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Koolpinyah Groundwater System Groundwater Flow Model Update

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PREPARED FOR DEPT ENVIRONMENT AND NATURAL RESOURCES BY
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EXECUTIVE SUMMARY

Objectives

The objective of the Koolpinyah Groundwater System modelling study is to update the existing FEFLOW (EHA, 2007) to included improved knowledge of the system and produce a groundwater model that is capable of supporting the analysis of possible impacts of land use and the associated groundwater development on groundwater levels and baseflow discharge within the Koolpinyah Groundwater system. The updated model will be designed to:

- support annual allocation process by forecasting the impacts of current pumping on the end of dry season groundwater levels and baseflow using wet season recharge estimates.
- examine the impacts of various pumping scenarios over a specified climatic period. Impacts are assessed by comparing the groundwater levels and changes to baseflow of development scenarios to a no-pumping or natural scenario.

Model design

The update to the Koolpinyah Groundwater System FEFLOW model incorporates the following components:

- Extension of the model domain to include the Middle Point area;
- Inclusion of structural information relevant to groundwater flow in the study area based on recent geological / geophysical investigations;
- Recent (2014) climatic data;
- Recent (2014) bore and pumping data;
- Recharge inputs determined from MIKESHE 1D soil column estimates.

The model developed for this study is considered to be Class 2, with the capacity to achieve Class 3, based on the following reasons:

- Observation data distribution both spatially and temporally, with reasonably long observation data set over the areas with greatest stress;
- Calibration to multiple lines of evidence (groundwater levels and baseflow fluxes);
- Mass balance closure error is less than 0.5% of total;
- Seasonal fluctuations are adequately replicated where these are important;
- Long-term trends are adequately replicated where these are important;

- Predictive pumping scenarios have stresses similar in magnitude to the calibrated model; and
- Length of predictive model is not excessive compared to length of calibration period.

Model uncertainty

There is uncertainty in the elevation data used to determine observation bore collars and the upper slice of the model representing the ground surface. The uncertainty in collar elevation (approximately half of observation bores) reduces the capacity of the model to match absolute groundwater levels. The elevation data impacts the areas of surface water groundwater interaction as the ground surface limits the groundwater level rises in the wet season.

Slice elevations of each layer are considered a source of model structural uncertainty. However, the uncertainty in the layer geometries is largely addressed in the process of model calibration where aquifer hydraulic conductivity is adjusted to achieve an appropriate distribution of effective aquifer transmissivity (i.e. aquifer hydraulic conductivity multiplied by aquifer thickness) to allow groundwater hydrographs to be replicated.

The pumping information used in the model has considerable uncertainty. A total of 2125 pumping bores have been identified in the study area extracting about 20 to 25 GL/yr from the Koolpinyah Groundwater System. The bores are being used as either Rural (1579), Irrigation (533) or Production (13). However, the only groundwater use that has metered extraction records are the Power and Water Corporation production bores, these account for approximately 25% of the total volume extracted from the Koolpinyah Groundwater System. The remaining 75% of extraction from the Koolpinyah Groundwater System is estimated based on land use, the uncertainty in pumping data cannot be easily addressed.

To overcome some of the uncertainties in the model, it has been constructed and calibrated to address the specific objectives of forecasting impacts on groundwater levels and stream depletion. These specific objectives are then assessed as a subtraction of two model results, which is considered less uncertain than assessing absolute model outputs.

Calibration

The Koolpinyah Groundwater System groundwater flow model was calibrated, over the period 1980 to 2014 using all groundwater levels and dry season discharge measurements, using the automatic inversion software PEST.

The uncertainty elevation data was expected to compromise the capacity of the groundwater model to match absolute measured and modelled groundwater levels. To address this issue the differences between each groundwater head measurement and the first measurement from each particular well were used in the objective function instead of absolute values. This will often facilitate better estimation of storage and/or recharge parameters than would result if head values alone were employed in the calibration process.

This approach resulted in a model that matches the dynamics of the groundwater system with seasonal head differences and long-term trends in the groundwater levels being generally well reproduced.

Dry season groundwater discharges at the three gauging sites used in the calibration, show the same magnitude and seasonal dynamics as the observed measurements.

Conclusions

The groundwater model presented by EHA (2007) has been updated to incorporate an additional seven years of climatic and pumping data. The model has been calibrated to additional data on groundwater level and dry season flows.

The current ground surface elevation in the model is derived from the SRTM elevation data, which compromises the ability of the model to match absolute groundwater levels, especially in areas where surface water / groundwater interactions occur.

Despite this limitation, the calibrated model reproduces the dynamics of the groundwater levels and dry season discharges.

The model is considered suitable for the purposes of assessing the impacts of groundwater development scenarios especially when impacts are assessed in terms of differences between the outputs of two model simulations (e.g. the difference between a stressed and unstressed or natural model) reducing the predictive uncertainty associated with model outcomes.

A comparison of natural and historic groundwater levels suggests that the increase in overall groundwater pumping associated with the expansion of horticultural enterprise in 1998/1999 has resulted in a long-term groundwater storage depletion in the area.

Faults incorporated into the updated groundwater model control groundwater flow and appear to compartmentalise the model domain into zones. The degree to which the fault features separate the various zones, however, should be investigated further as these features will determine if saline intrusion will become an issue.

Recommendations

To accurately resolve processes associated with surface water / groundwater interactions, it is highly recommended that, if an opportunity arises, a LIght Detection And Ranging (LIDAR) survey be completed over the groundwater management area encompassing the Koolpinyah Groundwater System to obtain accurate groundwater elevation data.

It should be noted that subsequent to the undertaking of this study, additional processing of the SRTM have become publically available. One such dataset is the National Digital Elevation Model (DEM) 1 Second Hydrologically Enforced product, derived from the National DEM SRTM 1 Second and National Watercourses, lakes and Reservoirs. (http://www.ga.gov.au/elvis/). It is recommended that this dataset be used in future modelling studies if the LiDAR surveys have not been completed.

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1 INTRODUCTION

1.1 Study area

The area under study is located approximately 27 km to the east and south east of Darwin. The study area includes much of the Darwin Rural Area, the majority of the Howard River catchment and the western portion of the Adelaide River catchment (see Figure 1-1 for locality). The study area overlies the Koolpinyah Groundwater System.

The Koolpinyah Groundwater System represents a significant groundwater resource hosted by a moderately complex aquifer system consisting of laterite and Mesozoic age sediments overlying Precambrian age dolomitic sediments.

As well as providing groundwater supplies to support local rural residential and agricultural subdivisions, this groundwater resource supports borefield extraction that supplements Darwin's town water supply. In addition, this groundwater resource sustains springs, wetlands and streamflow.

The study area covers approximately 1,600 km^2 and is bounded by the following features:

- to the north by the Timor Sea;
- to the north east by the Adelaide River;
- to the south east by a north east – south west geological boundary (Giants Reef Fault) nearly coincident with the Adelaide River to the south east of Middle Point; and
- to the south west by the catchment divide of the Howard River.

1.2 Scope

The scope for the updated FEFLOW model was to:

- Review existing hydrogeological conceptualisation for the model area including a review of relevant reports;
- Review of available surface water data and stream / groundwater discharge relationships;
- Review of available groundwater extraction data;
- Review of aquifer parameterisation including hydraulic parameters and flow system characterisation; and
- Review of aquifer recharge processes including spatial and temporal variability.

The practical steps involved in this process were:

- Extending the FEFLOW model domain used by EHA to incorporate the Middle Point area;
- Set up model layers and finite element grid and conceptual aquifer geometry data; and
- Calibrate the FEFLOW groundwater flow model and perform sensitivity analysis.

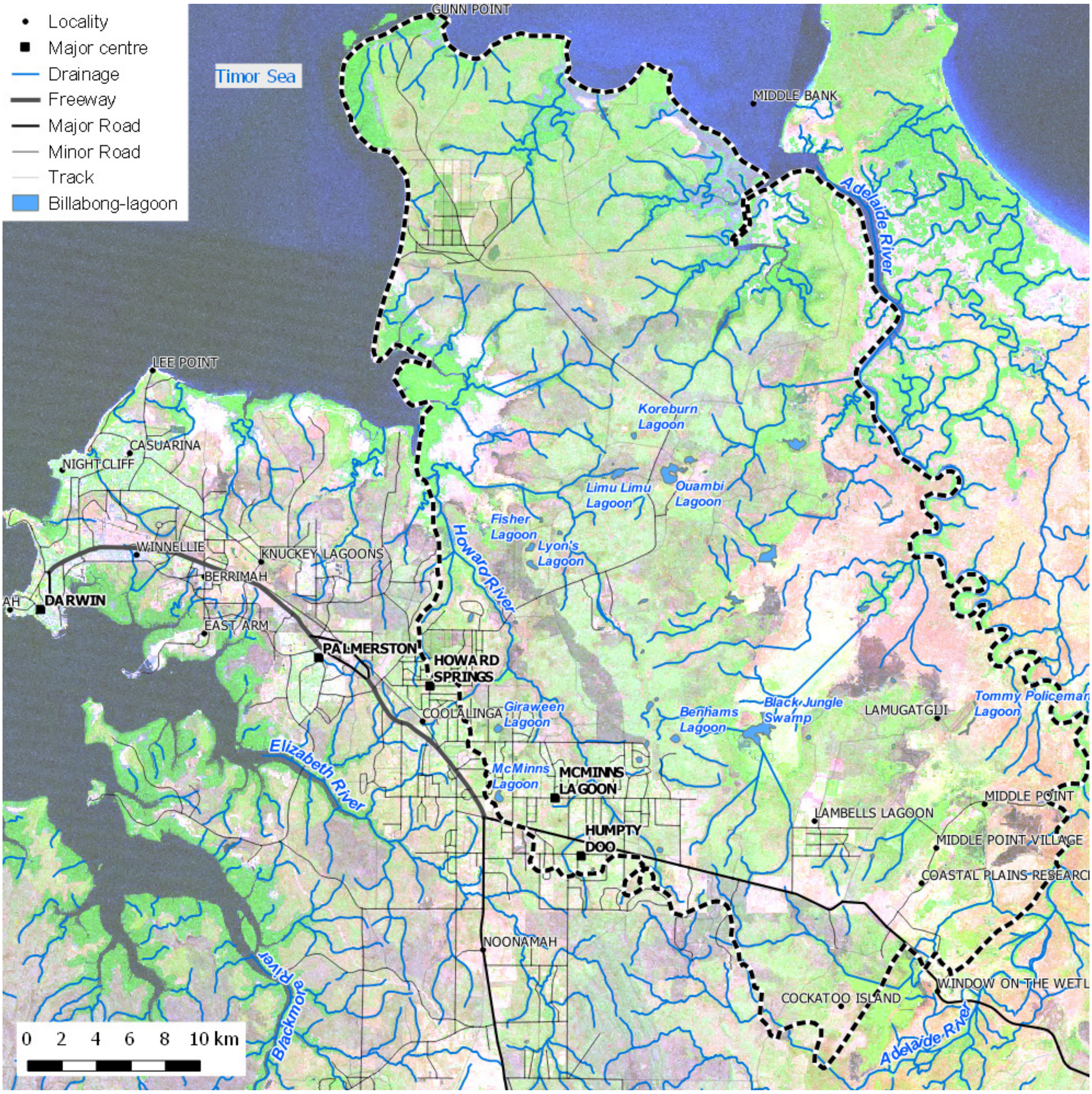


Figure 1-1 Location of the study area with relation to major centres.

1.3 Objectives

The objectives of this modelling study are to:

- Develop a groundwater flow model updating the existing FEFLOW (EHA, 2007) and MODFLOW (Yin Foo, 2003) models;
- Develop a groundwater flow model to support analysis of impacts of groundwater development, as a result of changes in land use, on water resources within the Darwin Rural Area; and
- Develop a model to provide the basis for the determination of annual allocations by forecasting dry season groundwater levels and flow regime at priority discharge areas such as Howard River and Howard Springs.

1.4 Model classification

The Australian Modelling Guidelines (Barnett et al, 2012) recommend assigning a confidence classification to a modelling study using metrics such as:

- observation data distribution both spatially and temporally;
- magnitude of stresses during prediction relative to stresses used during model calibration; and
- calibration to multiple lines of evidence including groundwater levels and groundwater discharge observations.

The model developed for this study is considered to be Class 2, with the capacity to achieve Class 3, based on the following reasons:

- Observation data distribution both spatially and temporally, with reasonably long observation data set over the areas with greatest stress;
- Calibration to multiple lines of evidence (groundwater levels and baseflow fluxes);
- Mass balance closure error is less than 0.5% of total;
- Seasonal fluctuations are adequately replicated where these are important;
- Long-term trends are adequately replicated where these are important;
- Predictive pumping scenarios have stresses similar in magnitude to the calibrated model; and
- Length of predictive model is not excessive compared to length of calibration period.

Impacts are then assessed as a subtraction of two model results, which is considered less uncertain than assessing absolute model outputs.

There is adequate spatial coverage of digital elevation model to define ground surface elevation however, the inherent errors in the elevation data compromises the capacity of the groundwater model to match absolute groundwater elevations, particularly in areas where surface water / groundwater interactions.

1.5 Limitations

The layer geometries are considered a source of model structural error and were largely addressed in the process of model calibration where aquifer hydraulic conductivity is adjusted to achieve an appropriate distribution of effective aquifer transmissivity (i.e. aquifer hydraulic conductivity multiplier by aquifer thickness) to allow groundwater hydrographs to be replicated.

2 MODEL INPUT UPDATES

The updates to the Koolpinyah Groundwater System groundwater flow model include updates to the model domain and mesh geometry as well as updating the input data incorporates the following components:

- Extending the model domain to include the Middle Point area;
- Incorporate Transfer BCs to represent the aquifer-river interaction along the Howard River and fluxes at the coast boundary;
- Inclusion of structural information expected to be relevant to groundwater flow in the study area based on recent geological / geophysical investigations;
- Include groundwater flow to the north of the model domain;
- Include groundwater discharge to the Adelaide River from the dolostone aquifer;
- Incorporate the most recent climatic data; and
- Incorporate the most recent bore and pumping data.

2.1 Available climatic data

EHA, (2007) provides a detailed summary of the climatic conditions for the study area. Some general comments made about the climatic conditions can be made:

- On average there is a marked dry season from May through September during which 2% of the annual rainfall is recorded whilst there is a markedly wetter period from October through April during which 98% of average rainfall occurs.
- Average potential evaporation exceeds monthly rainfall during December through March with the total deficit during the period being on average 894 mm.

EHA also identified that there are no active official Bureau of Meteorology (BoM) rainfall monitoring stations within the study area.

To provide a continuous record daily synthetic historical climatic data for the study area was obtained from the Queensland SILO Data Drill repository. The SILO Data Drill accesses grids of data interpolated from point observations collected and collated by the BoM. The SILO Data Drill provides meteorological variables that are useful for agro meteorological research and modelling and the surfaces are interpolated to 0.05 degrees spatial resolution (around 5 km).

The daily synthetic climatic for the study area (12° 27'S, 131° 12'E or -12.45°, 131.20°) was obtained for the period from 1 January 1900 to 31 October 2014.

Figure 2-1 provides a plot of monthly historical rainfall for the site using data drawn from the SILO data drill facility together with a plot of the cumulative differences from mean monthly rainfall (i.e. the rainfall mass residual curve). In groundwater systems where there is an appreciable component of recharge due to the direct infiltration of incident rainfall, groundwater hydrographs generally display strong correlation with the trace of the cumulative differences from mean monthly rainfall (EHA, 2007).

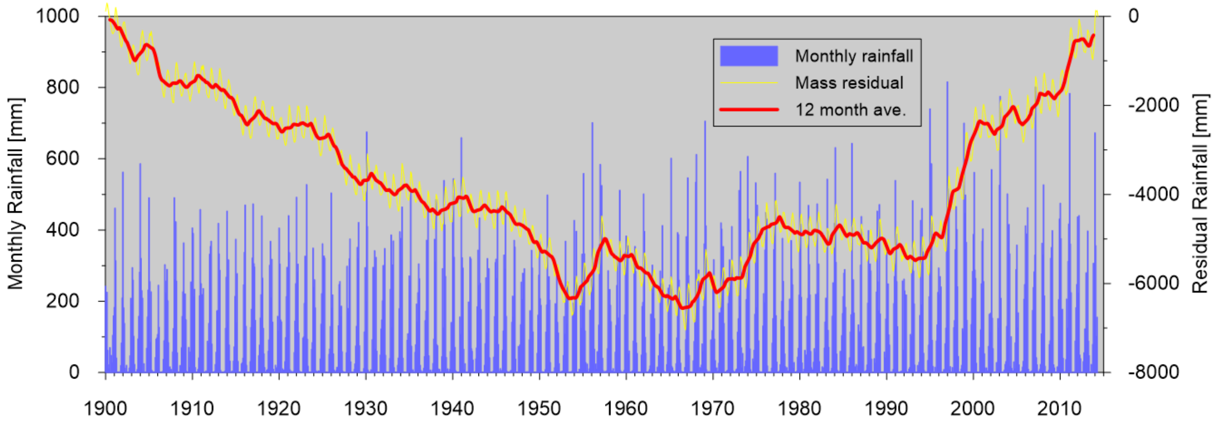


Figure 2-1 SILO Data Drill monthly rainfall and mass residual curves.

From Figure 2-1, it can be seen that the lowest value for the rainfall mass residual curve was in November 1966 and since this time, it has largely exhibited a rising trend, notwithstanding a relatively constant period between the late 1970s and the mid-1990s. It is of some note that since late 1994 there has been a sharp rise in rainfall.

2.2 Topography

2.2.1 Shuttle Radar Topography Mission (SRTM)

The Shuttle Radar Topography Mission (SRTM) digital terrain model (Farr, et al., 2007) is available for the entire Northern Territory (in fact the entire globe). The digital terrain model is presented below in Figure 2-2. The digital terrain model was also used to determine surface water sub-catchments based on the locations of pour points at the outlet of each sub-catchment.

Farr et al. (2007) noted that the SRTM did not always map the true ground surface and can produce elevations up to 15 metres above the actual ground level. Elevation data uncertainty is discussed further below.

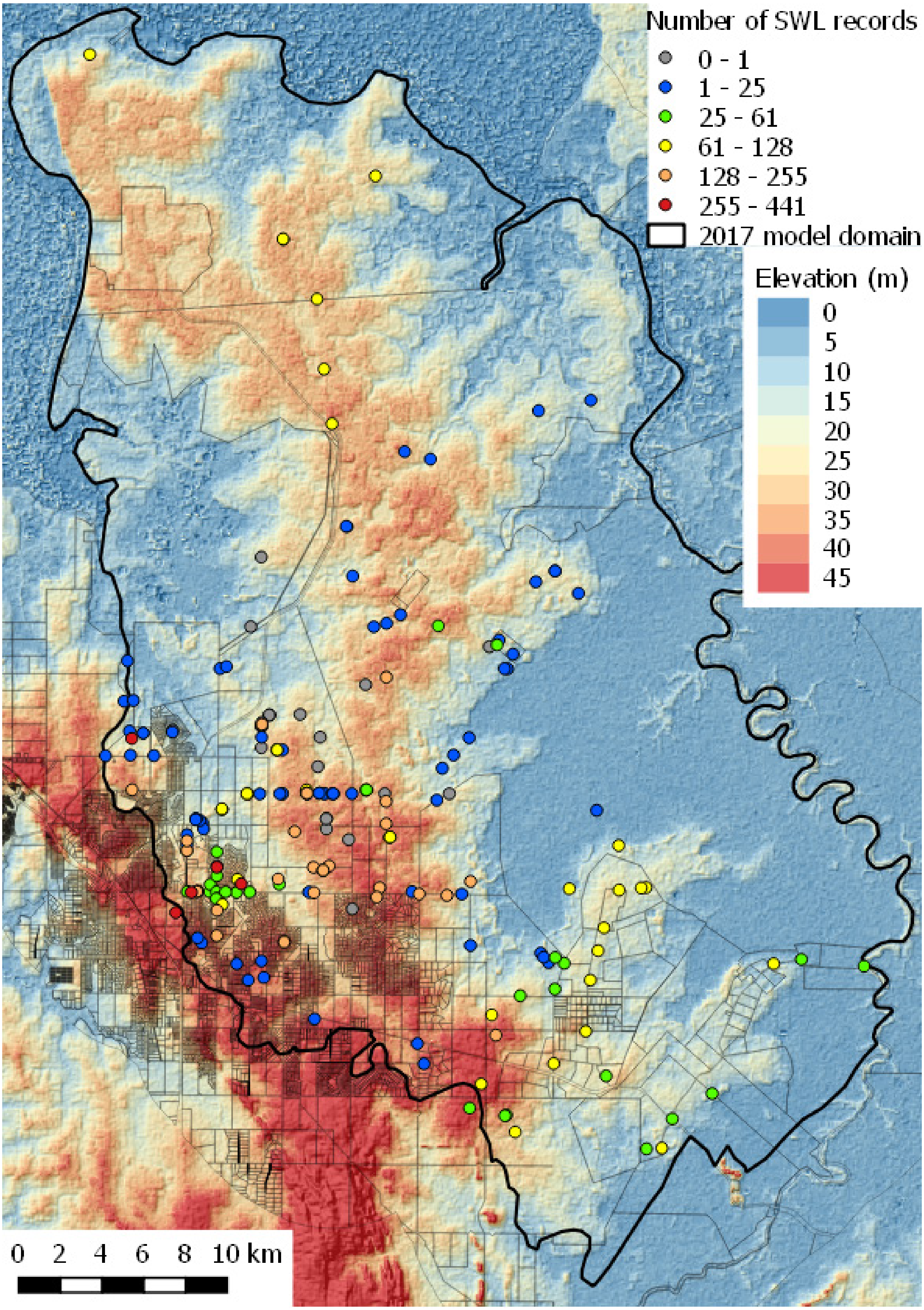


Figure 2-2 Topography of the study area derived from 3sec SRTM.

2.2.2 Topographic data uncertainty

The Shuttle Radar Topography Mission (SRTM) Digital Terrain Elevation Data (DTED) are used with the consensus view that it has a minimum vertical accuracy of 9 m absolute error at 90% confidence world-wide and the minimum vertical accuracy for Australia is 6 m (Farr, et al., 2007).

100 bores have been surveyed in the study area and the elevations from the SRTM data have been extracted at these locations to assess the errors and uncertainties. The surveyed and SRTM elevation data are presented as a scatter plot below in Figure 2-3. The scatter plot demonstrates the offset and random nature of errors, particularly at elevations below 20 to 30 metres.

The SRTM data shows a general offset of about +4.4 metres. The absolute maximum difference between the SRTM and surveyed RLs is 14.3 metres, the minimum is 0.1 metres, the mean is 5 metres and the RMSE is 5.5 metres.

The additional scatter observed in the lower elevations is attributed to the presence of dense vegetation. Farr et al. (2007) noted that the SRTM did not always map the true ground surface. Instead, it measured an effective height determined by the phase of the complex vector sum of all the returned signals from within the pixel being imaged. If the pixel contained bare ground, the phase reflected the height of the surface. If the ground was covered with vegetation, the return was influenced by the vegetation height, structure, and density. If the vegetation was dense enough, little or no signal returned from the ground below. An example of how the elevations can be affected is evident along the eastern boundary of the study area where the presence of mangroves can be observed.

The RMS error of 5.5 metres in elevations and a topographic range of 45 metres indicates a scaled RMS of 12% may be expected.

The uncertainty in the SRTM elevations will impact on the model in two ways by introducing uncertainties into:

1) the groundwater levels for bores that have not been surveyed (approximately 50%). These uncertainties are much greater than the measurement error; and
2) the ground elevation in areas where surface water / groundwater interactions occur, particularly as these areas are often associated with dense vegetation. The elevation data impacts the areas of surface water groundwater interaction as the ground surface limits the groundwater level rises in the wet season.

Given the inaccuracies in the elevation data it is likely that there will be relatively poor performance regarding matching absolute groundwater head elevations.

Given the importance of accurate definition of the ground surface elevation in relation to surface water / groundwater interactions, it is recommended that a LIght Detection And Ranging (LIDAR) survey be completed over the groundwater management area encompassing the Koolpinyah Groundwater System to obtain elevation data free of vegetation artefacts.

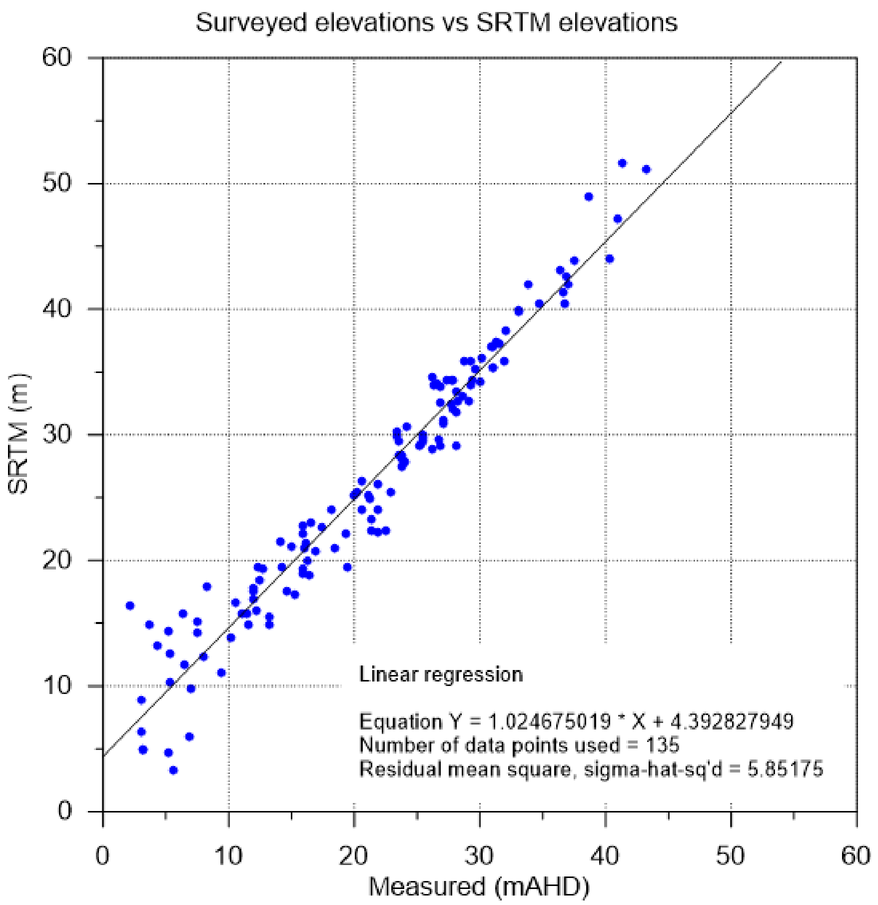


Figure 2-3 SRTM elevations compared to surveyed bore collar elevations.

2.3 Geology

2.3.1 Geological overview

Several studies describe the relevant geological units in the study area (EHA, 2007; Tan, et al., 2012). The bulk of the summary is based on the geological report on the Darwin SD52-4 1:250 000 scale geological map sheet by Pietsch & Stuart-Smith (1987). This report contains a detailed overview of the geology of the study area and the characteristics of the key relevant geological units. The key aspects of the regional geology as indicated in this report are:

- a basement of Archean to Early Proterozoic metamorphic rocks and granites that are not exposed in the study area but are unconformably overlain by;
- a Proterozoic age sequence of relatively poorly exposed arenaceous, lutitic, volcanic and dolomitic rocks of the Mount Partridge Group including the poorly outcropping dolomitic marble (major rock type) dolomitic metasediments and mica-quartz schist of the Koolpinyah Dolomite and the laminated lutitic rocks and minor quartz sandstone, quartzite, felsic volcanics and silicified dolomite of the Wildman Siltstone unconformably overlain by;
- a Cretaceous age sequence of sediments of the Bathurst Island Formation including the kaolinitic claystone, sandy claystone, clayey sandstone and conglomerate of the basal Darwin Member, the medium to coarse grained quartzose sandstone, clayey sandstone and sandy claystone of the Marligur Member, and the claystone of the upper Wangarlu Mudstone Member; and
- deep post-Cretaceous age weathering of the exposed rocks, particularly the Cretaceous age sediments of the Bathurst Island Formation to produce laterite including detrital laterite, pisolitic laterite, mottled laterite and concretionary laterite.

The northern extent of billabongs / lagoons suggests that this is also the northern extent of the unconfined Koolpinyah dolostone.

2.3.2 Basement structures

Since the development of the 2007 FEFLOW model (EHA, 2007) more detailed information has been obtained regarding the location of geological structures in the study area from the Geoscience Australia lead On-shore Energy study (Tan, et al., 2012).

Structural features have been mapped using total magnetics data with 1st vertical derivative applied to accentuate structural features such as faults (Tan, et al., 2012). A major NW-SE trending structure is seen to crosscut the Koolpinyah Groundwater System. Drilling identifies this feature to be a dolerite dyke. It is thought that this feature impedes groundwater flow across it, however, the magnetics data suggests that this feature has discontinuities where groundwater may move relatively unimpeded. It should be noted that some of the apparent discontinuities are actually artefacts due to flight line spacing.

2.3.3 Giants Reef Fault

The Giants Reef Fault is a major structural feature that coincides with the southeastern boundary of the model. Considerable displacement is observed along this feature and has been specified as a no-flow boundary in previous modelling in the Middle Point area (Middlemis, 1999). It has also been assumed to be a no-flow boundary for this modelling study.

2.4 Recharge update

2.4.1 Recharge mechanism

Recharge is the major driver for groundwater flow in the Koolpinyah Groundwater System. Previous modelling of the limestone / dolostone aquifer systems of the Northern Territory have employed a simple but effective soil moisture deficit model (SMD) to determine recharge based on rainfall developed by NRETAS (Jolly et al., 2000).

The conceptualisation of the recharge mechanism is described below:

- Under natural and minor pumping stresses the system can be described as 'fill and spill'.
- Currently, water tables rise within 2 to 3 m of the land surface, usually within 2 to 3 months of the onset of the wet season. It is not until this time that large volumes of runoff are generated as the system is essentially full and no more rainfall can infiltrate and become recharge.
- The capacity of the system to recover from groundwater extraction is a factor of the moisture deficit in the unsaturated zone, the infiltration rate of the soil and the annual rainfall.
- This indicates that recharge from year to year is therefore a factor of drawdown due to groundwater extraction.
- There will be a point at which extraction results in storage depletion which exceeds the maximum volume of water that can be infiltrated to recharge the groundwater system.
- The implication of this is that the system is likely to recover in most years provided that the infiltrated rainfall meets the moisture deficit.

2.4.2 Previous recharge modelling methodology

EHA, (2007) utilised a soil-vegetation-atmosphere transfer (SVAT) type model called SPLASH (Arunakumaren, 1997) to calculate the recharge to the Koolpinyah Aquifer System.

2.4.3 Current recharge modelling methodology

To improve on the soil moisture deficit (SMD) spreadsheet method and build upon the SVAT methodology employed by EHA, the process based MIKE SHE platform (Graham & Butts, 2005) was used to estimate recharge time series suitable for use in the FEFLOW groundwater model.

MIKESHE was employed because it has the scope to model processes in the soil and incorporate direct recharge due to macro-pores, which are considered an important recharge mechanism. The main purpose of the MIKESHE model was to provide an estimate of the actual evapotranspiration (for comparison with previous studies) and the amount of water that recharges the saturated zone. The MIKE SHE recharge modelling is discussed further in APPENDIX A.

2.5 Groundwater level monitoring data update

EHA, (2007) reviewed the monitoring network in the Koolpinyah Groundwater System and provided general comments about the coverage of the network, most of which are still valid:

- The monitoring bore network is very much spatially biased to the historical major areas of groundwater extraction (e.g. McMinns) with only a reconnaissance scale network in the areas remote from significant development;
- Generally, the monitoring network is very much biased towards bores tapping the dolomite sequence with there being only limited data points representing the Cretaceous age / laterite system and further of the limited number of laterite bores, a significant proportion do dry out seasonally;
- The northern section of the study area (i.e. through Gunn Point) has a very sparse network that is largely aligned north-south and cannot adequately represent the groundwater flow system towards the Adelaide River and to the west / south west towards Hope Inlet;
- In the Gunn Point area, nearly all of the monitoring bores tap the dolomite and very limited data is available regarding groundwater levels in the Cretaceous age / laterite system;

- A significant number of bores, particularly in the eastern section of the Lambell's Lagoon area display groundwater elevations that decline periodically below mean sea level.
- In areas where the aquifer system may be under stress the groundwater level trend diverges from rainfall mass residual trend, generally post 1998/1999;
- The bores that demonstrate the divergence of hydrograph traces with the rainfall mass residual trend are not wholly restricted to bores tapping the dolomite system. Most of the bores that tap the Cretaceous age sediments / laterite system also reflect this trend.

EHA (2007) also commented on the integrity of some bores in the monitoring network:

- Some of the bores tapping the laterite dry out and the data sets for model calibration require adjustment to reflect the presence of "dry pipe" readings (RN022170, RN022174, RN028969 & RN029077);
- Numerous monitoring bores are present in clusters and some of these bores appear to have non-functioning annular seals precluding the vertical discretisation of piezometric head (i.e. RN022291);
- Many of the monitoring sites are multiple bore installations yield groundwater level responses for supposedly vertically discrete monitoring levels in different stratigraphy that are so similar that the integrity of the annular seals is doubtful (e.g. the site at McMinns where bores RN021760, RN029421 and RN029422 are constructed; the site at McMinns where bores RN004433, RN022172, RN022173 & RN022174 are constructed; the site at McMinns where bores RN021765, RN021767, RN022068, RN022069, RN028969, and RN029077).
- Bore RN022296 at Gunn Point is periodically used as a pumping bore and when it is used, the values drawn from it are not useful for regional assessment of groundwater flow.

Since the 2007 EHA review of the monitoring network the following improvements have occurred:

- Previously quite short water level records have now had an additional 8 years of data collected;
- An additional 49 monitoring bores have been installed in the study area.

The locations of the 208 monitoring bores used in the calibration process are presented in Figure 2-4.

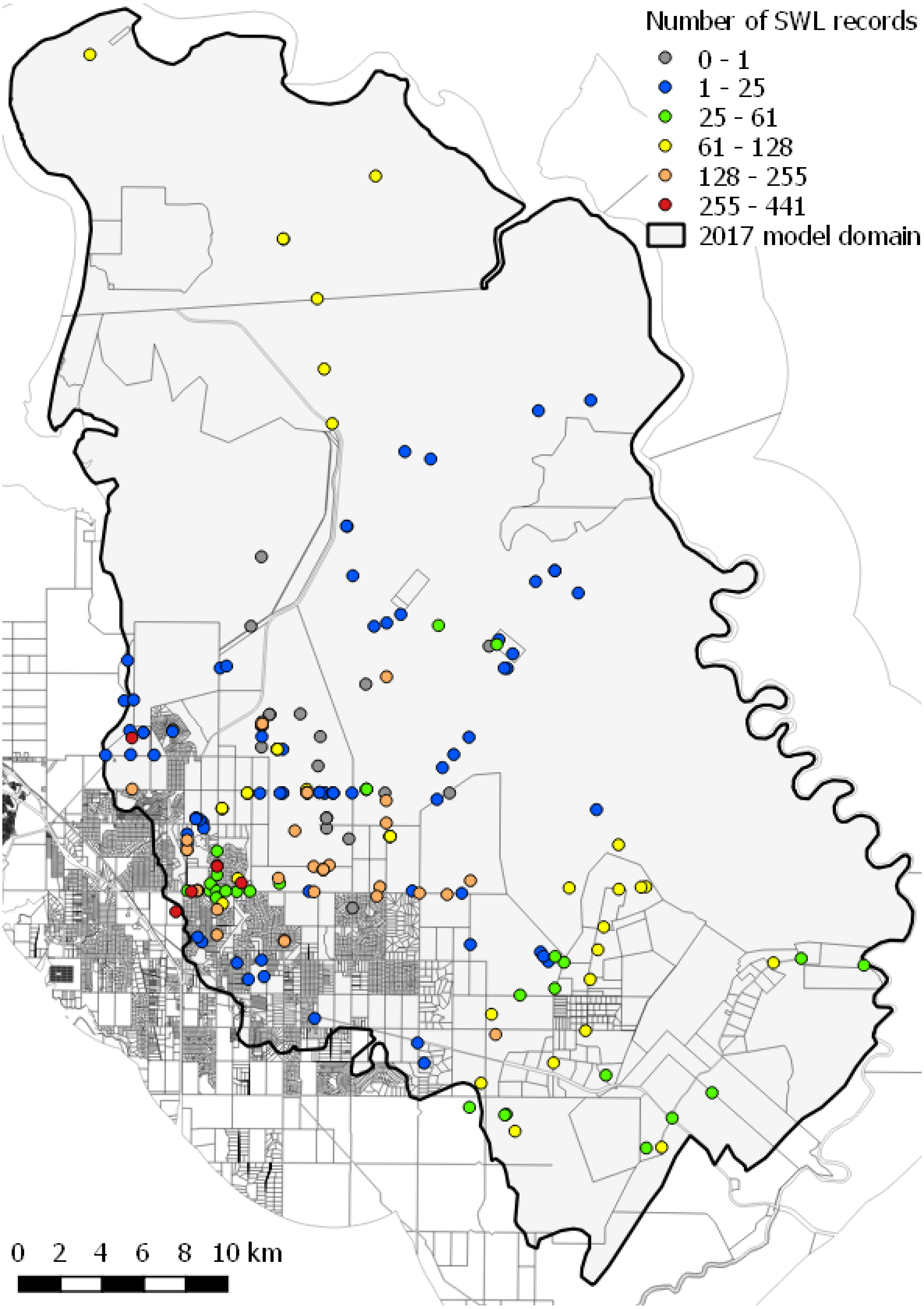


Figure 2-4 Distribution and number of groundwater level records

2.6 Groundwater extraction

Groundwater extraction is a major component of the Koolpinyah Groundwater System water balance. In recent years it is estimated that approximately 25000 ML (25GL) is extracted from the Koolpinyah Groundwater System annually. Groundwater extraction licences are only required for bores where the usage exceeds a rate of 15 l/s. Therefore, only the bores operated by the Power and Water Corporation are licensed with all other bores being below the 15 l/s (473 ML/yr) license threshold. However, the combined extraction from the PWC bores is approximately 25% of the estimated extraction from the Koolpinyah Groundwater System and, in order to understand the response of the groundwater system to pumping stresses there is a need to estimate groundwater extraction from other users.

A methodology has been developed to assign groundwater extraction to land use. The land use was based on the Land Use Mapping Project (LUMP) coverage for 2002 and 2008.

Three major categories of groundwater users have been identified in the model domain:

- Town water supply;
- Rural residential users (domestic and minor irrigation); and
- Horticultural users (irrigation).

Town water supply bores

The town water supply bore field situated in the McMinns area was established in the 1960s. There were 11, 9 and 5 town water supply bores in operation in 1971, 1972 and 1973 respectively. Since 1974, only 4 town water supply bores (RN006231, RN006310, RN007048 and RN007071) have been in operation.

The town water supply bores are the only bores currently metered in the study area and monthly groundwater pumping data is available from Power and Water Corporation (PWC) covering the period since 1971.

Rural residential

Very limited information is available regarding the volume and timing of rural residential water use. It has been assumed that the average annual groundwater pumping per rural residential bore is estimated to be 3500 kL. This figure is based on household water requirements and an allocation for irrigation application to lawns and garden during the dry periods June to December. Because of the marked wet / dry season, the demand for the outdoor component of rural residential groundwater demand could be expected to be seasonal and the adopted usage pattern indicated in Table 2-1 reflects this. Table 2-1 provides projected estimated monthly groundwater usage pattern for a typical rural residential bore.

Table 2-1 Rural residential monthly usage pattern after EHA, (2007)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Usage (% annual)	0.6	0.6	0.6	0.6	0.6	13.9	13.9	13.9	13.9	13.9	13.9	13.9
Usage per bore (kL)	20.2	20.2	20.2	20.2	20.2	485.6	485.6	485.6	485.6	485.6	485.6	485.6

Horticultural users

Horticultural bores are used to irrigate a variety of fruit trees to small crops (melons, tomatoes and an assortment of Asian leaf and root vegetables). The horticultural properties in the study area differ in sizes and in their unit irrigation applications which range from 5 ML/ha to 10 ML/ha during the intense irrigation period. In order to calculate groundwater pumping from the horticultural bores, the number of bores and the areas under irrigation were considered.

Annual groundwater pumping from the horticultural bores was estimated by application of the average unit groundwater use of 5 ML/ha to their relevant areas of irrigation defined using the LUMP data.

Table 2-2 Rural residential monthly usage pattern after EHA, (2007)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Usage (% annual)	0.3	0.3	0.3	2.5	10.2	12.7	12.7	12.7	12.7	12.7	12.7	10.2
Usage (kL/Ha)	12.7	12.7	12.7	127.2	508.9	636.1	636.1	636.1	636.1	636.1	636.1	508.9

2.6.1 EHA 2007 groundwater extraction estimate

EHA, (2007) generated a 'historic' groundwater regime based on pumping information provided by DLRM. The pumping data was based on the Departments registered bore database joined to the 2002 land use mapping project (LUMP) coverage, providing estimates of bore extraction associate with property size and land use. Using this methodology described above, a total of 1847 bores have been identified as being either Rural, Irrigation or Production.

- 1541 rural residential use bores were identified within the study area
- 293 horticultural irrigation use bores were identified within the study area.
- 13 are designated 'Production'.

The cumulative 'historic' pumping extraction (m^3/day or kL/day) from 1970 – 2006, used by EHA in the 2007 modelling study, is presented in Figure 2-5.

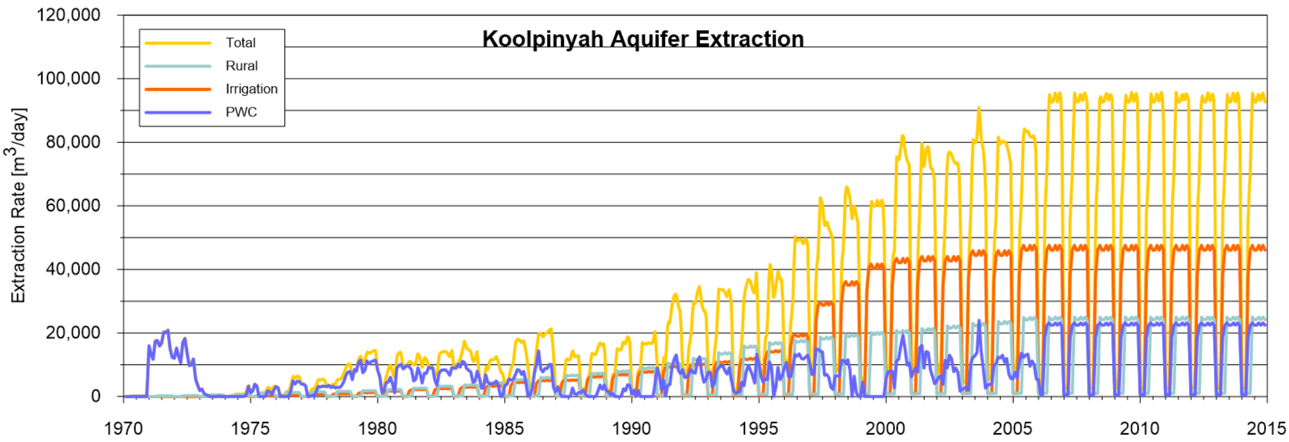


Figure 2-5 Cumulative extraction for the three user types and total combined extraction (kL/d) extended to 2015 assuming no further development (after EHA, 2007).

2.6.2 DLRM 2014 groundwater extraction estimate

The methodology used in the 2007 study, of mapping land use data to bore locations, has been adopted to extend the pumping scenario to 2014. The estimate is based on bore data from the DLRM bore database and the most recent LUMP coverage from 2008.

Steps involved in determining rural residential usage were:

- Select polygons designated 'Rural residential' or 'Rural living';
- Based on this selection select bores that are inside the selected polygons;
- Export the selected bores as Rural;
- Join attributes of 'Rural residential' or 'Rural living' polygons to Rural bores;
- It was assumed that only one bore was used per Rural property, using the LAIS code (or FID2 in the joined table) remove duplicates;
- The remaining bores are considered as 'Rural' and assigned 3.5 ML/yr usage.

A similar process was used to obtain Irrigation bores, however, more than one bore was allowed per property.

- Select polygons designated 'Irrigated%' where % is a wildcard character to select all features with some kind of irrigation;
- Using this selection select bores that are inside the selected polygons;
- Export the selected bores as Irrigation;

- Join attributes of 'Irrigated%' polygons to Irrigated bores;
- These bores are considered as 'Irrigation';
- Properties with multiple bores had the bores with 0 yield removed;
- Bores were then assigned usage based 5 ML/yr/Ha multiplied by the polygon area and each bore assigned a proportion of this by dividing the total usage by the number of bores within the polygon.

Using the methodology described above, a total of 2125 bores have been identified as being used as either Rural, Irrigation or Production in the study area.

- 1579 designated Rural (c.f.1541);
- 533 designated as Irrigation (c.f. 293);
- 13 are designated Production.

The EHA, (2007) methodology has been adopted to extend the pumping scenario to 2015. The groundwater extraction estimates have been developed using the updated bore database information and the 2008 LUMP coverage. The final daily extraction as applied to the groundwater model (m^3/day or kL/day) are presented in Figure 2-7. There is about a 10% increase in the irrigation extraction, this is predominantly associated with the inclusion of the Middle Point area, which was outside the original EHA (2007) model domain.

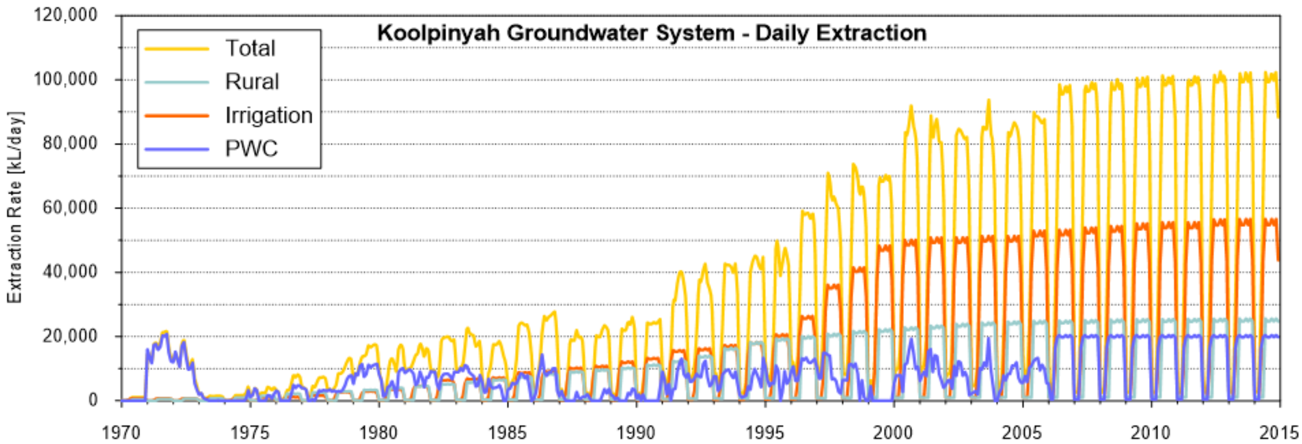


Figure 2-6 Updated daily extraction based on bore information available after 2006 and the 2008 LUMP data.

The daily extraction volumes have been combined into annual volumes in ML and are presented below in Figure 2-7. The plot is presented as stacked bars to provide total volumes across the different pumping categories and identify the relative contributions to the total pumping volume.

A point of interest, as identified previously, is that the PWC pumping rate (5400 ML/yr) is of the same magnitude as the combined extraction from the 'Rural' type users (5500 ML/yr) and approximately half that of the 'Irrigation' type users (13300 ML/yr). The locations of the bores and annual pumping volumes associated with each bore are presented in Figure 2-8 a). The highest range (473 - 800 ML/yr) corresponds with bores over the 15 l/s threshold. It can be seen that all but the PWC bores in the McMinns borefield are below this value.

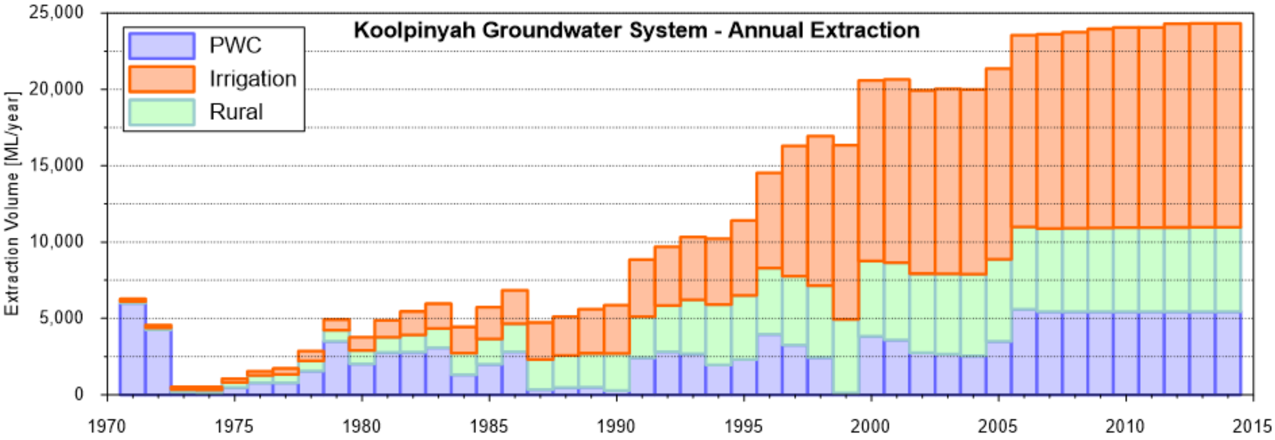


Figure 2-7 Updated annual extraction (stacked) based on bore information after 2006 and the 2008 LUMP data.

In an attempt to present the distribution of pumping demand in the model domain in a simple manner, a 'hotspot' map has been generated. This map (Figure 2-8 b) shows the density of pumping in ML/yr/Ha assuming a 750 metre zone of influence and using the 2014 extraction estimate. The irrigation at McMinns Lagoon, Lambells Lagoon, Benhams Lagoon and Middle Point are obvious areas of high groundwater usage as would be expected given the land use in these areas. Other obvious areas are the Power and Water Corporation McMinns Borefield.

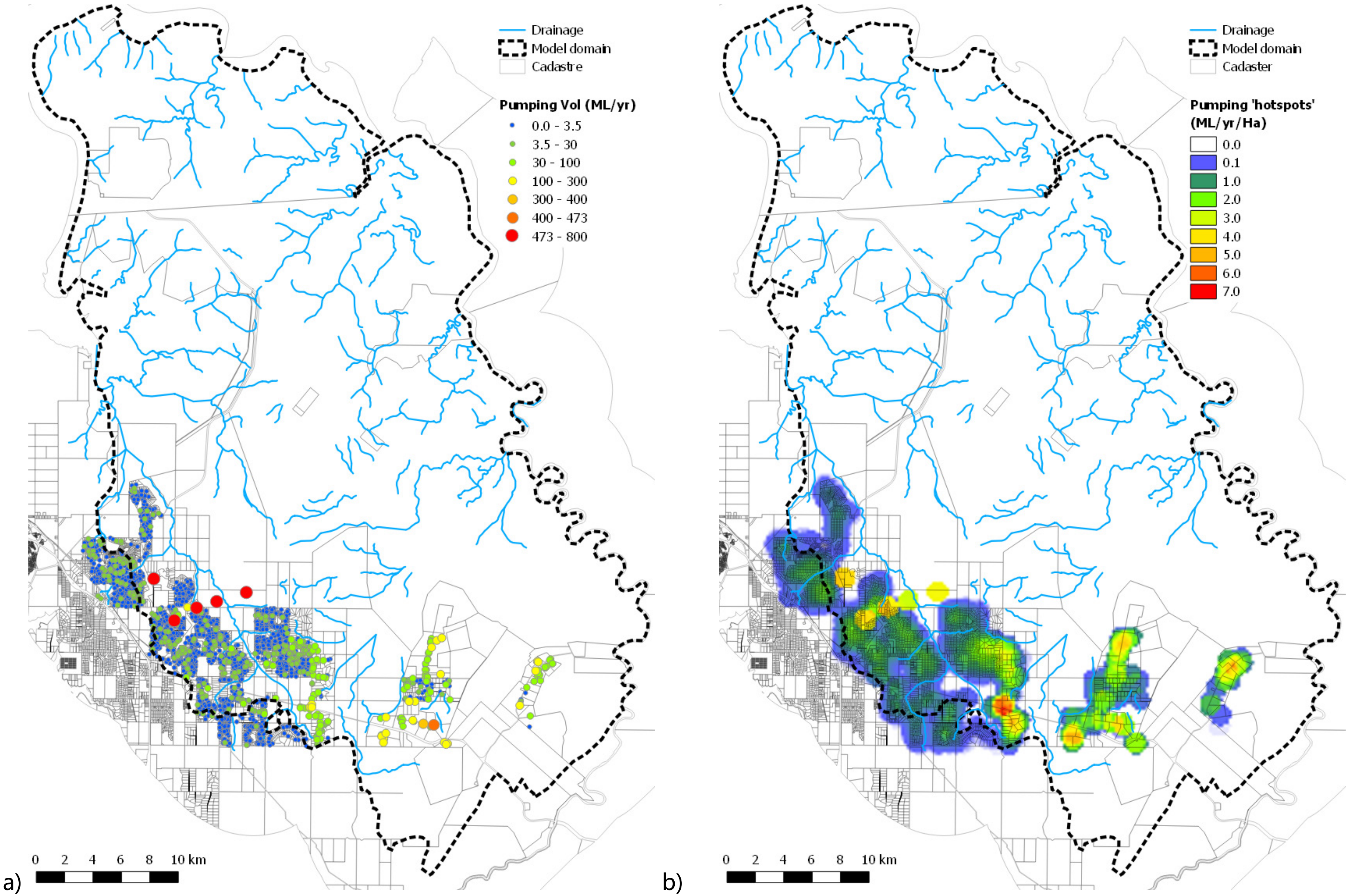


Figure 2-8 Pumping bore locations classified by a) annual (2014) pumped volume and b) pumping 'hotspots'.

3 HYDROGEOLOGICAL CONCEPTUALISATION

3.1 Hydrostratigraphy

The current modelling study builds on the hydrostratigraphic conceptualisation presented by EHA (2007) and is summarised as:

- A laterite aquifer extending generally from the surface into less weathered Cretaceous age sediments (hydrostratigraphic unit (HSU) 2);
- Cretaceous age sediments between the base of the laterite and the transitional zone of cherty, "quartzy", sandy and gravelly material over the fractured dolomite (HSU 3);
- A transitional zone between the lower Cretaceous age sediments and the fractured Koolpinyah dolomite, including deeply weathered dolomite and cherty, gravel and sandy material that generally included the basal conglomerate of the Darwin Member;
- Low permeability mudstones and siltstones of the Whites Formation to the west of the study area (HSU 4);
- A fractured dolomite beneath the transitional zone including some schistose facies overlying at depth less fractured / permeable dolomite (HSU 5 & 6);
- Faults (or dykes) which may impede groundwater flow (HSU 7, 8, 9 & 10).

3.2 Groundwater flow and dynamics

Groundwater flows are controlled by topography and by the ability of the aquifer to transmit water. The direction of groundwater flow is generally based on topographic variations, from relatively high to low elevation. The areas of discharge in the Howard River catchment are the Howard River, the small tributaries that drain into the black soil plains to the east, and subsurface throughflow to the north below Gunn Point (Jolly, 1983).

Seasonal groundwater levels tend to vary by ~8 m in the undeveloped upland parts of the study area, although extraction in developed areas has increased this to ~12 m. Groundwater usually comes to within 2 m of the surface during the wet season. The groundwater level trend is increasing slightly in undeveloped areas and falling moderately in the developed areas.

The variation in potentiometric surface of the Koolpinyah Groundwater System for the end of the 2010 dry season and end of the 2011 wet season as prepared by Fell-Smith and Sumner (2011) are presented below in Figure 3-2.

3.3 Recharge mechanism

As discussed in section 2.4, previous modelling has assumed that there are separate zones of recharge across the study area, this was based on the distinct groundwater hydrograph responses observed in the south and the north of the study area. It is the authors view that the available soil data and lithological data indicates that the recharge to the overlying laterite layer is probably consistent across the study site, and the variation in hydrograph response is due to varying degree of connection between the laterite aquifer and the deeper dolostone aquifer.

The variable connection is due to the degree of weathering and the presence (or absence) of intervening clay / claystone layers of the Cretaceous aged Marligur Member, which results in varying vertical leakage fluxes between the aquifers. To the south west of the study area the laterite is in relative good connection with the dolostone and deeper groundwater levels respond directly to recharge in the laterite. To the north of the study area recharge to the dolostone is considerably reduced / non-existent due to the presence of the claystone Marligur Member that thickens to the north.

As a proxy for recharge an assessment of the ability of the different soils to drain is provided as part of the land unit mapping completed by DLRM. The area is classified into three dominant types:

- Severe level of seasonal soil water logging;
- Moderate to high level of seasonal water logging; and
- Nil to low level of seasonal water logging.

The distribution of the ability of the soils to drain is presented in Figure 3-3 a).

Soils within the study area overlie the extensively weathered and lateritised, Koolpinyah surface, a late Tertiary 30 – 40 m deep sediment mantle extending from the Darwin region to the Arnhem escarpment of Kakadu National Park (Hutley, et al., 2001). Storage properties of these soils are poor with only 0.08 cm^3 cm^{-3} released between field capacity and wilting point (Cook, et al., 1998) and these soils overlie a surface aquifer (Laterite Formation) with the water table rising to within 2 m of the ground surface during the wet season.

3.4 Groundwater discharge

Key hydrological features within the study area include the Howard and Adelaide Rivers, and Melacca, Banka, Black Jungle and Howard springs. The Adelaide River has extensive floodplains whereas the Howard River appears to be fault-controlled; it drains to the northwest dissecting the Koolpinyah uplands. Figure 3-3 b) indicates the location of the DLRM surface water gauging sites in the study area.

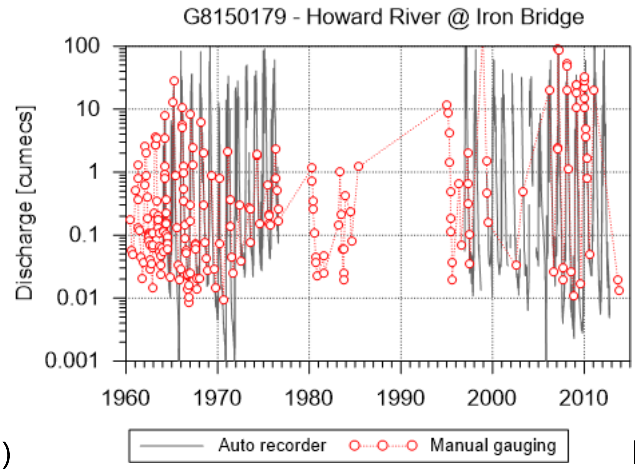
Groundwater discharge predominantly from the Koolpinyah Groundwater System aquifer has been observed at only a few sites. Melacca, Banka, Black Jungle and Howard springs are fed by groundwater from the Koolpinyah Groundwater System aquifer. Other discharge areas are defined on the basis of presence of groundwater dependent ecosystems, such as vine forests. Examples of this type of flow are Melacca Creek and Howard Springs.

Baseflow is contributed from direct discharge of deep groundwater to streams from major aquifers or from discharge of shallow groundwater. Through most of the dry season, stream flow discharge is dominated by baseflow from the deep groundwater aquifer systems.

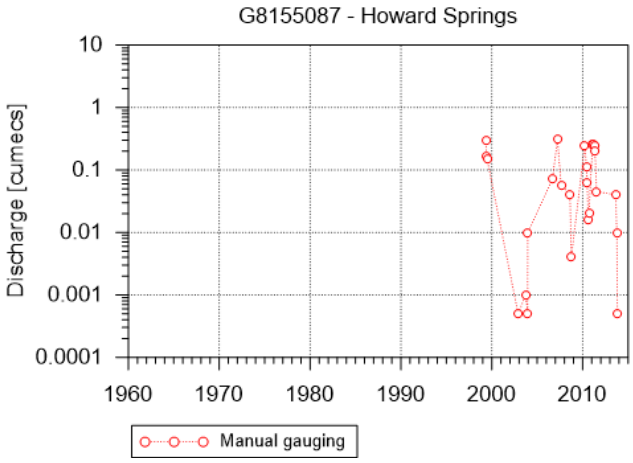
In June and July, mean runoff is greater than mean rainfall indicating that the Howard River is largely sustained by groundwater flows at this time. The upper Howard River, and occasionally Howard Springs, ceases to flow late in the dry season.

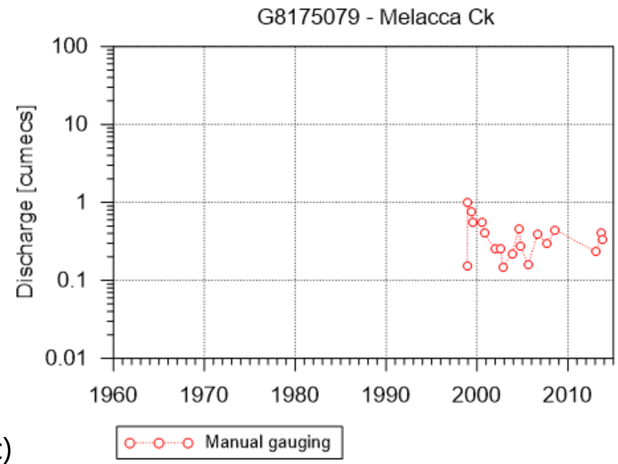
With the exception of gauging station G8150179 Howard River at Koolpinyah Station there is a relative paucity of long-term, relatively continuous stream gauging in the study area. Spot gaugings are available collected as part of an investigations into the springs in the study area. The three gauging sites used in the calibration are:

- G8150179 along Howard River (Figure 3-1 a) shows a distinctly seasonal pattern related to the wet and dry season climatic conditions. During the wet season, overall stream discharge comprises both baseflow and what is known as quick flow. Quick flow represents the direct catchment response to the rainfall events (i.e. surface run off and interflow to streams and tributary stream channels).
- G8155087 at Howard Springs (Figure 3-1 b) shows similar seasonal pattern in flows with variations from 0.3 cumecs (300 L/s) in early March, at the end of the wet season, to 0.02 cumecs (20 L/s) or less at the end of the dry.
- G8175079 at Melacca Creek (Figure 3-1 c) is one of the highest known discharge areas in the study area with end of dry season flow of approximately 0.1 to 0.2 cumecs (100 – 200 L/s).



a) b)





c)

Figure 3-1 Discharge records used in the calibration of the Koolpinyah Groundwater System flow model for sites a) G8150179 Howard R. @ Iron Bridge, b) Howard Sp. And c) Melacca Ck.

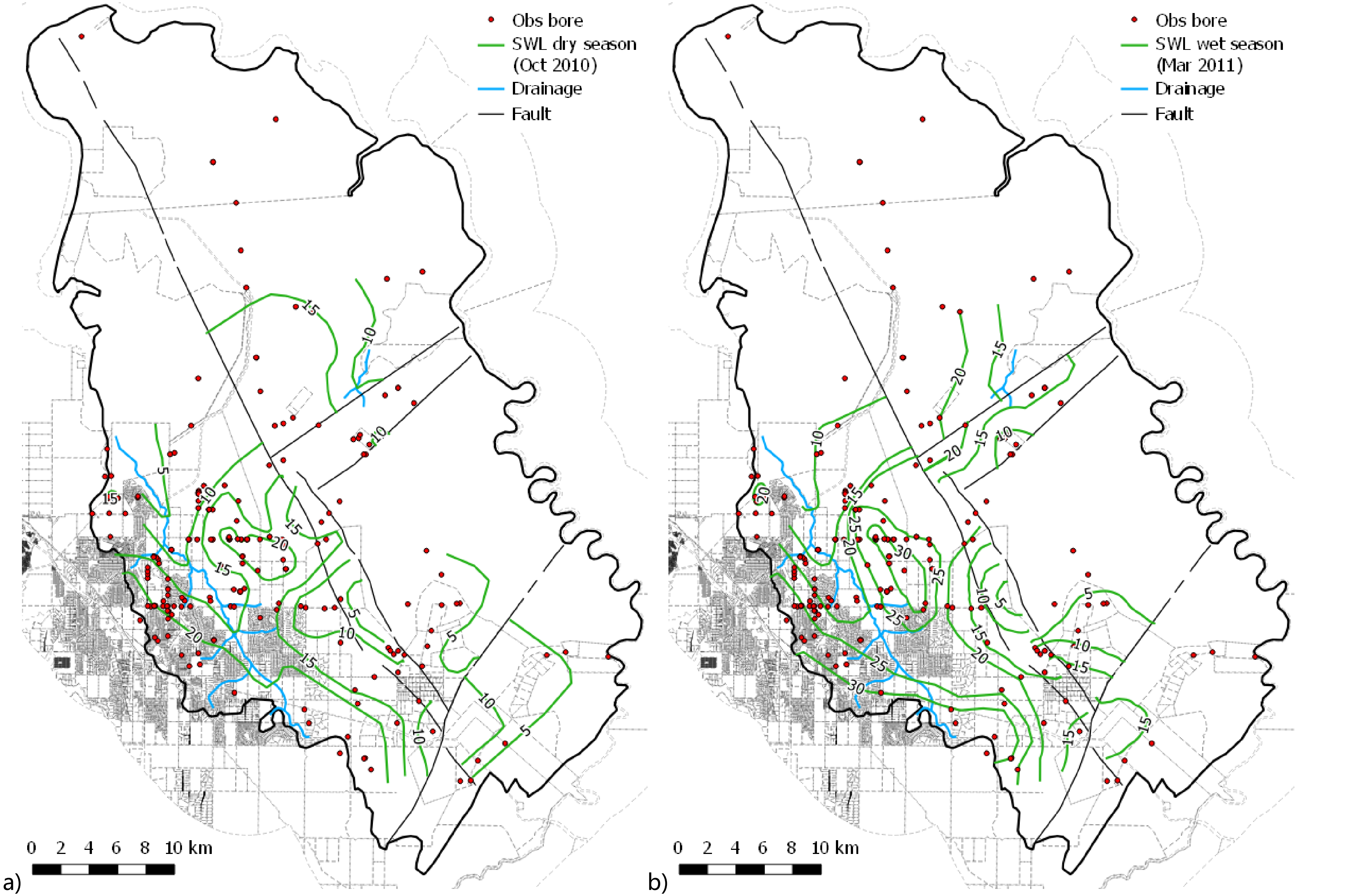


Figure 3-2 Interpreted potentiometric contours for a) end dry season (Oct 2010) and b) end wet season (Mar 2011) after Fell-Smith and Sumner (2011).

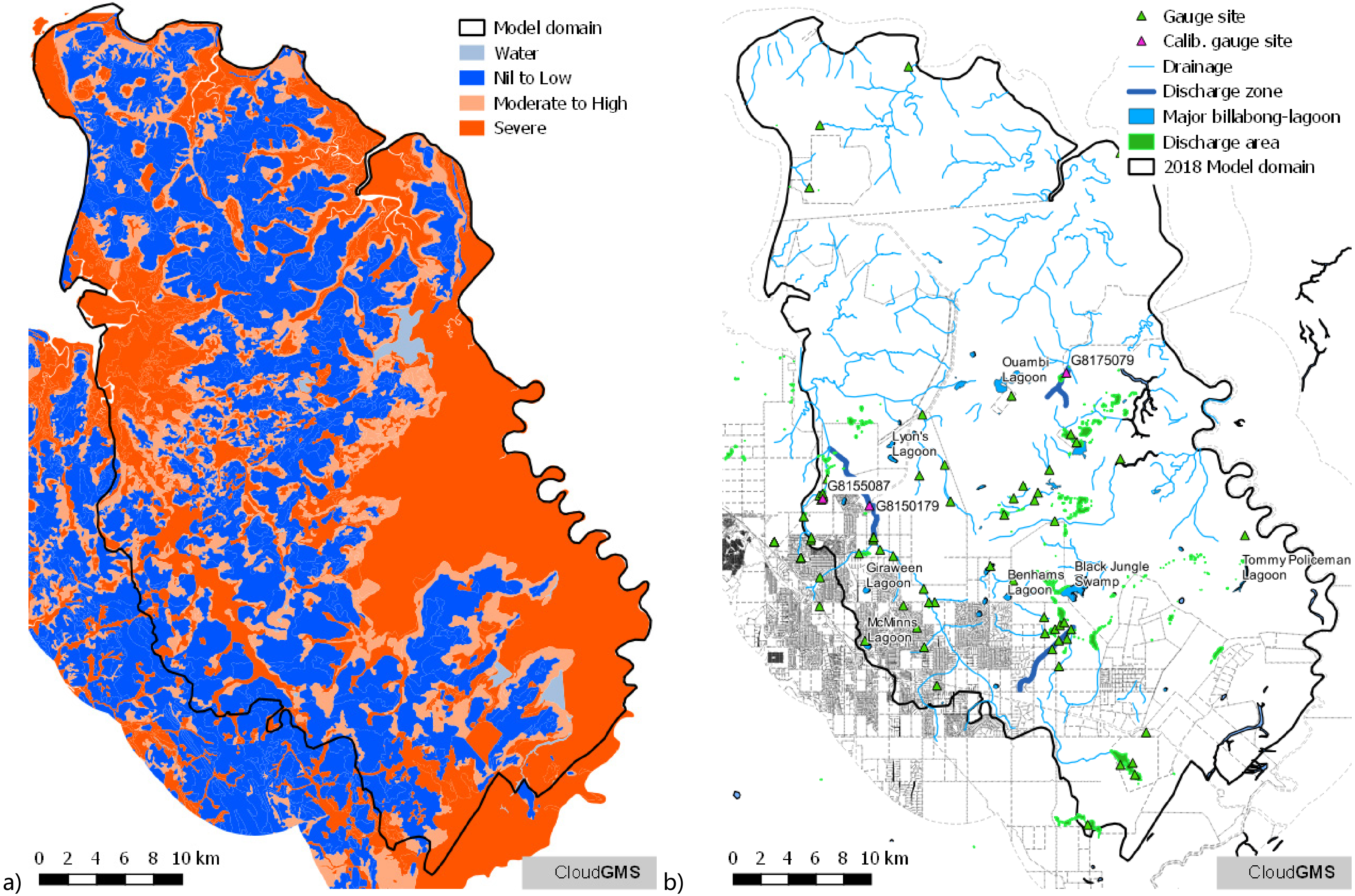


Figure 3-3 a) Recharge distribution based on degree of soil waterlogging; b) surface water / groundwater connectivity.

3.5 Surface water – groundwater connectivity

Groundwater discharge, predominantly from the Koolpinyah Groundwater System aquifer, has been observed at only a few sites. Melacca, Banka, Black Jungle and Howard springs are fed by groundwater from the Koolpinyah Groundwater System aquifer. Other diffuse discharge areas are defined on the basis of presence of groundwater dependent ecosystems, such as vine forests. Examples of this type of distributed discharge areas are to the southeast of Melacca Creek, Howard Springs and Black Jungle Swamp.

Howard Springs, Howard River, Black Jungle and Holland's Creek, show seasonal change in water quality. Early dry season chemical analyses of spring discharge indicate that the water source is the shallow Cretaceous sandstone aquifer. By the end of the dry season there is a change in water chemistry that indicates the discharge water is derived from both the shallow aquifer and from the deeper dolomite aquifer, although predominantly from the latter.

Surface water electrical conductivity (EC) data is available at G8150179 (Howard River) for the majority of 2007, the end of the dry season of 2008 and most of the dry season for 2013. It shows the variation in EC throughout the water year. There is a distinct seasonal trend with lower EC observed during the wet season and higher EC (~400mS/cm) towards the end of the dry season. The available data indicates a relatively rapid change from low EC to high EC from mid-June to mid-August (Figure 3-4).

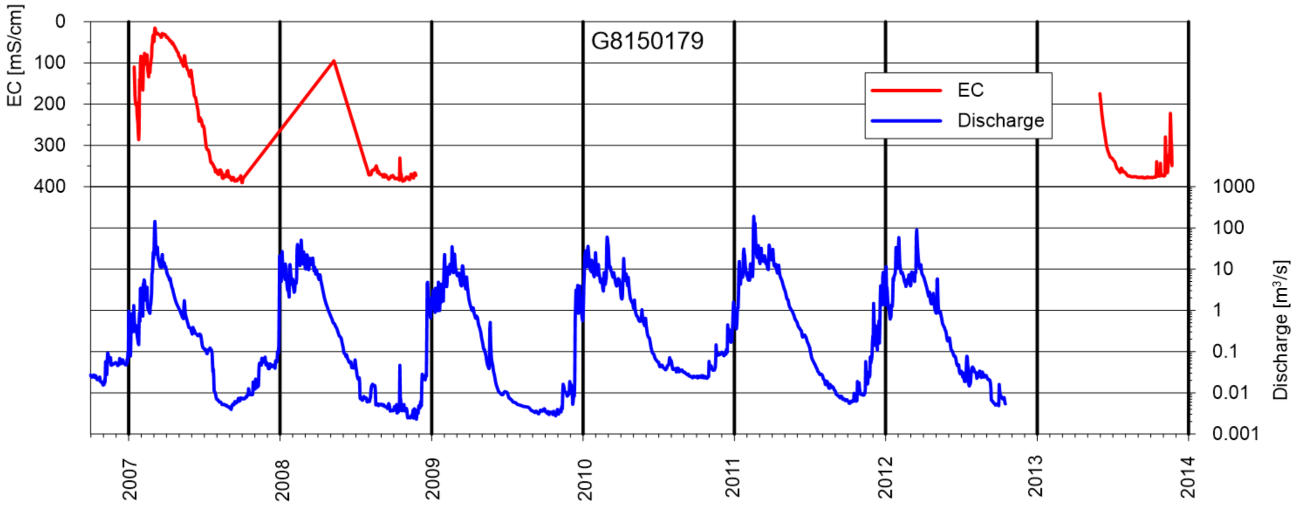


Figure 3-4 Flows at G8150179 compared to EC values indicating contribution to flow of laterite aquifer (low EC) and dolostone aquifer (high EC ~400mS/cm)

Over 100 lagoons exist in the study area, many of which are expected to be perched and not intimately connected to the groundwater system, filling in the wet season and then progressively dry out from May to October. A strong correlation exists between faults and photo lineaments and the location of shallow lagoons, suggesting a structural influence in their formation. The lagoons are likely to be karstic depressions (dolines).

3.6 Boundary conditions at the coast and along Adelaide River

Previously the entire outer boundary of the model domain was considered to be no-flow. However, it is expected that some flow will move from the aquifer and discharge either through exposure of the aquifer in the sub-marine environment or diffusely over a less well-defined area through the sea bed. Regardless of the exact mechanism, the gradient to the north observed in between bores RN022814, RN022294 and RN022292 indicate groundwater flows out of the model domain to the north and northeast of the study area.

Lu et al (2014) suggest using an equivalent fresh water head to incorporate density effects that may be present. It is likely that the coastal boundary is sufficiently distant from the areas of interest as to have little impact.

Similarly, along the eastern boundary coincident with the Adelaide River, it is suggested that the Koolpinyah dolostone will be incised by the river and discharge to it, possibly with some reduced connection due to deposition of fine grained sediments on the river bed. The degree of connection is represented using the transfer rate out parameter associated with the transfer (Cauchy BC) boundary condition.

4 MODEL DESIGN

4.1 Code used to construct model

The FEFLOW (Finite Element subsurface FLOW and transport system v 6.211) modelling code developed by DHI-WASY GmbH (Diersch, 2015) (Hutley, et al., 2001). This code is the standard groundwater modelling tool used by DLRM to study groundwater level behaviour within groundwater systems of the Northern Territory.

FEFLOW handles a broad variety of physical processes for subsurface flow and transport modelling and simulates groundwater level behaviour indirectly by means of a governing equation that represents the Darcy groundwater flow processes that occur in a groundwater system. FEFLOW also handles free surface flow, variably saturated flow and fracture flow.

4.2 FEFLOW model settings

The model settings used in this study are detailed in Table 4-1.

Table 4-1 Model settings

Model code	Feflow
Software version	7.0.11 (x64)
Mesh	
Element geometry	Triangle prism
Free surface	3d phreatic aquifer (fixed mesh)
Head limits for unconfined conditions	
Top of model domain	Unconstrained head
Storage change in phreatic top layer	Extend storage of unconfined layer to water table
Bottom of model domain	Unconstrained head
Numerical parameters	
Time stepping	Adams-bashforth/trapezoid rule (ab/tr) predictor-corrector
Error tolerance	
Euclidian l2 integral (rms) norm	1e-03
Maximum number of iterations per timestep	12
Equation system solver	Preconditioned conjugate-gradient method

4.3 Model domain

A major update from the previous modelling studies is the extension of the model domain to incorporate the Middle Point area. The updated model domain includes the majority of the Howard River catchment and has been extended to the north to incorporate the mapped extent of the Koolpinyah dolomite based on the Geoscience Australia interpretation of airborne magnetics and electromagnetics data (Tan et al., 2012).

4.4 Model domain mesh development

4.4.1 Super mesh development

FEFLOW contains a functionality to generate a finite element mesh from a super element mesh which consists of the model boundary and line and point features relevant to groundwater flow processes (eg. dykes, creeks, groundwater bores etc.).

The super element mesh and boundaries for the project area model were constructed taking into account the following key hydrological features:

- sub-cropping geological contact between Proterozoic rocks;
- the extent of the Cainozoic laterite;
- the Adelaide River flood plain boundary;
- Howard River;
- Melacca Creek;
- sub-cropping, weathered clayey dolerite dykes; and
- the 250m spaced aggregated bore locations points.

The super mesh incorporates polygons, polylines and point features. These features form the basis of the finite element mesh. The supermesh polygon layer incorporated the model domain and lithological boundaries such as the contact between the Proterozoic Whites Fm and Koolpinyah Dolostone and the extent of the Cainozoic laterite. The supermesh polyline layer incorporated linear features such as Howard River and the major dyke features. The supermesh point layer incorporated point features such as the 250 metre bore grid.

The supermesh elements used to generate the finite element mesh are presented in Figure 4-1 (a).

4.4.2 Finite element mesh development

The mesh was generated using the automatic Triangle option (Shewchuk, 2005). This feature offers the ability to define the local variation of mesh density by allowing for the refinement of the mesh around specified point and line features. The model mesh was also refined along the major structures and drainage features previously identified.

The finite element mesh was generated using the following settings for the Triangle generator in the Mesh Generator Options:

- Quality mesh, minimum angle <= 20 degrees
- Force all triangles to be Delaunay
- Fill all possible holes in mesh
- Divide-and-conquer meshing algorithm
- Refinement around line-add-ins – Gradation 3, Target element size = 300 metres
- Refinement around point-add-ins – Gradation 3, Target element size = 220 metres

An initial mesh density of 10000 elements was used in the Generate Automatically option to generate the mesh. and this mesh ultimately incorporated:

- 138378 finite elements (46126 finite elements per layer); and
- 94320 nodes (23580 nodes per slice).

The regional mesh was then smoothed by selecting all nodes not defined by an input feature identified in the supermesh (refer to Figure 4-1 a) and applying a smoothing option, leading to better (more regularly) shaped triangular elements.

The final mesh generated for the FEFLOW model is presented in Figure 4-1 (b).

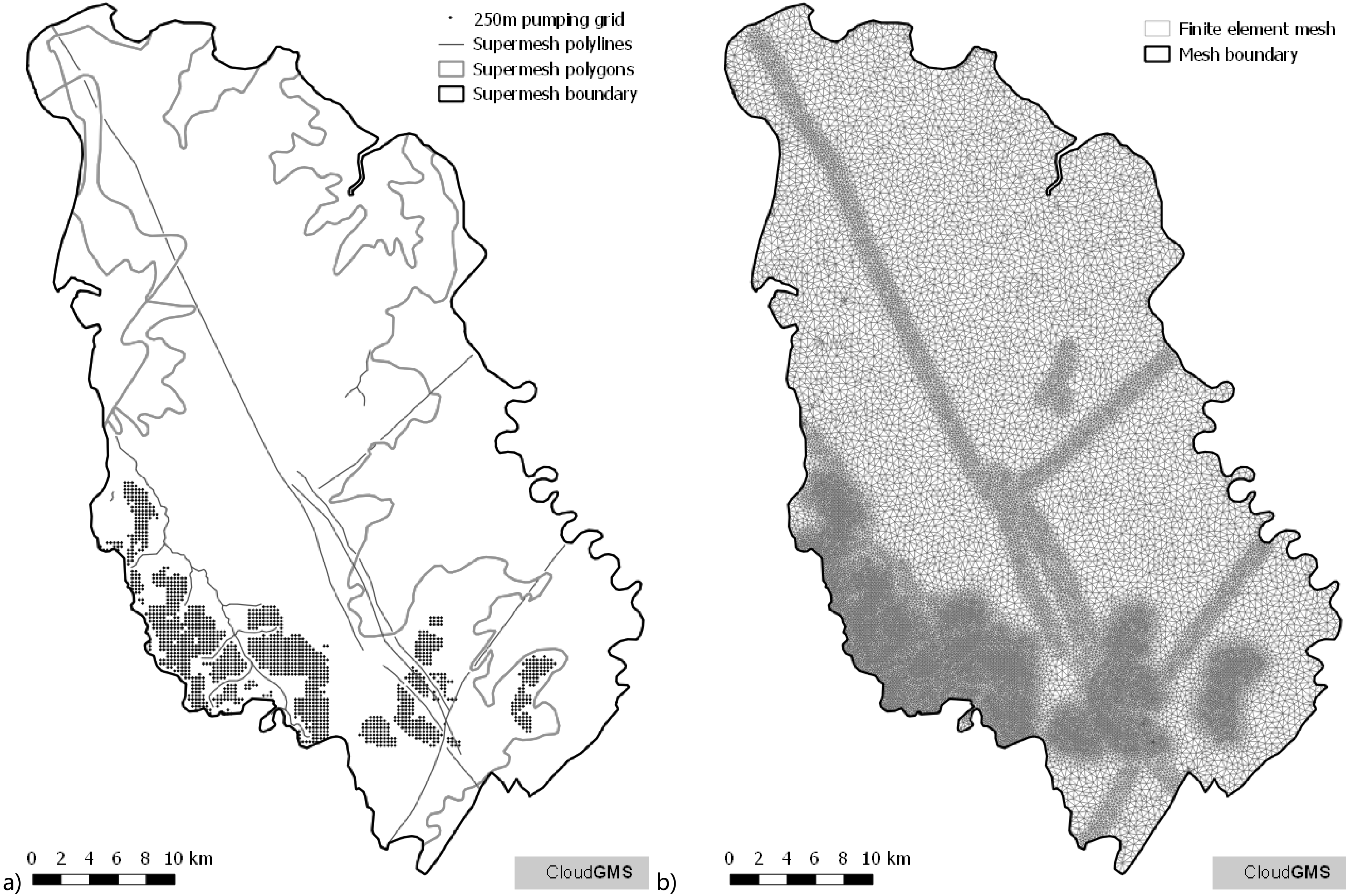


Figure 4-1 Koolpinyah Groundwater System FEFLOW model a) finite element supermesh and b) finite element mesh.

4.5 Layer geometry

Based on the conceptual model the model domain is discretized vertically into 3 layers:

- Layer 1 – laterite aquifer and floodplain (black soil);
- Layer 2 – combined Cretaceous age sediments underlying the laterite zone combined with the transitional zone of weathered dolomite at the uppermost section of the Koolpinyah Dolomite;
- Layer 3 – the fractured zone of the Koolpinyah Dolomite estimated to be 60 metres thick.

Three layers are considered the minimum required to adequately resolve the hydro-stratigraphic units and the maximum wanted to keep the model complexity and model run times to a reasonable level. The elevations of the bounding slices for each layer are presented below in Figure 4-2 and Figure 4-3.

The relationship between the hydrostratigraphic units (HSUs) and the numerical layers are presented below in Figure 4-4.

The layer geometries are considered a source of model structural uncertainty and were largely addressed in the process of model calibration where aquifer hydraulic conductivity is adjusted to achieve an appropriate distribution of effective aquifer transmissivity (i.e. aquifer hydraulic conductivity multiplied by aquifer thickness) to allow groundwater hydrographs to be replicated.

Aquifer parameters used in the model were broadly based on the previous groundwater modelling studies (Yin Foo, 2004; EHA, 2007).

The model domain has been separated into the 10 HSU zones, the zones represent areas of interpreted similar lithological / structural character. The zones used in the model are listed below.

1. Floodplain (black soil)
2. Laterite
3. Cretaceous weathered sandstone and claystone
4. Whites formation siltstone
5. SW Koolpinyah dolostone
6. NE Koolpinyah dolostone
7. NW -SE fault/dyke feature cross-cutting dolostone
8. Fault/dyke feature cross-cutting dolostone

9. Fault/dyke feature cross-cutting dolostone
10. Fault/dyke feature cross-cutting dolostone

60 pilot points were defined for each of the three layers with an additional 15 pilot points providing adjustment of fault features in layer 3. PlProc (Doherty, 2013) was then used to generate the finite element distribution of hydraulic conductivity, specific yield and transfer in / out rate for each layer using 10 zones considered to have similar hydraulic characteristics.

- The horizontal hydraulic conductivity anisotropy ratio between x and y components was 1.
- The vertical hydraulic conductivity was implemented by scaling the horizontal hydraulic conductivity by an initial factor of 0.1.

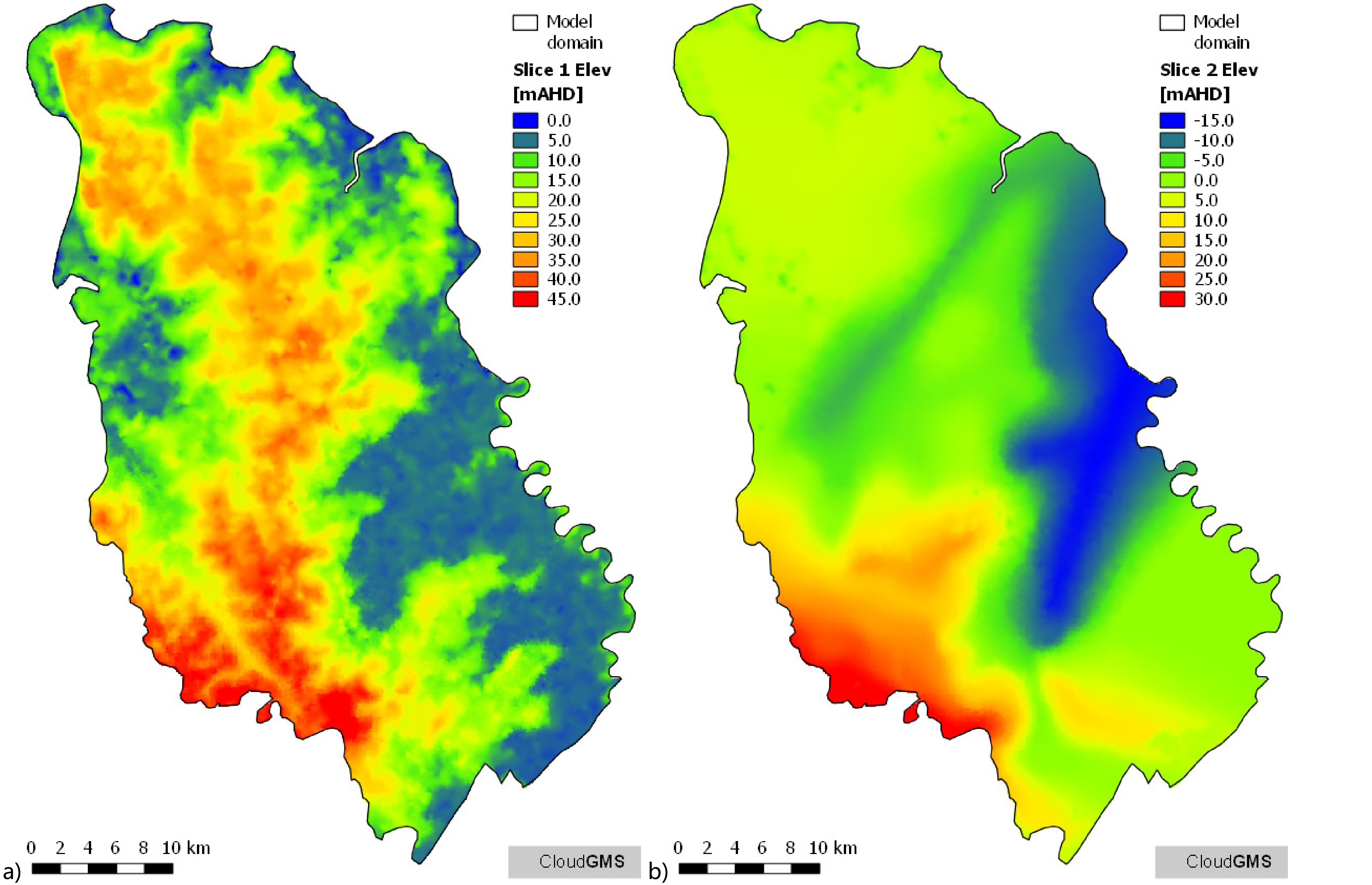


Figure 4-2 Slice elevations for a) ground surface b) indicates interpreted elevation contours for the bottom of model layer 1, the laterite aquifer.

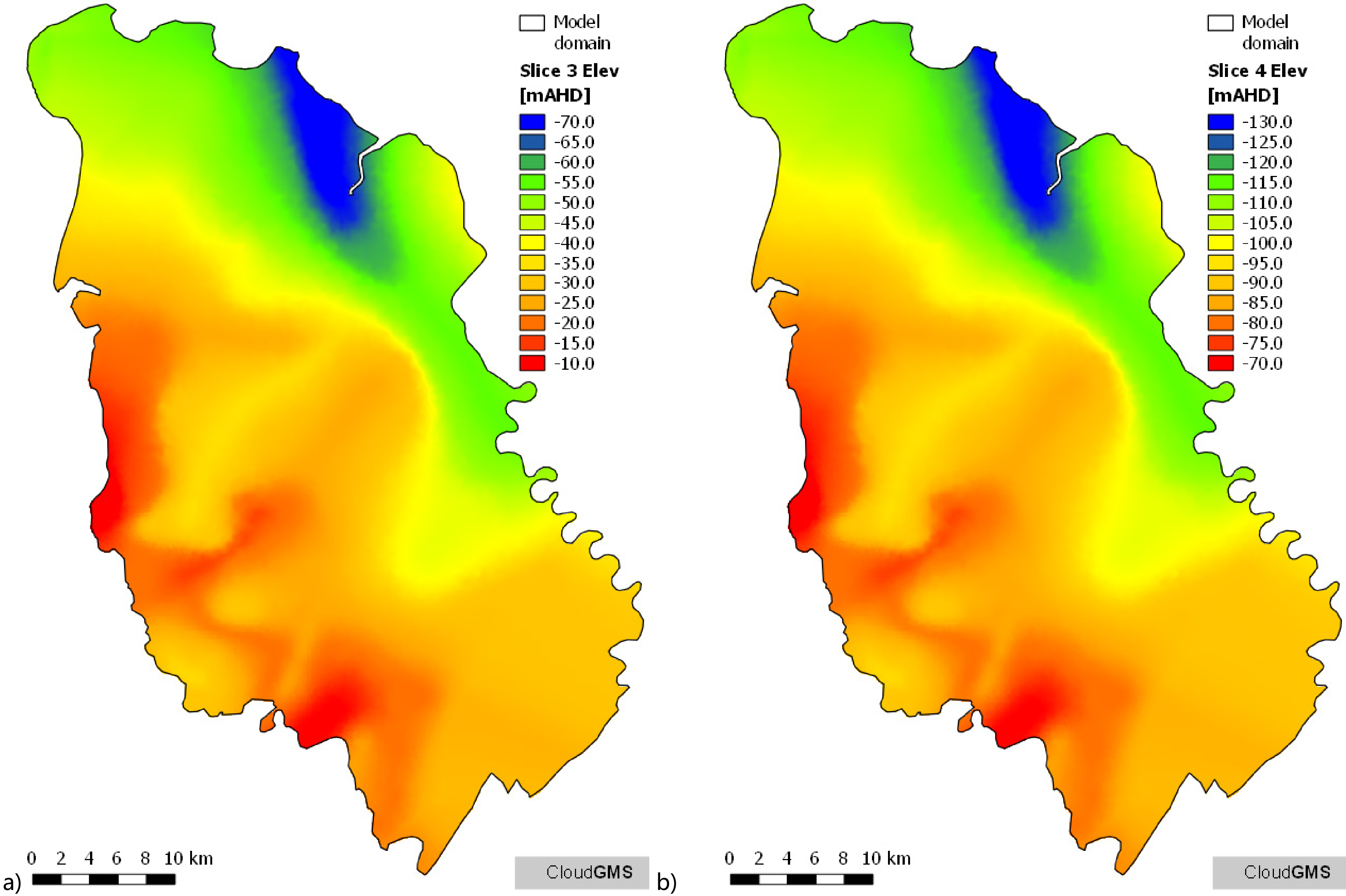

Model domain
Slice 3 Elev [mAHD]
-70.0
-65.0
-60.0
-55.0
-50.0
-45.0
-40.0
-35.0
-30.0
-25.0
-20.0
-15.0
-10.0
0 2 4 6 8 10 km
a)
CloudGMS
Model domain
Slice 4 Elev [mAHD]
-130.0
-125.0
-120.0
-115.0
-110.0
-105.0
-100.0
-95.0
-90.0
-85.0
-80.0
-75.0
-70.0
0 2 4 6 8 10 km
b)
CloudGMS

Figure 4-3 Slice elevations for a) slice 3 the interpreted bottom of model layer 2, the Cretaceous aged sediments and b) the bottom of model layer 3, the fractured dolomite.

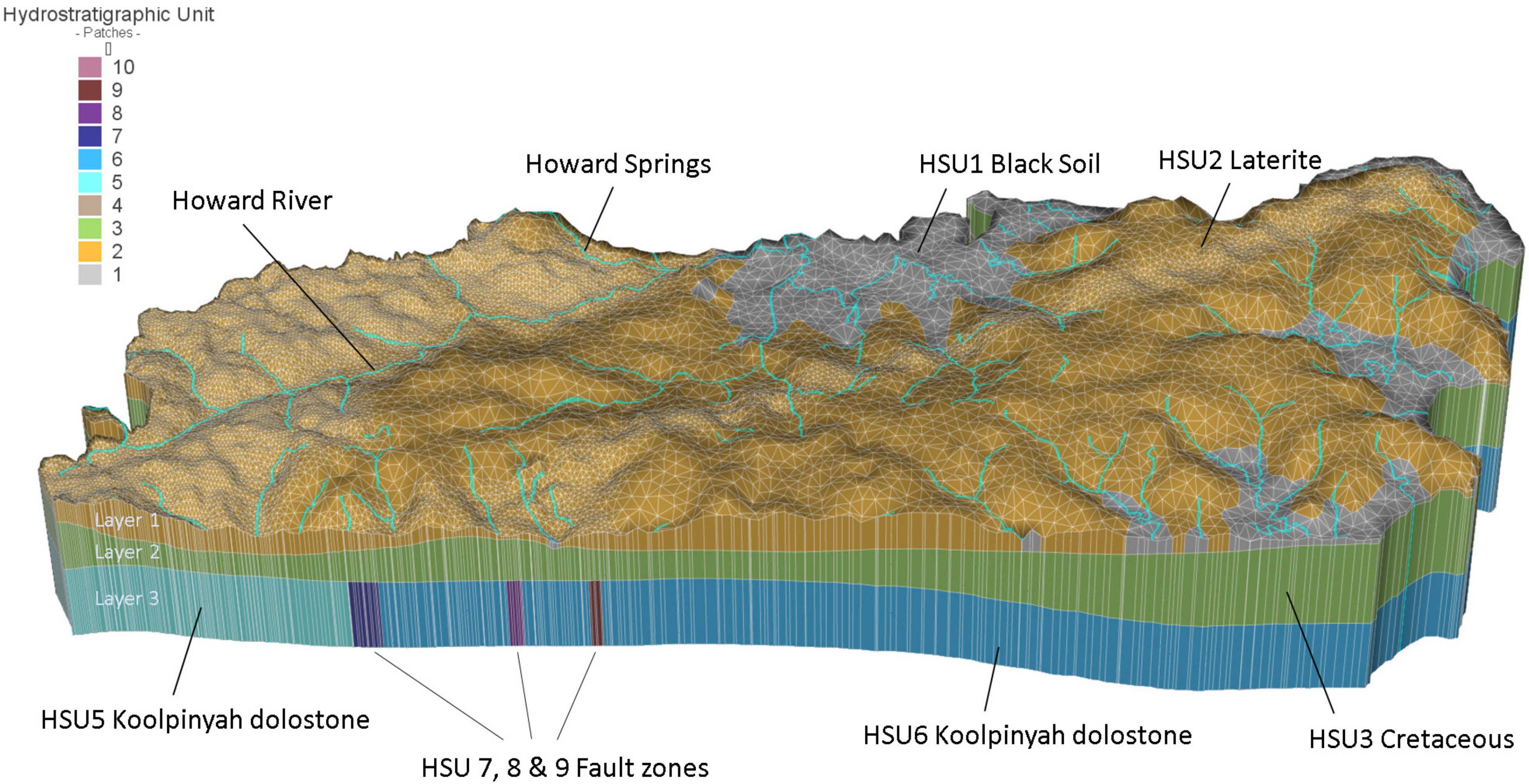


Figure 4-4 South – north section through the FEFLOW groundwater model showing the relationship between the hydrostratigraphic units (HSUs) and the model layers.

4.6 Areal fluxes – recharge & evapotranspiration

4.6.1 Recharge

Recharge fluxes have been determined using the MIKESHE catchment model (Graham & Butts, 2005). The model simulation is performed on a daily time-step using rainfall, pan evaporation, leaf area index and rooting depth for different stages of plant growth.

The model produces a simulated time series of actual evapotranspiration, run-off from the soil surface, recharge to the aquifer and discharge from the aquifer as baseflow.

As discussed in section 2.4 previous modelling has indicated that the recharge processes in the study area had separate zones, resulting in greater recharge to the south and less recharge to the north. This may be the case for groundwater flux to the deep dolostone aquifer system, however, the upper laterite aquifer would be expected to behave in a similar manner across the study area.

The recharge is applied to the model as an In / outflow on top / bottom flux using a Parameter Expression based on a user defined reference distribution.

The areal fluxes applied to the model have been implemented using a Parameter Expression. The Parameter Expression is a user-defined expression linking the time- varying values of recharge to the In / outflow on top / bottom parameter, based on the dependencies of other parameters, in this case the recharge reference distribution presented below in Figure 4-5 a). Scaling factors are applied to the time- varying recharge values to the recharge zones attributed to different soil types.

The MIKE SHE recharge time- varying values (refer section 11A.3).

4.6.2 Evapotranspiration

Evapotranspiration from the water table was implemented within FEFLOW using the expression editor such that maximum evapotranspiration will be when the water table is at the ground surface and is linearly reduced to zero when the water table is below the extinction depth (5 metres below the ground surface).

4.7 Boundary conditions

In a FEFLOW model, groundwater flow equations are solved subject to boundary conditions which are mathematical statements specifying the head or flow at the boundaries of the model area. There are five types of boundary conditions used in the updated model:

- No-flow boundary around the western and southern portions of the study area corresponding with geological features
- Seepage surface boundary conditions at the ground surface;
- Transfer (Cauchy) boundary conditions (representing discharge from the dolostone aquifer to rivers and springs);
- Transfer (Cauchy) boundary conditions (representing the equivalent fresh water heads / fluxes at the coast and the Adelaide River); and
- Well boundary conditions to represent groundwater withdrawal.

4.7.1 Seepage face boundary conditions at the ground surface

Yin Foo, (2004) identified that no significant amount of surface water inflows to the aquifer through creek beds and as such both previous modelling studies (Yin Foo, 2004; EHA, 2007) employed seepage face boundary conditions (equivalent to drain BCs in Modflow) assigned along the watercourses in order to allow the groundwater discharge from the upper layer to streams and springs when the groundwater elevation is above the stream bed elevation.

The current model seepage face reference heads have been interpolated from the available SRTM.

4.7.2 Cauchy boundary conditions - rivers / springs

Cauchy type boundary conditions are suitable to represent the surface water groundwater interaction processes along the water courses (i.e. infiltration of surface water into the aquifer and exfiltration for water from the aquifer into surface water). This boundary condition requires the prescribed boundary values of hydraulic heads (i.e. bed elevations) along the watercourses.

The previous modelling studies used a seepage face condition at the surface to represent discharge from both the laterite and dolostone aquifers, however, this method provides no capacity to determine the source of the groundwater leaving the model domain. To provide a separation of the source of the discharging groundwater and to improve the understanding system dynamics transfer boundary conditions were set along the Howard River, at Howard Springs and along Melacca Creek on slices 1, 2, 3 & 4 to explicitly determine the discharge from the dolostone aquifer. The locations of the Cauchy boundary conditions are presented below in Figure 4-5 b), and the reference elevations of the transfer boundary conditions are listed below:

- Howard River SRTM Elev – 3m
- Howard Sp = 4 mAHD
- Melacca Ck = 4 mAHD

4.7.3 Cauchy boundary conditions - coast

Previously the entire outer boundary of the model domain was considered to be no-flow. It is expected that some flow will occur across these boundaries where there is an imperfect connection with a water body such as the sea or a river. Transfer boundary conditions have been employed to represent these processes and the transfer in / out rate defined to represent the degree of connection between the model domain and the boundary condition.

4.7.4 Representation of production bores

As indicated in section 2.6.2 of this report, there are estimated to be 2125 production bores operating in the study area and most of these bores are concentrated in the McMinn's region.

Through the mesh generation code, it is possible to incorporate all pumping bores into the mesh, however, there are some drawbacks to this approach:

- The inclusion of all pumping bores would result in a finite element mesh that would have a lot of small elements, which would increase the computational burden and increase runtimes; and
- Adhering to this type of setup requires that the finite element mesh is updated whenever additional bores need to be included in the model.

In order to reduce the number of nodes and to avoid the need to re-generate the finite element mesh during the scenario modelling a relatively detailed but regularly spaced mesh was created in the areas with greatest density of pumping bores as described in section 4.4.

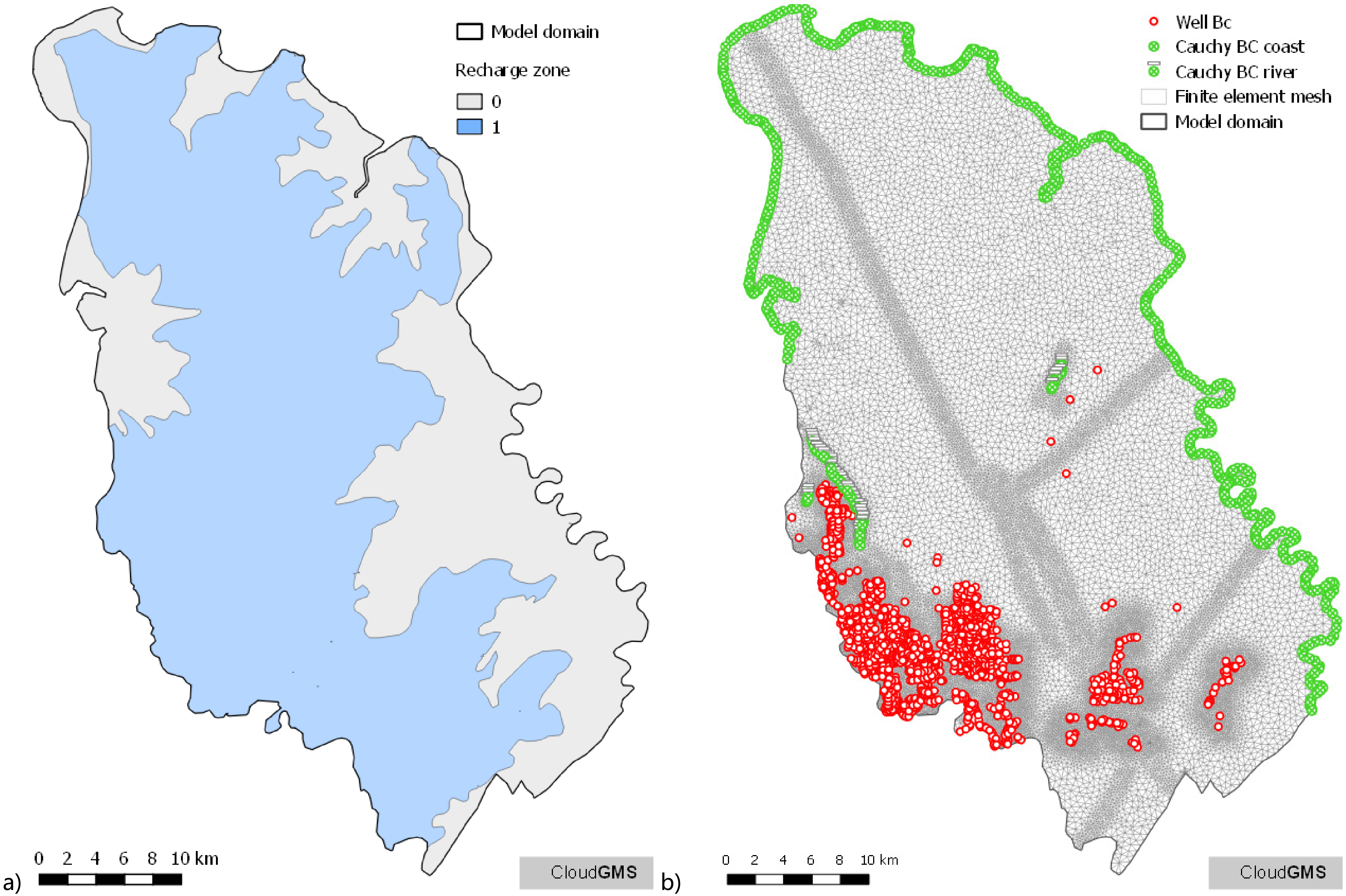


Figure 4-5 Koolpinyah Groundwater System FEFLOW model a) recharge zones and b) transfer (Cauchy) and well BCs.

The pumping bores are represented by well BCs assigned to the closest node using an IFM module called IfmAssignWells (CloudGMS, 2016). Prior to running the model the IfmAssignWells module is used to assign pumping rates for specified bores (bore coordinates and slice number are required in the input file) and generates pumping wells at the closest existing model mesh nodes. Pumping rates are combined if more than 1 bore is assigned to the same node.

The resultant 1690 well BCs assigned to the model domain generated from the existing 2125 pumping bores used in the calibration are presented below in Figure 4-5 b).

4.7.5 Reporting of boundary condition fluxes

FEFLOW is capable of reporting nodal fluxes at model run time. This provides feedback during the simulation as to the model performance. Various nodal distributions have been stored in the FEM problem file to facilitate the reporting of fluxes to / from the model domain. The fluxes from selected groups of BC nodes representing features such as the section of Howard River upstream of G8150179, Howard Springs upstream of G8155087 and Melacca Creek upstream of G8175079 were used in the calibration.

4.8 Aquifer parameters

The hydraulic parameters used by Yin Foo (2003) and EHA, (2007) are presented in Table 4-2. The range of parameters presented for the EHA (2007) model in the table are derived directly from the calibrated groundwater model.

Table 4-2 Hydraulic parameters used in previous modelling studies of the Koolpinyah Groundwater System

Yin Foo (2004)	Transmissivity [m^2/d]	Specific yield	Storage
1	50	0.03	
2			
3	150 - 700		
EHA (2007)	**Hydraulic conductivity [m/d]**	**Specific yield**	**Storage**
1	0.25 - 2.66	0.001 – 0.032	
2	0.24 – 2.62	0.0065 - 0.060	
3	10 - 130	0.0003 – 0.006	

The parameter ranges presented above are consistent with the conceptualisation of the system and have been employed in the current study. The most notable difference between this study and the previous two studies is the inclusion of the dyke features which have been assigned hydraulic conductivity values an order of magnitude lower than the values assigned to the aquifer materials.

The EHA (2007) model did not employ Transfer BCs. This study uses Transfer BCs to represent the aquifer-river interaction along the Howard River and fluxes at the coast boundary. The inclusion of Transfer BCs requires assigning Transfer In / out values, which have been determined during calibration.

5 PARAMETER ESTIMATION

5.1 Transient FEFLOW model setup

Parameter estimation of the Koolpinyah Groundwater System numerical flow model was undertaken using the PEST software suite (Doherty, 2010). Due to the relatively long run times of the model, methods were employed to reduce the model run times and the number of model runs required.

Model runtimes were reduced by employing a surrogate model (Burrows & Doherty, 2015) of the selected time period for calibration 01/11/1998 - 01/11/2005 (36100 - 38657). This period was chosen as it provides a dynamic portion of both the available groundwater level hydrographs and discharge records and has relatively low level of pumping, which at the moment is one of the biggest unknowns.

The calibration involved adjusting hydraulic parameters and comparing heads and the discharge at Howard River (G8150179), Howard Spring (G8155078) and Melacca Creek (G8175079).

The calibration involved adjusting the pilot point values either individually (to enable localized adjustment) or using scaling factors assigned to the parameter zone. The following parameters were adjusted.

- Horizontal hydraulic conductivity
- Horizontal / vertical hydraulic conductivity ratio
- Specific yield
- Storage coefficient
- Transfer out rate

5.1.1 Recharge

As identified in section 2.4 the recharge to the upper lateritic layer has been assumed to be consistent where the unit is present. The recharge distribution is based on the drainage capacity of the soils presented in section 3.3.

The areal fluxes have been implemented using the FEFLOW Expression Editor. A user-defined expression, which links the time- varying values of recharge to the In / outflow on top / bottom parameter, based on the dependencies of other parameters, in this case the recharge reference distribution. Scaling factors are applied to the time- varying recharge values based on the recharge reference distribution zone value.

The calibration of the recharge involved adjusting the scaling factors applied to the recharge zones. The Parameter Expression used for the Koolpinyah groundwater model is provided in the following equations.

$$AET = \begin{cases} PET & if\ ED.3 - Head\ \leq 0\ and\ ED.2\ \geq 0 \\ PET * \left(1 - \frac{ED.3 - Head}{ExtDep2}\right) & if\ ED.3 - Head < ExtDep2\ and\ ED.2 = 1 \\ PET * \left(1 - \frac{ED.2 - Head}{ExtDep1}\right) & if\ ED.3 - Head < ExtDep2\ and\ ED.2 = 1 \end{cases}$$

$$Qp = \left(0.001 * TS.MIKE_{RECH} * \begin{cases} 0.8\ if\ ED.2 = 1 \\ 0\ \ \ otherwise \end{cases}\right) - AET$$

where

$$ExtDep1 = 1$$

$$ExtDep2 = 5$$

$$PET = 0.004$$

$$ED.1 = Elemental\ distribution\ 'Model\_zones'$$

$$ED.2 = Elemental\ distribution\ 'Rech\_zones'$$

$$ED.3 = Elemental\ distribution\ 'Surface\_elev'$$

Figure 5-1 Example parameter expression describing the link between recharge time series (MIKERECH) and recharge reference distribution (ED.1) and the reference surface elevation (ED.3). AET defines the depth dependent ET from the water table.

5.1.2 Aquifer parameters

5.2 Parameter estimation

The calibration was performed using the PEST software suite (Doherty, 2010; Doherty, 2014).

Parameter optimisation was constrained by comparing the simulated groundwater levels to all available groundwater levels and the simulated discharges to the available observed surface water discharge data at G8150179.

5.2.1 Transient objective function

Section 2.2.2 discussed the uncertainty associated with the bore collar elevations estimated from the SRTM data. To address the issue of bore collar datum errors, the observations were converted from absolute levels in metres above Australian Height Datum to head differences relative to the first observation for each bore. Doherty and Hunt (2010) suggest that the use of differences between each head measurement and a user-specified reference level (for example the first measurement from each particular well) will often facilitate better estimation of storage and/or recharge parameters than would result if head values alone were employed in the calibration process. Thus, failure to exactly match absolute heads need not compromise the ability of the calibration process to estimate a set of parameters that captures the system dynamics, such as seasonal head differences.

Dry season discharge observations at G8150179, G8155079 and G8175079 were also included in the objective function as these constrain the overall water balance and these fluxes are used in assessing the impacts of development scenarios.

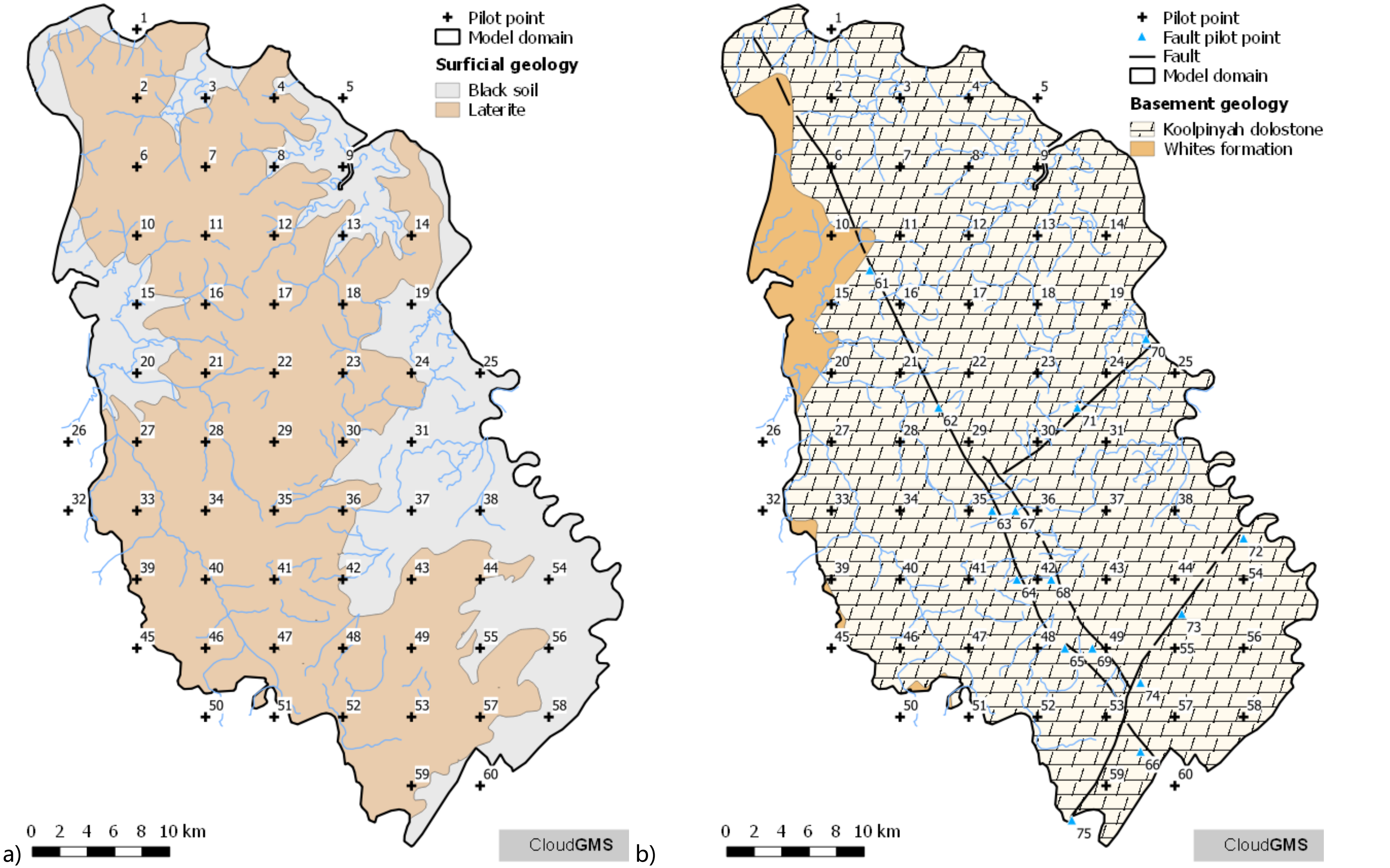


Figure 5-2 Pilot points for a) layer 1 & 2 b) layer 3.

5.3 Surrogate model

Burrows and Doherty (2014) present a methodology of using simplified surrogate models to improve the efficiency of optimisation and uncertainty analysis of detailed models with excessive runtimes. Adjustments to the original model to reduce runtimes are briefly discussed below.

5.3.1 Mesh refinement

The runtime of finite element groundwater model is correlated with the number of nodes used to define the layers in the model. In an attempt to reduce the runtime of the Koolpinyah groundwater model a coarse mesh was generated to reduce the number of nodes in the problem.

5.3.2 Free surface constraint

The free surface constraint where the water table touches the top surface can be set as either:

Constrained (seepage face mode)	The water level is not allowed to exceed the model top. In the nodes where the water level would otherwise be above the top, automatically a hydraulic head boundary condition is set with a value of the top elevation. Thus all water exceeding the top surface is removed.
Unconstrained (water table mode)	The water level is allowed to exceed the model top by extending the aquifer up to the actual water level.

The checking for nodes with a waterlevel higher than the top can be done once per time step (water table mode), setting the head boundary conditions for the next time step. Alternatively the boundary conditions can be set as a Seepage Face, i.e., with a constraint condition that only allows outflow. This causes an iterative setting of the condition per time step. Only up to 30 iterations are performed. If there are still changes in the location of these additional head boundary conditions, FEFLOW proceeds to the next time step.

It should be noted that applying the Constrained option influences the water balance of the model as internally head boundary conditions are set. The flow by these additional conditions is contained in the Dirichlet Boundary Conditions bar in the Budget panel.

Originally the model was set with the seepage face constraint at the surface with no inflows, however, due to the additional time required to determine the location of the seepage face BCs the free surface mode in the surrogate model was changed to unconstrained.

5.3.3 Free surface residual water depth

The default residual water depth = 0.00101 m, it was found that the model ran faster by increasing the residual water depth. A value of 0.01 m was adopted after some trial and error testing.

6 CALIBRATION PERFORMANCE

6.1 Introduction

Barnett et al (2012) recommend that the groundwater model acceptance should be based on a number of measures that may not be specifically related to model calibration. These measures are required to demonstrate that a groundwater model is robust, simulates the water balance as required and is consistent with the conceptual model on which it is based. The four measures recommended by Barnett et al (2012) are presented below in Table 6-1. The performance of the Koolpinyah Groundwater System FEFLOW model is discussed in the following sections.

Table 6-1 Recommended groundwater model performance measures (after Barnett, 2012)

Performance measure	Criterion
Model convergence	
The model must converge in the sense that the maximum change in heads between iterations is acceptably small.	The iteration convergence criterion should be one or two orders of magnitude smaller than the level of accuracy required in head predictions.
Water balance	
The model must demonstrate an accurate water balance, at all times. The water balance error is the difference between total predicted inflow and total predicted outflow, including changes in storage, divided by either total inflow or outflow and expressed as a percentage.	A value less than 1% should be achieved and reported at all times and cumulatively over the whole simulation. Ideally the error should be much less. An error of >5% would be unacceptable, and usually indicates some kind of error in the way the model has been set up.
Qualitative measures	
The model results must make sense and be consistent with the conceptual model. Contours of heads, hydrographs and flow patterns must be reasonable, and similar to those anticipated, based either on measurements or intuition. Estimated parameters must make sense and be consistent with the conceptual model and with expectations based on similar hydrogeological systems.	Qualitative measures apply during calibration, when comparisons can be made with historical measurements, but also during predictions, when there is still a need for consistency with expectations. There is no specific measure of success. A subjective assessment is required as to the reasonableness of model results, relative to observations and expectations. The modeller should report on relevant qualitative measures and discuss the reasons for consistency and inconsistency with expectations.
Quantitative measures	
The goodness of fit between the model and historical measurements can be quantified, using statistics such as RMS, SRMS, MSR and SMSR for trial-and-error calibration and the objective function in automated calibration.	Quantitative measures only apply during calibration. Statistics of goodness of fit are useful descriptors but should not necessarily be used to define targets. Targets such as SRMS < 5% or SRMS < 10% may be useful if a model is similar to other existing models and there is good reason to believe that the target is achievable. Even if a formal target is not set, these measures may provide useful guides.

6.2 Model convergence

Section 4.2 documents that the dimensionless error criterion in FEFLOW is used for the automatic time-stepping process. The Error tolerance (unit: 10^{-3}) is defined as the averaged absolute error (change in the primary variable) divided by the maximum value occurring in initial or boundary conditions (Diersch, 2015) and was set to the default of 1.

On completion of the transient model runs, the model log was queried to ensure all iterations converged to a value less than the error criterion.

6.3 Model water balance

The water balance for the simulation period 01/04/1980 – 01/09/2014 is presented below in Figure 6-1. The total water budget imbalance is 0.09%, which is well below the recommended value of less than 1%.

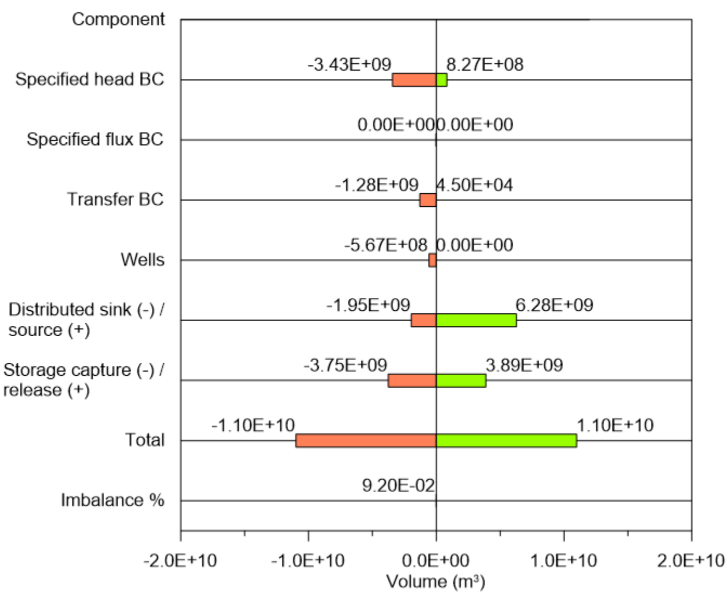


Figure 6-1 Historic transient model water balance for the calibration period 01/04/1980 to 01/09/2014.

6.4 Qualitative performance

The following assessment of qualitative performance:

- The final estimated parameters are considered to be consistent with the conceptual model and with expectations based on previous studies and similar hydrogeological systems.
- The modelled water budget is also considered to be consistent with the conceptual model.

- The contours of heads, hydrographs and flow patterns are reasonable, and similar to those anticipated, based on observed measurements.
- The absolute modelled groundwater levels are not always in agreement with the observed values with offsets evident in some, however, the groundwater levels do capture the system dynamics with seasonal or multi-seasonal head differences and long-term trends in the groundwater levels are generally well reproduced.
- The model inability to match individual hydrographs is in part due to the inaccuracies in the bore collar elevations and the uncertainties introduced from the surface elevation data. Similar issues were encountered during modelling of the Middle Point region to the southeast of the study area (Middlemis, 1999).

The modelled and observed heads used in the parameter estimation process are presented in APPENDIX B.

6.5 Quantitative performance

6.5.1 Groundwater level hydrographs

The 'goodness of fit' of the modelled to the observed data is often measured using root mean squared error (RMS) and scaled root mean squared error (SRMS), which is the RMS divided by the range of measured heads and expressed as a percentage.

At the conclusion of the parameter estimation process the overall groundwater elevation (RMS) error of 4.97 metres. Assuming a maximum head range of 48 metres then the scaled root mean squared (SRMS) is 10.2% (which is consistent with the target SRMS of 10% taking into account uncertainty in ground surface elevations and pumping volumes).

The measured and modelled groundwater levels at each observation bore are presented in Appendix B and the corresponding RMS values are provided as reference.

6.6 Parameter distributions

6.6.1 Hydraulic conductivity distributions

The final calibrated hydraulic conductivity distributions for each of the 3 model layers are presented below in Figure 6-2.

The optimised hydraulic conductivity distributions for layers 1, 2 & 3 are presented below in Figure 6-2 a), b) & c) respectively.

The layer geometries are considered a source of model structural error and were largely addressed in the process of model calibration where aquifer hydraulic conductivity was adjusted to achieve an appropriate distribution of effective aquifer transmissivity (ie. aquifer hydraulic conductivity multiplied by aquifer thickness) to allow groundwater hydrographs to be replicated.

6.6.2 Specific yield distributions

The final calibrated specific yield distributions for each of the 3 model layers are presented below in Figure 6-3.

Specific yield values are consistent with the conceptual model ranging from 0.0005 to 0.025 which are relatively low. The low specific yield is reflected in the very dynamic groundwater levels.

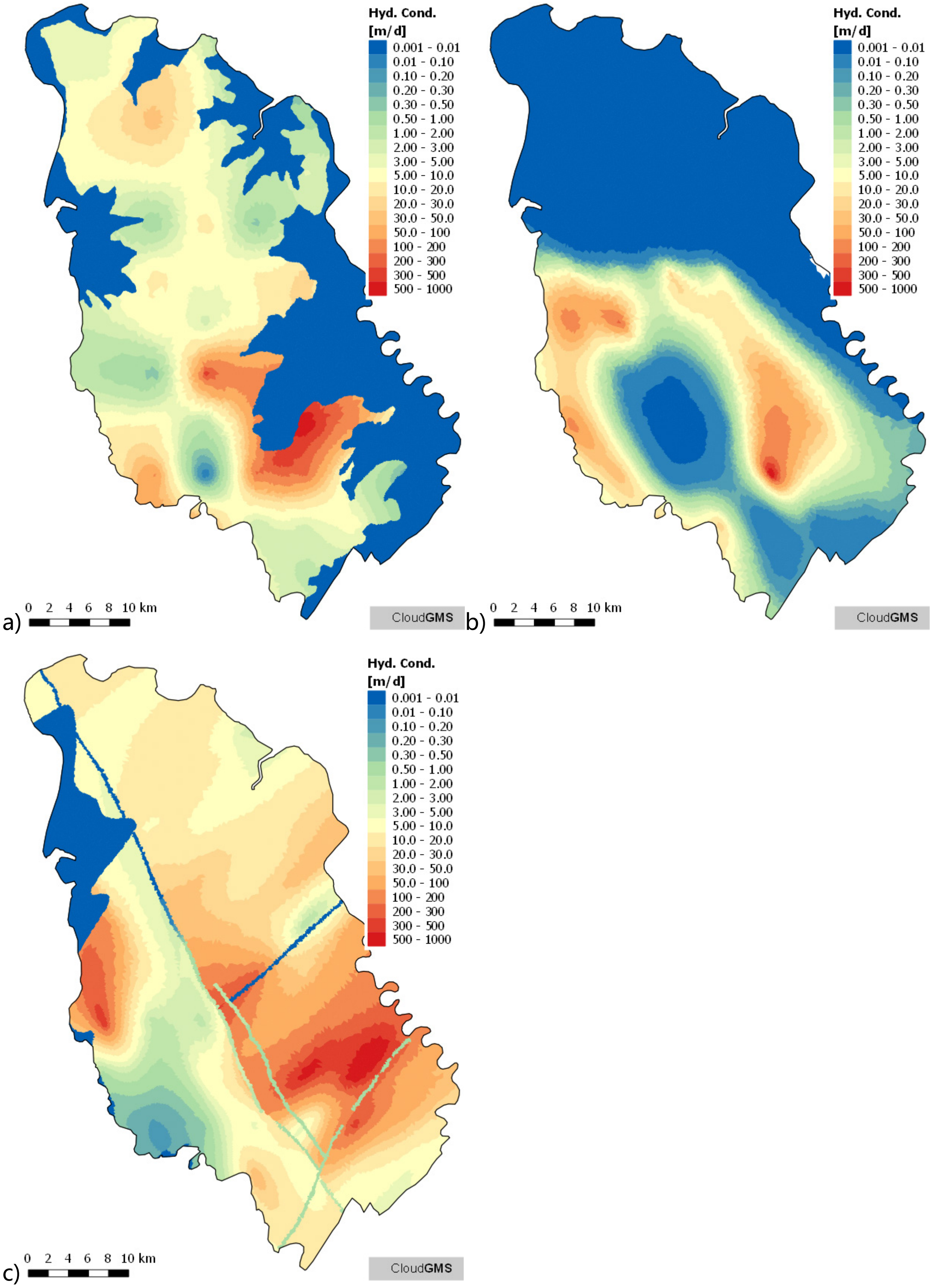


Figure 6-2 Horizontal hydraulic conductivity distributions for a) layer 1, b) layer 2 and c) layer 3.

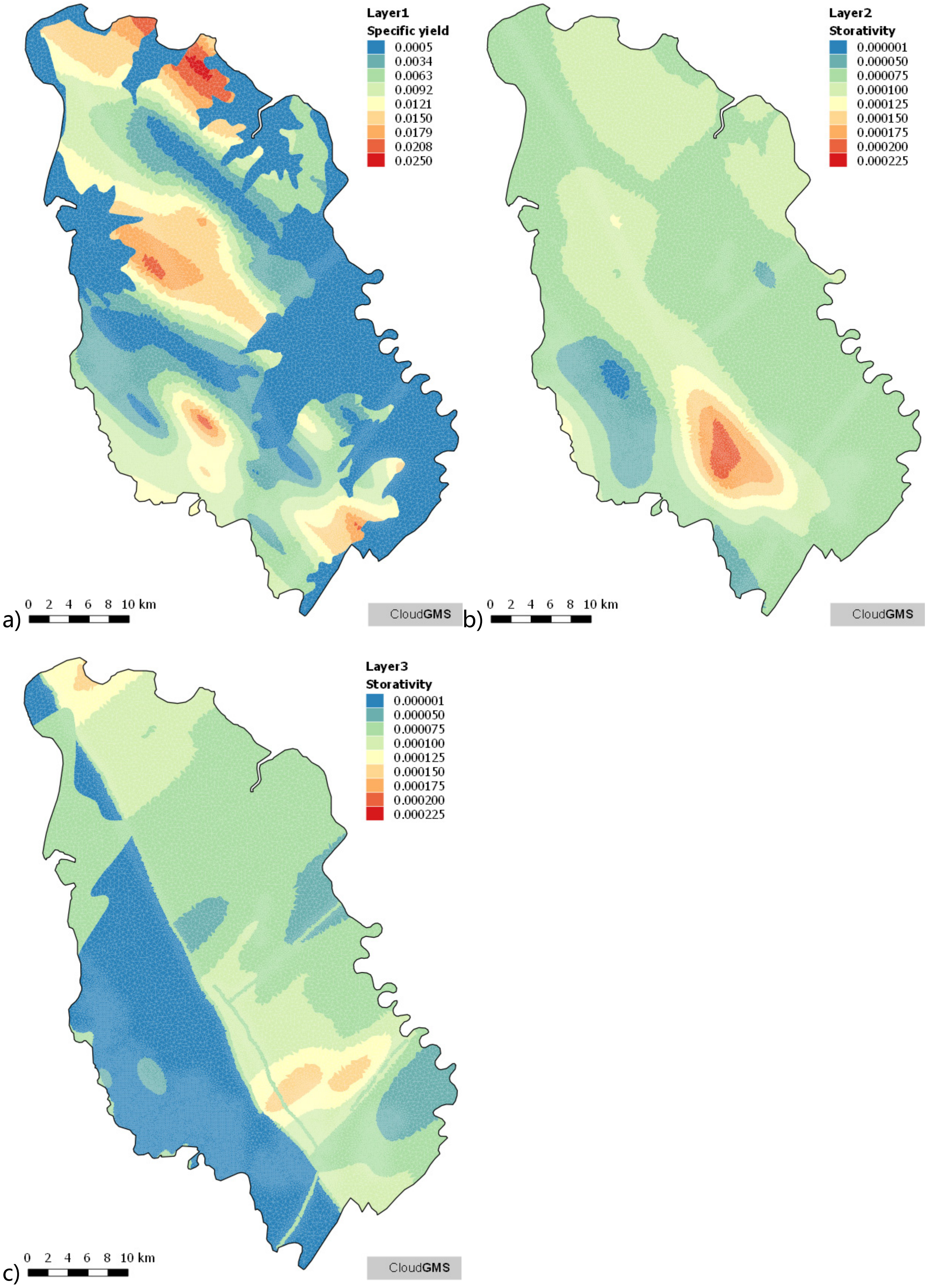


Figure 6-3 Storage coefficient distributions for a) layer 1, b) layer 2 and c) layer 3.

6.7 Model outputs

6.7.1 Layer 1 groundwater head contours

The groundwater head contours for layers 1 at the end of the 2003/04 wet season (38077d) and at the end of the following dry season (38352d) are presented below in Figure 6-4. The groundwater heads in layer 1 mirror the ground surface with high groundwater levels along the southeastern and central sections of the model coinciding with higher ground elevations. Groundwater levels in layer 3 are more subdued and show a general decreasing trend from the south to the north and northeast.

Heads are about 35m in the south to about 10 mAHD to the north and 0 mAHD to the east.

6.7.2 Layer 3 groundwater head contours

The groundwater head contours for layers 3 at the end of the 2003/04 wet season (38077d) and at the end of the following dry season (38352d) are presented below in Figure 6-5. Groundwater levels in layer 3 are more subdued and show a general decreasing trend from the south to the north and northeast.

Heads are about 35m in the south to about 10 mAHD to the north and 0 mAHD to the east.

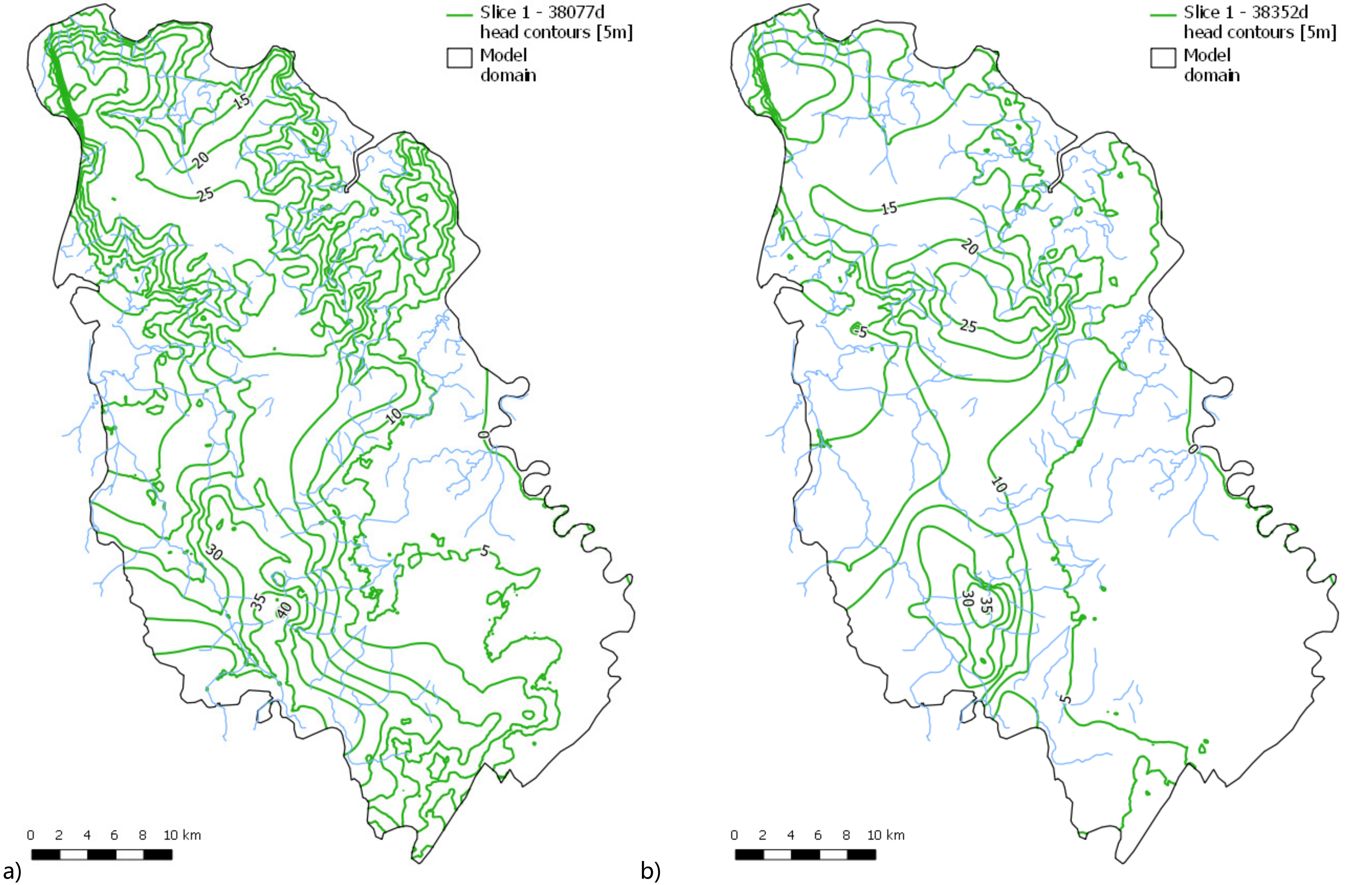


Figure 6-4 Layer 1 groundwater contours a) end of 2009/10 wet season (40268d) and b) end of 2009/10 dry season (40147d).

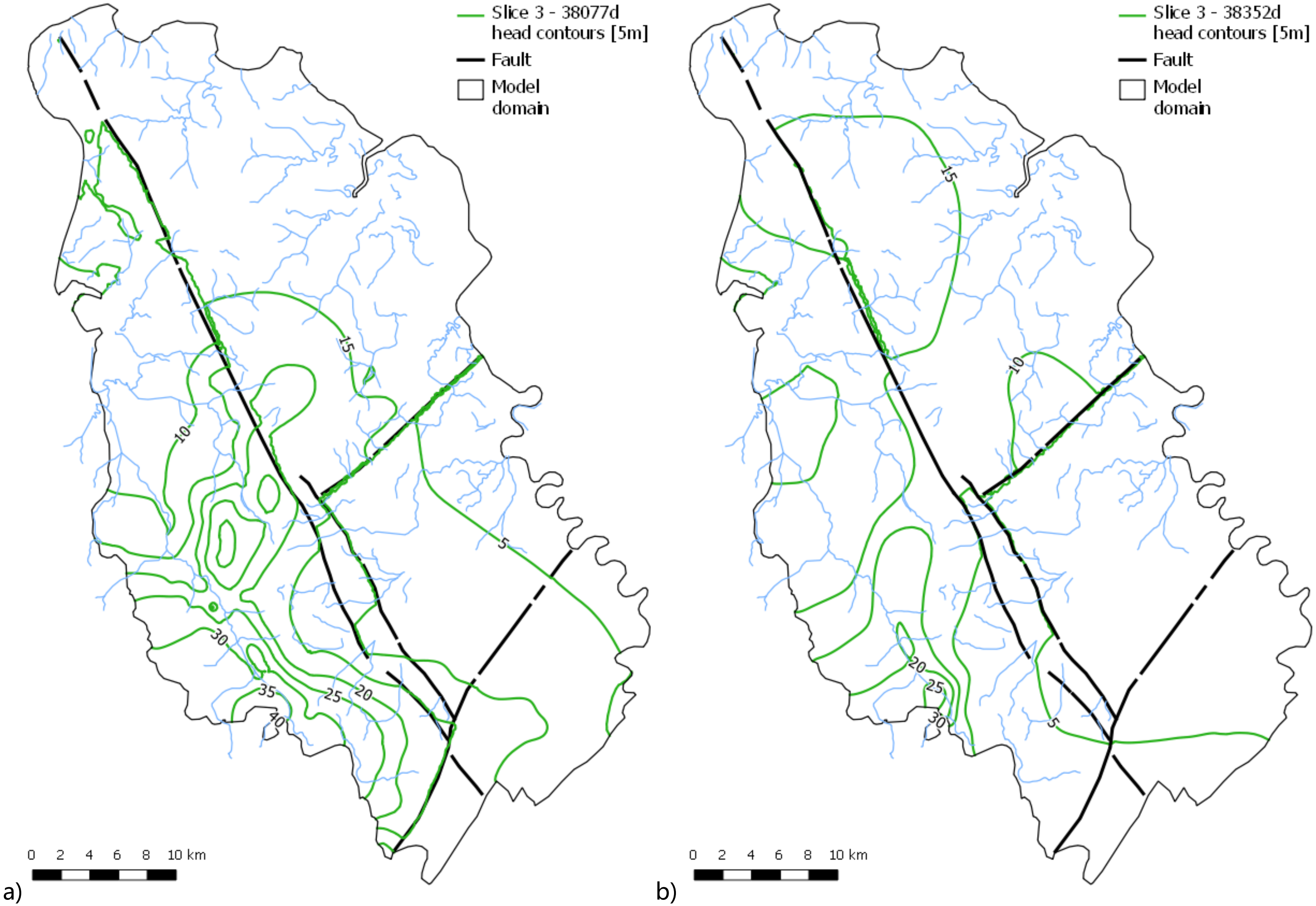


Figure 6-5 Layer 3 groundwater contours at a) end of 2003/04 wet season (38077d) and b) end of 2004/05 dry season (38352d).

6.7.3 Groundwater discharge at gauged locations

The groundwater discharge to the stream features at G8150179, G8155087 & G8175079 are presented below in Figure 6-6, Figure 6-7 and Figure 6-8 respectively. It should be noted that the modelled discharge does not include the quickflow component discussed previously in section 3.4.

Dry season groundwater discharges at the 3 gauging sites used in the calibration, show the same magnitude, seasonal dynamics and timings as the observed measurements.

The early dry season flows predicted at Howard Springs is underestimated, however, this component of the flow regime includes interflow or base flow from surficial sediments to the southwest, which are not included in the model domain.

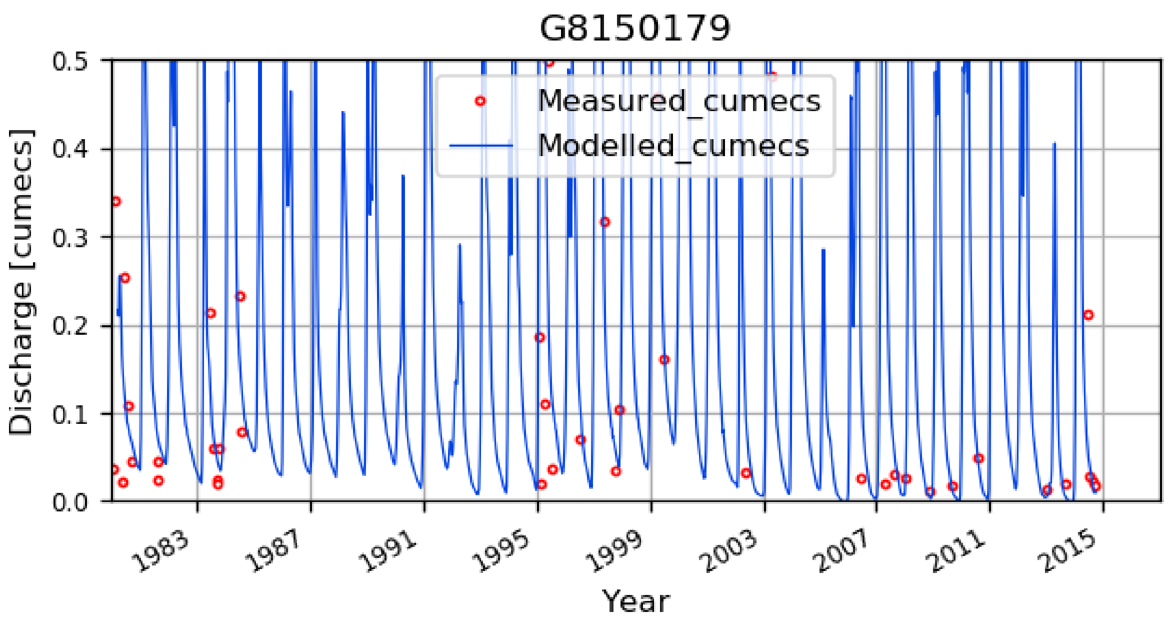


Figure 6-6 Groundwater discharge at G8150179 (Howard River @ Iron Bridge)

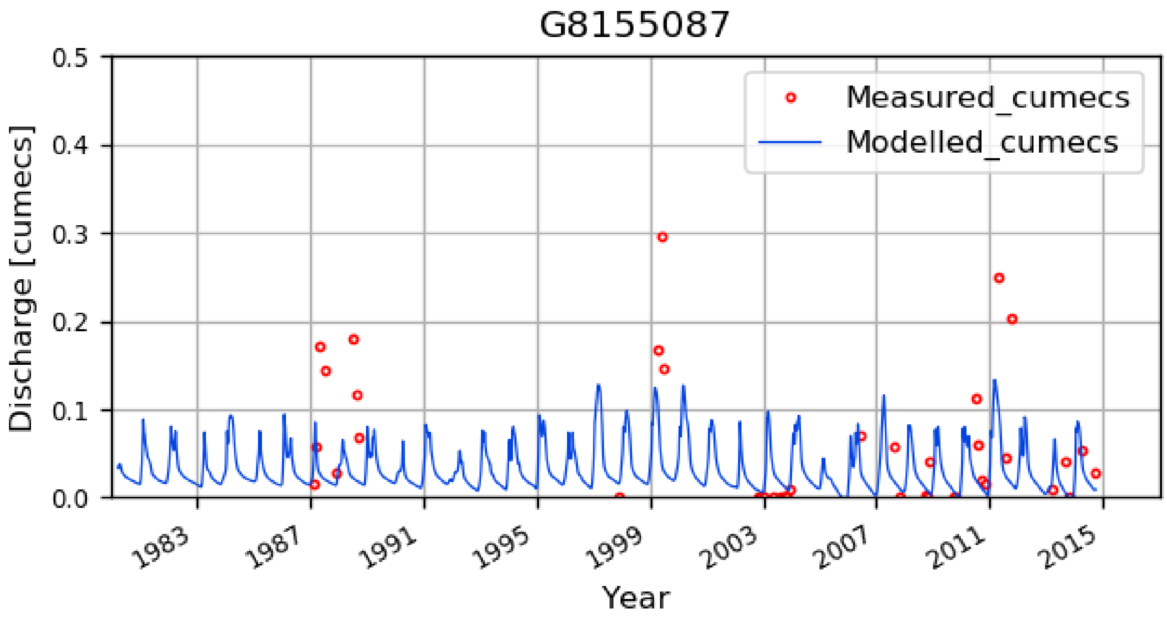


Figure 6-7 Groundwater discharge at G8155087 (Howard Springs).

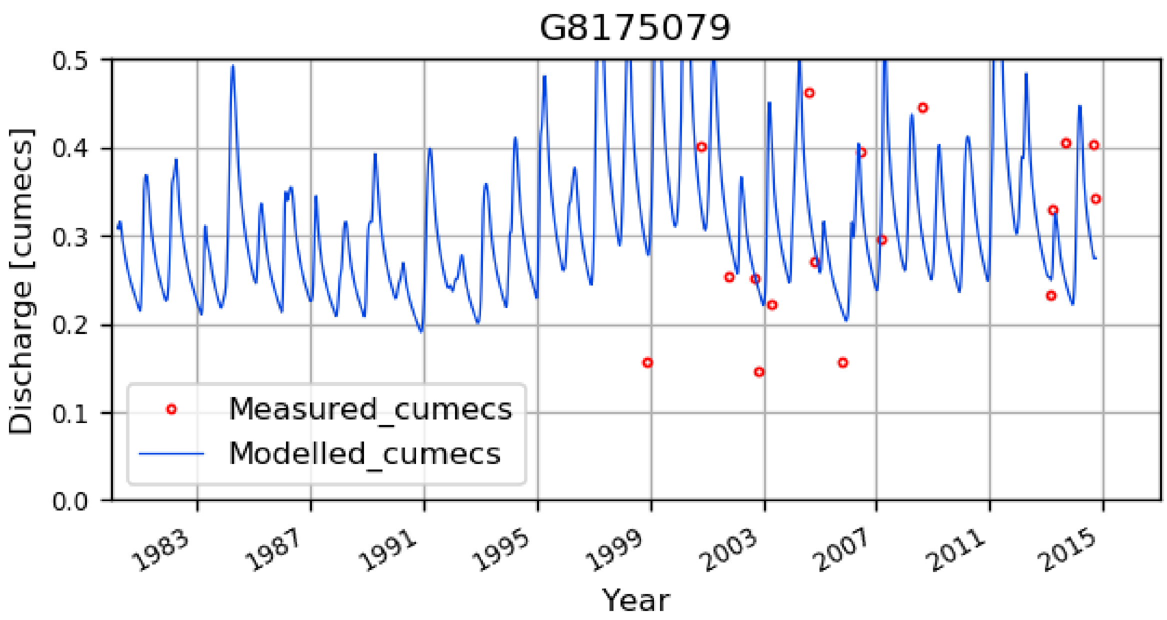


Figure 6-8 Groundwater discharge at G8175079 (Melacca Creek).

7 SENSITIVITY ANALYSIS AND UNCERTAINTY

An analysis of the sensitivity of particular model outputs to particular model inputs is part of an effort to increase the understanding of the processes simulated by the model.

All hydraulic conductivity and storage parameters adjusted during the calibration process have been used in a sensitivity analysis as reported by PEST (i.e. change in objective function to changes in a parameter).

7.1 Hydraulic conductivity

The sensitivity of the objective function to changes in the hydraulic conductivity are presented below in Figure 7-1, Figure 7-2 and Figure 7-3.

The most sensitive hydraulic conductivity values in layer 1 are located at pilot points pp33, pp34. These are located to the north of the nodes representing the section of the Howard River discharge reported at G8150179, which was used as a calibration target.

The most sensitive hydraulic conductivity values in layer 3 are located at pilot points pp39 and pp40. These are located to the north of the nodes representing the section of the Howard River discharge reported at G8150179, which was used as a calibration target.

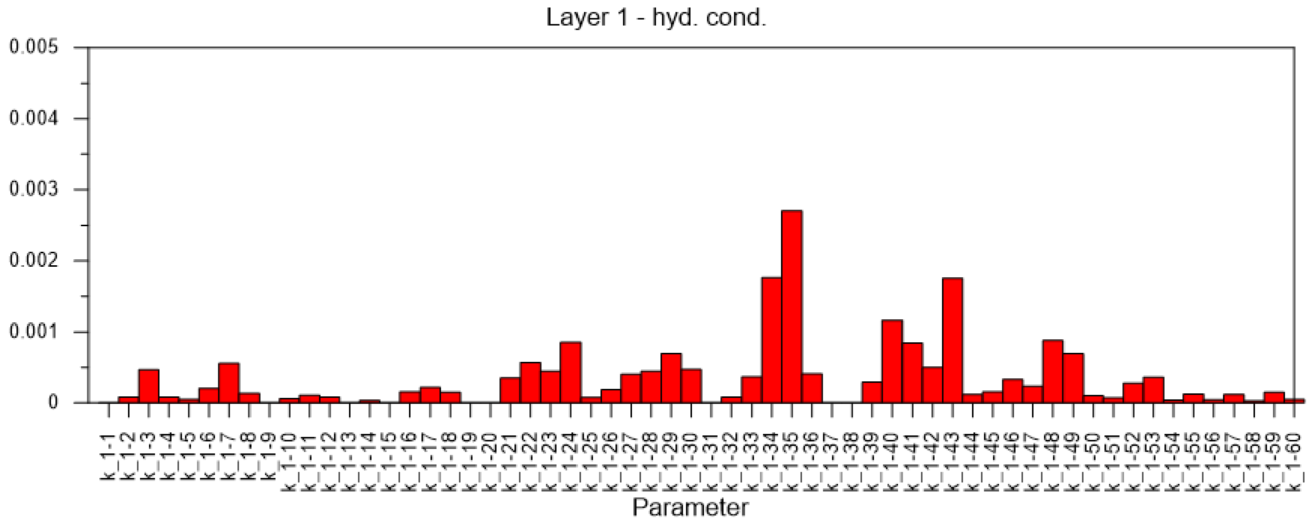


Figure 7-1 PEST parameter sensitivities for layer 1 hydraulic conductivities.

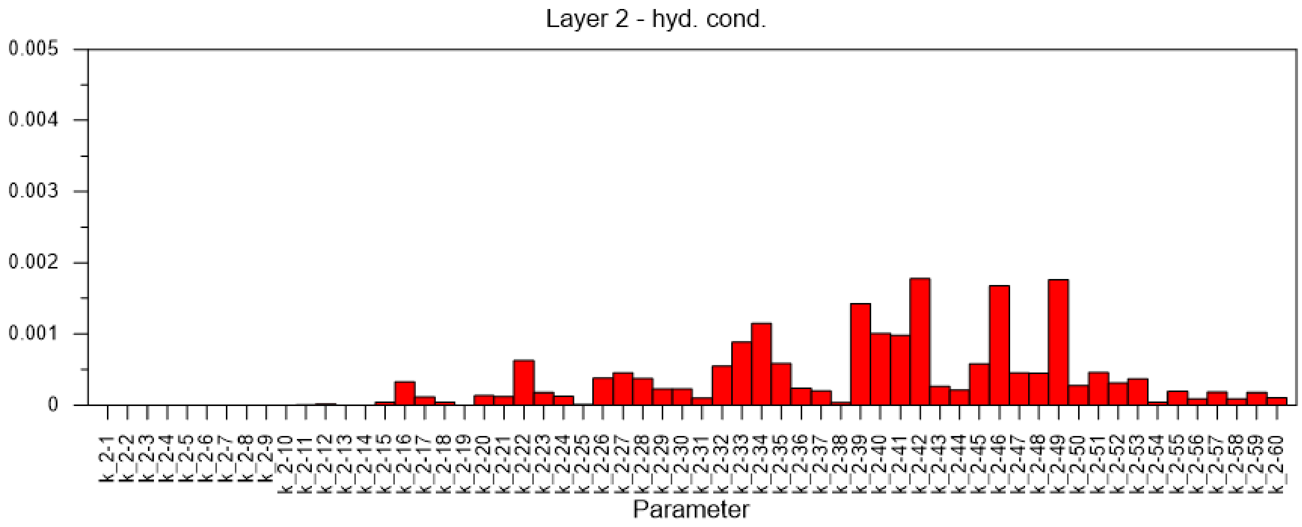


Figure 7-2 PEST parameter sensitivities for layer 2 hydraulic conductivities.

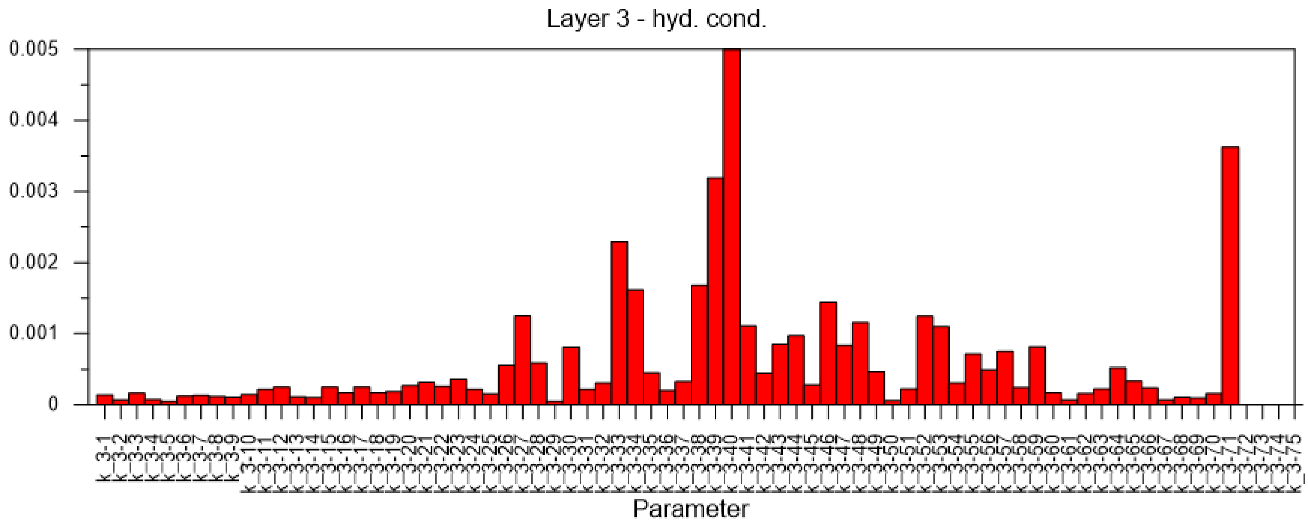


Figure 7-3 PEST parameter sensitivities for layer 3 hydraulic conductivities.

7.2 Storage parameters

The sensitivity of specific yield in layer 1 and the specific storage in layers 2 & 3 are presented below in Figure 7-4, Figure 7-5 and Figure 7-6. The locations of the pilot points are presented in Figure 5-2.

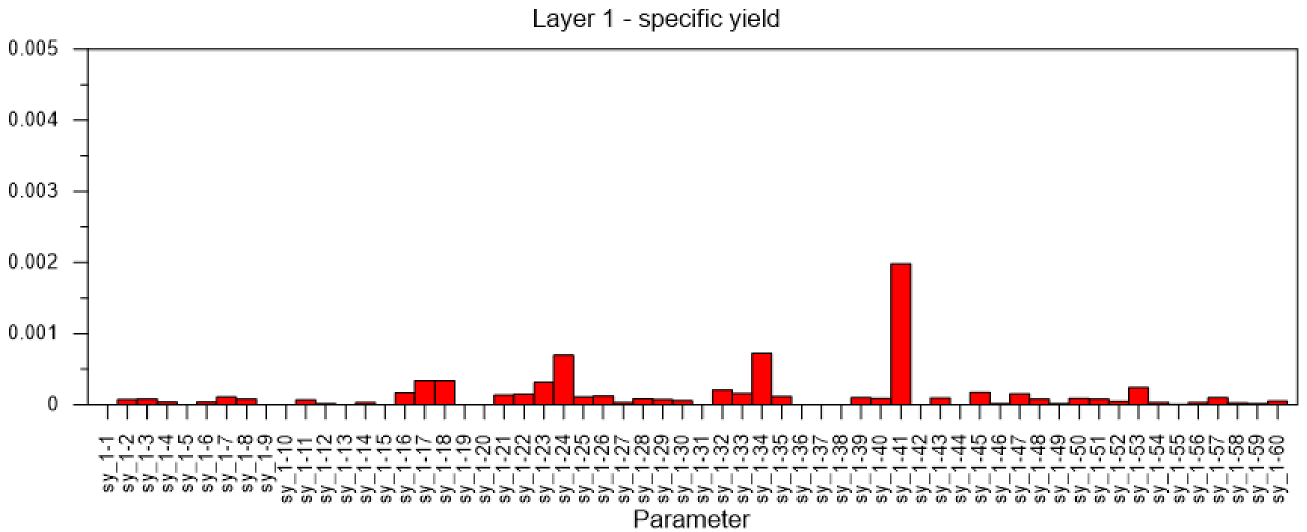


Figure 7-4 PEST parameter sensitivities for layer 2 drain-/fillable porosity (specific yield).

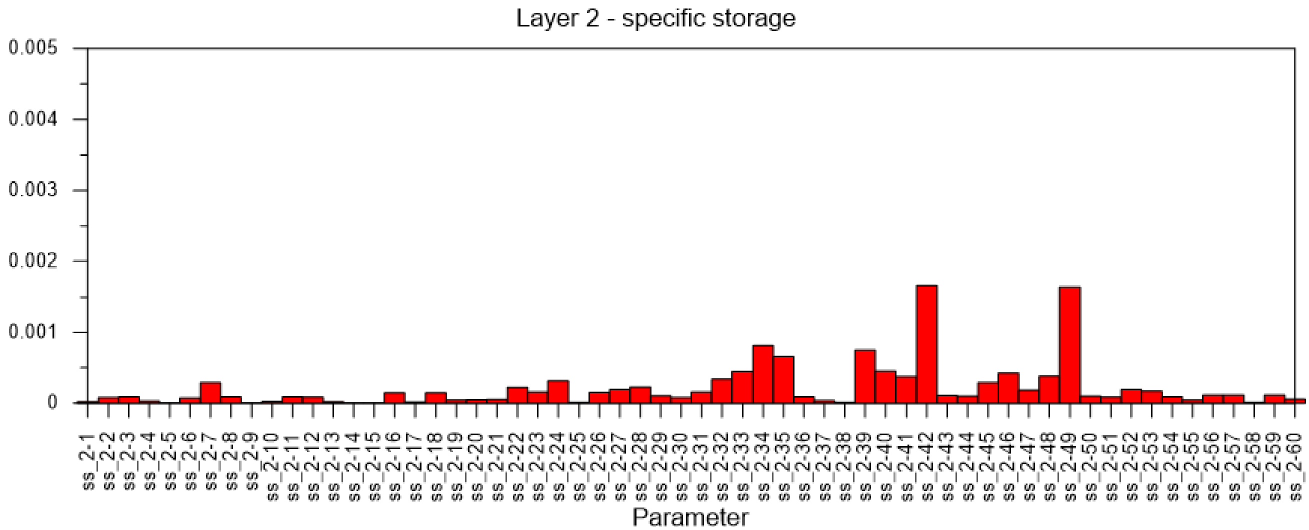


Figure 7-5 PEST parameter sensitivities for layer 2 specific storage.

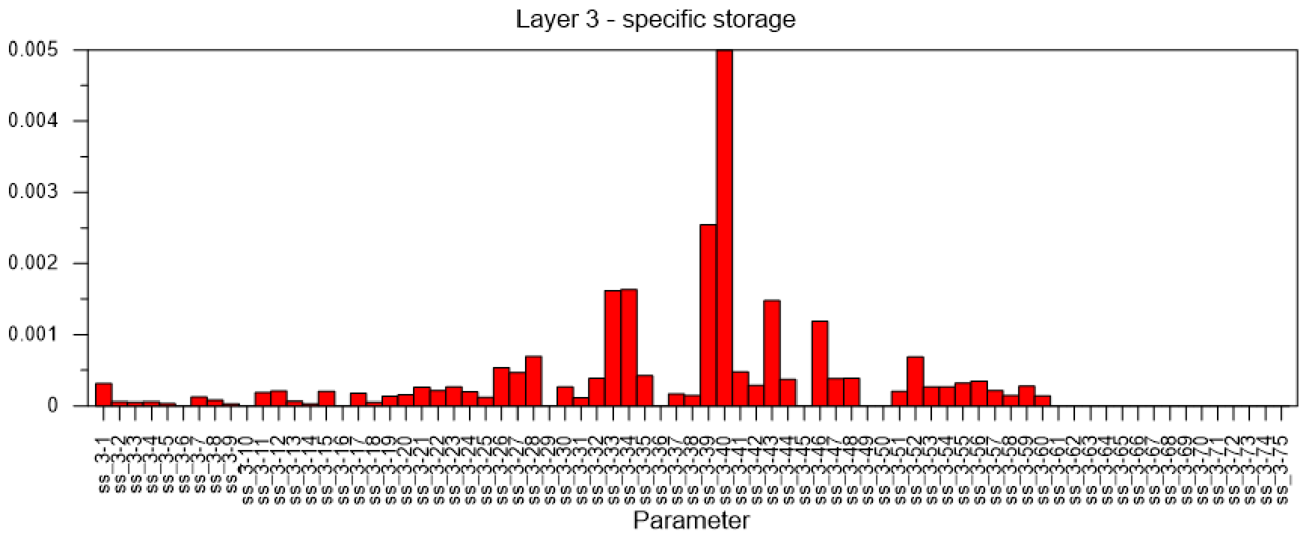


Figure 7-6 PEST parameter sensitivities for layer 3 specific storage.

7.3 River node elevations

The discharge at the rivers is quite sensitive to the elevation of the constant head BCs. Increasing the elevation of nodes along the Howard River by 1 metre results in a reduction in end of dry season discharges by approximately 0.050 cumecs (50 L/s). This is a particular issue as the elevation data available has considerable error in the areas of interest due to the presence of groundwater dependent vegetation.

7.4 Model uncertainty

The current uncertainty assessment is qualitative in nature where sources of uncertainty are identified and their impacts on the model outputs discussed. A more formal quantitative assessment is warranted.

There is uncertainty in the elevation data used to determine observation bore collars and the upper slice of the model representing the ground surface. The uncertainty in collar elevation (approximately half of observation bores) reduces the capacity of the model to match absolute groundwater levels. The elevation data impacts the areas of surface water / groundwater interaction as the ground surface limits the groundwater level rises in the wet season. The discharge at the rivers can be quite sensitive to the ground surface elevation and the levels of specific discharge features were adjusted during calibration.

Slice elevations of each layer are also considered a source of model structural uncertainty. However, the uncertainty in the layer geometries is largely addressed in the process of model calibration where aquifer hydraulic conductivity is adjusted to achieve an appropriate distribution of effective aquifer transmissivity (i.e. aquifer hydraulic conductivity multiplied by aquifer thickness) to allow groundwater hydrographs to be replicated.

The pumping information used in the model has considerable uncertainty. A total of 2125 pumping bores have been identified in the study area extracting about 20 to 25 GL/yr from the Koolpinyah Groundwater System. The bores are being used as either Rural (1579), Irrigation (533) or Production (13). However, the only groundwater use that has metered extraction records are the Power and Water Corporation production bores, these account for approximately 25% of the total volume extracted from the Koolpinyah Groundwater System. The remaining 75% of extraction from the Koolpinyah Groundwater System is estimated based on land use, the uncertainty in pumping data cannot be easily addressed. Under or overestimation of the applied pumping volumes is accounted for during the model calibration by adjusting recharge and storage parameters to allow outflows from the aquifer to be matched.

SENSITIVITY ANALYSIS AND UNCERTAINTY

To overcome some of the uncertainties in the model, it has been constructed and calibrated to address the specific objectives of forecasting impacts on groundwater levels and stream depletion. Impacts are then assessed as a subtraction of two model results, which is considered less uncertain than assessing absolute model outputs.

8 HISTORIC PUMPING IMPACTS COMPARED TO NATURAL CONDITIONS

The impacts of the historic development on the water resources of the Koolpinyah Groundwater System are presented as hydrographs, drawdown plots and stream depletion plots. The historic response is compared to the natural conditions determined by removing pumping stresses from the model.

8.1 Groundwater drawdown plots

The drawdown plots at the end of the dry season and end of the wet season for the water year 2009 / 10 are presented below in Figure 8-1. The plots were generated by subtracting the natural (no-pumping) water levels from the historic water levels at the same time step. The impacts are restricted to the southeastern area of the model domain.

Drawdowns at the end of the dry season are generally around 10-15 metres with a maximum of about 25 metres associated with irrigation of around Benham's Lagoon and to the east of Humpy Doo. This region corresponds to the 6   7 ML/yr/Ha area identified in the pumping 'hotspots' presented in Figure 2-8 b).

Drawdowns of about 5 metres are also evident at the end of the 2009 / 10 wet season, suggesting that the historic pumping is resulting in depletion of storage from the aquifer. This is also evident in the groundwater level hydrographs RN030039 and RN035972 discussed in the following section.

8.2 Groundwater level hydrographs

To demonstrate the temporal impacts of the historic pumping regime on groundwater levels, hydrographs from selected bores are presented below and the locations of the selected observation bores are presented in Figure 8-1. RN007424 is located to the northwest of the drawdown and RN022296 is located in the central portion of the model domain. The southeast - northwest fault bisecting the study area effectively separates the two areas and the impacts of pumping in the southwest are not observed in the central and northern portions of the study area.

HISTORIC PUMPING IMPACTS COMPARED TO NATURAL CONDITIONS

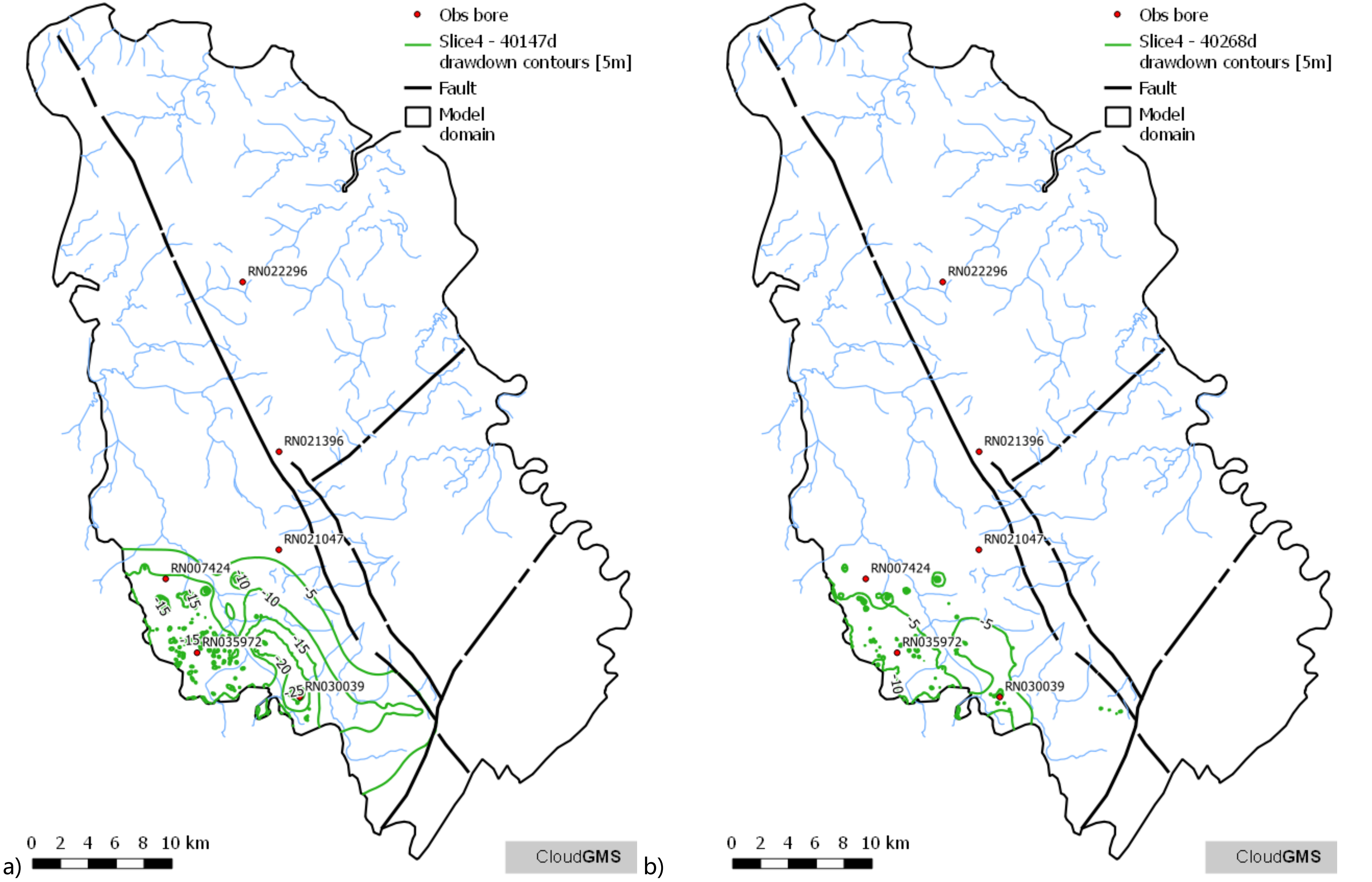
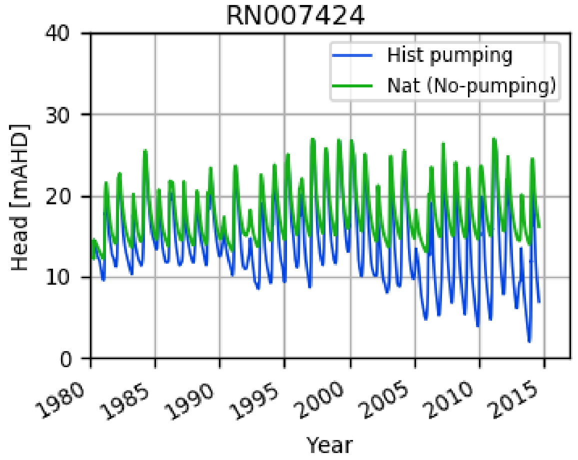


Figure 8-1 Drawdown difference between Nat and Hist scenarios contours at a) 40147d (Nov 2009) and b) 40268d (Mar 2010).

HISTORIC PUMPING IMPACTS COMPARED TO NATURAL CONDITIONS

The hydrographs indicate that the groundwater levels under historic pumping generally rebound to the wet season groundwater levels forecast under the natural scenario. However, there are years where this does not occur, particularly those years subsequent to horticultural enterprise in 1998/1999, where the natural groundwater level is subdued compared to the long-term response (e.g. 2005 & 2013).



a) b)

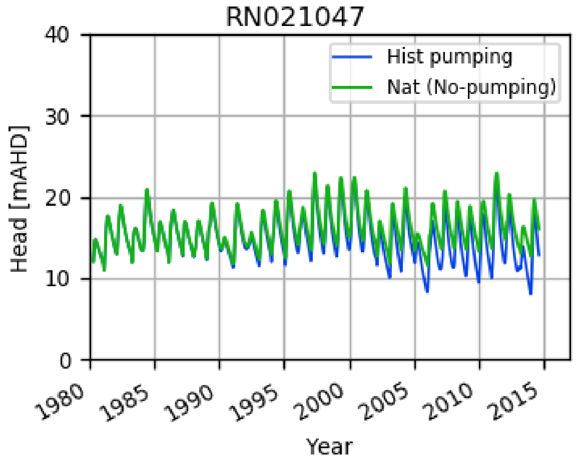
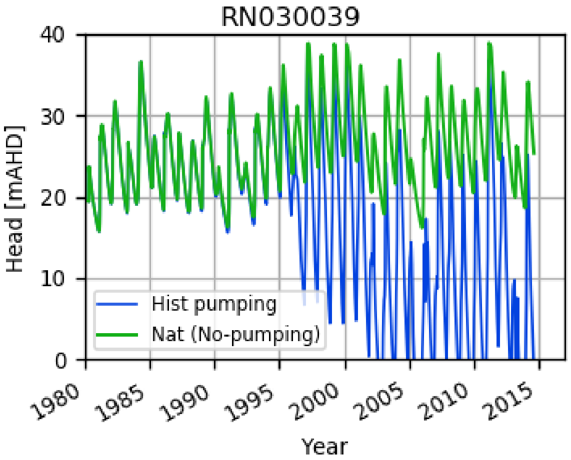
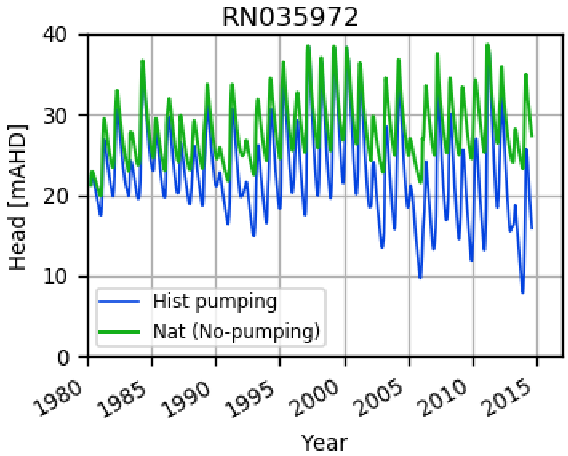


Figure 8-2 Comparison of natural and historic pumping groundwater level hydrographs for a) RN007424 and b) RN021047.

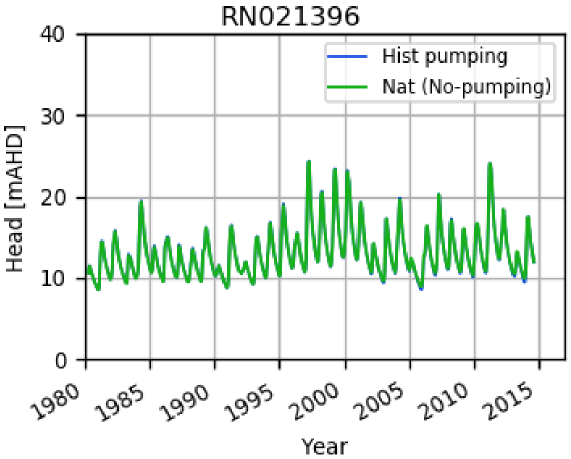


a)



b)

Figure 8-3 Comparison of natural and historic pumping groundwater level hydrographs for a) RN030039 and b) RN035972.



a)

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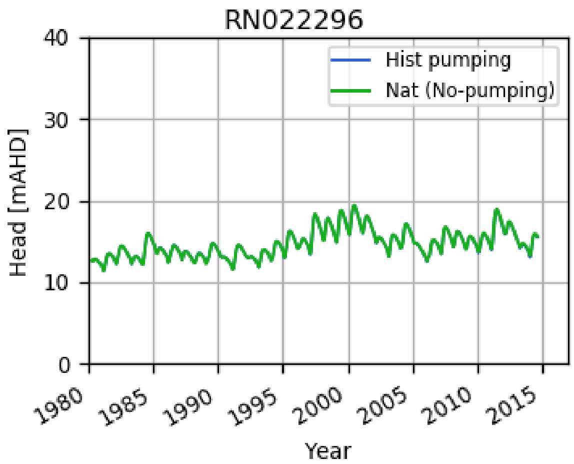

Figure 8-4 Comparison of natural and historic pumping groundwater level hydrographs for a) RN021396 and b) RN022296.

8.3 Stream depletion hydrographs

The impacts of historic pumping on flows at the 3 surface water gauging sites used in the calibration. The results for Howard River (G8150179), Howard Springs (G8155087) and Melacca Creek (G8175079) are presented below in Figure 8-5, Figure 8-6 and Figure 8-7 respectively.

Discharges at show increase in impacts due to pumping over the period of the simulation. Reductions in dry season flows of about 0.02 cumecs (20 L/s) are observed prior to 1990, increasing to about 0.08 cumecs (80 L/s) after 2005.

Discharges at Howard Springs (G8155087) show increase in impacts due to pumping over the period of the simulation. Reductions in dry season flows are limited prior to 1990, increasing to about 0.02 cumecs (20 L/s) after 2005.

The impacts of pumping are not observed at Melacca Creek, this is consistent with the modelled impact on groundwater levels in the northeastern portion of the study area (refer to Figure 8-4 a & b) .

A comparison of modelled natural and historic groundwater levels and dry season discharge suggests that the increase in overall groundwater pumping associated with the expansion of horticultural enterprise in 1998/1999 has resulted in a long-term groundwater storage depletion in the area.

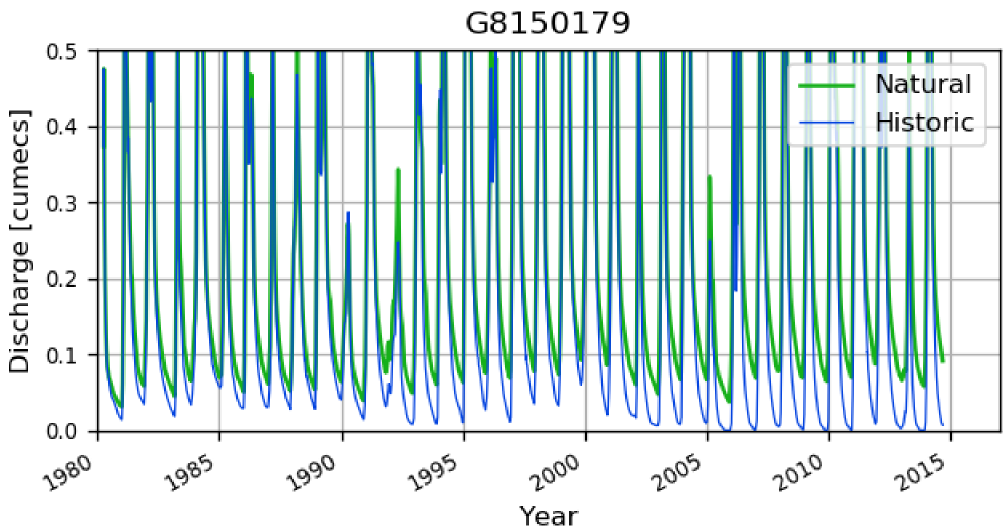

Figure 8-5 Comparison of baseflow at Howard River (G8150179) under natural (no-pumping) and historic pumping.

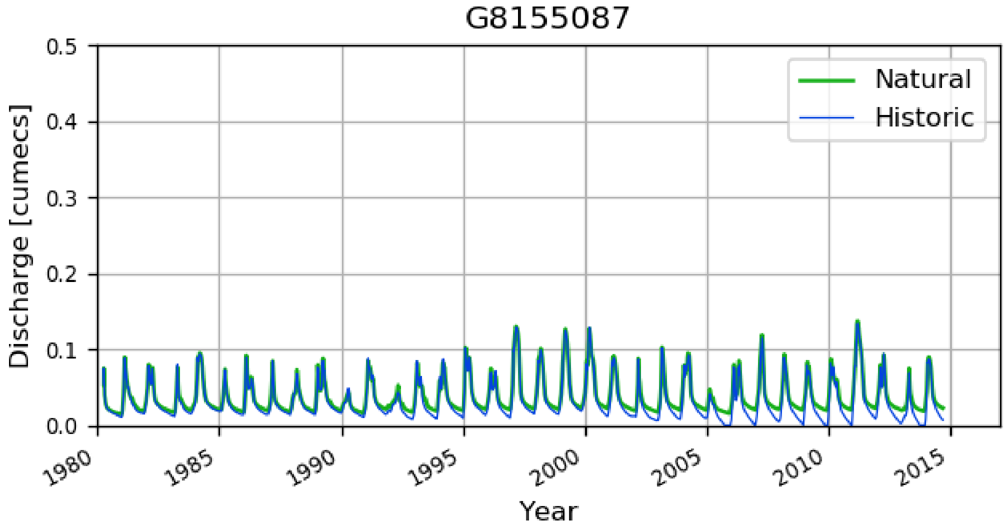

Figure 8-6 Comparison of baseflow at Howard Spring (G8155087) under natural (no-pumping) and historic pumping.

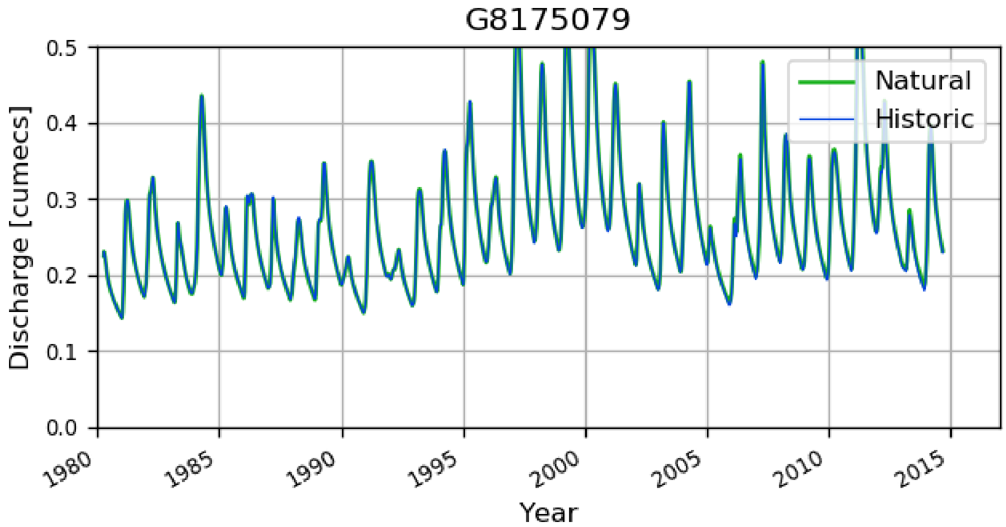

Figure 8-7 Comparison of baseflow at Melacca Creek (G8175079) under natural (no-pumping) and historic pumping.

9 CONCLUSIONS

The groundwater model presented by EHA (2007) has been updated to incorporate additional climatic and pumping data. The model has been calibrated to additional groundwater level and dry season flows.

The model undergoes limited annual assessment as part of the annual allocations process. Annual allocations involves updating recharge and pumping data and forecast dry season groundwater levels and discharges are estimated.

The model is considered suitable for the purposes of assessing the impacts of groundwater development scenarios especially when impacts are assessed in terms of model outputs obtained from calculating differences between two model simulations (e.g. the difference between a stressed and unstressed or natural model) can reduce the predictive uncertainty associated with model outcomes.

The current ground surface elevation in the model is derived from the SRTM elevation data, which compromises the ability of the model to match absolute groundwater levels, especially in areas where surface water / groundwater interactions occur.

Despite this limitation, the calibrated model reproduces the dynamics of the groundwater levels and dry season discharges.

A comparison of natural and historic groundwater levels suggests that the increase in overall groundwater pumping associated with the expansion of horticultural enterprise in 1998/1999 has resulted in a long-term groundwater storage depletion in the area.

Faults incorporated into the updated groundwater model control groundwater flow and appear to compartmentalise the model domain into zones. The degree to which the fault features separate the various zones, however, should be investigated further as these features will determine if saline intrusion will become an issue.

10 RECOMMENDATIONS

Accurate definition of the ground surface elevation is an important factor when modelling surface water / groundwater interactions. The current ground surface elevation in the model is derived from the SRTM elevation data, which in areas where vegetation is sparse or of limited height has errors of 4-5 metres. In areas where vegetation is dense the SRTM elevations reflect the elevation of the vegetation instead of the ground surface. It is suggested that if an opportunity arises that a LIght Detection And Ranging (LIDAR) survey be completed over the groundwater management area encompassing the Koolpinyah Groundwater System to obtain accurate groundwater elevation data.

It should be noted that subsequent to the undertaking of this study additional processing of the SRTM have become publically available. One such dataset is the National Digital Elevation Model (DEM) 1 Second Hydrologically Enforced product, derived from the National DEM SRTM 1 Second and National Watercourses, lakes and Reservoirs (http://www.ga.gov.au/elvis/). It is recommended that this dataset be used in future modelling studies if the LiDAR surveys have not been completed.

11 REFERENCES

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APPENDIX A MIKE SHE 1D RECHARGE MODELLING

A.1 Introduction

Seasonal changes in soil and atmospheric water content mainly control the areal flux as groundwater recharge to the aquifer, evaporation from the water table and evapotranspiration from vegetation. The soil water content and the ability of the soil to conduct water and the characteristics of vegetation influence the areal flow processes.

Vegetation of the study area is a mosaic of Eucalypt-dominated woodlands, open forests, closed forests, seasonally flooded swamps and wetlands (Hutley, et al., 2000).

Soils within the study area are extensively weathered and lateritised, weakly acidic and low in nutrient status and derived from the Koolpinyah surface, a late Tertiary 30 – 40 m deep sediment mantle extending from the Darwin region to the Arnhem escarpment of Kakadu National Park (Hutley et al. 2000). Storage properties of these soils are poor with only 0.08 cm^3 cm^{-3} released between field capacity and wilting point (Cook, et al., 1998) and these soils overlie a surface aquifer (Laterite Formation) with the water table rising to within 2 m of the ground surface during the wet season.

Cooperative Research Centre for the Sustainable Development of Tropical Savannas, Darwin carried out a series of experiments during 1996-98 in the Howard Springs area to estimate annual evapotranspiration from Eucalypt open-forest (Hutley, et al., 2000). They used three independent methods (eddy covariance, heat pulse and open-top chambers) to estimate the seasonal evapotranspiration from the wet-dry Eucalypt savannas of the study area. Total annual dry-canopy water loss was estimated to be 870 mm and understorey evapotranspiration contributed 557 mm to this flux.

A.2 MIKESHE software

With the above limited information, seasonal changes in soil water content in the upper soil horizon (1.5 m thickness) were simulated using a MIKE SHE (Graham & Butts, 2005) catchment model. The model simulation is performed on a daily time-step using rainfall, pan evaporation, leaf area index and rooting depth for different stages of plant growth.

MIKESHE covers the major processes in the hydrologic cycle and includes process models for overland flow, evapotranspiration, unsaturated flow and groundwater flow, and their interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the modelling study, the availability of field data and the modeller's choices, (Graham & Butts, 2005).

APPENDIX A

MIKESHE was employed because it has the scope to model processes in the soil and incorporate direct recharge due to macro-pores, which are considered an important recharge mechanism. The main purpose of the MIKESHE model was to provide an estimate of the actual evapotranspiration (for comparison with previous studies) and the amount of water that recharges the saturated zone.

The MIKE SHE unsaturated flow module used the Gravity Flow module which for a 1D soil profile provides fast execution times and requires a vertical discretisation of the soil profile. The simplified gravity flow assumes a uniform vertical gradient and ignores capillary forces and provides a suitable solution when the primary interested is in the time varying recharge to the groundwater table based on actual precipitation and evapotranspiration and not the dynamics in the unsaturated zone.

The simplified ET module includes the processes of interception, ponding and evapotranspiration. The UZ/ET model divides the unsaturated zone into a root zone, from which ET can occur and a zone below the root zone, where ET does not occur. The conceptualisation of the unsaturated module is presented below in Figure A-1.

The input for the model includes the characterisation of the vegetation cover and basic physical soil properties. The vegetation is described in terms of leaf area index (LAI) and root depth. The soil properties include a constant infiltration capacity and the soil moisture contents at the wilting point (θwp), field capacity (θfc) and saturation (θsat).

The model produces a simulated time series of vegetation use, run-off from the soil surface and recharge to the aquifer.

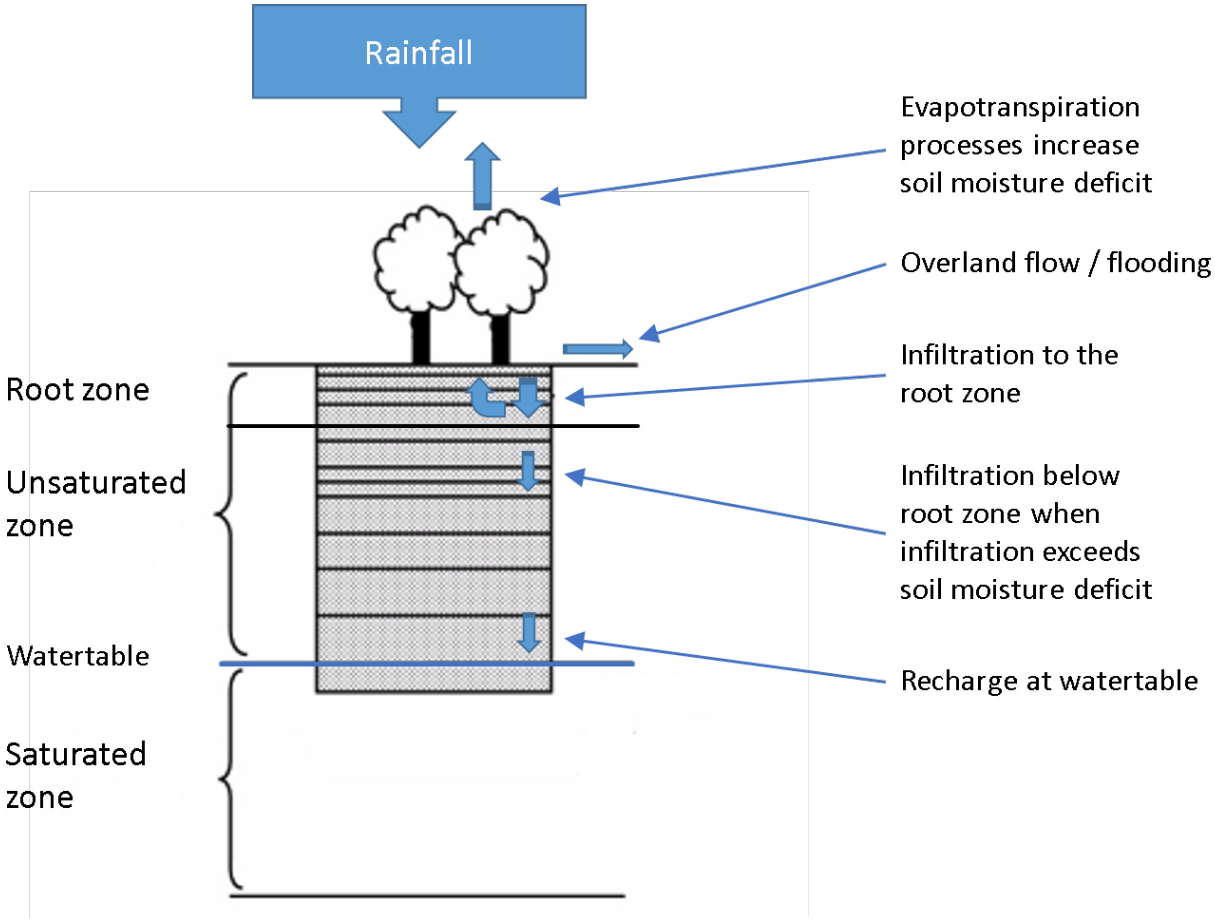


Figure A-1 Processes relevant to determination of recharge to the Koolpinyah Groundwater System.

A.3 MIKE SHE model setup

The MIKE SHE model determines recharge to both the interflow component and to the deeper groundwater component.

The Darwin River sub-catchment upstream of G8150179 has an area of 154.5 km^2.

The MIKE SHE model was developed with the following modules implemented.

- Overland flow – (Subcatchment Based)
- Evapotranspiration
- Unsaturated zone (Gravity Flow)
- Saturated zone (Linear Reservoir Storages)

The MIKE SHE results are consistent with both the Cook et al, (1998) water balance estimate and the EHA, (2007) recharge estimates for the Darwin River sub-catchment.

A.4 Overland flow

Overland flow was simulated using the subcatchment based lumped parameter method. The parameters used to describe the overland flow processes are presented below in Table A-1.

Table A-1 Overland flow parameters

Parameter	**Value**	**Unit**
Slope	0.001	[-]
Slope length	1000	[m]
Manning number	25	[$m^{1/3}$/s]
Initial depth	0	[mm]

A.5 Unsaturated zone

The unsaturated zone has been modelled using the MIKESHE gravity flow module. The simplified gravity flow procedure assumes a uniform vertical gradient and ignores capillary forces. The simplified gravity flow procedure provides a suitable solution when the primary interested is in the time varying recharge to the groundwater table based on actual precipitation and evapotranspiration and not the dynamics in the unsaturated zone.

The Governing Equation for the unsaturated flow using the simplified gravity flow procedure requires information about two hydraulic functions with respect to water content (θ); the hydraulic conductivity function, K(θ), and the soil moisture retention curve $\psi(\theta)$.

There are four principal parameters that must be defined for each soil type when using the gravity method:

- Soil water content at saturation (θs) - this is the maximum water content of the soil, which is approximately equal to the porosity;
- pFfc - This is the suction pressure of a soil when it is at field capacity. The pFfc (field capacity) is used as the initial condition in the unsaturated flow module. A typical value is about 2.0. The corresponding soil water content at field capacity (θfc) is the water content at which vertical flow becomes negligible. In practice, this is the water content that is reached when the soil can freely drain.
- pFw - This is the suction pressure of the soil when it is at the wilting point. The pFw (wilting) is typically about 4.2. The corresponding soil water content at the field wilting point (θw) is the lowest water content that plants can extract water from the soil.

- Saturated hydraulic conductivity (Ksat) - this is the saturated hydraulic conductivity of the soil.

UZ Hydraulic conductivity function

The hydraulic conductivity decreases strongly as the moisture content θ decreases from saturation. This is not surprising since the total cross-sectional area for the flow decreases as the pores are filled with air. In addition, when a smaller part of the pore system is available to carry the flow, the flow paths will become more tortuous.

Given that there is no data to define the water content and hydraulic conductivity relationship the Averjanov hydraulic conductivity relationship was chosen because only a single parameter is required.

In the Averjanov method, the hydraulic conductivity, K, is described as a function of the effective saturation (Se).

$$K_{(E)} = K_{sat}(S_e)^n$$

where

$$S_e = \frac{(\theta - \theta r)}{(\theta s - \theta r)}$$

θs θ and θr are saturated, actual and residual moisture contents, respectively.

The full knowledge about the hydraulic conductivity function is seldom available, however, the exponent n is usually small (2-5) for sandy soils and large (10-20) for clayey soils (DHI, 2016). In this context a value of 4 was selected for this study.

Table A-2 Averjanov unsaturated hydraulic conductivity parameters.

Parameter	Value	Unit
Hydraulic conductivity θs	1.9e-7	[m/s]
n	4	[-]
Saturated moisture content (θs)	0.28	[-]
Residual moisture content (θr)	0.05	[-]

UZ Soil moisture retention curves

The relationship between the water content, θ, and the matric potential, ψ, is known as the soil moisture retention curve, which is basically a function of the texture and structure of the soil. Similar to hydraulic conductivity, the pressure head decreases rapidly as the moisture content decreases.

The van Genuchten formula is the most widely used soil moisture-pressure relationship and has been adopted in this study.

$$\theta(\psi) = \theta_r + \frac{\theta s - \theta r}{[1 + (\alpha|\psi|)^n]^{1-\frac{1}{n}}}$$

θs and θr are saturated and residual moisture contents, respectively.

α = is related to the inverse of the air entry suction

n = is a measure of the pore-size distribution.

The UZ gravity module employs a pF log scale for representing soil matric potential. Thus,

$pF = \log_{10}(-100\psi)$

where ψ is the matric potential in metres of water and ψ is always negative under unsaturated conditions.

The adopted soil moisture retention parameters are presented below in Table A-3.

Table A-3 Unsaturated soil moisture retention parameters.

Parameter	**Value**	**Unit**
Saturated moisture content (θs)	0.399	[-]
Residual moisture content (θr)	0.06	[-]
Alpha (α) = is related to the inverse of the air entry suction	0.0111	[-]
N= is a measure of the pore-size distribution	1.472	[-]
pFfc = field capacity	2.27	[-]
pFw = wilting point	4	[-]

A.6 Simplified macro-pore flow (bypass flow)

Flow through macro-pores in unsaturated soil is important for many soil types. In the Gravity module, a simple empirical function is used to describe this process. The infiltration water is divided into one part that flows through the soil matrix and another part, which is routed directly to the groundwater table (bypass flow).

The bypass flow is calculated as a fraction of the net rainfall for each UZ time step. The actual bypass fraction is a function of a user-specified maximum fraction and the actual water content of the unsaturated zone, assuming that macro-pore flow occurs primarily in wet conditions. The macro-pore bypass constants were determined through trial and error and are presented below in Table A-4.

Table A-4 Macro pore bypass constants

Parameter	Value	Unit
Maximum bypass fraction	0.75	[-]
Water content for reduced bypass flow	0.39	[-]
Limit on water content for bypass flow	0.22	[-]

A.7 Vegetation data

Leaf area index (LAI) is the amount of leaf area directly above a square metre of ground. The vegetation of the area consisted of a mosaic of eucalypt-dominated woodlands, open forests, closed forests, seasonally flooded swamps and wetlands. In the Howard River catchment, eucalypt open-forest dominates. And the LAI of open woodland is likely to be in the range of 0.65 – 2.1 m2 leaf per m2 ground (Hutley, 2000). Given that much of the study area is savannah the leaf area index (LAI) was assumed to vary from between 2.1 during the wet season when ET from grasses dominate and 0.65 during the dry season when the ET is dominated by transpiration from trees. These assumptions are based on savannah water use in the Howard East region (Hatton et al., 1997; O'Grady et al., 2000; (Hutley, et al., 2001).

Kelley et al, (2002) presented analysis of soil water dynamics of the upper 4 m of soil it was concluded that it is unlikely that trees of the eucalypt open forest utilise groundwater to maintain dry season transpiration. During the wet season, changes in soil water store suggest that both overstorey and understorey vegetation used water in soil above a laterite duricrust layer at 1.2 m.

Following the cessation of wet season rains, soil water store in the upper soil was sufficient to maintain understorey transpiration for several weeks. Trees used water from both above and below the duricrust layer during the dry season and exclusively from soil below the duricrust by the end of the 1999 dry season. Change in soil water store to 4 m accounted for around 75% of late dry season transpiration. 100% of transpiration can be accounted for if rooting depth is set to 5 m.

The temporal distribution of the LAI was generated using the simple soil moisture deficit (SMD) model to determine available soil water for shallow rooted (<1500 mm) annual vegetation such as grasses. During the wet season the soil moisture deficit is less than 130 mm and the grasses and deep rooted vegetation are expected to be able to access the soil water and a corresponding leaf area index of 2.1 is assigned. As the year moves into the dry season the soil moisture deficit becomes greater than 130 mm and the soil in the upper 1500 mm water is unavailable to grasses and only deeper rooted vegetation continue to transpire with a corresponding LAI of 0.65. The time series plot of LAI for the period 01/01/1900 – 01/09/2014 is presented below along with root depth employed in the model. It was assumed that the total root depth of was 6000 mm.

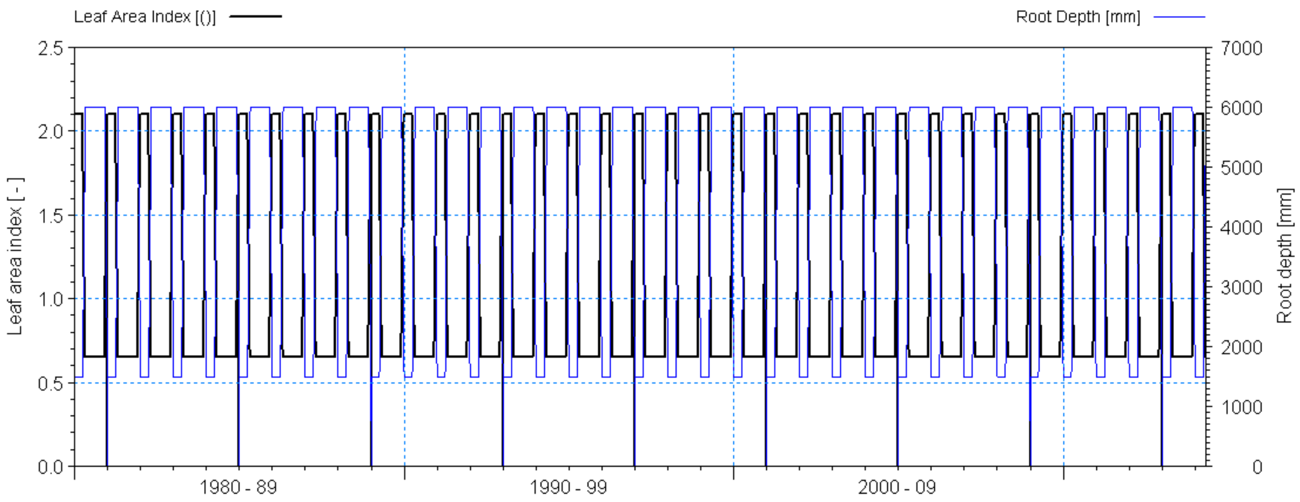


Figure A-2 MIKESHE leaf area index and root depth time series inputs.

A.8 Saturated zone

The saturated zone (interflow and baseflow) is simulated using the linear reservoir method available in MIKE SHE (DHI, 2012). The linear reservoir is an alternative to the physically based, fully distributed model approach and may be viewed as a compromise between the complexity of hydrological response and the advantages of model simplicity and their associated run times.

A linear reservoir is one whose storage is linearly related to the output by a storage constant with the dimension time, also referred to as a time constant.

APPENDIX A

In the case of the Koolpinyah Groundwater System 1D recharge model a linear reservoir is used for the interflow component, and the baseflow. The interflow reservoir parameters are presented below in Table A-5. The baseflow1 and baseflow2 reservoir parameters are presented below in Table A-6.

Table A-5 Interflow reservoir parameters.

Parameter	Value	Unit
Specific yield	0.03	[-]
Initial depth	5	[m]
Bottom depth	10	[m]
Interflow time constant	450	[d]
Percolation time constant	2500	[d]
Threshold depth	10	[m]

Table A-6 Baseflow1 & baseflow2 reservoir parameters.

Parameter	Baseflow1 Value	Baseflow2 Value	Unit
Specific yield	0.01	0.01	[-]
Time constant for baseflow	6000	11000	[d]
Dead storage fraction	0	0	[m]
UZ feedback fraction	0.5	0.5	[-]
Initial depth	25	30	[m]
Threshold depth for baseflow	25	30	[m]
Threshold depth for baseflow	25	30	[m]
Depth to bottom of the reservoir	25	30	[m]
Groundwater table for lower UZ boundary	-10	-10	[mBGL]

A.9 Recharge estimate

The modelled recharge to the saturated zone was determined using the MIKE SHE water balance tool and is presented below in **Error! Reference source not found.** as daily storage depth in mm and as cumulative storage depth in mm. The total recharge over the simulation period of 54 years is 17436mm resulting in an average annual recharge of 321mm.

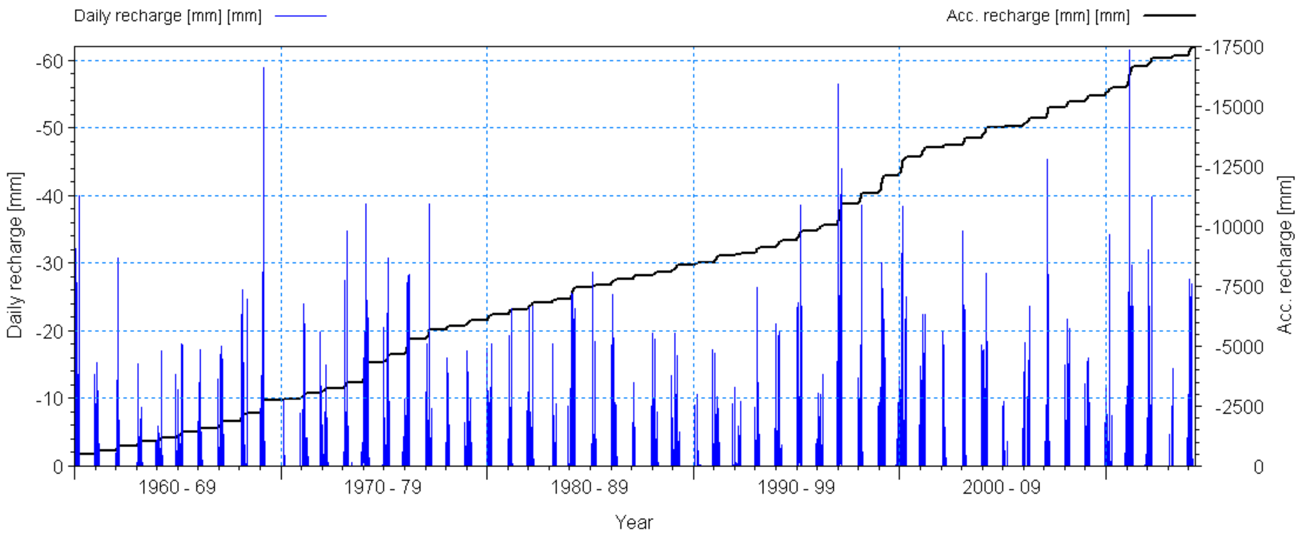


Figure A-3 Daily recharge and cumulative recharge determined from the MIKESHE recharge model.

A.10 River discharge estimate

The comparison of the MIKE SHE generated surface flows and the continuous recorded for G8150179 are presented in Figure A-4.

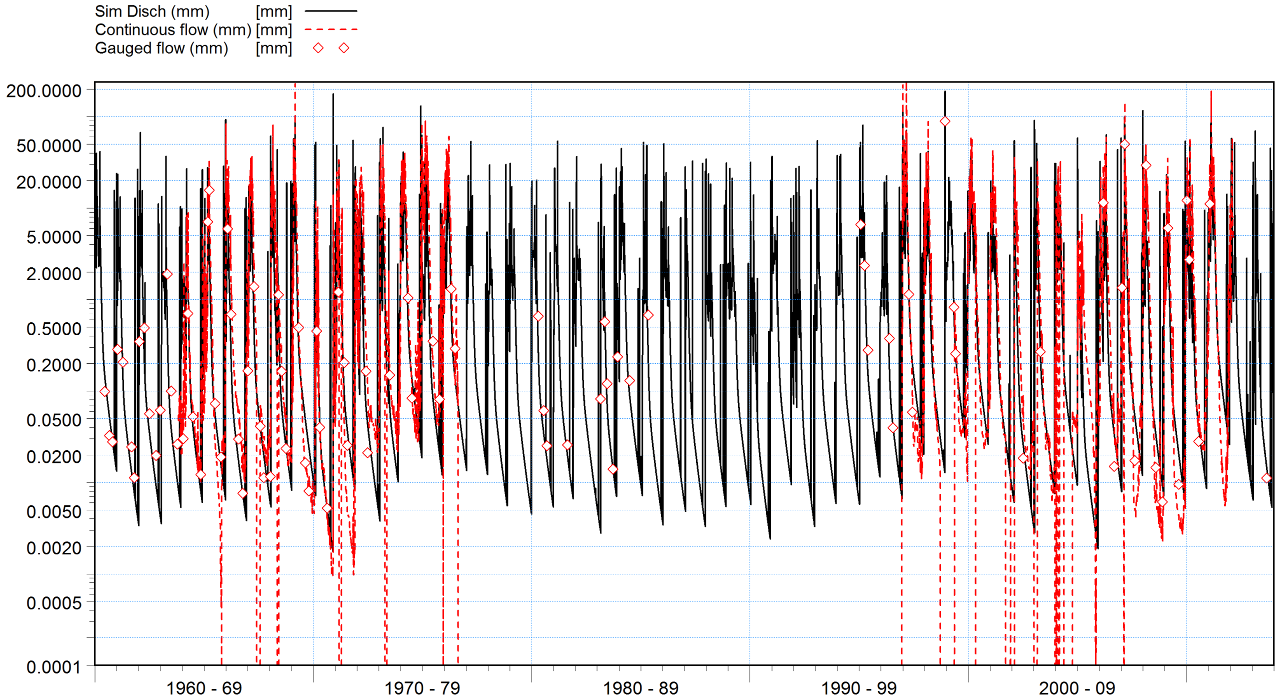


Figure A-4 Simulated MIKE SHE discharge at G8150179 compared to available continuous recorder and gauge data for G8150179 on Howard River.

A.11 Water budget

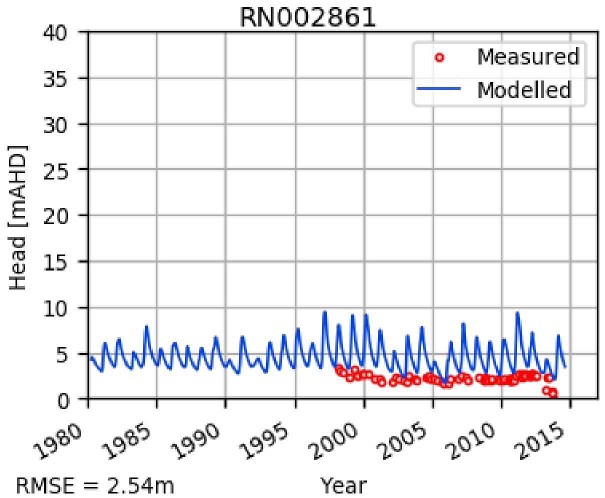
Cook et al, (1998) provided a water balance estimate for the Howard River catchment. The recharge is estimated at 180 mm/yr but there is also the runoff / inter flow component estimated at 410 mm/yr. Recharge to the laterite and dolostone aquifer system could therefore be between 180 mm/yr (0.5 mm/d) and 590 mm/yr (1.6 mm/d).

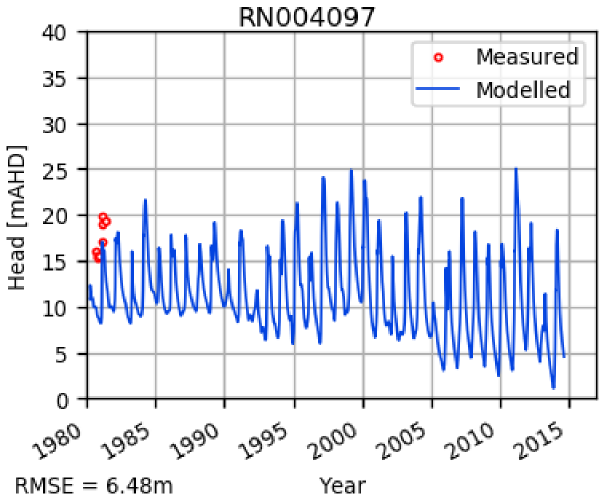
The total water budget for the MIKE SHE model is presented in Table A-7.

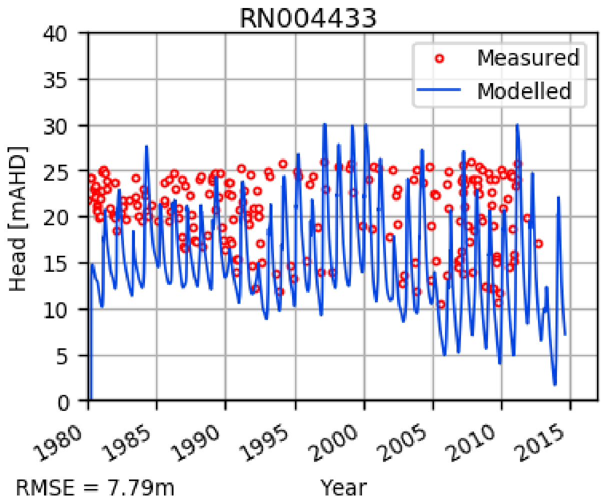
Table A-7 Water balance components determined from MIKE SHE modelling.

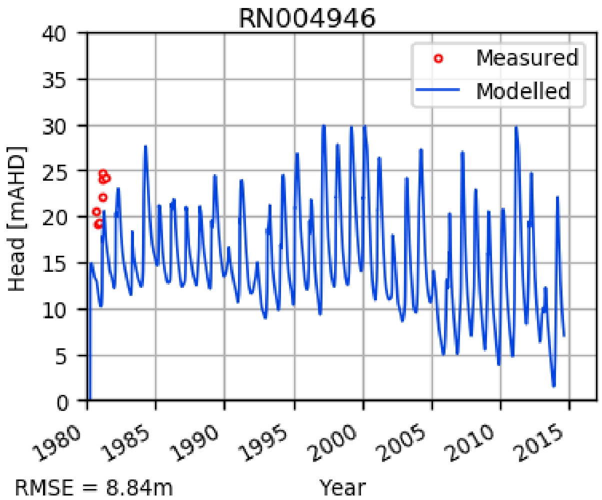
Component	Storage depth (mm) 54yrs	Storage depth (mm/yr)	Volume (GL/yr)
Inflows			
Rainfall	90634	1678	317.219
Outflows			
Evapotranspiration	63565	1445	222.478
Overland flows	10809	246	37.8312
Interflow & baseflow	15060	342	52.710

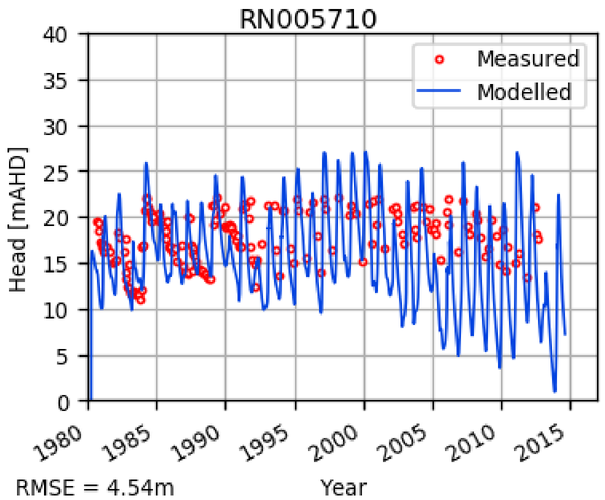
APPENDIX B GROUNDWATER LEVEL HYDROGRAPHS

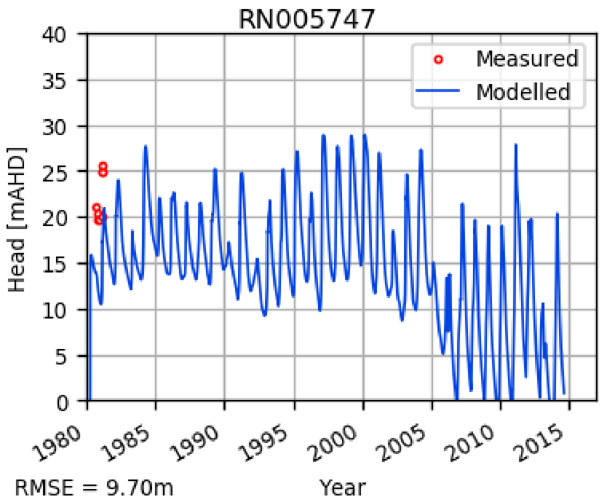




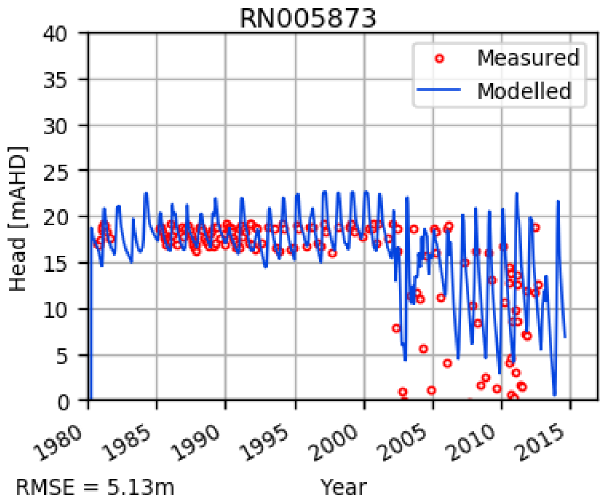








APPENDIX B


RN005873
Measured
Modelled
Head [mAHD]
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1980
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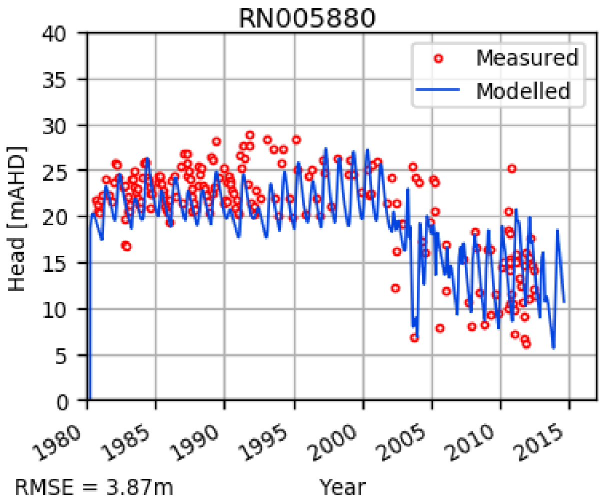
2000
2005
2010
2015
RMSE = 5.13m
Year


RN005880
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RMSE = 3.87m
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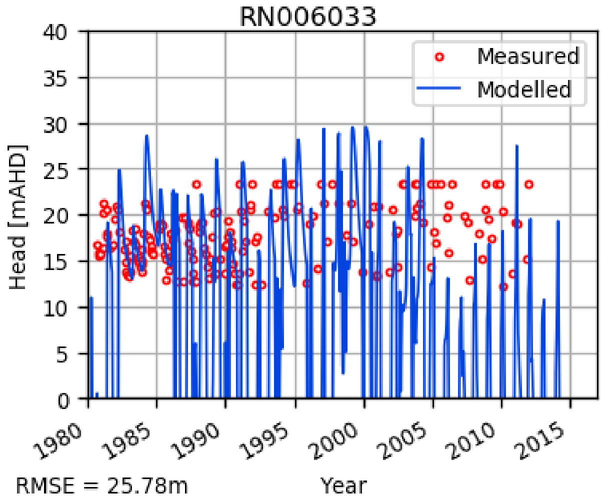
RN006033
Measured
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Head [mAHD]
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1980
1985
1990
1995
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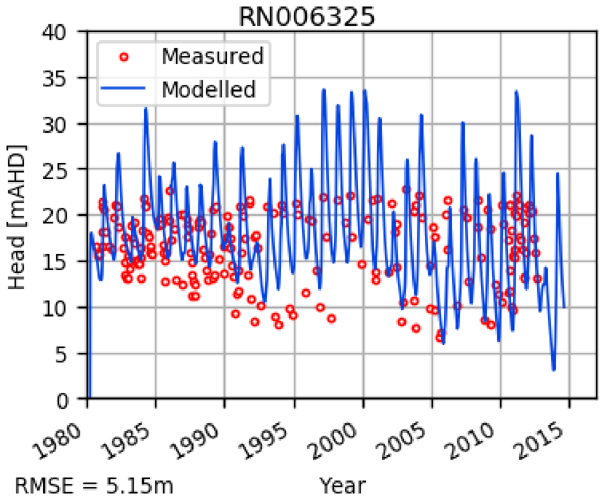
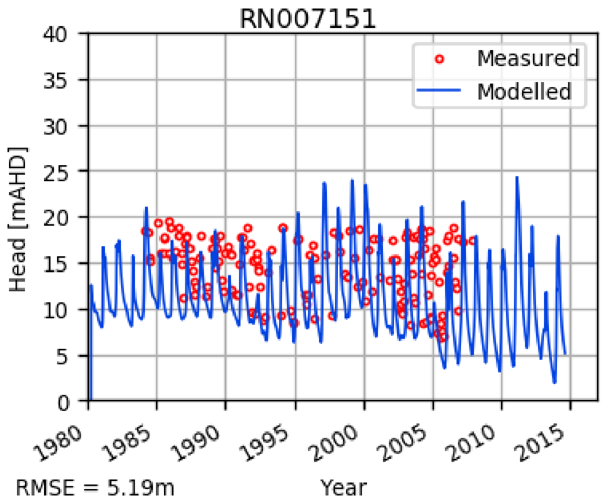
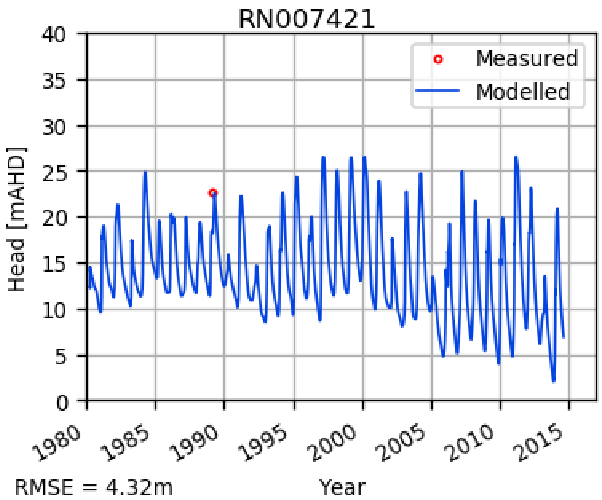
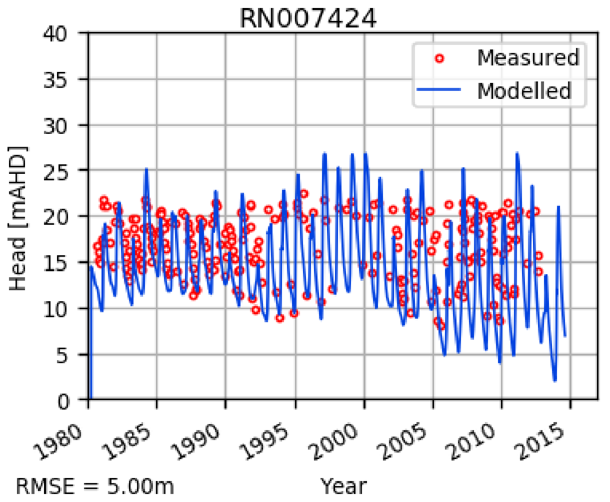
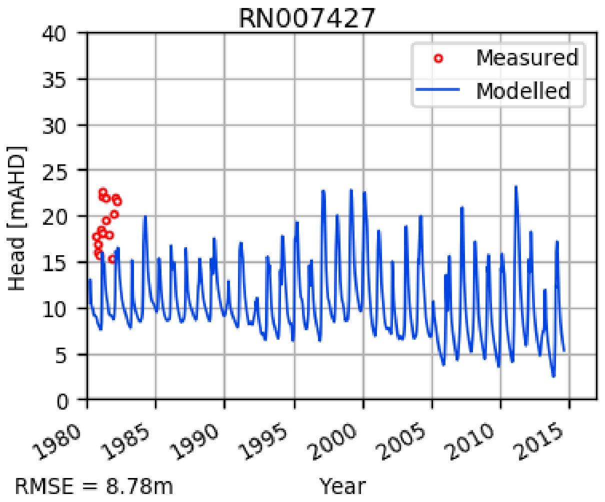
2005
2010
2015
RMSE = 25.78m
Year

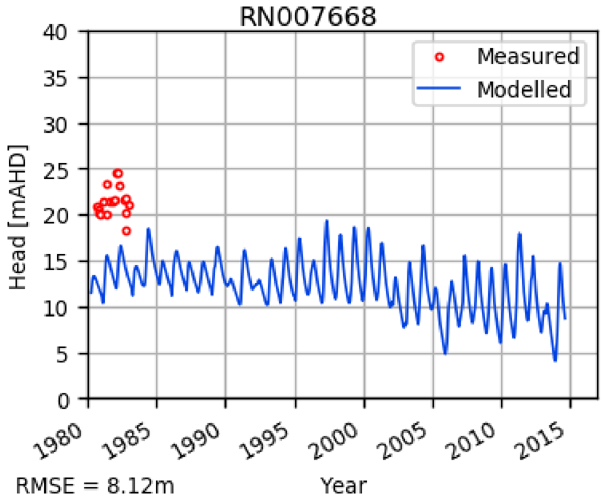

RN006325
Measured
Modelled
Head [mAHD]
40
35
30
25
20
15
10
5
0
1980
1985
1990
1995
2000
2005
2010
2015
RMSE = 5.15m
Year

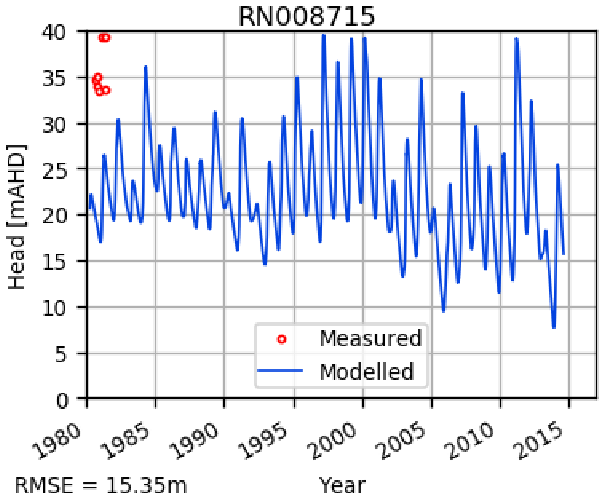

RN007151
Measured
Modelled
Head [mAHD]
40
35
30
25
20
15
10
5
0
1980
1985
1990
1995
2000
2005
2010
2015
RMSE = 5.19m
Year

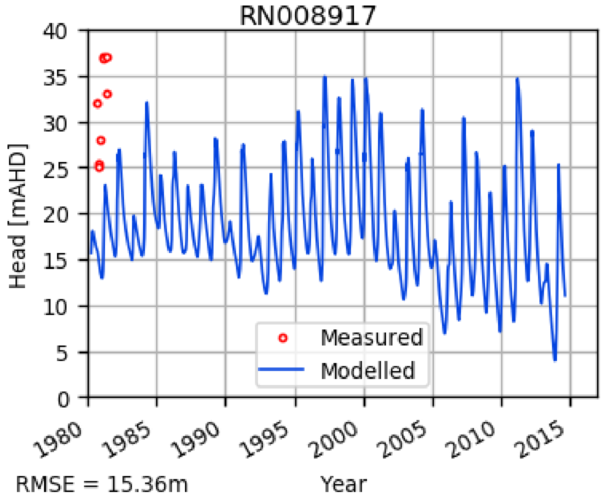

RN007421
Measured
Modelled
Head [mAHD]
40
35
30
25
20
15
10
5
0
1980
1985
1990
1995
2000
2005
2010
2015
RMSE = 4.32m
Year

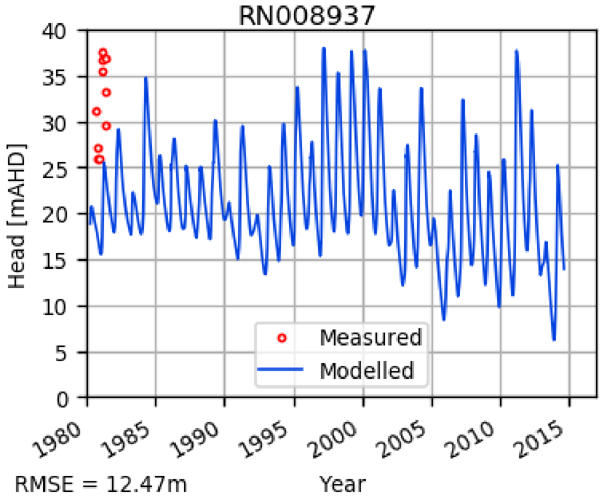

RN007424
Measured
Modelled
Head [mAHD]
0
5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 5.00m

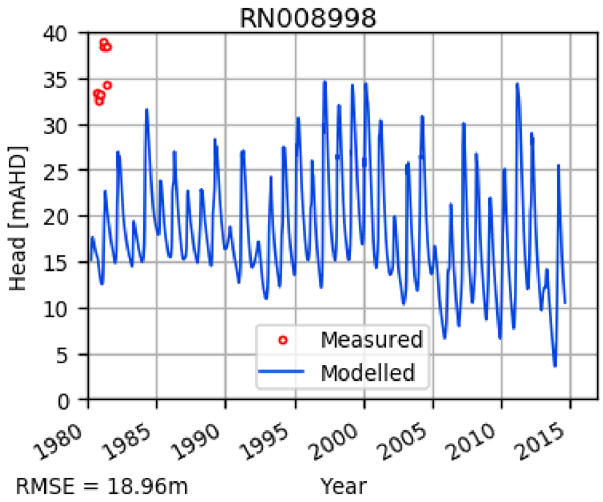

RN007427
Measured
Modelled
Head [mAHD]
0
5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 8.78m

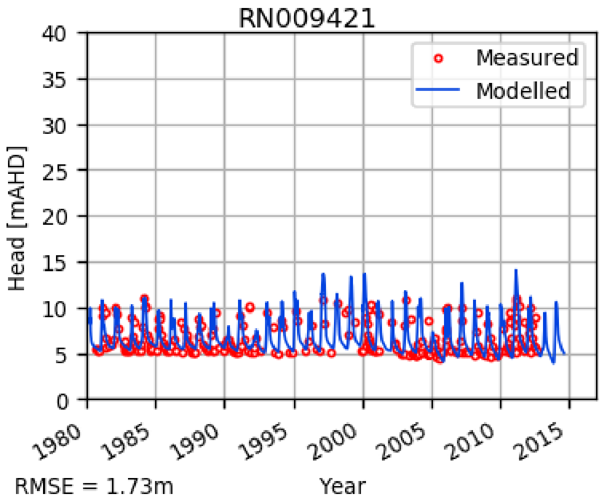

RN007668
Measured
Modelled
Head [mAHD]
0
5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 8.12m

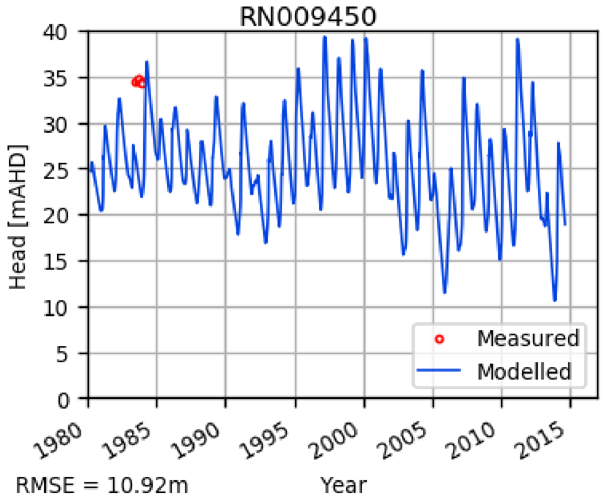

RN008715
Measured
Modelled
Head [mAHD]
0
5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 15.35m

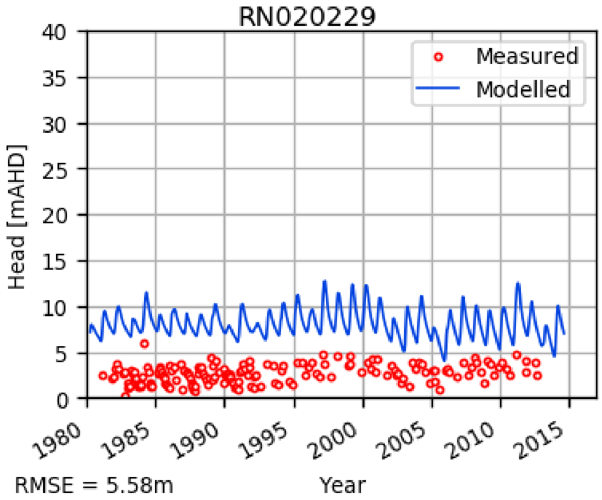

RN008917
Measured
Modelled
Head [mAHD]
0
5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 15.36m

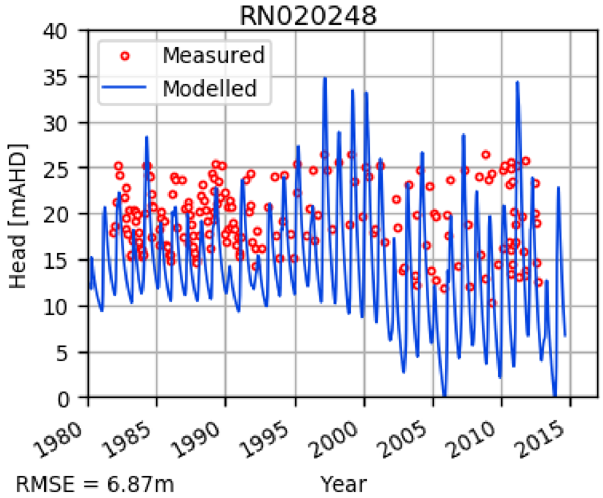

RN008937
Measured
Modelled
Head [mAHD]
0
5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 12.47m

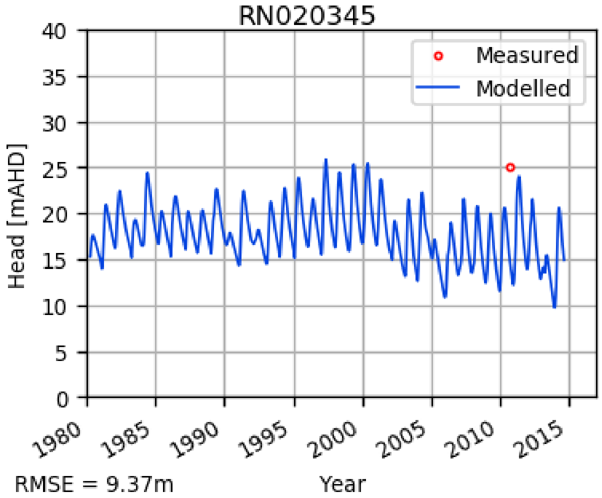

RN008998
Head [mAHD]
Measured
Modelled
Year
RMSE = 18.96m

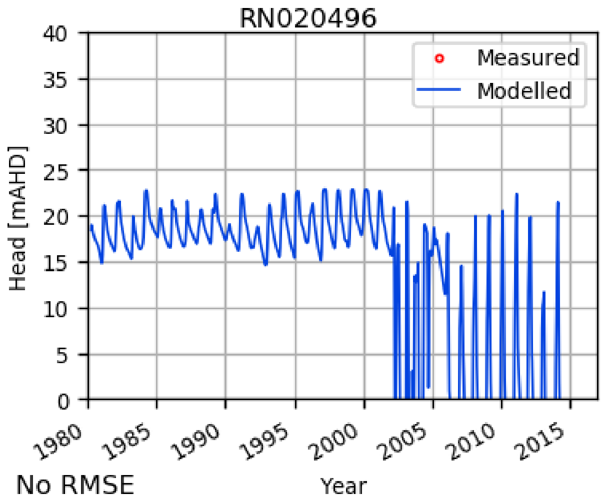

RN009421
Head [mAHD]
Measured
Modelled
Year
RMSE = 1.73m

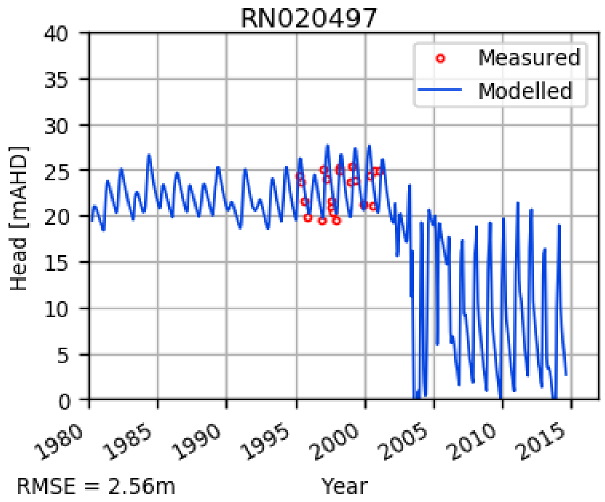

RN009450
Head [mAHD]
Measured
Modelled
Year
RMSE = 10.92m

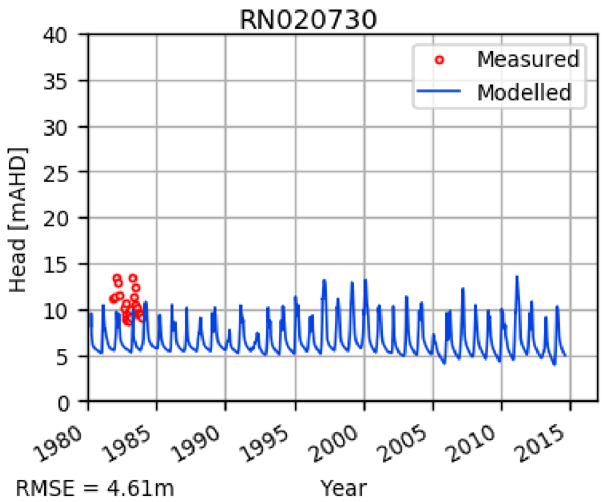

RN020229
Head [mAHD]
Measured
Modelled
Year
RMSE = 5.58m

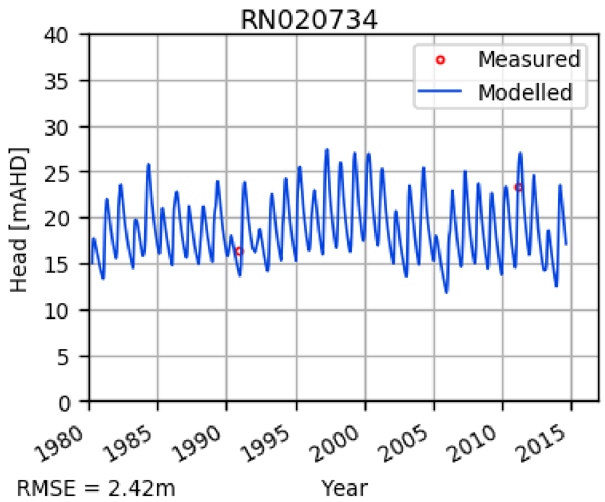

RN020248
Head [mAHD]
Measured
Modelled
Year
RMSE = 6.87m

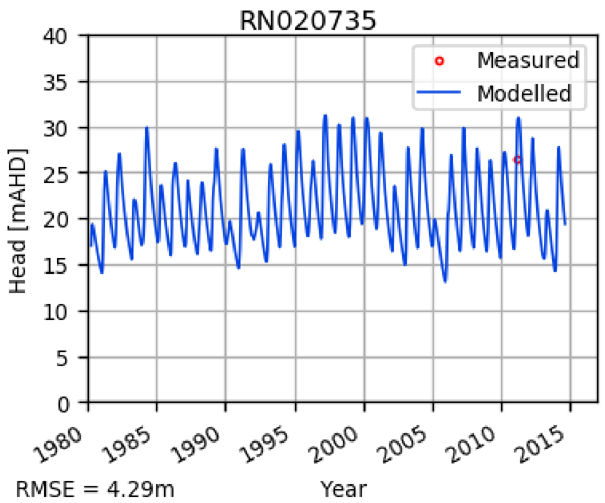

RN020345
Head [mAHD]
Measured
Modelled
Year
RMSE = 9.37m

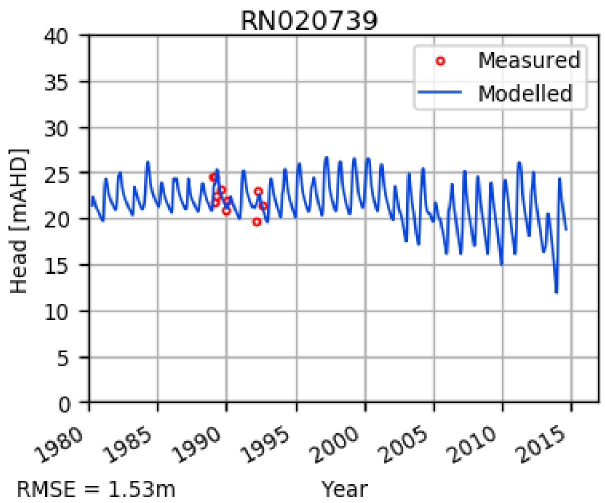

RN020496
Measured
Modelled
Head [mAHD]
Year
No RMSE


RN020497
Measured
Modelled
Head [mAHD]
Year
RMSE = 2.56m


RN020730
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.61m


RN020734
Measured
Modelled
Head [mAHD]
Year
RMSE = 2.42m


RN020735
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.29m


RN020739
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.53m

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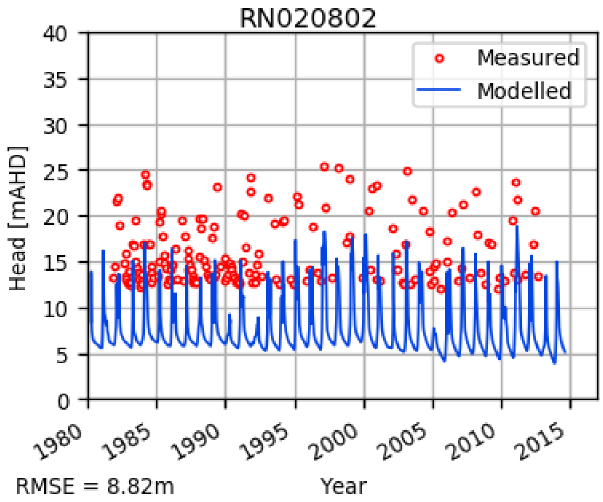
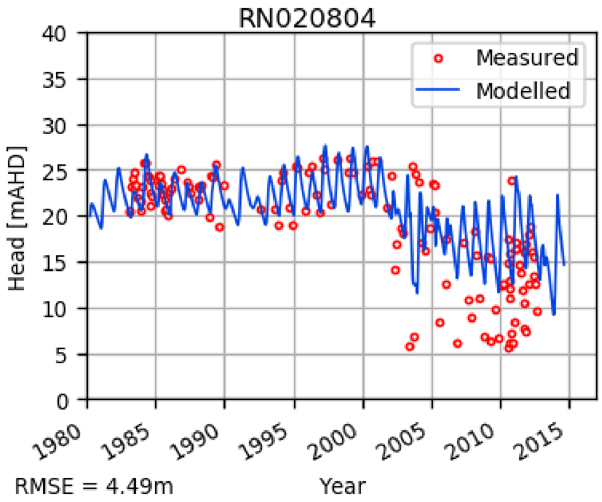
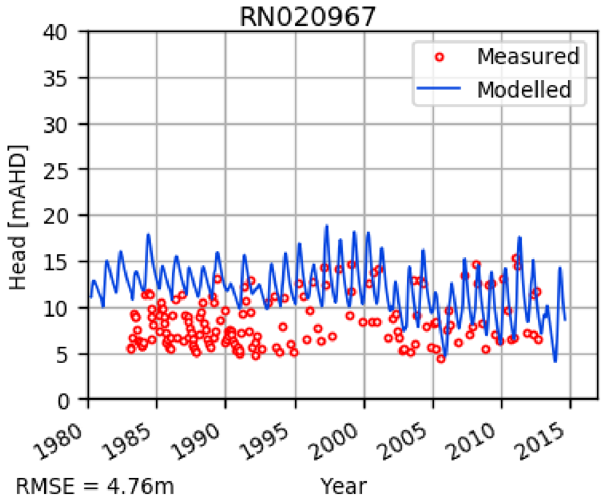
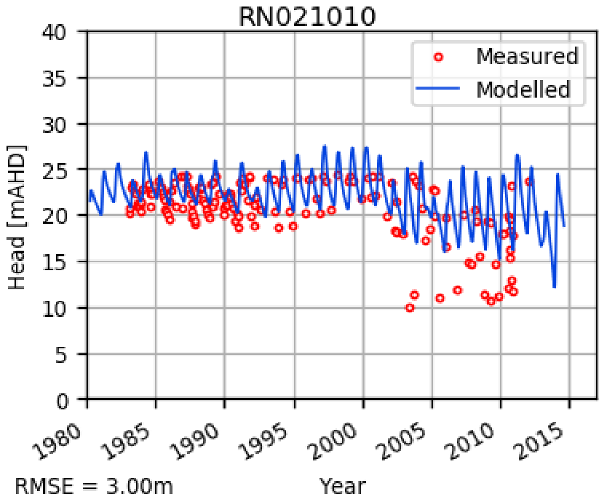
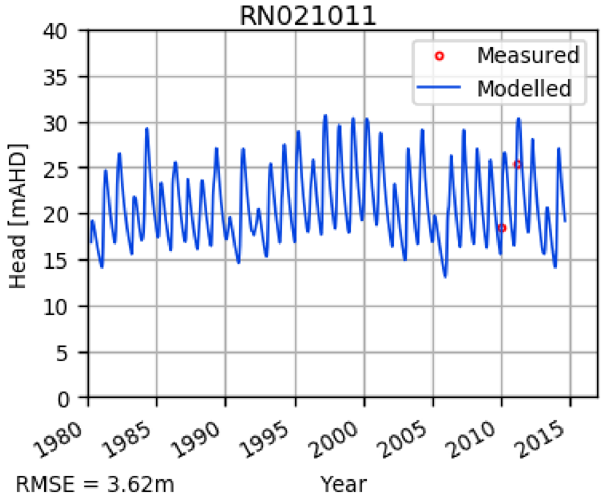
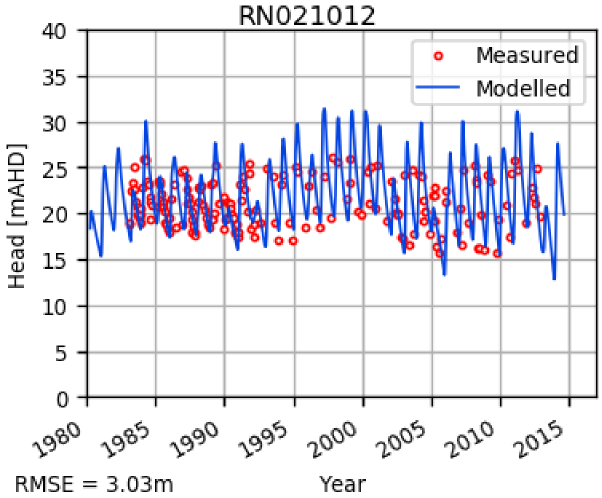

RN020802
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 8.82m
Year


RN020804
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 4.49m
Year


RN020967
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 4.76m
Year


RN021010
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 3.00m
Year


RN021011
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 3.62m
Year


RN021012
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 3.03m
Year

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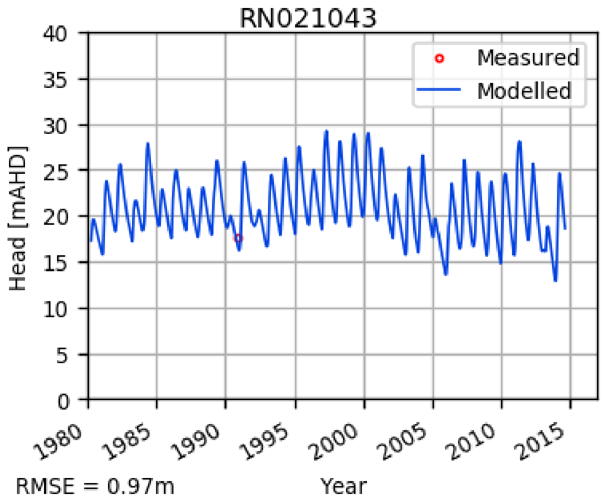
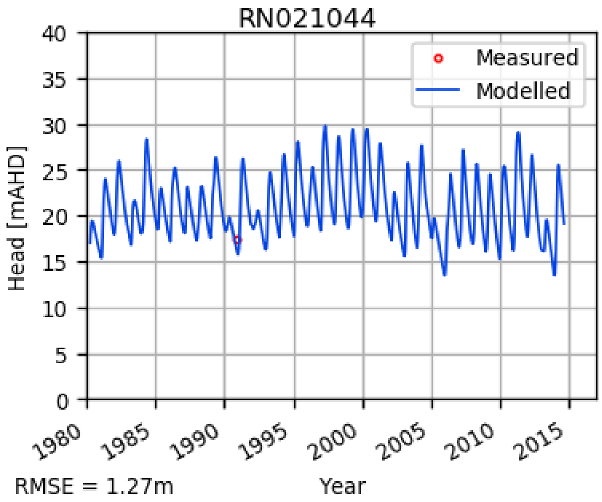
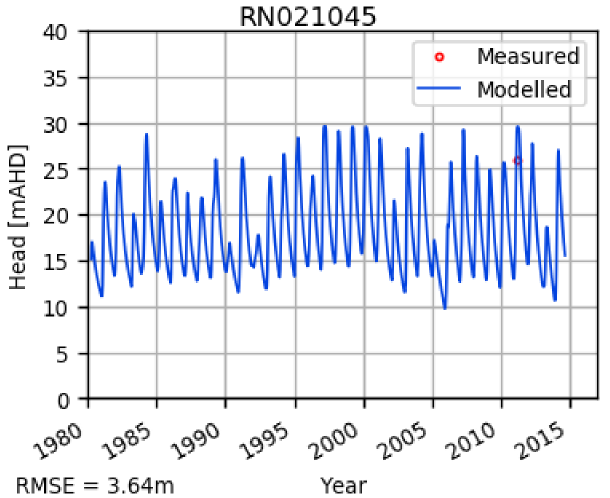
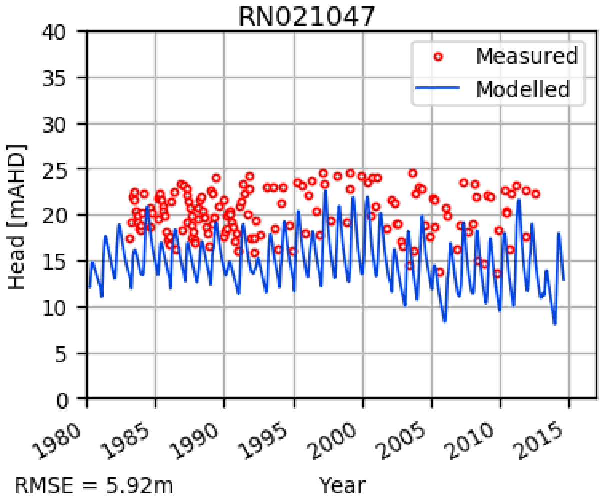
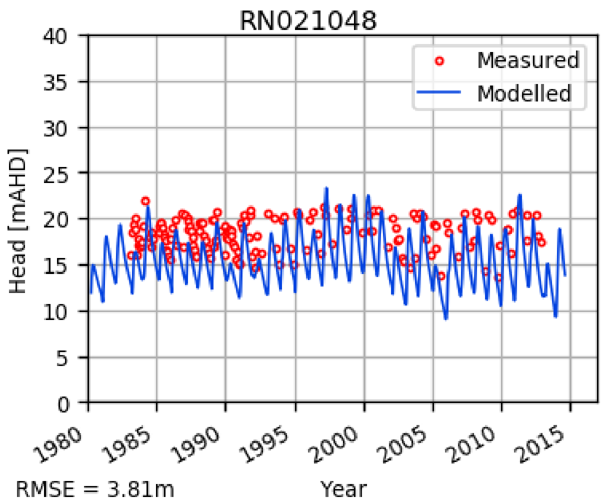
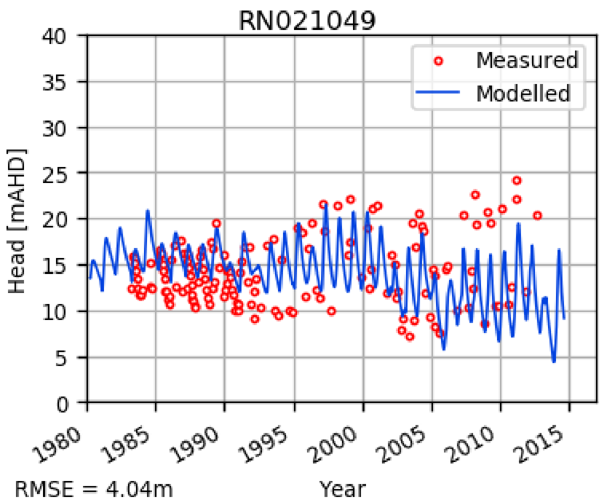

RN021043
Measured
Modelled
Head [mAHD]
Year
RMSE = 0.97m

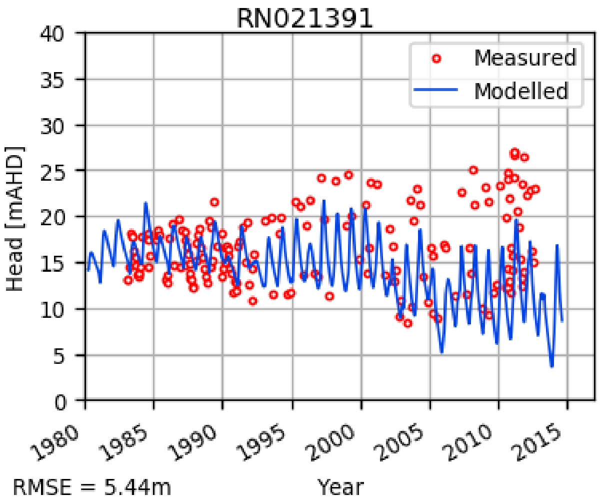

RN021044
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.27m

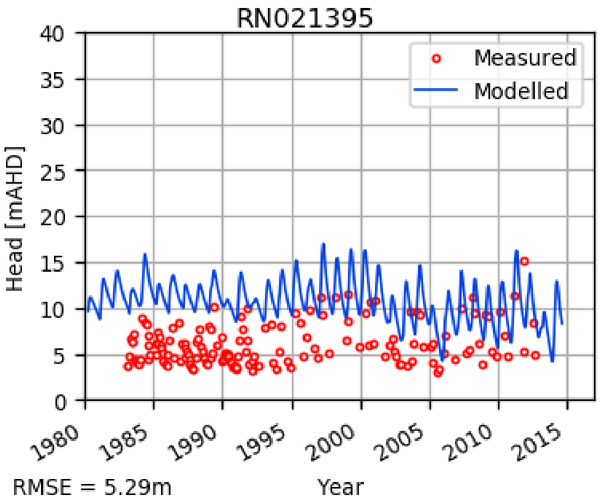

RN021045
Measured
Modelled
Head [mAHD]
Year
RMSE = 3.64m

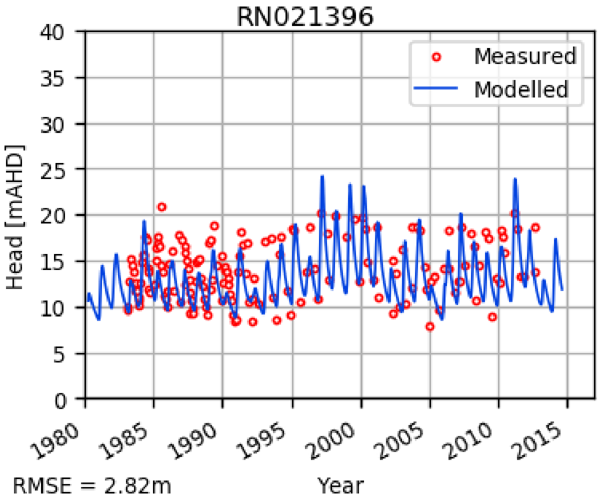

RN021047
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.92m

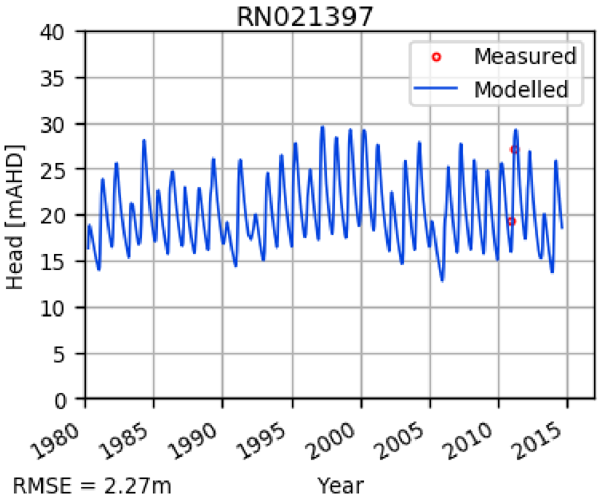

RN021048
Measured
Modelled
Head [mAHD]
Year
RMSE = 3.81m

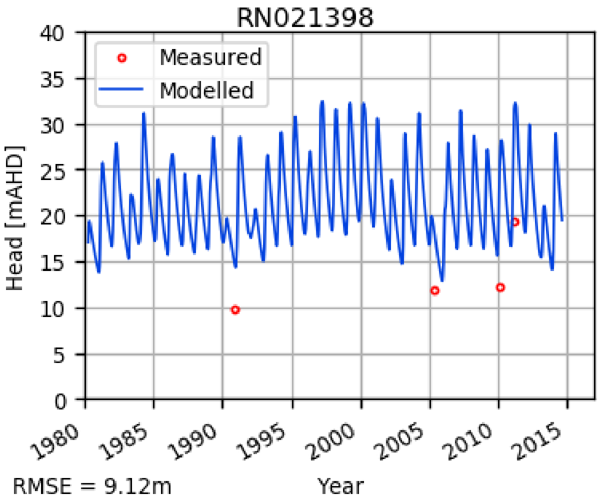

RN021049
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.04m

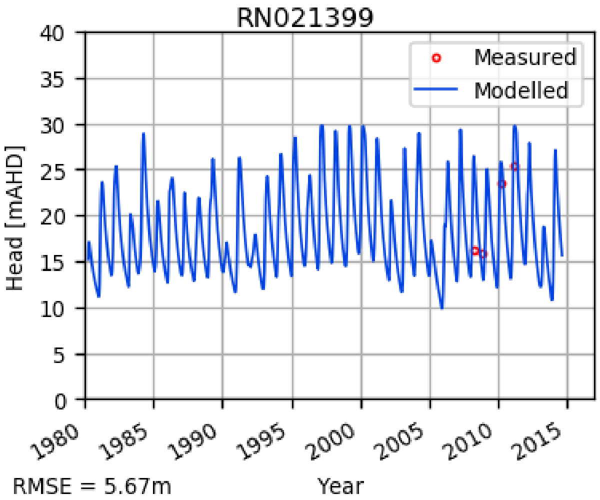

RN021391
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.44m


RN021395
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.29m


RN021396
Measured
Modelled
Head [mAHD]
Year
RMSE = 2.82m


RN021397
Measured
Modelled
Head [mAHD]
Year
RMSE = 2.27m


RN021398
Measured
Modelled
Head [mAHD]
Year
RMSE = 9.12m


RN021399
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.67m

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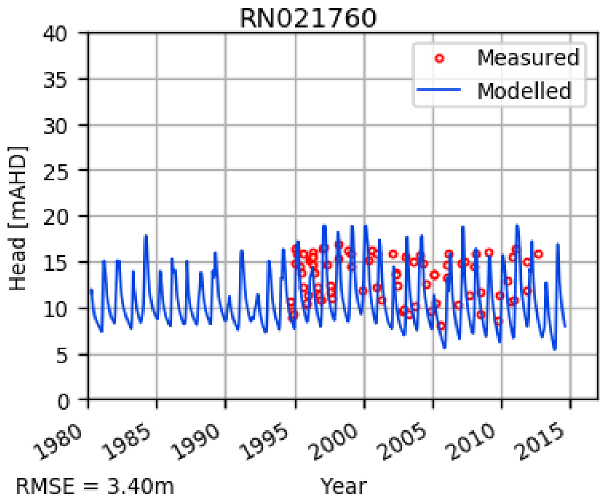
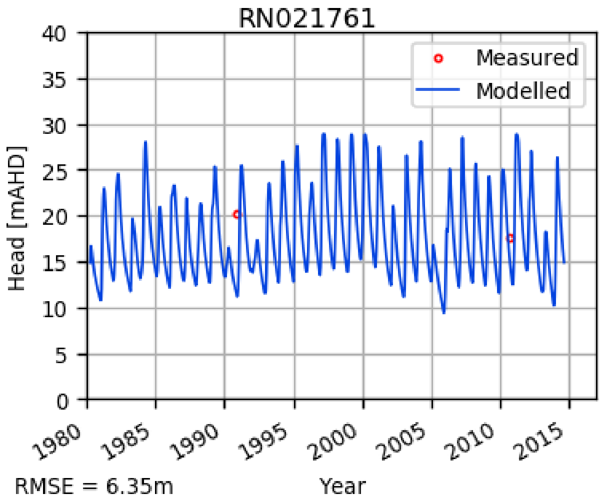
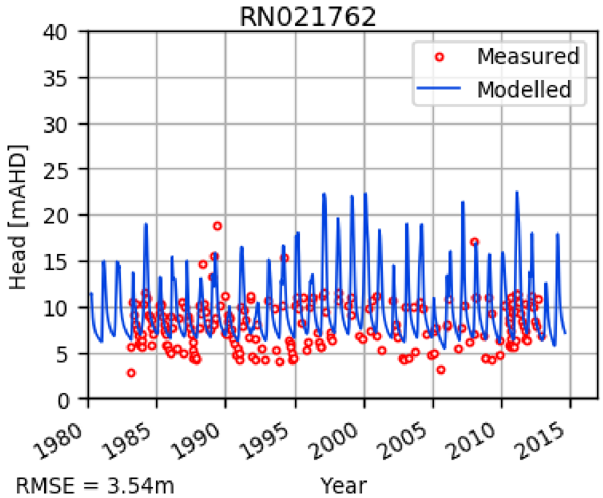
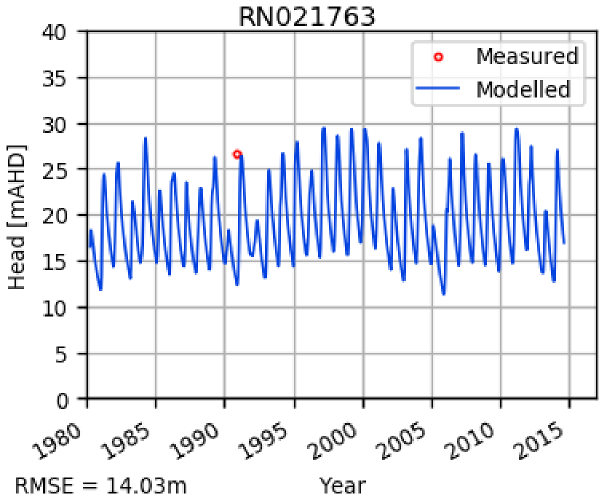
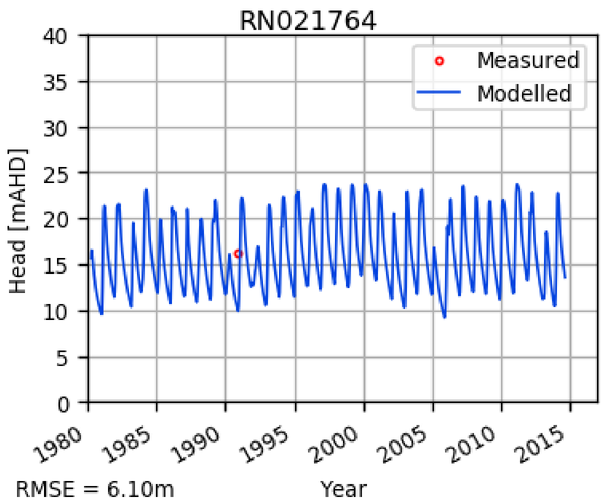
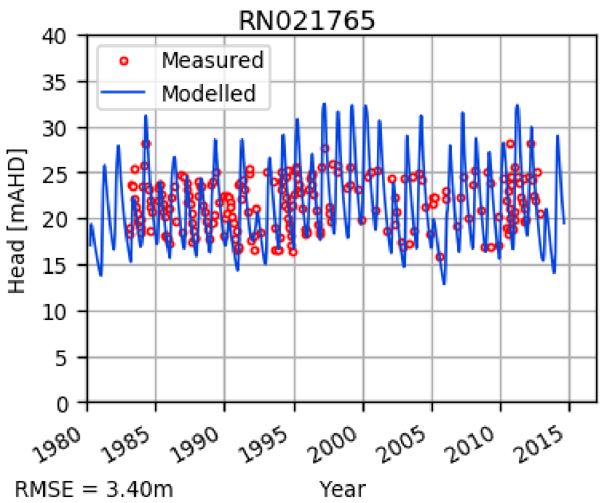

RN021760
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 3.40m
Year

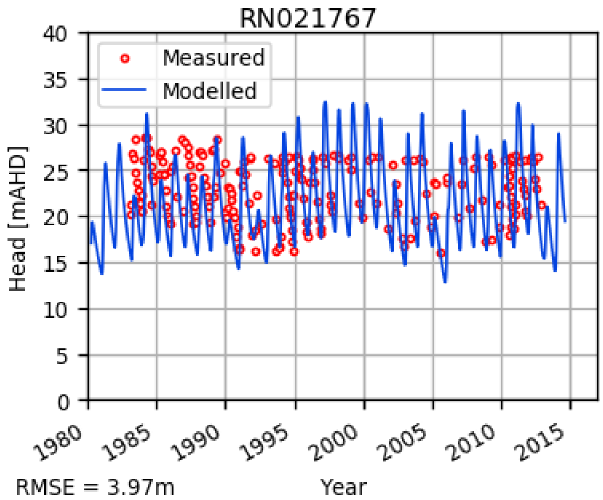

RN021761
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 6.35m
Year


RN021762
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 3.54m
Year

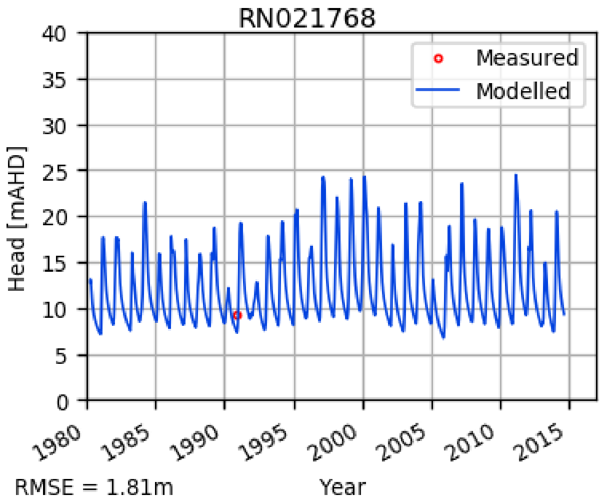

RN021763
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 14.03m
Year


RN021764
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 6.10m
Year

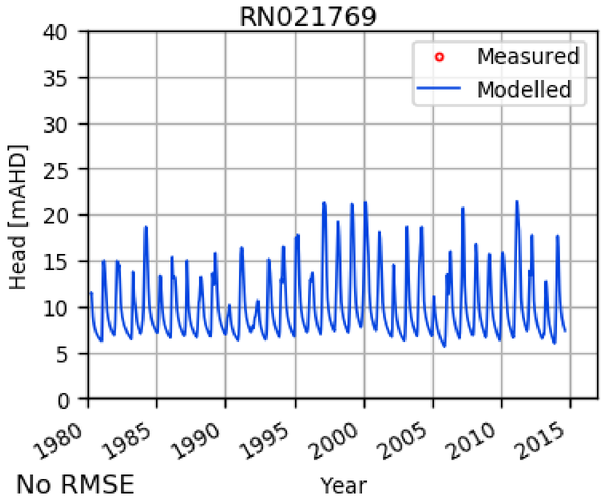

RN021765
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 3.40m
Year



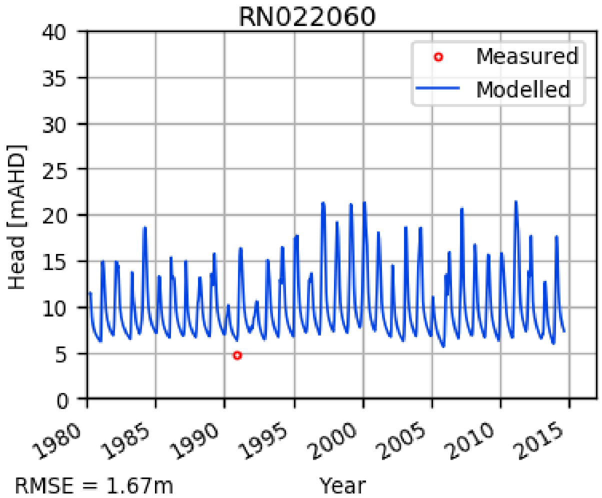
RMSE = 3.97m



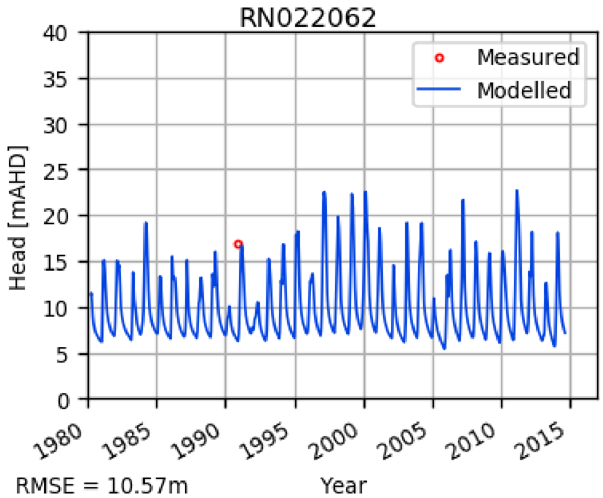
RMSE = 1.81m



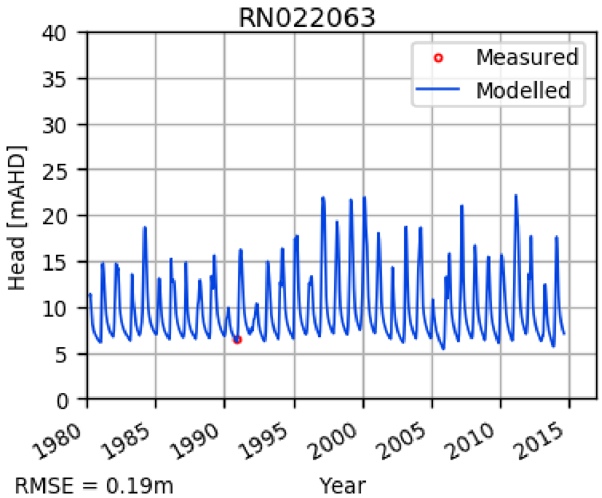
No RMSE



RMSE = 1.67m

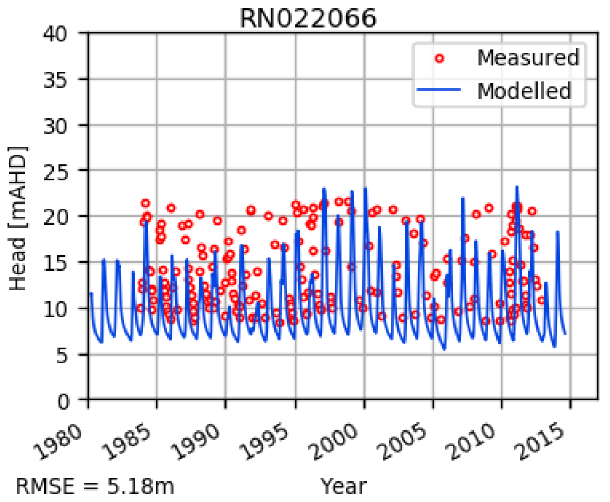


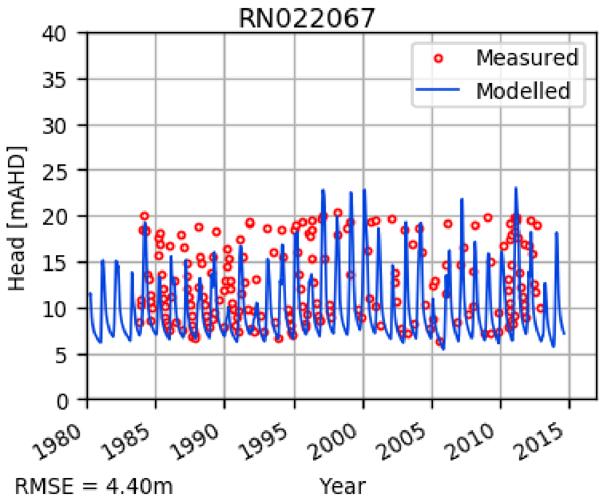
RMSE = 10.57m

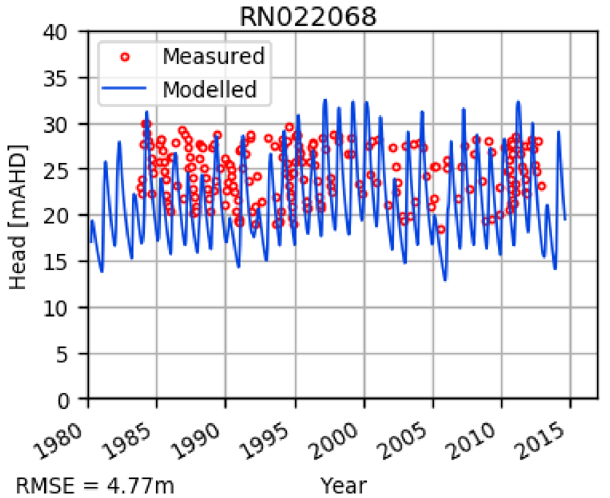


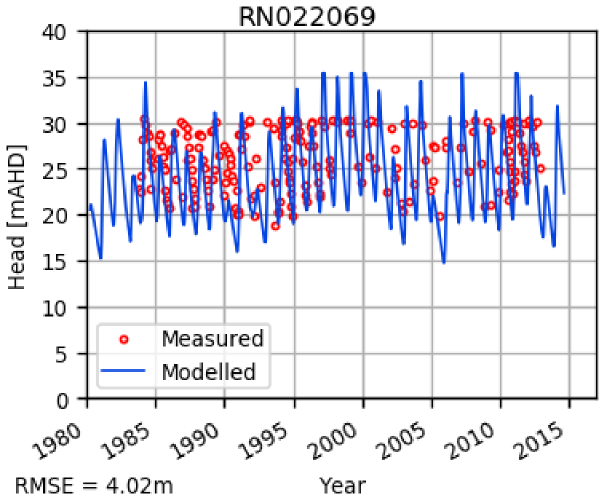
RMSE = 0.19m

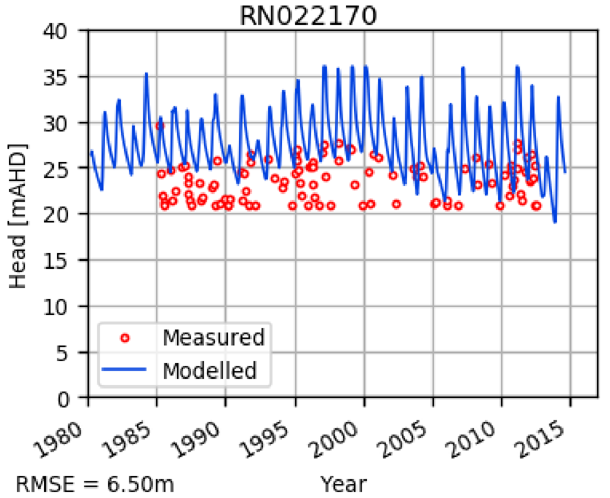
APPENDIX B

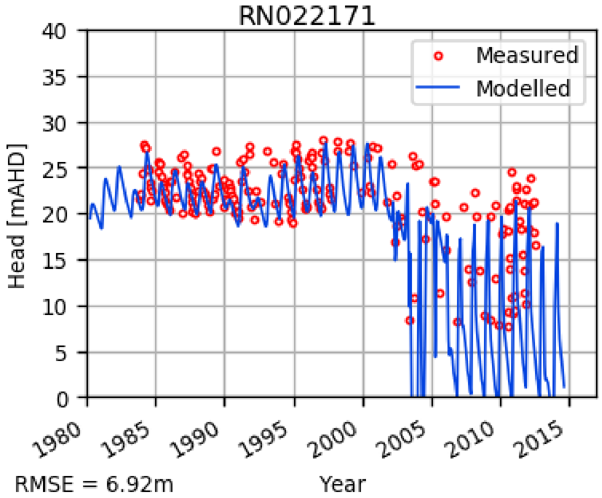

RN022066
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.18m

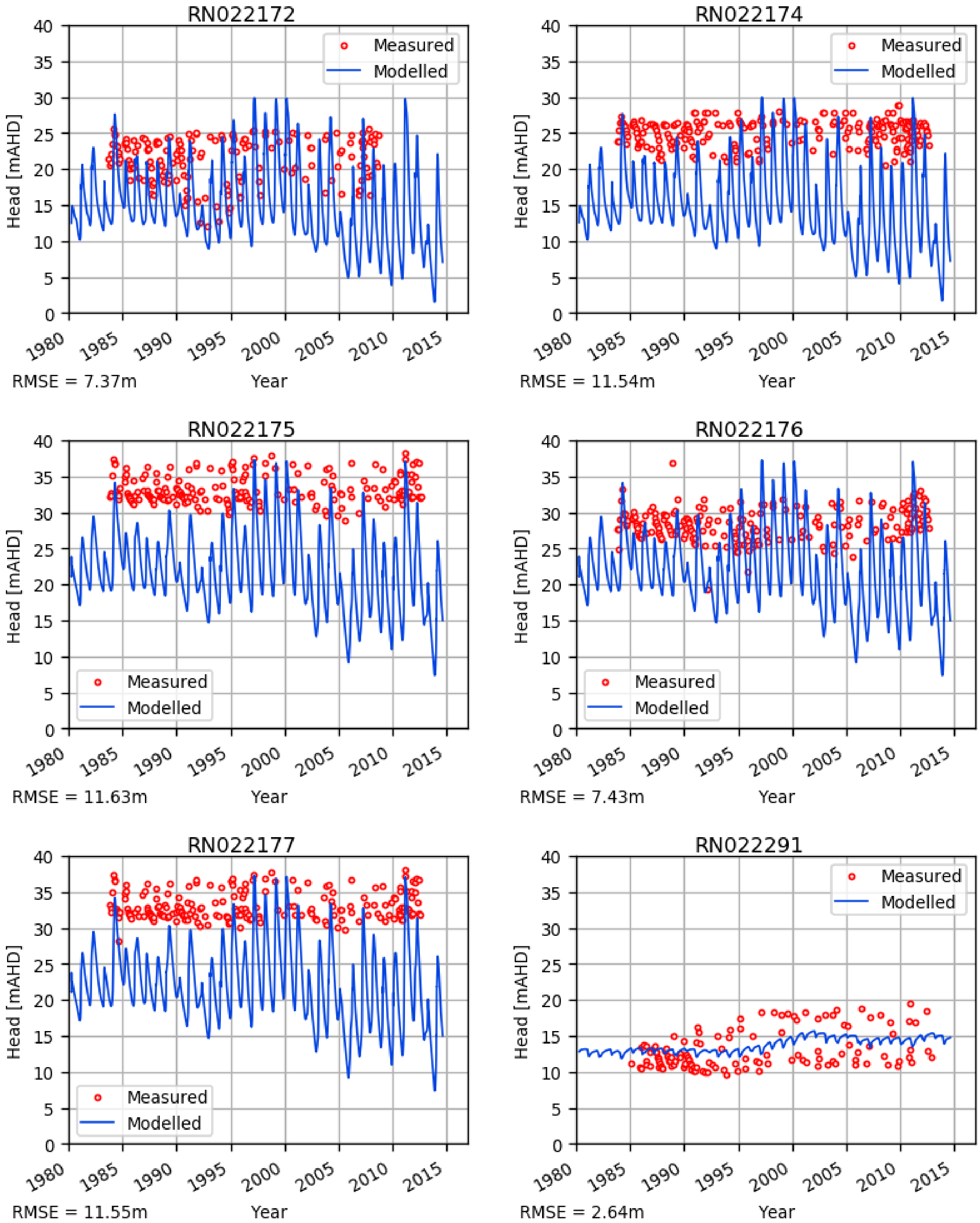

RN022067
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.40m

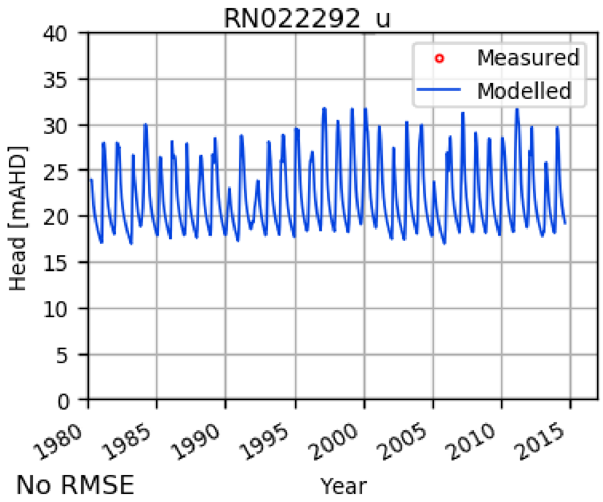

RN022068
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.77m

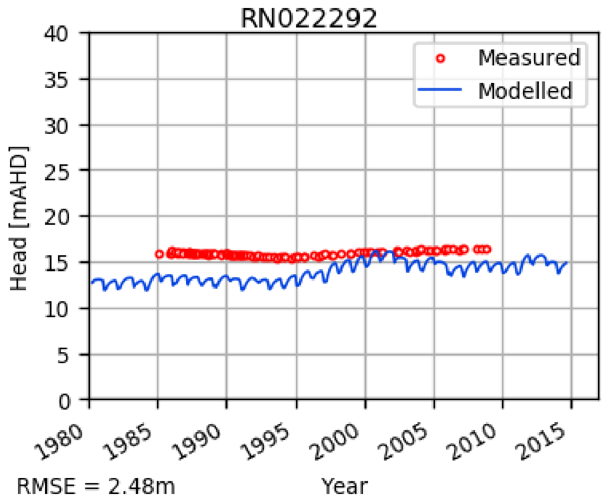

RN022069
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.02m

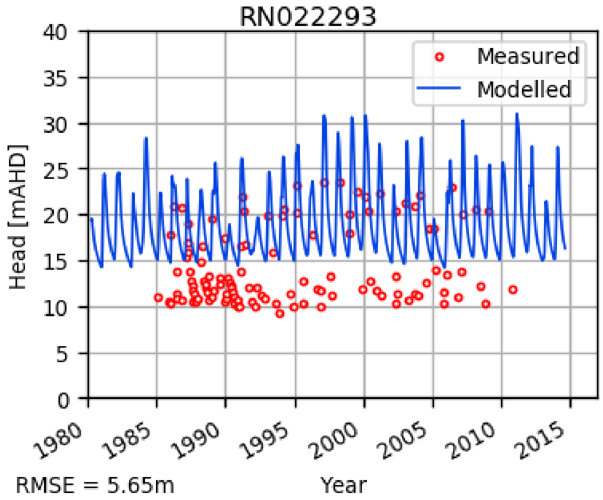

RN022170
Measured
Modelled
Head [mAHD]
Year
RMSE = 6.50m

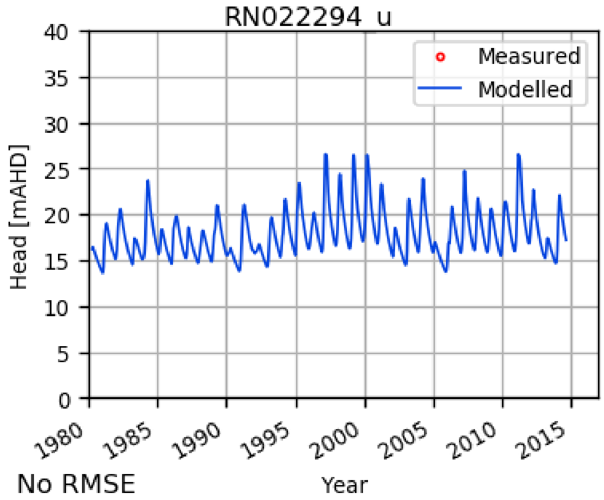

RN022171
Measured
Modelled
Head [mAHD]
Year
RMSE = 6.92m

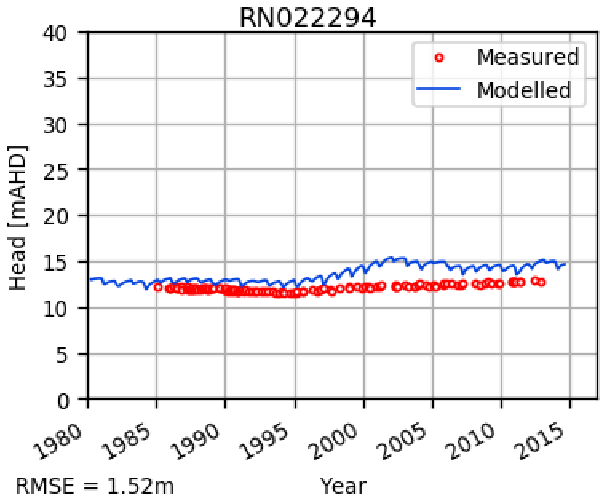

RN022172
Measured
Modelled
Head [mAHD]
Year
RMSE = 7.37m
RN022174
Measured
Modelled
Head [mAHD]
Year
RMSE = 11.54m
RN022175
Measured
Modelled
Head [mAHD]
Year
RMSE = 11.63m
RN022176
Measured
Modelled
Head [mAHD]
Year
RMSE = 7.43m
RN022177
Measured
Modelled
Head [mAHD]
Year
RMSE = 11.55m
RN022291
Measured
Modelled
Head [mAHD]
Year
RMSE = 2.64m

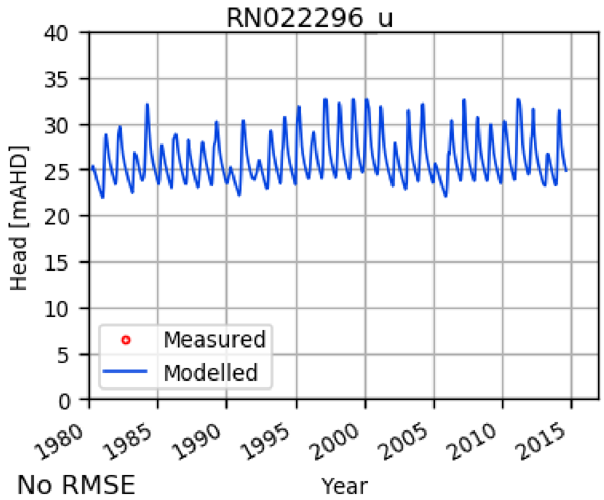

RN022292_u
Head [mAHD]
Year
Measured
Modelled
No RMSE


RN022292
Head [mAHD]
Year
Measured
Modelled
RMSE = 2.48m


RN022293
Head [mAHD]
Year
Measured
Modelled
RMSE = 5.65m


RN022294_u
Head [mAHD]
Year
Measured
Modelled
No RMSE


RN022294
Head [mAHD]
Year
Measured
Modelled
RMSE = 1.52m


RN022296_u
Head [mAHD]
Year
Measured
Modelled
No RMSE

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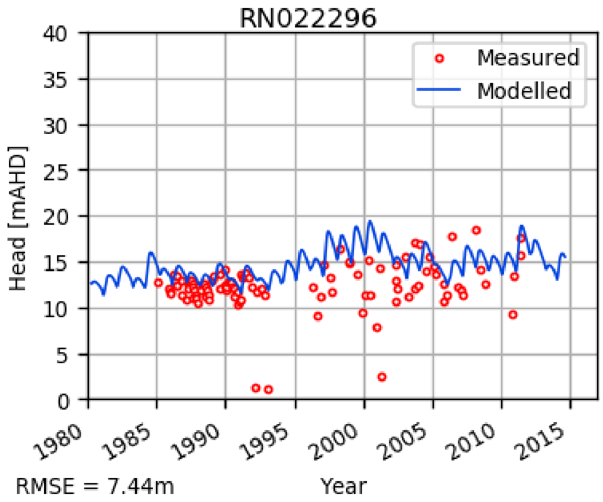
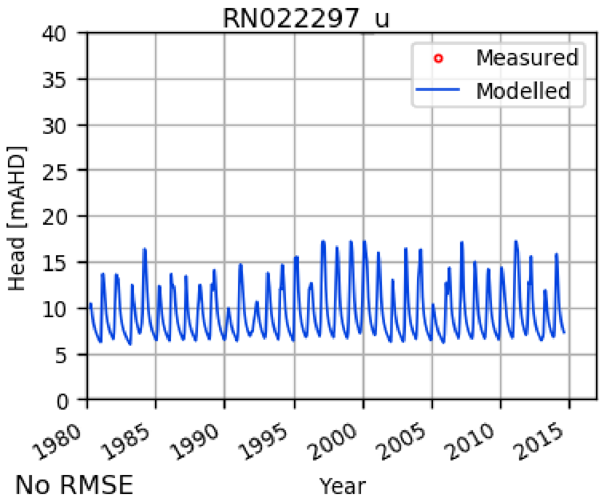
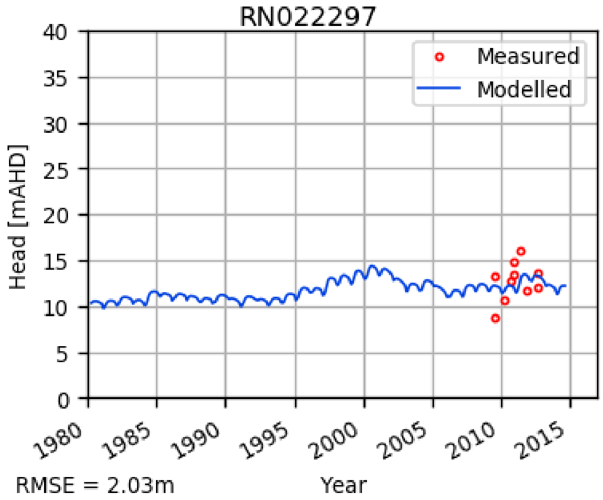
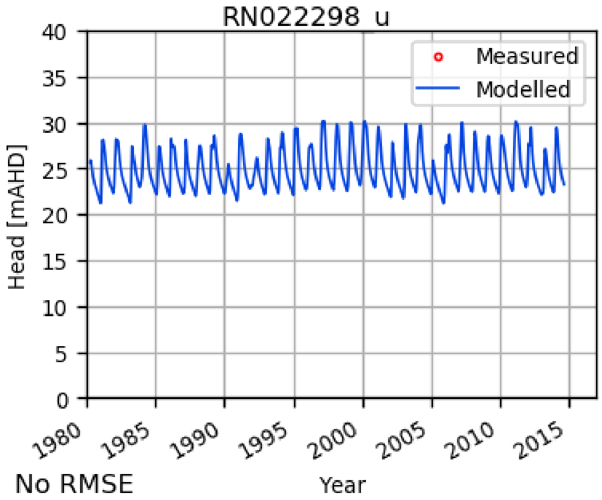
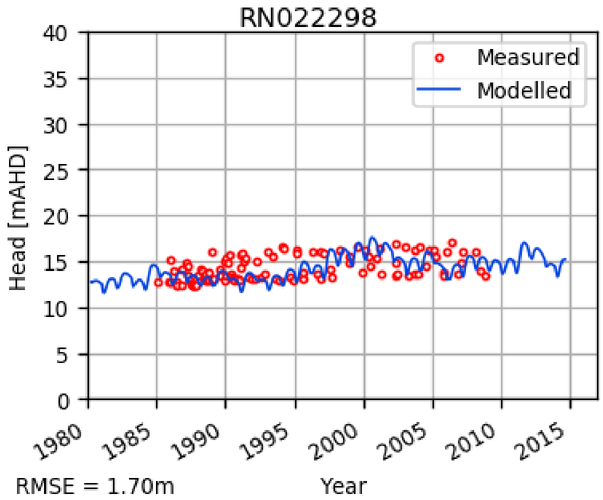
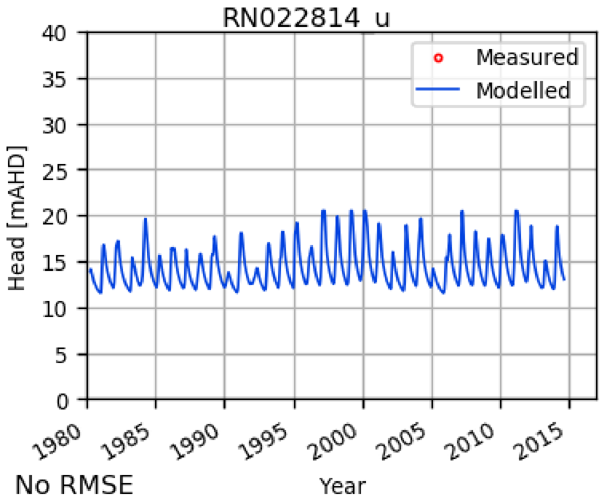

RN022296
Measured
Modelled
Head [mAHD]
Year
RMSE = 7.44m

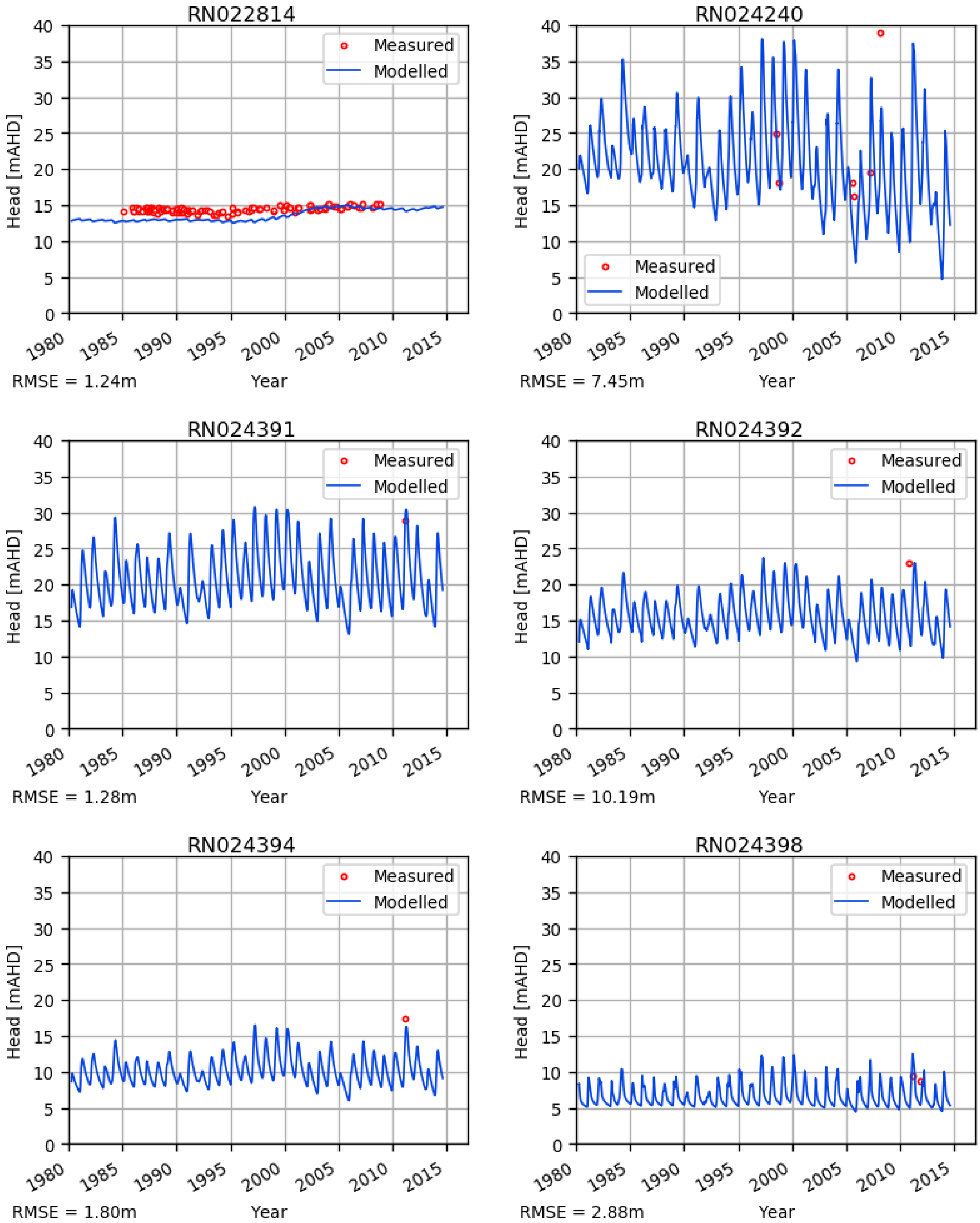

RN022297_u
Measured
Modelled
Head [mAHD]
Year
No RMSE


RN022297
Measured
Modelled
Head [mAHD]
Year
RMSE = 2.03m


RN022298_u
Measured
Modelled
Head [mAHD]
Year
No RMSE


RN022298
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.70m


RN022814_u
Measured
Modelled
Head [mAHD]
Year
No RMSE


RN022814
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.24m
RN024240
Measured
Modelled
Head [mAHD]
Year
RMSE = 7.45m
RN024391
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.28m
RN024392
Measured
Modelled
Head [mAHD]
Year
RMSE = 10.19m
RN024394
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.80m
RN024398
Measured
Modelled
Head [mAHD]
Year
RMSE = 2.88m

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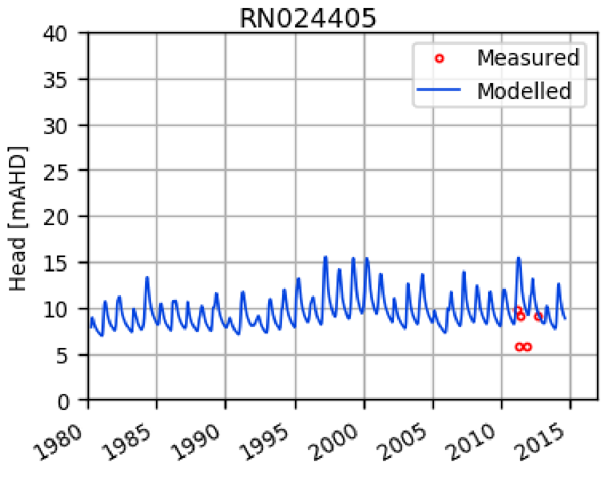
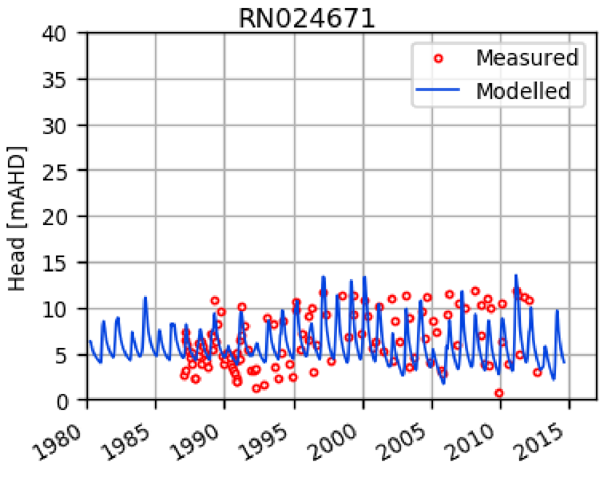
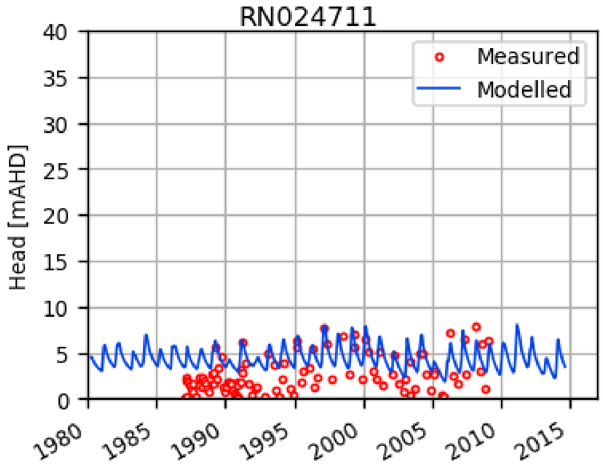


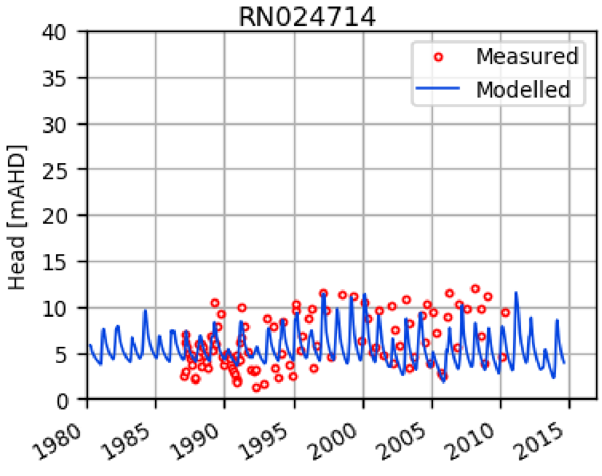
RMSE = 5.45m



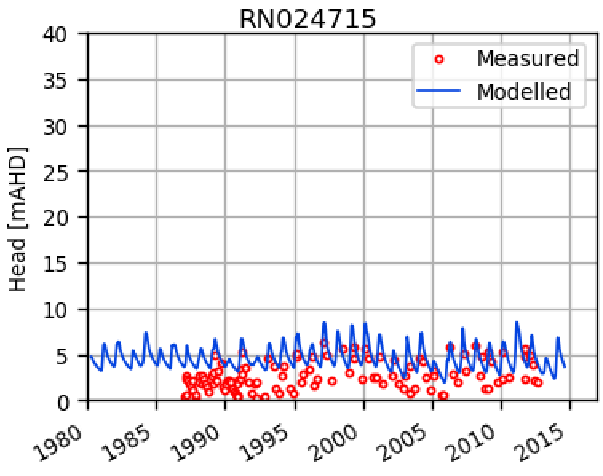
RMSE = 2.36m



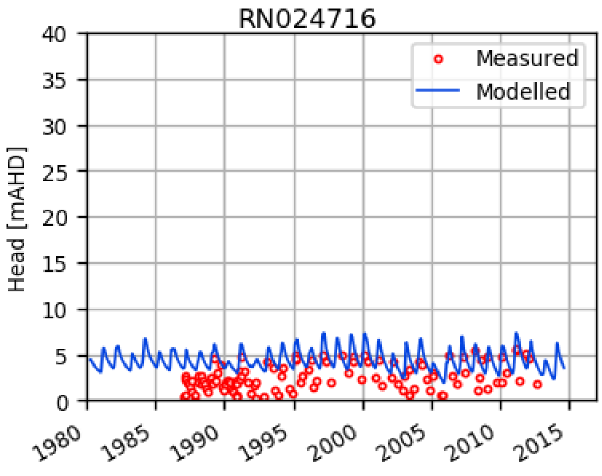
RMSE = 2.38m



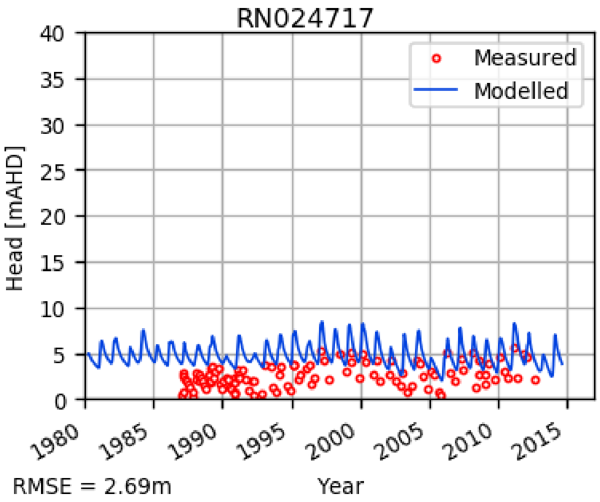
RMSE = 2.31m

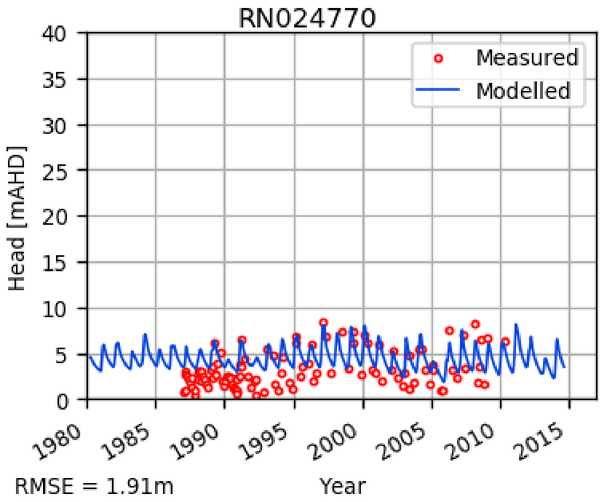


RMSE = 2.36m



RMSE = 2.24m


RN024717
Measured
Modelled
Head [mAHD]
0
5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 2.69m


RN024770
Measured
Modelled
Head [mAHD]
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25
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35
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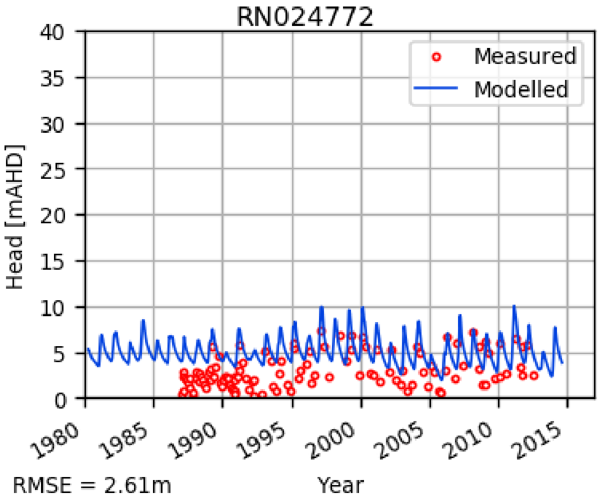
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 1.91m


RN024772
Measured
Modelled
Head [mAHD]
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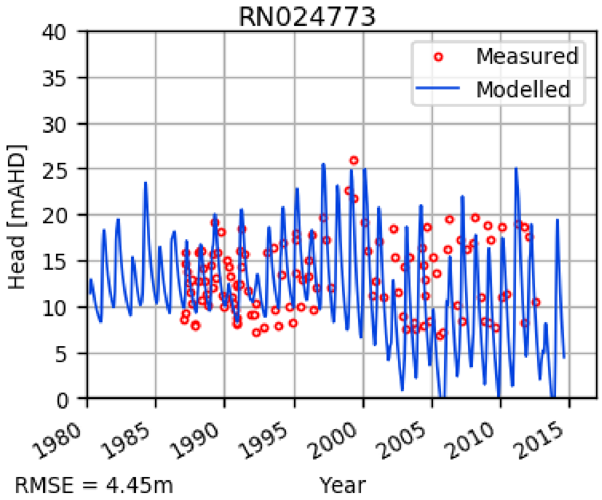
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 2.61m


RN024773
Measured
Modelled
Head [mAHD]
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40
1980
1985
1990
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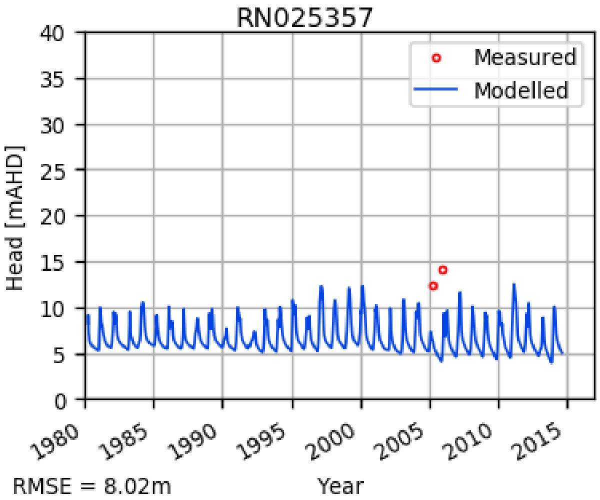
2000
2005
2010
2015
Year
RMSE = 4.45m


RN025357
Measured
Modelled
Head [mAHD]
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5
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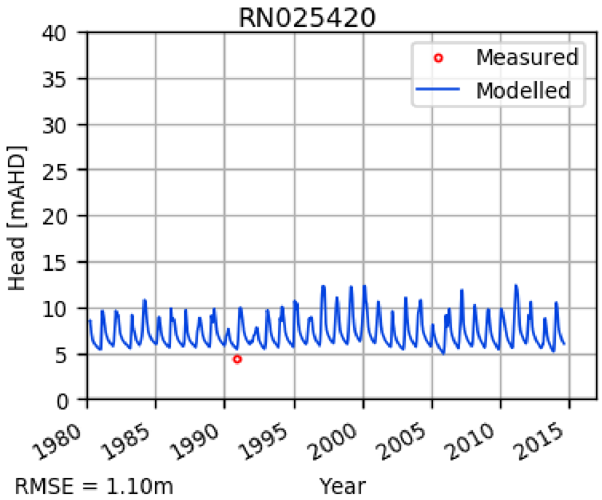
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 8.02m


RN025420
Measured
Modelled
Head [mAHD]
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5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 1.10m

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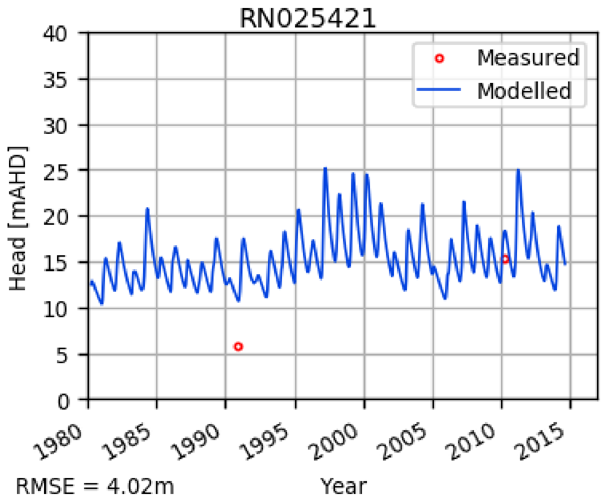
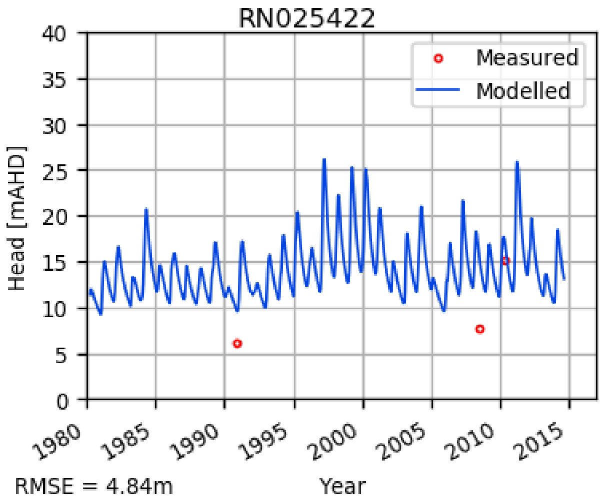

RN025421
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.02m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Measured
Modelled
Head [mAHD]
Year
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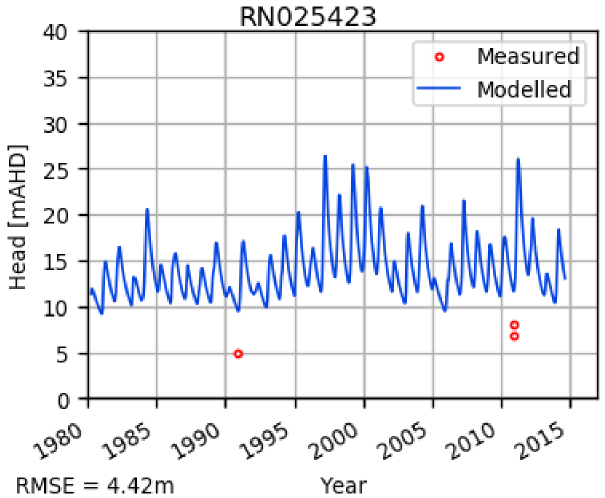
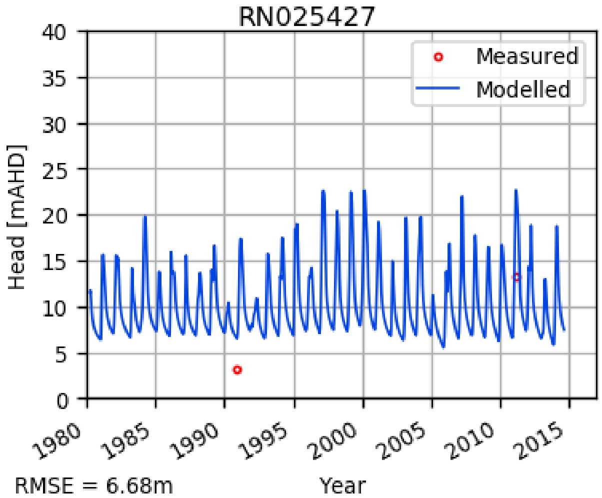

RN025423
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.42m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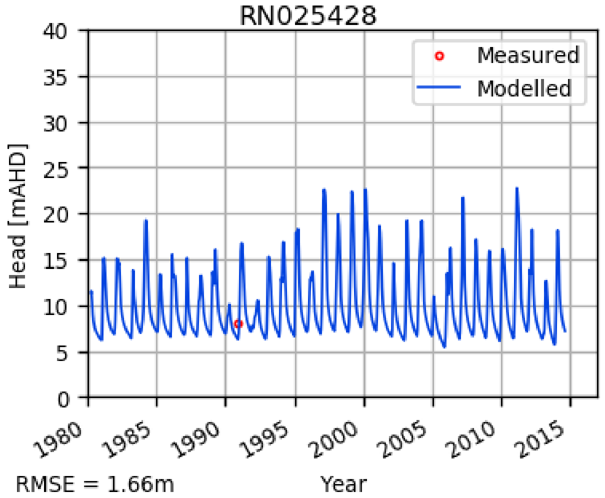
Measured
Modelled
Head [mAHD]
Year
RMSE = 6.68m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Measured
Modelled
Head [mAHD]
Year
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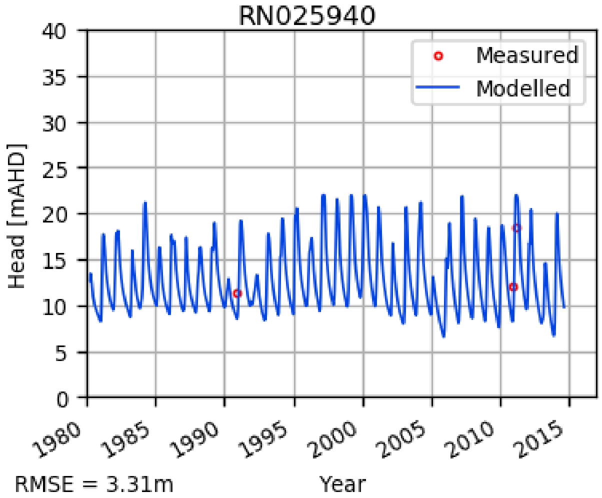
RN025940
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Modelled
Head [mAHD]
Year
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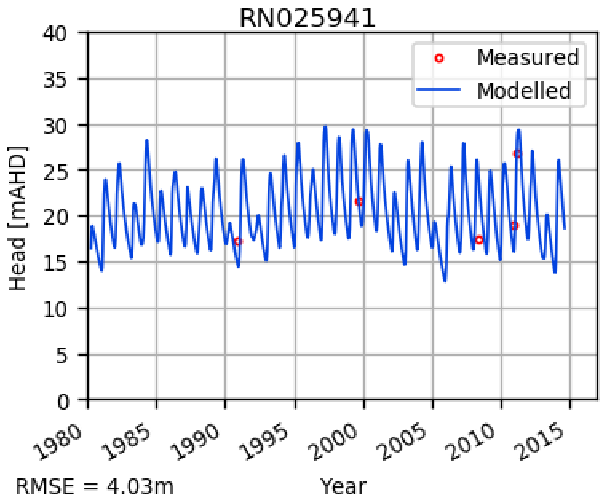
RN025941
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Year
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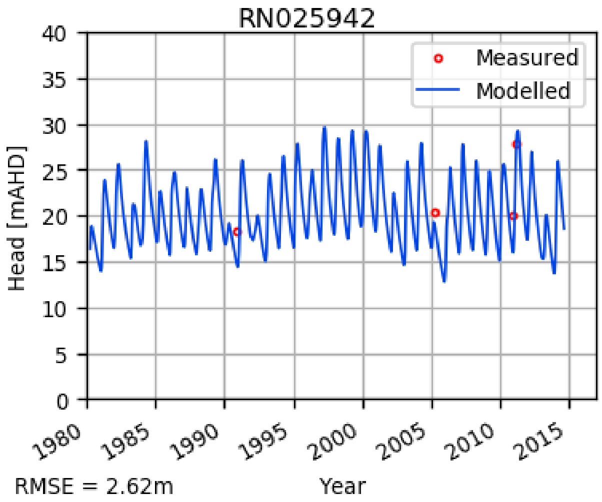
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Modelled
Head [mAHD]
Year
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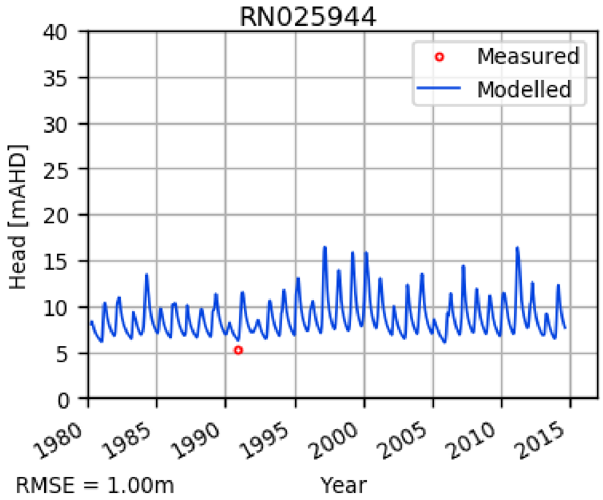
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Year
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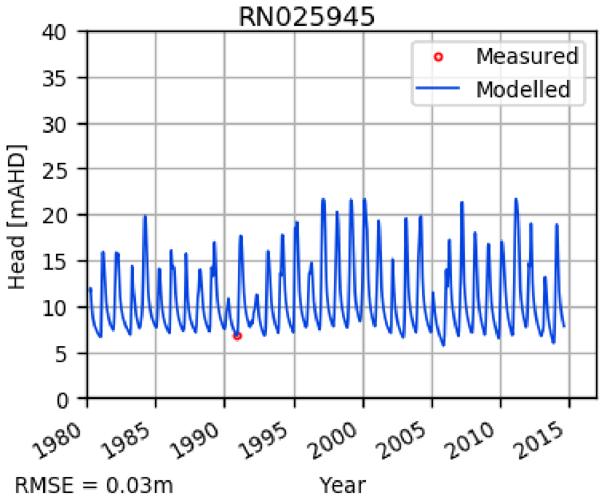
RN025945
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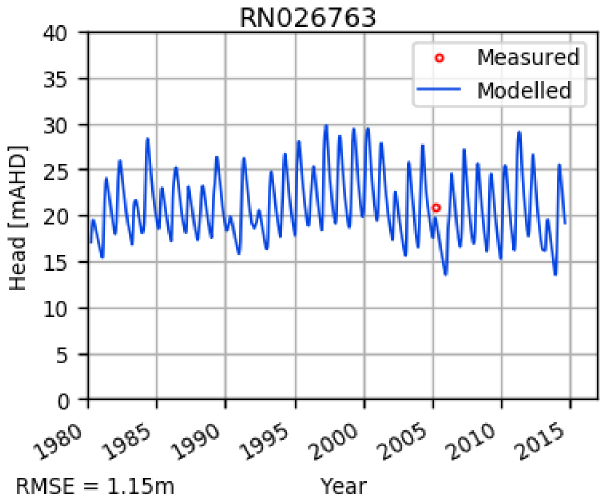
Year
RMSE = 0.03m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Measured
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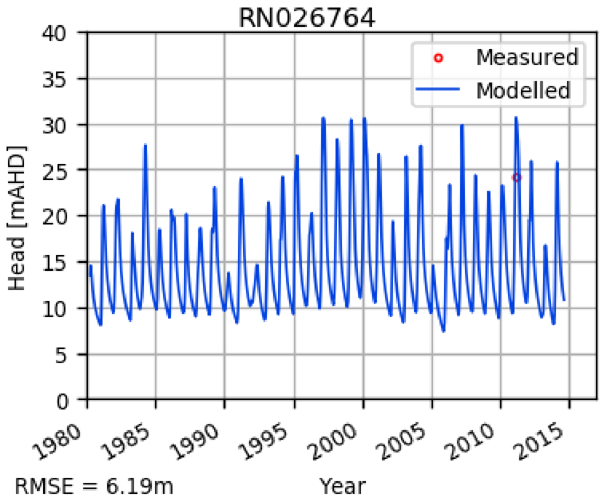
Head [mAHD]
Year
RMSE = 1.15m


RN026764
Measured
Modelled
Head [mAHD]
Year
RMSE = 6.19m

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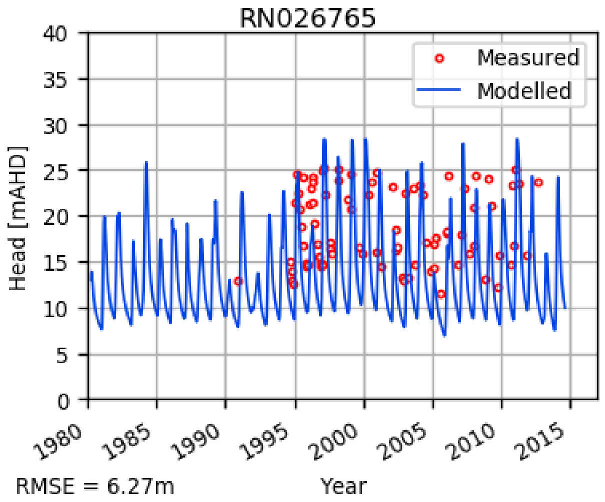
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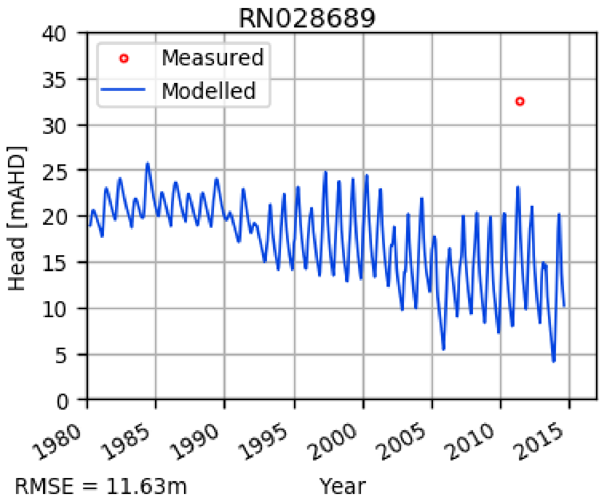
Head [mAHD]
Year
RMSE = 6.27m


RN028689
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Modelled
Head [mAHD]
Year
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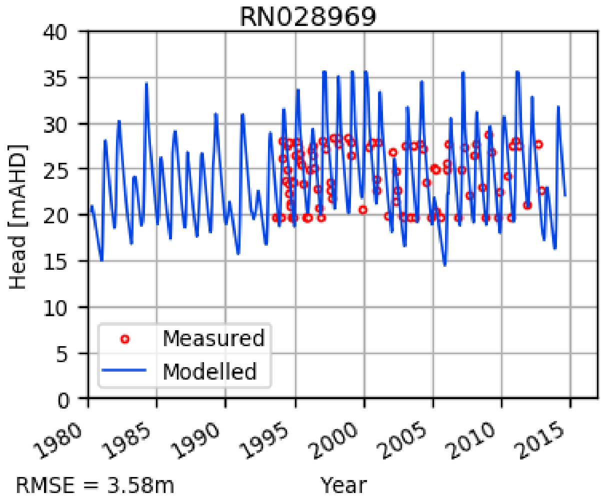
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Year
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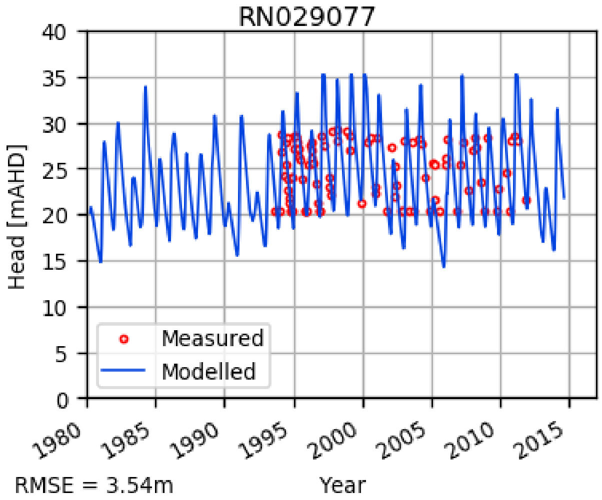
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Head [mAHD]
Year
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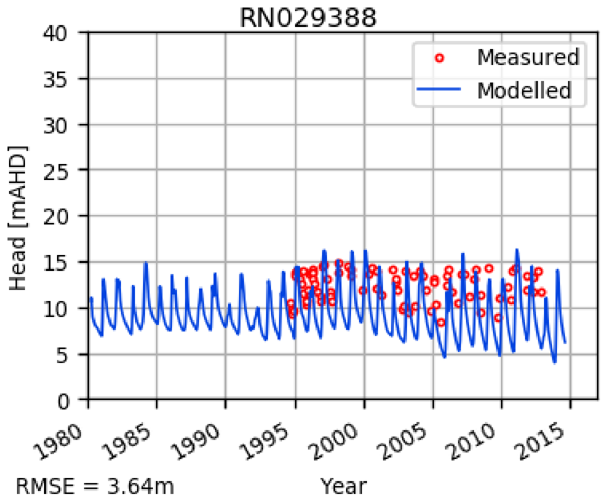
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Modelled
Head [mAHD]
Year
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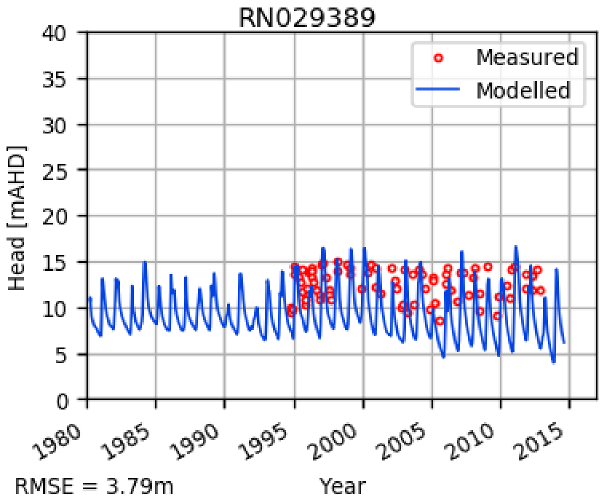
RN029389
Measured
Modelled
Head [mAHD]
Year
RMSE = 3.79m

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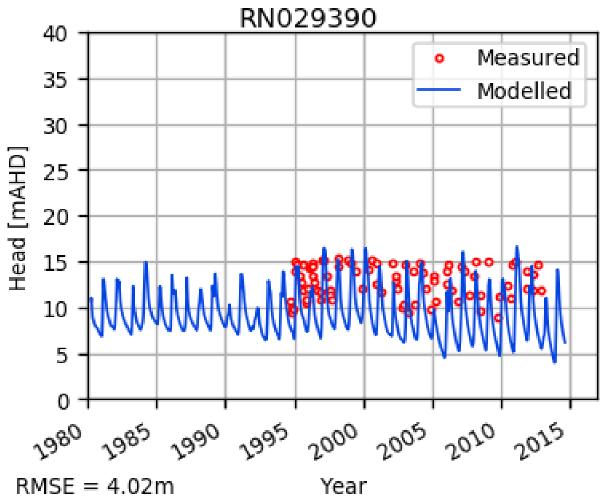
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Year
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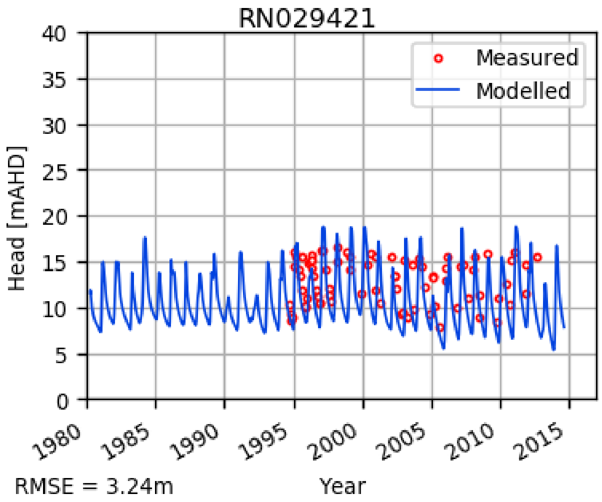
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Measured
Modelled
Head [mAHD]
Year
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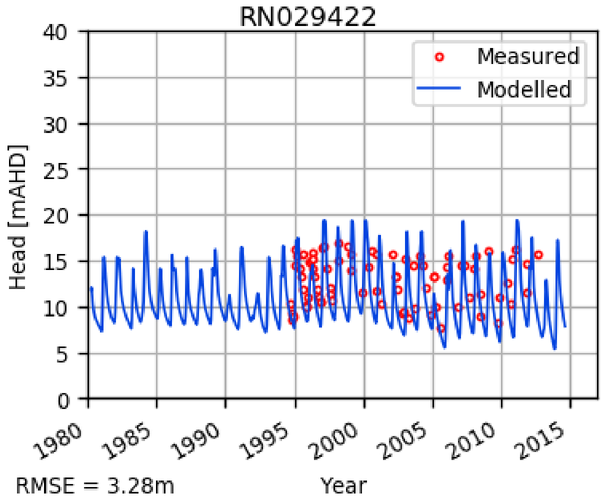
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Measured
Modelled
Head [mAHD]
Year
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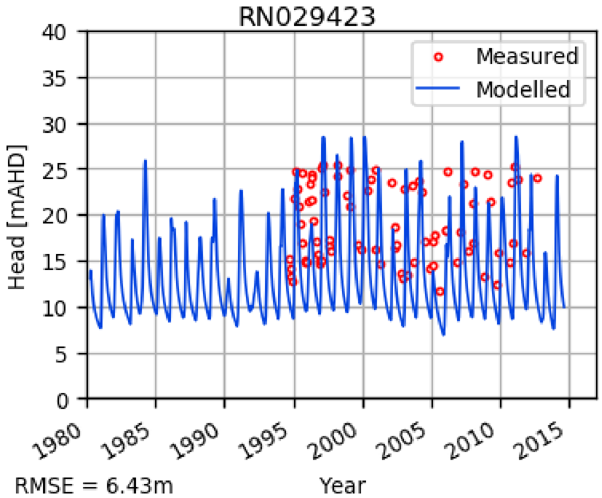
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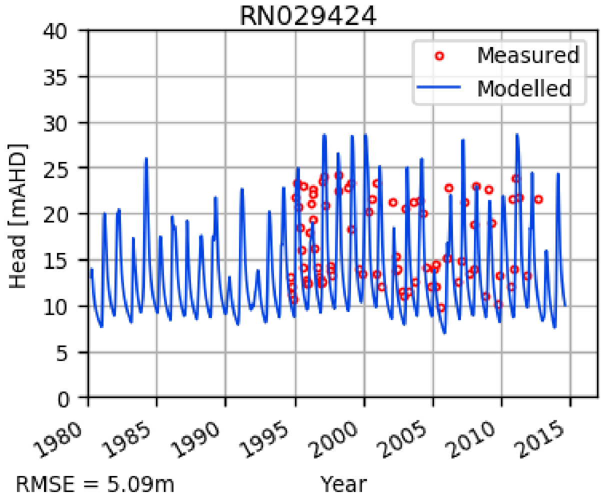
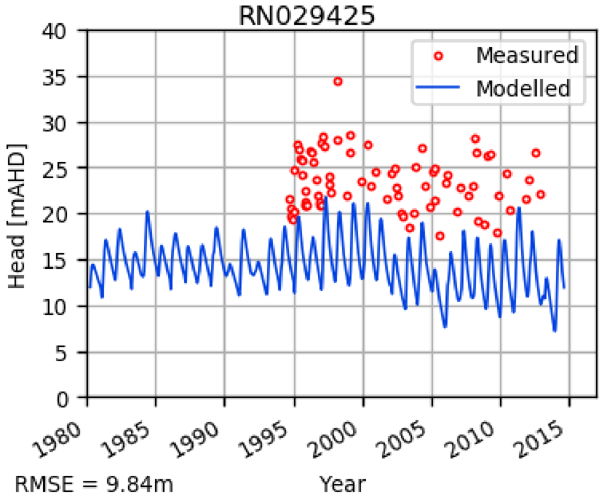
Measured
Modelled
Head [mAHD]
Year
RMSE = 6.43m


RN029424
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.09m


RN029425
Measured
Modelled
Head [mAHD]
Year
RMSE = 9.84m

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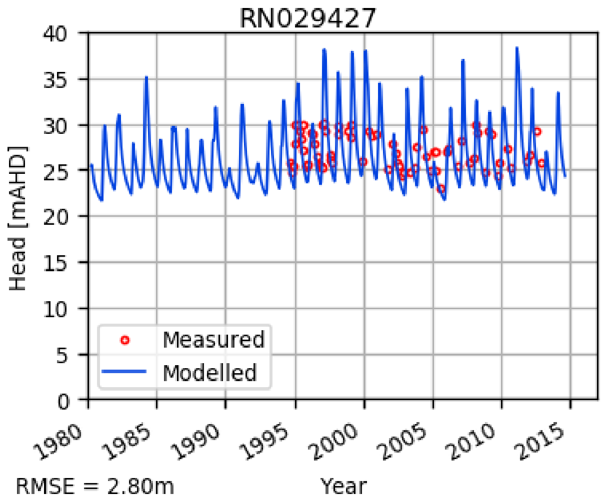
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Measured
Modelled
Year
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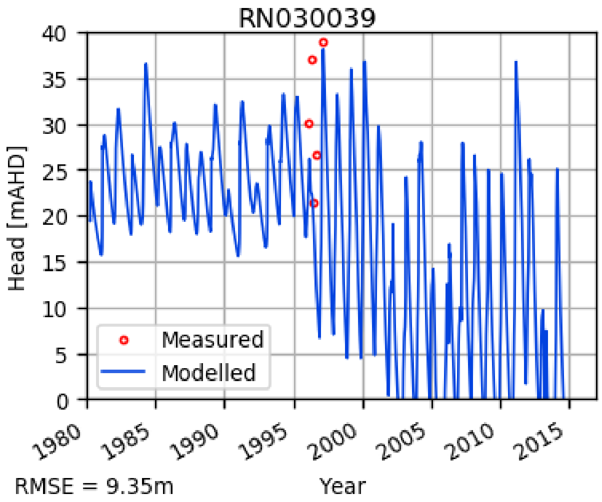
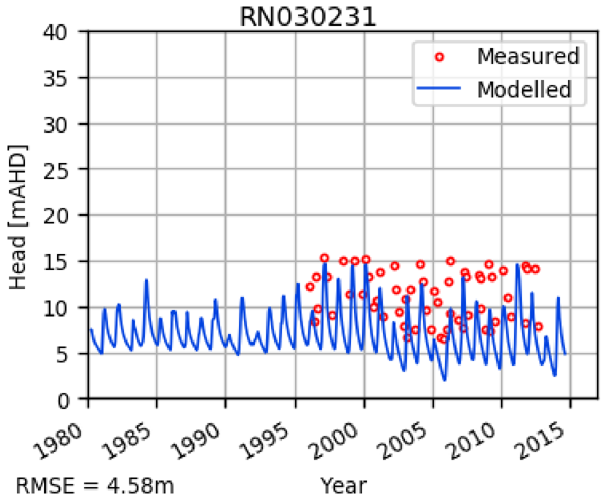

RN030039
Head [mAHD]
Measured
Modelled
Year
RMSE = 9.35m


RN030231
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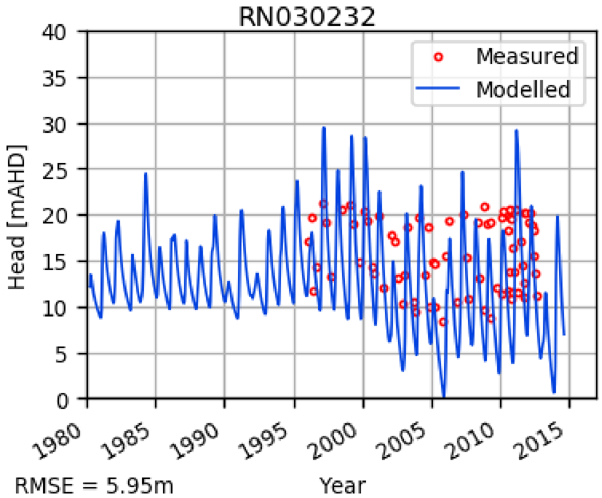
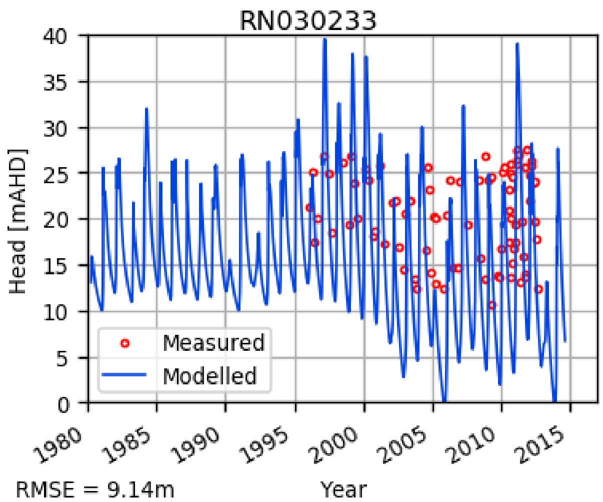
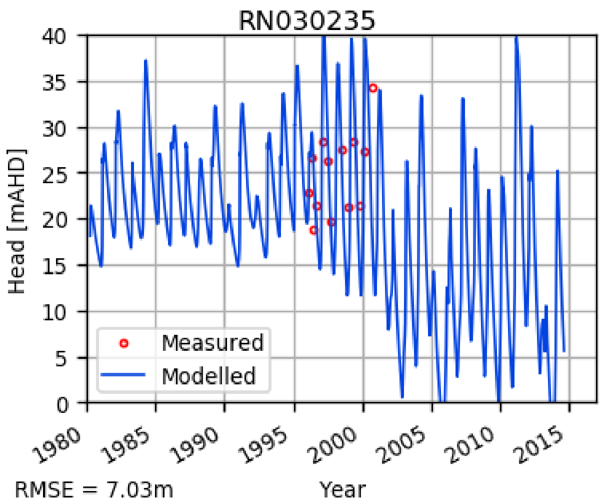
Measured
Modelled
Year
RMSE = 4.58m


RN030232
Head [mAHD]
Measured
Modelled
Year
RMSE = 5.95m


RN030233
Head [mAHD]
Measured
Modelled
Year
RMSE = 9.14m


RN030235
Head [mAHD]
Measured
Modelled
Year
RMSE = 7.03m

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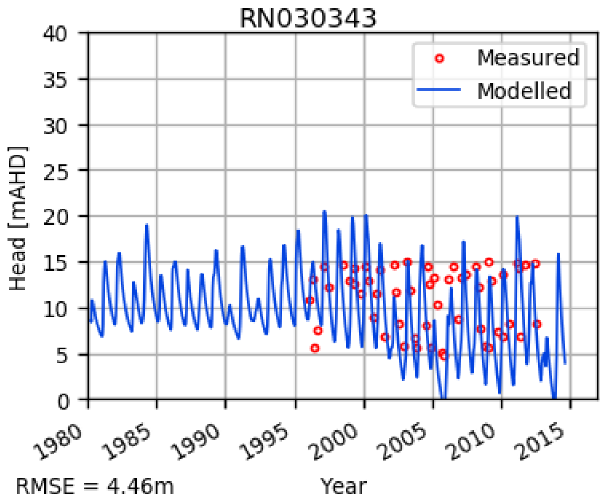
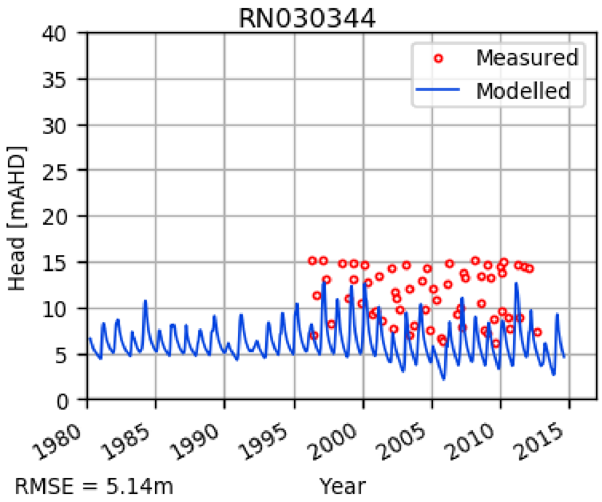
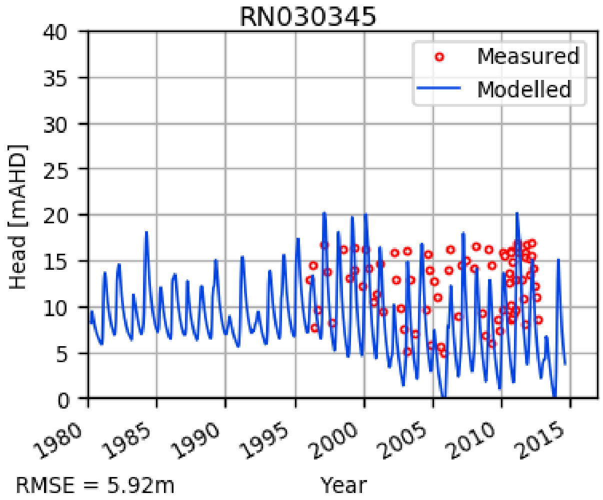
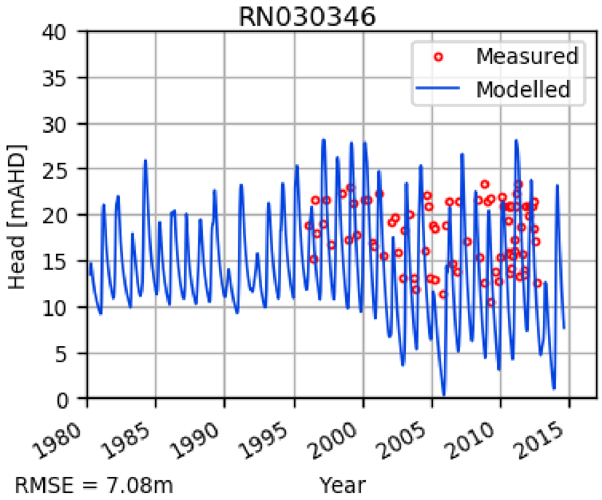
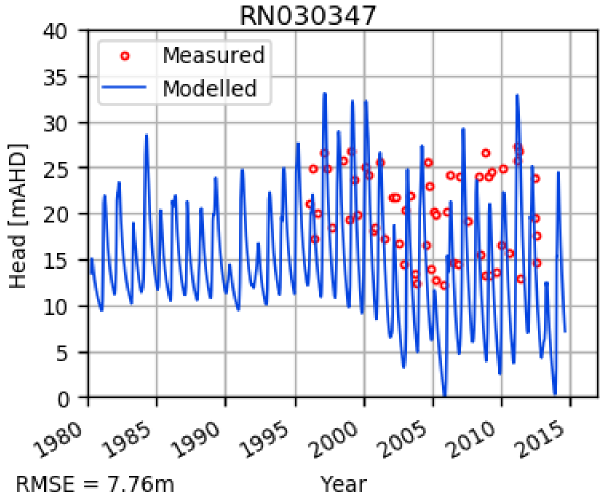
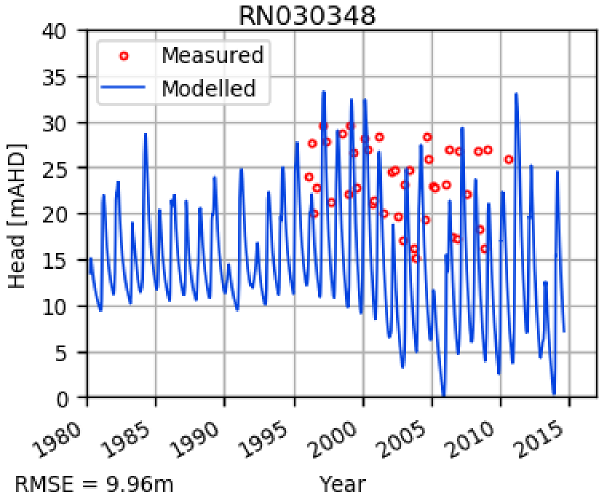

RN030343
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.46m


RN030344
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.14m


RN030345
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.92m


RN030346
Measured
Modelled
Head [mAHD]
Year
RMSE = 7.08m


RN030347
Measured
Modelled
Head [mAHD]
Year
RMSE = 7.76m


RN030348
Measured
Modelled
Head [mAHD]
Year
RMSE = 9.96m

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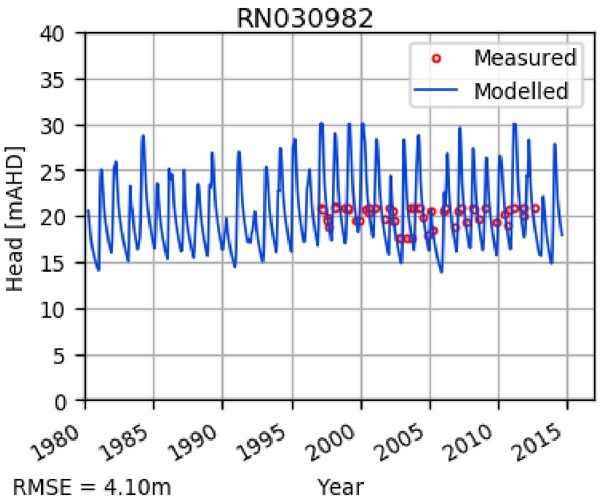
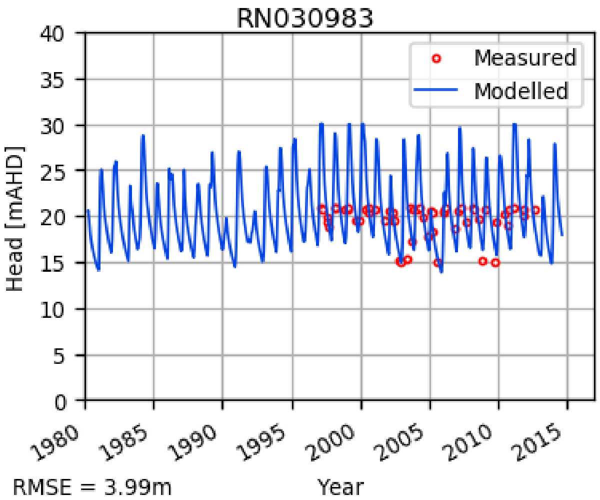

RN030982
Measured
Modelled
Head [mAHD]
0
5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 4.10m


RN030983
Measured
Modelled
Head [mAHD]
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5
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25
30
35
40
1980
1985
1990
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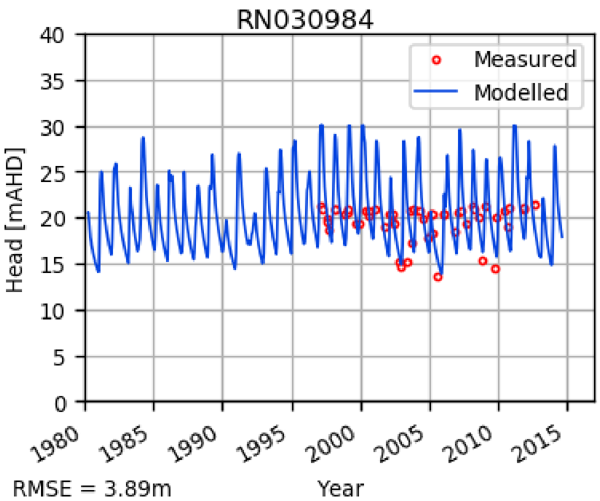
2010
2015
Year
RMSE = 3.99m


RN030984
Measured
Modelled
Head [mAHD]
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5
10
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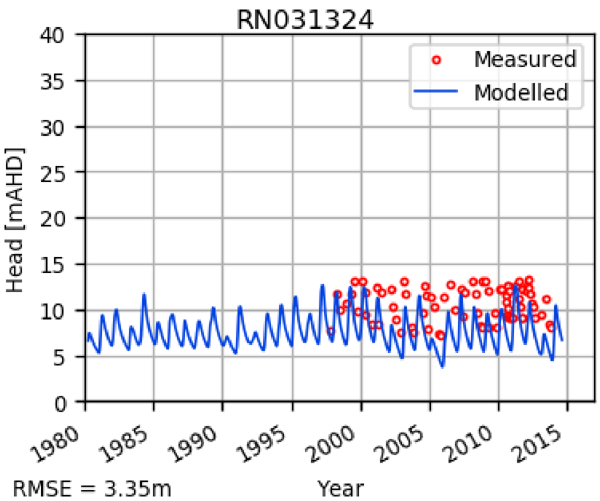
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 3.89m


RN031324
Measured
Modelled
Head [mAHD]
0
5
10
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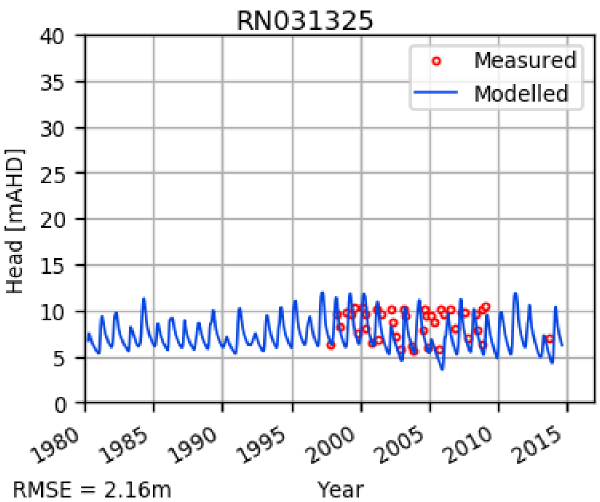
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 3.35m


RN031325
Measured
Modelled
Head [mAHD]
0
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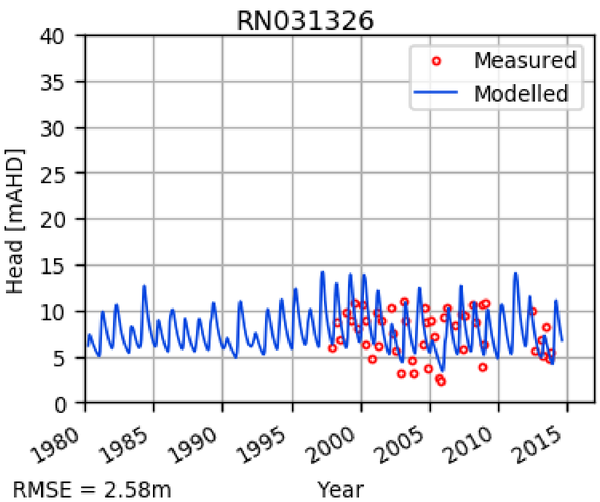
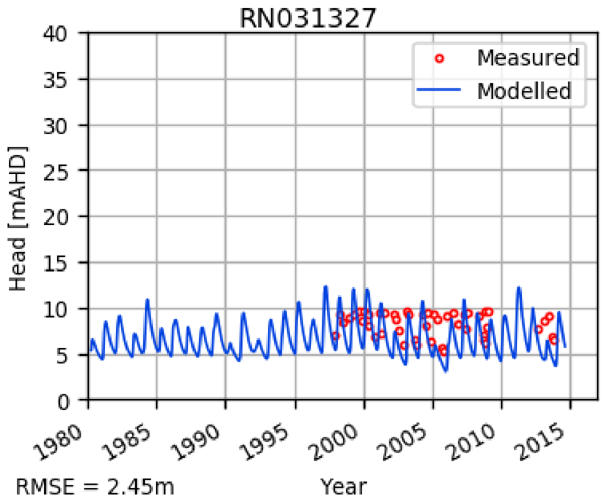
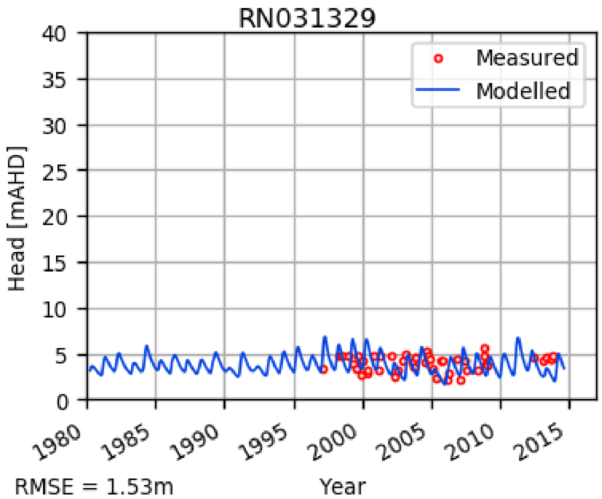
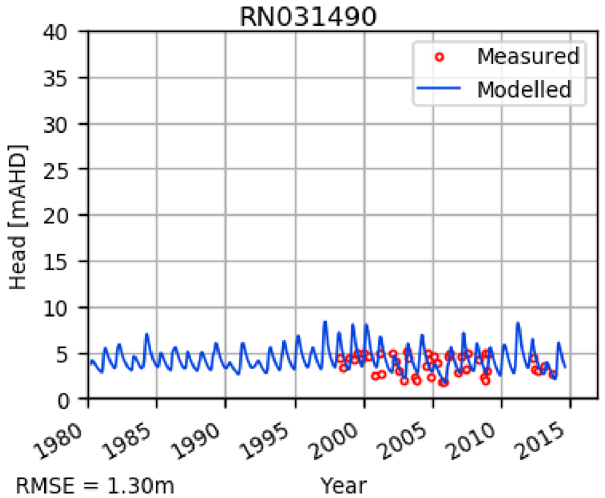
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 2.16m

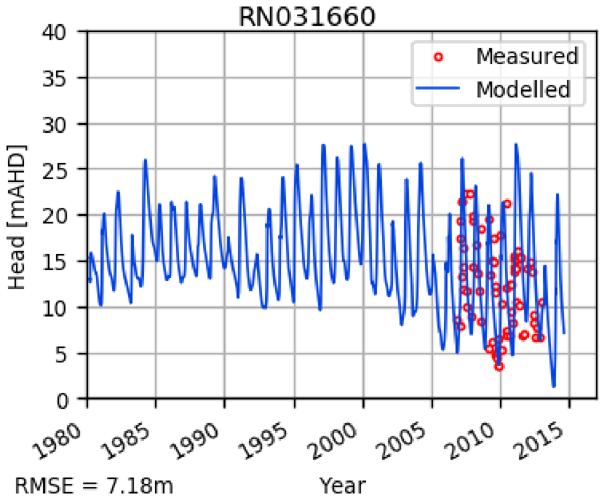

RN031326
Measured
Modelled
Head [mAHD]
0
5
10
15
20
25
30
35
40
1980
1985
1990
1995
2000
2005
2010
2015
Year
RMSE = 2.58m

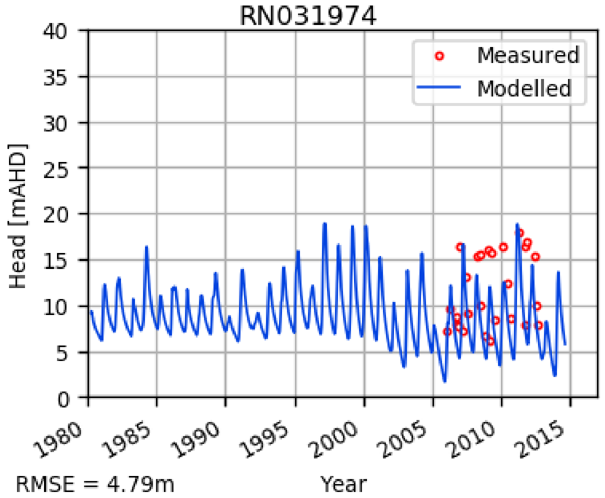
APPENDIX B

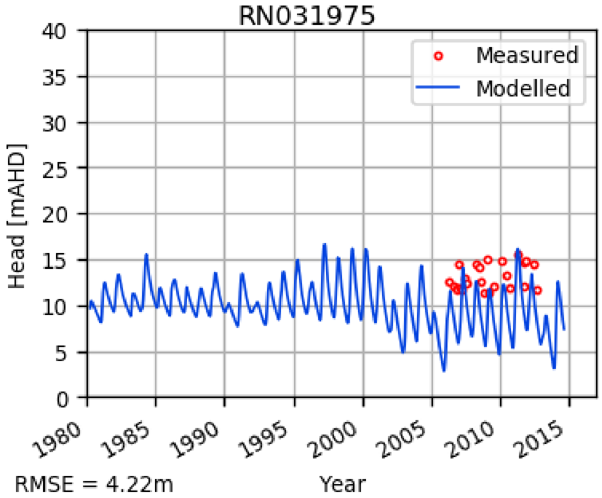

RN031327
Measured
Modelled
Head [mAHD]
Year
RMSE = 2.45m


RN031329
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.53m


RN031490
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.30m


RN031660
Measured
Modelled
Head [mAHD]
Year
RMSE = 7.18m


RN031974
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.79m


RN031975
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.22m

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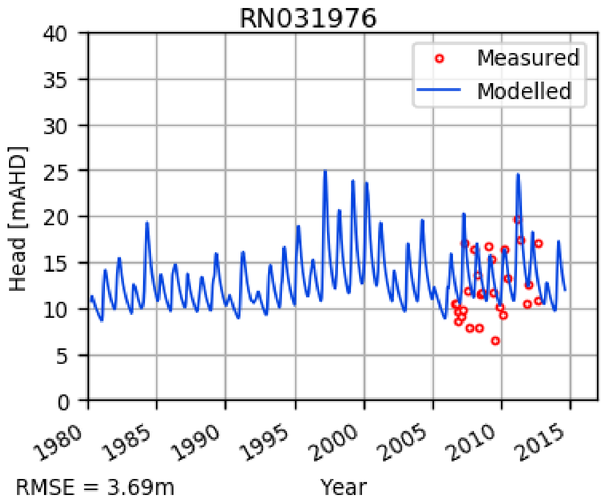
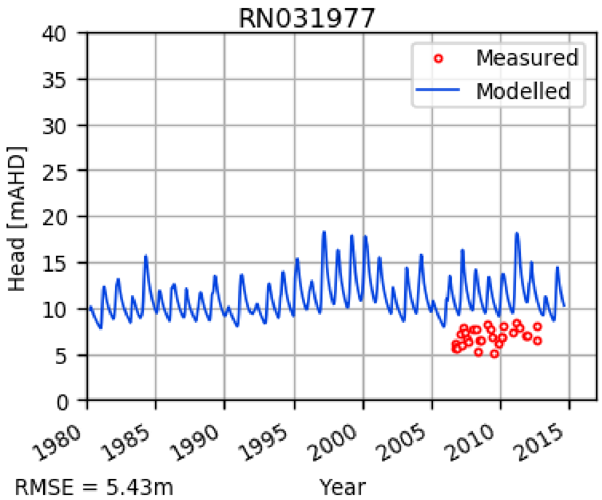
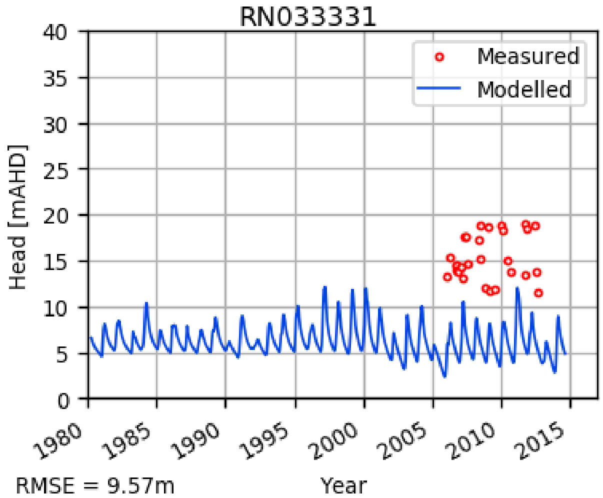
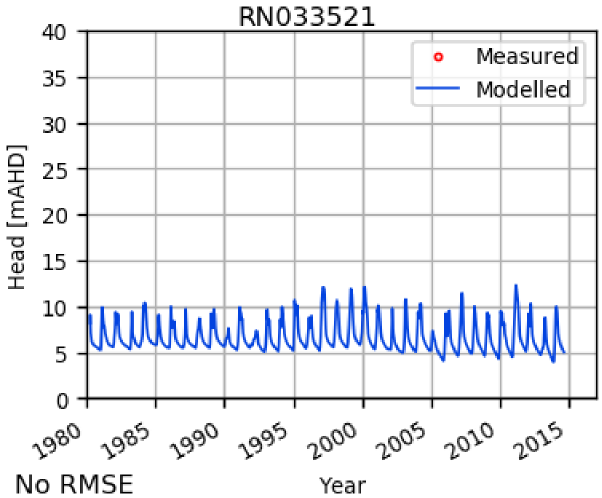
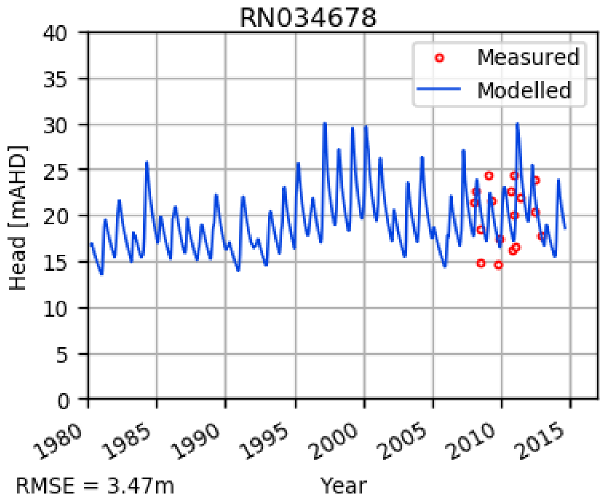
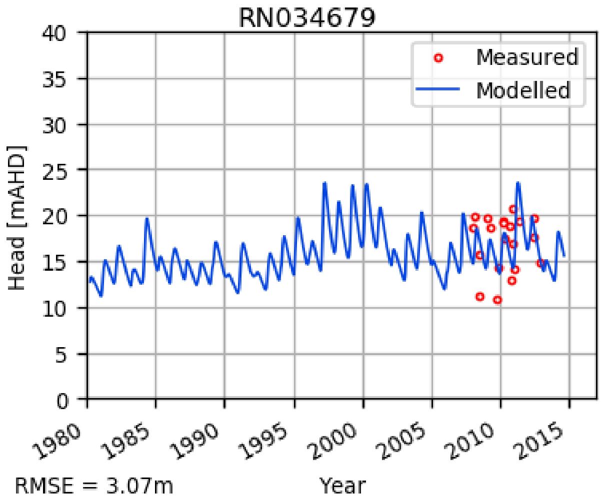

RN031976
Measured
Modelled
Head [mAHD]
Year
RMSE = 3.69m

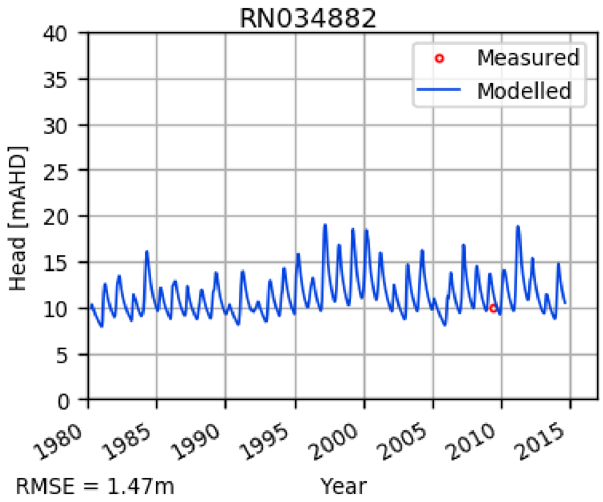

RN031977
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.43m

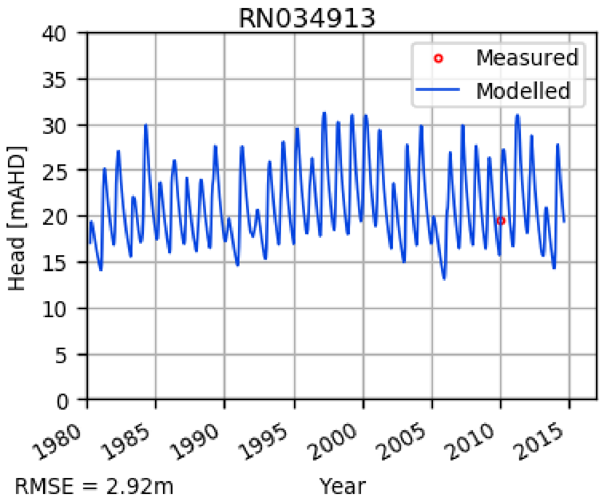

RN033331
Measured
Modelled
Head [mAHD]
Year
RMSE = 9.57m

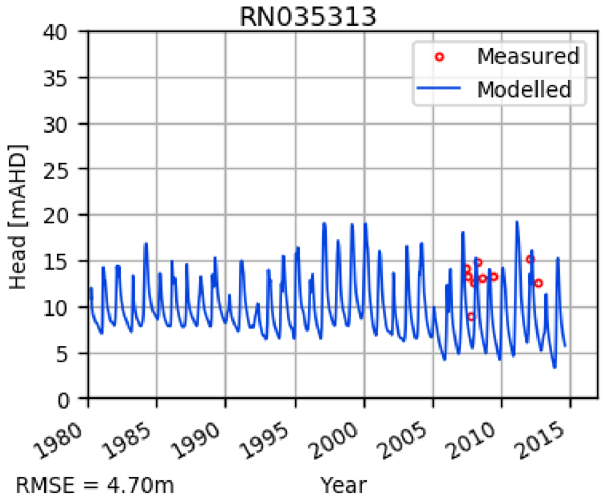

RN033521
Measured
Modelled
Head [mAHD]
Year
No RMSE

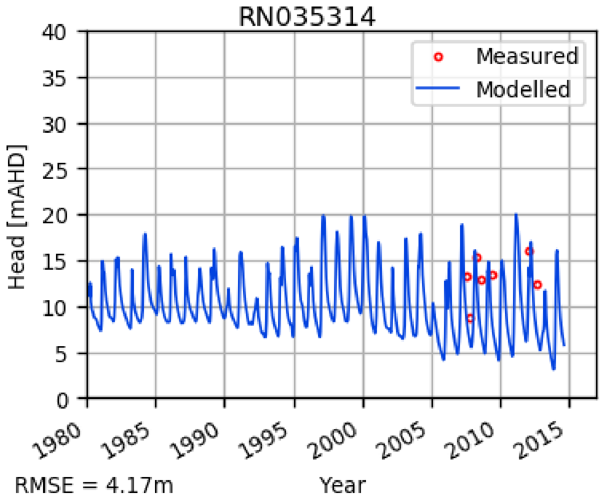

RN034678
Measured
Modelled
Head [mAHD]
Year
RMSE = 3.47m

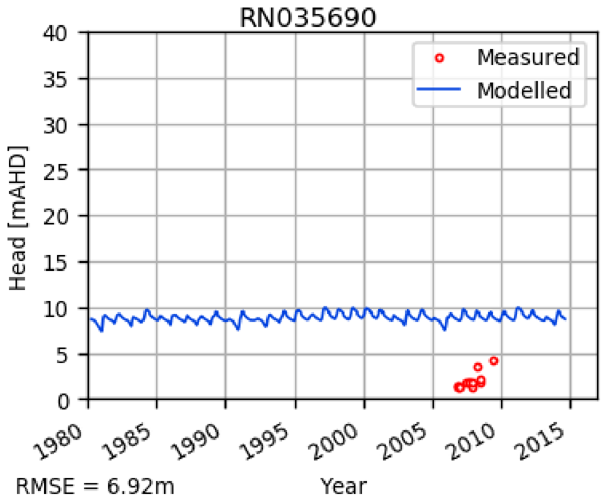

RN034679
Measured
Modelled
Head [mAHD]
Year
RMSE = 3.07m

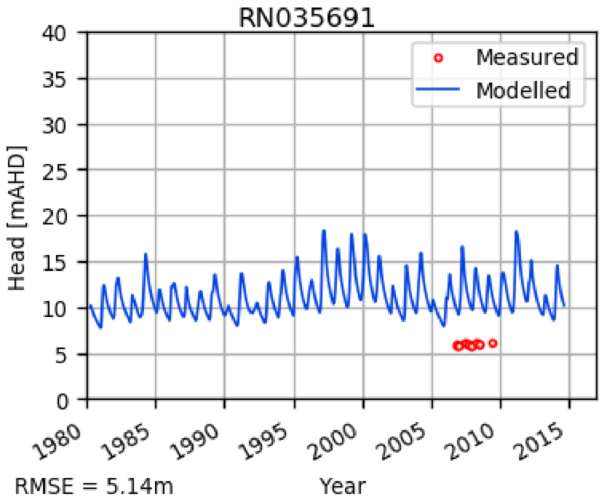

RN034882
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.47m

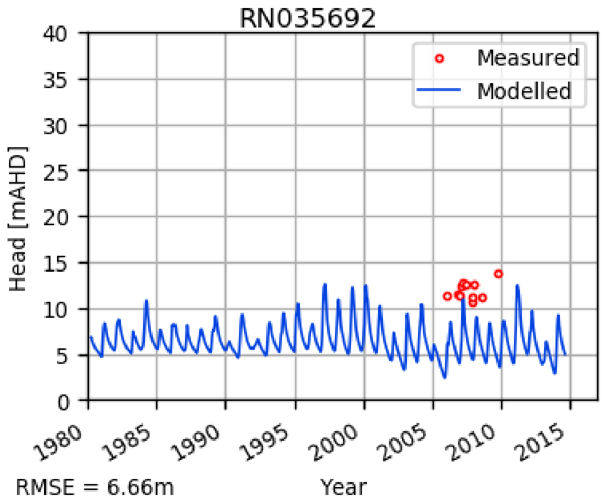

RN034913
Measured
Modelled
Head [mAHD]
Year
RMSE = 2.92m

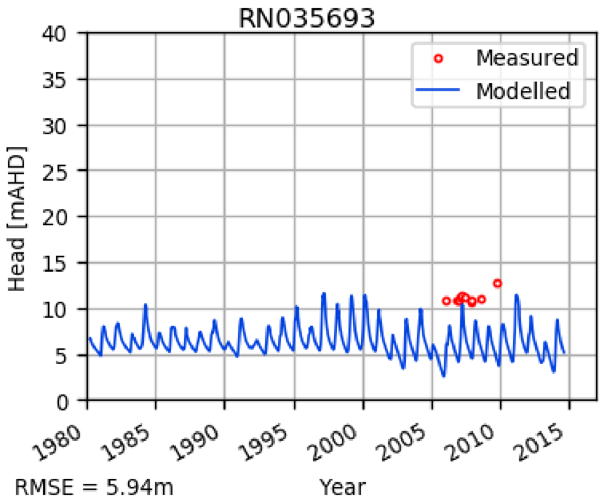

RN035313
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.70m

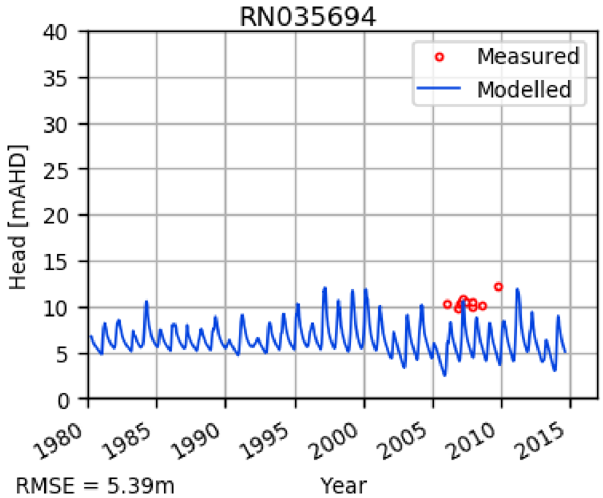

RN035314
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.17m

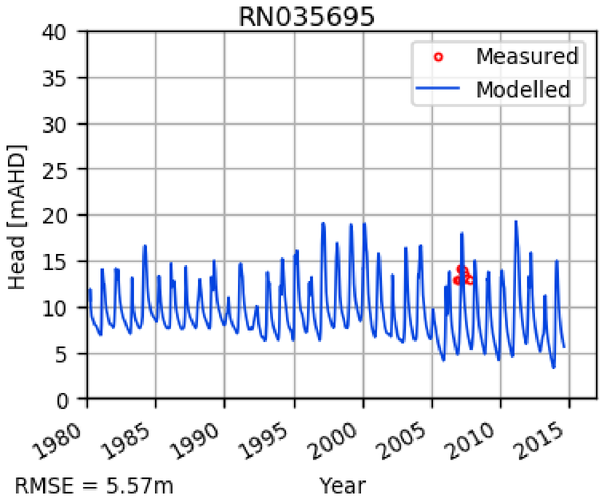

RN035690
Measured
Modelled
Head [mAHD]
Year
RMSE = 6.92m

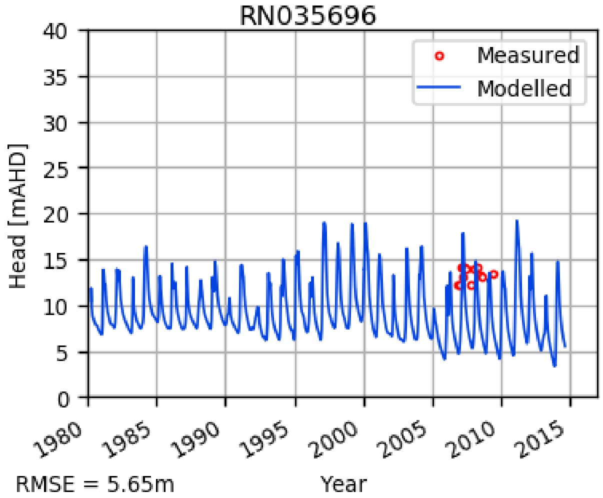

RN035691
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.14m

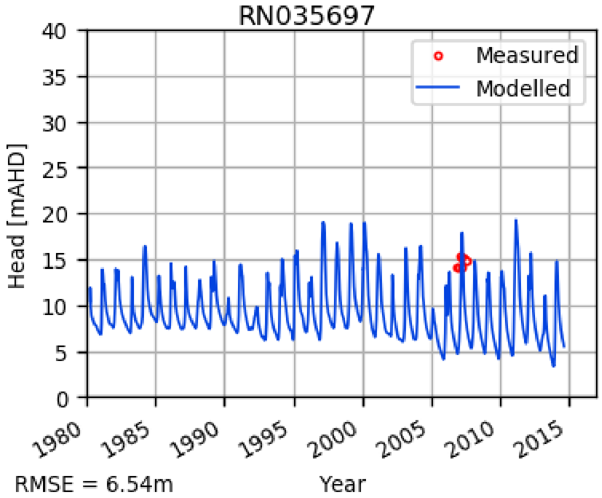

RN035692
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 6.66m
Year

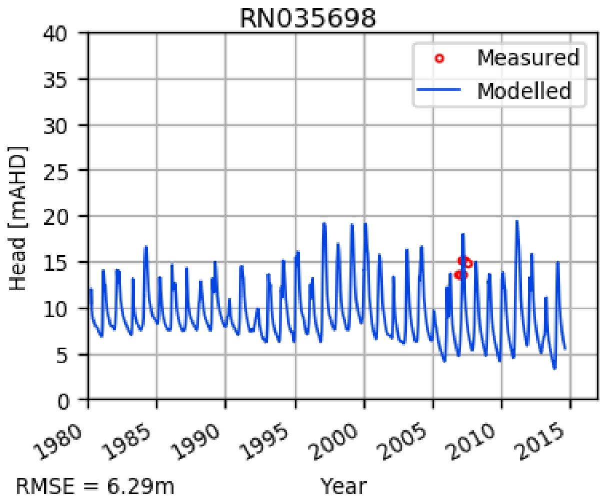

RN035693
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 5.94m
Year

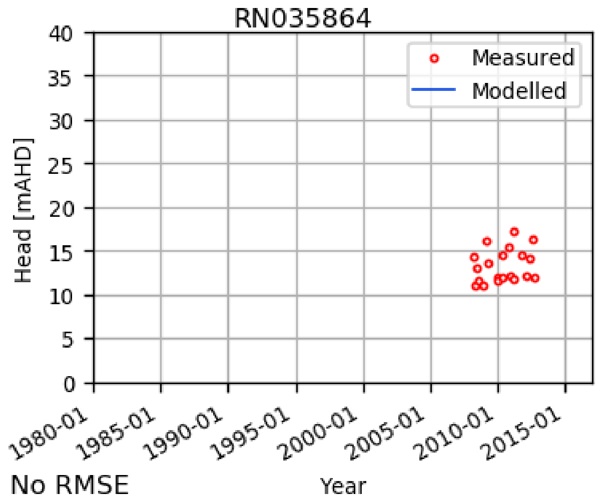

RN035694
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 5.39m
Year

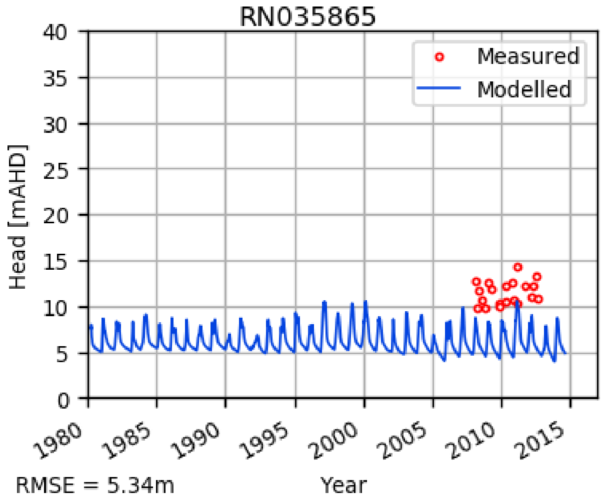

RN035695
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 5.57m
Year

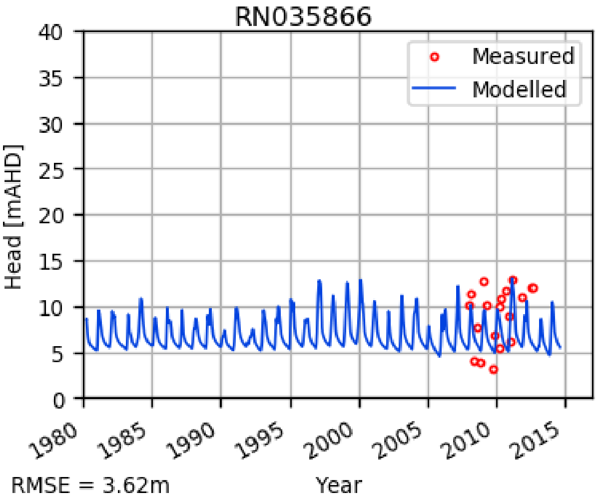

RN035696
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 5.65m
Year

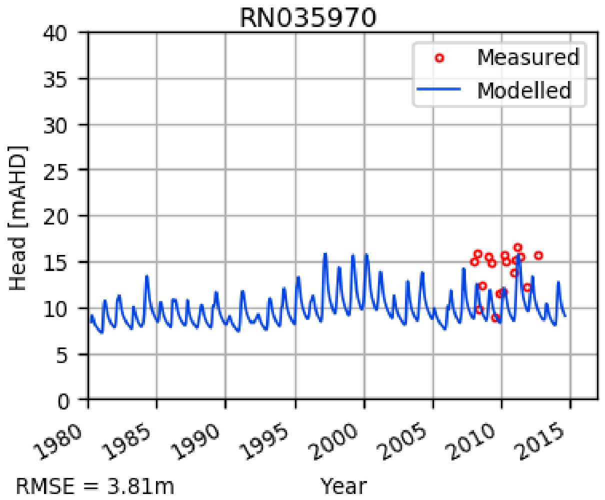

RN035697
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 6.54m
Year

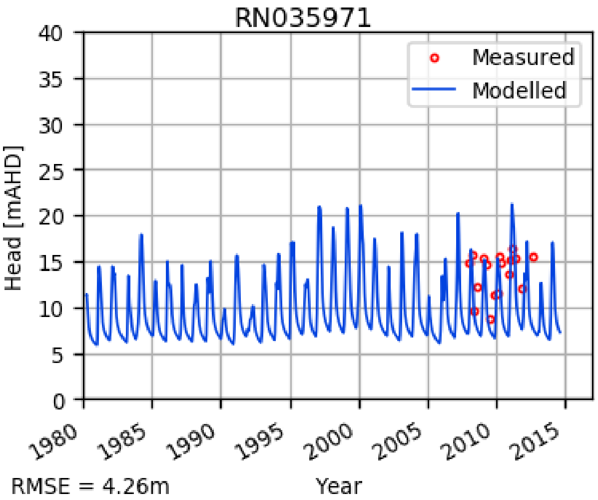

RN035698
Measured
Modelled
Head [mAHD]
Year
RMSE = 6.29m


RN035864
Measured
Modelled
Head [mAHD]
Year
No RMSE


RN035865
Measured
Modelled
Head [mAHD]
Year
RMSE = 5.34m


RN035866
Measured
Modelled
Head [mAHD]
Year
RMSE = 3.62m


RN035970
Measured
Modelled
Head [mAHD]
Year
RMSE = 3.81m


RN035971
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.26m

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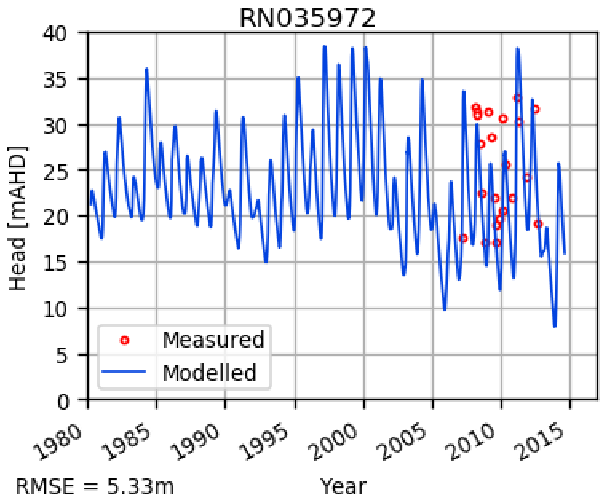
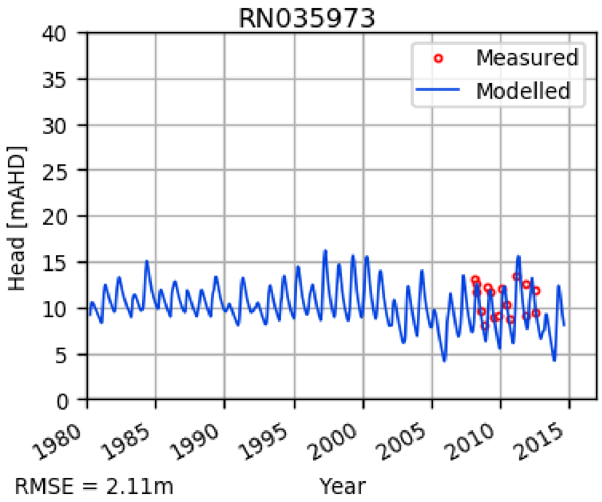
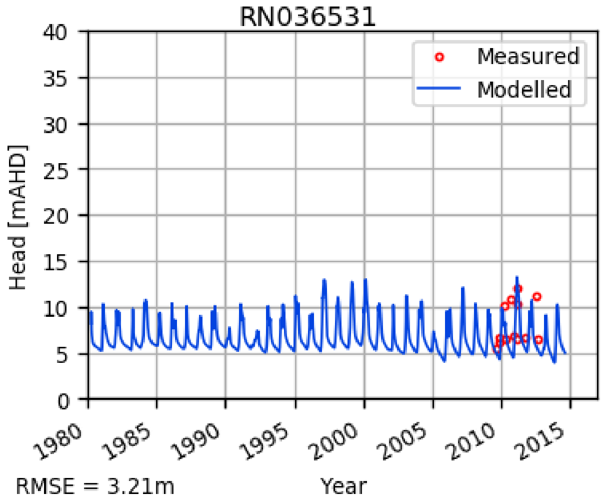
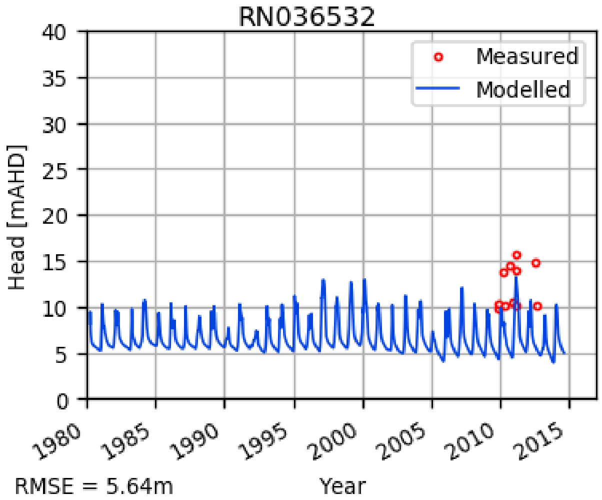
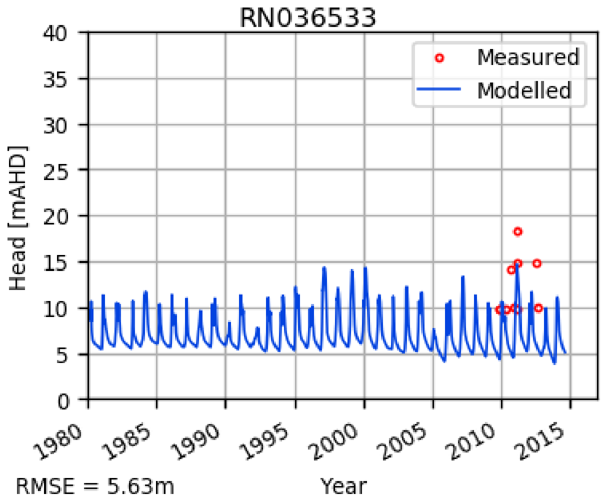
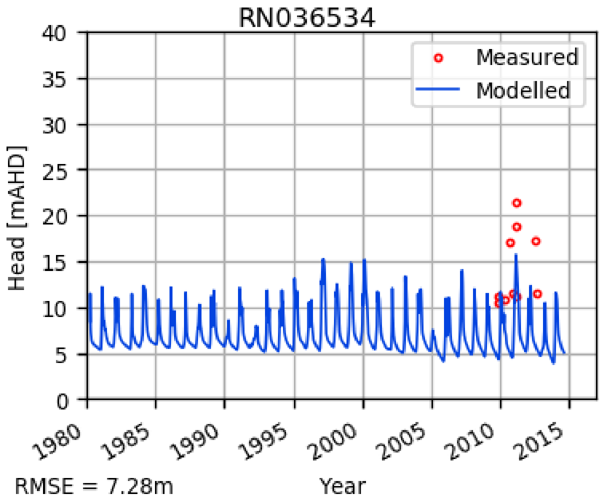

RN035972
Head [mAHD]
Year
Measured
Modelled
RMSE = 5.33m


RN035973
Head [mAHD]
Year
Measured
Modelled
RMSE = 2.11m


RN036531
Head [mAHD]
Year
Measured
Modelled
RMSE = 3.21m


RN036532
Head [mAHD]
Year
Measured
Modelled
RMSE = 5.64m


RN036533
Head [mAHD]
Year
Measured
Modelled
RMSE = 5.63m


RN036534
Head [mAHD]
Year
Measured
Modelled
RMSE = 7.28m

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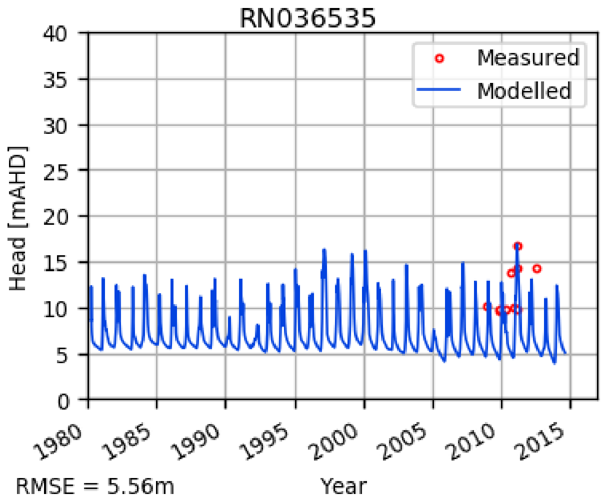
RN036535
Measured
Modelled
Head [mAHD]
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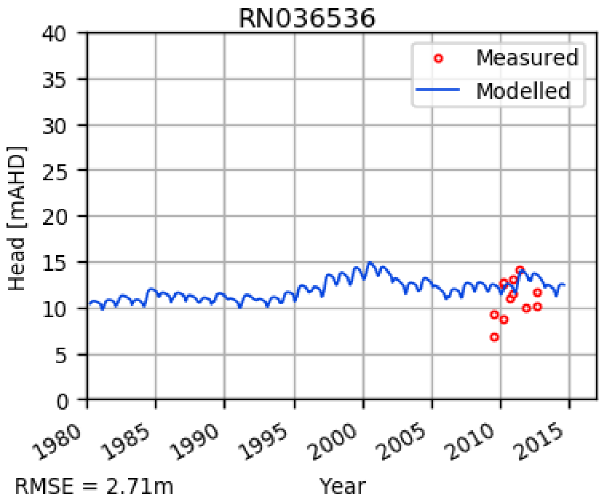
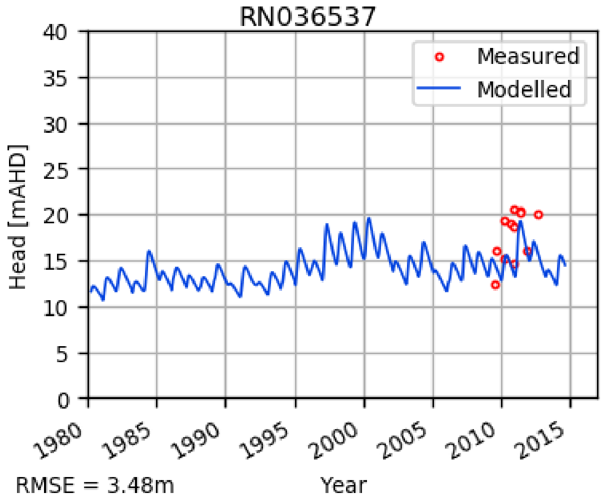
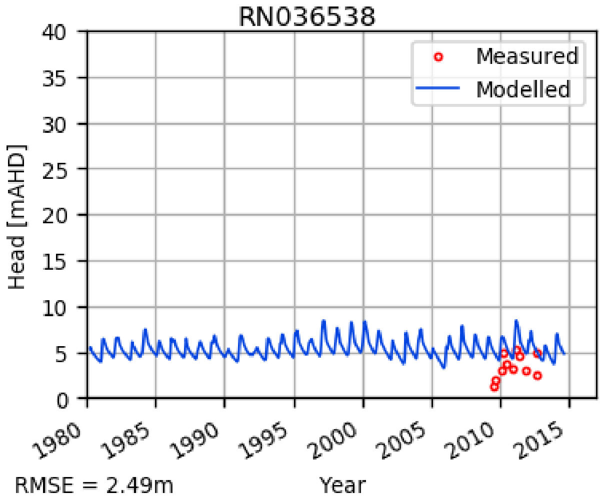
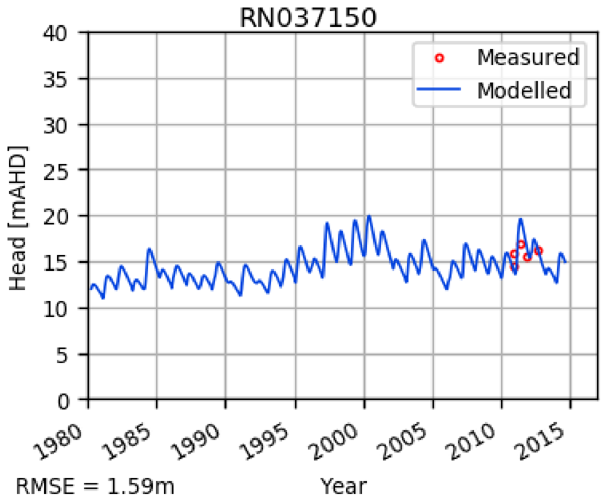
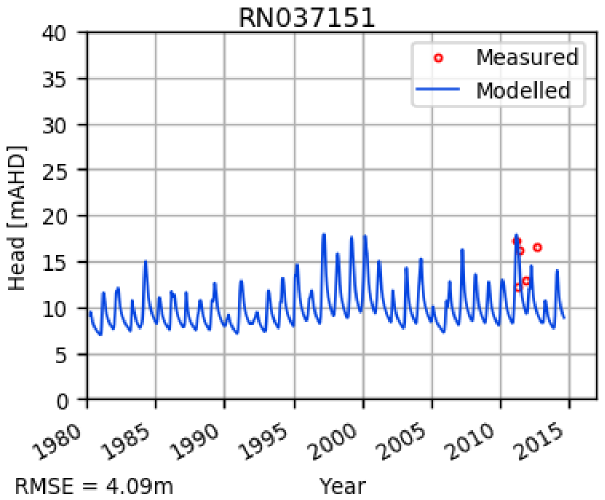
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 5.56m
Year

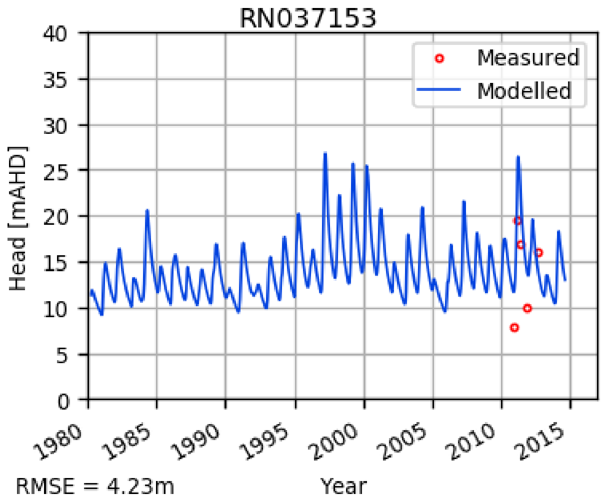

RN036536
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 2.71m
Year

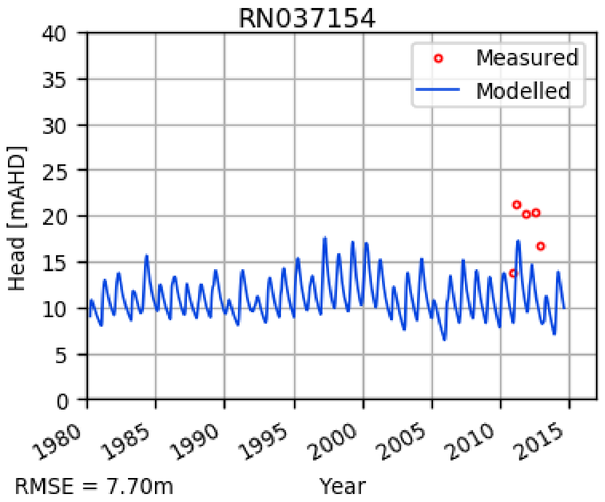

RN036537
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 3.48m
Year

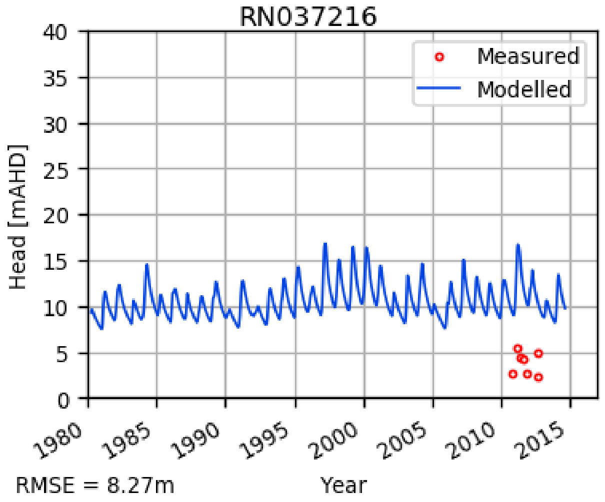

RN036538
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 2.49m
Year

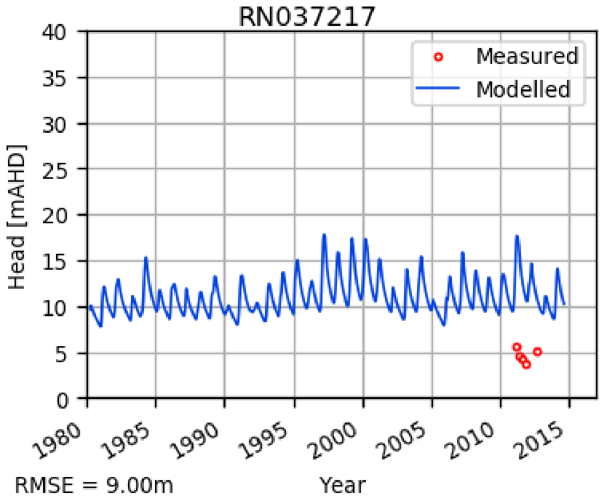

RN037150
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 1.59m
Year

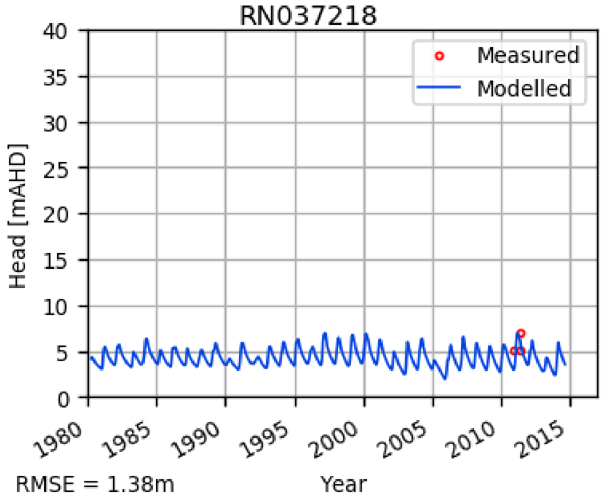

RN037151
Measured
Modelled
Head [mAHD]
0 5 10 15 20 25 30 35 40
1980 1985 1990 1995 2000 2005 2010 2015
RMSE = 4.09m
Year

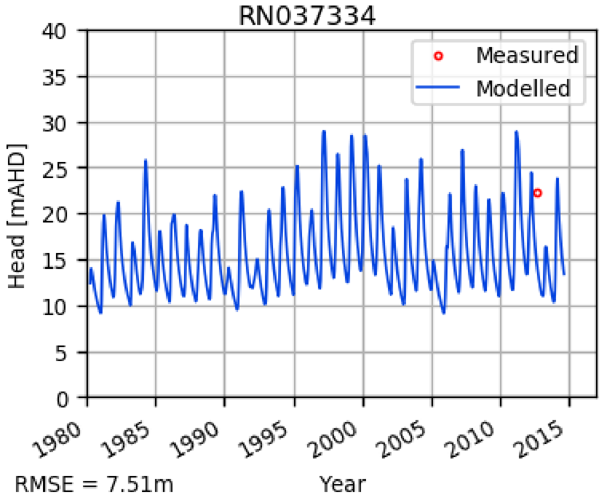

RN037153
Measured
Modelled
Head [mAHD]
Year
RMSE = 4.23m

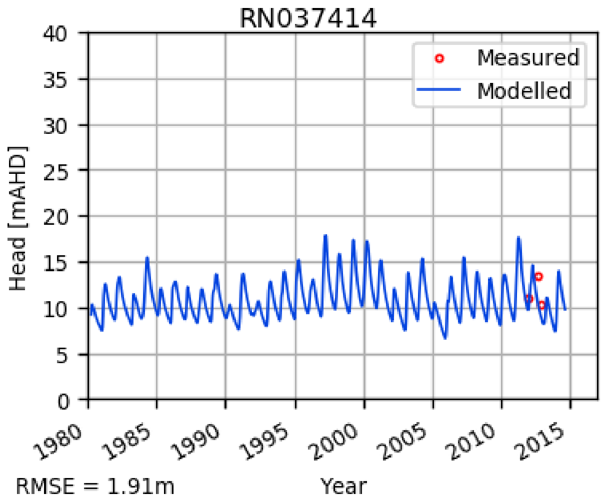

RN037154
Measured
Modelled
Head [mAHD]
Year
RMSE = 7.70m

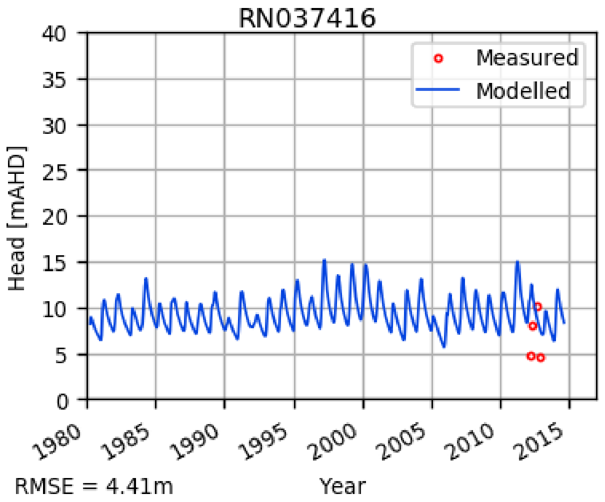

RN037216
Measured
Modelled
Head [mAHD]
Year
RMSE = 8.27m


RN037217
Measured
Modelled
Head [mAHD]
Year
RMSE = 9.00m


RN037218
Measured
Modelled
Head [mAHD]
Year
RMSE = 1.38m


RN037334
Measured
Modelled
Head [mAHD]
Year
RMSE = 7.51m


RN037414
Measured
Modelled
Head [mAHD]
40
35
30
25
20
15
10
5
0
1980
1985
1990
1995
2000
2005
2010
2015
RMSE = 1.91m
Year


RN037416
Measured
Modelled
Head [mAHD]
40
35
30
25
20
15
10
5
0
1980
1985
1990
1995
2000
2005
2010
2015
RMSE = 4.41m
Year