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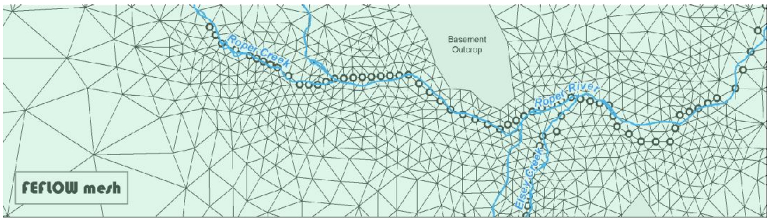
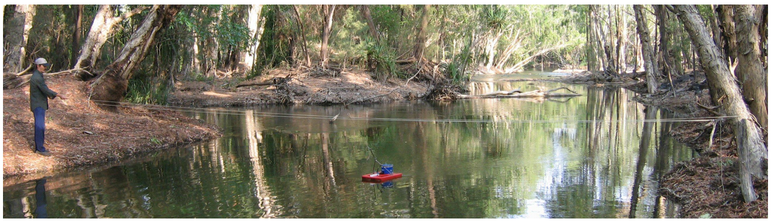
Gulf Water Study

Integrated Surface - Groundwater Model of the Roper River Catchment

Part C: FEFLOW Groundwater Model





Australian Government
Water Smart Australia

Department of Natural Resources, Environment, The Arts & Sport

Water Resources Branch, Technical Report No. 32/2009D

Gulf Water Study

An integrated surface – groundwater model of the Roper River Catchment, Northern Territory

Part C – FEFLOW Groundwater Model

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Department of **Natural Resources, Environment, The Arts & Sport**

Technical Report No. 32/2009D

ISBN 978-1-921519-63-5

Cover Image: top to bottom: Anthony Knapton at Bitter Springs, FEFlow Mesh and Flow Gauging on the Roper River

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Summary

The Gulf Water Study is a three year project funded jointly by the Australian Government's Water Smart Australia Program and the Northern Territory Government. The Smart Australia Program aims to accelerate the development and uptake of smart technologies and practices in water use across Australia.

Water reform through the Australian Government National Water Commission’s National Water Initiative (NWI) has established that environmental water provisions should be made prior to allocating to other consumptive uses. This has proven difficult in Southern Australia with its history of urban and rural developments. There is an opportunity here in the tropical north to do it smart. We can obtain the knowledge on environmental water provisions before allocation.

A key outcome of the Gulf Water Study is the development of an integrated surface – groundwater model of the Roper River. The integrated model of the Roper River will provide water allocation planners with quantitative information on the water resources and identifies likely groundwater dependent ecosystems. This information will help in long term decision making and identify the areas where further study is required. The integrated model also provides quantitative information, through the ability to undertake scenario modelling, that will ensure that the current and planned regional water development remain within ecologically sustainable limits.

A finite element numerical groundwater model has been developed to simulate groundwater flows in the carbonate aquifers and generate the fluxes that provide dry season base flows to the Roper River and its’ tributaries.

Two aquifer systems, in a Cambrian Limestone and a Mesoproterozoic Dolostone that discharge to the Roper River were modelled. The Cambrian Limestone at the headwaters of the Roper River is reasonably represented in terms of the dry season discharges and the groundwater levels. The Mesoproterozoic Dolostone aquifer has been less satisfactorily represented, primarily because of the limited amount of groundwater level and discharge data.

This report documents an ambitious attempt at modelling the entire Cambrian Limestone aquifer, with an emphasis on the area surrounding Mataranka and the head waters of the Roper River. This report also documents the preliminary modeling of the entire aquifer system developed in the Mesoproterozoic aged Dook Creek Formation.

1 Introduction

1.1 Background

Effective management of ecosystems requires a sound knowledge of its characteristics and the interrelationship between elements of the hydrologic cycle. In tropical northern NT with its Wet and Dry seasons, groundwater plays a key role in ecosystem survival by the provision of water to wetlands and rivers throughout the dry season. Therefore there is a high priority to identify groundwater discharges that sustain flows which maintain groundwater dependent ecosystems. Groundwater recharge, behaviour and response remain as the major knowledge gaps in the understanding of our tropical rivers.

Two major aquifers relevant to the Roper River are the:

- Cambrian Limestone aquifer system formed in the Wiso, Georgina and Daly Basins. It represents the source of the majority of the baseflow in the Roper River and also the Katherine, Flora and Douglas Rivers and;
- The Dook Creek aquifer system which provides baseflow to the major tributaries to the north of the Roper River namely Flying Fox Creek, the Mainoru River and the Wilton River and also the Blyth and Goyder Rivers which drain to the Arafura Sea.

Proposed horticultural development of groundwater from the Cambrian Limestone aquifer in the Mataranka region, represent a potential threat to the environmental flow regime of the river and cultural needs of the community particularly in low flow periods.

This report documents an ambitious attempt at modelling the entire Cambrian Limestone aquifer, with an emphasis on the area surrounding Mataranka and the head waters of the Roper River. This report also documents the preliminary modelling of the entire aquifer system developed in the Mesoproterozoic aged Dook Creek Formation.

1.2 Objectives

The objectives of this study were to:

- Develop two regional groundwater models that will provide a framework for the aquifer systems providing baseflow to the Roper River;
- Provide a basis for the assessment of development with respect to pumping scenarios and their effects on the dry season flows in the Roper River ie during periods when base flows are lowest.

During the development of the groundwater model the following items were also considered:

- Locate Transfer boundary conditions close to the MIKE11 H-Q points to enable coupling of the surface – groundwater models in the areas where discharge to the rivers has been identified;

This report presents the basis for the groundwater model development and identifies limitations in the conceptual model and areas in which data deficiencies exist.

1.3 Scope

This report details the assumptions and limitations used in the development of the finite element numerical groundwater flow model.

The scope of this study was to develop a saturated groundwater model of the aquifers in the Roper River catchment suitable for coupling to a MIKE11 surface water model. The model was developed using the following steps:

- Conceptual model development;
- Numerical model implementation;
- Development and calibration of a regional steady state model;
- Extension of the calibrated steady state model to the transient domain in the study area;
- Calibration of the model to the transient hydrologic data from 1994 to 2004 including rainfall/recharge data, water levels hydrographs, stream flow data and pumping data;

1.4 Location

The groundwater modelling study is centred on the Roper River catchment near Mataranka in the Northern Territory of Australia refer **Figure 1**. The model domain covers approximately 181 200 km^2 and includes the entire extent of the Cambrian Limestone of the northern Wiso Basin to the west, the northern Georgina Basin to the southeast and Daly Basin in the northwest. To the northeast the model includes the outcropping Dook Creek Formation.

The Roper River drains the basins through a dendritic tributary system. This system is shown in Figure 1, Figure 2 and in better detail in Figure 3 of Part B of this report..

1.5 Previous Groundwater Modelling Studies

Water Studies developed a detailed model centred on the unconfined occurrence of the Cambrian Limestone in the area of the Katherine River. The objective of the model was to determine the effects of pumping in the Venn Horticultural sub-division on groundwater levels and flows in the Katherine River.

Puhalovich, (2005) developed a model based on the work of Water Studies, (2001). The model was extended to the south east to include the groundwater divide between the Katherine and Roper River and the discharge zones at the Roper River. It incorporated the contribution to the

Cambrian aquifer from the inflows from the Cretaceous aquifers in the vicinity of the head waters of the King River using a General Head Boundary condition.

Knapton (2006) documents the development of a 2D finite element model designed to simulate groundwater flows primarily in the Katherine River area, however, it encompassed the known extent of the Tndall Limestone and incorporated the discharge from the aquifer to the Douglas, Flora and Roper Rivers.

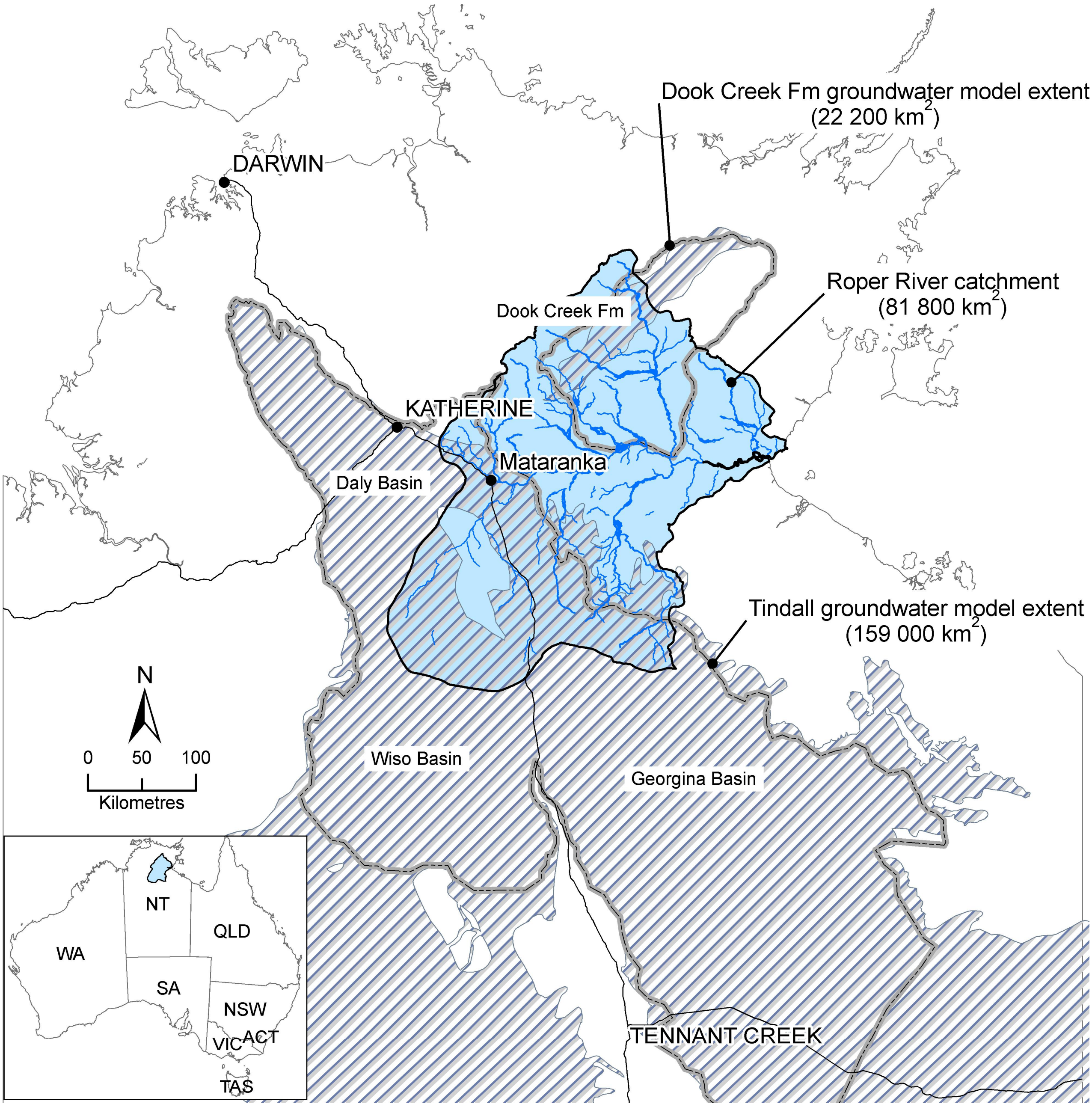

Figure 1 Location of the Roper River catchment with respect to the major groundwater basins.

URS (2008) extended the model to include the upper carbonate sequence (Oolloo dolostone) to model baseflow to the Daly River. The groundwater model was coupled to a surface water model developed by DHI. DHI (2007) documents the development of the surface water model.

No known numerical modelling has been completed for the Dook Creek Formation. Groundwater resources studies have been conducted for the Beswick water supply (Yin Foo, 1983) and the Bulman water supply (Verma and Rowston, 1992).

2 Regional Hydrogeology

2.1 Introduction

The major hydrogeological units of the Roper River catchment are the Cambrian limestones of the Daly, Wiso and Georgina Basins and the Mesoproterozoic dolomitic Dook Creek Formation of the McArthur Basin. These two major groundwater systems provide dry season inputs to the Roper River. The hydrogeology and water resources of the Cambrian Limestone are described in detail by Tickell, (2005).

Early Cretaceous rocks overlie much of the Cambrian Limestone to the southeast and the south western portions of the Dook Creek dolostone (refer **Figure 2**).

The aquifers of the Cambrian Limestone and the Dook Creek Dolostone are typical of karstic aquifers where chemical weathering has produced wide spread secondary porosity and permeability in the carbonates. The carbonate aquifers are expected to have greatest permeability within the weathered zone, up to a maximum of 100 – 150 metres below the surface. The karstic nature of the aquifers mean that on a local scale groundwater flow is via preferential pathways, however, previous modelling has demonstrated that at a basin wide scale the aquifers are considered to behave as an equivalent porous media with very high transmissivities (5,000 m^2/d for the Cambrian limestone and 1,000 m^2/d for the Dook Creek dolostone) and relatively low storage coefficient/specific yield with estimates ranging from 0.01 to 0.06 (1 to 6%). The geological units of importance to the study are discussed below.

2.1.1 Fractured basement rocks

The early Cambrian Antrim Plateau Volcanics is generally a flat lying, dark grey/green coarse grained tholeiitic basalt that underlies the Cambrian Limestone units (Tindall Limestone, Montejinni Limestone and Gum Ridge Formations) and forms the hydrogeological basement for much of the model extent.

A basement high separates the groundwater flow regimes of the Wiso and Georgina Basins. Groundwater flows in the Wiso Basin to the west of the basement high feed the springs in the Flora River whilst the Georgina Basin flows primarily provide discharge into the Roper River (Yin Foo and Matthews, 2001).

2.1.2 Mesoproterozoic Dook Creek Formation

The Mesoproterozoic Dook Creek Formation of the McArthur Basin is described as a dololutite, dolomitic sandstone and siltstone, stromatolitic and oolitic dolostone, chert, quartz sandstone, conglomerate, mudstone, siltstone.

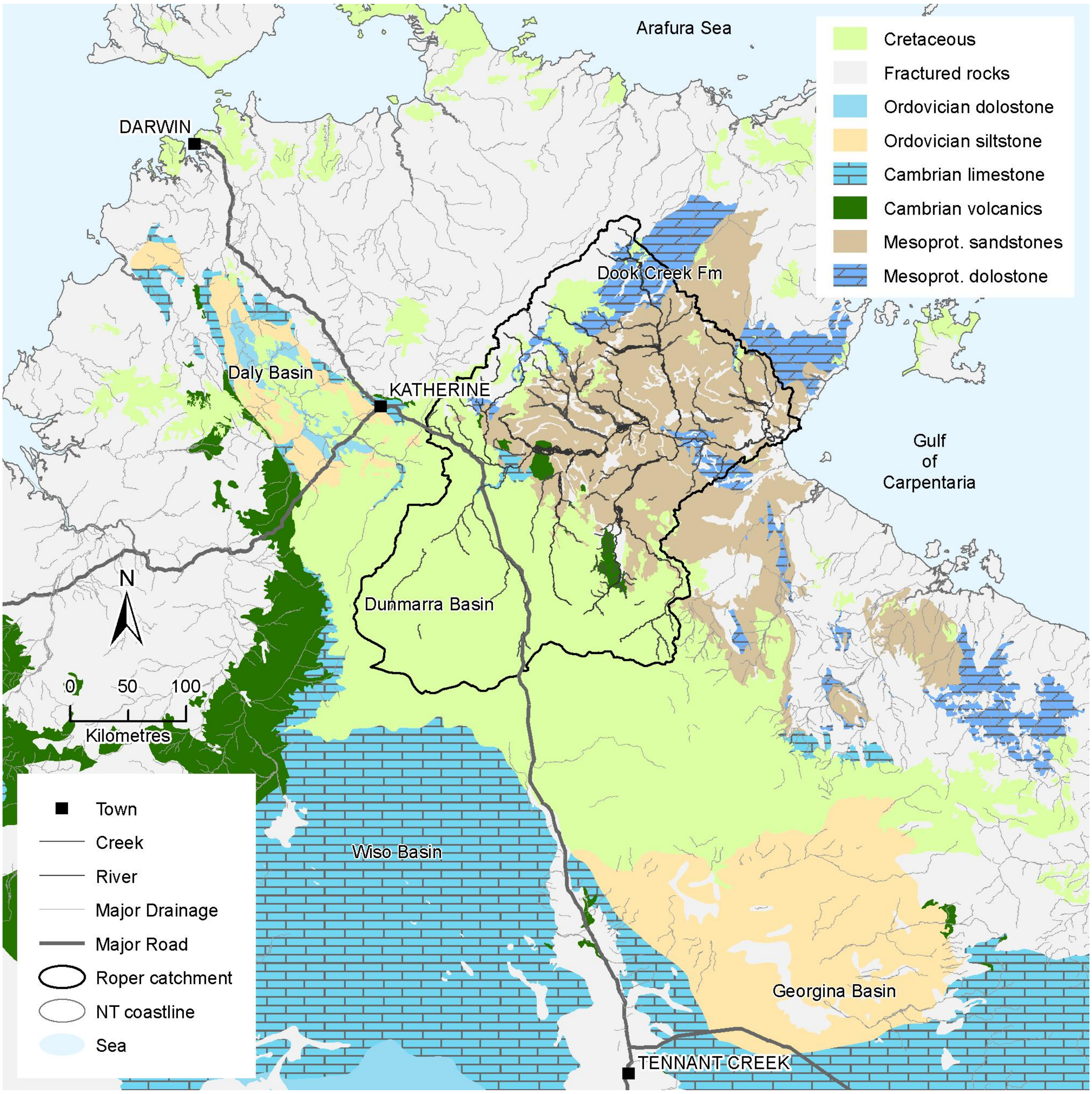

Figure 2 Regional geology of the study area.

The Dook Creek Formation is intensely weathered and silicified to a depth of 20 metres as a consequence of both pre and post Cretaceous weathering. The outcrop and sub-crop belt of the Dook Creek Formation is paralleled by a belt of sinkholes, developed in the carbonates as a consequence of deep weathering and its accompanying effects (Sweet et al., 1999).

The most widespread deep-weathering and silicification events occurred in the Cretaceous and Cainozoic – both before and after Cretaceous sedimentation. The later episode is widely regarded as of mid-Tertiary age, but could be as old as Late Cretaceous. Sinkhole development appears to post date this deep weathering and probably continues to present (Sweet et al., 1999).

Pumping tests conducted in the Dook Creek formation have been completed in the Beswick and the Bulman areas. Both reports indicate that the transmissivity of the aquifer can be substantial with estimates averaging 700 m^2/d in the Beswick study (Yin Foo, 1983) and of the order of 6000 m^2/d in the Bulman study (Verma and Rowston, 1992). Both studies identify that the high transmissivities are associated with secondary permeability developed in fault zones. The studies do however highlight that under suitable conditions high transmissivities can be expected in the Dook Creek Formation.

For the purposes of this study this formation is assumed to be represented as a single, extensive aquifer system and are referred to generally in this report as the ‘Dook Creek Dolostone aquifer’.

2.1.3 Mesoproterozoic Roper Group (Limmen Sandstone)

The Limmen Sandstone of the McArthur Basin is a quartz rich to sublithic, fine to coarse grained silicified sandstone which lies disconformably over the Dook Creek Formation (Sweet et al., 1999).

Currently the assumption is that the Limmen Sandstone confines the Dook Creek Formation and very little or no recharge to the Dook Creek aquifer occurs through this formation.

2.1.4 Cambrian Limestone – (Tindall Limestone, Gum Ridge Formation and Montejinni Limestone)

The time equivalent Cambrian limestone formations – the Tindall Limestone, the Montejinni Limestone and Gum Ridge Formations host the vast majority of the water resources in the region and have many stratigraphic similarities (Tickell, 2005).

The Tindall Limestone of the Daly Basin is a massive, thinly bedded, multi-coloured crystalline, dolomitised limestone with some chert nodules and mudstone bands, particularly in the lower layers. The Tindall Limestone becomes shaley to the northwest in the Douglas River area.

The Montejinni Limestone of the Wiso Basin consists of limestone, dolomitic limestone, dolomite and calcareous mudstone and siltstone. In many parts of the basin, a threefold division has been recognised with an upper and lower limestone unit each approximately 25 metres thick and an intervening red/brown mudstone about 10 metres thick (Tickell, 2005).

The Gum Ridge Formation of the Georgina Basin, although similarly sequenced to the Tindall Limestone Formation, is generally described as consisting of limestone, fine grained sandstone and siliclastic mudstone and nodular chert. The depositional environment of this formation has resulted in a greater proportion of carbonate sediment.

(Lauritzen & Karp, 1993) concluded that the Tindall Limestone karst aquifer developed before the Cretaceous period. The permeability of the karst aquifer has been further enhanced since then by the movement of acidic groundwater from the aquifer developed in the basal Cretaceous sandstone where it overlies the limestone.

For the purposes of this study, no hydrogeological distinction is made between each of the Cambrian Limestone formations as they represent a single, extensive aquifer system and are referred to generally in this report as the 'Cambrian Limestone aquifer'.

2.1.5 Ordovician Siltstone - (Jinduckin Formation, Hooker Creek Beds and Anthony Lagoon Beds)

The laterally equivalent formations of the Ordovician aged Jinduckin Formation, Hooker Creek Beds and Anthony Lagoon Beds occur in the Daly Basin, Wiso Basin and Georgina Basins respectively.

In the Daly Basin the Jinduckin Formation overlies the Tindall Limestone whereas in the Wiso Basin the Hooker Creek Beds overlie the Montejinni Limestone and in the Georgina Basin the Anthony Lagoon Beds overlie the Gum Ridge Formation. They are mainly of dolomitic siltstone, interbeds of dolomitic sandstone-siltstone and dolostone. The Jinduckin Formation has been eroded off over most of the Sturt Plateau and only exists in the Daly Basin and in the north of the Wiso Basin, where it is overlain by Mullaman Beds. Similarly, a partial section of the Anthony Lagoon Beds is seen in the Larrimah area where highly weathered remnants may be detected in gamma logs. The formation continues to thicken towards the south-east into the Georgina Basin where approximately 60 metres of its lower section may be identified in bore RN27958 east of Dunmarra.

The Jinduckin and Anthony Lagoon formations overlie and confine the major Cambrian Limestone aquifers of the region. Aquifers are only sparsely developed in this formation (Sanders, 1993). Where they exist below the water table, they may host viable aquifers, however, these are generally of limited extent low permeability and low yield. Dissolution of evaporite beds within these formations result in water with significant levels of sulphate and sodium chloride salts.

For the purposes of this study, no hydrogeological distinction is made between each of the formations and represent an extensive aquitard, confining the Cambrian Limestone aquifer and preventing recharge and is referred to as the 'Ordovician Siltstone'.

2.1.6 Cretaceous Rocks of the Dunmarra Basin

The Cretaceous aged Mullaman Beds of the Dunmarra Basin form a mantle of lateritised claystone and sandstone covering a large proportion of the study area. The beds are sub-horizontal and may be divided into an upper cream coloured claystone and siltstone unit and a basal marine sandstone unit.

Outcrop is generally sparse due to the soft nature of the rock but in places silicification has altered them to porcellanite and quartzite which outcrop reasonably well. The thickest accumulations in the Daly Basin are preserved along its axis, running from the north side of the King River, through Florina Station and then following the north east side of the Daly River as far as Stray Creek (Tickell, 2002).

The Cretaceous rocks consist predominantly of an upper clay, claystone and a basal sandy clay with lesser sandstone, sand and clayey sand. The main influence of the Cretaceous sediments is to reduce the recharge to the carbonate aquifers. The effect of reduced recharge is due to the lithology of the rocks, which are predominantly clay/clayey sand. There is a distinct subdued response of groundwater hydrographs for the bores located in areas where Cretaceous rocks cover the underlying carbonate aquifer reflecting the reduction in recharge. Water balance and hydrograph analysis in the vicinity of Katherine indicates that recharge is approximately 25% of the recharge observed in areas with outcropping carbonates (Knapton (2004) and (Knapton, 2006)).

The thickness of the basal sandy unit is variable and ranges from less than 5 metres thick, up to 25 metres thick in parts of the central plateau area. The sandstone is generally friable, however, siliceous outcrops of the unit are located in the vicinity of Gorrie Station. Where the upper claystone is thin and eroded, the potential recharge to the underlying limestone aquifer is increased. In all places, the Mullaman Beds are above the regional water level.

Mapping of the outcrop of these two distinct phases of the Mullaman Beds will provide greater control on the distribution of recharge.

Where it overlies relatively impermeable basement the Cretaceous sandstone contributes significant dry season flows to rivers such as the Waterhouse River.

Table 1 Hydrogeological units relevant to the groundwater modelling study.

Unit name	Age	Dominant Lithology	Hydrologic type	Comment
Dook Creek Formation	Mesoproterozoic	Dolostone	Karstic aquifer	Aquifer with major discharge
Limmen Sandstone - Roper Group	Mesoproterozoic	Sandstone	Confining aquiclude	Overlies and confines the Dook creek Formation
Antrim Plateau Volcanics	Middle Cambrian	Basalt	Hydrologic basement	Underlies the Cambrian Limestone.
Cambrian Limestone and equivalents	Middle Cambrian	Limestone	Karstic aquifer	Extensive aquifer with major discharge
Ordovician Siltstone and equivalents	Early Ordivician	Shale, sandstone and dolostone	Confining aquitard	Overlies and confines the Cambrian Limestone
Mullaman Beds	Early Cretaceous	Claystone and basal sandstone		Overlies large protions of the Cambrian and Dook Creek and reduces the amount of

				recharge

2.2 Structural Controls

At its southern extent of the Cambrian Limestone is a relatively flat lying layer approximately 150 – 200 metres thick. Although generally flat lying, drilling indicates a major fault exists between the Wiso Basin and Georgina Basin with a displacement of approximately 200 metres. The Georgina Basin is on the down throw side of the fault (Yin Foo and Matthews, 2001). The location of the fault is shown in Knapton (2000) The Daly Basin is a synclinal feature with a maximum depth of 600-700 metres. Currently it is assumed that the fault separating the Wiso Basin and Georgina Basin does not extend north into the Daly Basin and that the limestone forms a continuous layer approximately 200 – 250 metres thick in this area.

The Bulman Fault cuts across the outcropping Dook Creek aquifer near the community of Bulman (Verma, et al, 1992). Some lateral displacement is evident from the surface geology. Some of the major springs discharging from the Dook Creek aquifer are located in close proximity to the fault (eg Weemol Spring), however, the influence of this feature on regional groundwater flows is unknown.

3 Available Data

3.1 Water Levels

Water levels were obtained from the Northern Territory Government groundwater database Hydstra. Levels were supplemented by non recorded water levels in driller submitted bore statements and Reports (eg. (Sanders, 1993)). Based on this information 55 bores drilled into the Cambrian limestone have one or more water level records. 9 bores have been drilled into the Dook Creek formation, 6 are within the Roper River catchment. Of the 55 bores 16 are within 100 kilometres of the head waters of the Roper River, the majority of these bores have been drilled recently and have a relatively short groundwater level record (1 – 5years). The locations of the bores used in the model development and calibration are identified in **Figure 3**.

The elevation of the bore collars have been largely derived by extracting surface elevations from the Shuttle Radar Terrain Model (SRTM) raster grid (Farr et al., 2007) digital terrain model using the bore location as stored in the Hydstra database. Bores drilled as part of the Gulf Water Study have been surveyed using differential GPS techniques (Knapton, 2008).

Figure 3 Location of observation bores within the Cambrian Limestone and the Dook Creek Formation with monitoring data. The colours for the geology are consistent with Figure 2.

3.2 Gauged River Discharge

Manual gaugings of the Roper River, where groundwater discharge from the Cambrian Limestone occurs, are at the sites G9030013 (Elsey Homestead) and G9030176 (Elsey NP). The locations of the gauging stations are presented in **Figure 4**. The Cambrian Limestone aquifer is considered to be a continuous layer therefore the sites measuring discharge from the Cambrian Limestone to the other rivers in the Daly Basin were also employed in the calibration process and included G8140001, G8140301, G8140044 and G8145107 (Douglas River).

The observations used in the calibration of the model are dominated by dry season flow gaugings, which are assumed to be a proxy for groundwater discharge from both the Cambrian Limestone and Dook Creek aquifer systems. Five sites with manually gauged flows are available for rivers with discharge from the Dook Creek Formation in the Roper River study area. These are G9030176, G9030013, G9030108, G9030074 and G9030003.

7 sites with gauged flows outside the Roper River catchment were also used in the calibration of the Dook Creek groundwater model (refer

Table 3 and **Figure 4**).

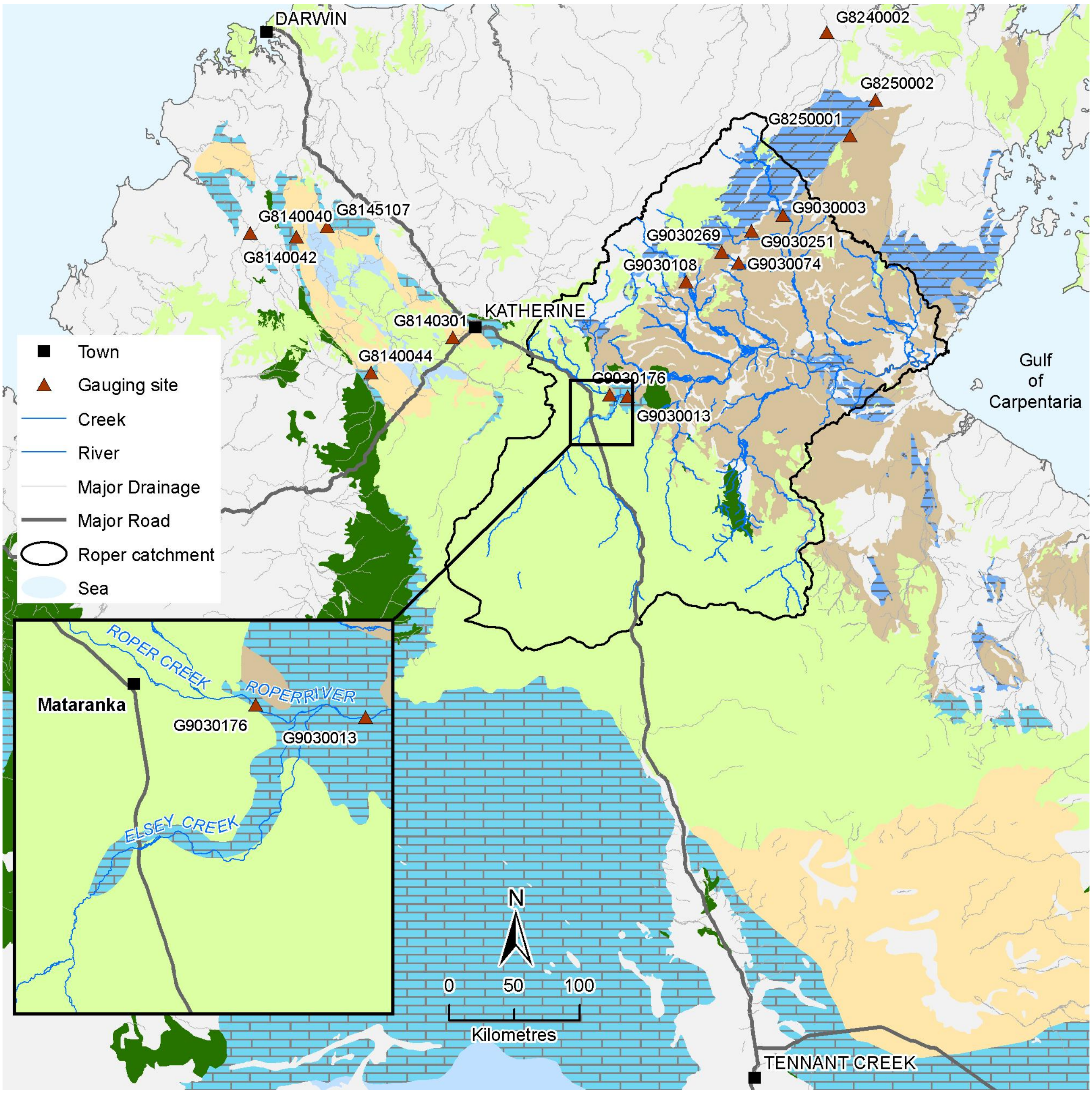

Figure 4 Locations of the gauging data used in the development of the groundwater model.

3.3 Geological data

Digital surface geology data is available from Geoscience Australia at 1:1 000 000 scale for the entire Northern Territory (Liu, 2007). This data provided controls on the extents of the aquifers, the confining units and the overlying Cretaceous units. Cross-sections from the 1:250 000 geological mapping series was used to constrain the layer geometry, particularly for the Dook Creek Formation.

Stratigraphic data are available for many of the water bores and all of the diamond drillholes completed by the Northern Territory Geological Survey (NTGS). The stratigraphic information derived from bore hole information including the downhole geophysical logs provided controls on the depth to the base of the Cambrian Limestone aquifer in the Sturt Plateau area and the Daly Basin (Yin Foo and Matthews, 2001; Tickell, 2005). Contours of the depth to the base of the Cambrian Limestone (Tindall Limestone) in the Daly Basin have been determined based on this stratigraphic information (Tickell, 2005).

3.4 Surface elevations

The upper slice of the groundwater model represents the ground surface. The elevation of this slice has been calculated using the Shuttle Radar Terrain Model (SRTM) raster grid (Farr et al., 2007). The SRTM elevations are currently available at 90 x 90 metre cells with approximately 5 metre accuracy where vegetation is relatively sparse. One problem associated with the available version of the SRTM data is that in areas where dense vegetation occurs, eg along perennial drainage or wetlands, the measured elevations in these areas can be in error by at least as much as the height of the vegetation (ie up to 15 metres).

FEFLOW uses gridding techniques to generate parameter distributions such as slice elevation, it was therefore necessary to convert the finite element node locations to a point shape file and extracting the SRTM raster grid values to points using ArcGIS.

3.5 Data gaps

- Observation bores in the Cambrian Limestone (RN031483, RN029091, RN029012, RN28082 and RN29013) require reinstating or inclusion into the NRETAS monitoring network. This information will enable assessment of recharge mechanisms where the Cretaceous cover exists.
- Observation bores in the Dook Creek Formation are sparse and have very limited data.
- The Roper River gauging site (G9030176) is several kilometres upstream of the contact between the Cambrian Limestone and the fractured basement rocks to the east. The relative contribution and variation in the flow along this section of the Roper River is currently unknown.

4 Conceptual Groundwater Models

4.1 Overview

The aquifers of the Cambrian Limestone and the Dook Creek Dolostone are typical of karstic aquifers where chemical weathering has produced wide spread secondary porosity and permeability in the carbonates. The carbonate aquifers are expected to have greatest permeability within the weathered zone, up to a maximum of 100 – 150 metres below the surface. The karstic nature of the aquifers mean that on a local scale groundwater flow is via preferential pathways, however, on a basin wide scale the aquifers are considered to behave as an equivalent porous media with very high transmissivities and low storage (**Table 2**).

The Jinduckin Formation overlies large areas of the Cambrian Limestone. Aquifers are only sparsely developed in this formation (Sanders, 1993). The bulk of the formation is shale and siltstone with little fractured porosity. The vertical hydraulic conductivity is expected to be very low. The Jinduckin Formation confines the Cambrian Limestone. The unconfined areas, are where the majority of the inputs / outputs of the system occur.

The Limmen Sandstone overlies and confines the Dook Creek dolostone resulting in minimal recharge.

The Cretaceous rocks consist predominantly of clay, claystone and sandy clay with lesser sandstone, sand and clayey sand. The main influence of the Cretaceous sediments is to reduce the recharge to the carbonate aquifers. There is a distinct subdued response of groundwater hydrographs for the bores located in areas where Cretaceous rocks cover the underlying carbonate aquifer reflecting the reduction in recharge. Water balance and hydrograph analysis in the vicinity of Katherine indicates that recharge is approximately 25% of the recharge observed in areas with outcropping carbonates (Knapton, 2004 and Knapton, 2006).

Table 2 Parameters used to describe the hydrostratigraphic units of the Roper River groundwater model.

Formation	Formation character	Discharge	Thickness [m]	Transmissivity range [m^2/d]	Storage coefficient/ Specific Yield
Dook Creek Formation	karstic dolostone	Flying Fox Creek, Mainoru River and Wilton River		500 - 1000	0.01
Roper group	Silicified sandstone - aquitard	N/A		low	0.0001
Cambrian limestone	karstic limestone	Roper River	150-200	2000 - 5000	0.04
Ordivician siltstone		N/A			

4.2 Groundwater flow

Regionally the groundwater flow within the Cambrian Limestone is from the south east to the north west where it discharges to the Roper River and Flora River along the bed of the rivers and via discrete springs. A component of the regional flow is discharging to the Katherine River, Douglas River and Daly River.

The groundwater flow within the Dook Creek dolostone locally is from the topographically high areas to topographically lower areas along the rivers. Regionally the flow is from the south west to the north east.

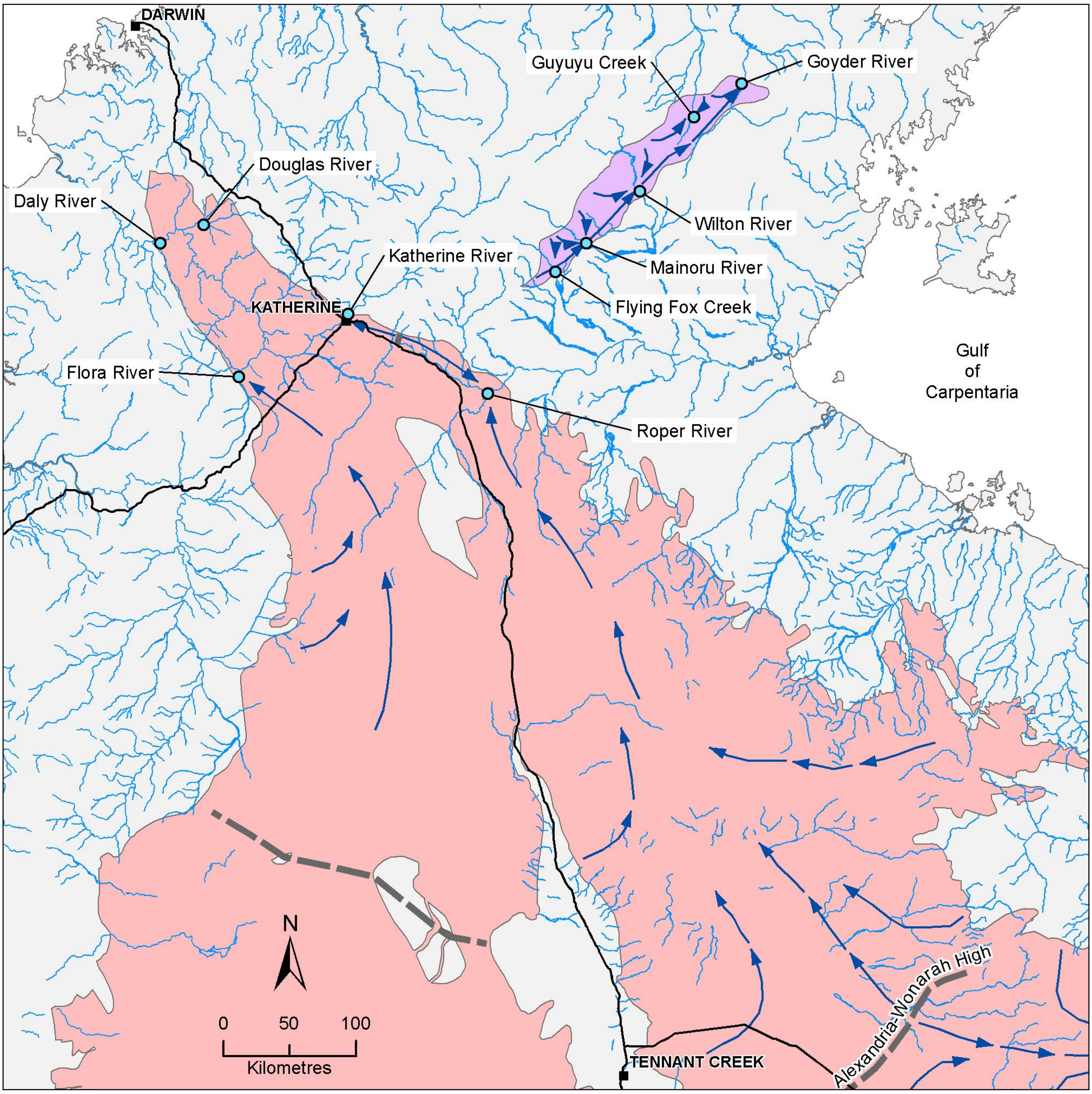

Figure 5 Regional groundwater flow in the Cambrian Limestone (red) and Dook Creek Formation (purple). The Dook Creek Formation shows local groundwater flow from topographic highs to the adjacent river there is also a regional flow direction from south west to north east.

4.3 Recharge

Groundwater recharge rates are variable across the landscape, and depend on soil type, vegetation and topography as well as rainfall amount and other climate variables. The complex interplay between these parameters means there is not a direct relationship between groundwater recharge rates and rainfall amount. There are also complex pathways for water infiltration to water tables. Recharge occurs only in the wet season when rainfall intensity and duration are sufficient and where the aquifers are unconfined. Recharge leads to the rise in groundwater levels and an increase in discharge to the rivers and at the springs. Recharge in the model domain is thought to be via five mechanisms.

- direct recharge where water is added to the groundwater in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone, it is thought that this is the dominant mechanism in areas with Cretaceous cover;
- macro-pores where precipitation is preferentially 'channeled' through the unsaturated zone and has a limited interaction with the unsaturated zone;
- localised indirect recharge where surface water can be channeled into karstic features such as dolines (sinkholes), this is a poorly understood component of recharge;
- river recharge when the stage height of the river exceeds the adjacent groundwater level in the aquifer. This is thought to be a minor component of the overall water budget;
- localised indirect recharge along ephemeral drainage in the arid southern regions, this component is poorly understood and quantified.

Limited study of recharge of regions with outcropping carbonates in the Daly River catchment, an area with similar hydrogeological characteristics to the study area, indicate it is dominated by macro-pore and local indirect recharge (Wilson et al., 2006). Water balance and hydrograph analysis have estimated the recharge in outcropping areas of carbonate is approximately 120-140 mm/yr and in areas of Cretaceous cover it is estimated at 40-50 mm/yr (Jolly, 2002). Calibration of the groundwater models concur with these values (Knapton, 2006).

Large decadal changes in the discharge to the Roper River suggest that most of the recharge input to the groundwater is relatively close to the discharge area. This is because the discharge from localised systems fluctuate more widely whereas discharge from larger scale systems is much steadier ie there is buffering present from the storage in the large groundwater system (Dahl and Nilsson, 2005).

4.3.1 Cambrian Limestone recharge estimates

An empirical estimate of the water balance for the Cambrian Limestone aquifer system discharging the Roper River is presented by Jolly et al., (2004). This analysis was based on three separate methods and determined that recharge ranged from between 5 and 20 mm/yr. Using average annual discharge from the river of 120 000 ML/yr measured at G9030013 (3.8 m^3/s) and an assumed area of recharge (15 000 km^2) the estimated recharge rate was 8 mm/yr. Accounting for the estimated ET losses this was doubled to a value of 16 mm/yr (Jolly et al., 2004). The area contributing to recharge is expected to be half to two thirds the area identified in 2004, therefore diffuse recharge rates are probably two to three times greater than those estimated.

Recharge to the outcropping Cambrian Limestone in the Georgina Basin has been estimated on throughfow calculations. The aquifer in the northern Georgina Basin is assumed to have a transmissivity of approximately 1000 – 2000 m^2/d (Read, 2003), the groundwater gradient is approximately 0.0001 (Tickell, 2003) across a section 200 km wide, the estimated throughflow is 20,000 – 40 000 m^3/d (or 230 – 460 l/s). The area of outcropping Cambrian Limestone is estimated at 19 750 km^2 a diffuse rate of 0.4 – 0.8 mm/yr is expected.

There is a component of groundwater flow from the southern portion of the Georgina Basin which contributes to the discharge to the Roper River. Recharge in this arid region is expected to occur where runoff from the outcropping basement along the edges of the Georgina Basin flows over the outcropping Cambrian Limestone (Gum Ridge Formation) to the north east of Tennant Creek. The recharge volumes and mechanism are poorly understood at present, and only first order estimates are available. Recharge to the groundwater system in the southern Georgina Basin which discharges to Lawn Hill and the Gregory River in Queensland is estimated to be between 2 and 6 mm / year (Read, 2003). Based on throughflow calculations and the area of outcrop indicate a recharge of approximately 1 mm/yr (Tickell, 2003).

4.3.2 Dook Creek Formation recharge using volumetric analysis

The estimated recharge to the Dook Creek Formation based on volumetric analysis is summarised below:

Estimated average total discharge from the Dook Creek Formation of 449 280 m^3/d (5.2 cumecs)

Estimated area for recharge based on unconfined area of the Dook Creek Formation = 7.711 x 10^9 m^2 (7711 sq km).

Annual recharge (discharge / area) is approximately 5.781 x 10^{-5} m/d (or 21mm/yr).

4.3.3 Dook Creek Formation recharge using chloride mass balance

Recharge to the Dook Creek Formation based on chloride concentrations in the rainfall ($Cl_{precip.}$) and the groundwater (Cl_{gw}). Where recharge is determined using the relationship:

Rech = Precipitaion x (Cl_{gw} / $Cl_{precip.}$)

This is based on the following assumptions:

- Rainfall Cl = 0.16 – 0.28 mg/l (Keywood et al., 1997)
- Groundwater Cl = 10.5 – 23 mg/l
- Average Annual Rainfall = 990 mm/yr

Recharge is therefore estimated to be between 7 mm/yr to 26 mm/yr. It should be noted that this method assumes that there are no sources of chloride in the system.

The outcropping basal unit of the Cretaceous aged rocks is considered to represent the areas where significant recharge occurs. The mapping of this unit enable the better definition of recharge distribution.

Further work is required to understand and quantify recharge along ephemeral drainage in the arid regions of the Northern Territory.

4.4 Discharge

During the dry season the groundwater levels decline as groundwater is either transpired or discharged to wetlands or rivers where it evaporates or is discharged to the sea.

Natural groundwater discharge is thought to be via 3 dominant mechanisms.

- through the river bed
- via discrete springs
- as diffuse discharge via evapotranspirational processes

Major discharges occur along the Roper River as it intercepts the much groundwater flow from the northern Georgina Basin. The groundwater from the Cambrian Limestone discharges along the bed of the river (eg Bitter Springs) and via discrete springs (eg, Rainbow Spring and Fig Tree Spring).

Diffuse discharge occurs in the Elsey National Park where the basement approaches the surface forcing groundwater levels above the ground surface (Jolly et al., 2004; Tickell, 2005).

Within the Roper River catchment the Dook Creek Formation discharges to the Flying Fox Creek, Mainoru River and the Wilton River where they intersect the dolostone aquifer, several discrete springs have also been mapped eg Weemol Spring. Discrete springs occur where fractures in the Limmen Sandstone allow groundwater to flow to the surface under pressure eg Lindsay Spring, White Rock Spring and Top Spring. Outside of the Roper River catchment the Dook Creek Formation also discharges to Guyuyu Creek in the Blyth River catchment and Goyder River and some of its tributaries in the Goyder River catchment (refer **Figure 5** and **Figure 7**).

Table 3 Gauging sites used in the calibration of the FEFLOW groundwater model.

Catchment	Gauge Site	River	Average Dry Season discharge [m3/s]
Roper River	G9030176	Roper	1.5
	G9030013	Roper	3.1
	G9030108	Flying Fox	0.8
	G9030074	Mainoru	1.0
	G9030003	Wilton	1.0
Daly River	G8140301	Katherine	1.6
	G8140044	Flora	2.3
	G8145107	Douglas	1.0
	G8140040	Daly	1.0
Goyder River	G9250001	Annie Creek	0.5
	G8250002	Goyder River	2.5
Blyth River	G8250002	Blyth	1.0

4.4.1 Cambrian Limestone aquifer

During the dry season the groundwater levels decline as groundwater is either transpired or discharged to wetlands or rivers where it evaporates or is discharged to the sea. Regionally the groundwater flow within the Cambrian Limestone is from the south to the north where it discharges to the Katherine River, Flora River, Douglas River and Daly River along the bed of the rivers and via discrete springs. Major discharges occur along the Roper River as it intercepts the much larger groundwater flows from the Georgina Basin. A smaller scale sub-basin occurs in the Katherine River area where a groundwater divide occurs approximately coincident with surface water catchment divide of the King River. Groundwater flow is towards the Katherine River from the divide in the south east and from the area to the south east of the Edith River. Similar small scale sub-basins discharge into the Douglas River and Daly River.

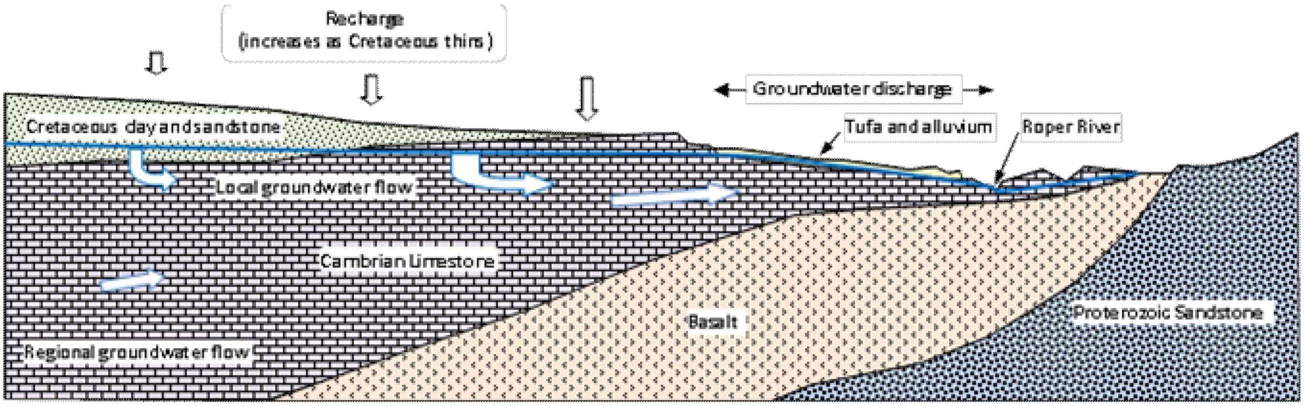

Figure 6 Conceptual model of the Cambrian Limestone where it discharges to the Roper River in the area near Mataranka.

Diffuse groundwater discharge occurs in the area around Mataranka because the Cambrian Limestone tapers where the basalt basement comes close to the surface. The groundwater is either discharged to the river as overland flow or is evapotranspired (refer **Figure 6**).

Documentation of the pumping extraction in the Mataranka region has been poor until relatively recently, it is assumed to be minimal and historically pumping from the aquifer has been negligible. Current entitlements for extraction from the Cambrian Limestone in the Mataranka area are approximately 3500 ML/yr (or 111 l/s). The development of the model reflects the low level of development with no pumping being included in the model during calibration.

4.4.2 Dook Creek aquifer

Discharge within the Roper River catchment occurs in the areas where the rivers of the Flying Fox, Mainoru and Wilton Rivers incise into the dolostone aquifer. Discharge also occurs to the Guyuyu Creek, Annie Creek and Goyder River to the north east of the Roper River catchment. Discrete spring occur where fractures in the Limmen Sandstone allow groundwater to flow to the surface under pressure (eg Lindsay Spring, White Rock Spring, Emu Spring, Top Spring, and Weemol Spring).

Minor discharge from the groundwater system is also through evapotranspiration from the riparian zone along the rivers.

No major pumping extraction from the Dook Creek Formation occurs except at Bulman - one of the major communities in the Roper River catchment.

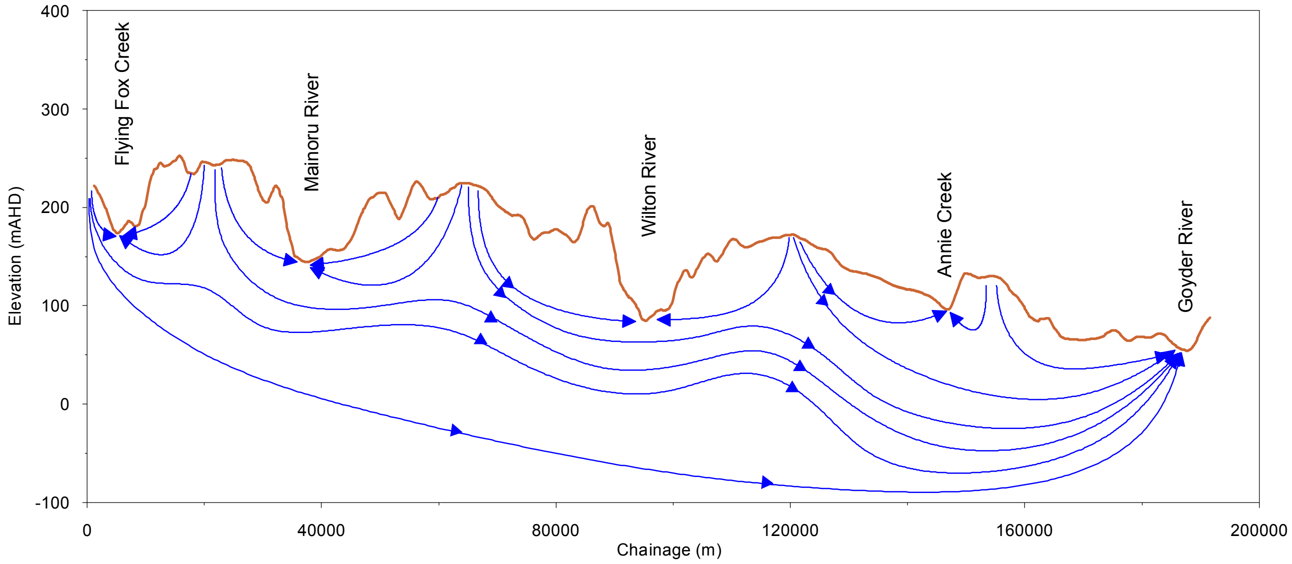

Figure 7 Conceptual groundwater flow in the unconfined Dook Creek Formation along a southwest to northeast transect.

5 Model Development

5.1 Introduction

The coupling to the MIKE11 surface water model using IFMMIKE11 assumes that the model is three dimensional and that the top 2 slices are connected to the river via transfer boundary conditions.

The groundwater sources of the Roper River region are represented with a redeveloped, calibrated, regional-scale, FEFLOW numerical groundwater flow model of the Cambrian Limestone (Knapton, 2006). A groundwater model of the Dook Creek formation was also developed to examine groundwater flows to the northern tributaries of the Roper River. The groundwater models are then coupled to a calibrated MIKE11 surface water model.

The Cambrian Limestone FEFLOW groundwater model encompasses an area of approximately 159 000 km^2 and includes the entire extent of the Cambrian Limestone in the Daly Basin, northern Wiso Basin and northern Georgina Basin (refer **Figure 3**). The outer boundary of the basin and the model is considered no-flow.

The Dook Creek FEFLOW groundwater model encompasses an area of approximately 22 220 km^2 and incorporates the entire extent of the unconfined areas of the Dook Creek Formation and includes the entire catchments of the Flying Fox Creek, Mainoru River, Wilton River, Guyuyu Creek and Goyder Rivers (refer **Figure 3** **and Figure 3, Part B**).

Based on the geology the Dook Creek groundwater system is unconfined to the north west of the Central Arnhem Highway and confined to the south east. The extent of the confined region of the model was arbitrarily defined using the sub-catchments of the rivers which source flows from the Dook Creek Formation. This assumption may prove to be inadequate.

Both of the major aquifers in the Roper River basin are karstic and are dominated by secondary porosity / permeability due to chemical weathering. For simplicity the systems have been modelled as an equivalent porous media using calibrated regional aquifer parameters to reproduce the regional groundwater levels and observed discharge to the rivers. This assumption means that the actual flow paths cannot be modelled and that there is no intention for this model to be used for contaminant transport problems.

Recharge to the Cambrian limestone and Dook Creek dolostone is considered to be largely due to preferential pathways, however, this mechanism is not well understood and poorly represented numerically. In previous studies the recharge was estimated as diffuse using a simple soil moisture deficit model using rainfall and estimated evapotranspiration. It has been found that this methodology is inadequate to quantify the increase in recharge during wetter periods in the rainfall record when compared to groundwater level hydrographs and gauged flows. Recent estimates of recharge have been determined using MIKE SHE® which enables a more process based estimate of recharge to be calculated including an estimate of by-pass flow (refer to **section 6**).

Recharge is applied to the model according to the calibrated steady state recharge distribution. The recharge distribution was constrained by the mapped geology and empirical recharge estimates. The input time series recharge for this study was generated from the MIKE SHE model and scaled using the steady state distribution (refer to **section 5.6**) during the groundwater model calibration process to reproduce observed water levels and discharges.

Recharge is also expected to occur during periods when the river stage height is greater than the groundwater level adjacent to the river. However, to improve the model run times during the calibration of the groundwater model, the level in the river was assumed to be constant at the average dry season level. The coupled model, however, does simulate change in stage height.

Distribution of hydraulic parameters hydraulic conductivity, storage coefficient and transfer in /out were determined by inverse modelling using the PEST code (Doherty, 2004)

The model was calibrated to match observed streamflow and groundwater levels in monitoring bores in the area of the Cambrian Limestone that contributes discharge to the Roper River (refer **Figure 3**). Unlike previous modelling attempts, which used steady state conditions at large distances from the area of interest, the entire model domain has transient inputs.

5.2 Model Package

The finite element package FEFLOW® v5.311 from DHI-WASY was used to simulate the saturated flow processes. FEFLOW® is a fully three dimensional finite-element package capable of simulating unsaturated and saturated flow and contaminant transport. FEFLOW® also has built-in mesh-design, problem editing and graphical post processing display modules that allow rapid model development, execution and analysis (Diersch, 2004). A 32-bit PC laptop under Windows XP was used as the platform for the numerical simulations (transient simulations over 108.9 years typical took 15-20 minutes).

The high-level graphical interface, the Geographic Information System (GIS) capabilities, and the capacity for detailed mesh generation built into FEFLOW are important features that have allowed the rapid development and testing of the models described in this report.

Finite elements provide greater flexibility in the mesh design than the rectilinear grids employed by finite difference code (eg ModFlow), allowing for the refinement of the mesh around points such as bores and linear features such as rivers. The finite difference codes have discretisation issues where both regional and local scaled features are required in the problem.

The code is proprietary and as such has limitations because the software requires a licence to run – unlike the core code for ModFlow which is “freeware” from the US Geological Survey. The requirement for a licence means that the developed models can not be transferred to parties without a licence. Similarly the use of parameter optimisation code on parallel computers (ie Parallel PEST) requires a valid licence for each computer involved in the parallel optimisation process.

5.3 Model extent and mesh generation

The model mesh was developed to facilitate two levels of detail in the modelling.

- The first being a regional model encompassing the extent of the carbonate aquifers of the Cambrian Limestone and the Dook Creek Formation. The coarse nature of the model at this regional level was considered reasonable as these areas are not very dynamic.
- The second area with the greater level of detail around the rivers where surface – groundwater interactions probably occur. The regional mesh was refined along the major rivers where baseflow from the carbonate aquifers has been identified.

5.3.1 Spatial Discretisation

The superelement, mesh and model were developed with the FEFLOW® package. The mesh was generated using the automatic Triangle option (Shewchuk, 2002). 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 drainage features previously identified, where significant discharge from the aquifers occurs.

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

- Quality mesh, minimum angle <= 30 degrees
- Force all triangles to be Delaunay
- Fill all possible holes in mesh
- Divide-and-conquer meshing algorithm
- Refinement around line-addins – Gradation 2, Target element size = 1000 metres

An initial mesh density of 4000 elements was used in the Generate Automatically option to generate the mesh. The regional mesh was then refined in the Mataranka area using the Mesh Geometry Editor. The resultant mesh used in the modelling is presented in **Figure 8** and comprises 49 540 elements and 38 559 nodes.

Figure 8 Finite element mesh used in the groundwater modelling.

5.4 Model 3D geometry

The groundwater models of the Cambrian Limestone and the Dook Creek Formation have been developed as 3D and comprise three slices: **Slice 1** represents the ground surface, **Slice 2** represents the upper 20 metres of the carbonate aquifer, or where the confining beds exist the top of the aquifer and **Slice 3** represents the contact between the carbonate aquifers and the basement. The elevations for this surface in the Cambrian Limestone component of the model was developed using the stratigraphic information from available drilling information and contours of basement depth (Tickell, 2005). The contour information and point elevations were gridded using Surfer (Golden Software Inc., 2006) and applied to the model using the Kriging data regionalisation.

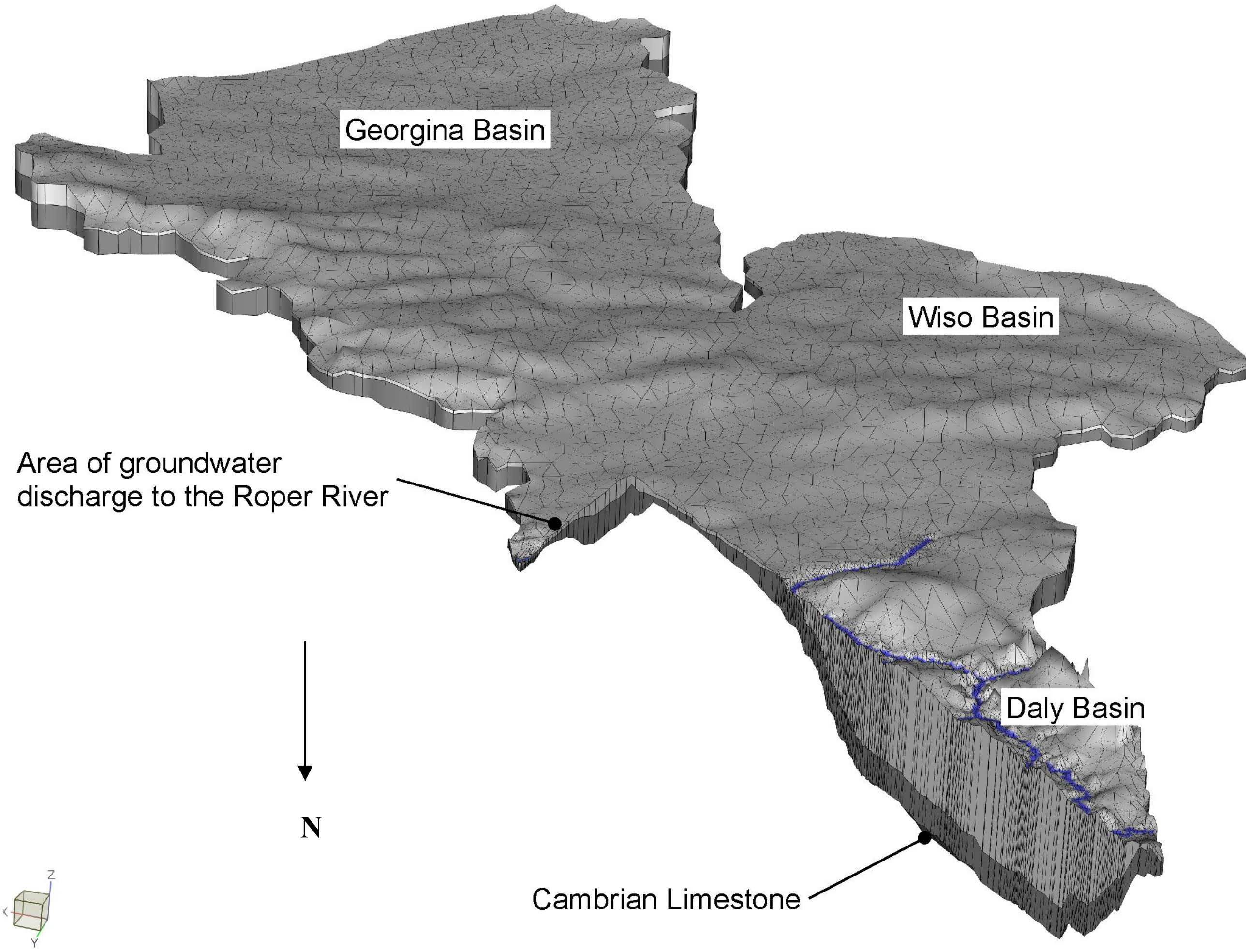

Figure 9 3D view of the Cambrian Limestone component of the FEFLOW model with cutaway along the axis of the Daly Basin to Mataranka.

5.4.1 Boundary Conditions

The groundwater model includes the following boundary conditions (BCs):

- Recharge and evapotranspirational losses are represented by areal fluxes applied at the top slice of the model using a combination of element distributions and functions (refer to **section 5.6**).

- Groundwater / surface water interactions. The conceptual model assumes that the dominant mechanism for discharge of groundwater from the system is through the river bed and via spring flow to the rivers and that the river and groundwater are in dynamic connection. Based on this assumption the discharge to the rivers has been implemented using the transfer BC (Diersch, 2008). The transfer boundary is similar to the RIV package used by ModFlow (Anderson and Woessner, 2002). The transfer boundary condition describes a reference hydraulic head which has an imperfect hydraulic contact with the groundwater body caused by a colmation layer (related to the stream bed conductance). It should be noted that to enable coupling of the FEFLOW model to the MIKE11 model it is assumed that the transfer BCs are defined on the two upper slices of the groundwater model.

- Pumping bores for stock and domestic and horticultural use were implemented using Well BCs. The Well BC describes the injection or withdrawal of water at a single node in m^3/d. Pumping rates were applied either as at a steady state value equal to the annual pumped volume for the bore converted to m^3/d or as a variable pumping rate using power functions to define the transient pumping schedule for each bore. Given that there has been very little development of the groundwater resources in the Roper River catchment pumping bores are only relevant to scenario modeling to examine future impacts.

- Discrete springs discharging from the Mesoproterozoic dolostone through the confining Limmen Sandstone (eg Lindsay Spring and Top Spring) were simulated using constant head BCs.

- The extent of the Cambrian limestone and Mesoproterozoic dolostone form the boundary of the model domain where the Antrim Plateau Volcanics outcrop or occurs above the groundwater level is implemented as no-flow boundaries.

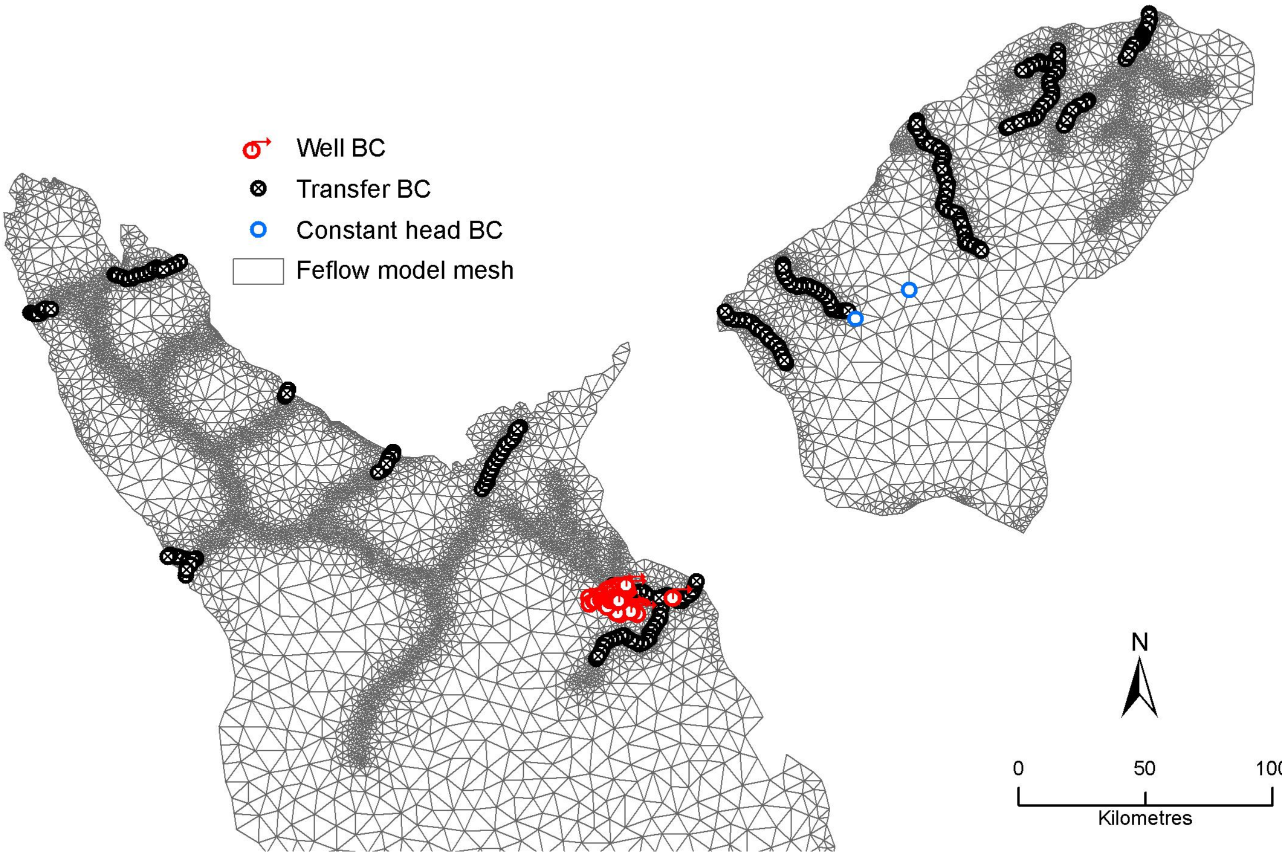

Figure 10 Groundwater model mesh with respect to the Roper River and its tributaries

5.5 Hydraulic parameters

Four hydraulic parameters were assigned in the development of the groundwater model:

Hydraulic conductivity (xy)

Hydraulic conductivity (z)

Storage coefficient

Transfer In / Out

5.5.1 Hydraulic conductivity

The hydraulic conductivity values and distribution for the Cambrian limestone were calculated from the transmissivity values presented in previous work in the Daly Basin (Knapton, 2006). The upper layer was assigned the calculated hydraulic conductivities in the unconfined areas of the Cambrian limestone. The areas where the Ordovician siltstones confined the Cambrian limestone were assigned low hydraulic conductivities (~1 m/d). The entire bottom layer was assigned the hydraulic conductivity distribution of the Cambrian limestone and assumed that the limestone aquifer was continuous throughout the model domain. During the calibration process it was found that this assumption is probably incorrect and that a region of low hydraulic conductivity was necessary along the long axis of the Daly Basin to produce the head distribution and discharge observed at the rivers. This was particularly so for the Roper and Katherine Rivers to the north and the Flora River to the south. It is now considered that the regional fault evident to the south between the Wiso and Georgina Basins extends into the Daly Basin and that the displacement results in a poor connection or discontinuity of the aquifer north and south of the fault.

5.5.2 Storage coefficient

Previous work has identified that a regional unconfined specific yield of 0.04 is suitable for much of the model domain. The storage coefficient for the confined portions of the aquifer was set to 0.0001. During calibration it was found that the area in the vicinity of the Douglas River and Daly River that a storage coefficient of 0.01 was more appropriate.

No hydraulic data exists for the Mesoproterozoic dolostone aquifer. However, the unconfined specific yield value of 0.01 and storage coefficient of.0001 in the confined regions are considered suitable. Achievement of model calibration is a demonstration that these values are within the bounds of acceptability.

5.5.3 Transfer Out

The transfer out parameter was assumed to be equal for this model. The non zero distribution of transfer out was limited to a buffer area around the areas where groundwater discharge to the rivers has been mapped. The transfer out parameter was set to a value of 200 d^{-1}, which during steady state calibration provided a reasonable match with the observed discharge to the rivers. The transfer out distribution was then determined using automatic parameter estimation.

5.6 Recharge and Areal ET Flux

The steady state recharge for the unconfined areas was determined from previous studies and then adjusted during the calibration process. The confined regions of both models had a fixed recharge rate of 0 m/d.

Transient recharge was assigned using the steady state recharge distribution and a time series recharge rate determined using MIKE SHE for the period 1900 – 2008 see **section 6**.

The MIKE SHE recharge power function was imported into the model using the Time–varying power function editor dialog as a constant curve type. Evapotranspiration was estimated using a ramp function similar to that used in the ModFlow package EVT and is based on the following conditions:

- When the water table is at or above the ground surface (Slice 1), evapotranspiration loss from the water table occurs at the maximum rate specified.
- When the elevation of the water table is below the ‘extinction depth’ evapotranspiration from the water table is 0.

- Between these limits, evapotranspiration from the water table varies linearly with water table elevation.

The resulting recharge / evapotranspirational function is presented in **Equation 1**.

$$\mathrm{TermA} = \begin{cases} \mathrm{TermB} & \text{if } \mathrm{REFDSTR.ET} = 1 \\ 0 & \text{otherwise} \end{cases} \qquad \mathrm{TermB} = \begin{cases} 0.002 & \text{if } \mathrm{Head} \geq \mathrm{REFDSTR.GndSurface} \\ 0.002 \cdot \left(1 - \left(\frac{\mathrm{REFDSTR.GndSurface} - \mathrm{Head}}{1}\right)\right) & \text{if } \left(\mathrm{REFDSTR.GndSurface} - \mathrm{Head} < 1\right) \\ 0 & \text{otherwise} \end{cases}$$

$$Q_p = 0.004 \cdot \mathrm{REFDSTR.RECH} \cdot \mathrm{POWER.MikeSHE.Rech} - \mathrm{TermA}$$

Equation 1 Recharge / evapotranspiration function Qp is in m/d.

where:

Qp is the recharge (or ET) applied to each element for a given timestep.

REFDSTR.ET is the areas defined as having ET.

REFDSTR.GndSurface is the elevation of Slice 1 derived from the SRTM data.

Head is the calculated groundwater head

REFDSTR.RECH is the steady state recharge distribution determined during the steady state calibration

POWER.MikeSHE.Rech is the time series recharge power function estimated using MIKESHE

TermA uses a reference distribution to determine if an element should have ET calculated using TermB to determine the ET rate.

TermB determines the ET rate based on the groundwater head and the surface elevation.

5.7 FEFLOW settings

5.7.1 Problem class

The model was defined as a saturated, flow only and unconfined (phreatic) problem with the following three dimensional free surface definitions:

- Slice 1	Free & movable
- Slice 2	Unspecified
- Slice 3	Fixed.

The free surface constraints were set for the water table:

- Falling Dry at Bottom was Constrained as Seepage Face.

- Touching the Top Surface was Unconstrained.

The residual water depth for dry (phreatic) elements was set to 0.4 metres. This setting was found to produce the most stable steady state model during calibration.

The remaining specific option settings were left at their default values.

5.7.2 Temporal and control data

During the transient runs the time step control was set to automatic with an initial time of 0 days (equivalent to 01/01/1900) and a final time of 39692 days (equivalent to 01/09/2008). The step size upper bound, under the specific options for time step control schemes, was limited to 10 days. This limit was selected to provide stability in the coupling process (improved by shorter time steps) and reduce model run times (improved by longer time steps).

5.8 Limitations

The model has been assumed that given the scale of the system the karstic aquifer can be modelled as an equivalent porous media. This assumption holds for determining the water balance of the system, however, the model is not designed to examine localised solute transport problems where travel times and distribution of the solute are influenced by preferential pathways.

The methodology for estimating recharge appears to be adequate for the current study. However, process based and fully distributed estimation of recharge would be preferred and further work is warranted.

Although the model provides a relatively high resolution finite element mesh in the areas where rivers are important boundary conditions the resolution of the finite element mesh is too coarse to define the discrete springs. The quantification of the discharge at the discrete springs and the impacts from development are an important metric for allocation planning. Future works on the model development will attempt to deliver this level of detail.

6 MIKE SHE Recharge Modelling

Recharge is the major driver for flow in the groundwater system. Previous modelling of the limestone / dolostone aquifers of the Northern Territory have employed a simple but effective soil moisture deficit model to determine recharge based on rainfall developed by (Jolly et al., 2000). To improve on this method the process based MIKE SHE was used to estimate recharge.

The water balance above the saturated zone was modelled using MIKE SHE (Système Hydrologique Européen) (Graham and Butts, 2005). MIKE SHE covers the major processes in the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel 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, (Butts et al. 2004).

MIKE SHE was employed because it has the scope to model processes in the soil and incorporate direct recharge due to macro pores. Macro pores either as voids in the soil or as dolines a part of the karstic terrain associated with limestone / dolostone lithologies are an important recharge mechanism.

The simplified ET module includes the processes of interception, ponding and evapotranspiration. While MIKE SHE's unsaturated flow module using either the Richards Flow or simplified Gravity Flow solutions requires a detailed vertical discretization of the soil profile, the Two-Layer Water Balance module considers the entire unsaturated zone to be consist of two layers representing average conditions in the unsaturated zone. This results in a quicker computational time and requires much fewer parameters to be estimated.

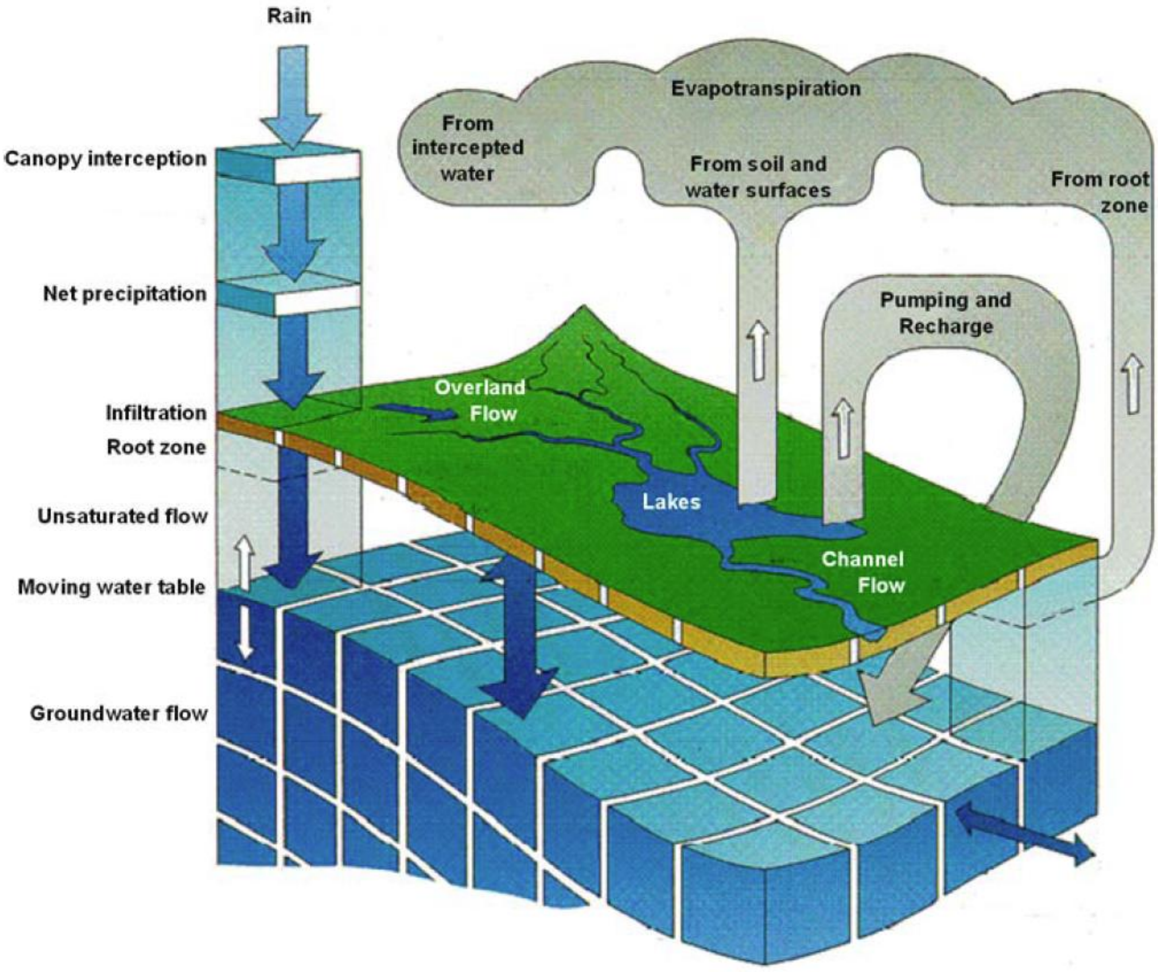

Figure 11 Conceptualisation of Mike SHE modelling components. In this case the groundwater flow was modelled using FEFLOW.

MIKE SHE uses a simplified ET model that is used in the Two-Layer unsaturated flow (UZ) / evapotranspiration (ET) model. The Two-Layer 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 Two-Layer UZ/ET module is based on a formulation presented in Yan and Smith (1994). Its main purpose is to provide an estimate of the actual evapotranspiration and the amount of water that recharges the saturated zone.

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, field capacity and saturation.

Simplified Macro-pore Flow (bypass flow)

Flow through macro-pores in unsaturated soil is important for many soil types. In the Two Layer Water Balance 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.

Typically, macro-pore flow is highest in wet conditions when water is flowing freely in the soil (e.g. moisture content above the field capacity, θ_{FC}) and zero when the soil is dry (e.g. moisture content at the wilting point, θ_{WP}).

6.1 Model Inputs

6.1.1 Climatic data

The two climatic inputs to the model are the daily rainfall and daily evaporation data taken from the SILO data drill database record at Katherine. The input rainfall and evaporation data for the period 01/01/1900 – 01/09/2008 are presented graphically in Figures 12 and 13 respectively.

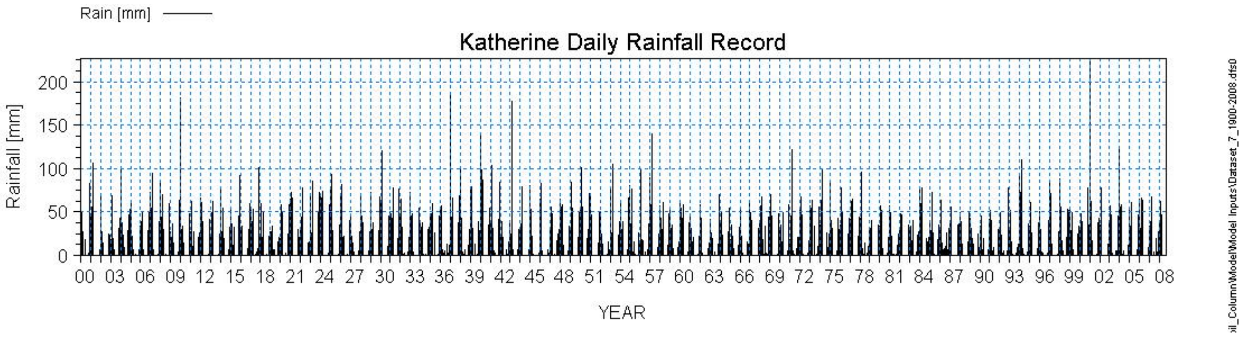

Figure 12 Input rainfall data to the MIKE SHE recharge model.

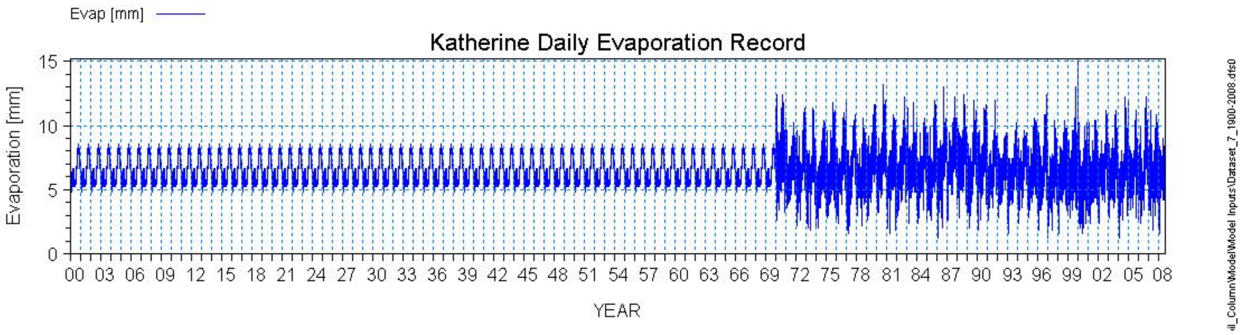

Figure 13 Input evaporation data (proxy for actual ET) to the MIKE SHE recharge model.

6.1.2 Soil data

There are four principal parameters that must be defined for each soil type in the Two-Layer Water Balance method as presented in Table 4:

Soil water content at saturation (θ_{sat}) - this is the maximum water content of the soil, which is usually approximately equal to the porosity,

Soil water content at field capacity (θ_{FC}) - this 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. Although, it is usually higher than the residual saturation, which is usually defined as the minimum saturation that can be achieved in a laboratory test.

Soil water content at the field wilting point (θ_{WP}) - this is the lowest water content that plants can extract water from the soil.

The average moisture content of the upper ET layer can range between the field capacity, θFC, and the wilting point, θ_{WP}.

Infiltration rate (K_{inf}**)** - this is the saturated hydraulic conductivity of the soil.

Bypass Constants The bypass parameters include:

byp - the maximum bypass fraction (between 0 and 1.0) of the net rainfall,

thr1 - the threshold water content below which the bypass fraction is reduced, and

thr2 - the minimum water content at which bypass occurs.

6.1.3 Vegetation data

Leaf area index (LAI) is the amount of leaf area directly above a square metre of ground. The LAI of open woodland is likely to be in the range of 1.2 - 0.6 m^2 leaf per m^2 ground, while that of a closed forest is likely to be 2 – 4 m^2 leaf per m^2 ground (Eamus et al., 2006). Given that much of the study area is savanna the leaf area index (LAI) was assumed to vary from between 1.29 during the wet season when ET from grasses dominate and 0.47 during the dry season when the ET is dominated by transpiration from trees. These assumptions are based on savanna water use in the

Katherine region (Hutley et al., 2001). The temporal distribution of the LAI was generated using a 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 1.29 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 0.5. The time series plot of LAI for the period 01/01/1900 – 01/09/2008 is presented in **Figure 14** along with root depth employed in the model. It was assumed that the total root depth of was 4000 mm.

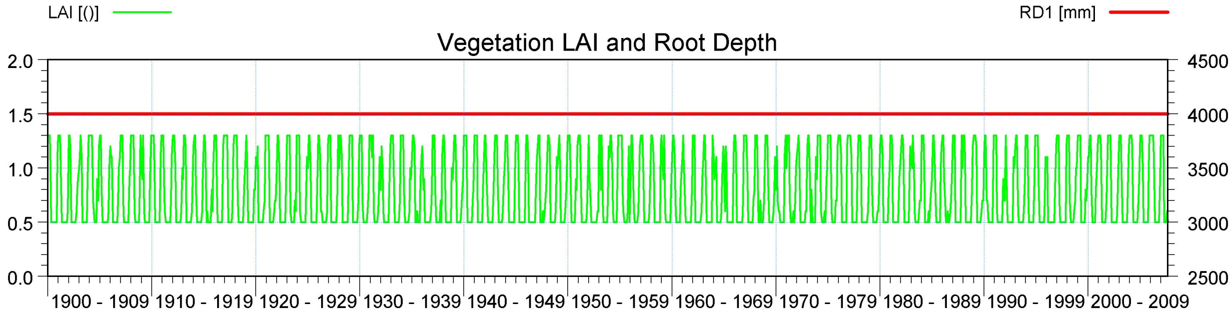

Figure 14 Time series leaf area index (green line) determined from typical wet and dry season values of LAI (Hutley et al., 2001) and the soil moisture deficit model. Included is the root depth (red line).

6.1.4 Calibration

Recharge estimates used in the numerical groundwater modelling of the Cambrian Limestone aquifer in the Daly Basin (Knapton, 2006) were based on the soil moisture deficit (SMD) model described by (Jolly et al., 2000). During the groundwater model calibration process the results of the SMD model were found to overestimate the actual recharge by a factor of approximately 2.8 times or conversely the calibrated recharge is 0.36 times the calculated SMD recharge. Closer inspection of the SMD model indicates that the recharge values generated are the excess of Precipitation minus ET and therefore include overland flow. It is expected that the excess 0.64 of the SMD recharge is due to overland flow.

Based on this information the MIKE SHE model was calibrated against the scaled cumulative SMD recharge determined during the groundwater model calibration (ie 0.36 x SMD cum. recharge).

Estimates of soil properties were taken from (Kelley, 2002) and (Wilson et al., 2006). Estimates of the infiltration rates were taken for Tippera loamy red earths when bare and initially dry have infiltration rates of around 180 mm/h (Day, 1977). After 20 minutes of flooding, infiltration rates ranged from 9 – 18 mm/hr. However, values for Blain sandy red earths were initially about 425 mm/hr and 115 mm/h after 20 minutes (Dilshad et al., 1996).

Table 4 **Soil parameters used in the recharge model.**

Parameter	Unit	Documented Range	Calibrated Value
θ_{sat}	cm^3/cm^3		0.4
θ_{FC}	cm^3/cm^3	0.18 - 0.27	0.25
θ_{WP}	cm^3/cm^3	0.12 - 0.15	0.15
K_{inf}	mm/hr	425 – 180 & 9 – 115	3.6
Soil suction at wetting front	m		-0.25
byp			0.75
thr1	cm^3/cm^3		0.3
thr2	cm^3/cm^3		0.2

The proportion of overland flow and recharge identified in the Daly River modelling (URS, 2008) were also used to constrain the model.

The cumulative recharge determined by the SMD model and the MIKE SHE model for the period 01/01/1900 – 01/01/2006 are presented in **Figure 15** and are expressed as depth in millimetres - the negative values reflecting the loss of water from the soil profile as recharge to the groundwater. Trends in the accumulated recharge are similar for both models prior to the water year 1972/73, however, after 1973 the accumulated recharge calculated by the two models diverge. The MIKE SHE model shows increased recharge relative to the SMD model. Prior to 1972/73 the average daily recharge is approximately 0.2 mm/d for both models. After 1972/73 the average daily recharge increases to approximately 0.3 mm/d for the SMD model and 0.4 mm/d for the MIKE SHE model. The increase is assumed to be due to the macro-pore component of flow in the MIKE SHE model.

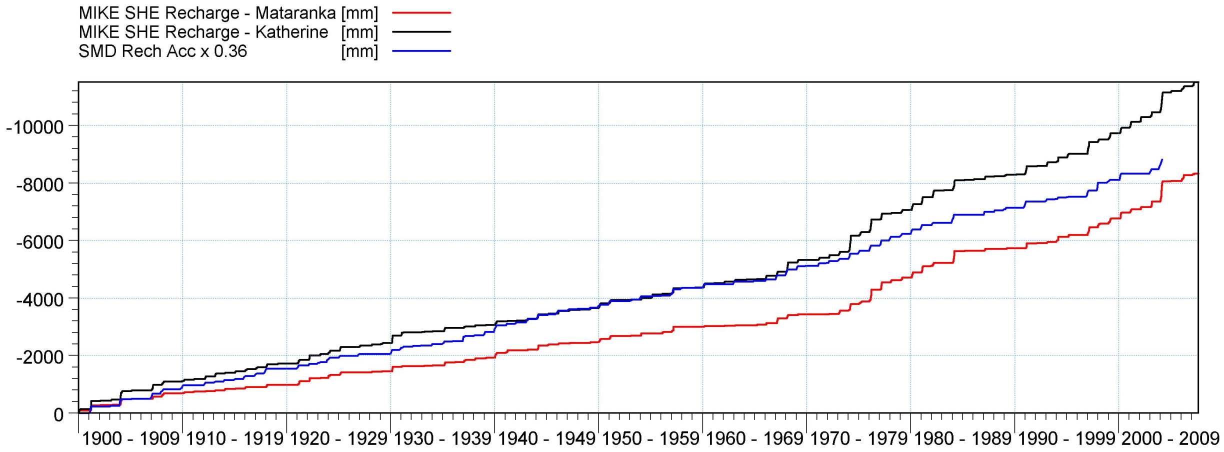

Figure 15 **Comparison of cumulative recharge for 01/01/1900 to 1/01/2006 as determined by the SMD model (black line) and the Mike SHE model incorporating macro pore bypass (blue line).**

7 FEFLOW Calibration

7.1 Model Optimisation Using Parameter ESTimation (PEST)

7.1.1 Introduction

PEST is a model independent parameter optimizer that uses the Gauss – Marquardt – Levenberg non-linear estimation technique. Using ASCII input and output files PEST is adapted to run the existing model. The purpose of PEST (which is an acronym for Parameter ESTimation) is to assist in data interpretation, model calibration and predictive analysis. PEST will adjust model parameters and/or excitations until the fit between model outputs and laboratory or field observations is optimised in the weighted least squares sense.

It should be noted that the parameter estimation process does not provide an estimate of systematic error, ie that error associated with an oversimplified conceptual model and model design. If, however, measured values can not be matched, it is a sign of a wrong conceptual model.

7.1.2 Parameter estimation process

The inputs to PEST are the observed and simulated groundwater levels and discharges and the outputs are the new model parameters. To achieve integration between Parallel PEST and FEFLOW several utility programs were required.

Discharge was exported from the model by an IFM DLL module using grouped flux from specified observation point groups defined along each of the rivers. It should be noted that to correctly report the flux all the nodes on each of the slices with transfer BCs need to be defined in the same observation group.

The two aquifer systems were calibrated separately to speed up the individual model runs required in the Parallel PEST process. The parallellisation was accomplished using 4 2.66 GHz quad-core windows based PCs connected via a TP-LINK fast Ethernet switch. Individual model runs generally took 30 – 60 minutes to complete.

7.1.3 Estimated parameters

The parameters estimated using PEST are the steady state recharge, hydraulic conductivity and transfer out rate.

7.1.4 Pilot points

Pilot points were employed to generate the spatial distributions of the various model parameters. The parameter values for each of the elements in the model were then generated using the pilot point values and the kriging algorithm. The distribution of the pilot points in the model domain depended on the available observation data and the level of variability expected in the parameter being estimated. The locations of the pilot points used for calculating the various parameter distributions are presented in **Figure 16**.

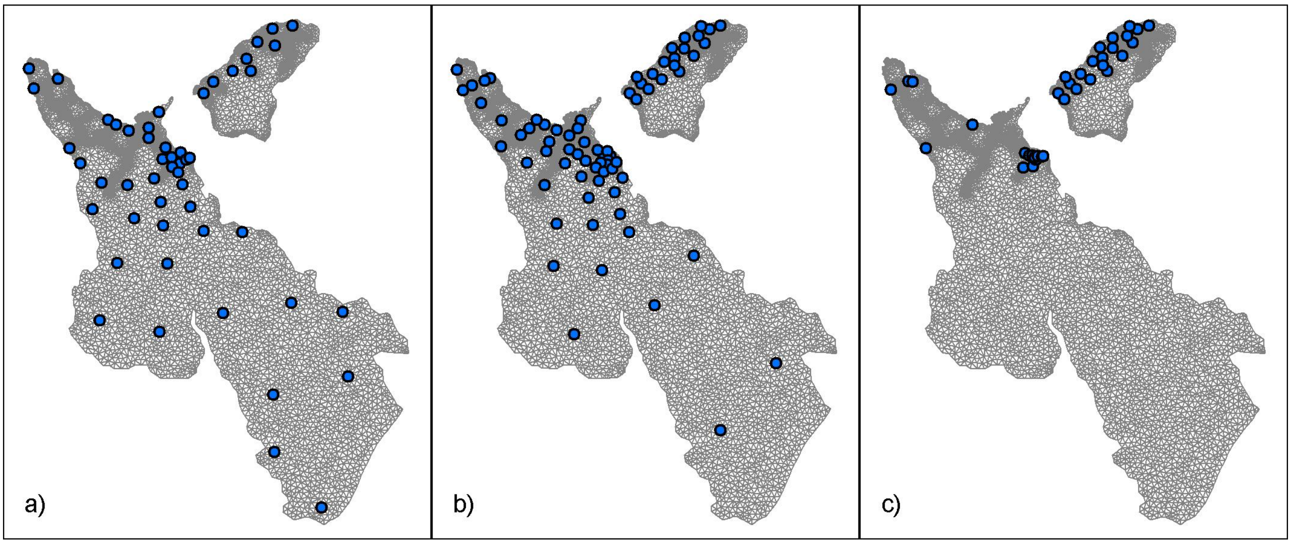

Figure 16 Locations of pilot points used in the parameter estimation process a) recharge, b) hydraulic conductivity and c) transfer in / out

7.1.5 Objective function

PEST uses the sum of squared residuals to determine the objective function or "goodness of fit" between the simulated response and the observed response. The Cambrian Limestone aquifer was calibrated against discharge measurements for 6 gauging sites and groundwater levels at 55 observation bores over the period 1960 – 2000. The Dook Creek groundwater model was calibrated against the discharge flow record for the 5 rivers and 8 observation bores in the area for the period of 1960 - 1988. Objective function scale factors were applied to the observed data to provide equal weighting to groundwater levels and gauged discharge values during the optimisation process.

7.1.6 Steady state model results

Using PEST resulted in a reasonable match to the groundwater levels and the observed discharge for each of the rivers used in the calibration process. A comparison of the assumed steady state heads and discharges and the modelled results are presented in **Figure 17**.

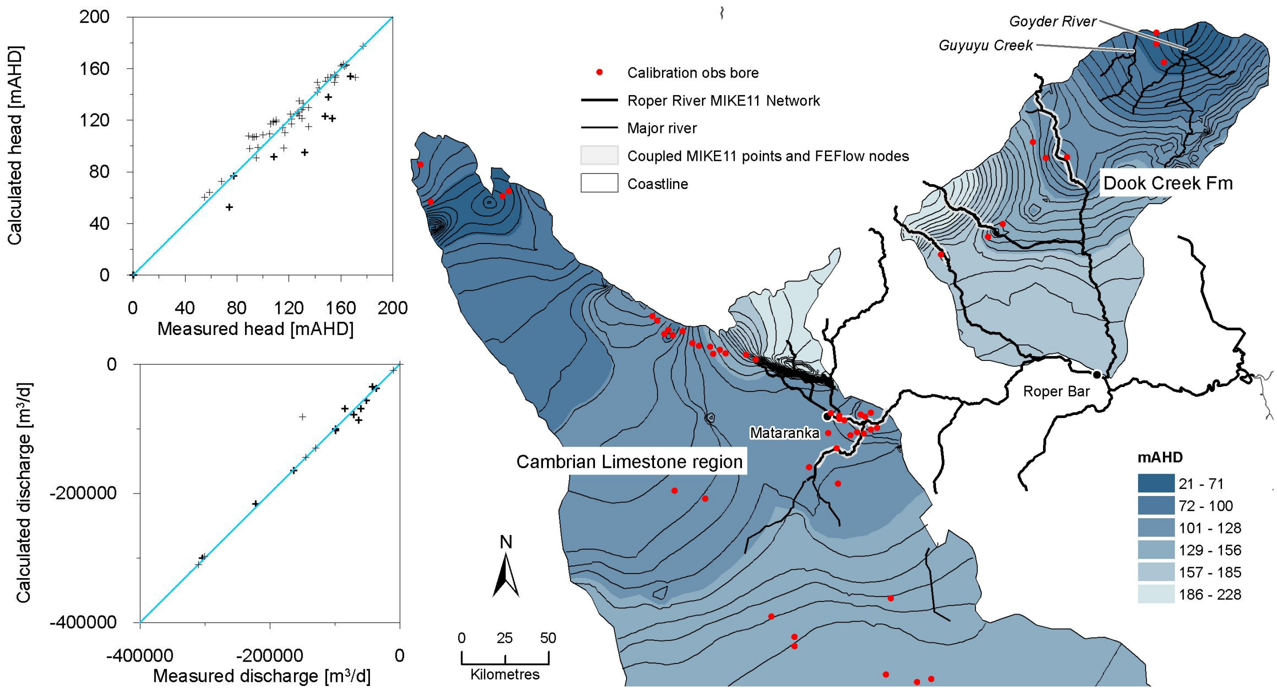

Figure 17 Calibrated steady state heads and discharge for the combined Cambrian Limestone and Dook Creek Formation models. The

7.2 Steady state recharge distribution

The spatial distribution of recharge for the Cambrian groundwater model was based initially on a zonal approach, where areas of constant recharge were applied to the model using a reference distribution and a piecewise function relating recharge to zone Id.

The trial and error approach to estimating the recharge distribution was then optimised using PEST.

During the calibration it was found that the assumption that the Cambrian Limestone forms a continuous layer is unlikely and that the fault separating the Wiso Basin from the Georgina Basin is likely to extend into the Daly Basin.

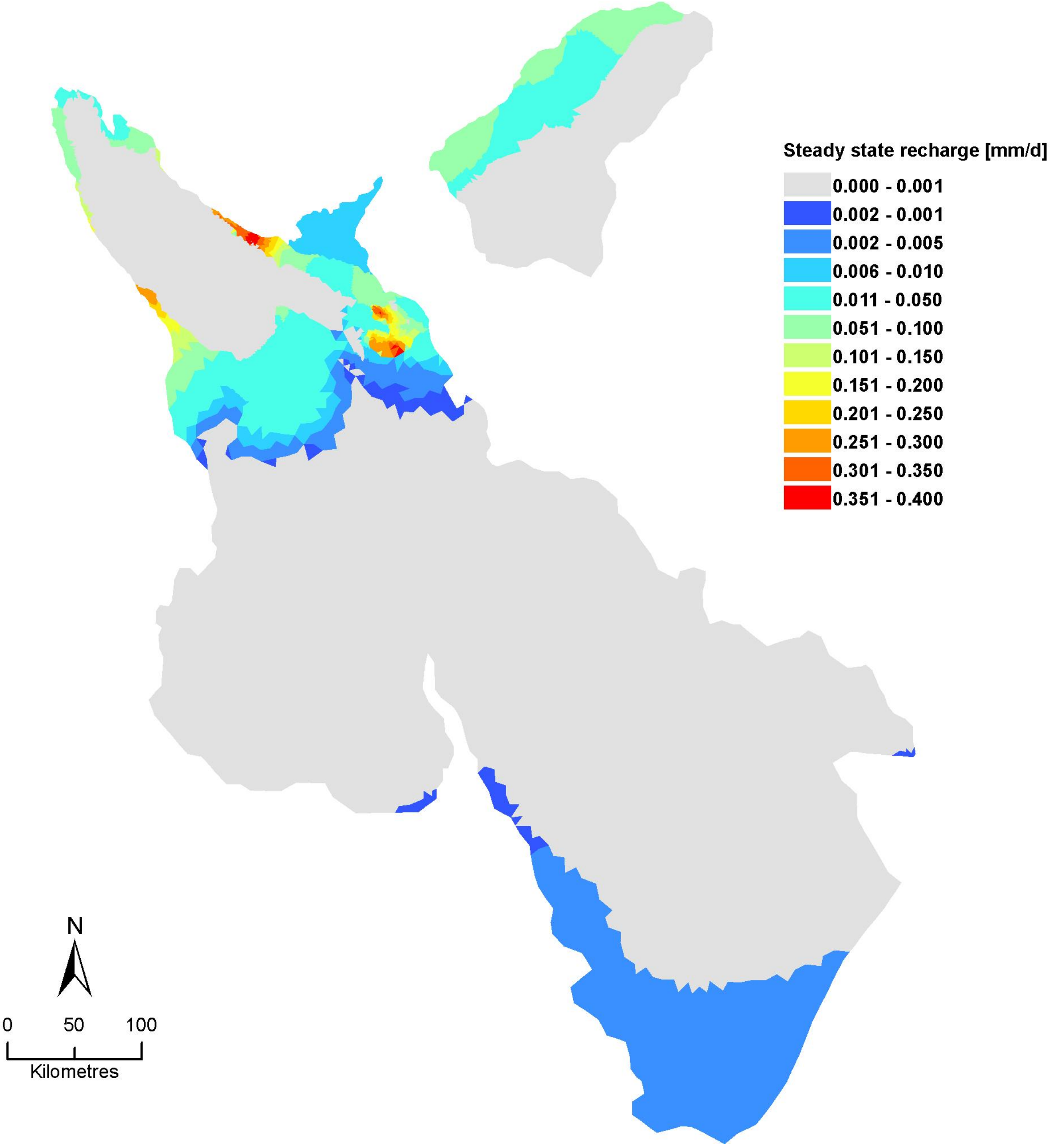

Figure 18 **Steady state recharge distribution presented as mm/d. The steady state recharge distribution was used to scale the transient recharge estimated using MIKE SHE. Zero recharge was applied where confining beds overlay the aquifers.**

8 Modelling Results

The simulated discharge results compared to the available discharge observations are presented in **Appendix A**. The simulated groundwater level results and the observed groundwater levels are presented in **Appendix B**.

Discharges are of the same magnitude of discharge as the observed data especially for the low flows measured during the dry season and show the same year to year trends. The discharges simulated for the Dook Creek Dolostone aquifer are less satisfactorily simulated, and this is primarily a result of the poor groundwater level constraints, and the limited number of groundwater flow measurements especially for the Wilton River (G9030003) and the Mainoru River (G9030074).

Generally the modelled groundwater levels for the Cambrian Limestone aquifer match the average levels, dynamic ranges and trends of the observed data. The area where water levels show the greatest divergence from the observed levels is in the area near the Douglas and Daly rivers some 200 – 300 km from the Roper River which is the main area of interest. It is possible that the storage coefficient is over estimated in this area. Future work will involve using PEST to optimise the parameters in the transient model to improve the fit.

9 Conclusions

A groundwater model of the Cambrian Limestone aquifer of the Georgina, Wiso and Daly Basins and the Dook Creek Dolostone aquifer has been developed based on the available data and conceptual hydrogeological model. The model has been designed to enable coupling to a surface water model.

Modelling of karstic systems as equivalent porous media has been found to be suitable in simulating regional groundwater flow using regional aquifer parameters adequately reproducing the regional groundwater levels and observed discharge to the rivers.

The current methodology for estimating recharge appears to be adequate for this situation. However, a distributed and process based estimation of recharge would be preferred and further work in this this area is recommended.

Currently the proportion of groundwater flow from long flow paths is unknown and in this study this component has been estimated. It may be possible to determine this by further study to better quantify recharge and using hydrochemical modelling and isotopic tracer analysis to compliment this work.

Calibration of large groundwater systems required automated parameter optimisation, in this case PEST. It has been found that the relatively long run times of the transient models necessitated the implementation of Parallel PEST running on 4 computers. This method requires access to multiple FEFLOW licenses. The utilities created to generate the updated FEM files are quite effective, however, they could probably be implemented more efficiently using IFM modules. Further work is warranted on the integration of Parallel PEST and FEFLOW.

Although the model provides a relatively high resolution finite element mesh in the areas where rivers are important boundary conditions the resolution of the finite element mesh is too coarse to define the discrete springs. The quantification of the discharge at the discrete springs and the impacts from development are an important metric for allocation planning. Future works on the model development will attempt to deliver this level of detail.

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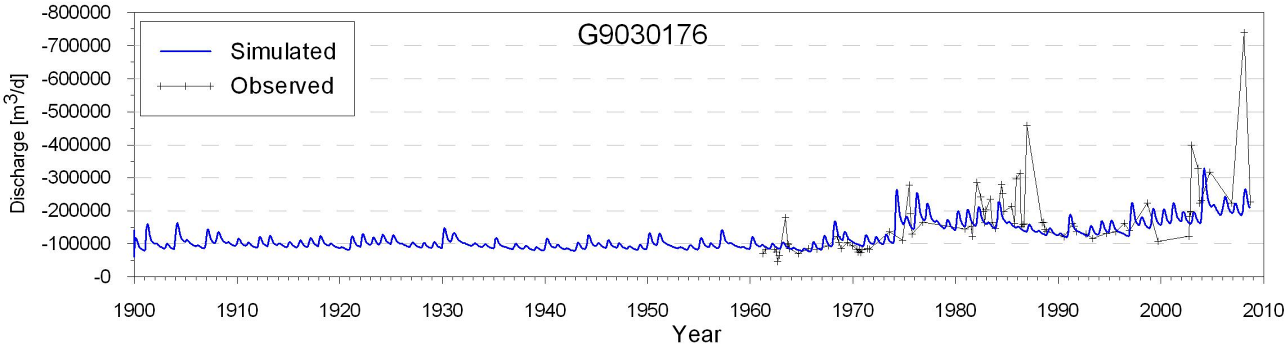
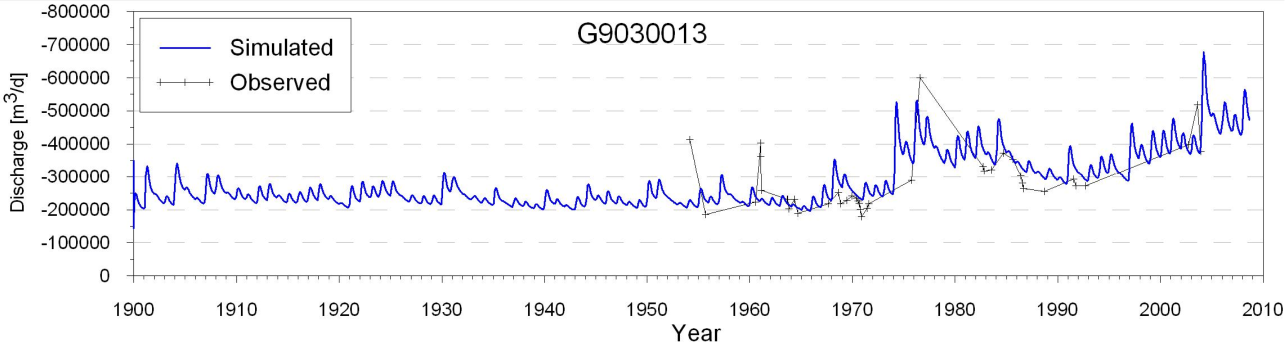
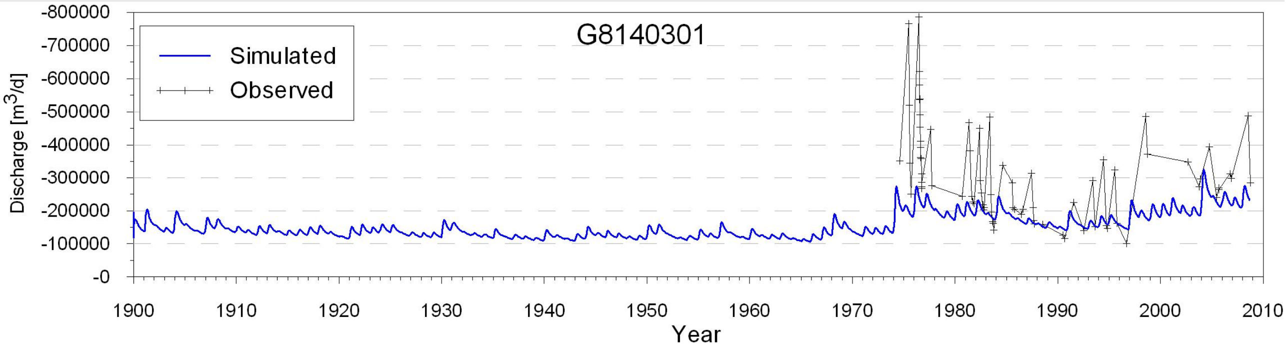
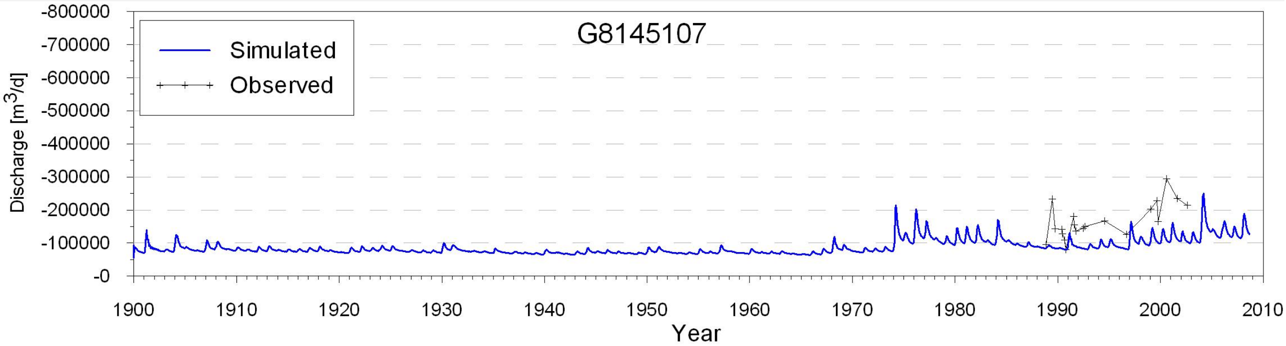
APPENDIX A – Calibrated Groundwater Discharge

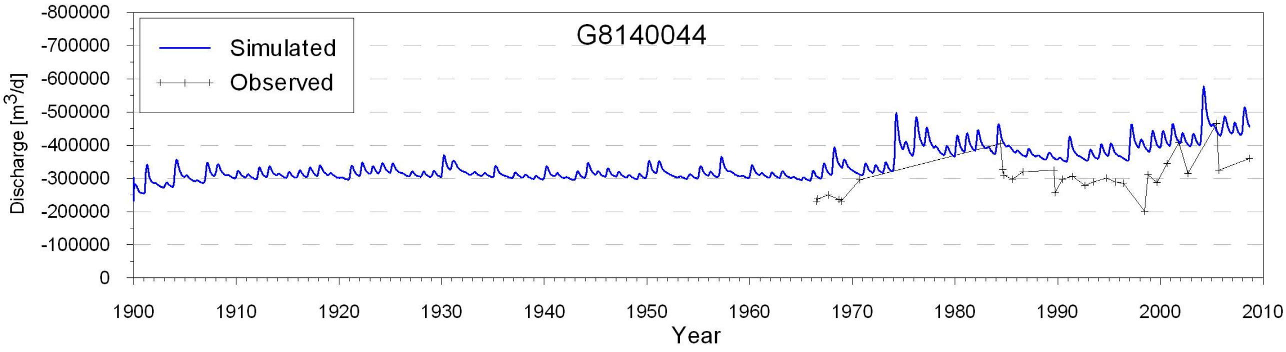
Cambrian Limestone Aquifer



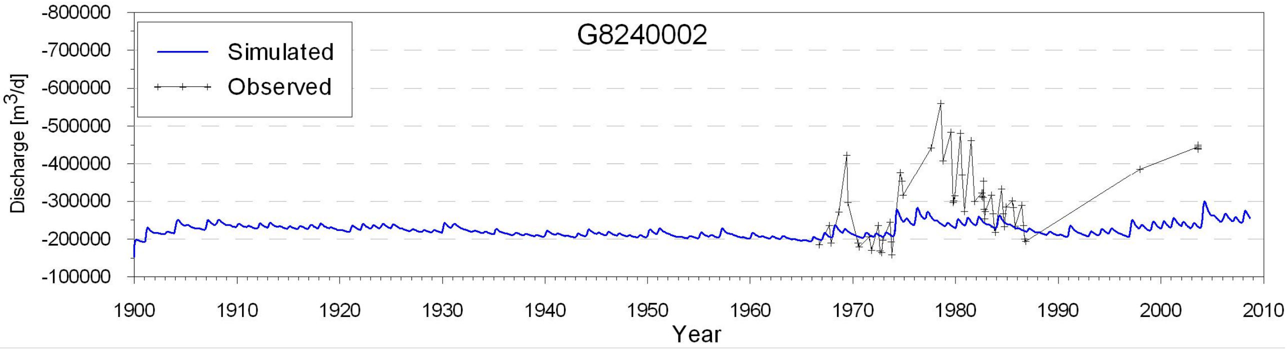


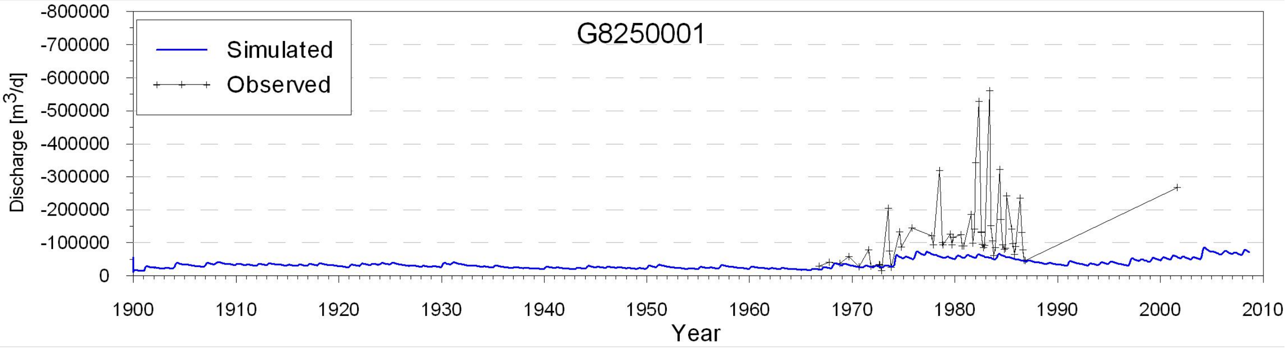


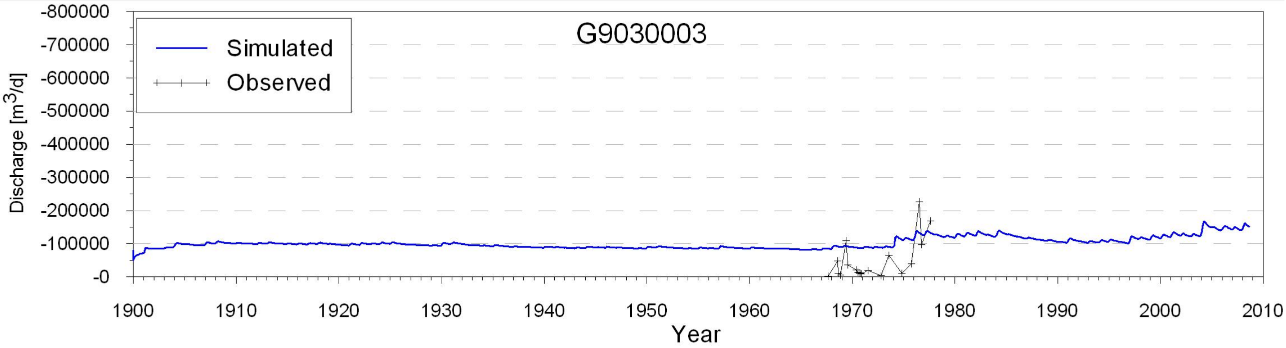


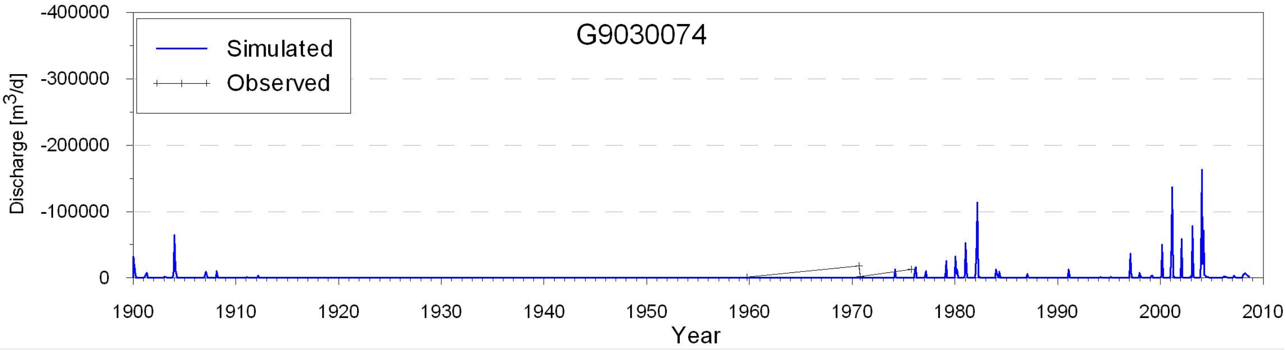


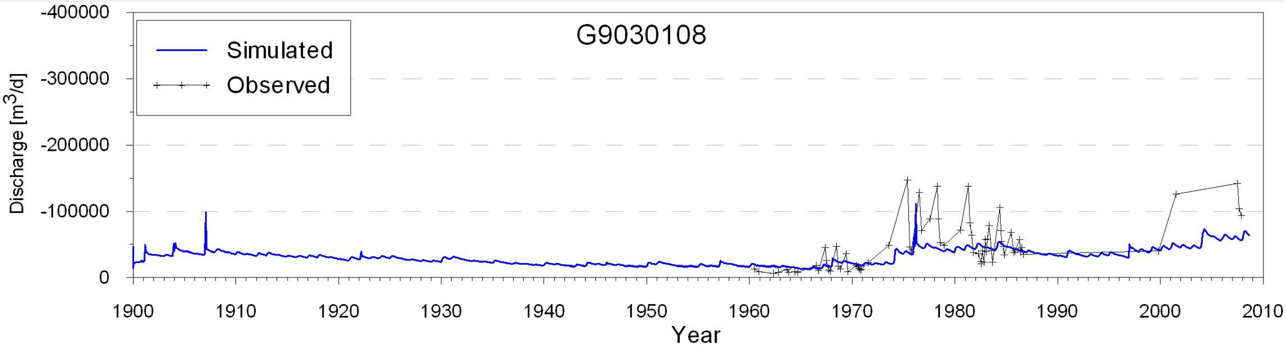
Dook Creek Formation



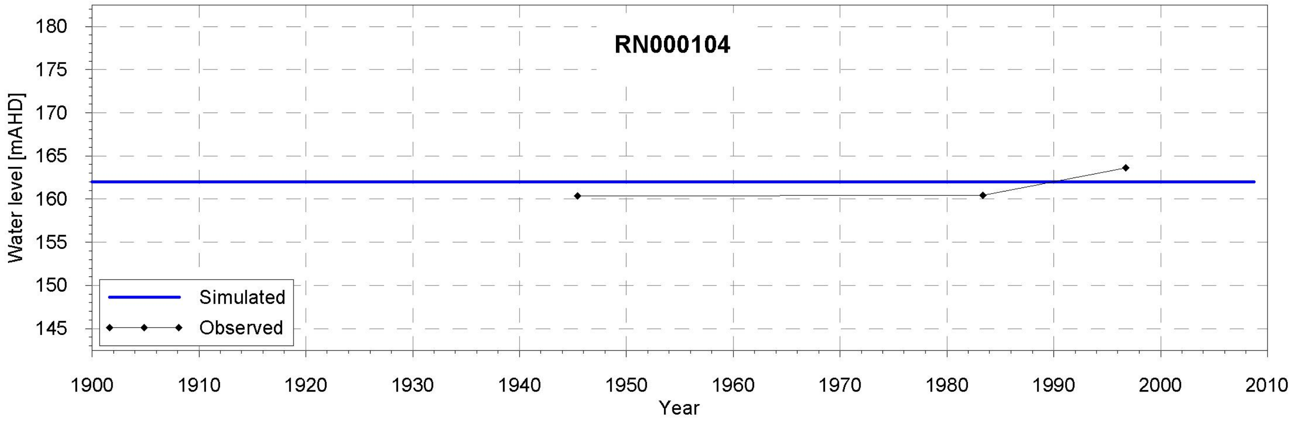


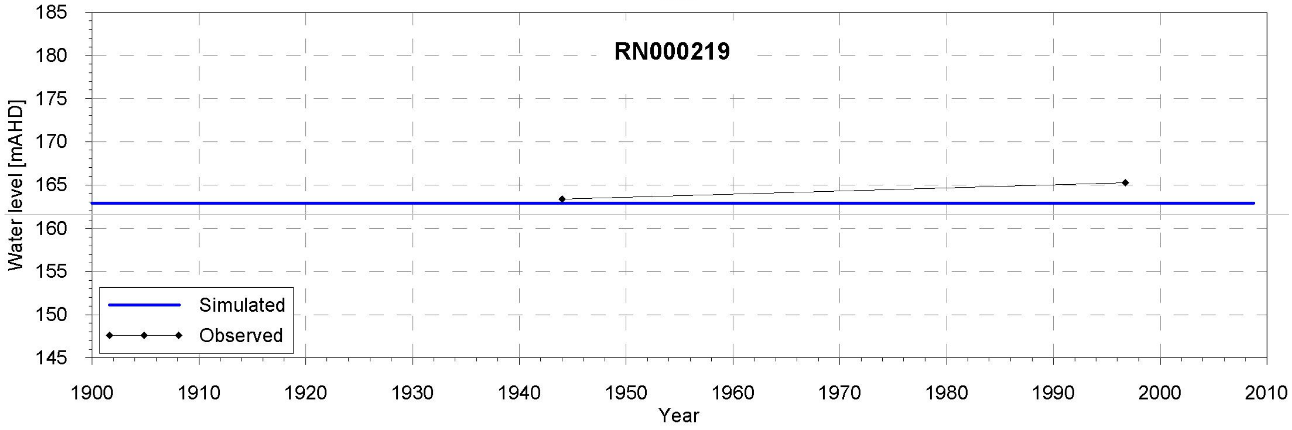


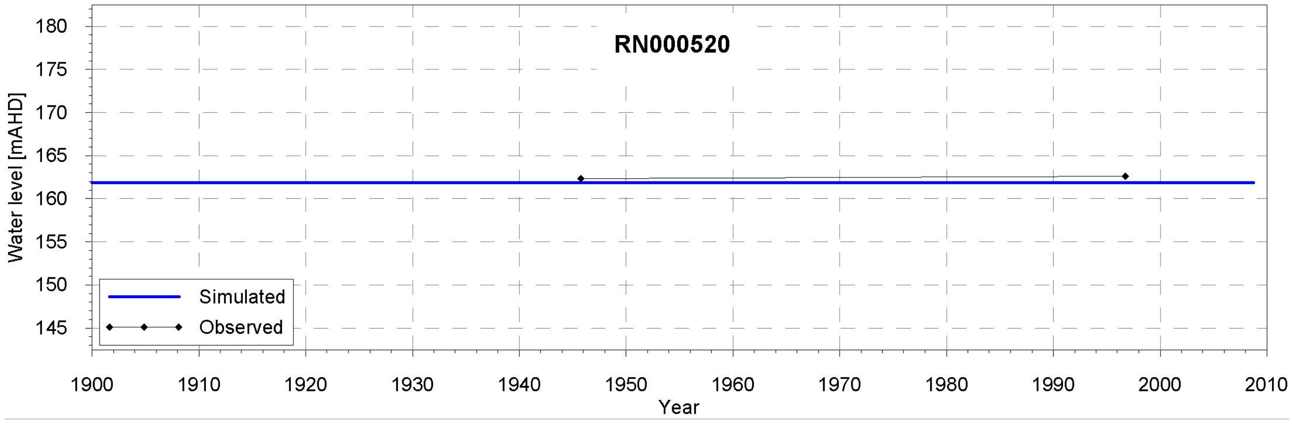


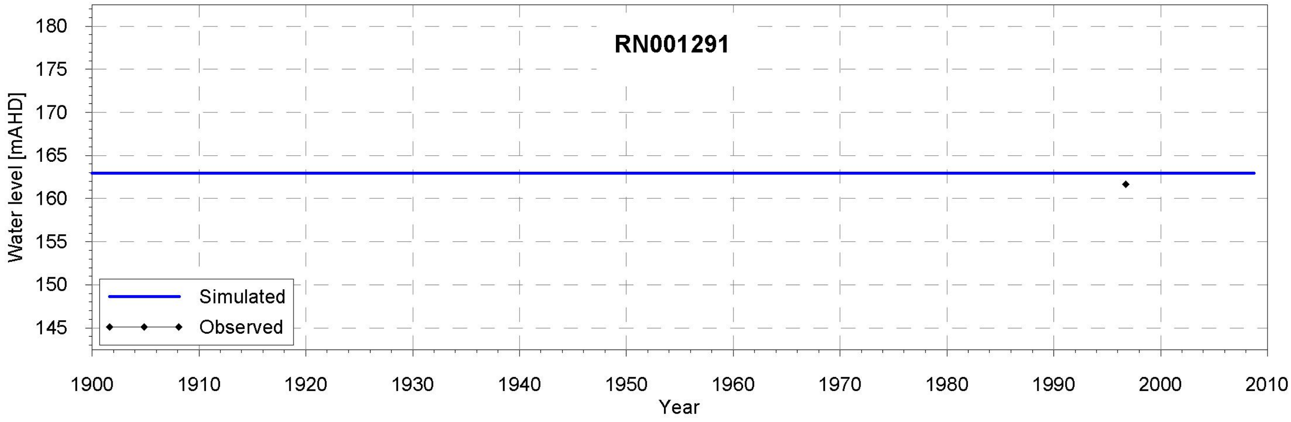


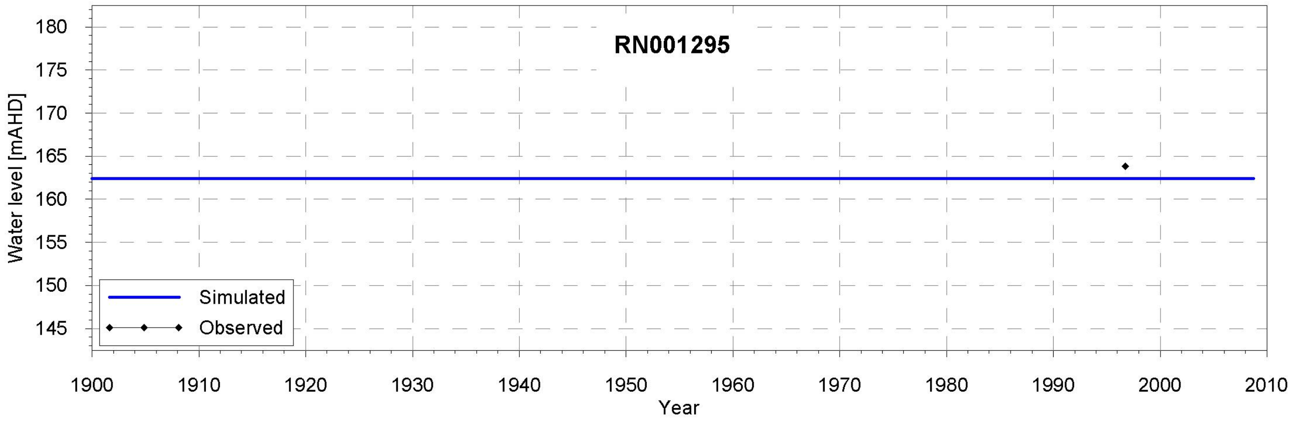
APPENDIX B –Calibrated Groundwater Levels







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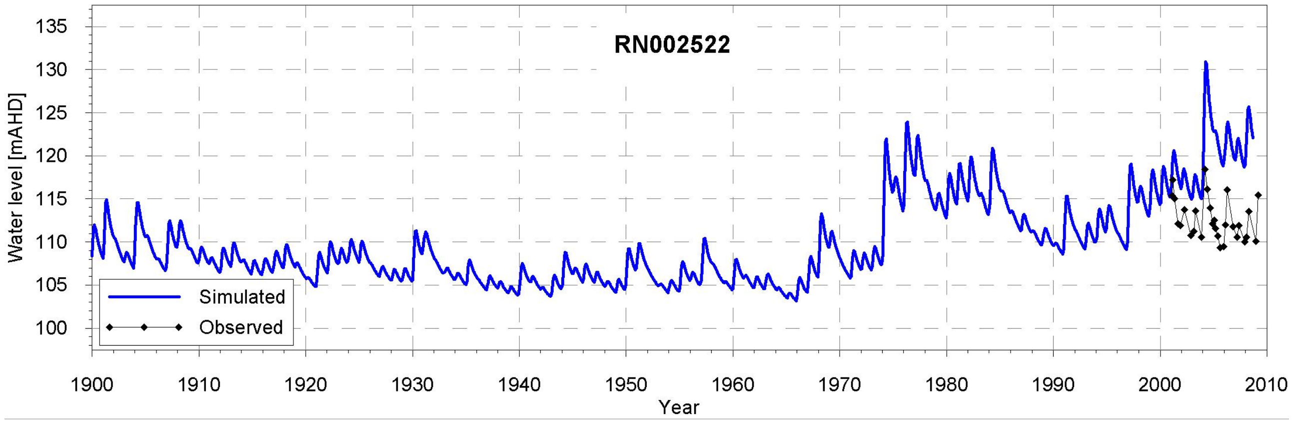
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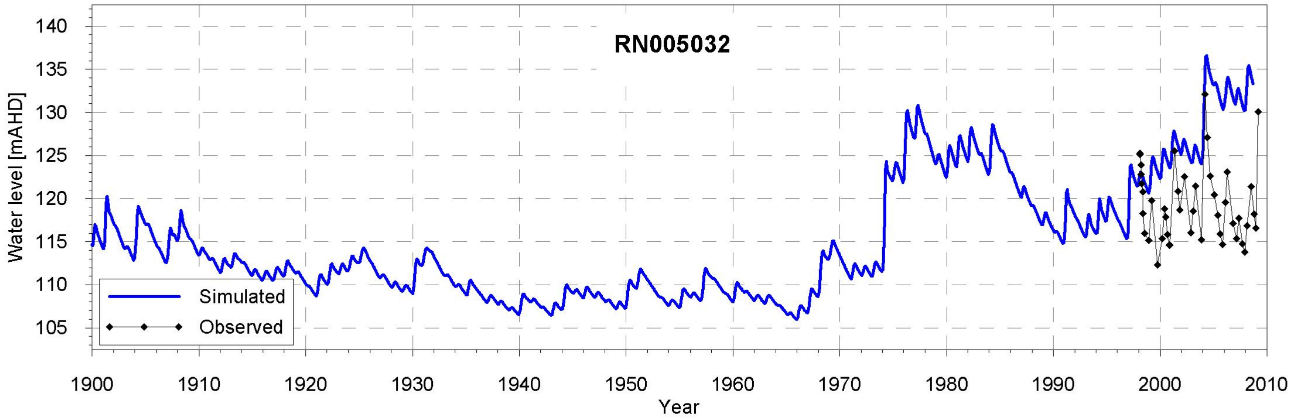
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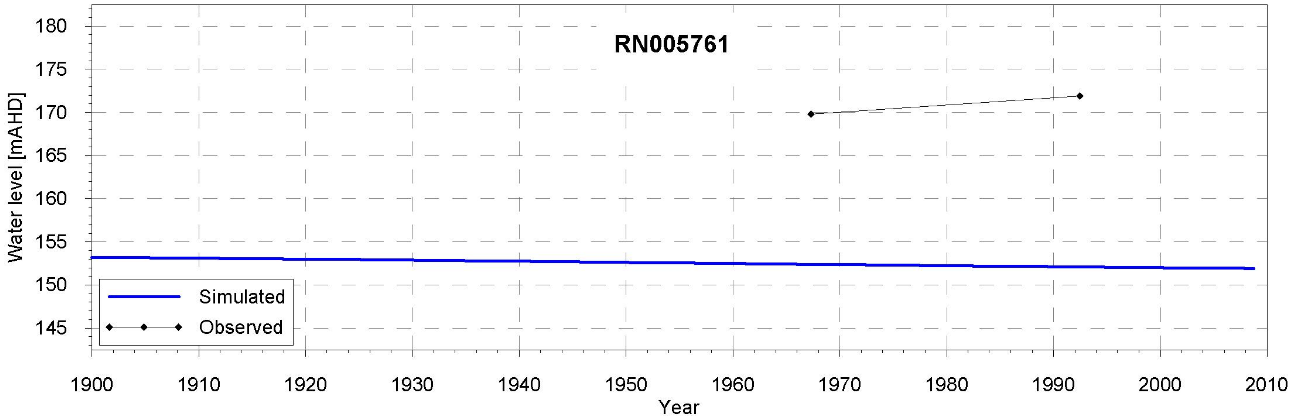
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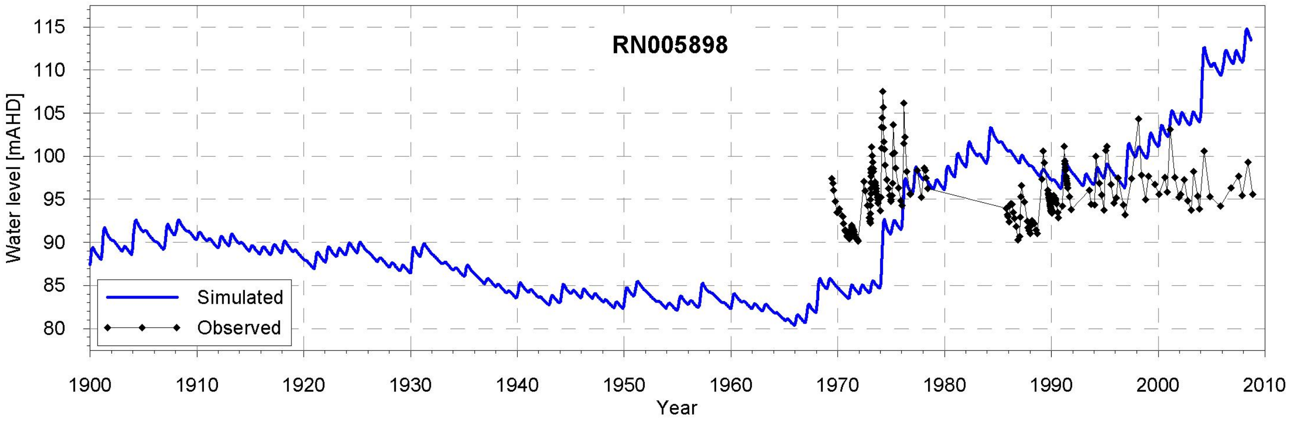
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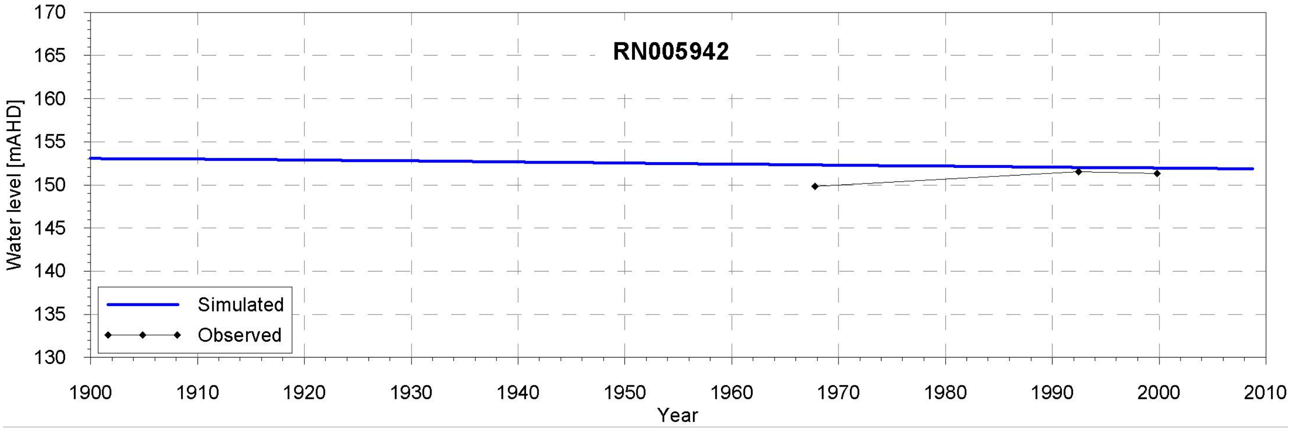
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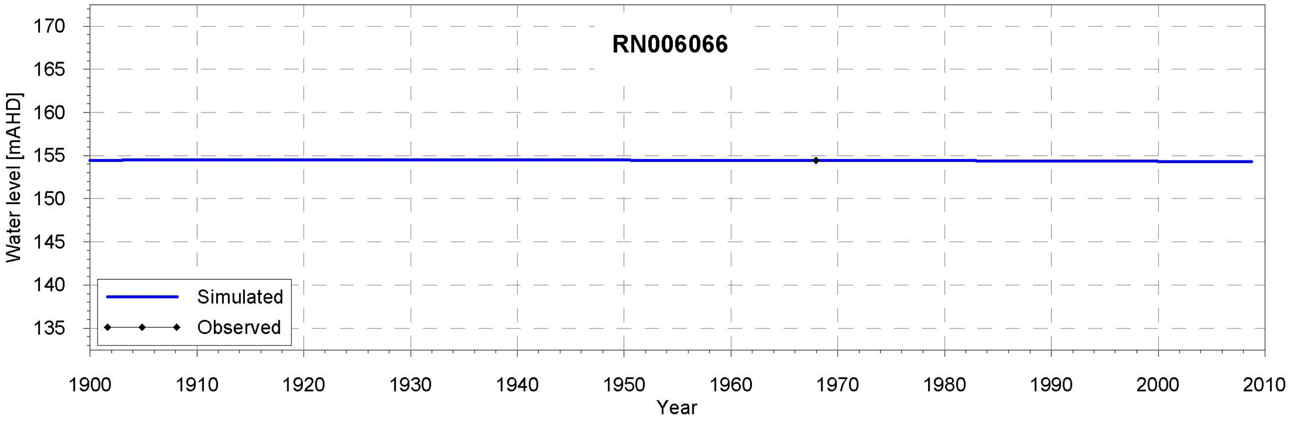
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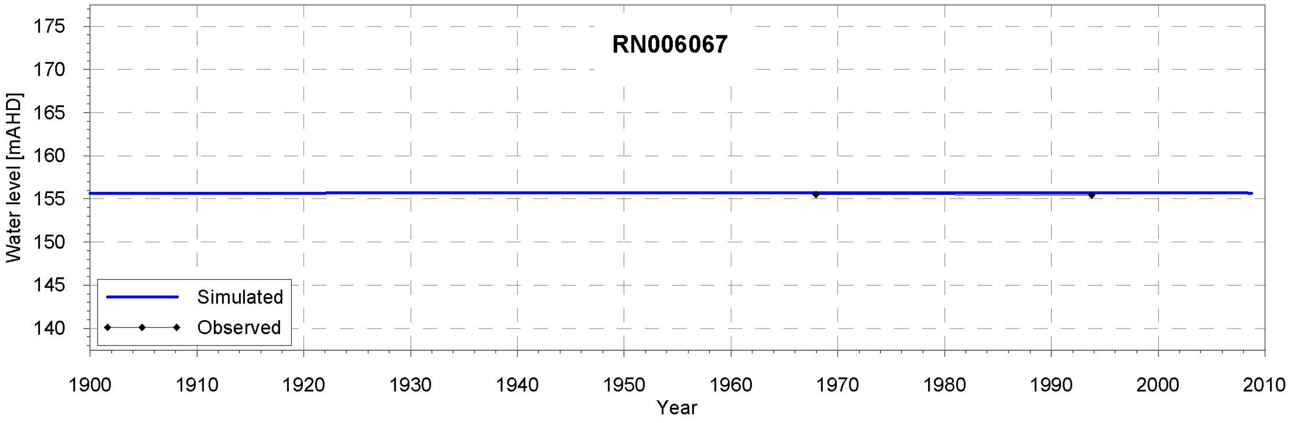
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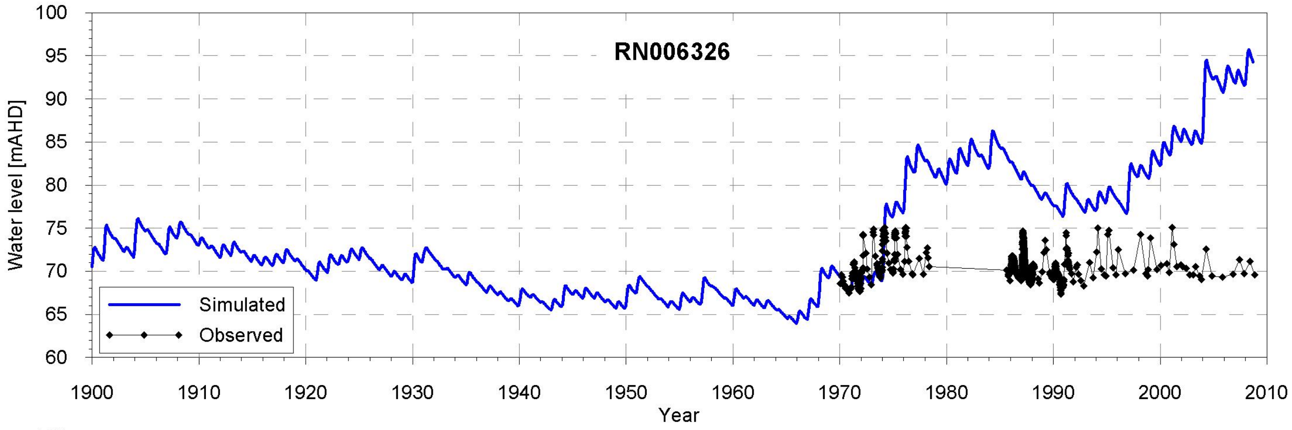
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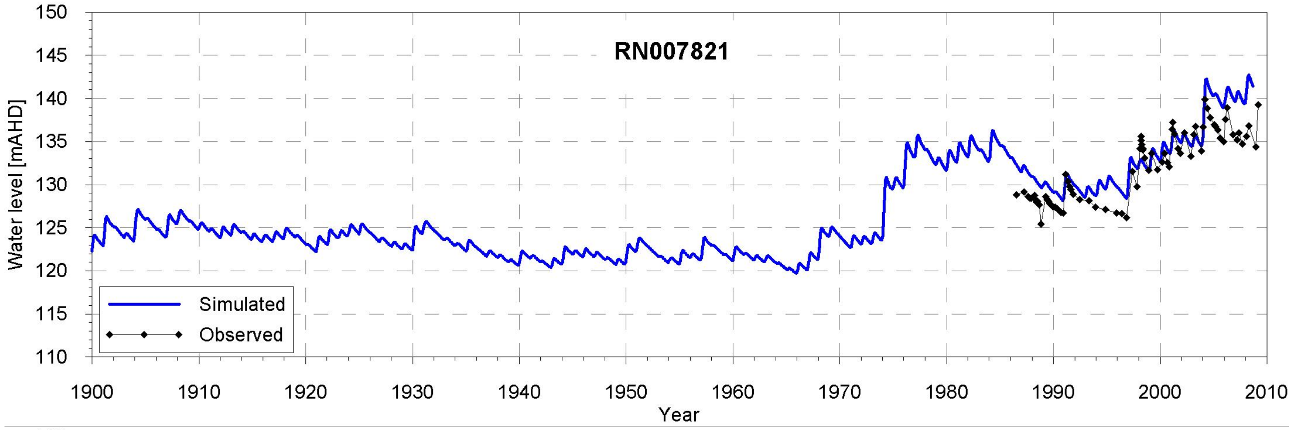
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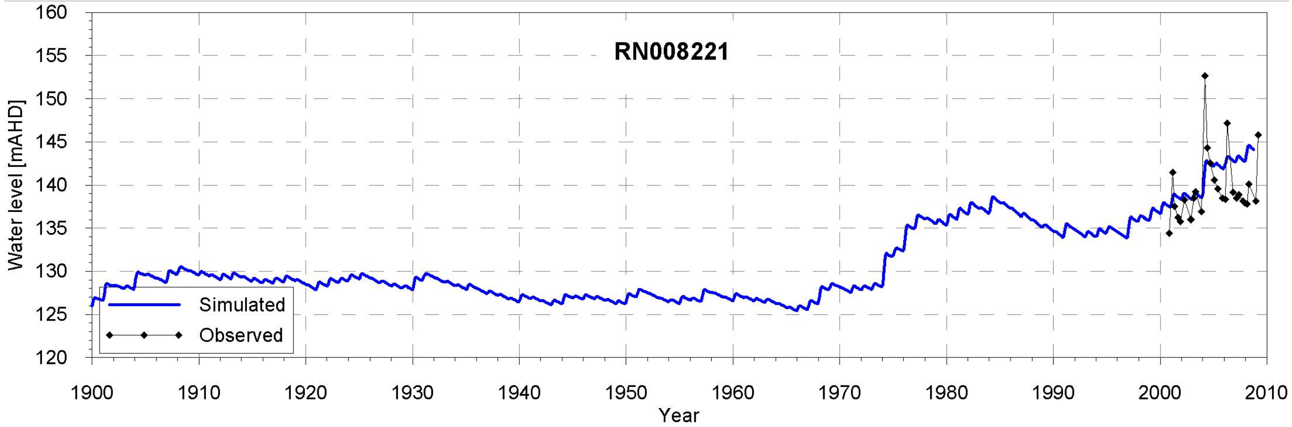
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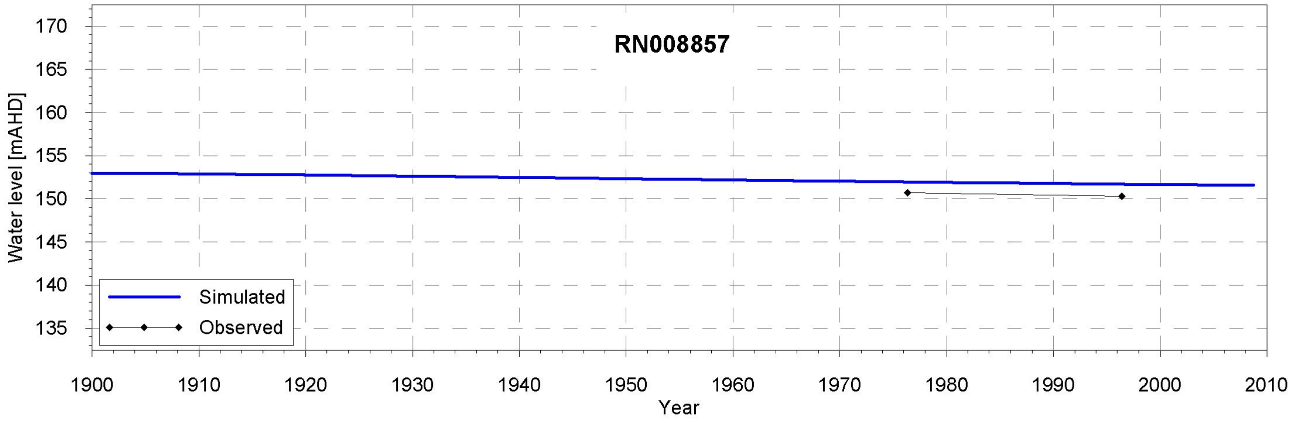
Simulated
Observed


RN008857
Water level [mAHD]
170
165
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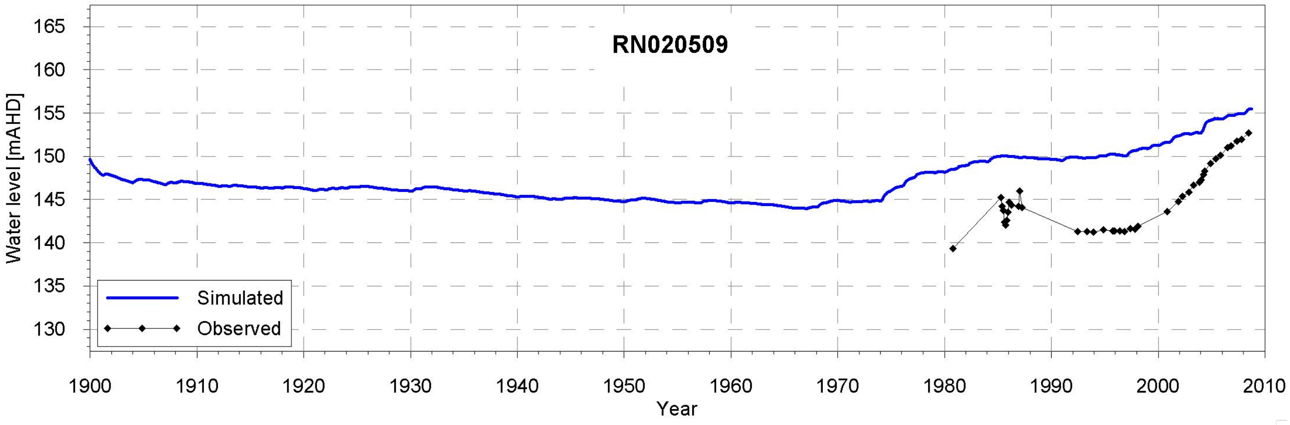
2000
2010
Year
Simulated
Observed


RN020509
Water level [mAHD]
165
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Simulated
Observed
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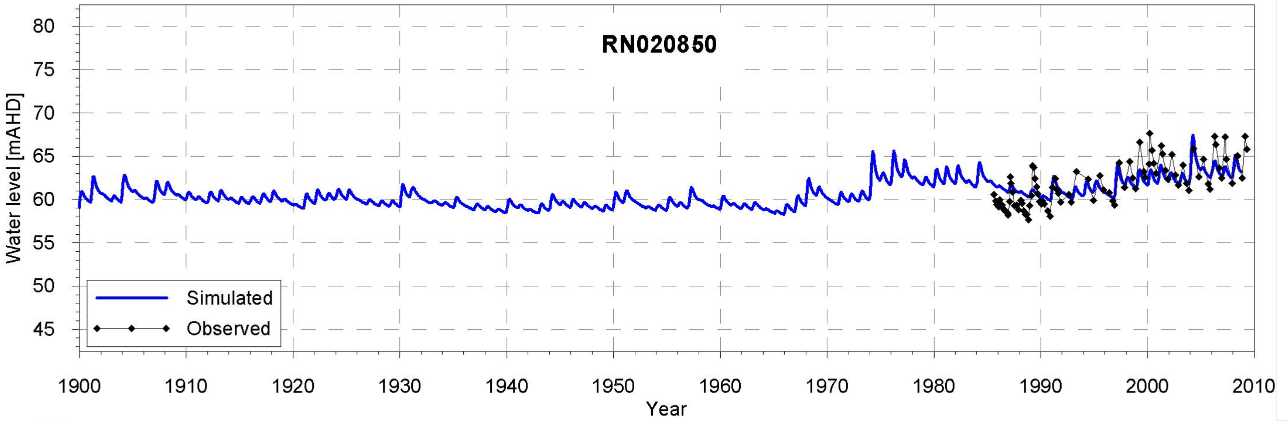
2010
Year


RN020850
Water level [mAHD]
80
75
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Simulated
Observed
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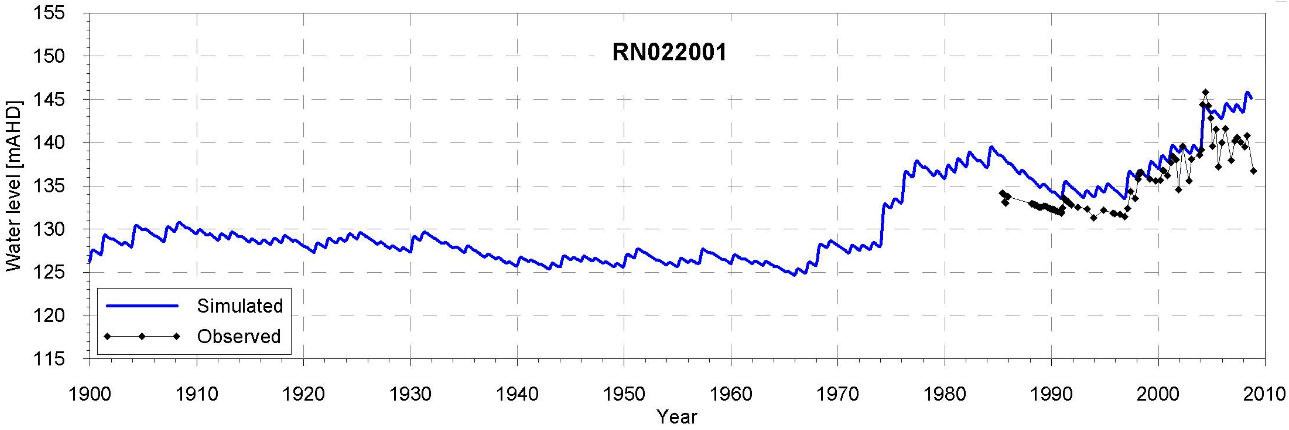
2010
Year


RN022001
Water level [mAHD]
155
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Simulated
Observed
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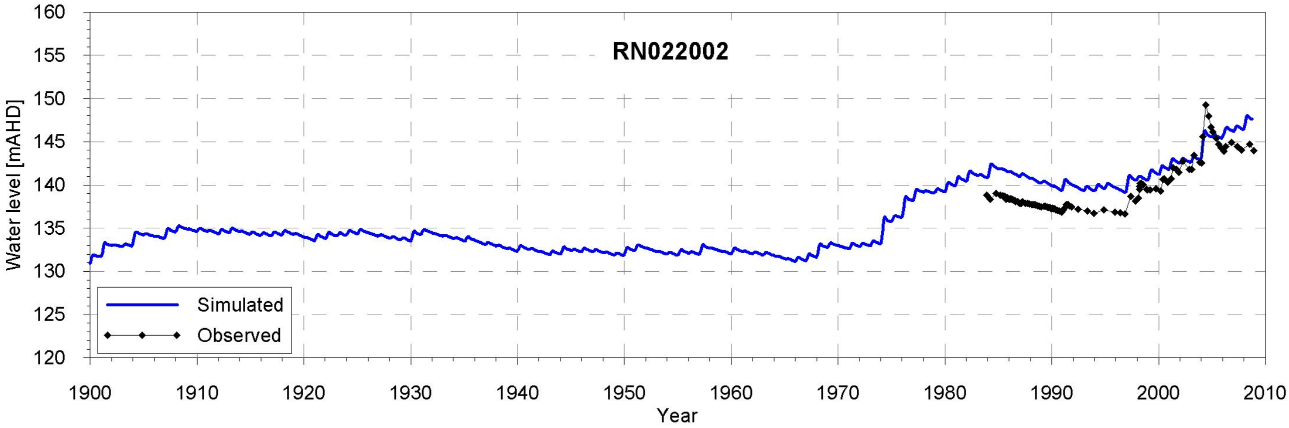
RN022002
Water level [mAHD]
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Simulated
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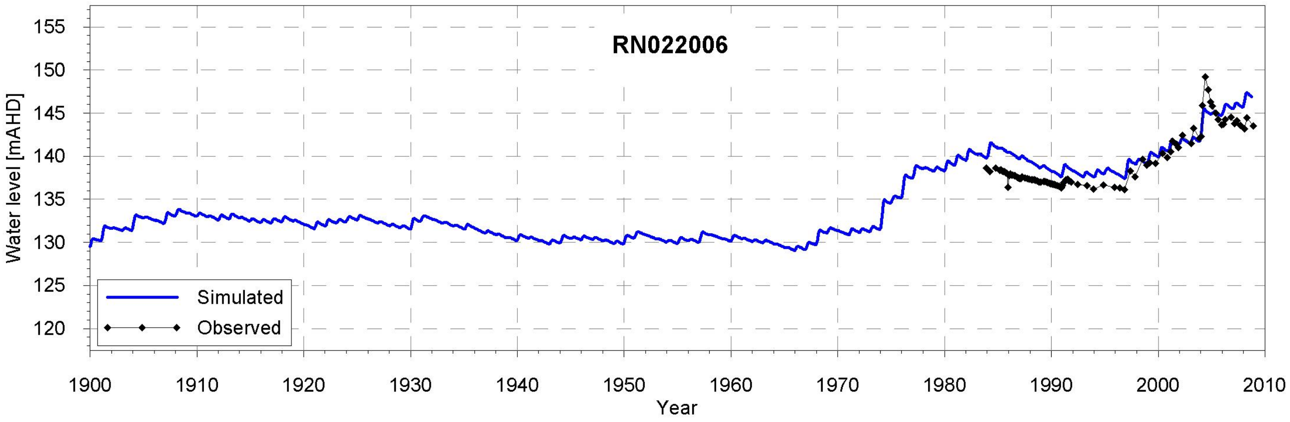
RN022006
Water level [mAHD]
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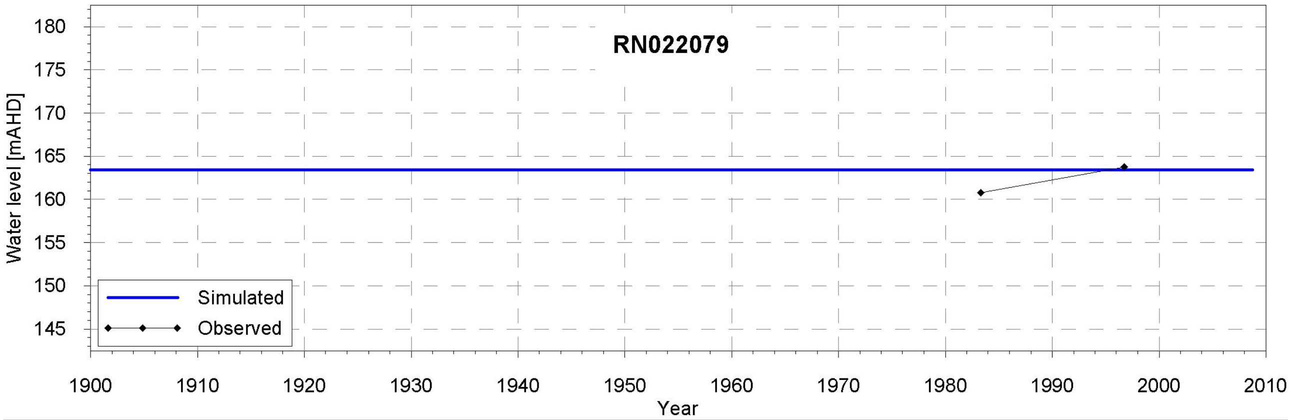
RN022079
Water level [mAHD]
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Simulated
Observed
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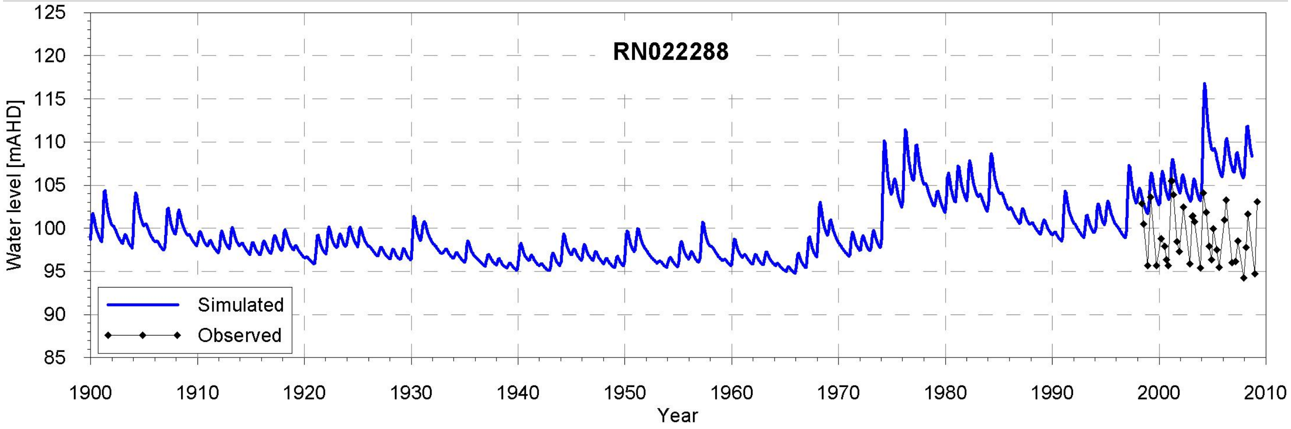
RN022288
Water level [mAHD]
125
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110
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Simulated
Observed
1900
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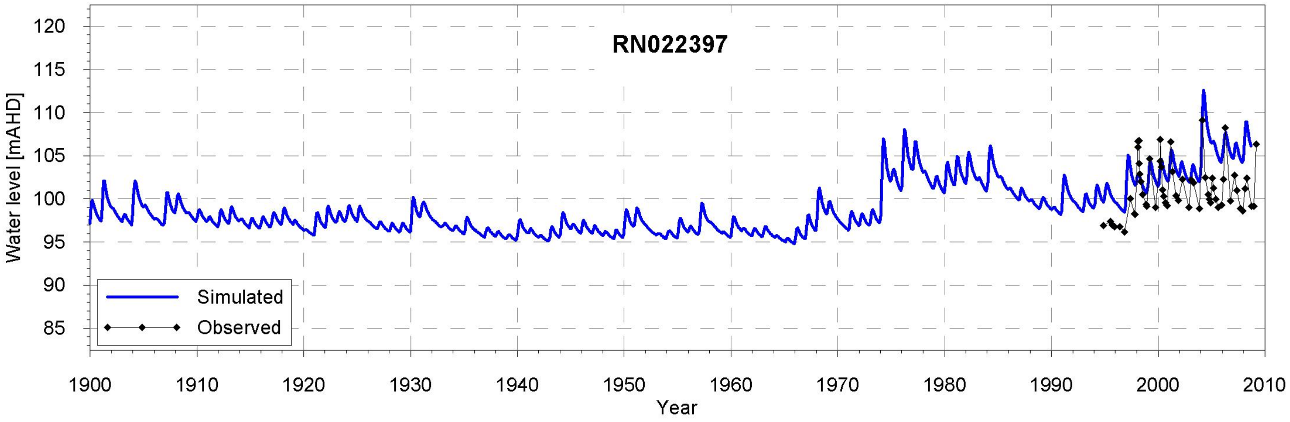
Year


RN022397
Water level [mAHD]
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Simulated
Observed
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2010
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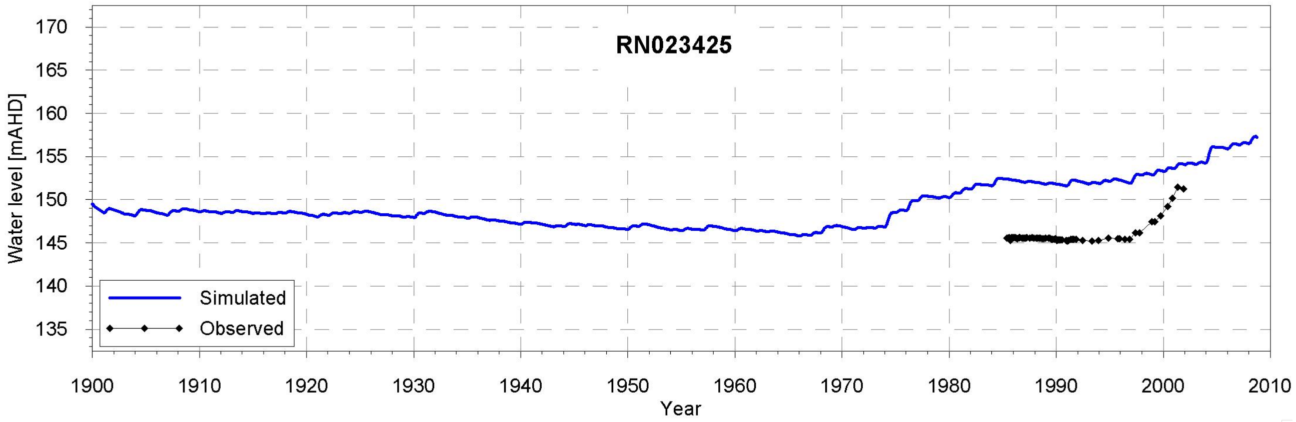
RN023425
Water level [mAHD]
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Simulated
Observed
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2010
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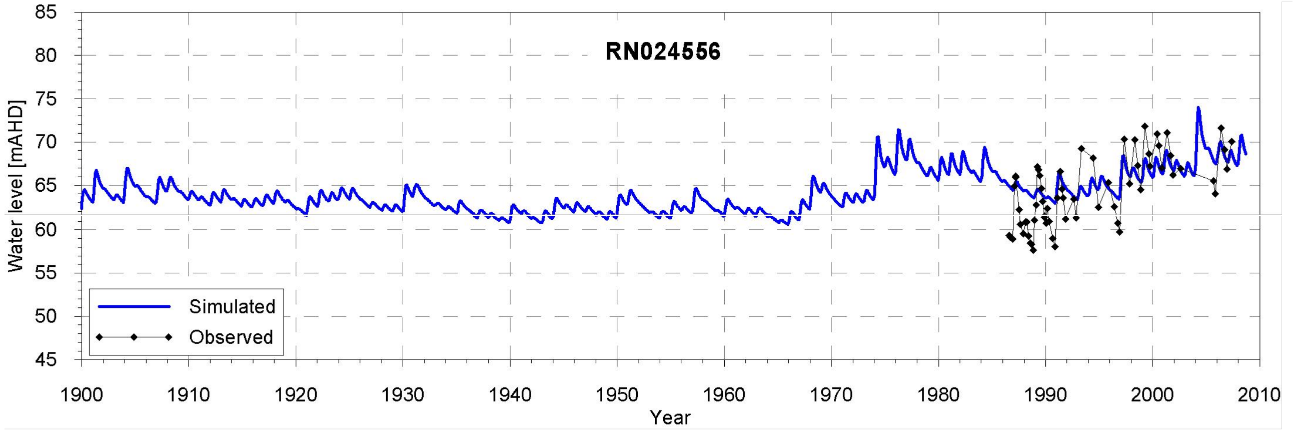
RN024556
Water level [mAHD]
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Simulated
Observed
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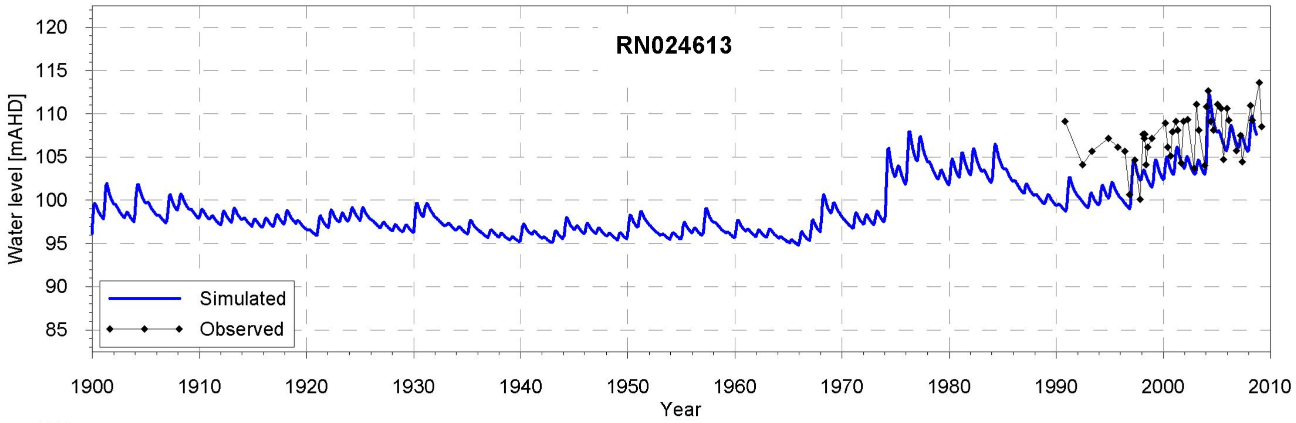
2010
Year


RN024613
Water level [mAHD]
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Simulated
Observed
1900
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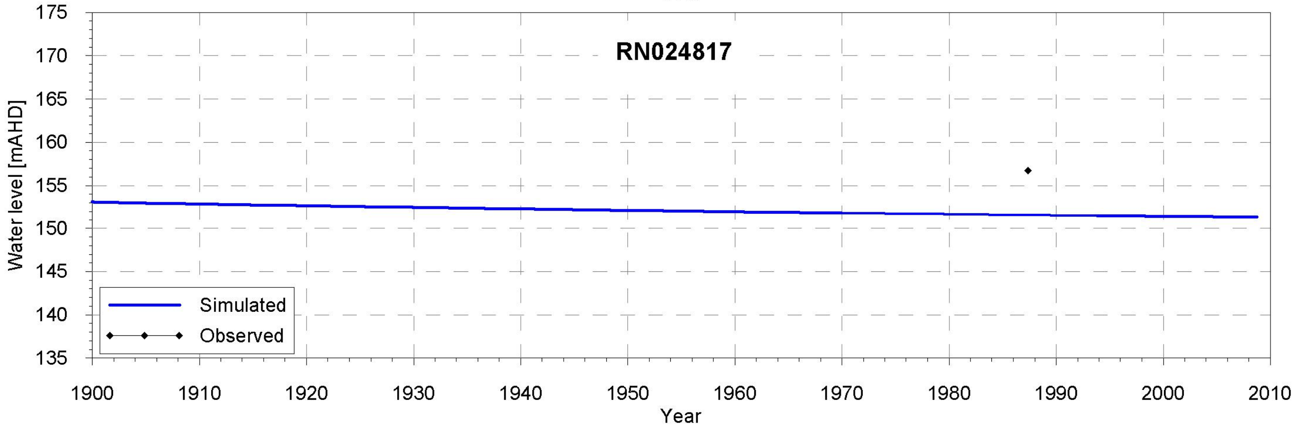
2000
2010
Year


RN024817
Water level [mAHD]
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Simulated
Observed
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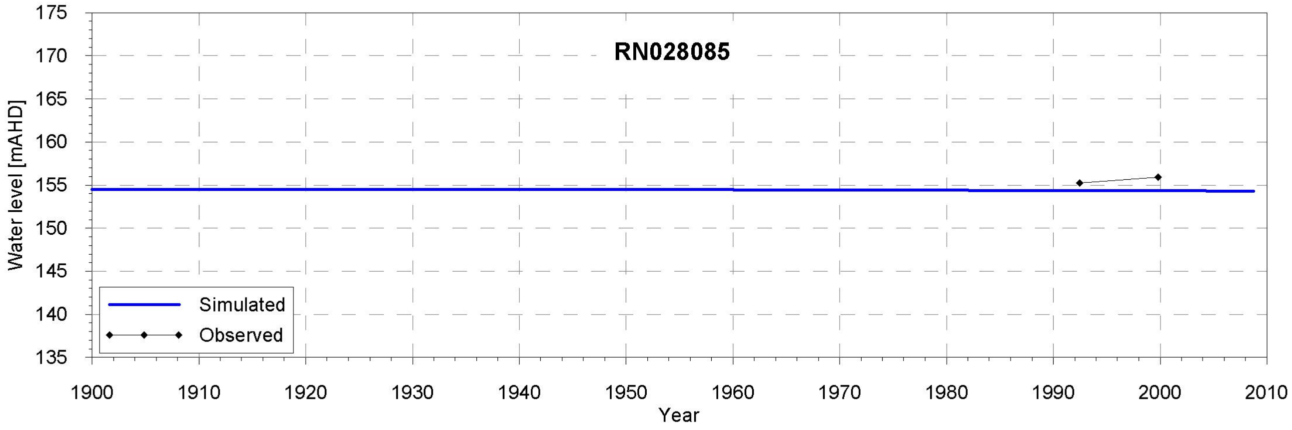
2010
Year


RN028085
Water level [mAHD]
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Simulated
Observed
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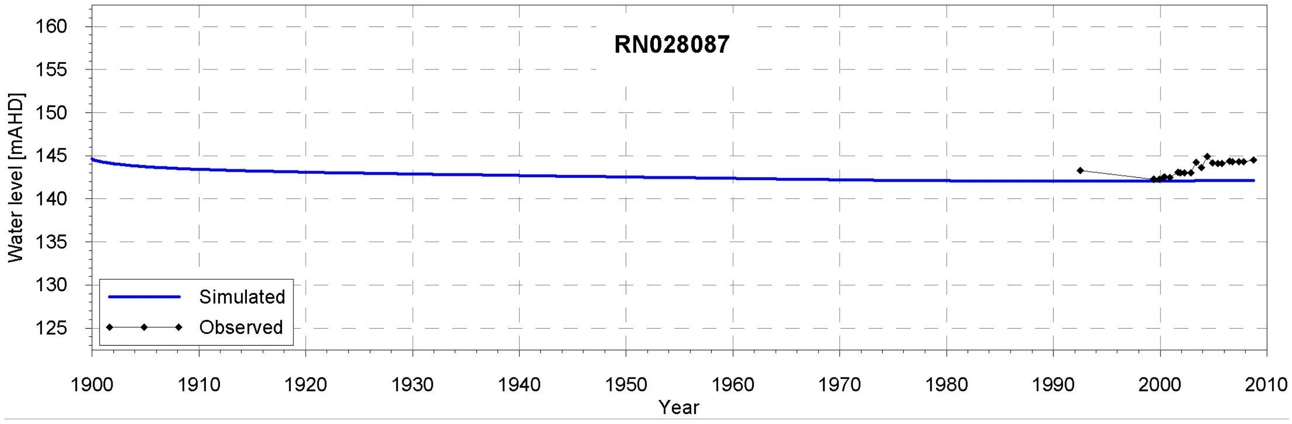
2010
Year


RN028087
Water level [mAHD]
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Simulated
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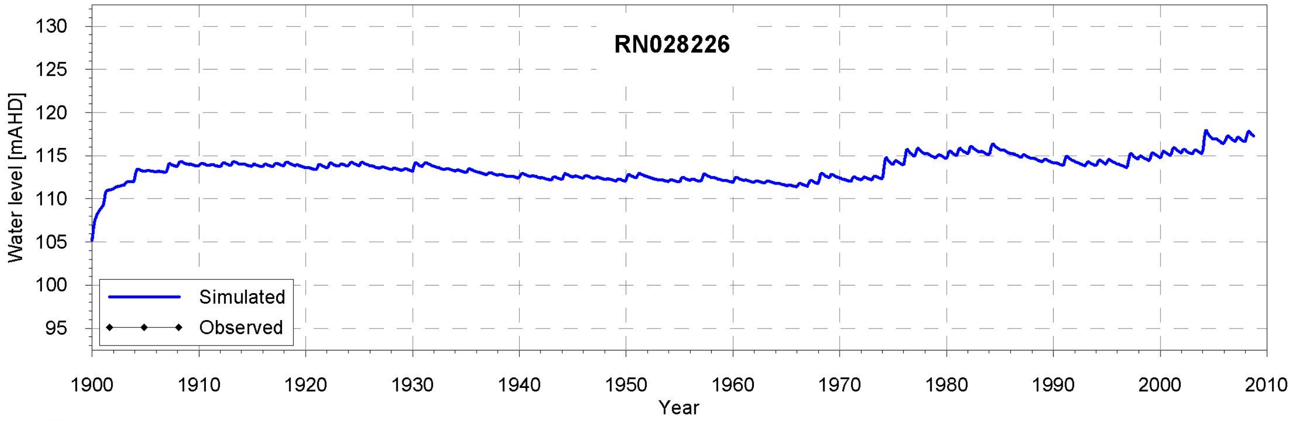
Year


RN028226
Water level [mAHD]
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Simulated
Observed
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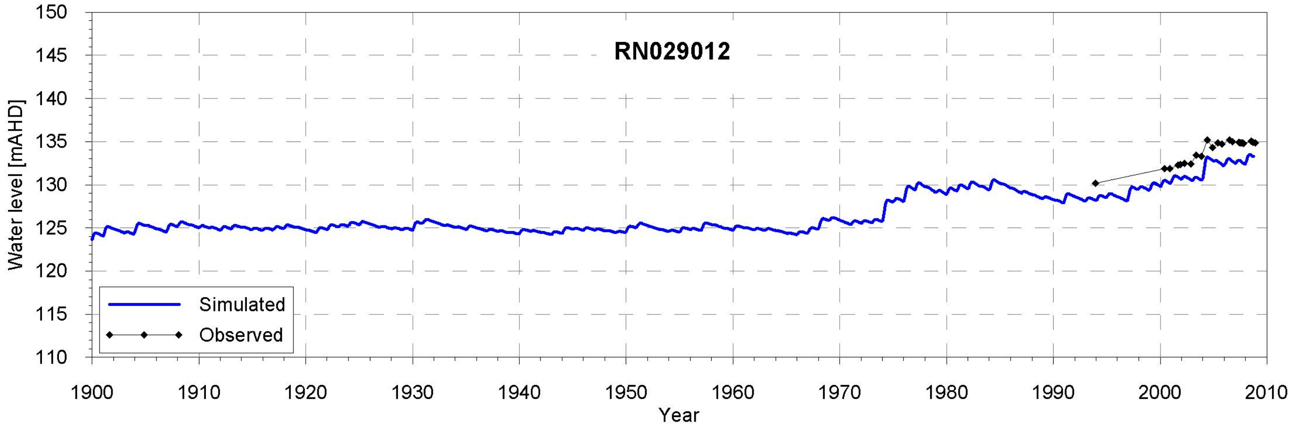
2010
Year


RN029012
Water level [mAHD]
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Simulated
Observed
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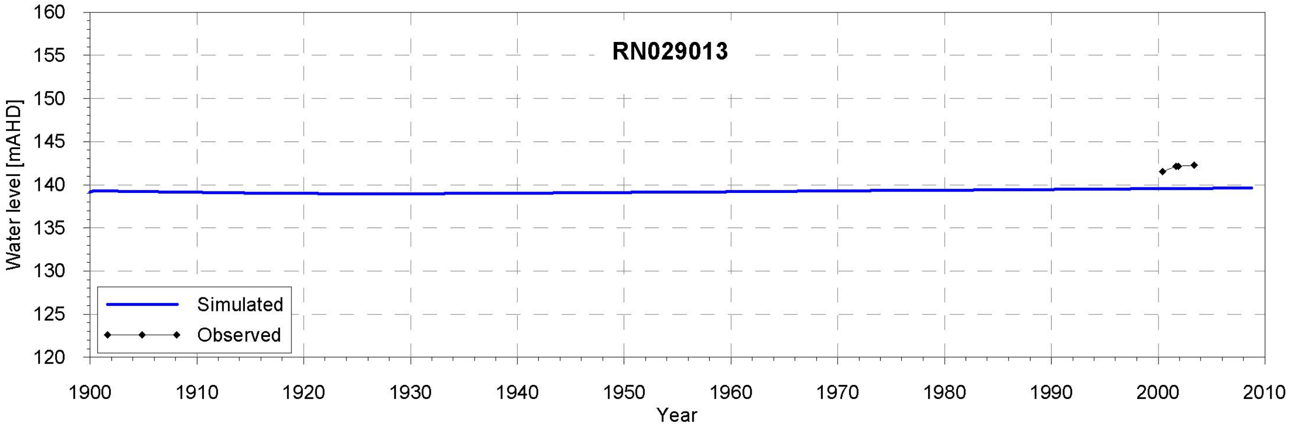
2010
Year


RN029013
Water level [mAHD]
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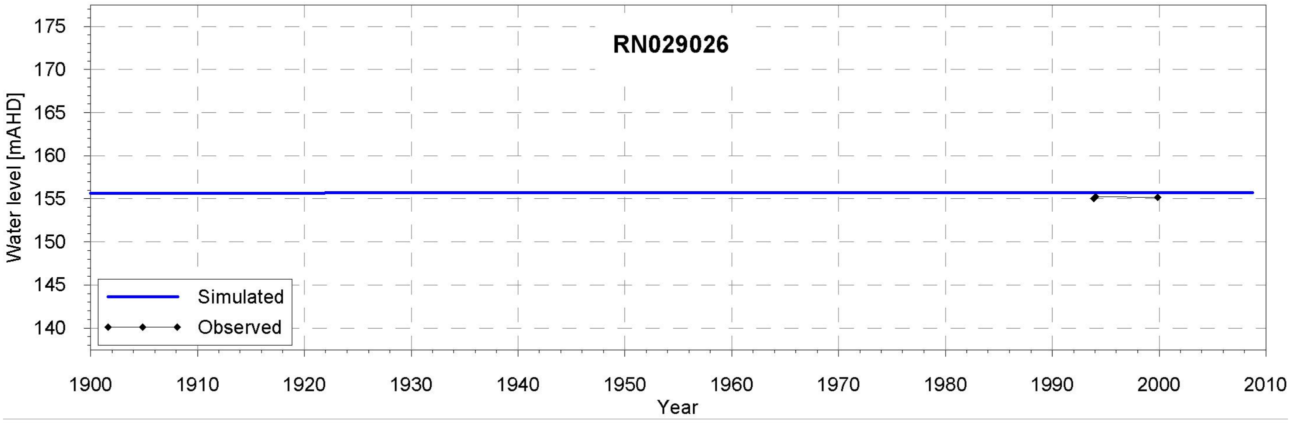
Year
Simulated
Observed


RN029026
Water level [mAHD]
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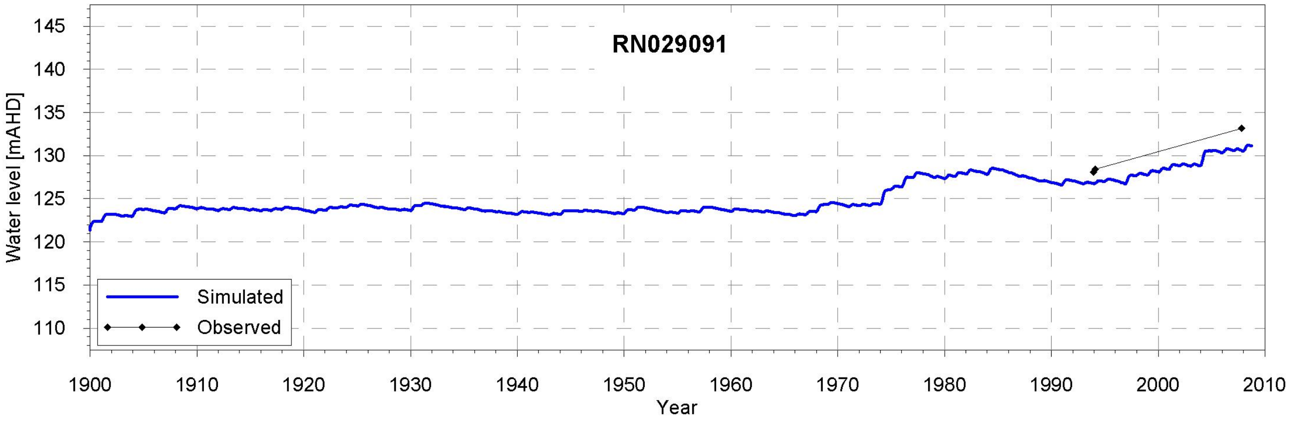
Year
Simulated
Observed


RN029091
Water level [mAHD]
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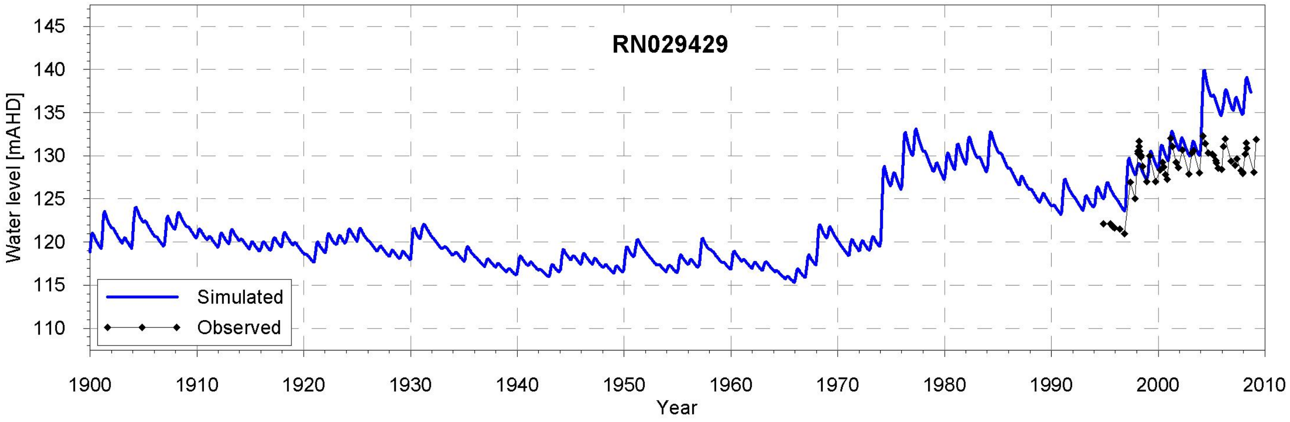
2010
Year
Simulated
Observed


RN029429
Water level [mAHD]
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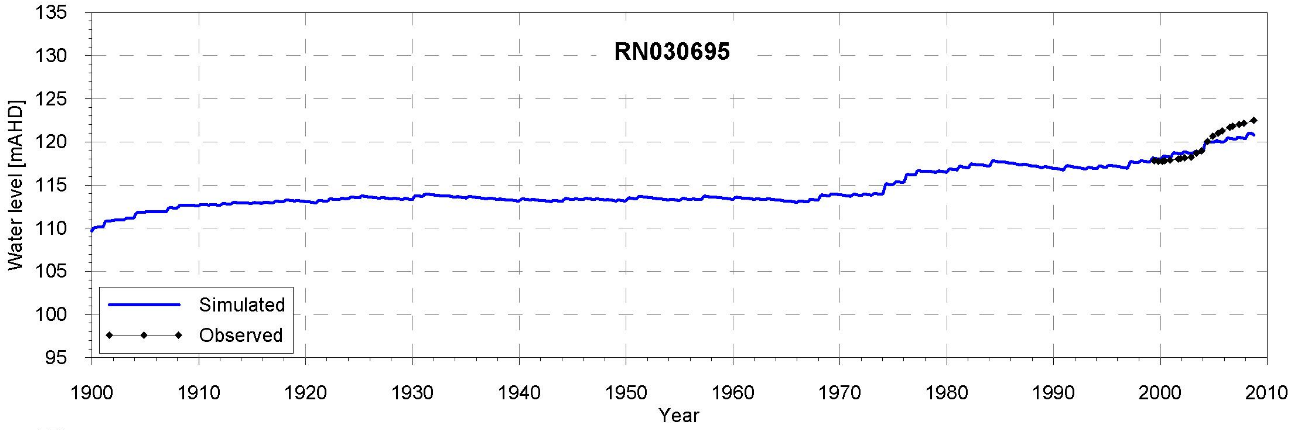
Year
Simulated
Observed


RN030695
Water level [mAHD]
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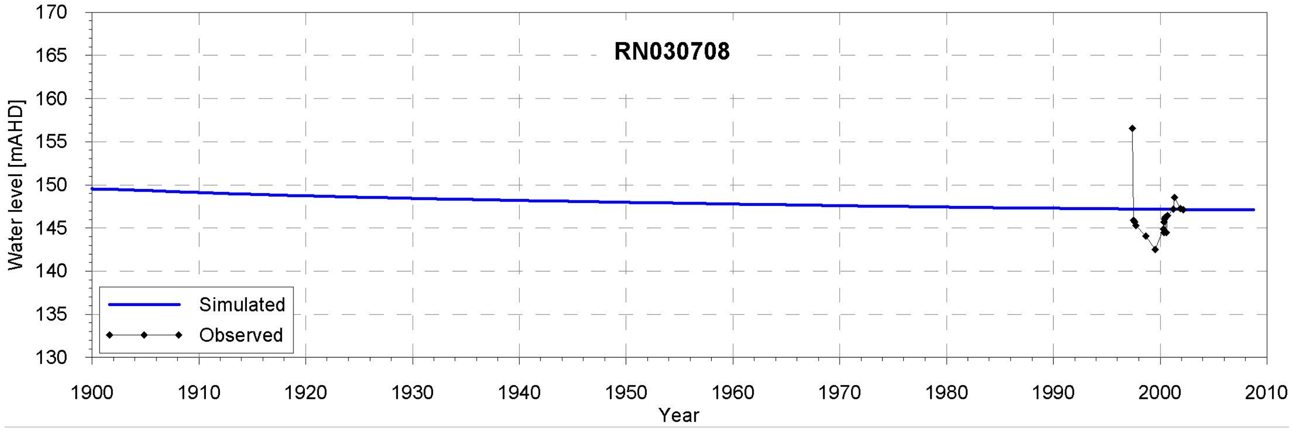
Year
Simulated
Observed


RN030708
Water level [mAHD]
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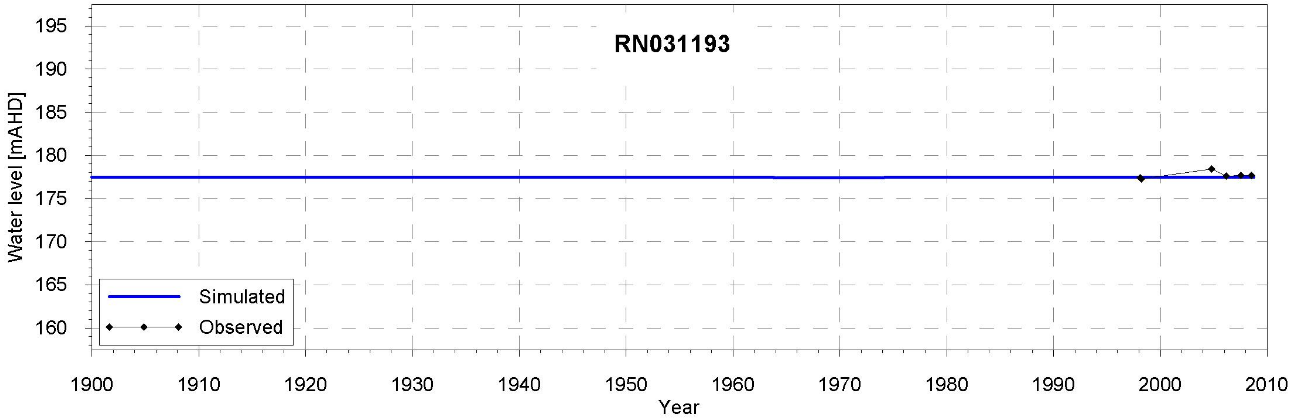
Year
Simulated
Observed


RN031193
Water level [mAHD]
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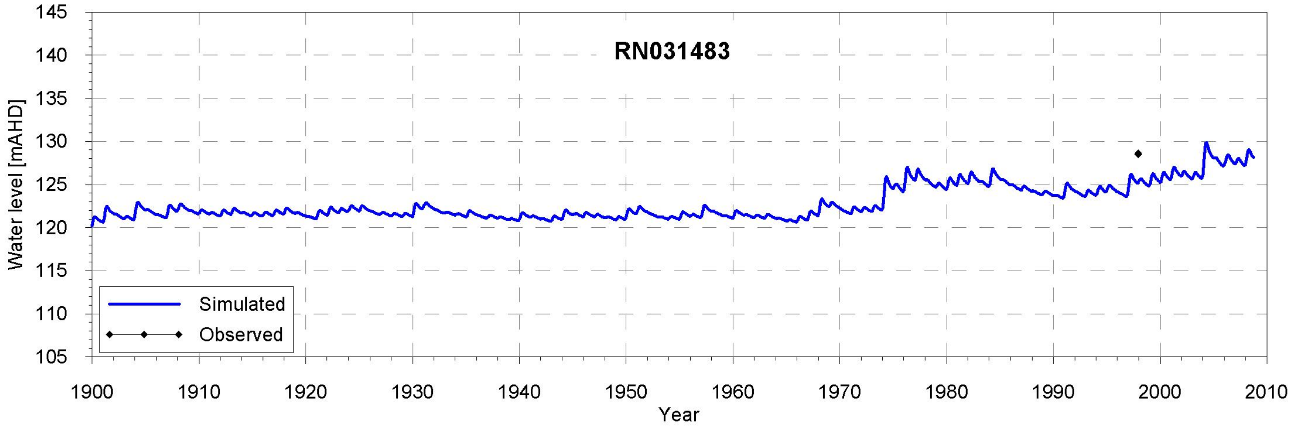
Year
Simulated
Observed


RN031483
Water level [mAHD]
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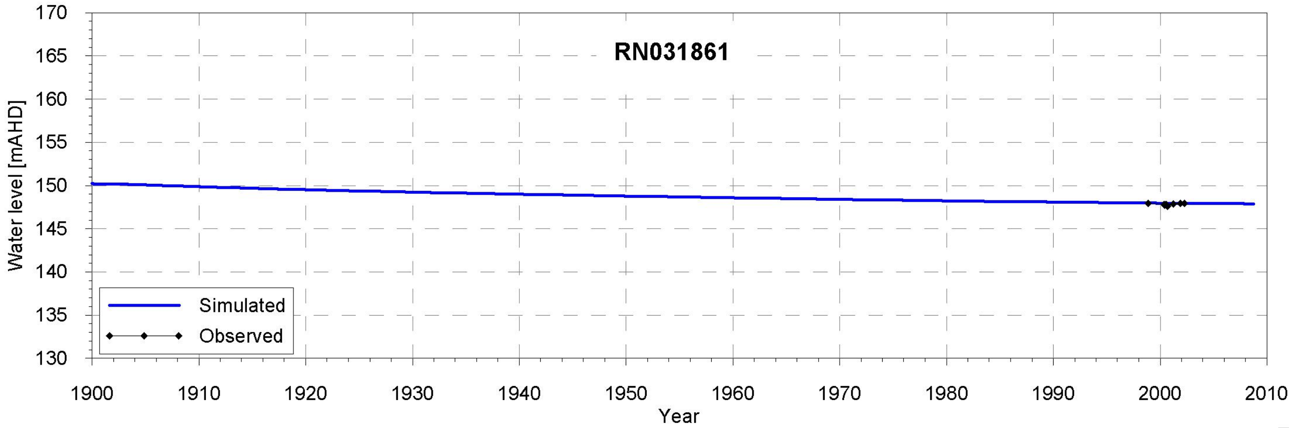
Observed


RN031861
Water level [mAHD]
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Simulated
Observed
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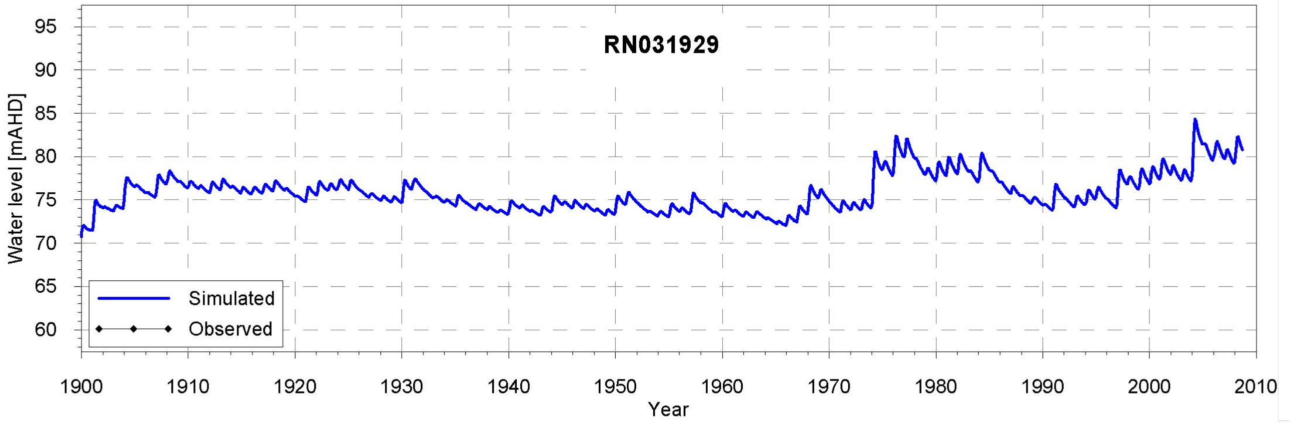
RN031929
Water level [mAHD]
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Simulated
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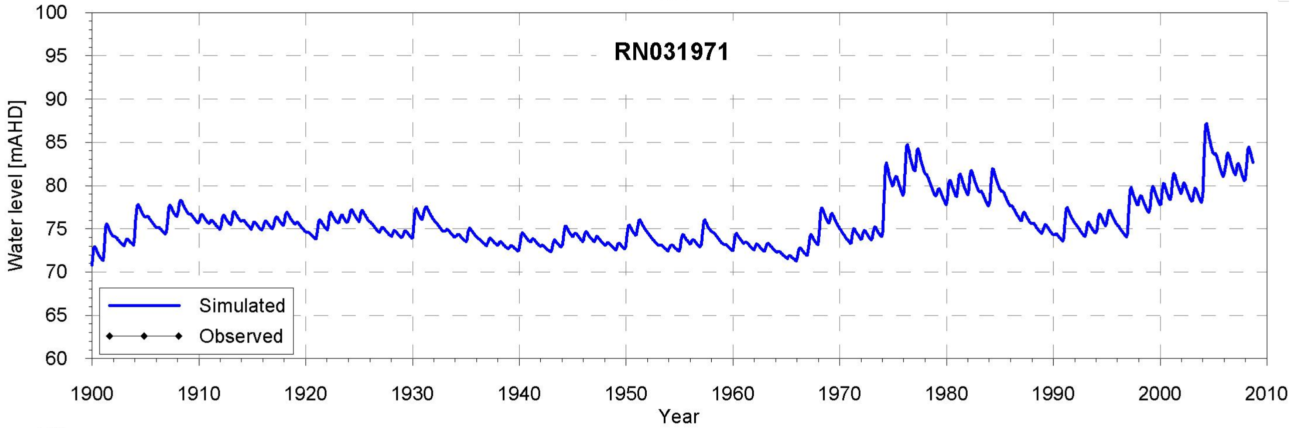
RN031971
Water level [mAHD]
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Simulated
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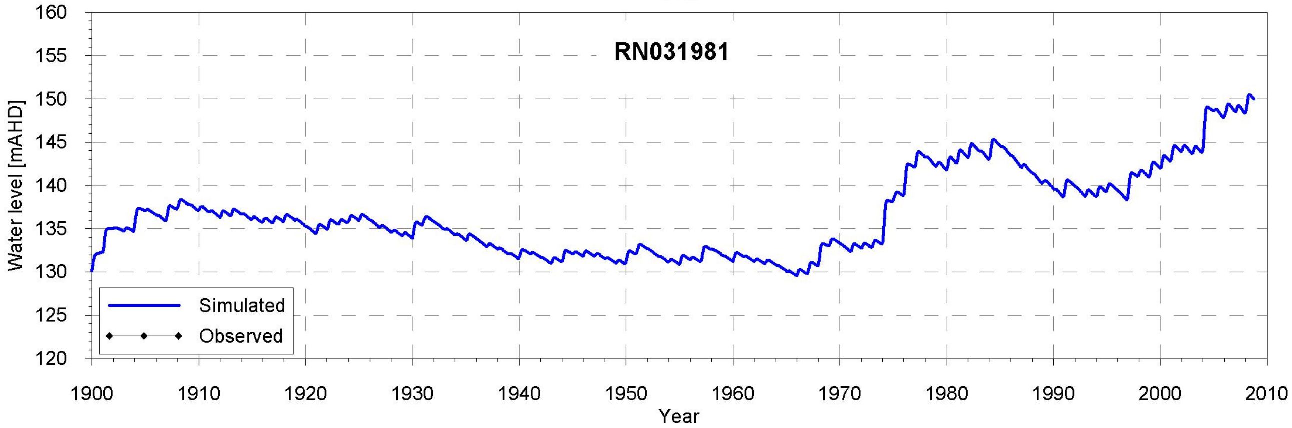
RN031981
Water level [mAHD]
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Simulated
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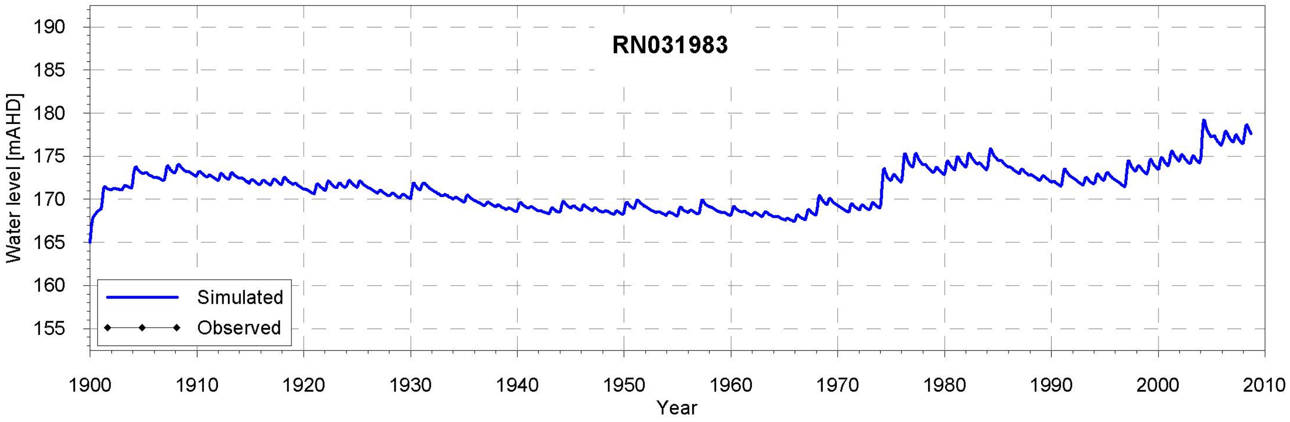
RN031983
Water level [mAHD]
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Simulated
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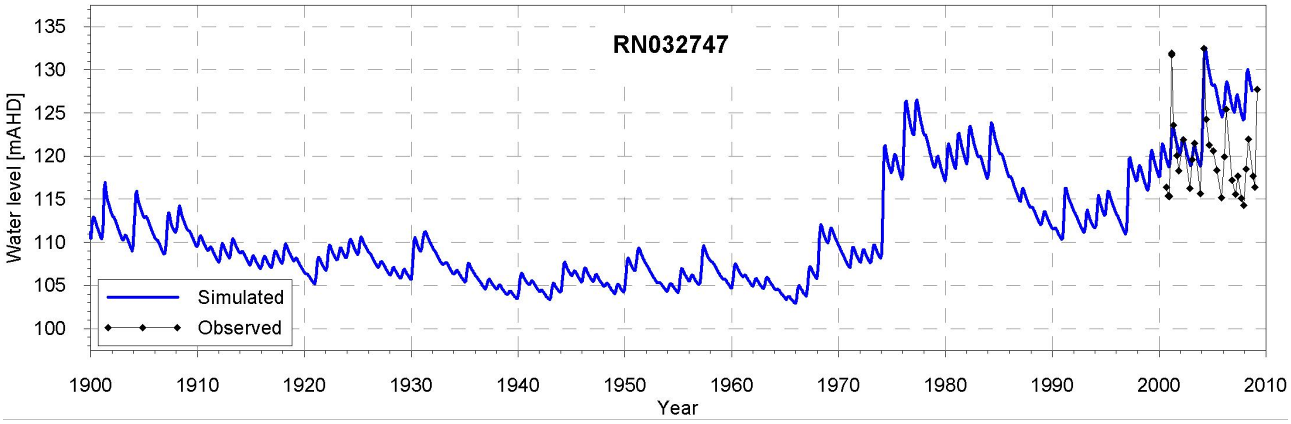
RN032747
Water level [mAHD]
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Simulated
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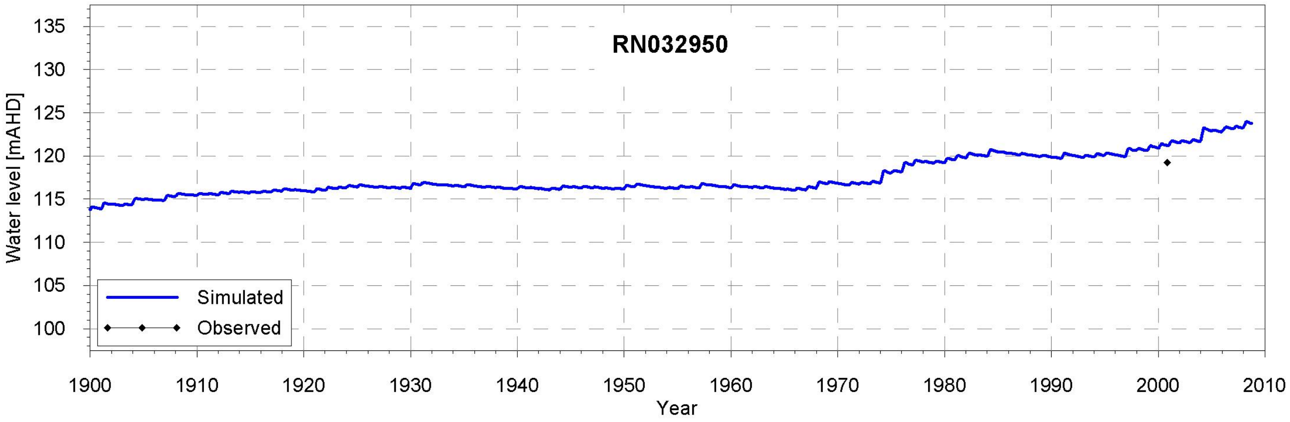
RN032950
Water level [mAHD]
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Simulated
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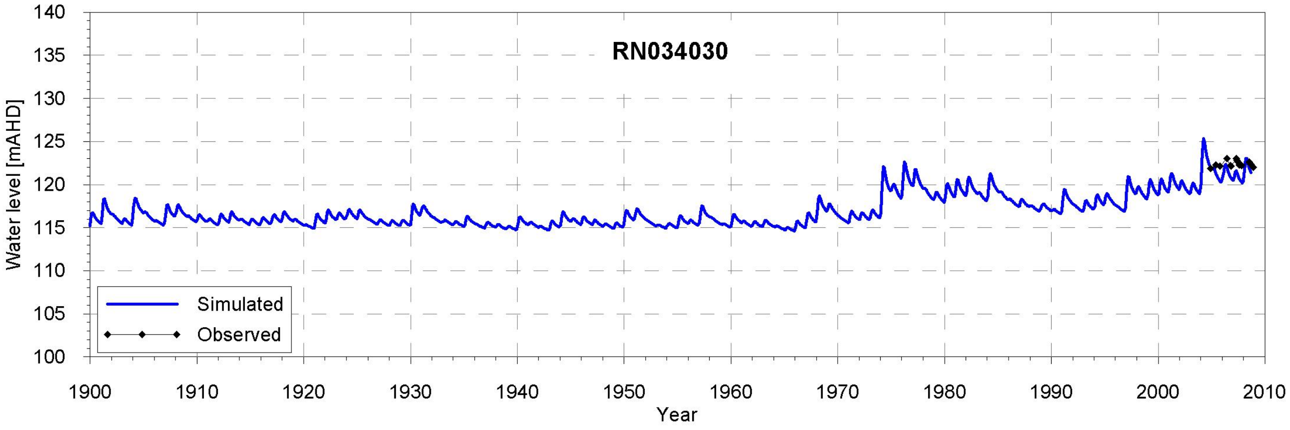
RN034030
Water level [mAHD]
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Simulated
Observed
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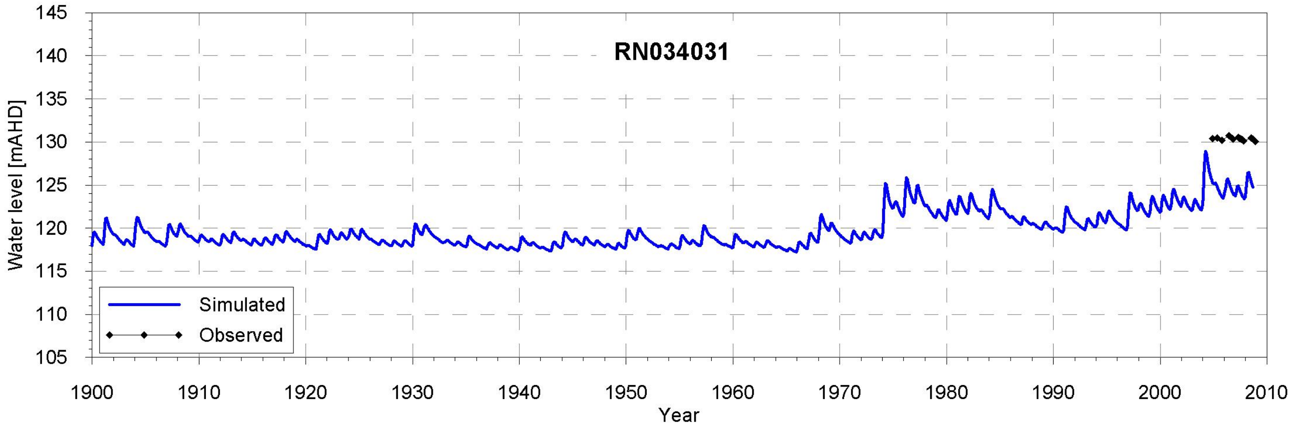
2010
Year


RN034031
Water level [mAHD]
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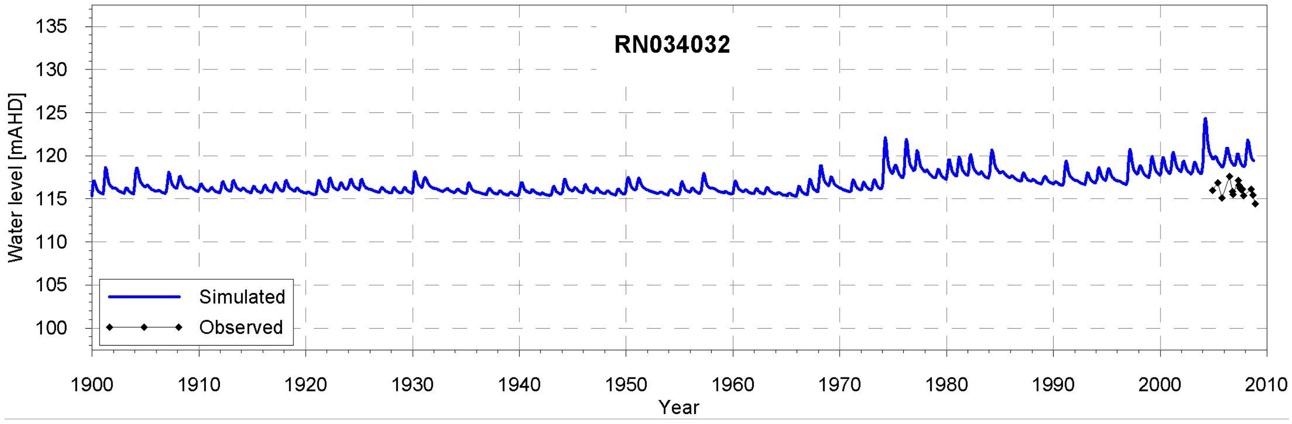
Year
Simulated
Observed


RN034032
Water level [mAHD]
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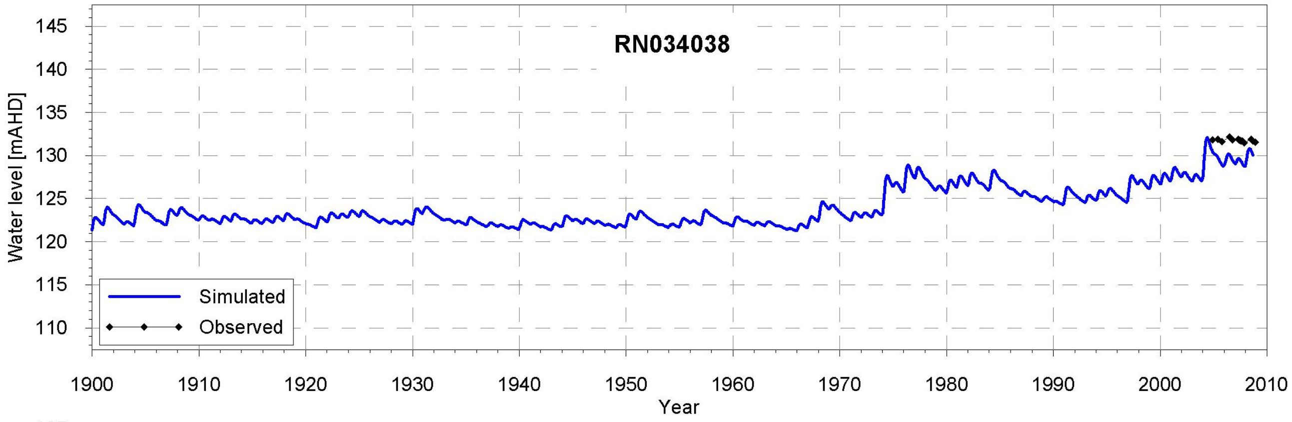
Year
Simulated
Observed


RN034038
Water level [mAHD]
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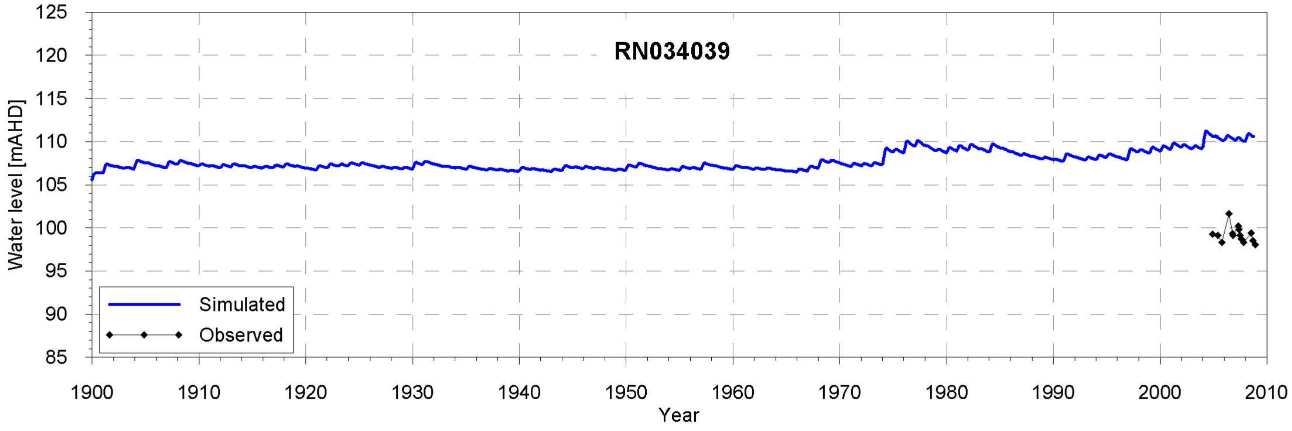
Year
Simulated
Observed


RN034039
Water level [mAHD]
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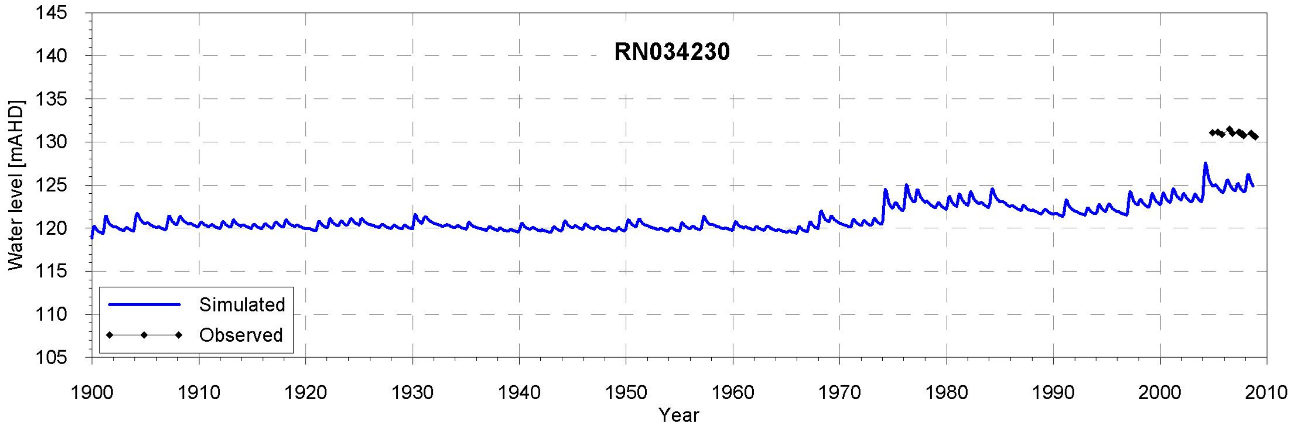
Year
Simulated
Observed


RN034230
Water level [mAHD]
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Simulated
Observed
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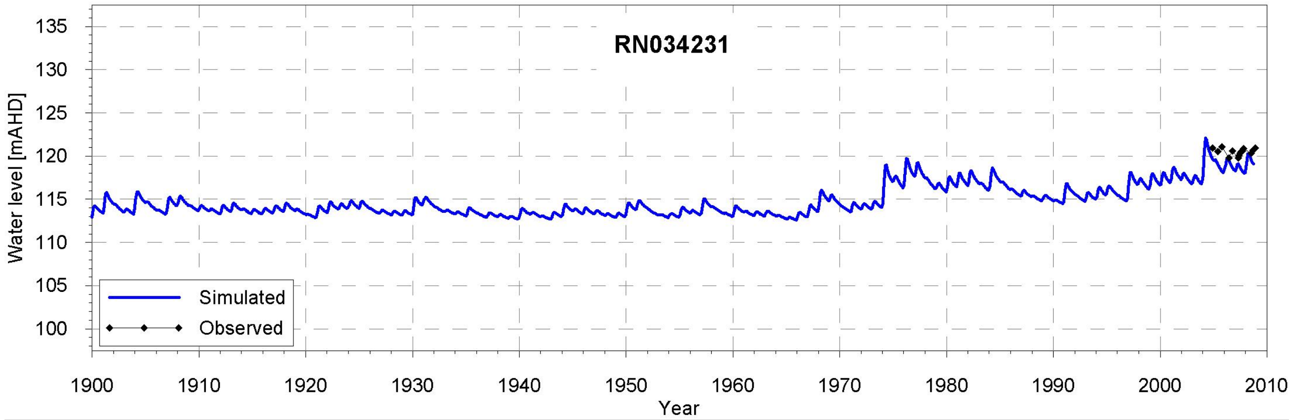
2010
Year


RN034231
Water level [mAHD]
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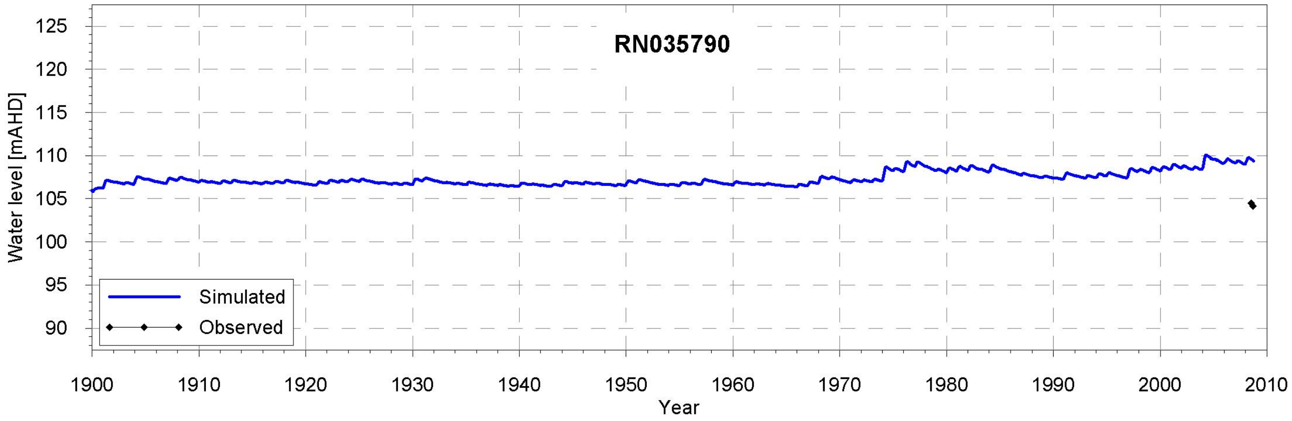
RN035790
Water level [mAHD]
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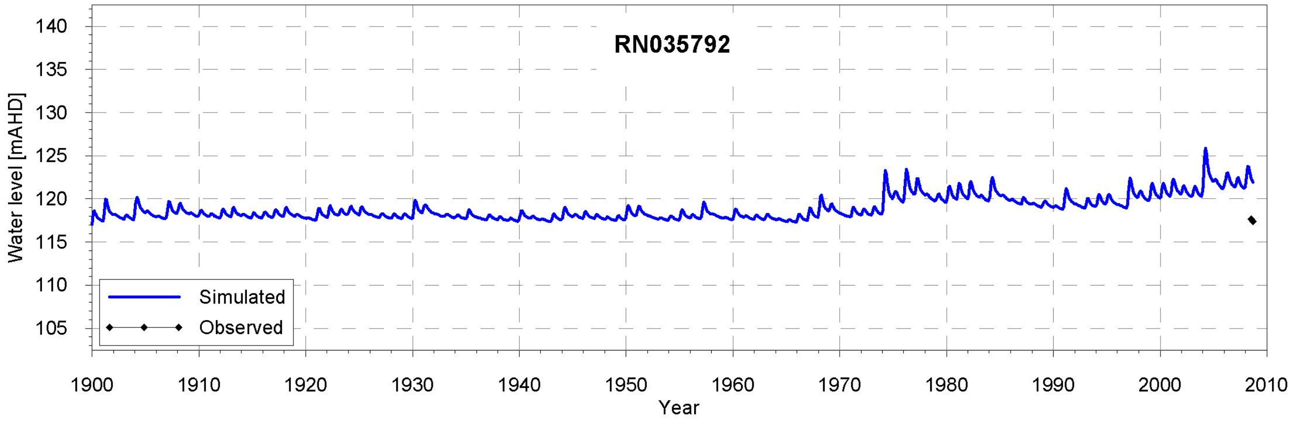
RN035792
Water level [mAHD]
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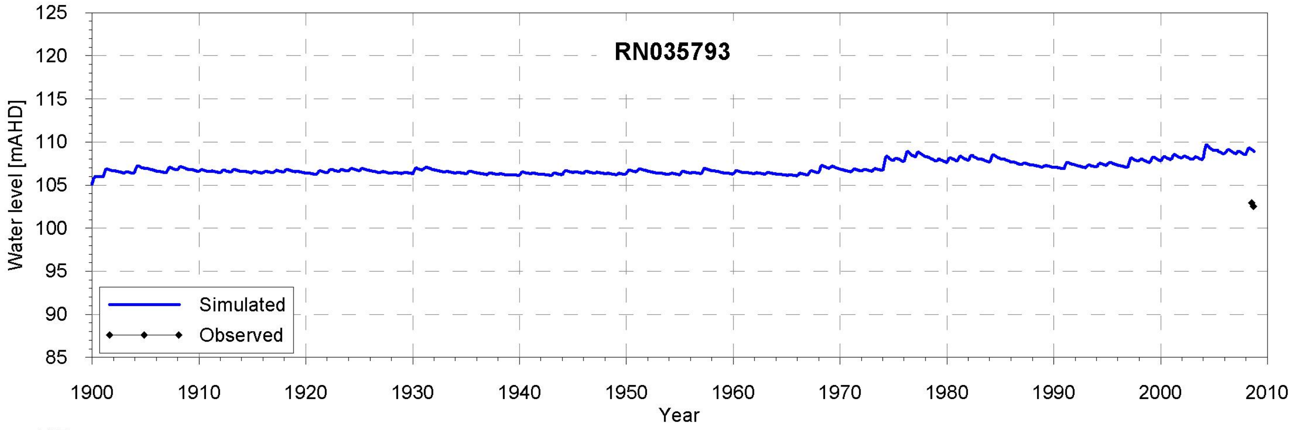
RN035793
Water level [mAHD]
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1980
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2000
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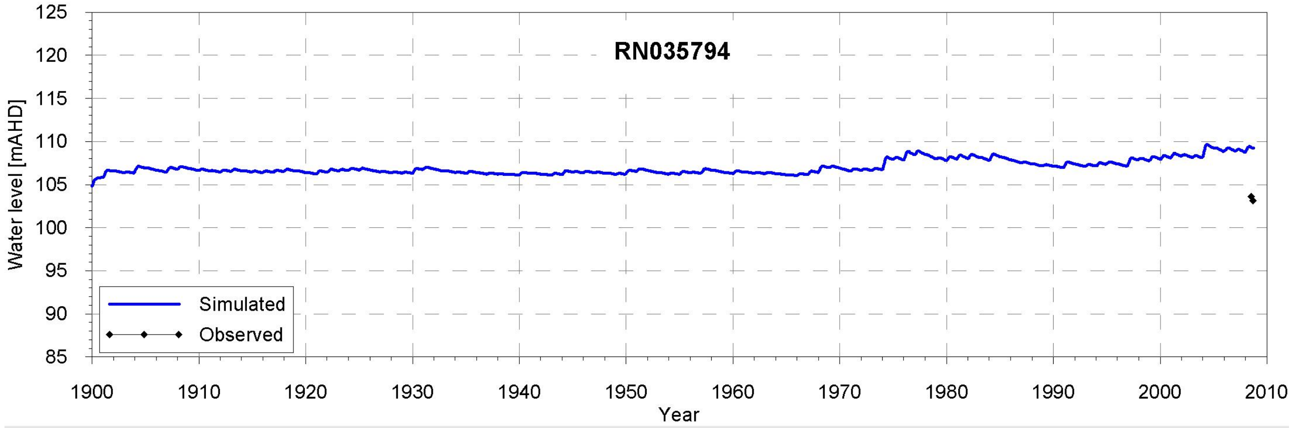
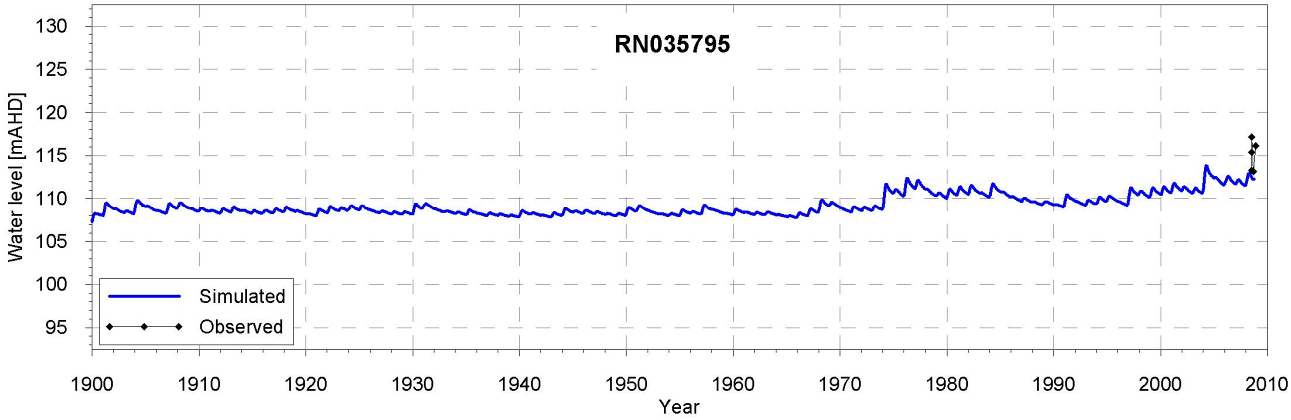
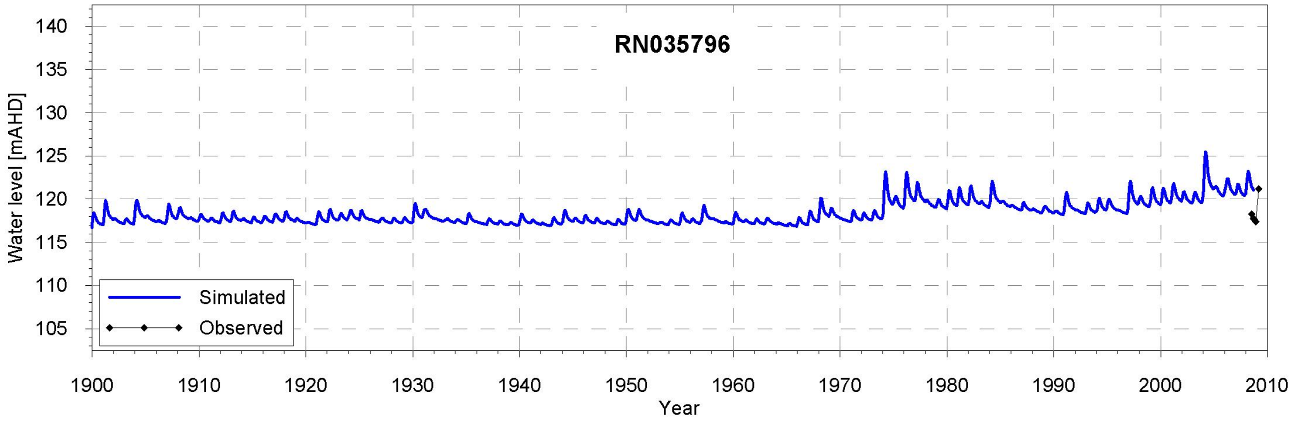
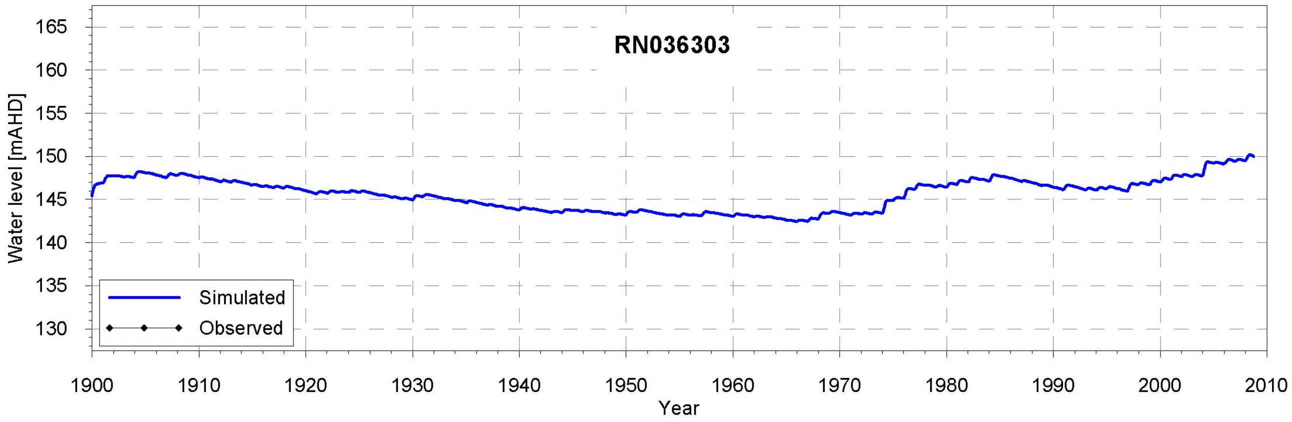
Year
Simulated
Observed


RN035794
Water level [mAHD]
125
120
115
110
105
100
95
90
85
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
Simulated
Observed


RN035795
Water level [mAHD]
130
125
120
115
110
105
100
95
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
Simulated
Observed


RN035796
Water level [mAHD]
140
135
130
125
120
115
110
105
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
Simulated
Observed


RN036303
Water level [mAHD]
165
160
155
150
145
140
135
130
Simulated
Observed
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year