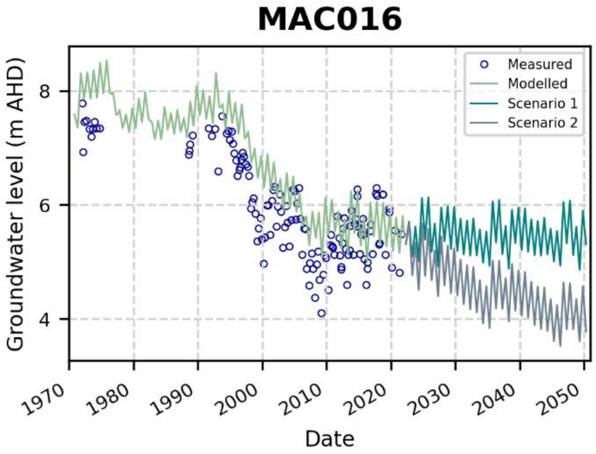
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Date
Measured
Modelled
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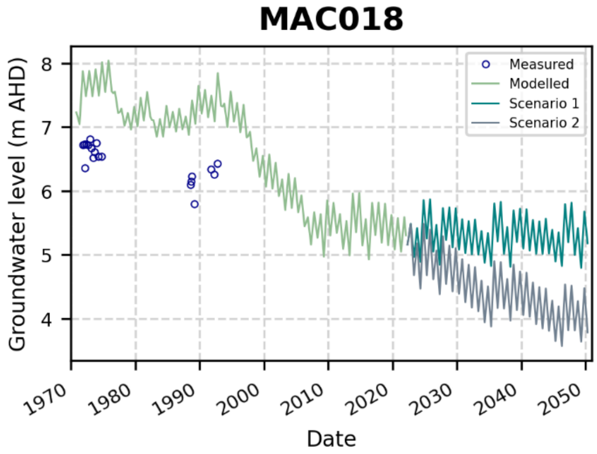
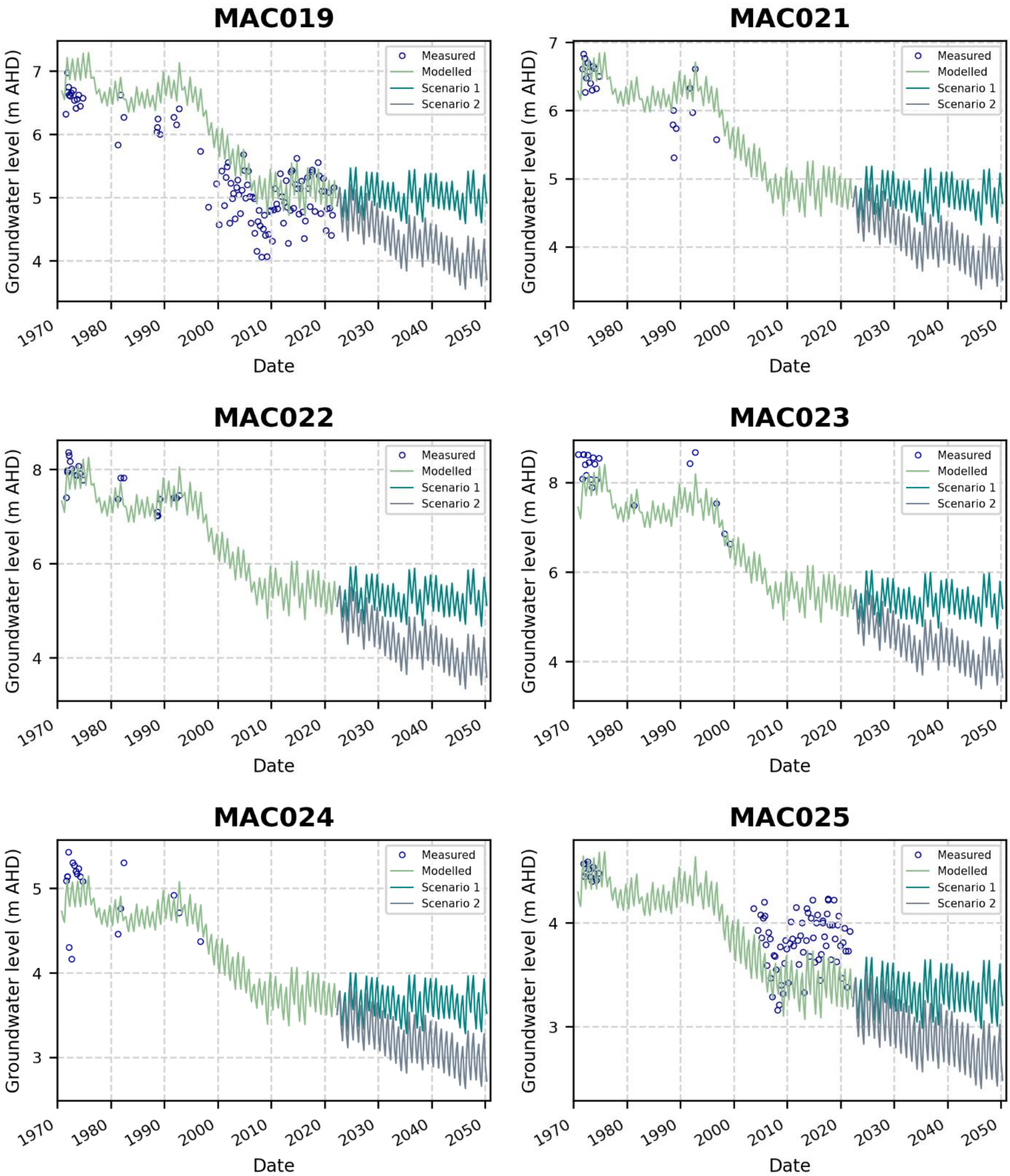
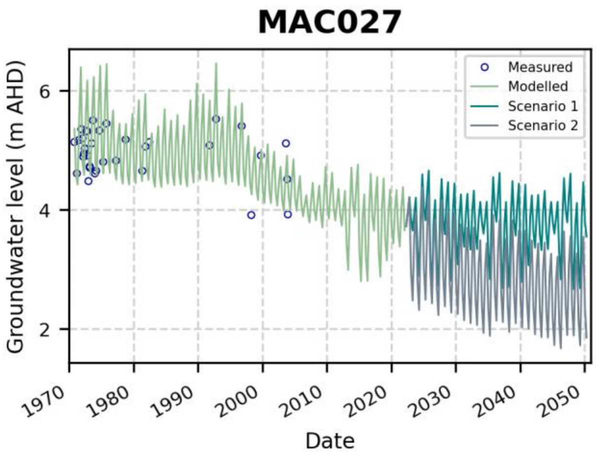
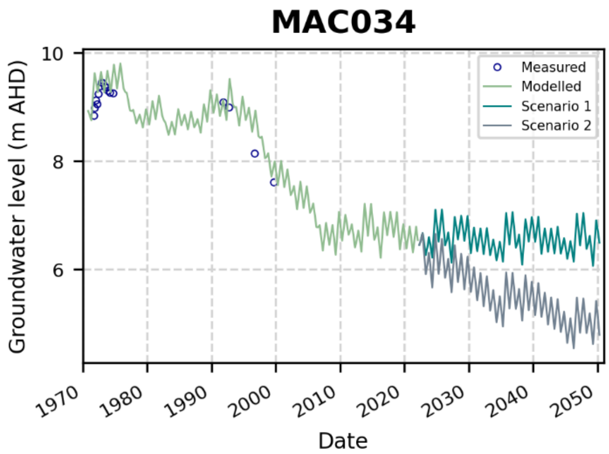
Scenario 2


MAC018
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC019
MAC021
MAC022
MAC023
MAC024
MAC025
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC027
Groundwater level (m AHD)
2
4
6
1970
1980
1990
2000
2010
2020
2030
2040
2050
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC034
Groundwater level (m AHD)
6
8
10
1970
1980
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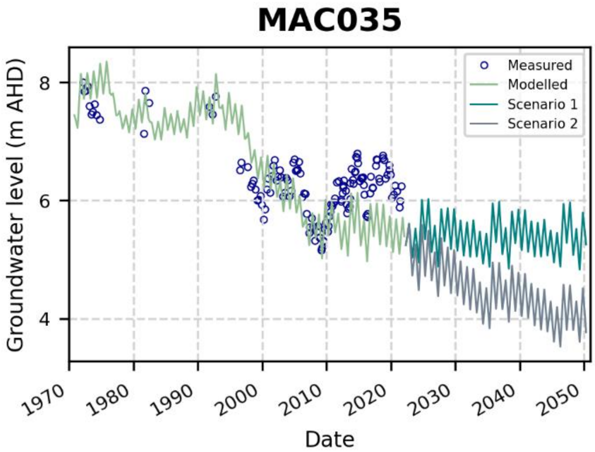
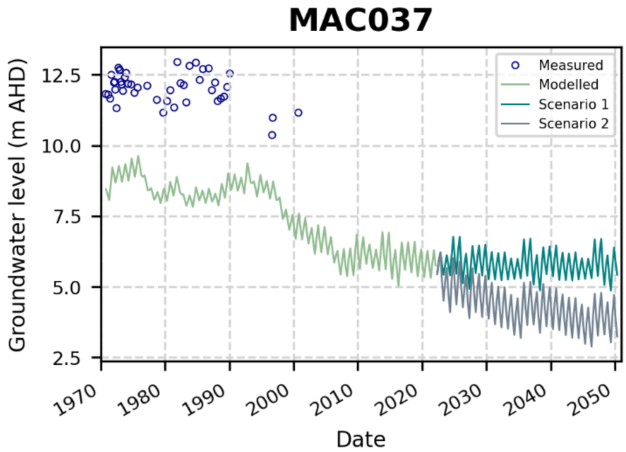
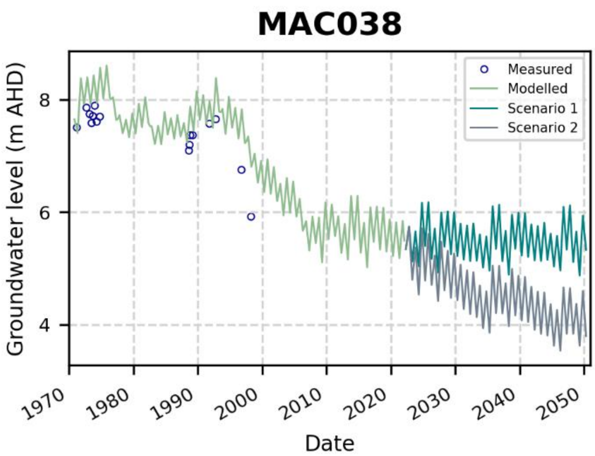
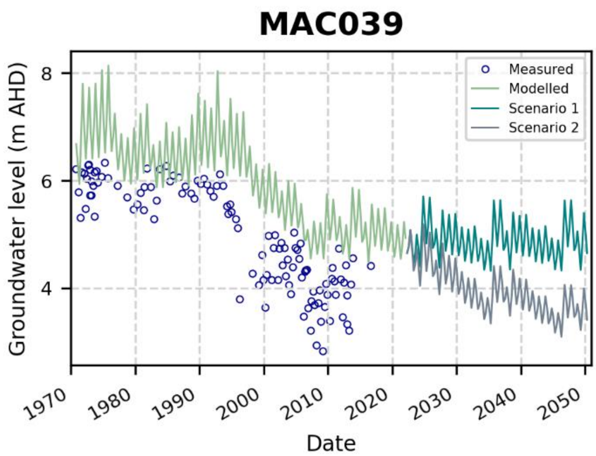
2010
2020
2030
2040
2050
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC035
Groundwater level (m AHD)
4
6
8
1970
1980
1990
2000
2010
2020
2030
2040
2050
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC037
Groundwater level (m AHD)
2.5
5.0
7.5
10.0
12.5
1970
1980
1990
2000
2010
2020
2030
2040
2050
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC038
Groundwater level (m AHD)
4
6
8
1970
1980
1990
2000
2010
2020
2030
2040
2050
Date
Measured
Modelled
Scenario 1
Scenario 2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Groundwater level (m AHD)
4
6
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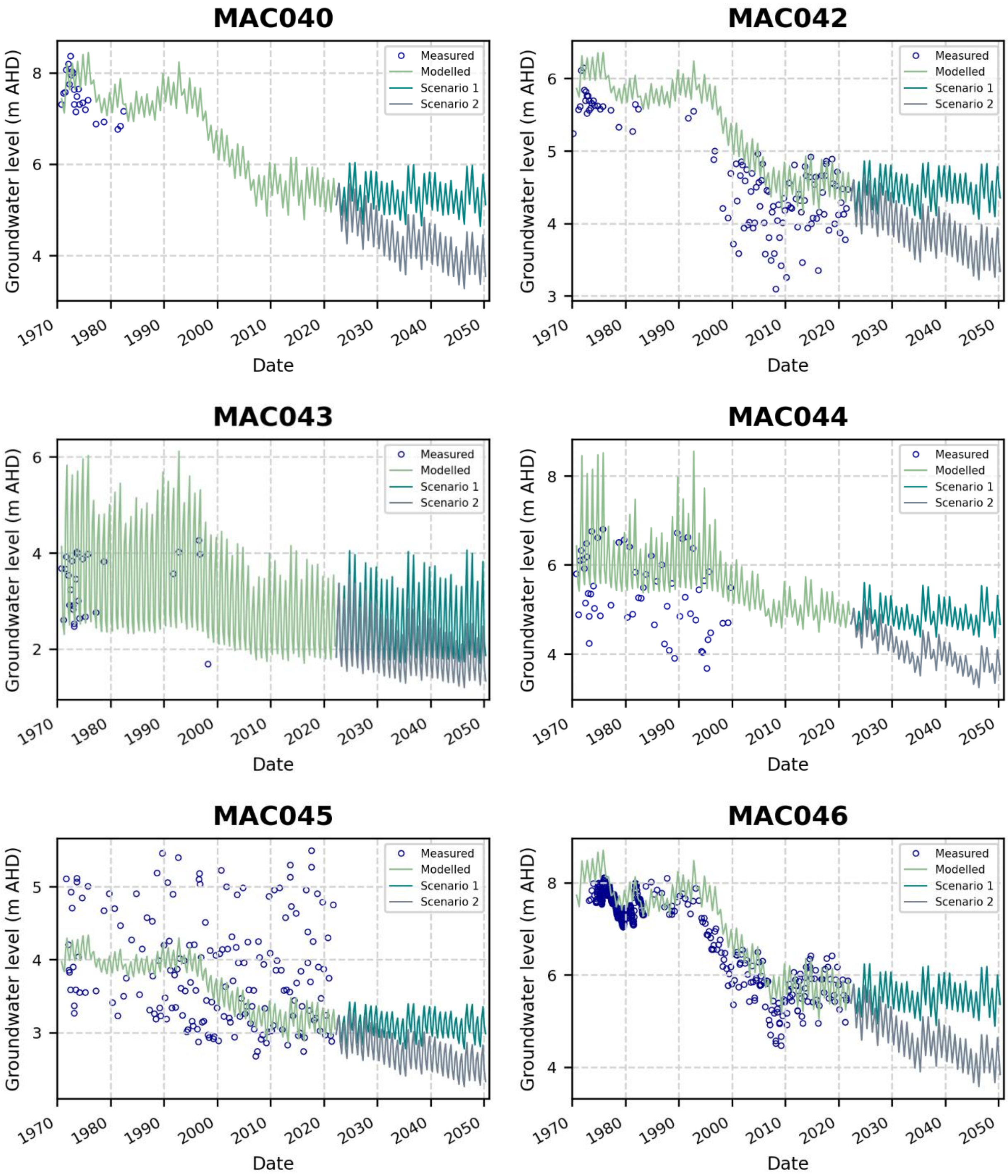
1970
1980
1990
2000
2010
2020
2030
2040
2050
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC040
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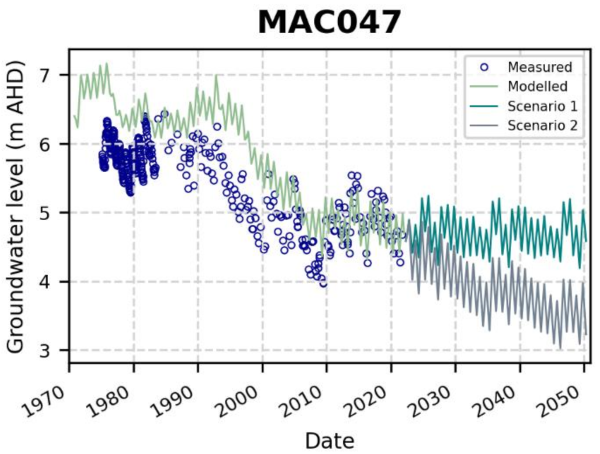
MAC043
MAC044
MAC045
MAC046
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2


MAC047
Groundwater level (m AHD)
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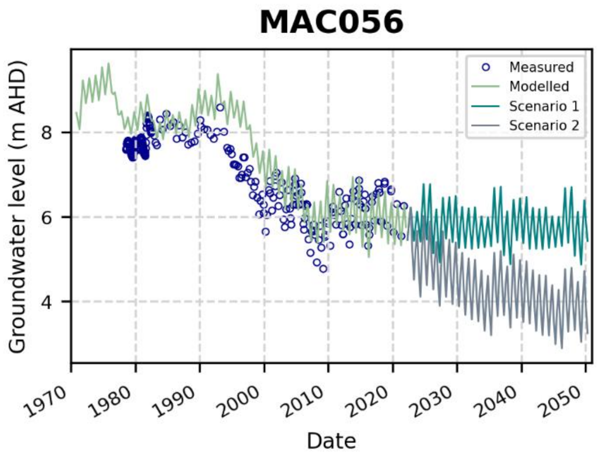
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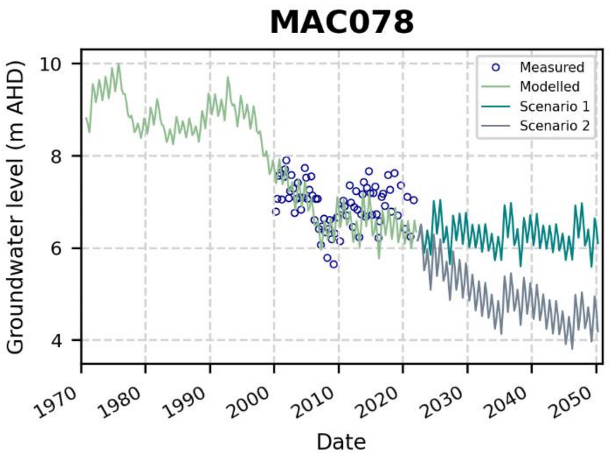
Modelled
Scenario 1
Scenario 2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Measured
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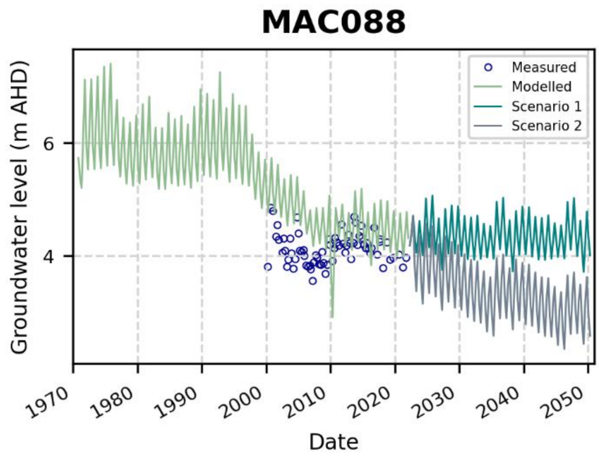
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Groundwater level (m AHD)
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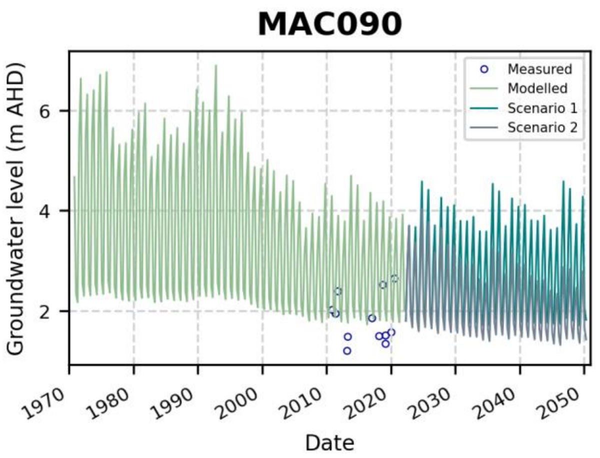
Scenario 2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Groundwater level (m AHD)
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Scenario 1
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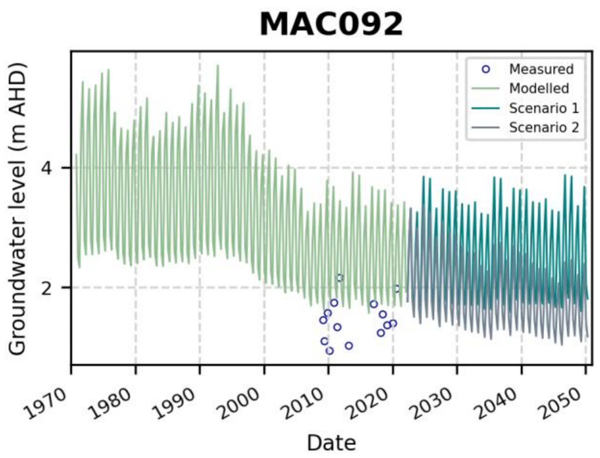
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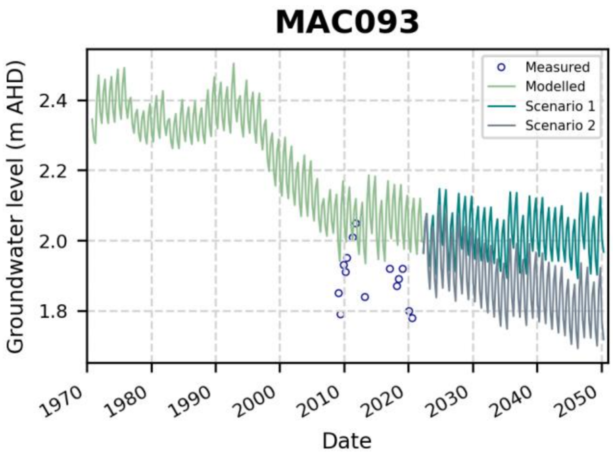
Scenario 2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Groundwater level (m AHD)
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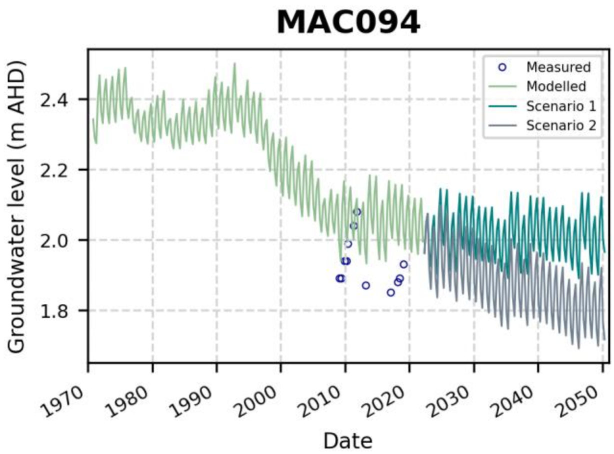
MAC094
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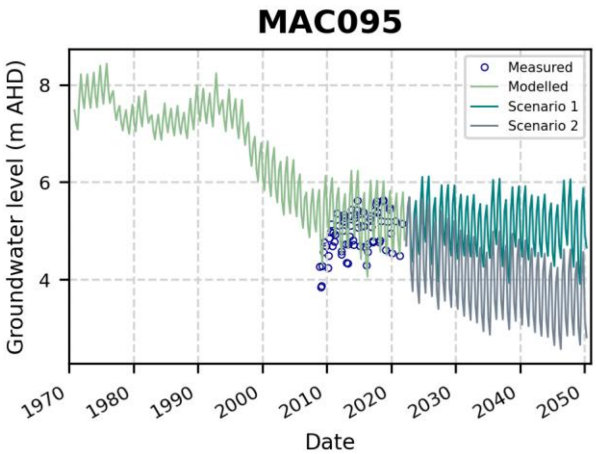
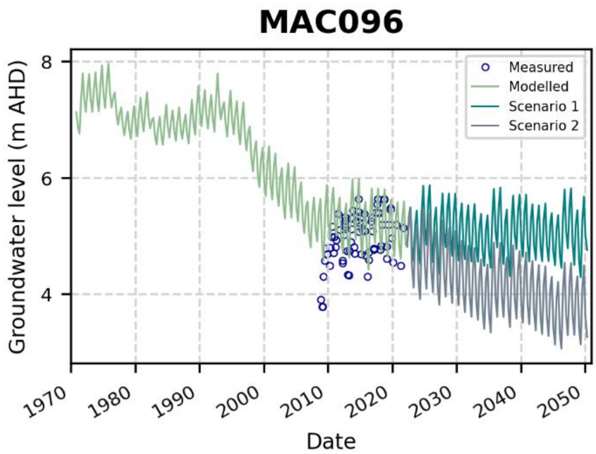
Modelled
Scenario 1
Scenario 2
Groundwater level (m AHD)
Date


MAC095
Measured
Modelled
Scenario 1
Scenario 2
Groundwater level (m AHD)
Date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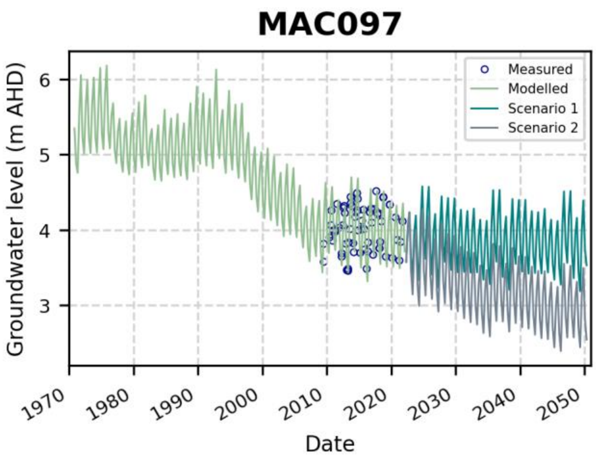
Modelled
Scenario 1
Scenario 2
Groundwater level (m AHD)
Date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Modelled
Scenario 1
Scenario 2
Groundwater level (m AHD)
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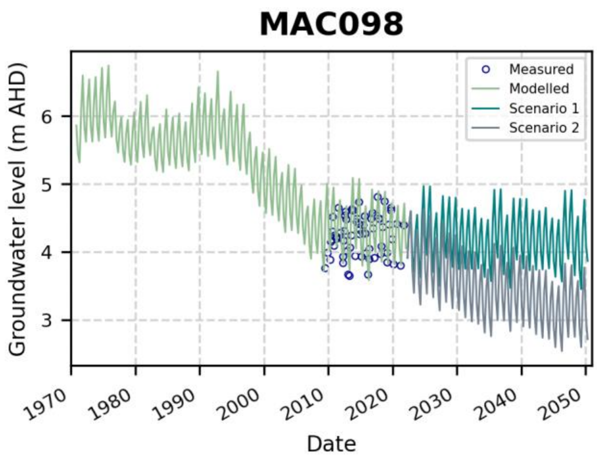
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Modelled
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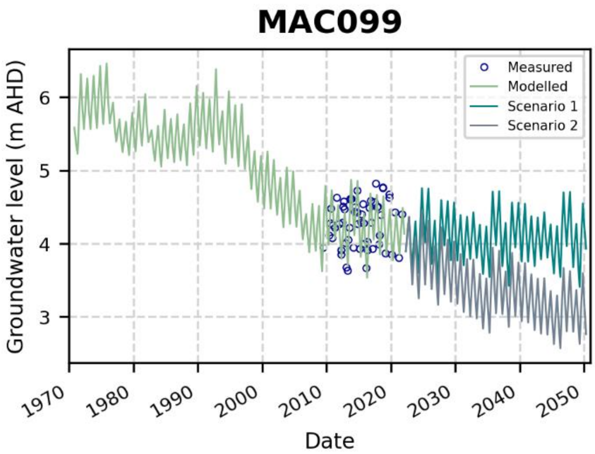
Groundwater level (m AHD)
Date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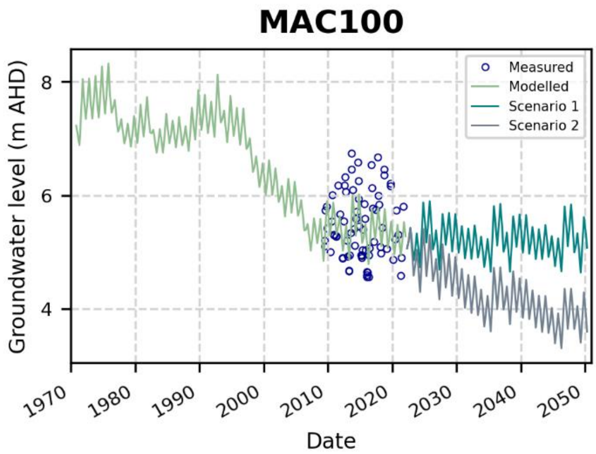
Modelled
Scenario 1
Scenario 2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Groundwater level (m AHD)
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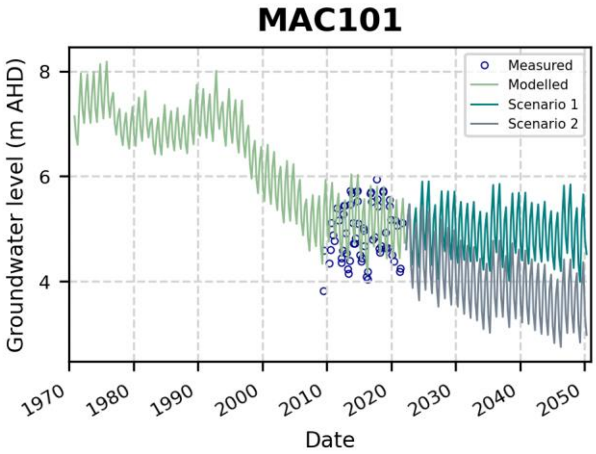
Scenario 2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Groundwater level (m AHD)
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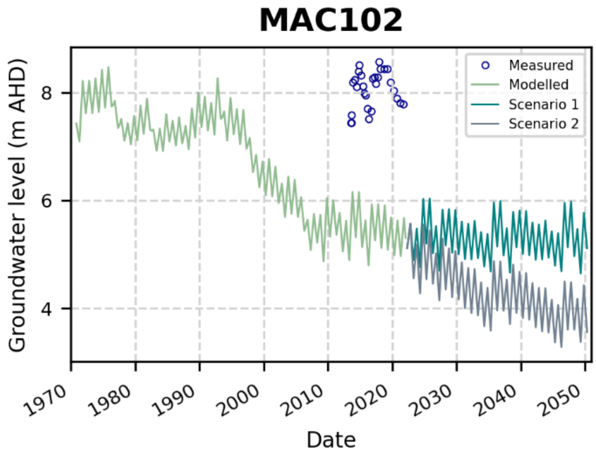
Scenario 2


MAC102
Groundwater level (m AHD)
Date
Measured
Modelled
Scenario 1
Scenario 2

9 References

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