Technical Report

Northern Australia Sustainable Yields Project

An investigation into the Effects of Climate Change and Groundwater Development Scenarios on the Water Resources of the Daly River Catchment using an Integrated Groundwater/Surface Water Model

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Cover Image: Late dry season flow at Oolloo Crossing on the Daly River, Nov 2006.

(Anthony Knapton, 2006)

CONTENTS

Acknowledgments .... **vi**

Executive Summary .... **vii**

1. Introduction **1**
- 1.1. Background 1
- 1.2. Objectives 1
- 1.3. Scope 1

2. Setting **2**
- 2.1. Location of the Daly River Catchment 2
- 2.2. Daly River 2
  - 2.2.1. Flow Regime 2
  - 2.2.2. Groundwater Contribution to Surface Flow 3
  - 2.2.3. Surface Water / Groundwater Connectivity 4
- 2.3. Hydrogeology 4
- 2.4. Management Zones 5

3. Modelling Approach **6**
- 3.1. Introduction 6
- 3.2. Previous Modelling 6
- 3.3. Model Description 7
- 3.4. Modelling Approach 8

4. Surface Water Model **8**
- 4.1. Introduction 8
- 4.2. NAM Rainfall/Runoff Modelling 8
  - 4.2.1. NAM Model Structure 9
  - 4.2.2. Hydrological Data 9
  - 4.2.3. NAM Catchment Breakdown 11
  - 4.2.4. NAM Calibration 11
  - 4.2.5. NAM Subtraction of Baseflow 11
- 4.3. MIKE11 Model 12
  - 4.3.1. MIKE11 river network 12
  - 4.3.2. MIKE11 cross-sections 12
  - 4.3.3. MIKE11 hydrodynamic parameters 13
  - 4.3.4. MIKE11.ini file settings 13
- 4.4. MIKE11 Calibration 13
  - 4.4.1. MIKE11 hydraulic roughness calibration 13

5. Groundwater Model **13**
- 5.1. Introduction 13
- 5.2. Conceptual Model 13
  - 5.2.1. Recharge 13
  - 5.2.2. Regional Groundwater Flow 14
  - 5.2.3. Groundwater Discharge 14
- 5.3. Model Development 15
- 5.4. Calibration 16
  - 5.4.1. Introduction 16
  - 5.4.2. Parameter Estimation Process 16
  - 5.4.3. Estimated Parameters 16
  - 5.4.4. Objective Function 16

5.4.5. Results 16
5.5. Coupling Module (IFMMIKE11).... 17
5.6. Limitations 18
6. Scenario Modelling 19
6.1. Scenario Definitions.... 19
6.2. Development Scenarios.... 19
6.2.1. Surface Water Development Scenarios 19
6.2.2. Groundwater Development Scenarios....19
6.3. Reported Metrics 20
6.3.1. Groundwater Metrics....20
6.3.2. Surface Water Metrics 21
6.4. Historic Climate (Scenario A).... 22
6.4.1. Scenario A – Water Balances....22
6.4.2. Scenario A – Groundwater Levels....23
6.4.3. Scenario A – Groundwater Discharge 25
6.5. Recent Climate (Scenario B) 27
6.5.1. Scenario B – Water Balances....27
6.5.2. Scenario B – Groundwater Levels....27
6.5.3. Scenario B – Groundwater Discharge 29
6.6. Future Climate (Scenario C' and D') 30
6.6.1. Scenario C' & D' – Water Balances....30
6.6.2. Scenario C' & D' – Groundwater Levels 31
6.6.3. Scenario C' & D' – Groundwater Discharge 35
7. Discussion 37
7.1. Scenario A.... 37
7.2. Scenario B.... 37
7.3. Scenario C' and D'.... 37
8. Conclusions....38
9. References....38
Appendix A – Calibrated Groundwater Levels....40
Appendix B – Calibrated Grounwater Discharges....54

LIST OF FIGURES

Figure 1 Location of the Daly River catchment and its' relationship to the groundwater systems of the Daly, Wiso and Georgina Basins.... 2
Figure 2 Demonstration of exponential regression of dry season flows at G8140067 – Dorisvale.... 3
Figure 3 Areas with high surface water / groundwater connectivity in the Daly River catchment. Identified areas are highly connected. 4
Figure 4 Areas used to provide water balance information within the Daly River catchment. 6
Figure 5 Layout of the MIKE 11 model including SILO climate data sites (maroon square), NAM sub-catchments (black line) and the MIKE11 river network (thick pale blue line). Details of the locations of the SILO data drill sites are presented in Table 2. 10
Figure 6 MIKE11 river network computational points (cyan), cross-section locations (mustard parallelograms) and boundary condition locations (magenta rectangles). 12

Figure 7 Relationship between the two regional karstic aquifers and their respective regional groundwater flow paths. The stippled region identifies the areas where the Tindall Limestone aquifer is confined by the Jinduckin Formation. 15
Figure 8 Calibrated parameter distribution for the FEFLOW groundwater model a) hydraulic conductivity and b) storage coefficient. 17
Figure 9 Schematic depicting the groundwater and surface water components of the integrated model and the sites used for reporting the scenario modelling results. 22
Figure 10 Scenario A groundwater level hydrographs for the 5 reporting sites showing Ahis groundwater levels to 2007 and the groundwater levels to 2030 using the Adry, Amid and Awet sequences. a) RN007595 b) RN008660 c) RN020614 d) RN022006 and e) RN029249 25
Figure 11 Scenario A groundwater discharge hydrographs at selected reporting sites a) G8140301 – Galloping Jacks including magnified period from 01/09/2000 – 01/09/2007, b) G8140067 – Dorisvale and c) G8140040 – Mt Nancar. 26
Figure 12 Scenario B groundwater level hydrographs for the 5 reporting sites showing Ahis groundwater levels to 2007 and the groundwater levels to 2040 using the scenario B. a) RN007595 b) RN008660 c) RN020614 d) RN022006 and e) RN029249 29
Figure 13 Scenario B groundwater discharge hydrographs at selected reporting sites a) G8140301 – Galloping Jacks, b) G8140067 – Dorisvale and c) G8140040 – Mt Nancar. 30
Figure 14 Scenario C' and D' groundwater level hydrographs for the 5 reporting sites showing Ahis groundwater levels to 2007 and the groundwater levels to 2030 using the C'dry, C'mid and C'wet sequences. a) RN007595 b) RN008660 c) RN020614 d) RN022006 and e) RN029249.. 34
Figure 15 Scenario C' and D' groundwater discharge hydrographs at selected reporting sites a) G8140301 – Galloping Jacks, b) G8140067 – Dorisvale and c) G8140040 – Mt Nancar. 36

LIST OF TABLES

Table 1 Hydrostratigraphic units of the Daly Basin... 5
Table 2 SILO data drill site locations.. 9
Table 3 Mean precipitation weighting factors used to generate precipitation and evaporation values based on Theissien polygons... 10
Table 4 NAM Root Zone Parameters 11
Table 5 NAM Groundwater Parameters 11
Table 6 IFMMike11 module settings.. 17
Table 7 Period of record used for Scenario A climatic sequences 19
Table 8 Extraction totals for the Katherine and Oolloo areas for the 5 scenarios investigated. 20
Table 9 Gauging sites and the corresponding MIKE11 branch name and chainage. 21
Table 10 Scenario A average annual water balance for the Katherine area 22
Table 11 Scenario A average annual water balance for the Oolloo area 23
Table 12 Median groundwater levels for scenario A 25
Table 13 Median groundwater discharges at the 3 gauging sites on the Katherine River (G8140301) and Daly River (G8140067 and G8140040)..................................... 27
Table 14 Scenario B average annual water balance for the Katherine area. 27
Table 15 Scenario B average annual water balance for the Oolloo area. 27
Table 16 Median groundwater levels for scenario B 29
Table 17 Median groundwater discharge for Scenario B at selected sites along the Katherine River and Daly River. 30
Table 18 Water balances for scenario C' and D' in the Katherine area............................... 31
Table 19 Water balances for scenario C' and D' in the Oolloo area.................................... 31

Table 20 Median groundwater levels for Scenario C' and D' under the 3 different climatic sequences. 32
Table 21 Median groundwater discharge for Scenario C' and D' at selected sites along the Katherine River and Daly River. 35

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EXECUTIVE SUMMARY

Background

The Daly River catchment lies in the wet / dry tropics of northern Australia. Its rainfall and runoff is characterised by a four month wet season with significant runoff and an eight month dry season with negligible surface runoff. During this period, aquifers within the Daly River catchment supply approximately 10 m^3/s of baseflow to the Daly River through the river bed and springs. The Daly River has continuous inflows along the majority of its' length from two separate aquifer systems.

Increased development within the basin for irrigation or other land use is likely to increase demands on groundwater resources. Additional groundwater abstraction from the high-transmissivity aquifers could lower groundwater levels and thereby reduce the base flow of the rivers during the dry season. To ensure sustainable development, a groundwater/surface water model of the Daly River catchment has been developed. This model will be used as a management tool to assess impacts on dry season river flows for a range of development scenarios.

This study was completed for the Australian Government as part of the CSIRO Northern Australia Sustainable Yields Project.

Objectives and scope

The objectives of this investigation were to assess the impacts of climate and water resources development on the water resources of the Daly River catchment using four different scenarios:

- Scenario A - historical climate (based on the period 1930 – 2007) and current development,
- Scenario B - recent climate (based on the period 1996 – 2007) and current development,
- Scenario C - future climate (~2030) and current development,
- Scenario D - future climate (~2030) and future development.

Given that currently the majority of exploitable water resources available for development are groundwater resources the focus of this study was, therefore, to examine the components of the groundwater systems of the Daly River catchment.

Model description

The groundwater/surface water model consists of a one dimensional river hydraulic model (MIKE11) coupled to a three dimensional finite element ground water model (FEFLOW). Interaction between the groundwater and surface water model occurs where the MIKE11 channels are coupled to the FEFLOW transfer boundary conditions.

The FEFLOW model encompasses an area of approximately 159 000 km^2 and includes the entire extent of the Oolloo Dolostone and the entire extent of the Tindall Limestone in the Daly Basin and its' equivalents in the northern Wiso Basin, northern Georgina Basin.

The MIKE11 model encompasses the entire Daly River catchment an area of 52 500 km^2.

The models were developed with available river geometry and aquifer data. The model was calibrated with all available rainfall, river flow, river level and groundwater level data.

The recharge input to the FEFLOW model for the 4 scenarios was generated using the WAVES model (Crosbie et al., 2009).

River flows for the future climatic scenarios were determined by scaling the calibrated MIKE11 rainfall-runoff (Petheram et al., 2009).

Reporting areas

Two areas are currently subject to water allocation plans the Tindall WAP and the Oolloo WAP. In this study the unconfined portion of the Tindall Limestone discharging to the Katherine River is referred to as the Katherine area. The unconfined Oolloo Dolostone is referred to as the Oolloo area.

Reported metrics

- Water balances are documented for 2 areas within the model domain the Katherine area and the Oolloo area.
- Water levels are documented for 5 groundwater level sites, 2 in the Katherine area and 3 in the Oolloo area.
- Groundwater discharge is reported at 3 sites, 1 along the Katherine River and 2 along the Daly River.

Conclusions

Conclusions from the study were:

- Recent climatic conditions have resulted in recharge being much greater than the long term average.
- Using the historic climate to simulate the future climate to 2030 the water balances, groundwater levels and discharge in the Katherine area suggests that extractions under the current allocations will have significant impacts on the groundwater discharge from the Tindall Limestone to the Katherine River.
- Similarly the future allocations will have an even greater impact on discharge from the Tindall Limestone to the Katherine River. The full impacts of extraction are probably not evident in the 23 year future scenarios.
- Although the predicted future climate scenarios are wetter than the historic climatic conditions future groundwater development will still impact on the river discharge.
- Lag times between the commencement of extraction and the full impacts on river discharge is likely to be beyond the 2030 timeframe of this study. It is suggested that climatic regimes are extended by repeating climatic sequences to reach dynamic equilibrium.

1. INTRODUCTION

1.1. Background

The Department of Natural Resources, Environment, The Arts and Sport was engaged to run, extract and assess the results from a coupled surface water – groundwater model of the Daly River catchment as part of the Northern Australia Sustainable Yields (NASY) Project. This report outlines the development of the surface water and groundwater models, the processing of the input data to generate the scenarios required for the study and finally presents and discusses some of the key results from the study.

The NASY Project aims to assess the surface water and groundwater resources of Northern Australia to 2030. The project will provide information on the current and likely future water availability across Northern Australia.

Where possible the NASY project used sophisticated computer models to assess water resources on an individual catchment and aquifer basis, providing an assessment of the impact of current and future predicted water resource development at key environmental asset locations.

The climate change scenarios are based on results from 15 global climate models (GCMs) which provide a large variation in the expected future climate. Rather than present results for all GCMs only results from an extreme ‘wet’, ‘mid’ and extreme ‘dry’ variant are shown (for Scenario C these are referred to as scenarios C’wet, C’mid and C’dry).

Under Scenario C’wet, results from the second highest increase in mean annual recharge from the high global warming scenario are used. Under Scenario C'dry, results from the second highest reduction in mean annual recharge from the high global warming scenario are used. Under Scenario C’mid, the median mean annual recharge results from the medium global warming scenario are used.

Scenario D results all include the extreme ‘wet’, ‘mid’ and extreme ‘dry’ variant of the climate change scenarios with the addition of proposed future development (i.e. D’wet, D’mid, D’dry). In considering changes to the hydrological regime under different scenarios all results were assessed relative to current conditions (i.e. Scenario A, which is based on historical climate and current development).

1.2. Objectives

The objectives of this investigation were to assess the impacts of climate and water resources development on the water resources of the Daly River catchment using four different scenarios:

- Scenario A - historical climate and current development,
- Scenario B - recent climate for the last 11 years and current development,
- Scenario C - future climate (~2030) and current development,
- Scenario D - future climate (~2030) and future development.

1.3. Scope

This report describes the modelling approach, the components of the coupled surface water / groundwater model, the scenarios and the results of running these scenarios.

The focus of this report is on the groundwater dynamics as this is the resource with the greatest level of development in the Daly River catchment. Although metrics were provided for the stream flow, the development of surface water resources were not considered given that presently there are very few surface water extraction licences.

Considerations of changes in water demand and changes in water use efficiency are outside the scope of the project.

Potential changes in flow regime at sites of important environmental assets were identified; these sites are often also important social and cultural sites. Another component of the NASY Project provides an assessment of the model results with respect to these environmental assets and are presented in a separate CSIRO report (McJannet et al., 2009).

2. SETTING

2.1. Location of the Daly River Catchment

The Daly River is located in the wet / dry tropics of northern Australia approximately 300 km south southeast of Darwin, the capital of the Northern Territory (refer to **Figure 1**).

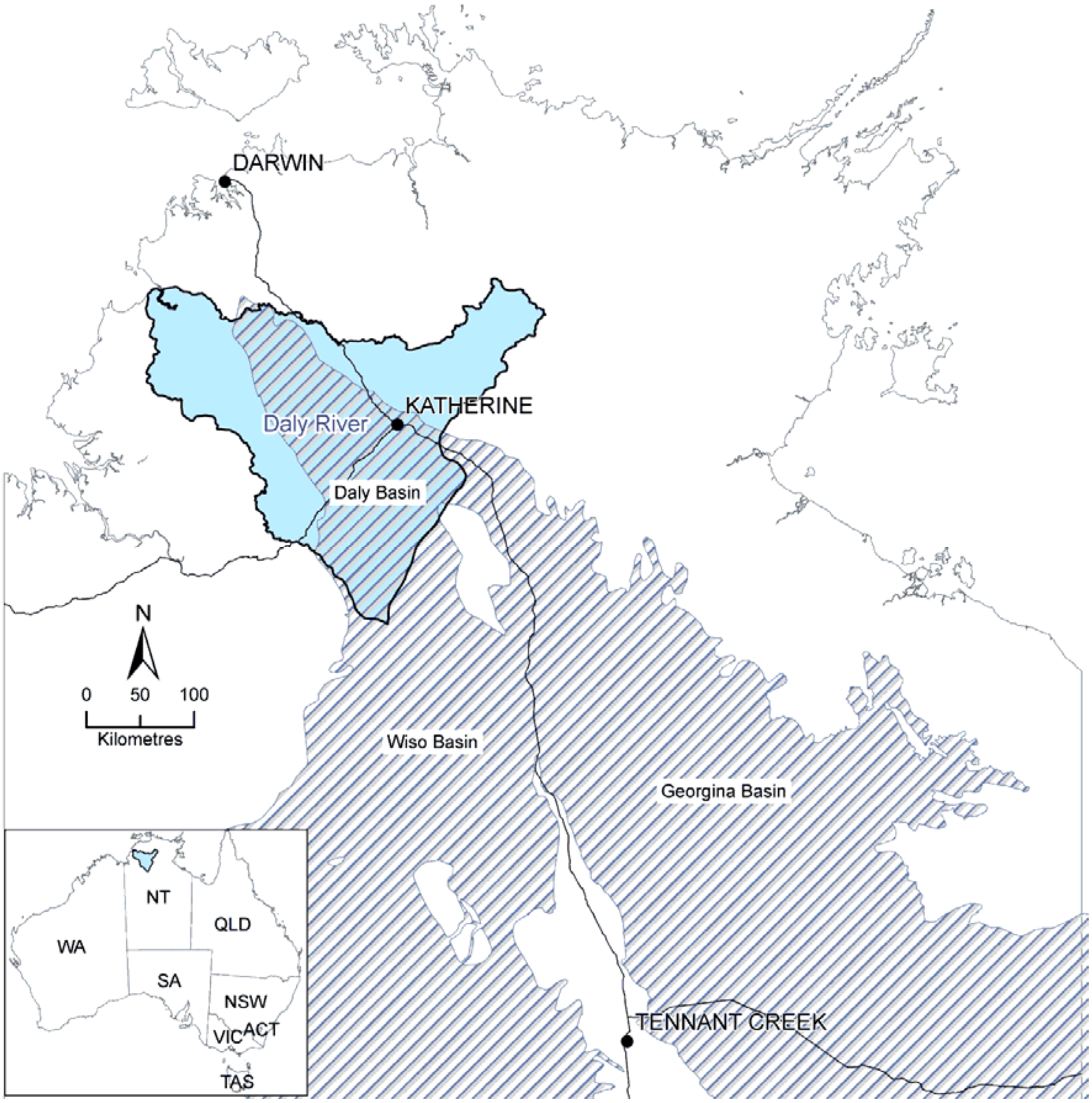


Figure 1 Location of the Daly River catchment and its' relationship to the groundwater systems of the Daly, Wiso and Georgina Basins.

2.2. Daly River

2.2.1. Flow Regime

The Daly River is a perennial river with a catchment area of 53 000 km^2. The river has a distinct seasonal flow regime of high water levels and discharges during the wet season (November through April) and much lower water levels and discharges towards the end of the dry season. Several of the rivers and streams within the Daly River catchment have persistent stream flow or baseflow, due to groundwater discharge from regional aquifers. Approximately 5-10% of the total annual runoff in the Daly River catchment is baseflow.

The dry season baseflow of the Daly River is sourced from the regional carbonate aquifers of the Daly Basin. The Daly River incises the Oolloo Dolostone whilst its' tributaries the Katherine River, Flora River and Douglas River are incised into the Tindall Limestone. Aquifers in the Daly Basin supply >10 m^3/s of baseflow to the Daly River.

Dry season discharge from Seventeen Mile Creek contributes between <0.2 – 1.0 m^3/s to flows in the Katherine River. The discharge to Seventeen Mile Creek is sourced from Cretaceous aged sediments of sands, clayey sands and clay.

2.2.2. Groundwater Contribution to Surface Flow

Groundwater contributions to flow in the Daly River are clearly observed in the signal from the rated gauging stations located along the length of the Katherine and Daly Rivers. The exponential regression of dry season flows, evident as straight lines when plotted on a logarithmic scale (refer to **Figure 2**), were examined to provide long term analytical estimates of baseflow to the rivers of the Daly River catchment using historic rainfall data (Jolly et al., 2000).

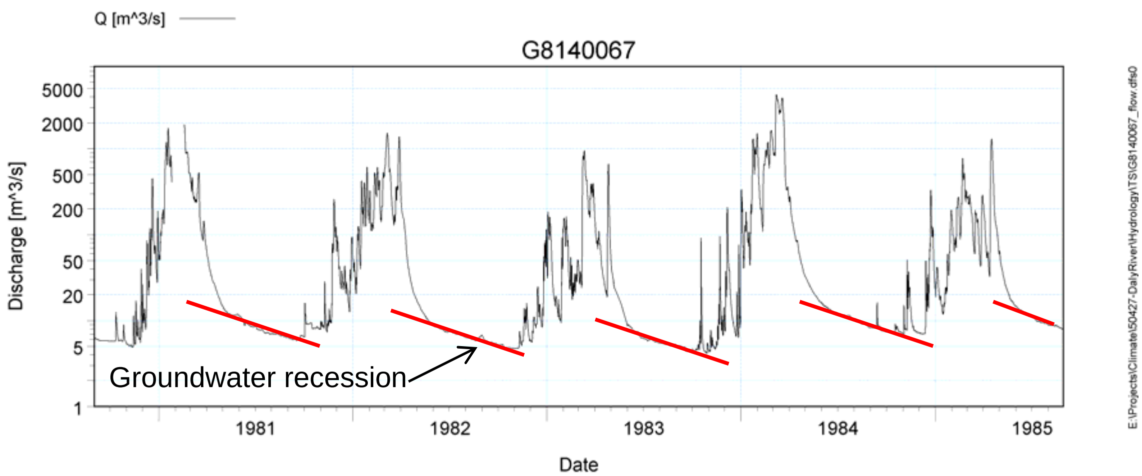


Figure 2 Demonstration of exponential regression of dry season flows at G8140067 – Dorisvale.

The average late dry season groundwater discharge to the river is between 10-20 m^3/second (Jolly et al., 2000), based on flow data at G8140042 – Mt Nancar during the 1980s and early 1990s. This amounts to ~5-10% of the annual discharge from the river.

Jolly (2001) presented below average, average and above average flow gauging results along the Daly River for October/November in 1970, 1982 and 2000, respectively. The data enable the calculation of groundwater discharge to the river between the various gauging locations. The groundwater discharge between Dorisvale (G8140067) and Stray Creek for the three measurement times is approximately 2.4, 4.8, and 6.7 m^3/s. The corresponding groundwater discharge between Dorisvale and Mt Nancar is approximately 5.7, 14.3, and 15.5 m^3/second.

Based on this information there appears to be a relatively consistent relationship between the total flow in the section of river between Dorisvale – Mt Nancar and the groundwater discharge upstream of Stray Creek. Groundwater discharge upstream of Stray Creek is approximately 30-40% of the total flow in the Dorisvale–Mt Nancar section of the Daly River.

A comprehensive survey (early September 2001) of 100 sites of dry season groundwater inflows to the river along the section between Dorisvale and Douglas River is presented in Tickell, (2002b). The groundwater contribution upstream of Stray Creek to the total river flow between Dorisvale and Mt Nancar was approximately 40%.

Groundwater discharge (baseflow) to the Daly River has been documented in various NRETAS reports (Tickell, 2002a; Tickell et al., 2002; Tickell, 2007; Tickell, 2008a; Tickell, 2008b). Based on the 2002 survey, 33.6 m^3/second was discharging from the Daly Basin aquifers, of which 15.8 m^3/second (47%) discharged from the Tindall Limestone and 17.8 m^3/second (53%) from the Oolloo Dolostone (Tickell *et al*, 2002).

2.2.3. Surface Water / Groundwater Connectivity

Surface water / groundwater connectivity is strongly controlled by the prevailing geological conditions. Regions where the carbonate sediments outcrop exhibit high connectivity with the rivers. Connectivity is via features associated with the karstic carbonate rocks of the Tindall Limestone and Oolloo Dolostone. The connectivity between the rivers and the aquifer are reduced in areas where Cretaceous aged sediments are present. The locations of areas where there is high connectivity between the surface water and groundwater are presented in **Figure 3**.

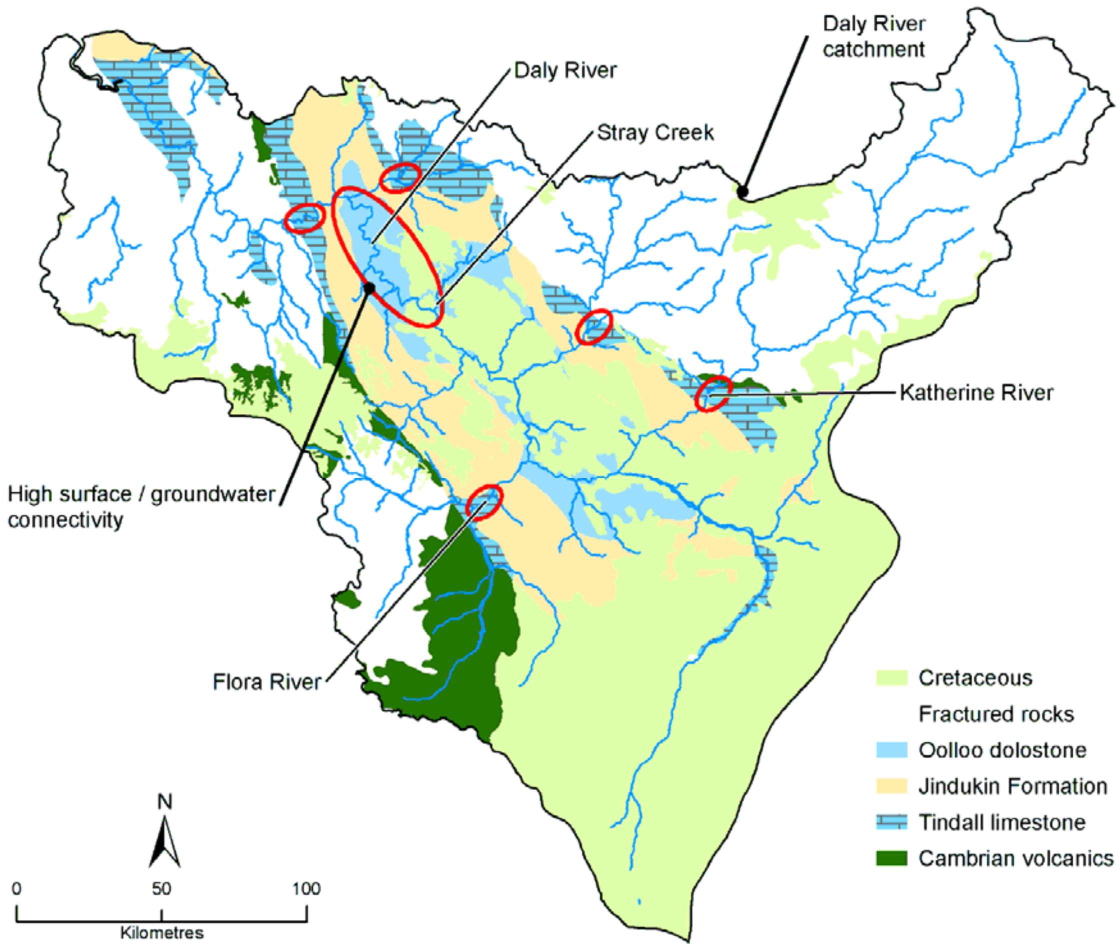


Figure 3 Areas with high surface water / groundwater connectivity in the Daly River catchment. Identified areas are highly connected.

2.3. Hydrogeology

The major hydrogeological feature of the Daly River catchment is the Cambrian-Ordovician Daly Basin comprising the Cambrian Tindall Limestone, Jinduckin Formation and the Ordivician Oolloo Dolostone. Early Cretaceous rocks overlie much of the Oolloo Dolostone and large areas of the Tindall Limestone to the southeast (refer to **Figure 3**). The groundwater resources of the Tindall Limestone and the Oolloo Dolostone are detailed in (Tickell, 2002b; Tickell, 2005). The important hydrogeological features relevant to the Daly River catchment are summarised below.

The aquifers of the Oolloo Dolostone and the Tindall Limestone 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 200 metres below the top of the formation. 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 relatively low storage coefficient.

Table 1 Hydrostratigraphic units of the Daly Basin.

Catchment	Formation	Discharge	Formation character	Transmissivity range	Storage coefficient
Daly River					
	Tindall Limestone	Katherine, Flora, Douglas and Daly Rivers	karstic limestone	2 000 – 5 000	0.04
	Jinduckin Formation	N/A	aquitard	<100	0.001
	Oolloo Dolostone	Daly River	karstic limestone	5 000 – 10 000	0.04

The bulk of the Jinduckin Formation is shale and siltstone with little fractured porosity. Minor cavernous and fractured rock aquifers are developed in the thicker dolostone beds. The Jinduckin Formation confines the Tindall Limestone and it is in these areas that the groundwater is considered to be ‘dead water’, with the majority of the inputs / outputs of the system occurring in the unconfined regions of the Tindall Limestone at the edges of the Daly Basin.

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 Oolloo Dolostone aquifer. The effect of reduced recharge is based on the lithology of the unit, which is predominantly clay/clayey sand and the subdued response of groundwater hydrographs for the bores located in areas where Cretaceous rocks cover the underlying carbonate aquifer.

2.4. Management Zones

By 2011 two areas within the Daly River catchment will be managed under water allocation plans (WAPs). The first will be for the Tindall Limestone aquifer which discharges to the Katherine River, in this report the unconfined Tindall Limestone area where major groundwater recharge / discharge occurs is referred to as the Katherine area. The Katherine area currently has a WAP declared which also includes the entire Katherine River catchment. The second water allocation plan will be for the Oolloo Dolostone aquifer, in this report this area is referred to as the Oolloo area. The WAP for this zone is currently under development. The extents of the two areas used to provide groundwater balance information are presented in **Figure 4**.

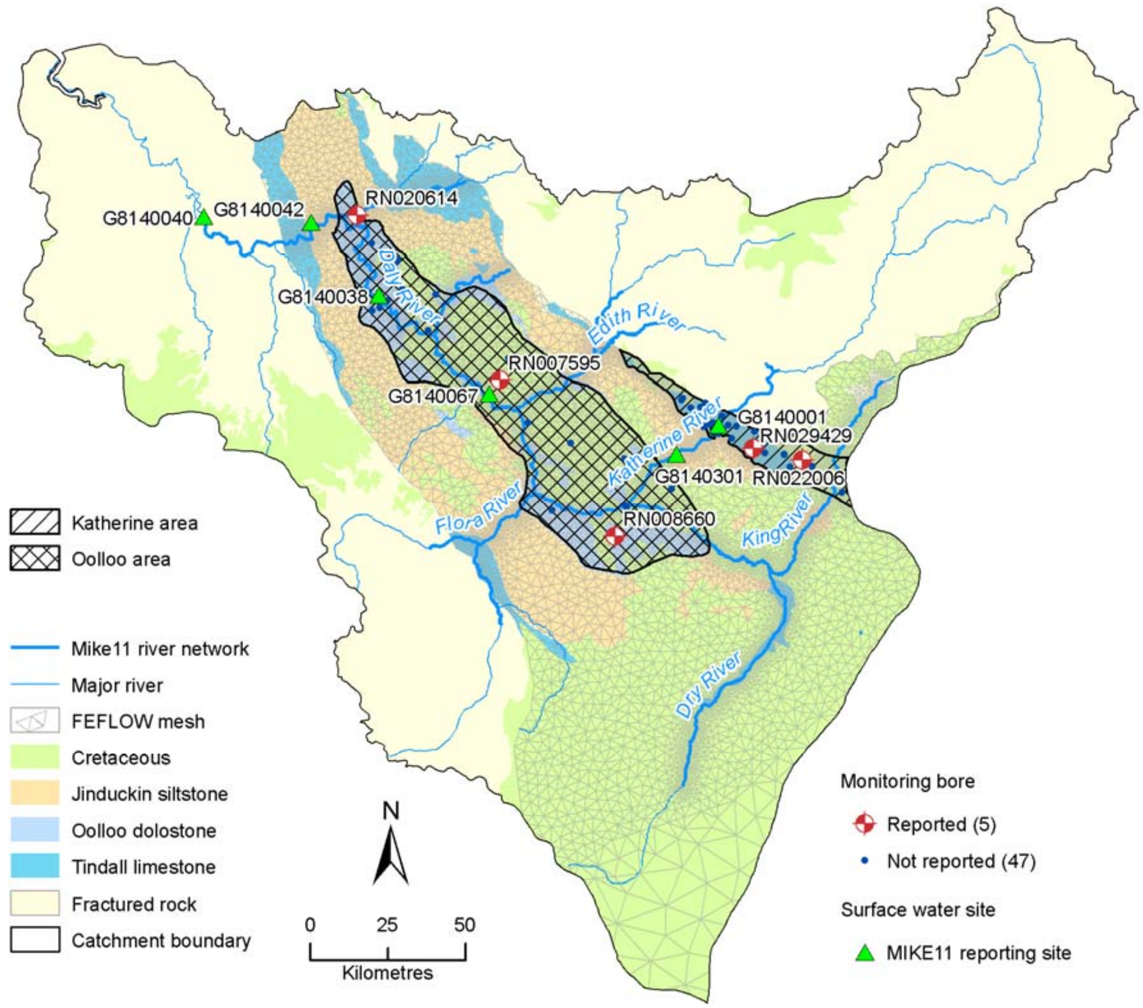


Figure 4 Areas used to provide water balance information within the Daly River catchment.

3. MODELLING APPROACH

3.1. Introduction

There are several reasons why it is useful to couple surface water and groundwater models these include:

- Rivers are complex head boundaries to groundwater aquifers
- River levels are highly dynamic
- River levels depend on surface runoff and groundwater baseflow
- Surface water / groundwater interaction driven by the head difference between the river and aquifer
- Acknowledges the issue of 'double accounting' where resources are considered separately (Sophocleous, 2002; Evans, 2007)
- Groundwater and surface water extraction can be considered in same model

3.2. Previous Modelling

Modelling studies of the Daly River include the 2002 HecRAS modelling to investigate the effects of surface water extraction on aquatic fauna (Georges et al., 2002).

Previous studies of groundwater modelling the aquifers of the Daly River include groundwater modelling of the Tindall Limestone in the area of the Katherine River; (Puhalovich, 2005) and (Water Studies, 2001); groundwater modelling of the Cambrian

Limestone aquifers (including the Tindall Limestone) of the Daly, Georgina and Wiso Basins, (Knapton, 2006b). Groundwater modelling of the Oolloo Dolostone has been documented in (Knapton, 2005) and (Knapton, 2006a).

The FEFLOW model was originally designed to examine the effects of groundwater extraction on river flows for the Tindall Limestone in the Katherine River area (Knapton, 2006b) and the Oolloo Dolostone (Knapton, 2005).

(URS, 2008) documents the integration of the two groundwater models described by (Knapton, 2005) and (Knapton, 2006b) and the coupling of a calibrated MIKE11 surface water model.

Knapton et al, (2009) documents the details of the recalibration of the coupled Daly River catchment model and investigated the effects future climatic predictions and groundwater extraction development scenarios on groundwater levels and river flows.

3.3. Model Description

The surface water / groundwater model of the Daly River catchment is based on a calibrated three dimensional finite element groundwater model coupled to a calibrated 1D finite difference channel flow model.

The groundwater model covers an area of 159 000 km^2 and represents the unconfined areas of the two regional aquifers of the Daly Basin and extends into the Wiso Basin to the south and the Georgina Basin to the southeast (refer to **Figure 1**).

The finite element groundwater model was developed in the FEFLOW simulation code (Diersch, 2008) and consists of two layers. It is the result of combining two separately developed groundwater models of the Tindall Limestone (Knapton, 2006b) and the Oolloo Dolostone (Knapton, 2005).

The groundwater model includes boundary conditions that define the interaction between the rivers and the groundwater system (transfer boundary nodes). The transfer in / out terms vary spatially across the model domain. Extraction for stock and domestic and horticultural use is simulated from the model domain is via well boundary nodes.

The model is sub-divided into recharge zones based primarily on the mapped geology (Knapton, 2005; Knapton, 2006b).

The timeseries recharge flux was initially determined using a simple spreadsheet based soil moisture deficit model using rainfall and estimated evapotranspiration (Jolly et al., 2000). Recent estimates of recharge have been determined using MIKE SHE (DHI, 2008) which enables a more process based estimate of recharge to be calculated including an estimate of by-pass flow. Recharge is also expected during periods when the river stage height is greater than the groundwater level adjacent to the river where the river overlies the aquifers.

Distribution of hydraulic parameters hydraulic conductivity, storage coefficient and transfer in /out were determined using Parallel PEST (Doherty, 2004) and the pilot point method (Doherty, 2003). The model was calibrated to match all available historic groundwater discharge and water levels in the area of the Tindall Limestone that contributes discharge to the Katherine River and the entire Oolloo Dolostone (refer **Figure 7**). The rest of the model domain was calibrated to match steady state conditions and act as boundary conditions for the transient areas within the model domain.

The upper layer of the groundwater model is coupled to a MIKE11 river model. The surface water model encompasses the entire Daly River catchment covering an area of 52 600 km^2.

MIKE11 uses an implicit, finite difference scheme for the computation of unsteady 1D flows in rivers and estuaries (DHI, 2005).

The upstream model boundaries to the MIKE11 surface water model consist of sub-catchment rainfall-runoff discharges generated using the NAM model within MIKE11. The conceptual NAM model treats each catchment as a single unit, allowing some of the model parameters to be evaluated from physical catchment data.

The NAM inputs included precipitation and potential evapotranspiration (estimated using pan evaporation). Rainfall and evapotranspiration data were sourced from the Queensland Natural Resources and Mines Enhanced Metrological Datasets “Data Drill” - which uses interpolation of BoM station records <http://www.longpaddock.qld.gov.au/silo/datadrill/index.frames.html>.

The MIKE11 model is coupled to the FEFLOW model using a module called IFMMike11 developed by WASY (Monninkhoff, 2005).

Groundwater / surface water interaction along the rivers occurs where the MIKE11 model is joined to the FEFLOW model.

3.4. Modelling Approach

The modelling approach involved the following steps:

- FEFLOW groundwater flow model development;
- MIKESHE timeseries recharge estimation;
- FEFLOW model calibration using Parallel PEST on 5 separate computers;
- Development and calibration of a MIKE11 (DHI, 2007) surface water model;
- Coupling of the MIKE11 model and the FEFLOW model using the module IFMMIKE11 (Monninkhoff, 2005).
- Scaling of WAVES recharge to match calibrated FEFLOW model historic inputs
-
- Scaling of Amid recharge to generate Cdry, Cmid and Cwet sequences
- Scaling of runoff components for the corresponding climatic sequences

4. SURFACE WATER MODEL

4.1. Introduction

The surface water model of the Daly River catchment was developed by DHI Water & Environment Pty Ltd (DHI) using MIKE11 2005 (URS, 2008). The components of the model relevant to the generation of runoff for the future climate sequences are described below. This study employed the MIKE11 2008 release.

The MIKE11 model encompasses the entire Daly River catchment (refer to **Figure 5**) and includes 13 sub-catchments.

The upstream model boundaries to the surface water model consist of rainfall-runoff from each of the sub-catchments. The rainfall-runoff values were generated using the NAM module within MIKE11. The conceptual NAM model treats each catchment as a single unit, allowing some of the model parameters to be evaluated from physical catchment data.

The calibration of the MIKE11 model involved adjusting the rainfall runoff model parameters to ensure that recorded channel discharges estimates within the river system were simulated adequately. The simulated water levels were then calibrated to recorded levels by adjustment of the channel roughness parameter (Manning’s ‘n’). The channel roughness was modified both laterally across the section and longitudinally down the river system.

4.2. NAM Rainfall/Runoff Modelling

Rainfall runoff modelling was completed to determine surface water runoff, typically during the wet season.

The MIKE11 rainfall runoff model (NAM) was used to assess catchment runoff characteristics at a catchment scale.

4.2.1. NAM Model Structure

The conceptual NAM model treats each sub-catchment as a single unit, allowing some of the model parameters to be evaluated from physical catchment data (DHI, 2007). However, final parameter estimates and runoff discharges were calibrated against time-series hydrological observations.

The model inputs were precipitation and potential evapotranspiration.

4.2.2. Hydrological Data

Rainfall and Evapotranspiration Data

The inconsistent periods and poor coverage of rainfall and evaporation data resulted in the use of synthetically derived data from the Bureau of Meteorology's SILO Data Drill, which was used for 10 sites across the Daly River catchment.

The SILO Data Drill accesses grids of data derived by interpolating the Bureau of Meteorology's station records. Interpolations are calculated by splining and kriging techniques. The data in the Data Drill are all synthetic; there are no original meteorological station data left in the calculated grid fields. However, the Data Drill does have the advantage of being available for any set of coordinates in Australia.

Interpolated surfaces of potential evaporation have been computed using data recorded from Class A pans. Observational data prior to 1970 have not been interpolated because various measuring devices were in use before 1970, resulting in inconsistent and unreliable data (Queensland Dept of Natural Resources and Mines, (2009)).

Table 2 SILO data drill site locations.

Site ID	Latitude	Longitude	Easting	Northing
Dataset_10	-13.60	130.50	12764.1	8492005.1
Dataset_9	-13.65	133.15	299887.3	8490218.8
Dataset_8	-15.30	131.60	134803.4	8305630.6
Dataset_7	-14.60	132.10	187539.1	8383920.5
Dataset_6	-13.75	131.20	88926.1	8476678.6
Dataset_5	-14.15	132.70	251724.0	8434465.7
Dataset_4	-15.25	132.25	204602.4	8312156.9
Dataset_3	-13.95	131.85	159603.0	8455546.0
Dataset_2	-14.55	131.30	101158.8	8388206.5
Dataset_1	-14.25	130.70	35760.4	8420330.7

Rainfall and Evaporation data distribution

NAM calculation of runoff requires rainfall and evaporation data for each sub-catchment. The data were determined using Theissien polygons.

The parameters presented in **Table 3** indicate the weighting factors used to generate the precipitation and evaporation time series for each sub-catchment. These values are necessary to update the inputs to the NAM model using recent rainfall and evaporation data. **Table 4** and **Table 5** identify the NAM parameters for the soil / root zone and the groundwater 'recharge' and discharge decay time constant values.

Table 3 Mean precipitation weighting factors used to generate precipitation and evaporation values based on Theissien polygons

Station No.	1	2	3	4	5	6	7	8	9	10
BASIN A	0.637	0.102	0	0	0	0.178	0	0	0	0.083
BASIN B	0	0.416	0.045	0	0	0.538	0	0	0	0
BASIN C	0	0	0.417	0	0	0.583	0	0	0	0
BASIN D	0	0	0.755	0	0.064	0	0.181	0	0	0
BASIN E	0	0	0.635	0	0.365	0	0	0	0	0
BASIN G	0	0	0	0	0.769	0	0.157	0	0.074	0
BASIN H	0	0	0	0.450	0.118	0	0.432	0	0	0
BASIN I	0	0	0	0.730	0	0	0	0.270	0	0
BASIN J	0	0.334	0	0.009	0	0	0	0.657	0	0
BASIN L	0	0.185	0.078	0.048	0	0	0.638	0.051	0	0
BASIN M	0	0	0.917	0	0	0.083	0	0	0	0
BASIN N	0	0	0	0	1.000	0	0	0	0	0

Observed Runoff

For model calibration, 13 gauging stations were used. For further details refer to the MIKE11 model development report (URS, 2008).

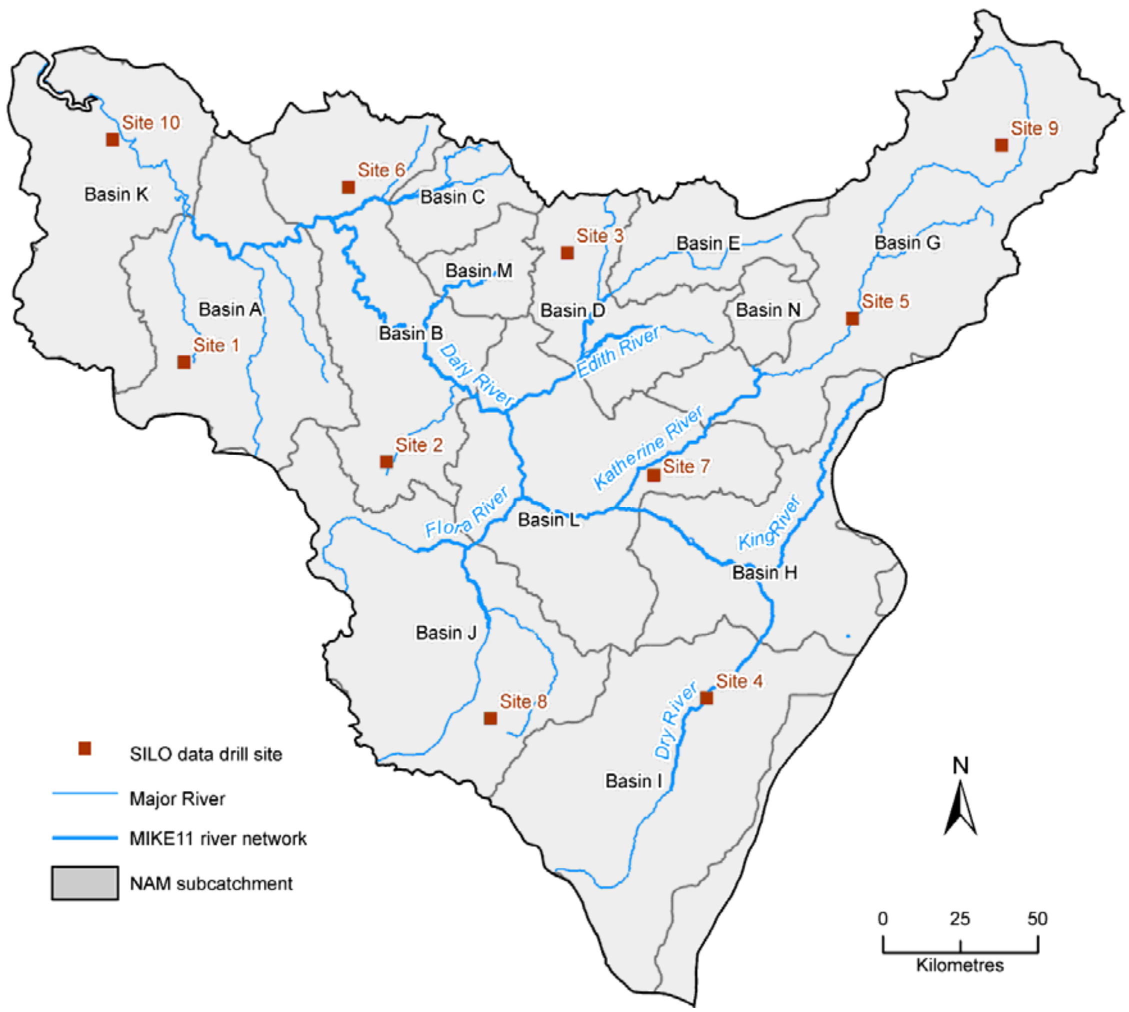


Figure 5 Layout of the MIKE 11 model including SILO climate data sites (maroon square), NAM sub-catchments (black line) and the MIKE11 river network (thick pale blue line). Details of the locations of the SILO data drill sites are presented in Table 2.

4.2.3. NAM Catchment Breakdown

13 sub-catchments were defined for the Daly River catchment in the NAM model using the SRTM digital terrain model and the locations of gauging sites with suitable flow data.

4.2.4. NAM Calibration

Calibration of the NAM runoff was completed by DHI Australia (URS, 2008) and initially involved matching runoff for sub-catchments where suitable river gauging data were available. Hydrological parameters were adjusted manually to match the observed run-off characteristics.

For ungauged catchments, it was assumed that the NAM parameters from nearby catchments would have similar properties.

4.2.5. NAM Subtraction of Baseflow

On completion of the calibration of the MIKE11 model it was necessary to subtract the NAM baseflow from the runoff data, because the groundwater component was to be generated by coupling to the FEFLOW groundwater model.

Baseflow subtraction was achieved by subtracting the NAM Lower Baseflow component from the Runoff discharge for each of the sub-catchments where baseflow from the carbonate aquifers has been identified. This process was done using the MIKEZero calculator. Sub-catchments Basin B, Basin J and Basin L had baseflow subtracted.

Basin N (Seventeen Mile Creek) provides baseflow to the Katherine River, however, the water is sourced from Cretaceous aged rocks and is not simulated by the FEFLOW model, the baseflow component was not removed from the NAM Runoff discharge for this catchment.

Table 4 NAM Root Zone Parameters

Name	Umax	Lmax	CQOF	CKIF	CK1,2	TOF	TIF
BASIN A	5.54	225	0.7	270	48	0	0.694
BASIN B	4.18	225	0.41	270.7	48	0.000005	0.694
BASIN C	9.95	360	0.706	168	24.8	0.462	0.99
BASIN D	10	250	0.6	50	30	0.2	0.9
BASIN E	24	317	0.667	48	31.2	0.249	0.849
BASIN G	10	350	0.5	150	8	0.3	0.2
BASIN H	3.62	513	0.324	473.2	79.6	0.000018	0.185
BASIN I	44.9	421	0.957	1.7	52.8	0.784	0.96
BASIN J	6.33	300	0.371	36	37.8	0.2	0.99
BASIN L	10	350	0.5	150	8	0.3	0.2
BASIN M	9.95	360	0.706	168	24.8	0.462	0.99
BASIN N	15	250	0.6	122.9	16.2	0.3	0.1

Table 5 NAM Groundwater Parameters

Name	TG	CKBF	Carea	Sy	GWLBF0	GWLBF1	Cqlow	Cklow
BASIN A	0.987	500	1	0.1	10	0	0	10000
BASIN B	0.987	400	1	0.1	10	0	60	200000
BASIN C	0.7	240	1	0.1	10	0	40	4800
BASIN D	0.5	360	1	0.1	10	0	10	5000
BASIN E	0.5	360	1	0.1	10	0	0	10000
BASIN G	0.5	240	1	0.1	10	0	9	1800
BASIN H	0.99	2	1	0.1	10	0	0	10000
BASIN I	0.99	1.4	1	0.1	10	0	0	10000
BASIN J	0.3	100	1	0.1	10	0	20	100000
BASIN L	0.5	240	1	0.1	10	0	9	1800

Name	TG	CKBF	Carea	Sy	GWLBF0	GWLBF1	Cqlow	Cklow
BASIN M	0.7	240	1	0.1	10	0	0	10000
BASIN N	0.3	240	1	0.1	10	0	35	12000

4.3. MIKE11 Model

4.3.1. MIKE11 river network

The Daly River is represented by the MIKE11 river network (Daly_2008.nwk11). The plan view of the network is presented in **Figure 6**.

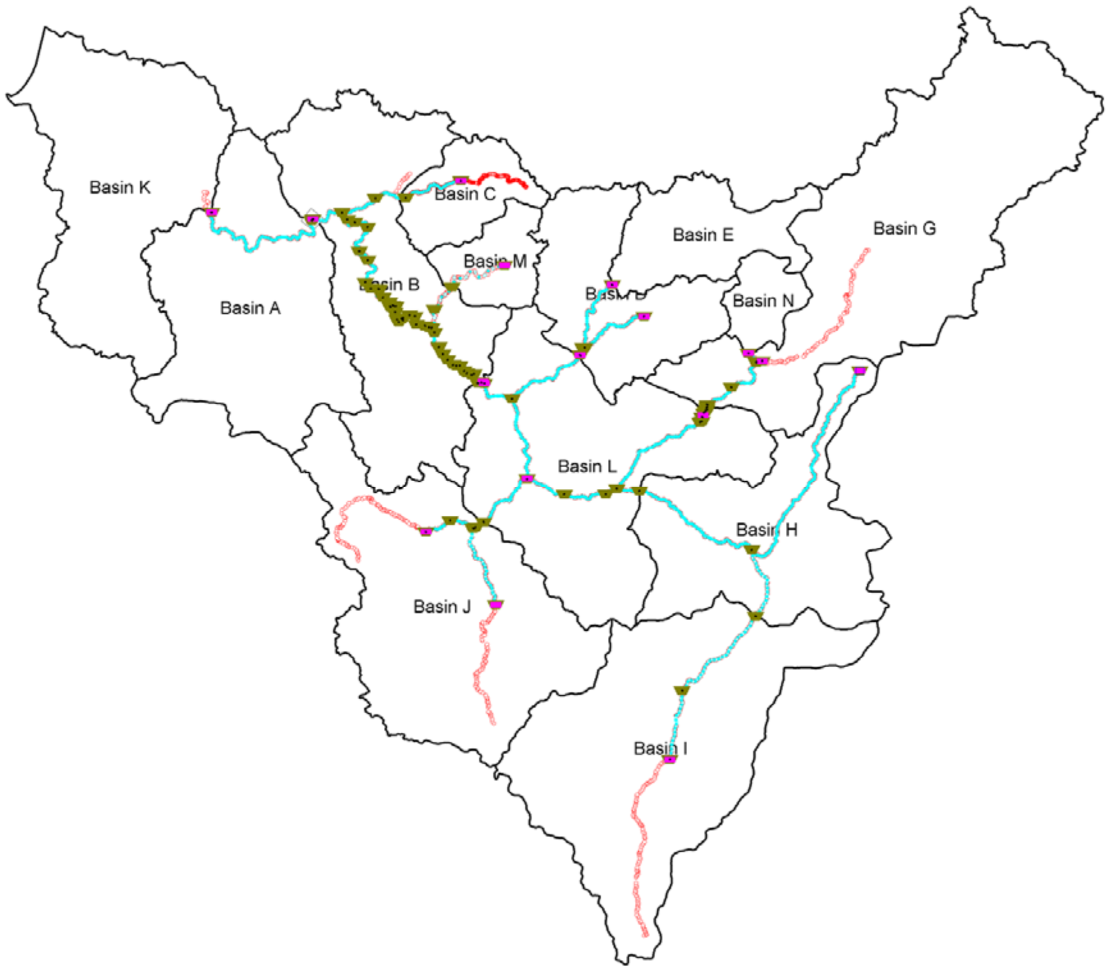


Figure 6 MIKE11 river network computational points (cyan), cross-section locations (mustard parallelograms) and boundary condition locations (magenta rectangles).

4.3.2. MIKE11 cross-sections

The MIKE 11 cross-sections were sourced from the following information:

- Gauging stations cross-sections database (NRETAS);
- Top End Water Ways project: Daly River catchment (Faulks, 1998);
- HecRAS model of the Daly River (Georges et al., 2002).

The cross-section information is stored in a binary file (Daly_2008.xns11) which is specific to the release 2008 of MIKE11.

4.3.3. MIKE11 hydrodynamic parameters

The HD parameters (Daly_2008.hd11) were generally left to the default settings.

4.3.4. MIKE11.ini file settings

The MIKE11.ini-file offers a possibility of changing settings within the calculation part of MIKE11 by adjusting values for the initiation of the hydrodynamic engine (HD) environment variables.

HD-Variable no 3 (WL_EXCEEDANCE_FACTOR). The exceedance of water level above any cross section bank-levels during a simulation can be controlled by adjusting the variable WL_EXCEEDANCE_FACTOR. This variable was necessary since the cross-sections did not include the flood plain and large flow events were confined to the river channel. During large flood events this meant that the river level far exceeded the actual stage height. For the Daly River model this variable was set to 40.

4.4. MIKE11 Calibration

4.4.1. MIKE11 hydraulic roughness calibration

The roughness parameters (Manning's n) were adjusted for river branches at various flow rates until the modelled surface water level / flow discharge matched the data at each gauging station. The model calibration focused on low flows. No data were available on low flow control structures downstream of the gauging stations, which resulted in poor calibration at low flows for a number of gauges.

Modelled high flows were generally higher in elevation than the gauged data since floodplains are not included within the river cross sections. It is expected that when coupled to the FEFLOW model this will result in over estimation of the river recharge to the groundwater during large flood events.

5. GROUNDWATER MODEL

5.1. Introduction

The FEFLOW model encompasses an area of approximately 159 000 km^2 and includes the entire extent of the Tindall Limestone in the Daly Basin and its' equivalents in the northern Wiso Basin, northern Georgina Basin (refer to **Figure 7**).

Both of the major aquifers in the Daly Basin are karstic and are dominated by secondary porosity / permeability due to chemical weathering. For simplicity the system has been modelled as an equivalent porous media using calibrated regional aquifer parameters to reproduce the regional groundwater levels and observed discharge to the rivers.

5.2. Conceptual Model

Conceptually on a regional scale the groundwater systems developed in the karstic aquifers appear to behave as porous media. The water level and discharges dynamics observed are characteristic of a highly permeable media with relatively limited storage.

Recharge and discharge processes are expected to dominate within the unconfined portions of both the groundwater systems.

5.2.1. Recharge

The dominant recharge mechanism in the areas of outcropping Tindall limestone and Oolloo dolostone is via preferential pathways, however, this mechanism is not well understood and poorly represented numerically. The recharge was therefore estimated as diffuse recharge using a simple soil moisture deficit model using rainfall and estimated evapotranspiration (refer to section). It has been found that this methodology has not quantified 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. Recharge is also expected during periods when the river stage height is greater than the groundwater level adjacent to the river where the river overlies the aquifers and the model simulates this process.

Recharge is thought to be via four 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 ‘channelled’ through the unsaturated zone and has a limited interaction with the unsaturated zone;
- localised indirect recharge where surface water can be channelled 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.

Recharge to the groundwater of the outcropping carbonates is thought to be dominated by macro-pore and local indirect recharge. 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 agree with these values.

Macro-pore recharge is thought to dominate in the Oolloo dolostone, as there are few doline features in this formation, however, chloride mass balance analysis indicates that up to 75% of the water recharging the aquifer does not have appreciable interaction with the unsaturated zone.

Recharge to the groundwater of the Tindall Limestone is thought to be dominated by macro-pore and localised indirect recharge.

5.2.2. Regional Groundwater Flow

The groundwater flow within the Tindall 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 rivers and via discrete springs. Major discharges occur along the Flora River as it intercepts the much larger groundwater flows from the Wiso Basin (refer to **Figure 7**). A smaller scale sub-basin is evident in the Katherine River area where a groundwater divide occurs roughly coincident with surface water catchment divide of the King River. Groundwater flow is towards the Katherine River from the divide to 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.

On a basin scale the groundwater flow within the Oolloo dolostone is from the southeast to the northwest, locally the flow is to the Daly River (refer to **Figure 7**).

5.2.3. Groundwater Discharge

The groundwater flow within the Tindall 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 rivers and via discrete springs. Major discharges occur along the Flora River as it intercepts the much larger groundwater flows from the Wiso Basin (refer to **Figure 7**). A smaller scale sub-basin is evident in the Katherine River area where a groundwater divide occurs roughly coincident with surface water catchment divide of the King River. Groundwater flow is towards the Katherine River from the divide to 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.

The majority of groundwater discharged to the Daly River from the Oolloo dolostone occurs downstream of the gauging station G8140067 at Dorisvale (refer to **Figure 3**).

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

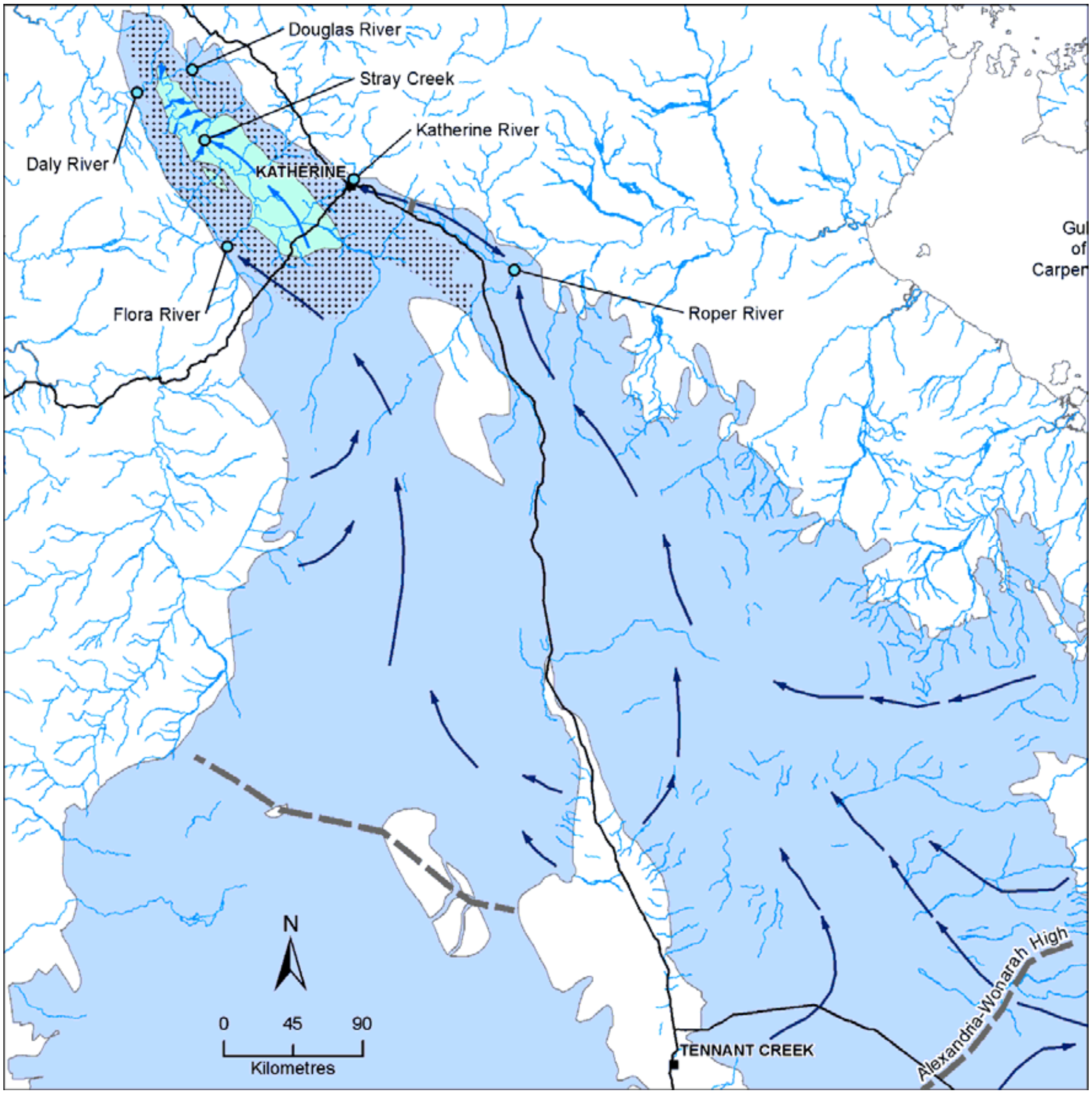


Figure 7 Relationship between the two regional karstic aquifers and their respective regional groundwater flow paths. The stippled region identifies the areas where the Tindall Limestone aquifer is confined by the Jinduckin Formation.

5.3. Model Development

Recharge is applied to the model according to recharge zones. Each recharge zone was determined primarily from the underlying geology (Knapton, 2005; Knapton, 2006b). The input recharge for this study was generated from the WAVES modelling and scaled to match the calibrated groundwater model recharge.

The groundwater model includes boundary conditions that define the interaction between the rivers and the groundwater system (transfer boundary nodes). The transfer in / out rates vary spatially across the model domain. Extraction for stock and domestic and horticultural use is simulated from the model domain is via well boundary nodes.

Discharge from the rivers is implemented using transfer boundary conditions (similar to river cells in ModFlow). The groundwater model assumes that recharge / discharge to the rivers where they are in connection with the aquifer is relatively uniform between adjacent nodes. Areas of preferential recharge / discharge are simulated by adjusting the transfer in / out parameters. Springs are not included in the model as discrete pathways are too poorly understood and at a scale too small to be adequately represented.

The transient model was calibrated to match historic groundwater discharge and groundwater levels in monitoring bores in the Tindall Limestone within the Katherine Management Zone and the Oolloo Dolostone (refer to **Appendix A**). The rest of the model domain was calibrated to match steady state conditions and act as boundary conditions for the transient areas within the model domain.

5.4. Calibration

5.4.1. Introduction

The original FEFLOW model developed used regional zones for the hydraulic parameter distributions (URS, 2008). It was felt that an improved representation of groundwater levels and discharge could be achieved if the distribution of hydraulic conductivity, storage coefficient and transfer out parameters were spatially varying. The spatial distribution of hydraulic parameters was determined using pilot points and inverse modelling via the PEST code (Doherty, 2003).

5.4.2. Parameter Estimation Process

PEST was used to optimize the recharge, hydraulic conductivity, storage coefficient and transfer out parameters based on the discharge flow record for the 4 rivers in the area for the period of 1900 - 1988.

The input to PEST is the simulated and observed response, (ie groundwater levels and groundwater discharge), and the outputs are the new model parameters (ie hydraulic conductivity distribution). To achieve the integration of PEST and FEFLOW several utility programs were required. An IFM DLL module was developed to run during the simulation to export fluxes for observation groups of the transfer boundary conditions defined along each river.

5.4.3. Estimated Parameters

The parameters estimated using PEST were the hydraulic conductivity, storage coefficient and transfer out and a scaling factor for the recharge time series generated using MikeSHE.

5.4.4. 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. In the case of the Daly River groundwater model the observed response consisted of all available groundwater level data and dry season discharge from the aquifer to the 5 major rivers. A total of 2219 observations were used to calibrate the model.

5.4.5. Results

The results of the calibration for all groundwater level observation points are presented in **Appendix A**.

Using PEST and the ability to adjust 72 parameters resulted in a reasonable match to the observed discharge record for each of the rivers used in the calibration process. The resulting distribution of the hydraulic conductivity, storage and transfer out parameters are presented in **Figure 8**. A comparison of the model results and the observed data are presented in **Appendix A**.

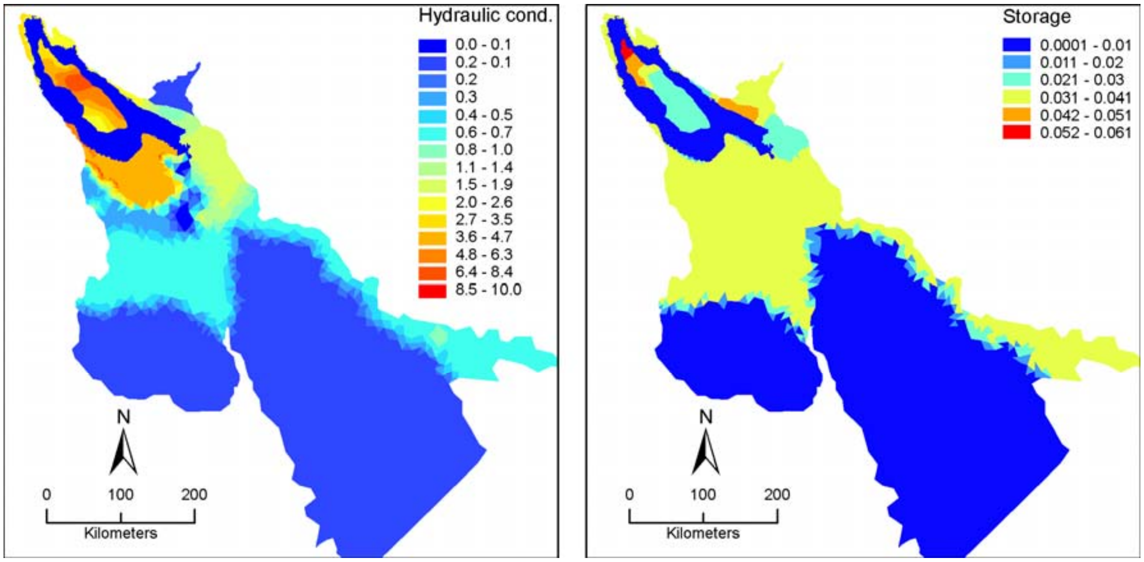


Figure 8 Calibrated parameter distribution for the FEFLOW groundwater model a) hydraulic conductivity and b) storage coefficient.

5.5. Coupling Module (IFMMIKE11)

Interaction between the groundwater and surface water model occurs where the MIKE11 river network is coupled to the FEFLOW transfer boundary conditions. The coupling between FEFLOW and MIKE11 is done through a module managed through FEFLOWs Interface Manager.

The coupling involves setting a snapping distance and using a reference distribution.

During the coupling of the MIKE11 model and the FEFLOW model the settings for the IFMMIKE11 module were adjusted to provide a stable model with the most efficient run times. The following parameters were employed by the IFMMIKE11 module.

Table 6 IFMMike11 module settings

FEFLOW / MIKE11 Patching	Option	Setting
	Patch option	Both: Aut. & Obs. Groups
	Snap Dist. [m]	5000
Initial Timestep		
	Relative to Timestep FEFLOW (0-1)	0.25
	Absolute maximum of Timestep [min.]	1
General Settings		
	Show Logfile	Yes
	All Results	Yes
	Exclude Dry H-Points	Yes
	Wmin [cm]	10
Timestep Control Mike11		Variable
Variable Timestep Control		
	Decrease dT at dH [m]	0.15
	Increase dT at dH [m]	0.02
	In / Decrease dT with factor (0.01-0.99)	0.66
	Min dT [Min.]	0.0001
	Max dT [Min.]	30

The time step for the FEFLOW model is constrained to a maximum of 10 days and results are stored for each time step. The MIKE11 model has a maximum time step of 30 minutes.

The MIKE11 results are stored every 48 time steps, which for much of the model run means flow is recorded daily.

Where streams are naturally ephemeral or have become intermittent in flow due to excessive groundwater extraction it is important to introduce a mechanism by which the boundary condition can be activated and de-activated to allow recharge of the aquifer only when they flow. IFMMIKE11 enables this by disabling the FELOW transfer boundary conditions if the water depth in the river channel falls below a specified threshold.

It has been found that the setting “Show Logfile” enables the MIKE11 log file to be displayed at the end of a simulation, it also displays statistics on the flux leaving the FEFLOW model and the status of the FEFLOW boundary conditions.

Transfer boundary conditions outside the Daly Basin river network (ie the areas where there is discharge to the Roper River) were not coupled by ignoring these nodes using the ‘IFMMIKE11 ignore’ FEFLOW internal nodal reference distribution. Nodes with transfer boundary conditions to be ignored were set to a value of ‘1’ and nodes with transfer boundary conditions patched to the MIKE11 points were set to a value of ‘0’.

5.6. Limitations

Current assumptions and limitations of the model are:

- Equivalent porous media has been used to represent karstic systems;
- The recharge and runoff components of the surface water budget are not interlinked. The water budget for the various components indicate that they are, however, relatively consistent;
- Recharge is assumed to be diffuse, however, bypass flow via macropores / sinkholes is known to be a dominant recharge mechanism. It is expected that for the years with above average rainfall that the WAVES recharge will underestimate actual recharge;
- Areas where the Tindall Limestone is confined by the Jinduckin Formation are not adequately represented. Development of groundwater resources in regions where bores access groundwater in the Tindall Limestone beneath the Jinduckin Formation cannot be assessed. The model currently assumes that storage loss results in a direct reduction in groundwater level in the unconfined areas of each aquifer;
- Little understanding of actual river / aquifer interactions. Especially with respect to the flows from the river to the groundwater system;
- It is expected that when coupled to the FEFLOW model this will result in over estimation of the river recharge to the groundwater during large flood events;
- MIKE11 cross-sections are typically to the top of the river bank, this results in greater heads being generated during events where the top of the bank is exceeded and the water level is constrained within the low flow channel;
- Discharge is determined by geology and is represented by adjusting the transfer rate in/out of the transfer BCs;
- Individual springs are not considered in the model as the distributions of the discrete pathways are too poorly understood and at a scale too small to be adequately represented;
- Regional flow model only - groundwater model assumes approx homogeneous isotropic conditions and not suited to analysis of local karstic terrains (say, for tracking of pollutant flow);
- Surface water model not intended to analyse flood flows (or wet season conditions with great accuracy);
- The evapotranspiration (ET) has not been explicitly considered in the FEFLOW model, however, evaporation is removed from the river via the coupled MIKE11 model using daily pan evaporation to simulate loss fluxes.

6. SCENARIO MODELLING

6.1. Scenario Definitions

This section discusses the results from the 4 scenarios input into the coupled surface water / groundwater model.

The first scenario (Ahis) is based on the historical climate sequence. This is taken as the observed climate (rainfall and potential evapotranspiration (PET)) for water years from 1930 to 2007. For modelling river flows under this scenario, the current levels of surface and groundwater development were assumed. Scenario A will be used as the baseline against which assessments of relative change will be made. Three 23 year sequences were derived from the historic climate data reflecting dry, mid and wet climatic sequences.

The time periods for each of the climatic sequences used in Scenario A are summarised in **Table 7**.

Table 7 Period of record used for Scenario A climatic sequences

Climatic Sequence	Date From	Date To
Ahis	01/09/1930	31/08/2007
Adry	01/09/1940	31/08/1963
Amid	01/09/1978	31/08/2001
Awet	01/09/1959	31/08/1982

The second scenario (Scenario B) is a “recent climate” scenario. It is based on a 33-year climate series generated from rainfall and PET characteristics of the past 11 years (1996–2007). Once again, under this scenario, the current level of surface and groundwater development was used. Scenario B is therefore used to assess water availability should the climate in the future prove to be similar to that of the last 10 years.

The third scenario (Scenario C) is a future climate and current development scenario. It was based on a 33-year climate series derived from a range of global climate model (GCM) projections of ~2030 climate. The range of GCM projections encompassed different GCMs and several global warming scenarios (Crosbie et al., 2009). The GCM projections were used to modify the observed historical daily climate sequences. River flows for the future climatic scenarios were determined by scaling the calibrated MIKE11 rainfall-runoff (Petheram et al., 2009).

Once again, for modelling river flows under this scenario, the current level of surface and groundwater development were assumed.

The fourth scenario (Scenario D) is a future climate and future development scenario. It uses the same climate sequences as Scenario C, but groundwater development considered growth in groundwater use up to future allocation levels.

6.2. Development Scenarios

6.2.1. Surface Water Development Scenarios

In running the surface water model it has been assumed that the land use and therefore the hydraulic characteristics of each sub-catchment do not vary in time. Surface water allocations were not considered as part of this study.

6.2.2. Groundwater Development Scenarios

The extraction regimes used for each of the scenarios were generated by identifying bores utilised for either stock and domestic or horticulture supplies.

Bores identified as being used for stock and domestic supplies were assumed to extract 3.5 ML/yr and to have been used since the bore was first drilled.

Bores used for horticulture are licensed and have entitlements associated with each bore. All the scenarios run except for Ahis assumed a pumping rate based on the entitlement specified in each extraction license.

Stock and domestic extraction is a small component of the total water extracted from the two areas. For example in the Katherine area stock and domestic use is approximately 5% of entitlements identified for horticultural use, whilst in the Oolloo area this figure is approximately 2%.

Ahis employed an estimate of the historic extraction in the model to 01/09/2007. The pumping rate of bores identified as horticulture were assumed to increased linearly each month from the day the bore was drilled and completed to the current extraction rate. The current extraction rate was taken to be the actual documented extraction reported for each bore for the water year 2005 – 06.

It was assumed that the Oolloo aquifer had very little development up until 01/09/2007 and no extraction was included in this area for this scenario.

Scenarios A, and C' employed an extraction regime based on the current estimates of stock and domestic extraction and the documented current entitlements for 2007 for both the Tindall and the Oolloo areas. The average rate was converted to a daily extraction rate and applied over the entire duration of each scenario. The average annual extraction used for the two areas are presented in **Table 8**.

Scenario D' employed an extraction regime based on the current estimates of stock and domestic use and the expected future entitlements to 2018 for both the Tindall and the Oolloo areas. The average rate was converted to a daily extraction rate and applied over the entire duration of each scenario. The average annual extraction used for the two areas are presented in **Table 8**.

Table 8 Extraction totals for the Katherine and Oolloo areas for the 5 scenarios investigated.

	AHis	A	B	B'	C'	D'
	GL/yr					
Area						
Katherine	-1.2	-27.9	-27.9	-27.9	-27.9	-35.8
Oolloo	0.0	-16.8	-16.8	-16.8	-16.8	-43.8
Total	**-1.2**	**-44.7**	**-44.7**	**-44.7**	**-44.7**	**-79.6**

In the Katherine area scenario D' represents a 7.9 GL/yr or 28% increase in extraction over scenario C' total of 27.9 GL/yr. In the Oolloo area scenario D' represents a 37 GL/yr or 160% increase in extraction over scenario C' figure of 16.8 GL/yr. It should also be noted that the locations of the pumping bores in scenarios A and C' differ from the locations of the pumping bores in scenario D'.

6.3. Reported Metrics

6.3.1. Groundwater Metrics

Water balances are documented for the two management zones within the model domain (refer to **Section 2.2**).

Groundwater levels are documented for five sites. The locations of the reporting sites are presented in **Figure 9**. The FEFLOW model mesh and MIKE11 branch locations have been included for comparison.

Two of the groundwater level sites are located within the Tindall Limestone in the Katherine area. One site is representative of areas with outcropping Tindall Limestone (RN029429) and the other site is representative of areas where Cretaceous cover exists (RN022006). Three sites are located in the Oolloo area. Two sites are in areas where the Oolloo dolostone outcrops (RN008660 and RN020614) and one is located where the Cretaceous sediment cover exists (RN007595).

The median groundwater levels for each of the sites were calculated to provide a simple indicator of the effects of each scenario on the groundwater system.

Groundwater discharge is reported at 3 sites. The discharge was calculated by summing fluxes at the boundary conditions nodes using observation point groups (Diersch, 2008).

6.3.2. Surface Water Metrics

River discharges are presented for three of the 6 gauge sites G8140301, G8140067 and G8140040. These sites are considered to represent the overall flow dynamics of the Katherine and Daly Rivers especially with respect to the impacts of pumping on low flows.

Median groundwater discharge at the 3 locations along the Katherine River and Daly River have also been calculated to provide simple indices to indicate changes to the discharge regime.

Surface water discharges were also extracted from the MIKE11 results file for the chainages corresponding to the node closest to the location of the gauging site. The gauging site and the corresponding MIKE11 chainage are presented in **Table 9**. The results of the MIKE11 data are not discussed further in this report.

Table 9 Gauging sites and the corresponding MIKE11 branch name and chainage.

Gauge Site	Branch	Chainage
G8140001	Katherine River	212147.0
G8140301	Katherine River	231327.2
G8140067	Daly River	44001.0
G8140038	Daly River	110443.0
G8140042	Daly River	169359.0
G8140040	Daly River	229713.0

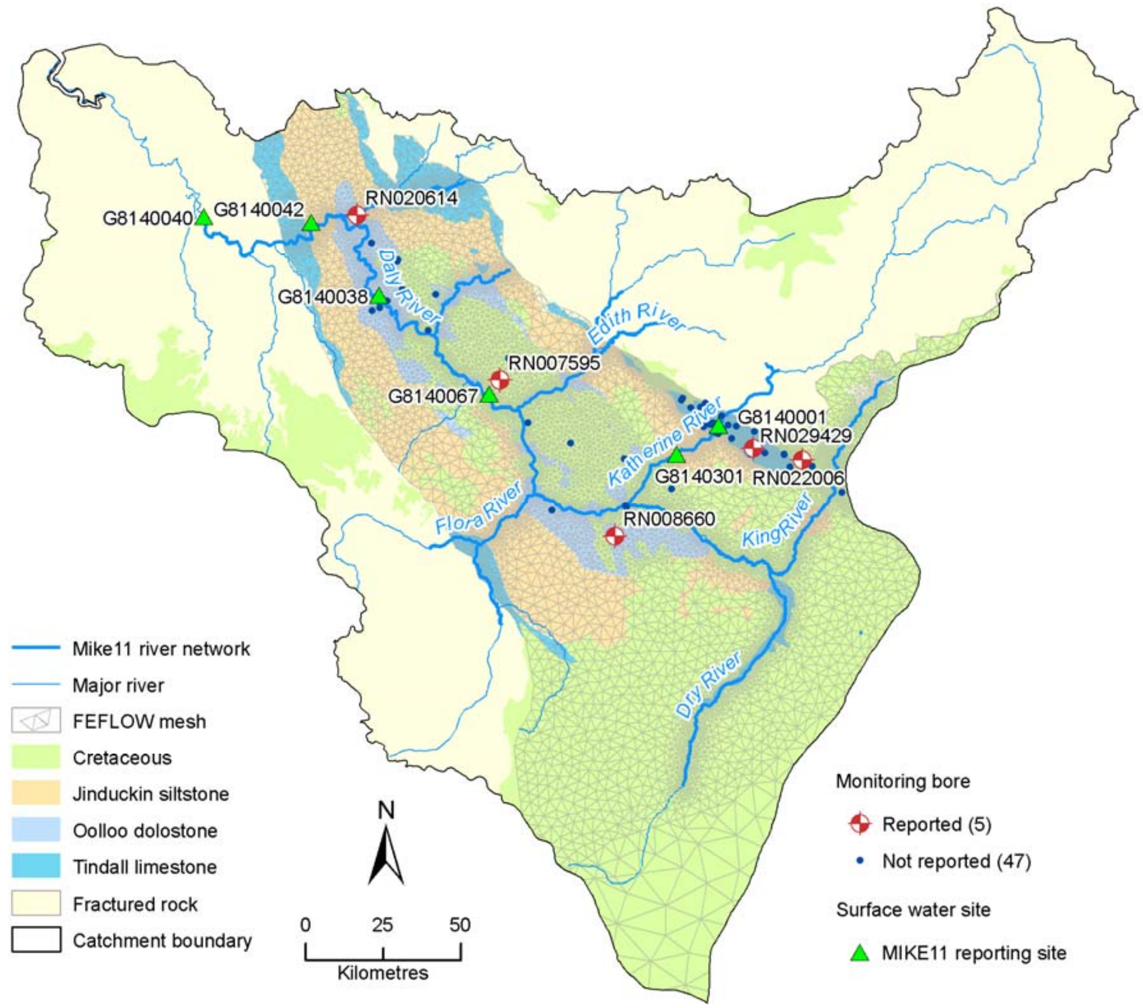


Figure 9 Schematic depicting the groundwater and surface water components of the integrated model and the sites used for reporting the scenario modelling results.

6.4. Historic Climate (Scenario A)

6.4.1. Scenario A – Water Balances

The Ahis average annual groundwater balance for the Katherine area (**Table 10)** and the Ooloo area (**Table 11**) indicates that the model is in dynamic equilibrium with inputs and outputs ranging in difference from 1 to 3 %.

Table 10 Scenario A average annual water balance for the Katherine area

	Ahis	Adry	Amid	Awet
	GL/yr			
Recharge (gains)				
Rainfall	41.2	35.3	41.2	50.2
Cretaceous	3.6	4.8	4.6	4.1
From river	0.4	0.4	1.2	0.7
Sub-total	45.2	40.5	47.0	55.0
Discharge (losses)				
Extraction	-1.2	-27.9	-27.9	-27.9
To rivers	-43.0	-26.8	-29.0	-33.0
Sub-total	-44.2	-54.7	-56.9	-60.9
Change	1.0	-14.2	-9.9	-5.9

Table 11 Scenario A average annual water balance for the Oolloo area

	Ahis	Adry	Amid	Awet
	GL/yr			
Recharge (gains)				
Rainfall	295.6	253.0	293.0	356.0
From river	38.6	31.6	46.6	38.0
Sub-total	334.2	284.6	339.6	394.0
Discharge (losses)				
Extraction	0.0	-16.8	-16.8	-16.8
To rivers	-339.5	-308.0	-334.0	-380.0
Sub-total	-339.5	-324.8	-350.8	-396.8
Change	-5.3	-40.2	-11.2	-2.8

Adry corresponds to a 16% reduction in average annual recharge (after scaling) than for the Ahis period. The water balance for this scenario (**Table 10** and **Table 11**) indicates that discharge to the river and from extraction is greater than the recharge and that water is being lost from storage.

Amid period resulted in a 3 to 4% reduction in average annual recharge from Ahis. Although this scenario has approximately average recharge conditions, the system has developed relatively high groundwater levels and discharges from the preceding decade or so of the Ahis.

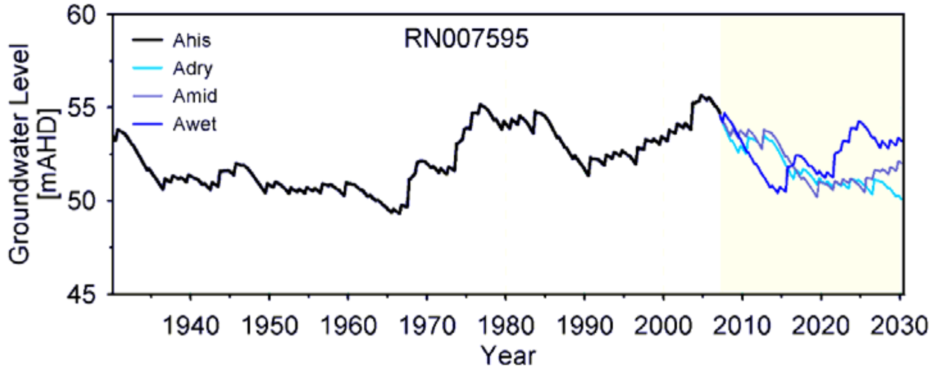
Awet corresponds to a 9 % increase in the average annual recharge with respect to the Ahis recharge (**Table 10** and **Table 11**).

6.4.2. Scenario A – Groundwater Levels

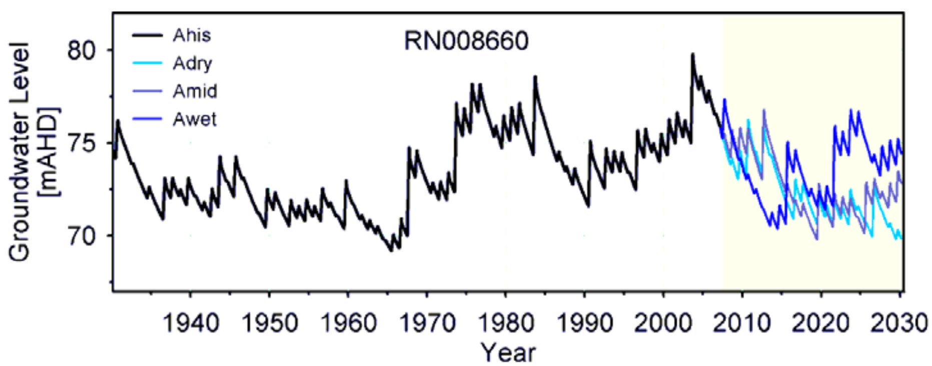
The water levels for the five reported sites show an upward trend over the 77 year model run from 1930 to 2007 and are presented in **Figure 10**. The hydrographs also show the hydrographs for the three climatic sequences for the period 2007-2030.

Each of the individual hydrographs reflect the different recharge conditions prevailing in the vicinity of each of the reporting sites. RN029429, RN08660 and RN020614 are all located in areas where the carbonate aquifers outcrop and exhibit a more "peaky" response and have considerably more dynamic range than RN022006 and RN007595 which are located in areas overlain by Cetaceous. RN020614 is located in close proximity to the Daly River (refer to **Figure 7**) and the groundwater hydrograph reflects the connectivity of the surface water and the groundwater. The lower level of the hydrograph is controlled by the water level in the river during the dry season resulting in a relatively steady trend in the overall level.

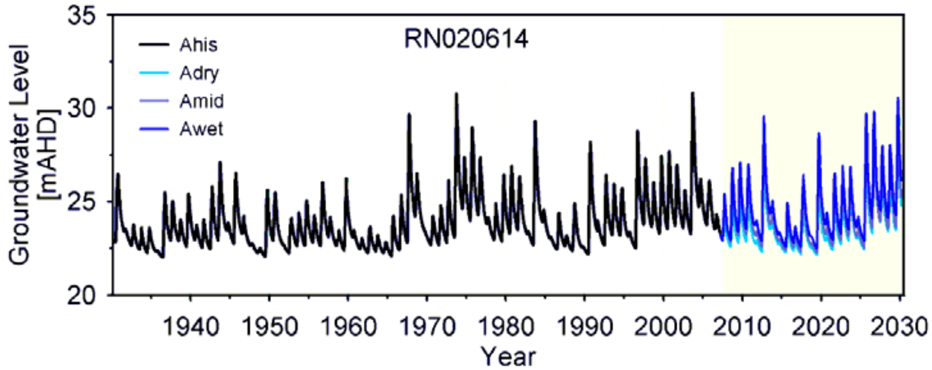
The hydrographs reflect this with falling trends in both the Katherine area and the Oolloo area. The elevated groundwater levels from the initial conditions prevailing at the end of Ahis can not be sustained and the continuing downward trend of all hydrographs indicate that it is unlikely that a new dynamic equilibrium is met during the 23 year period from 2007 to 2030 (refer to **Figure 10**).


RN007595
Ahis
Adry
Amid
Awet
Groundwater Level [mAHD]
Year
60
55
50
45
1940 1950 1960 1970 1980 1990 2000 2010 2020 2030

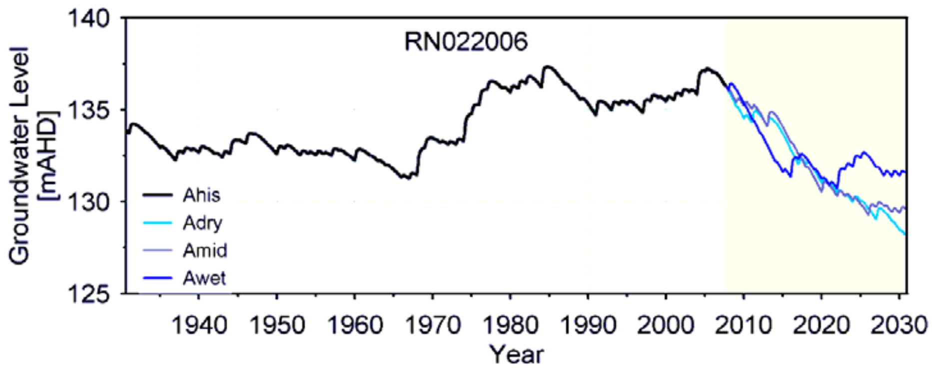
a)


RN008660
Ahis
Adry
Amid
Awet
Groundwater Level [mAHD]
Year
80
75
70
1940 1950 1960 1970 1980 1990 2000 2010 2020 2030

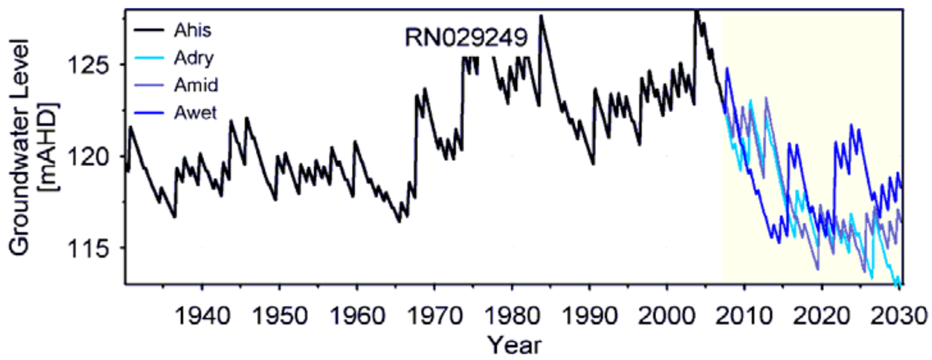
b)


RN020614
Ahis
Adry
Amid
Awet
Groundwater Level [mAHD]
Year
35
30
25
20
1940 1950 1960 1970 1980 1990 2000 2010 2020 2030

c)


RN022006
Ahis
Adry
Amid
Awet
Groundwater Level [mAHD]
Year
140
135
130
125
1940 1950 1960 1970 1980 1990 2000 2010 2020 2030

d)



e)

Figure 10 Scenario A groundwater level hydrographs for the 5 reporting sites showing Ahis groundwater levels to 2007 and the groundwater levels to 2030 using the Adry, Amid and Awet sequences. a) RN007595 b) RN008660 c) RN020614 d) RN022006 and e) RN029249

The median groundwater levels for each of the sites was determined to provide a simple indicator of the effects of each reported groundwater sites are presented in (**Table 12**). Median groundwater levels also reflect the loss of groundwater from storage.

Table 12 Median groundwater levels for scenario A

	RN029429	RN022006	RN007595	RN008660	RN020614
Scenario			m AHD		
AHis	121.0	133.6	51.9	73.1	23.6
Adry	116.5	131.7	51.3	71.9	23.3
Amid	116.6	131.3	51.6	72.3	23.6
Awet	118.4	132.1	52.6	73.9	23.7

6.4.3. Scenario A – Groundwater Discharge

The historic groundwater discharges for the Katherine River at G8140301, the Daly River at G8140067 and for the Daly River at G8140040 are presented in **Figure 11**. The groundwater discharge range at each of the sites has been clipped in order to accentuate the range where dry season discharges dominate. The discharge hydrographs at each of the sites during the wet season is typified by short duration reductions in discharge or even recharge from the river to the groundwater (-ve discharge on the hydrographs). The recharge from the river occurs when flood heights are greater than the groundwater levels adjacent to the river. To demonstrate the effects of river recharge the period from 01/09/2000 – 01/09/2007 has been magnified with the full dynamic range presented.

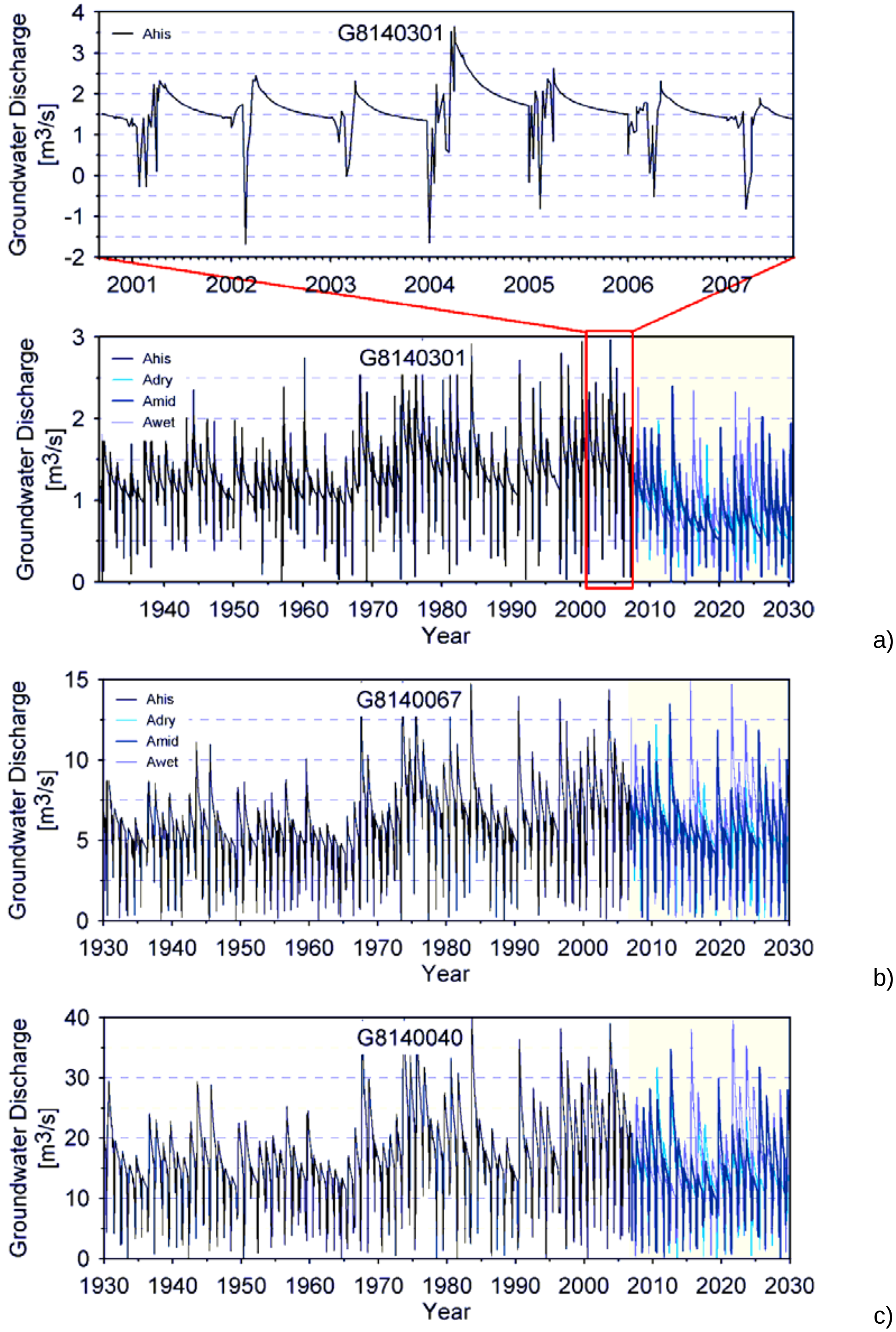


Figure 11 Scenario A groundwater discharge hydrographs at selected reporting sites a) G8140301 – Galloping Jacks including magnified period from 01/09/2000 – 01/09/2007, b) G8140067 – Dorisvale and c) G8140040 – Mt Nancar.

Discharge to the Katherine River continues to decline for each of the Scenario A sequences reflecting the loss in storage and capture of groundwater due to groundwater extraction and continued reduction in groundwater heads.

Table 13 Median groundwater discharges at the 3 gauging sites on the Katherine River (G8140301) and Daly River (G8140067 and G8140040).

	G8140301	G8140067	G8140040
Scenario		m^3/s	
Ahis	1.31	6.03	14.76
Adry	0.81	5.41	13.78
Amid	0.86	5.73	14.83
Awet	0.92	6.07	15.21

6.5. Recent Climate (Scenario B)

6.5.1. Scenario B – Water Balances

This scenario uses the historic climatic data from 01/09/1996 – 31/08/2007 to generate the WAVES recharge and NAM runoff data. The resulting recharge and runoff data were then repeated 3 times to synthesise 33 years of data.

Scenario B represents a 48% increase in average annual recharge in the Katherine River area and a 16% increase in average annual recharge in the Oolloo area. The system should be in dynamic equilibrium given that this is a repeat of the preceding 11 years.

Table 14 Scenario B average annual water balance for the Katherine area.

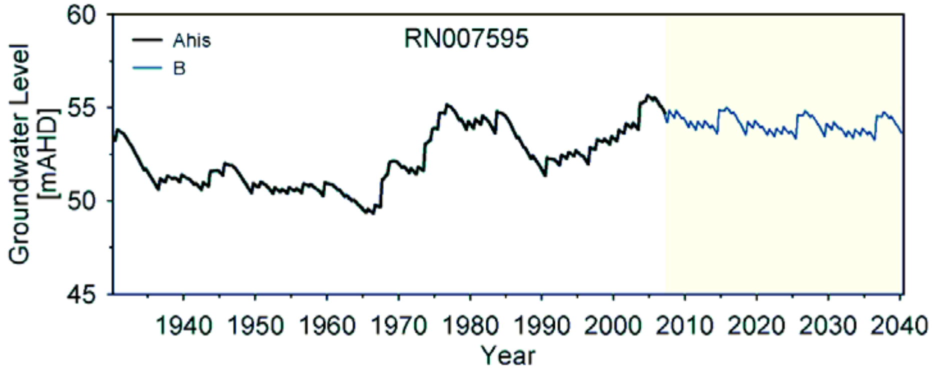
	AHis	Amid	B
Recharge (gains)			
Rainfall	41.2	41.2	66.0
Cretaceous	3.6	4.6	3.1
From river	0.4	1.2	1.0
Sub-total	45.2	47.0	70.1
Discharge (losses)			
Extraction	-1.2	-27.9	-27.9
To rivers	-43.0	-29.0	-41.8
Sub-total	-44.2	-56.9	-69.7
Change	1.0	-9.9	0.4

Table 15 Scenario B average annual water balance for the Oolloo area.

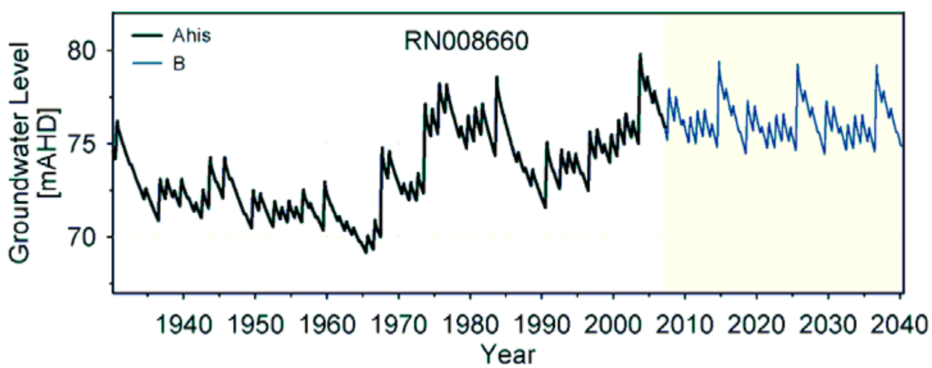
	AHis	Amid	B
Recharge (gains)			
Rainfall	295.6	293.0	368.5
From river	38.6	46.6	51.1
Sub-total	334.2	339.6	419.5
Discharge (losses)			
Extraction	0.0	-16.8	-16.8
To rivers	-339.5	-334.0	-409.9
Sub-total	-339.5	-350.8	-426.7
Change	-5.3	-11.2	-7.2

6.5.2. Scenario B – Groundwater Levels

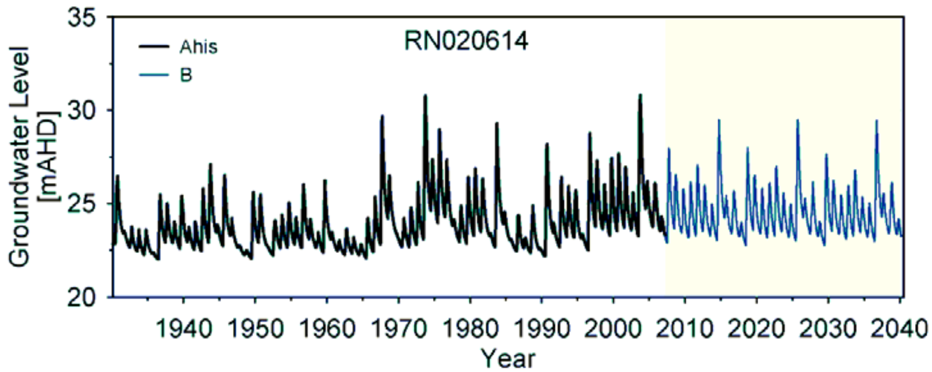
Groundwater levels for scenario B are relatively steady with no dramatic upward or downward trends evident.


RN007595
Ahis
B
Groundwater Level [mAHD]
Year

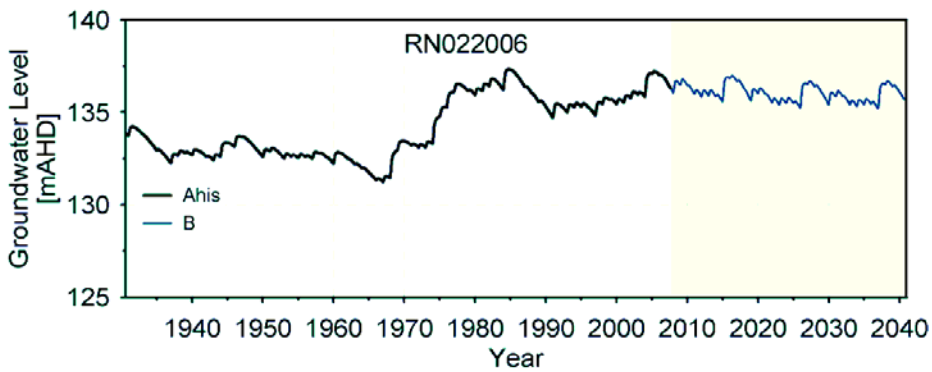
a)


RN008660
Ahis
B
Groundwater Level [mAHD]
Year

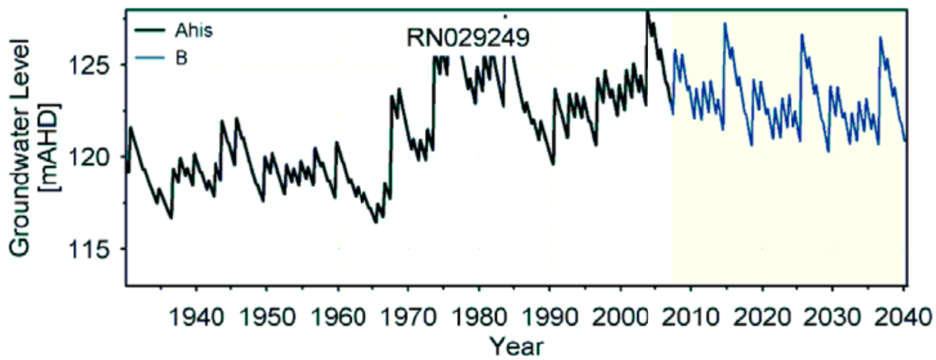
b)


RN020614
Ahis
B
Groundwater Level [mAHD]
Year

c)


RN022006
Ahis
B
Groundwater Level [mAHD]
Year

d)



e)

Figure 12 Scenario B groundwater level hydrographs for the 5 reporting sites showing Ahis groundwater levels to 2007 and the groundwater levels to 2040 using the scenario B. a) RN007595 b) RN008660 c) RN020614 d) RN022006 and e) RN029249

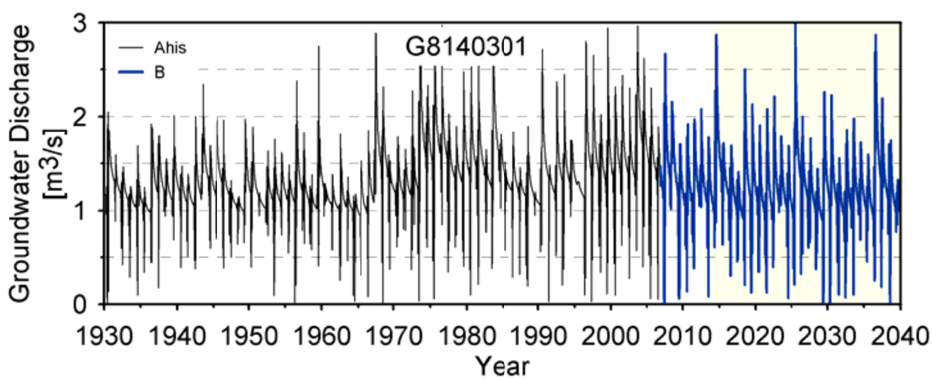
Groundwater levels reflect the steady trend with the median values being above both the Ahis and Amid median values.

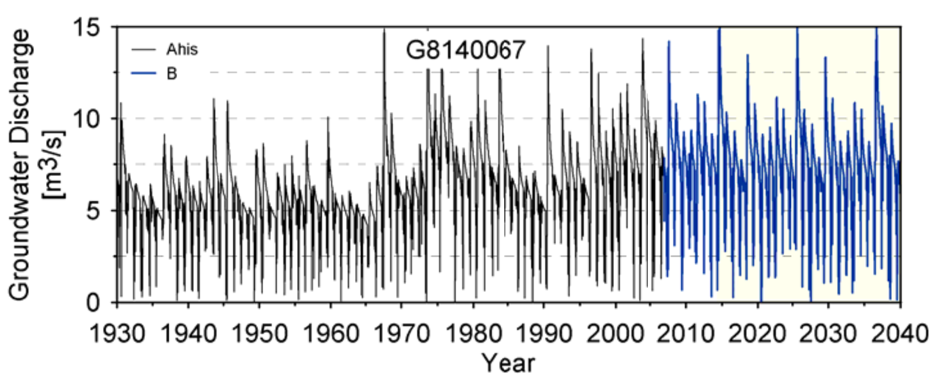
Table 16 Median groundwater levels for scenario B

	RN029429	RN022006	RN007595	RN008660	RN020614
Scenario			m AHD		
AHis	121.0	133.6	51.9	73.1	23.6
Amid	116.6	131.3	51.6	72.3	23.6
B	122.8	136.1	54.0	76.0	24.2

6.5.3. Scenario B – Groundwater Discharge

Groundwater discharge hydrographs for scenario B show relatively steady trends with only relatively small initial declines from the discharges observed in the preceding 11 years.





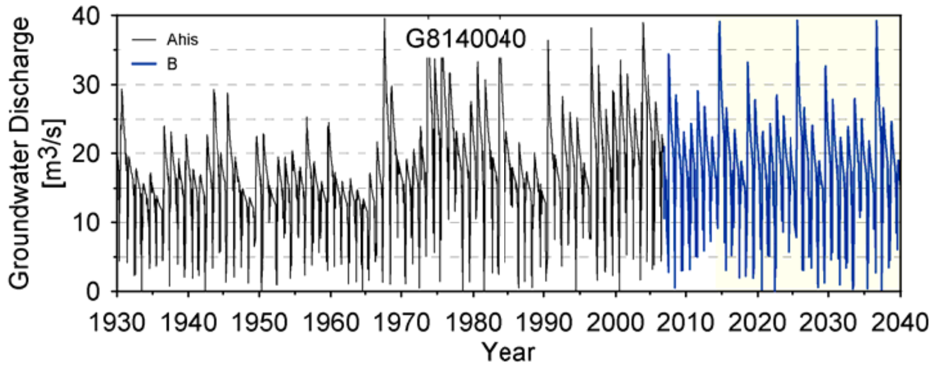


Figure 13 Scenario B groundwater discharge hydrographs at selected reporting sites a) G8140301 – Galloping Jacks, b) G8140067 – Dorisvale and c) G8140040 – Mt Nancar.

The median groundwater discharge values reflect this with scenario B values considerably higher than the median values for Ahis and Amid.

Table 17 Median groundwater discharge for Scenario B at selected sites along the Katherine River and Daly River.

	G8140301	G8140067	G8140040
Scenario		m^3/s	
Ahis	1.31	6.03	14.76
Amid	0.86	5.73	14.83
B	1.22	7.60	18.81

6.6. Future Climate (Scenario C' and D')

Two scenarios were used to examine the effects of current and future entitlements in conjunction with the 3 future climatic sequences on the catchment water balance, groundwater levels and discharge to the river. The three input sequences (dry, mid and wet) represent changes in the average annual recharge of approximately -3%, 10% and 42% from the recharge sequence employed in scenario Amid.

6.6.1. Scenario C' & D' – Water Balances

The water balances for each of the climatic sequences indicate that recharge for Amid is somewhere in between the dry and mid climatic sequences. The water balances for scenario C' and D' for the Katherine and Oolloo areas are presented in **Table 18** and **Table 19** respectively.

In the Katherine area scenario D' represents a 7.9 GL/yr or 28% increase in extraction over scenario C'.

In the Katherine area the discharge to the Katherine River under Scenario D' shows a decrease of approximately 6 GL/yr relative to Scenario C'. This is a change of -23%, -21% and -18% from the discharge reported for C'dry, C'mid and C'wet respectively.

The water balance in the Katherine area shows an increase in the imbalance of the system by 1 GL/yr for each of the climatic sequences due to the increase in extraction. The imbalance expressed as a percentage of recharge are -25%, -17% and -2% for C'dry, C'mid and C'wet respectively, whilst in scenario D' the imbalance expressed as a percentage of recharge is -27%, -20% and -4% for D'dry, D'mid and D'wet respectively.

Table 18 Water balances for scenario C' and D' in the Katherine area.

	Amid	C'dry	C'mid	C'wet	D'dry	D'mid	D'wet
				GL/yr			
Recharge (gains)							
Rainfall	41.2	38.7	43.5	55.7	38.5	43.4	55.8
Cretaceous	4.6	4.9	4.6	4.0	5.0	4.6	4.0
From river	1.2	0.7	0.9	0.9	1.8	1.9	1.7
Sub-total	47.0	44.3	49.1	60.6	45.2	49.9	61.6
Discharge (losses)							
Extraction	-27.9	-27.9	-27.9	-27.9	-35.8	-35.8	-35.8
To rivers	-29.0	-26.0	-28.7	-34.0	-20.0	-22.7	-28.0
Sub-total	-56.9	-53.8	-56.6	-61.9	-55.8	-58.5	-63.8
Change	-9.9	-9.5	-7.6	-1.3	-10.6	-8.6	-2.3

In the Oolloo area scenario D' represents a 27 GL/yr or 160% increase in extraction over scenario C'. The water balances for the Oolloo dolostone aquifer reflect the increased extraction with an increase in the imbalance of ~12 GL/yr between the C' and D' climate scenarios refer to **Table 19**.

In the Oolloo area under Scenario D' there is a 12 to 13 GL/yr reduction in discharge to the Daly River from Scenario C', which is a reduction of 4%, 4% and 3% from the discharge reported for C'dry, C'mid and C'wet respectively.

Table 19 Water balances for scenario C' and D' in the Oolloo area.

	Amid	C'dry	C'mid	C'wet	D'dry	D'mid	D'wet
				GL/yr			
Recharge (gains)							
Rainfall	293.0	272.0	308.9	403.7	271.2	308.7	405.0
From river	46.6	39.4	44.8	44.9	41.7	46.6	46.7
Sub-total	339.6	311.4	353.7	448.6	312.9	355.3	451.7
Discharge (losses)							
Extraction	-16.8	-16.8	-16.8	-16.8	-43.8	-43.8	-43.8
To rivers	-334.0	-301.7	-335.6	-403.2	-288.2	-322.2	-391.3
Sub-total	-350.8	-318.5	-352.5	-420.0	-332.1	-366.0	-435.2
Change	-11.2	-7.2	1.2	28.5	-19.1	-10.7	16.5

In scenario C' the imbalance in the Oolloo area expressed as a percentage of recharge is -3%, 0% and 7% for C'dry, C'mid and C'wet respectively, whilst in scenario D' the imbalance in the Oolloo area expressed as a percentage of recharge is -7%, -3% and 4% for D'dry, D'mid and D'wet respectively.

Despite this decrease in discharge there is only a 1-2 GL/yr increase in the recharge from the river to the aquifers in both the reporting areas.

6.6.2. Scenario C' & D' – Groundwater Levels

The water balance results for each of the climatic sequences indicate that recharge for Amid is somewhere in between the dry and mid climatic sequences, this is reflected in both the median groundwater levels and the groundwater level hydrographs for scenario C'.

Groundwater level hydrographs for scenario C' and D' at the 5 reporting sites are presented in **Figure 14**. The individual groundwater level hydrographs for each of the sequences for the C' and D' scenarios show much greater similarity compared to those for scenario A. This reflects the methodology used to generate the three climatic sequences within each scenario. The groundwater level hydrographs respond in a manner as would be expected for the three sequences, that is, the dry sequences show the lowest groundwater levels, the wet sequences show the highest groundwater levels and the mid sequences groundwater levels sit somewhere in between the two extremes.

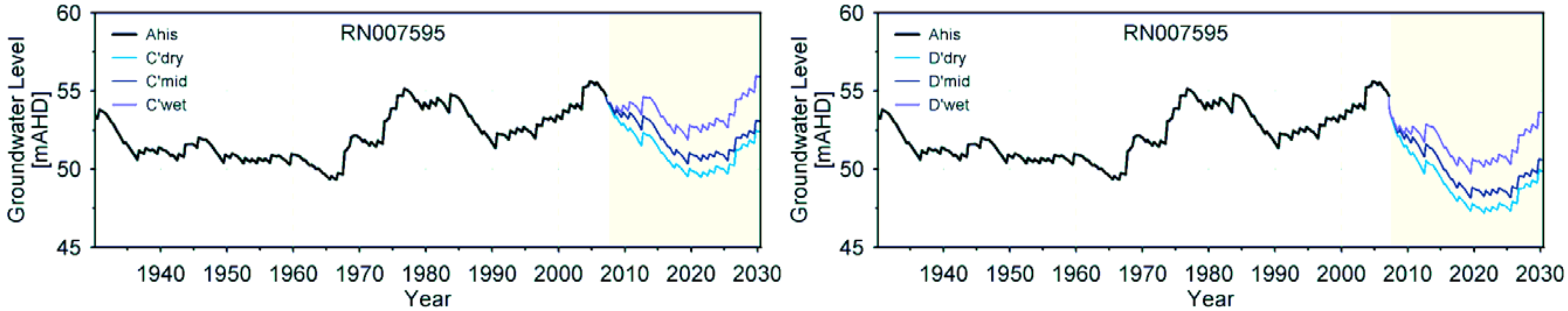
Based on the groundwater level hydrographs both scenarios appear to reach dynamic equilibrium after approximately 10-15 years.

Median groundwater levels (refer to **Table 20**) for the C’ scenarios are generally comparable to or higher than Amid. In contrast the water levels for scenario D’ are generally lower than those for Amid except at RN022006. The groundwater levels for the Oolloo dolostone aquifer (RN007595 and RN008660) are most notably affected and reflect the 160% increase in extraction (refer to **Table 8**).

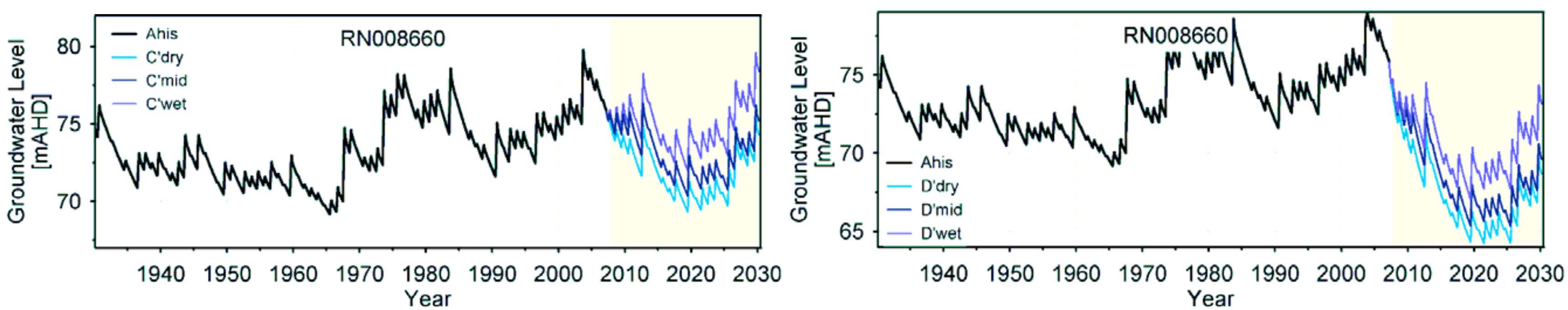
Table 20 Median groundwater levels for Scenario C’ and D’ under the 3 different climatic sequences.

	RN029429	RN022006	RN007595	RN008660	RN020614
Scenario	m AHD				
Amid	116.6	131.3	51.6	72.3	23.6
C'dry	116.1	130.3	51.2	71.8	23.3
C'mid	117.3	131.5	52.0	73.0	23.7
C'wet	120.4	133.5	53.6	74.8	24.2
D'dry	114.3	130.2	48.9	67.0	23.3
D'mid	115.4	131.3	49.6	67.9	23.7
D'wet	118.7	133.3	51.8	70.4	24.3

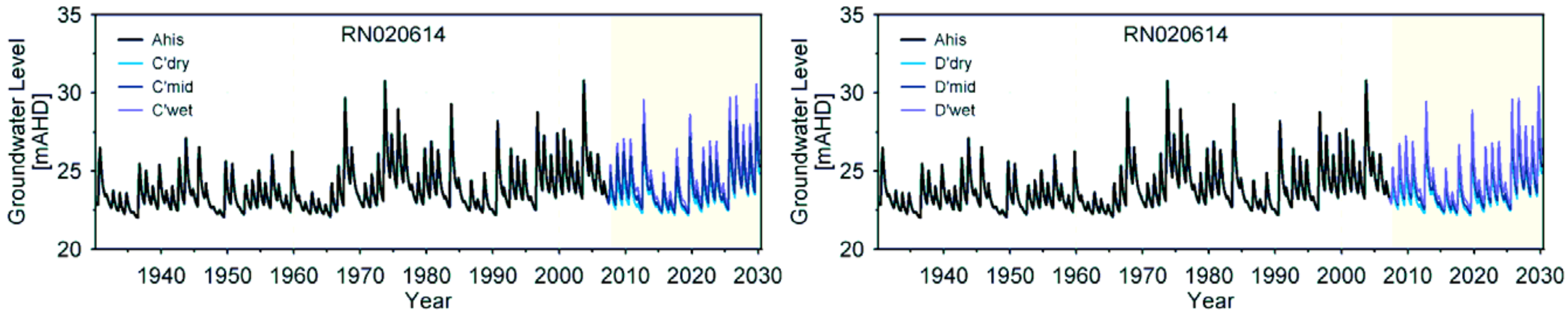
Groundwater levels for Scenario D’ are generally much lower than any recorded historic levels.


RN007595
Ahis
C'dry
C'mid
C'wet
Groundwater Level [mAHD]
Year
RN007595
Ahis
D'dry
D'mid
D'wet
Groundwater Level [mAHD]
Year

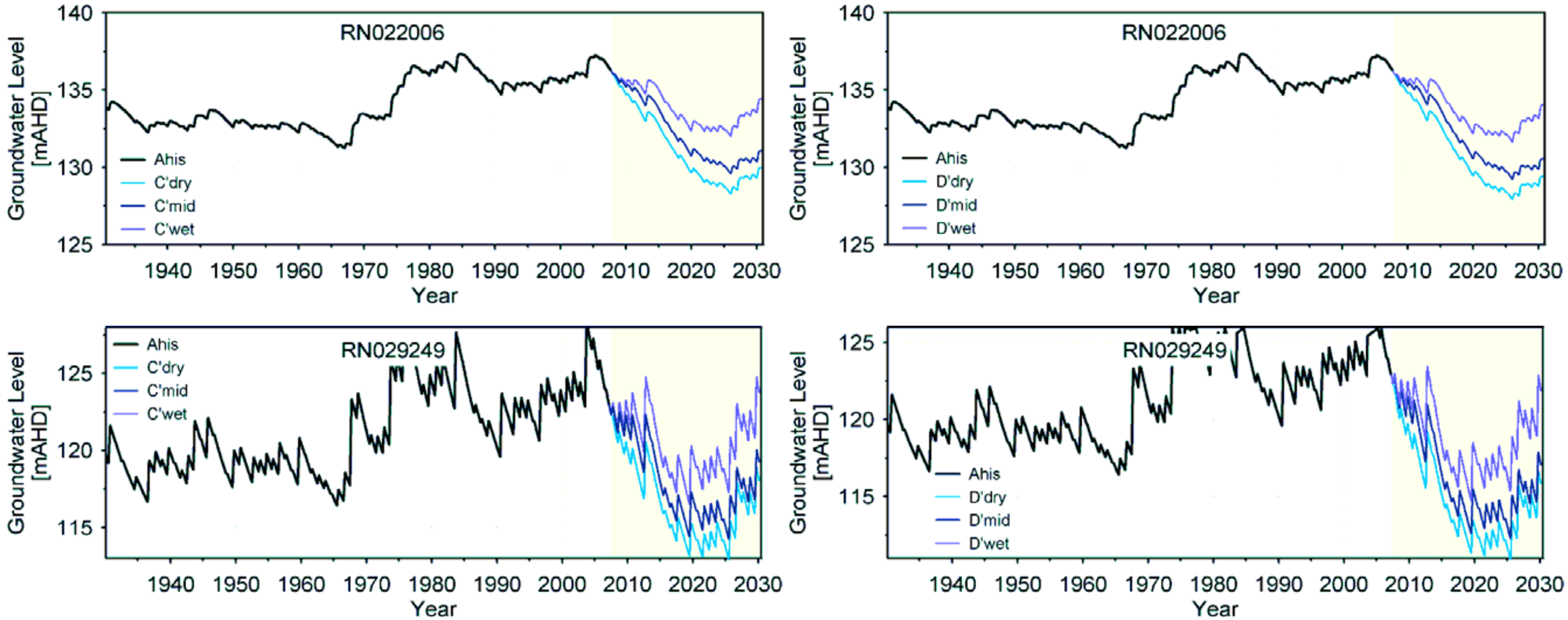
a)


RN008660
Ahis
C'dry
C'mid
C'wet
Groundwater Level [mAHD]
Year
RN008660
Ahis
D'dry
D'mid
D'wet
Groundwater Level [mAHD]
Year

b)


RN020614
Ahis
C'dry
C'mid
C'wet
Groundwater Level [mAHD]
Year
RN020614
Ahis
D'dry
D'mid
D'wet
Groundwater Level [mAHD]
Year

c)



d)

e)

Figure 14 Scenario C' and D' groundwater level hydrographs for the 5 reporting sites showing Ahis groundwater levels to 2007 and the groundwater levels to 2030 using the C'dry, C'mid and C'wet sequences. a) RN007595 b) RN008660 c) RN020614 d) RN022006 and e) RN029249

6.6.3. Scenario C' & D' – Groundwater Discharge

Simulated groundwater discharge at the three sites under scenario C' and D' are presented in **Figure 15**. The graphic highlights the effects of the increased extraction in scenario D' relative to scenario C'. This is also evident in the median groundwater discharges at each site presented in **Table 21**. Only site G8140040 at Mt Nancar exhibits median discharges for both scenarios which are greater than those simulated in scenario Amid.

Table 21 Median groundwater discharge for Scenario C' and D' at selected sites along the Katherine River and Daly River.

	G8140301	G8140067	G8140040
Scenario		m^3/s	
Ahis	1.31	6.03	14.76
C'dry	0.80	5.34	15.75
C'mid	0.88	5.88	17.55
C'wet	1.06	6.89	20.64
D'dry	0.57	4.83	15.11
D'mid	0.66	5.40	16.90
D'wet	0.85	6.35	20.02

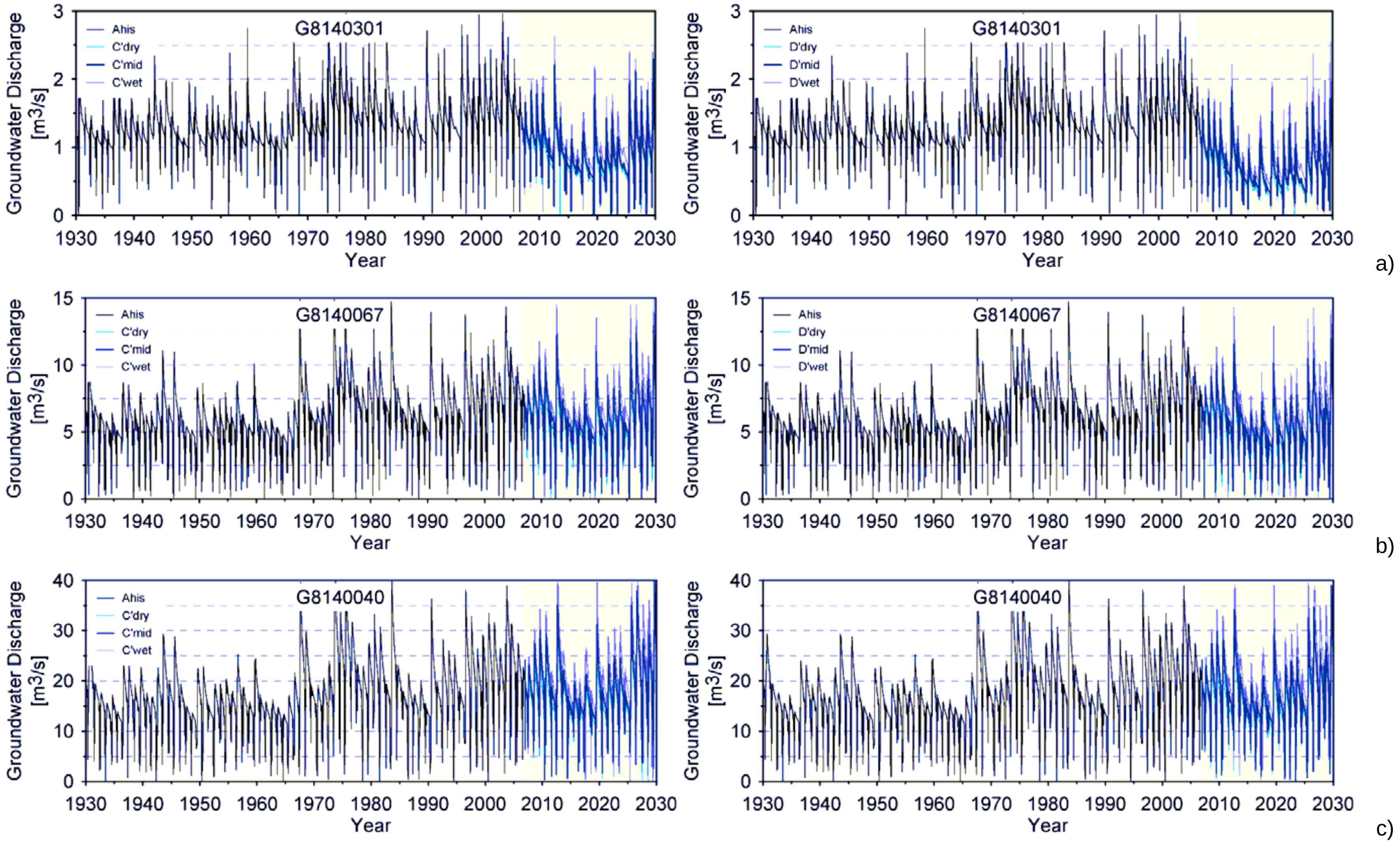


Figure 15 Scenario C' and D' groundwater discharge hydrographs at selected reporting sites a) G8140301 – Galloping Jacks, b) G8140067 – Dorisvale and c) G8140040 – Mt Nancar.

7. DISCUSSION

The groundwater levels and discharge at the end of the historic climatic sequence (Ahis) are not sustained by any of the sequences predicting the future climate. This indicates that in the recent past the climate has been at its' wettest over the 77 year period from 1930 to 2007.

7.1. Scenario A

Based on the continuing downward trend of all but the wet Scenario A hydrographs it is unlikely that a new dynamic equilibrium is met during the 23 year period. Water balance data also indicates that the groundwater system is not in dynamic equilibrium for the Adry and Amid sequences with relatively large negative imbalances.

Discharge to the Katherine River continues to decline for each of the scenario A sequences reflecting the loss in storage and capture of groundwater due to groundwater extraction and continued reduction in groundwater heads. The dry season flows after 2015 appear to approach a value approximately half of the lowest historic flow (compare ~1.0 m^3/s with ~0.5 m^3/s).

Modelling completed by Knapton, (2006) identified that in the case of the Tindall aquifer in the Katherine area that there is a time lag between the commencement of extraction and the impacts of extraction on the discharge at the river. Bores greater than 20 kilometres from the river can expect to only have 50 to 60% of their extraction rate impact upon the river after a 20 to 30 year period.

In the Oolloo area the groundwater levels and less so the discharge hydrographs, indicate the effects of the increased extraction regime from 0.0 to 16.8 GL/yr. The annual water balance information for the dry and mid sequences show relatively large negative imbalances. This reflects the loss in storage as evidenced by declining trends in the groundwater levels for these two sequences and it is unlikely that a new dynamic equilibrium is met during the 23 year period. The groundwater levels and discharge hydrographs for the wet sequence, however, suggest a new dynamic equilibrium is achieved. Water balance information for the wet sequence supports this assessment.

7.2. Scenario B

Scenario B represents a 47% increase in recharge from the Amid recharge in the Katherine River area and a 15% increase in recharge in the Oolloo area. Similar trends in the groundwater levels are observed. The water balance for the Katherine area suggests that the system should be in dynamic equilibrium given that this is a repeat of the recent 11 years of relatively high rainfall. The water balance in the Oolloo area suggests that the system is not in dynamic equilibrium and that water is being lost from storage. Groundwater levels and discharge results also suggest that the system is at or near dynamic equilibrium.

7.3. Scenario C' and D'

The groundwater discharge to the Daly River as indicated by the two reporting sites Dorisvale and Mt Nancar appear to show minimal effects from the pumping. However, the water balance information shows that despite the 12 – 15 GL/yr decrease in discharge to the Daly River in response to the 27 GL/yr increase in extraction there is only a 2 GL/yr increase in recharge from the river, indicating that the system has not achieved a new dynamic equilibrium in for the dry and mid sequences and that groundwater is being lost from storage.

It should be noted that Scenario C' and Scenario D' are not directly comparable as the locations of the extraction bores are different. In particular the distribution of bores with high extraction rates is quite different. Scenario C' has the extraction bores located in the area close to Stray Creek. Scenario D' has the extraction bores located in the area to the north east of Dorisvale Crossing. This is reflected in the differences in discharge between the sequences. The reduction in median discharge between scenario C' and scenario D' at Dorisvale Crossing is ~0.3 m^3/s. However for the section of river between Dorisvale and Mt

Nancar the reduction in median discharge between scenario C' and scenario D' is ~0.15 m^3/s. Although the river is in poorer connection it appears that the effects of the change in location of the bores with high extraction rates impacts on the reach upstream of Dorisvale Crossing.

Similar to the situation identified in the Katherine area there will be a time lag between between the commencement of extraction and the impacts of extraction on the discharge at the river. However, the reduced connection upstream of Dorisvale Crossing means that the full impact of the future extraction regime is probably not observed as the cone of influence needs to migrate further to capture the discharge required to equalise the losses due to extraction.

8. CONCLUSIONS

An integrated surface water / groundwater model has been utilised to investigate the effects of 4 scenarios that include climate change and groundwater development on the water resources of the Daly River. From this investigation the following conclusions have been made:

- Recent climatic conditions have resulted in recharge being much greater than the long term average.
- Using the historic climate to simulate the future climate to 2030 the water balances, groundwater levels and discharge in the Katherine area suggests that extractions under the current allocations will have significant impacts on the groundwater discharge from the Tindall Limestone to the Katherine River.
- Similarly the future allocations will have an even greater impact on discharge from the Tindall Limestone to the Katherine River. The full impacts of extraction are probably not evident in the 23 year future scenarios.
- Although the predicted future climate scenarios are wetter than the historic climatic conditions future groundwater development will still impact on the river discharge.
- Lag times between the commencement of extraction and the full impacts on river discharge is likely to be beyond the 2030 timeframe of this study.
- Based on the statement above it is suggested that climatic regimes are extended by repeating climatic sequences to reach dynamic equilibrium.

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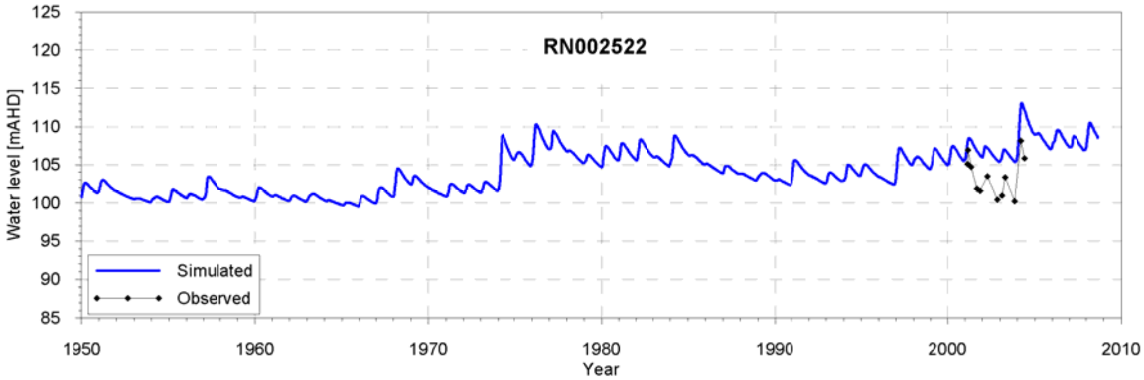
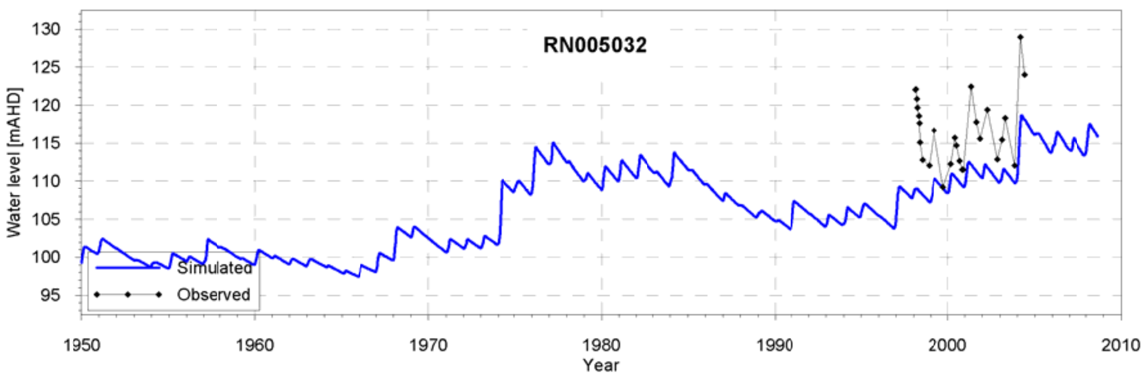
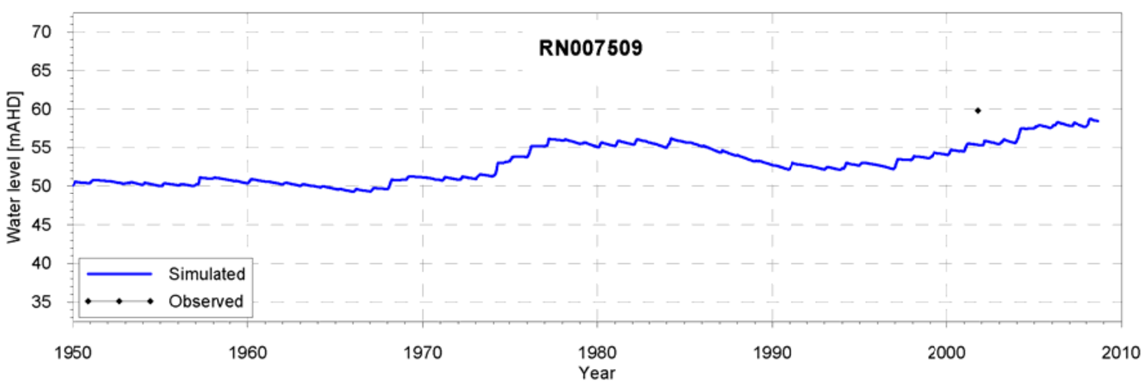
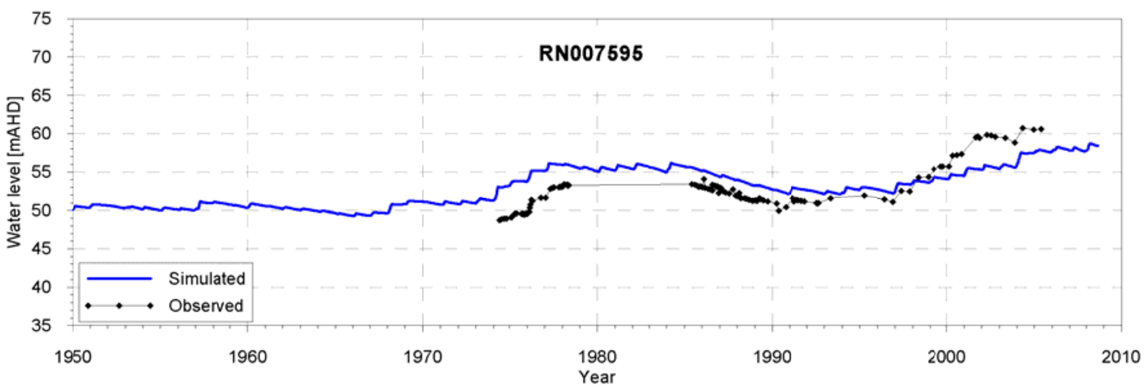
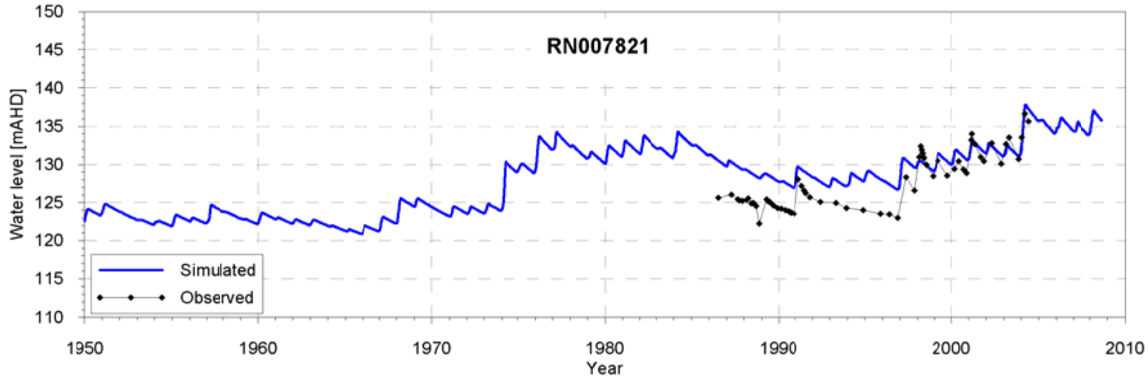
APPENDIX A – CALIBRATED GROUNDWATER LEVELS







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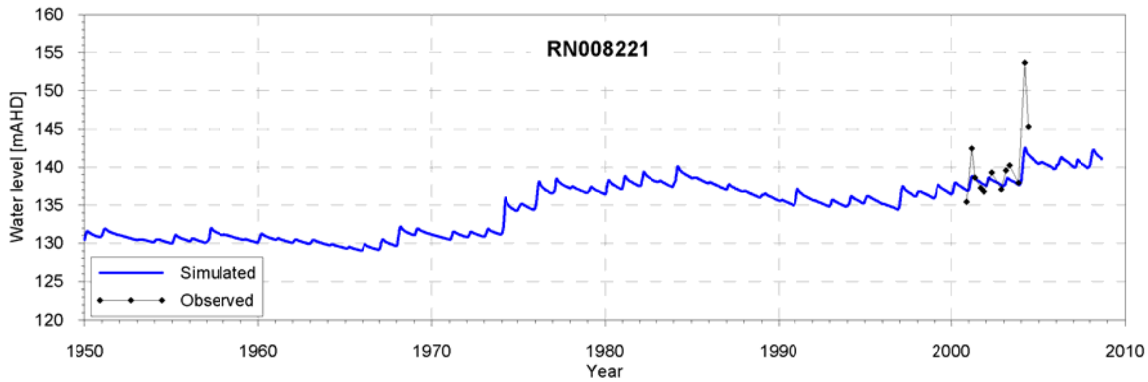
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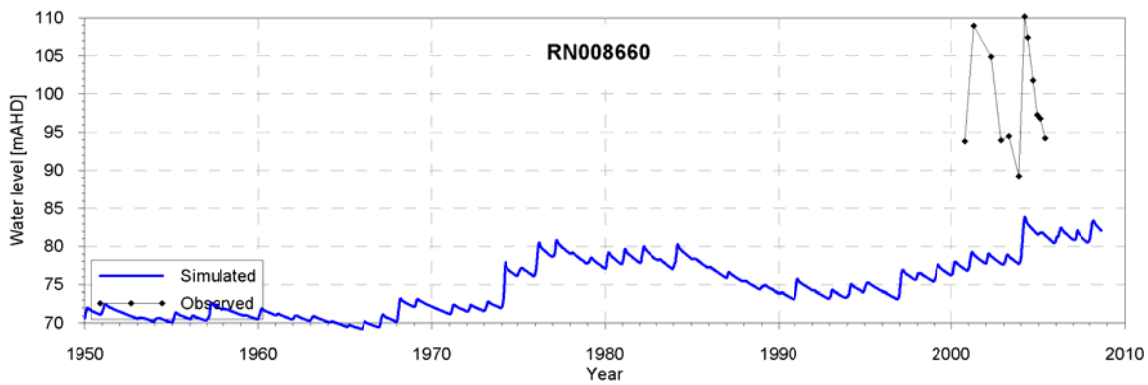
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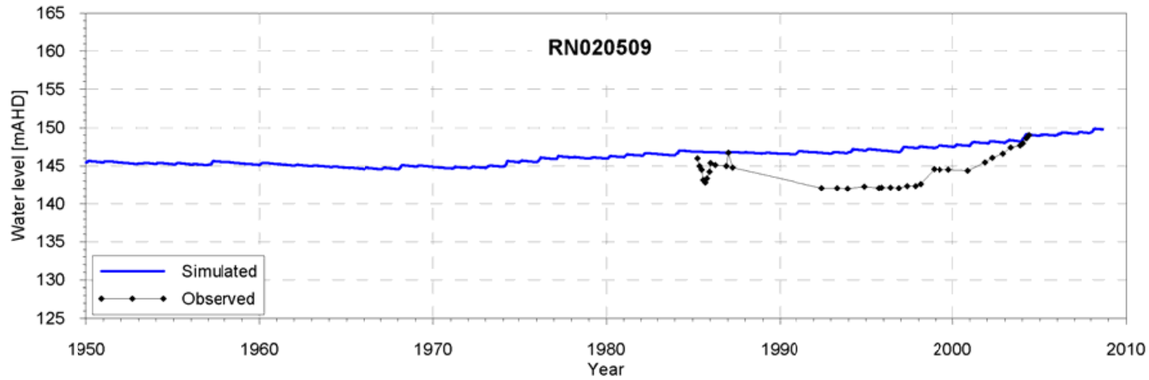
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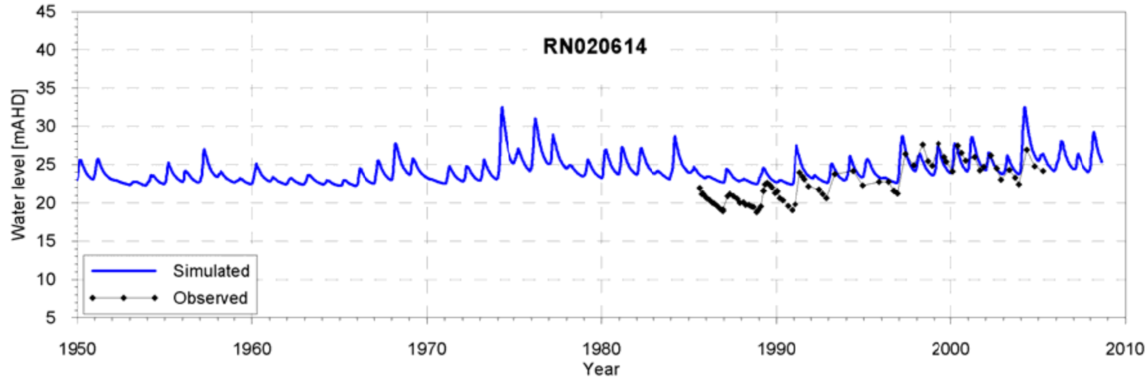
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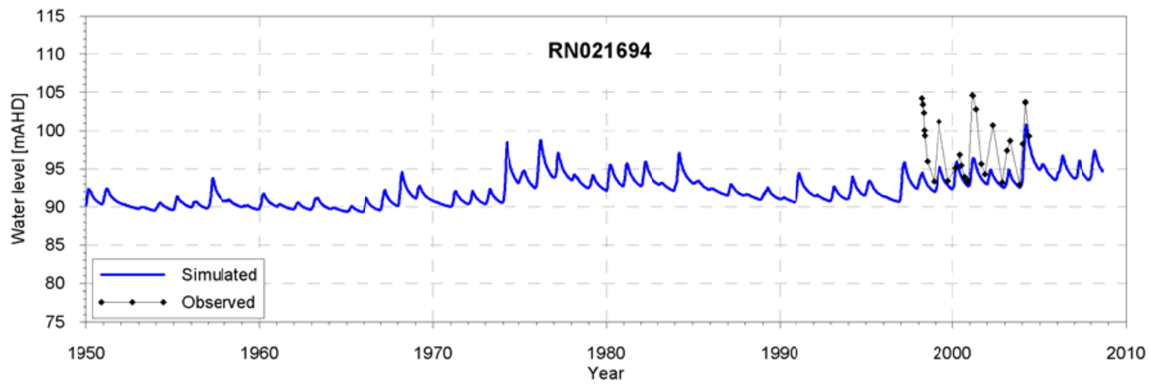
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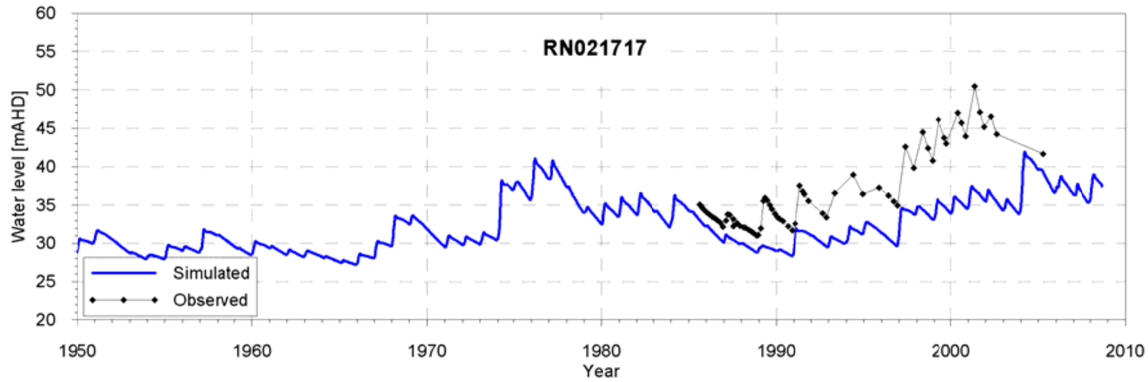
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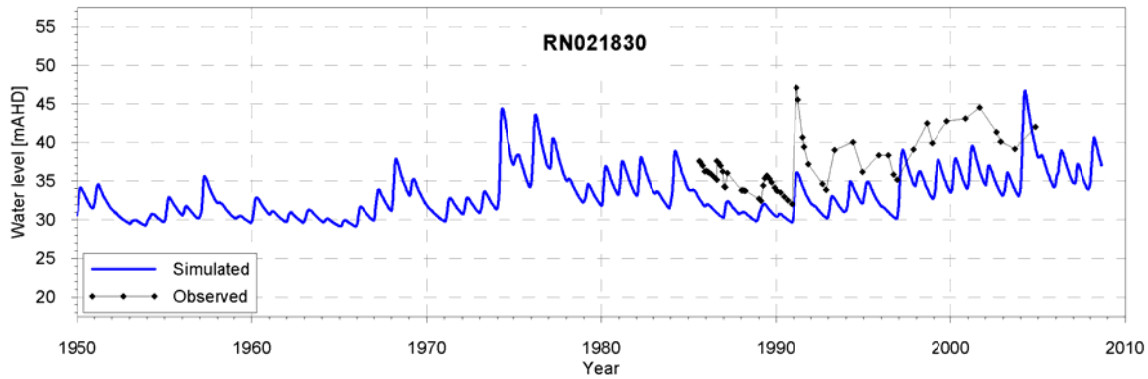
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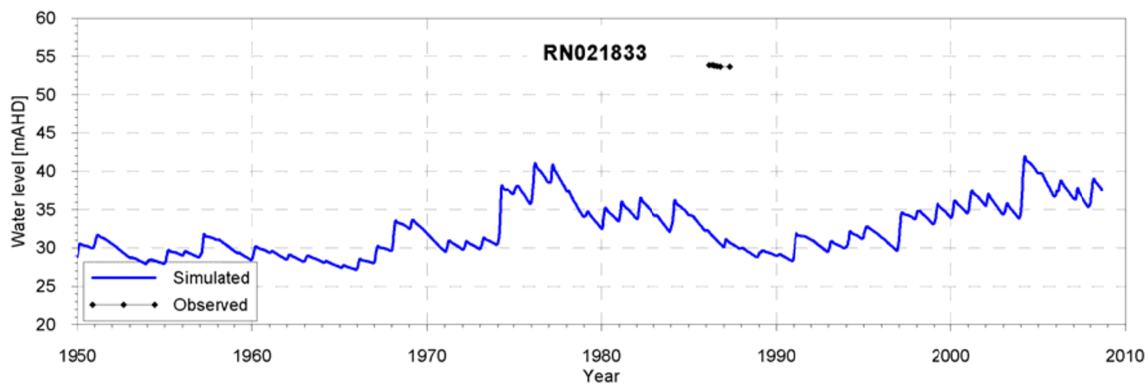
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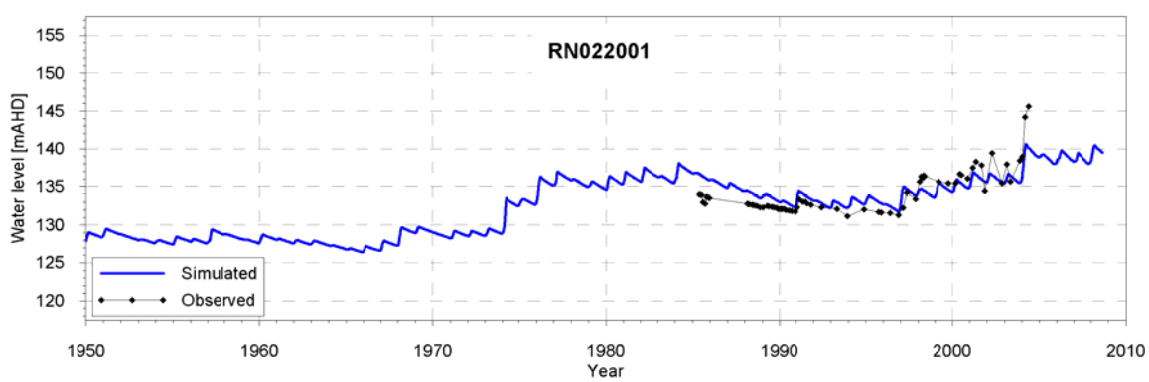
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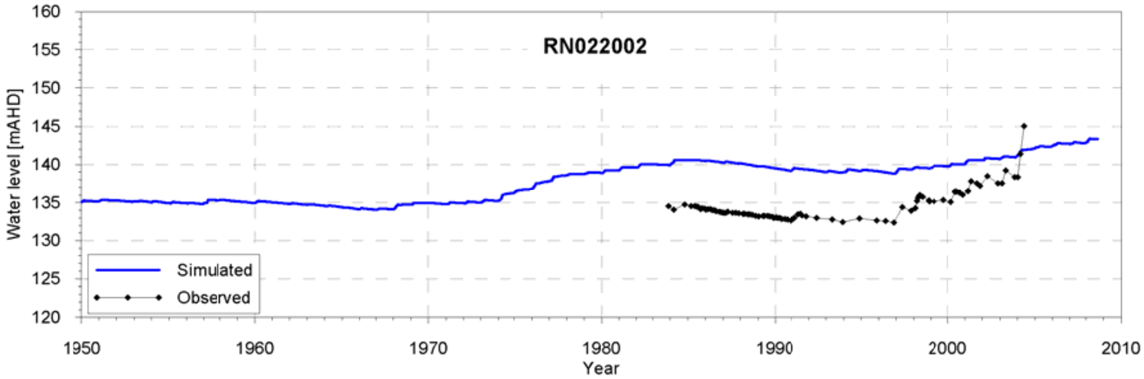
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1980
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2000
2010
Year
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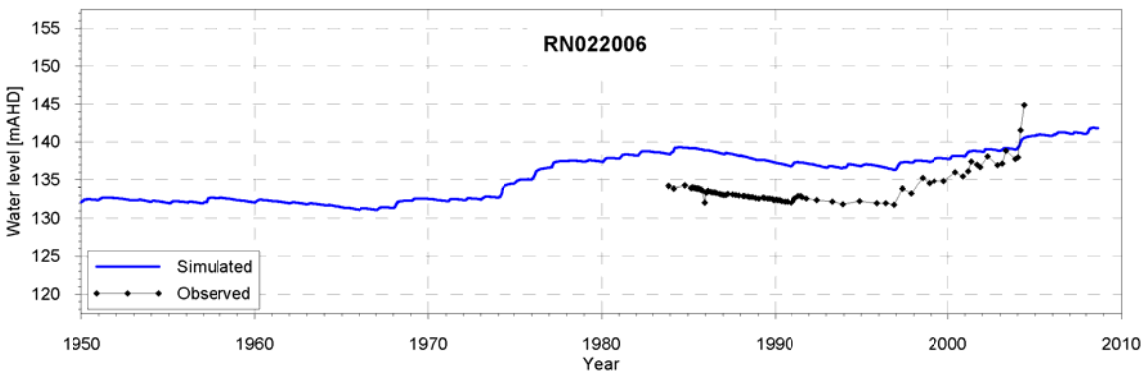
Observed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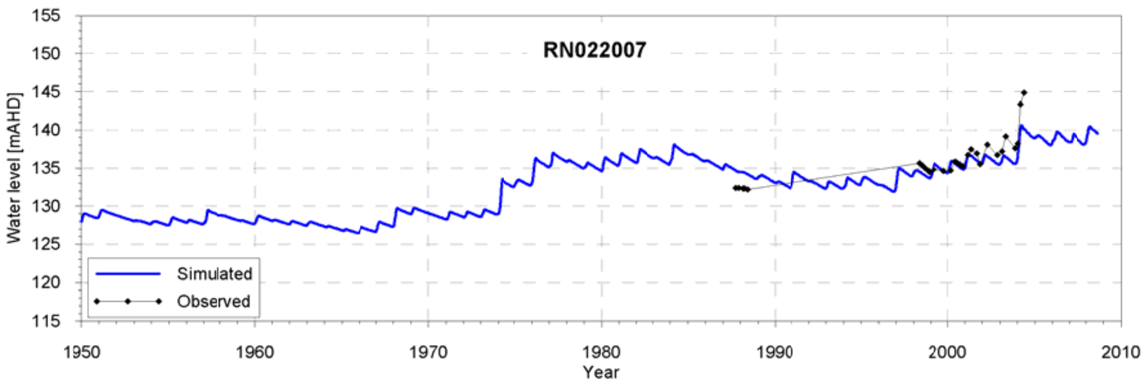
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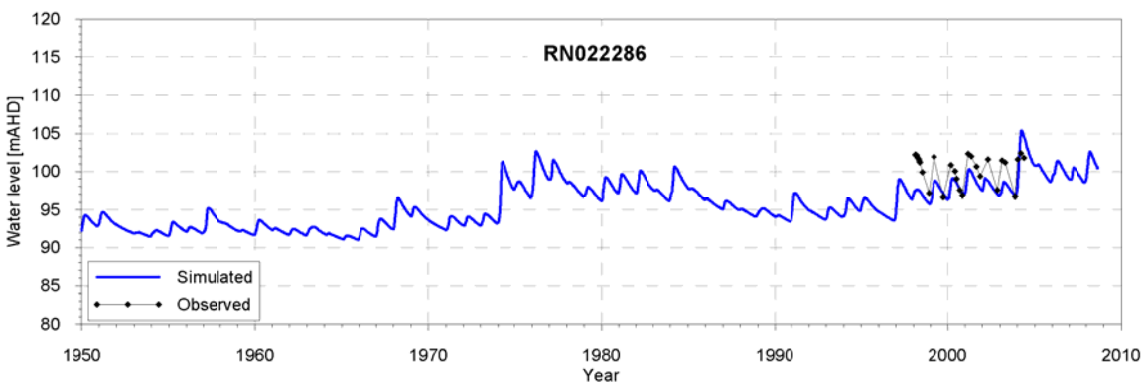
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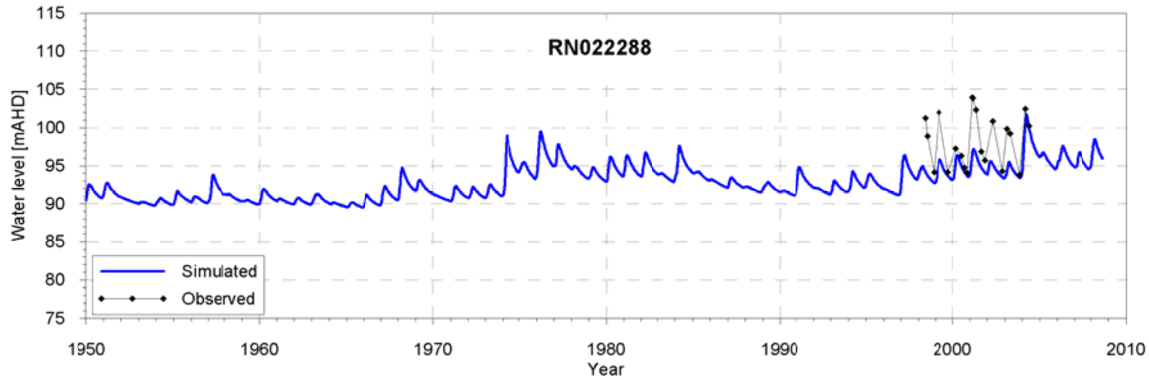
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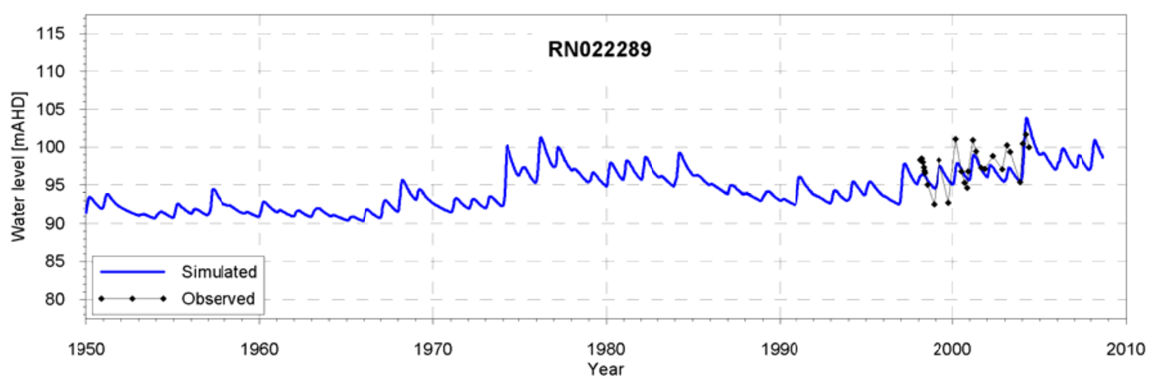
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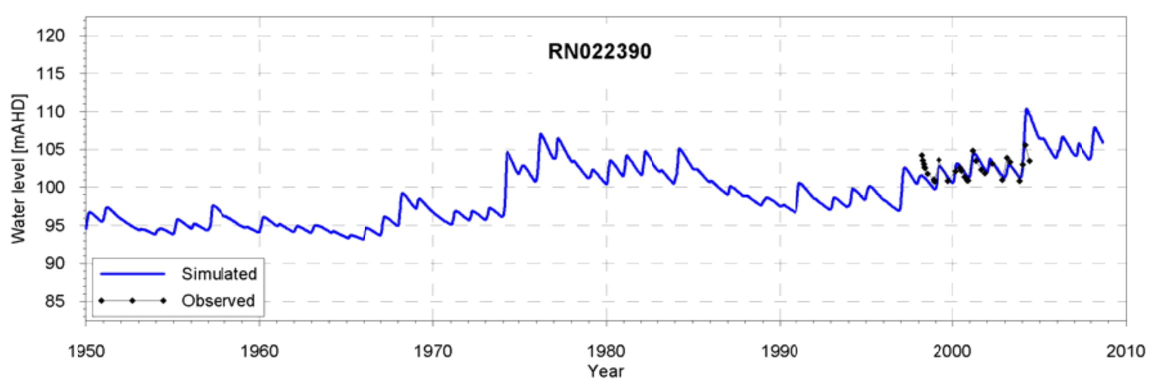
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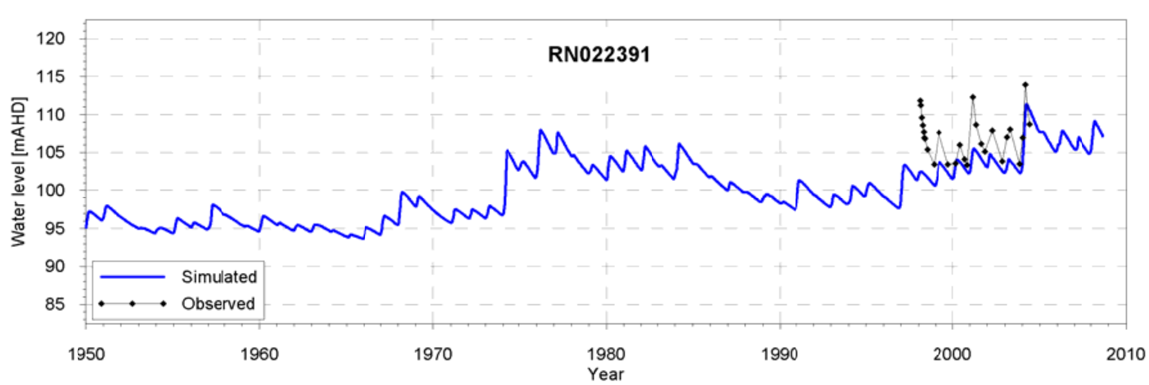
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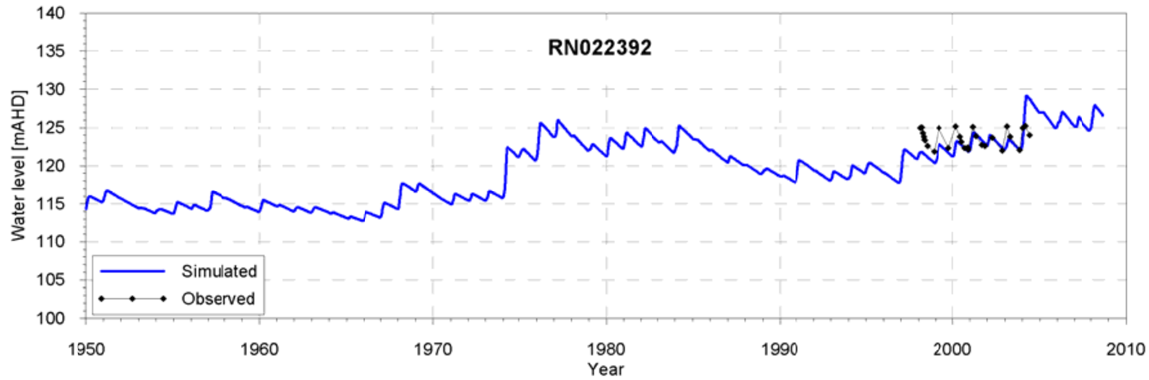
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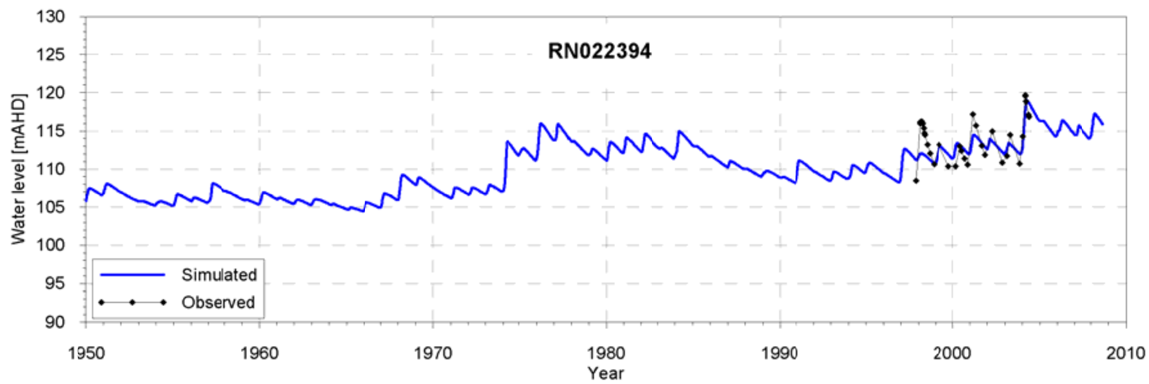
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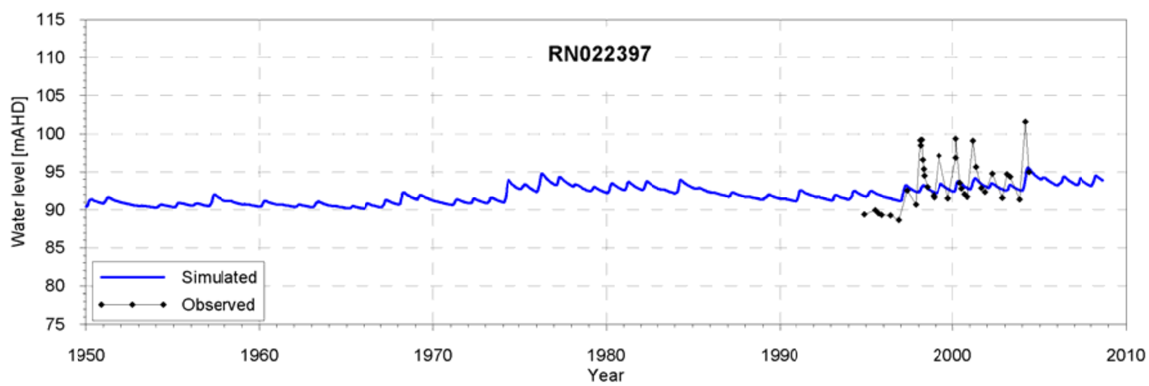
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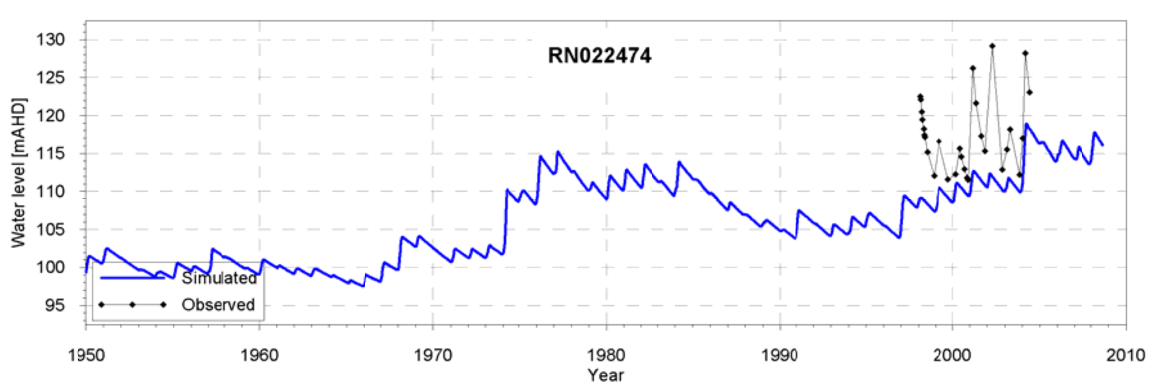
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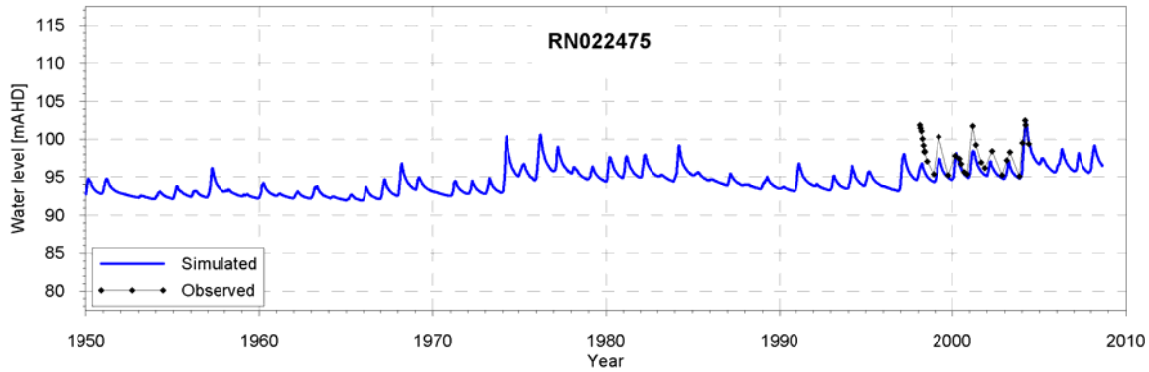
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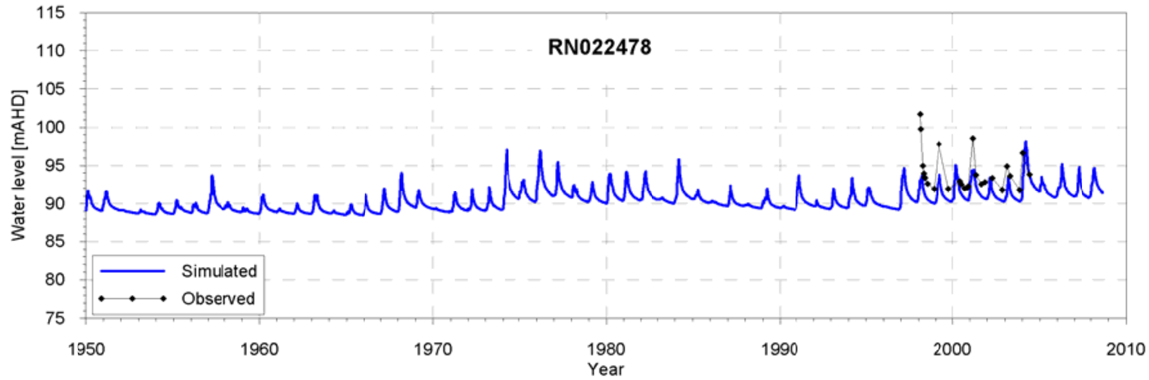
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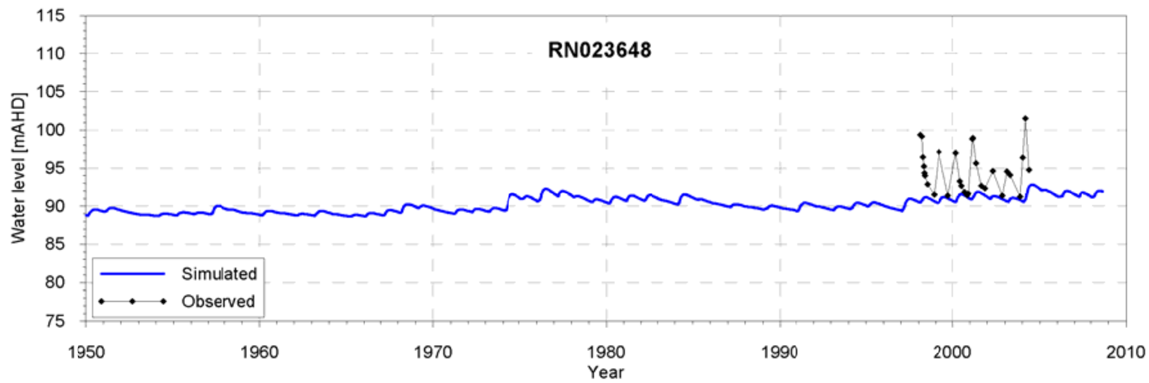
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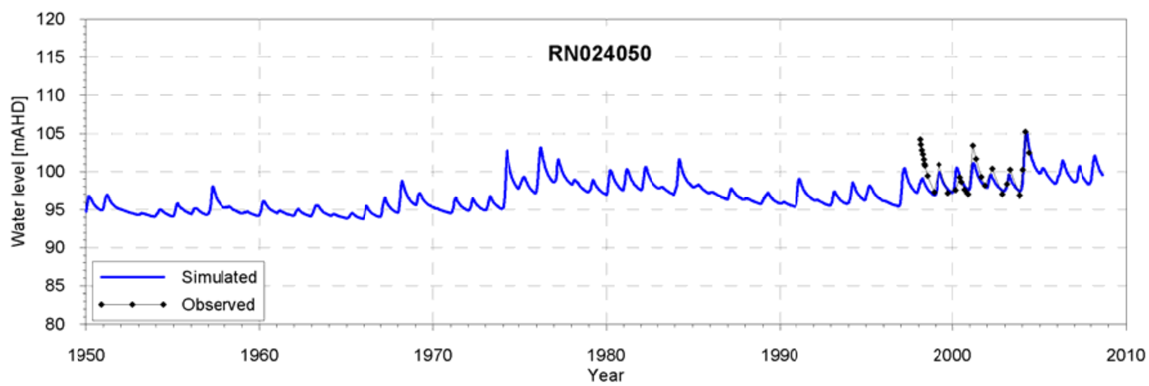
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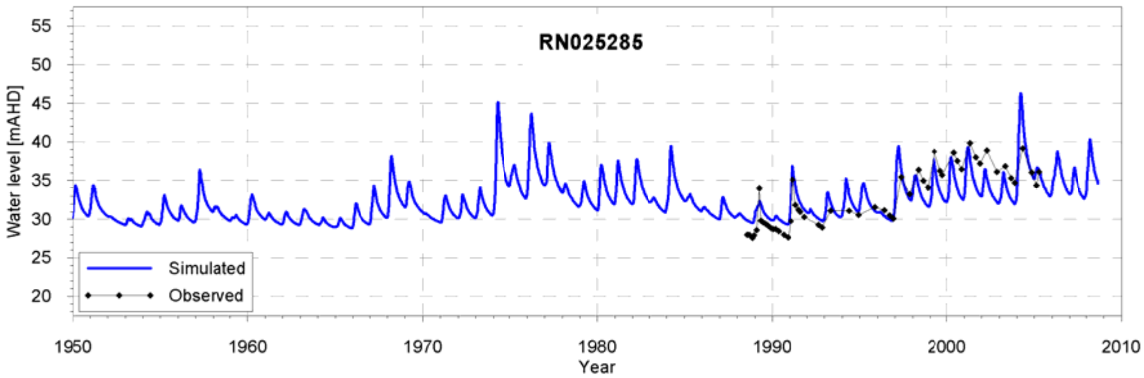
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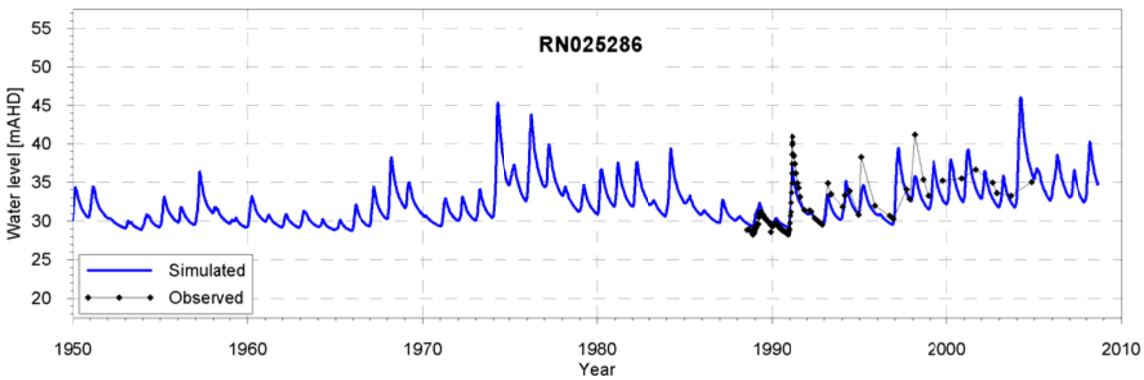
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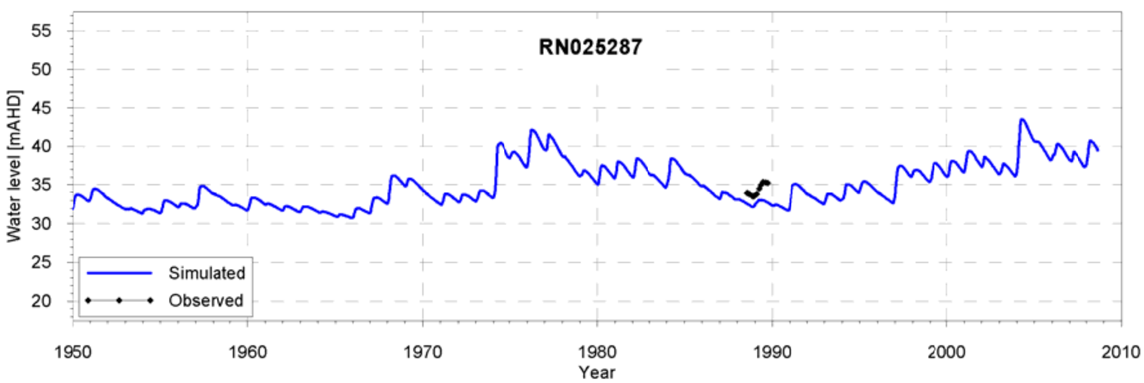
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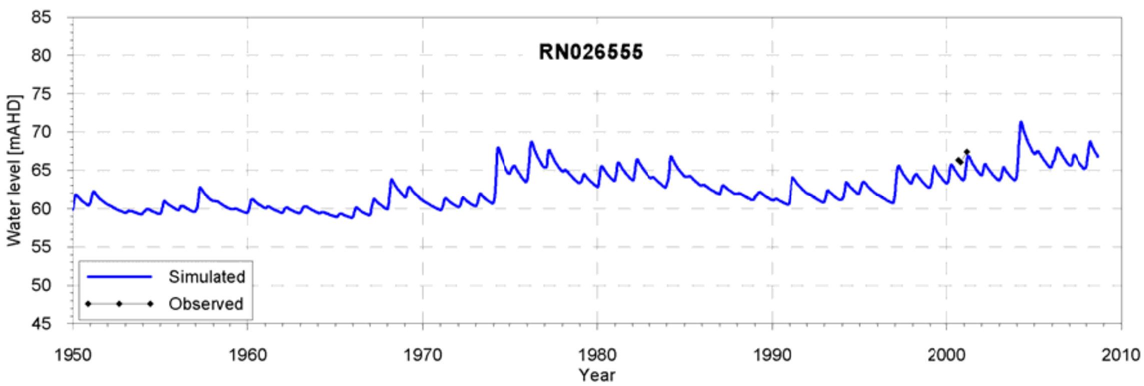
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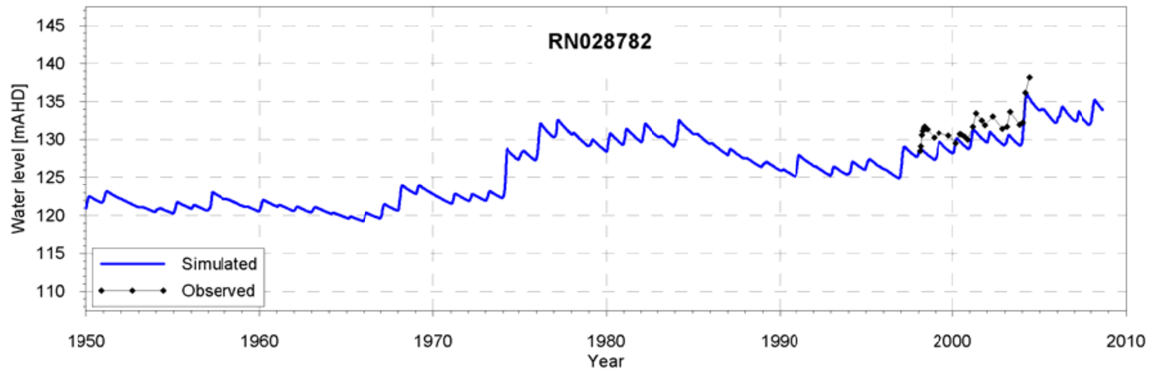
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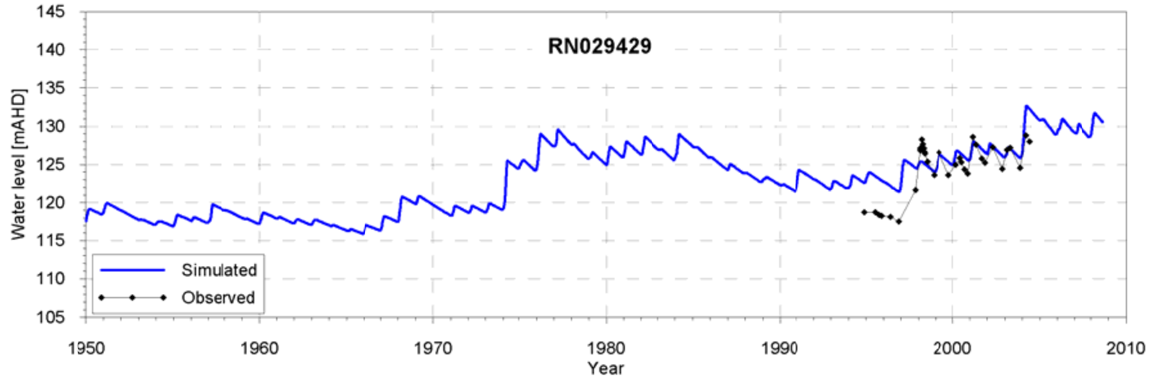
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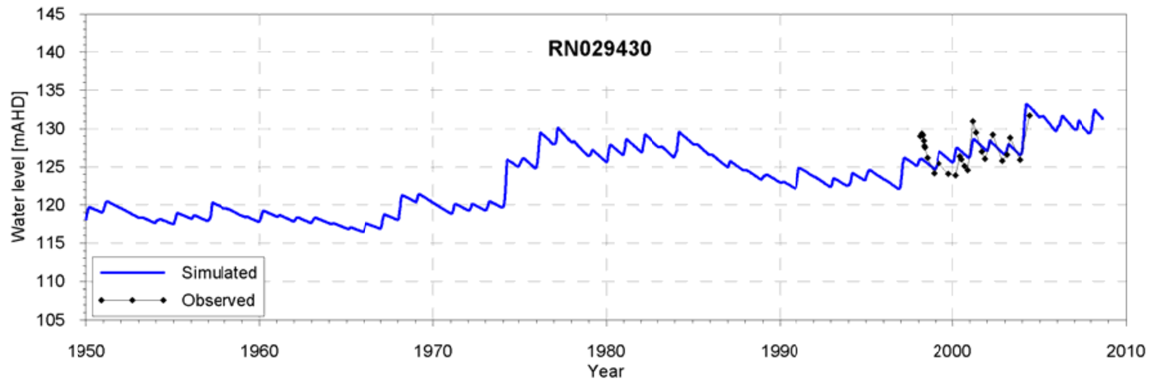
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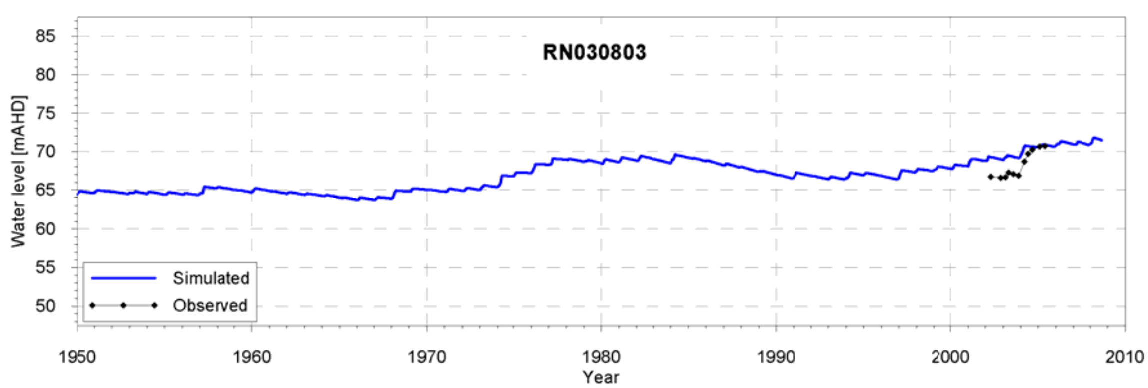
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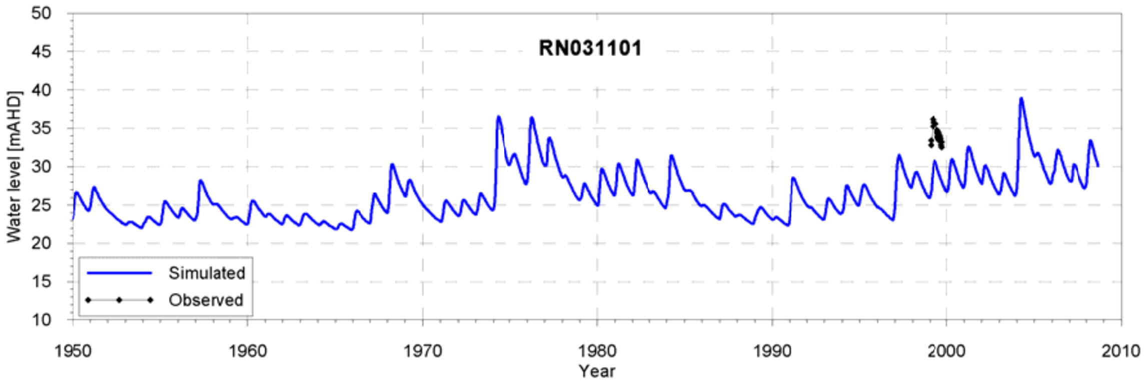
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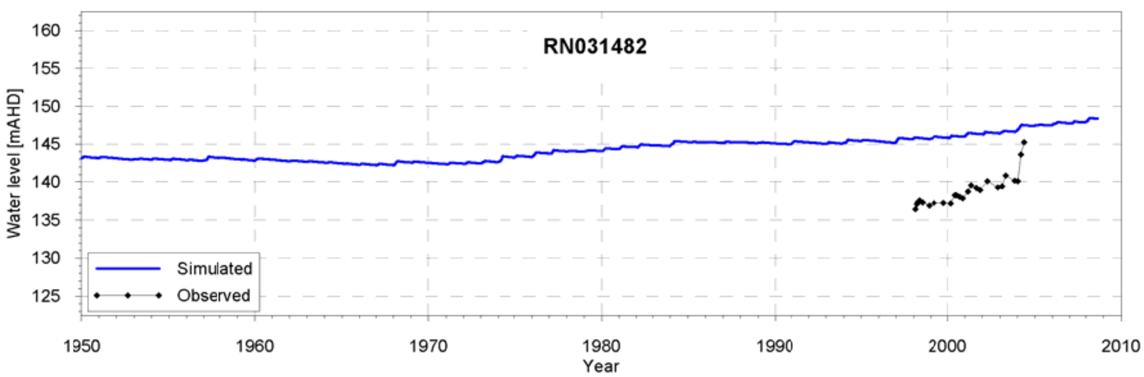
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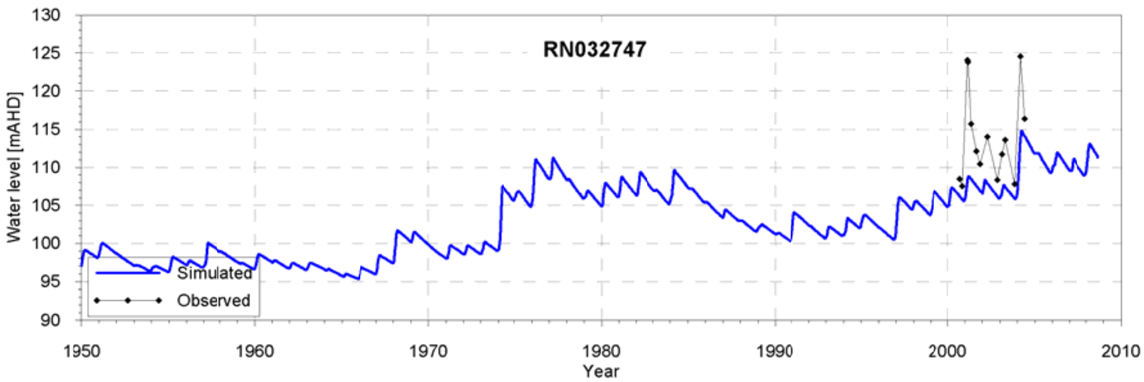
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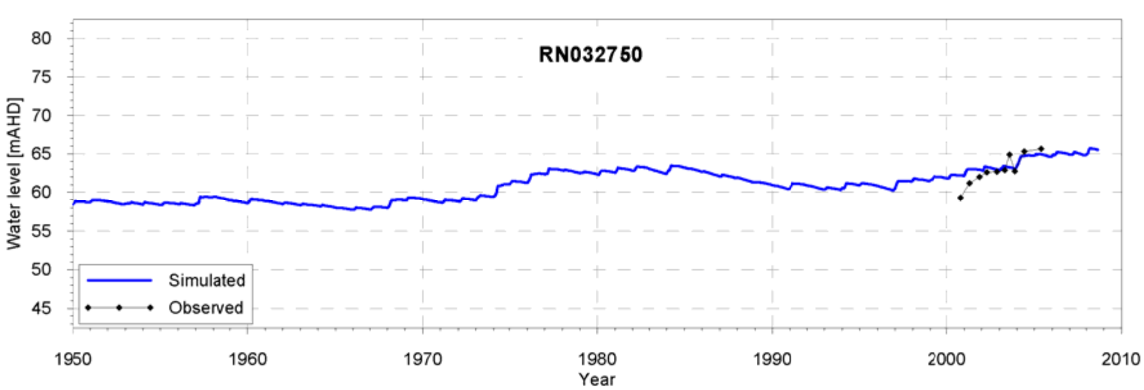
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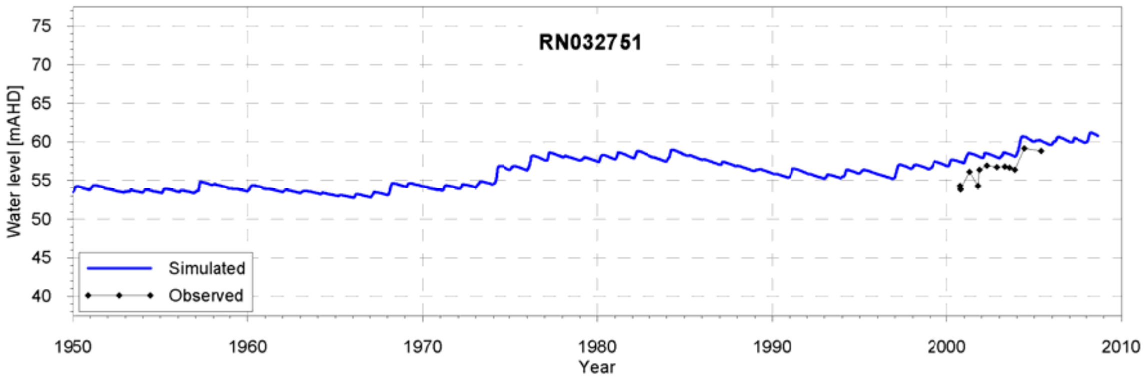
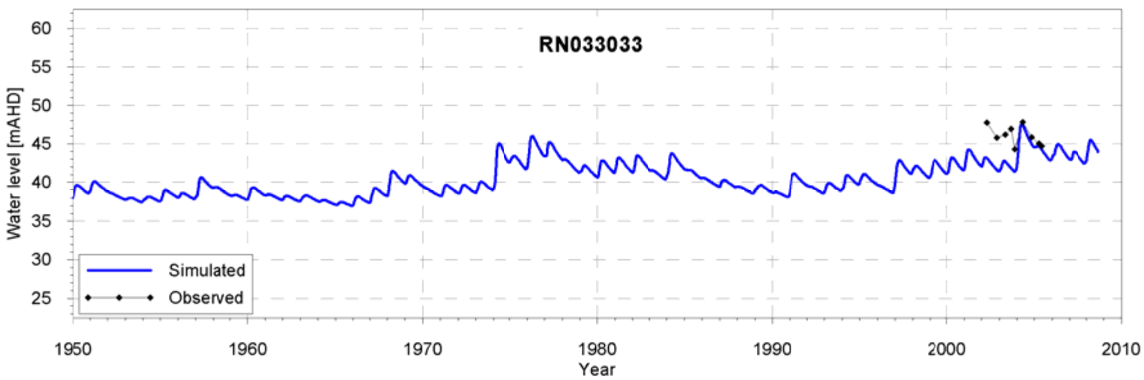
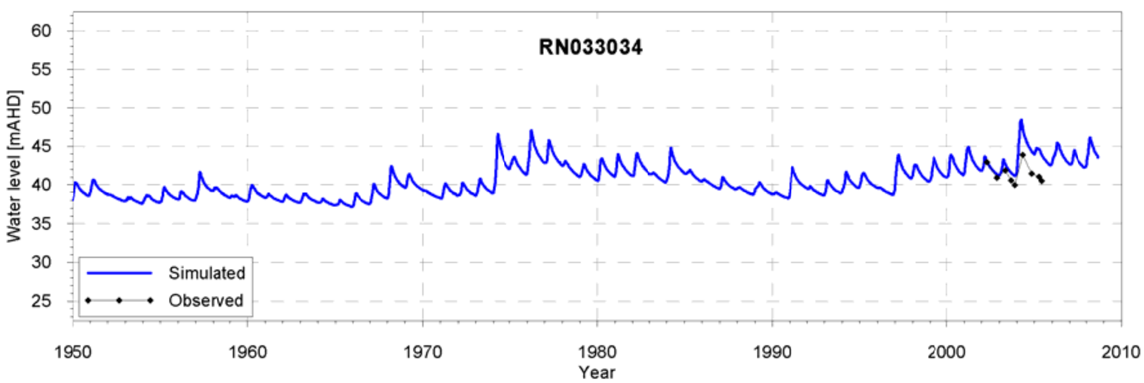
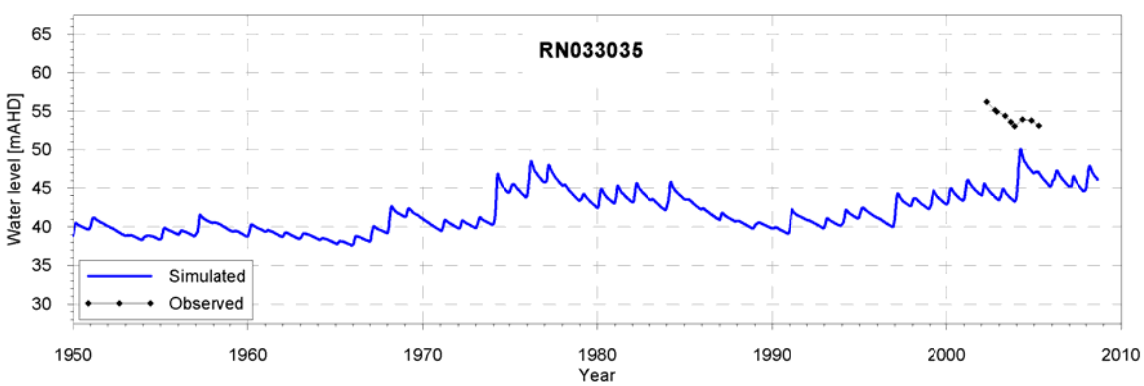
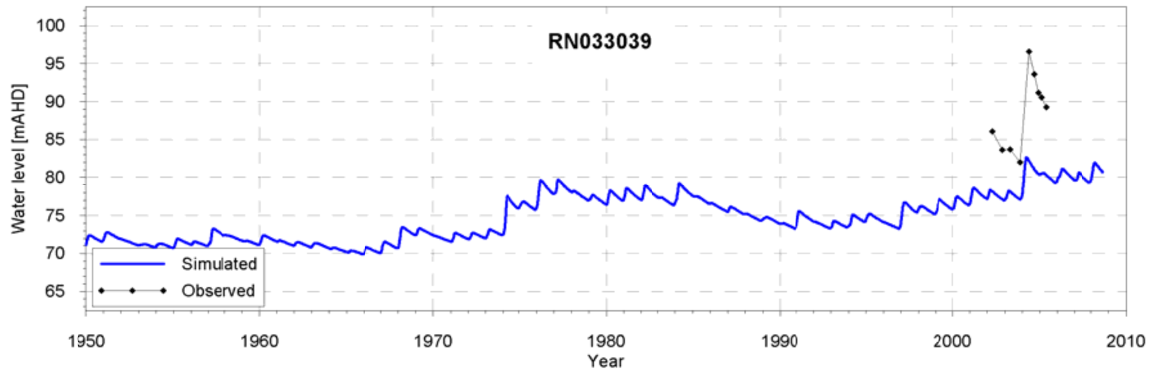
Simulated
Observed


RN032751
Water level [mAHD]
75
70
65
60
55
50
45
40
Simulated
Observed
1950
1960
1970
1980
1990
2000
2010
Year

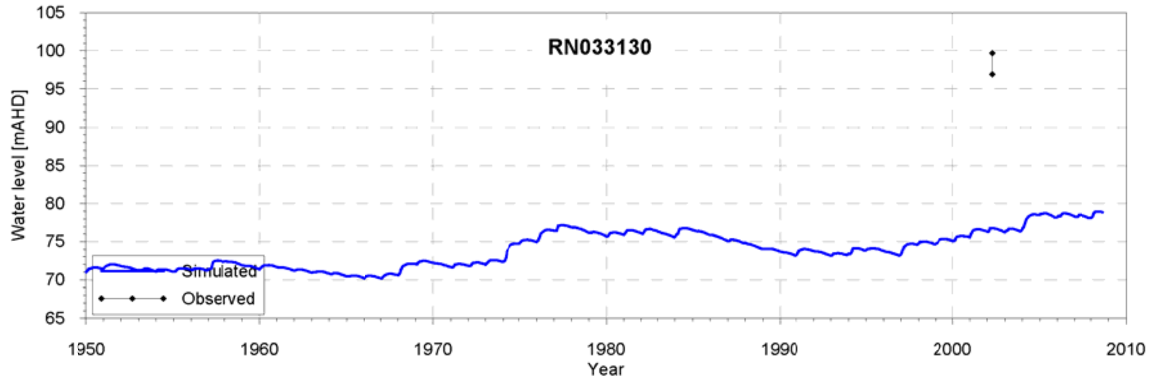

RN033033
Water level [mAHD]
60
55
50
45
40
35
30
25
Simulated
Observed
1950
1960
1970
1980
1990
2000
2010
Year


RN033034
Water level [mAHD]
60
55
50
45
40
35
30
25
Simulated
Observed
1950
1960
1970
1980
1990
2000
2010
Year

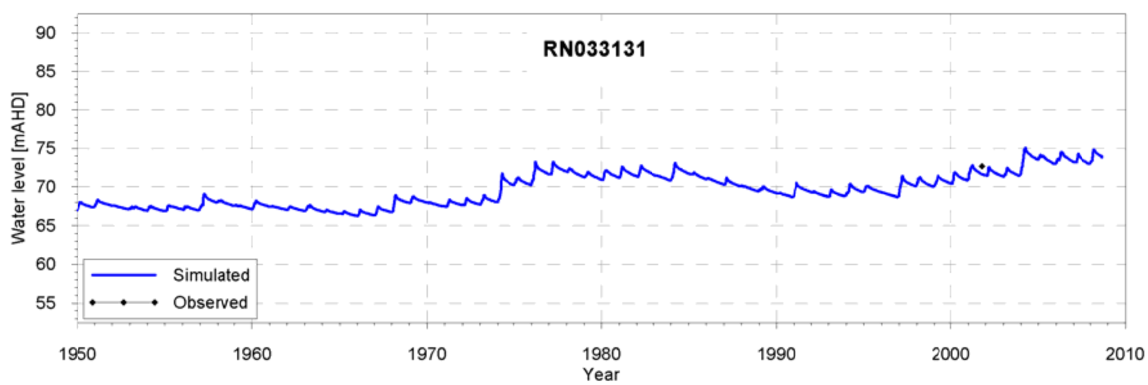

RN033035
Water level [mAHD]
65
60
55
50
45
40
35
30
Simulated
Observed
1950
1960
1970
1980
1990
2000
2010
Year



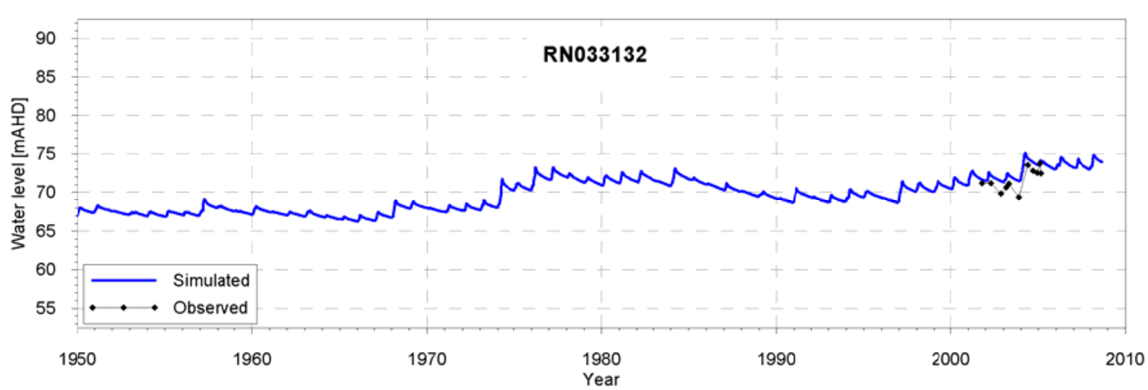
RN033039
Water level [mAHD]
Year
Simulated
Observed



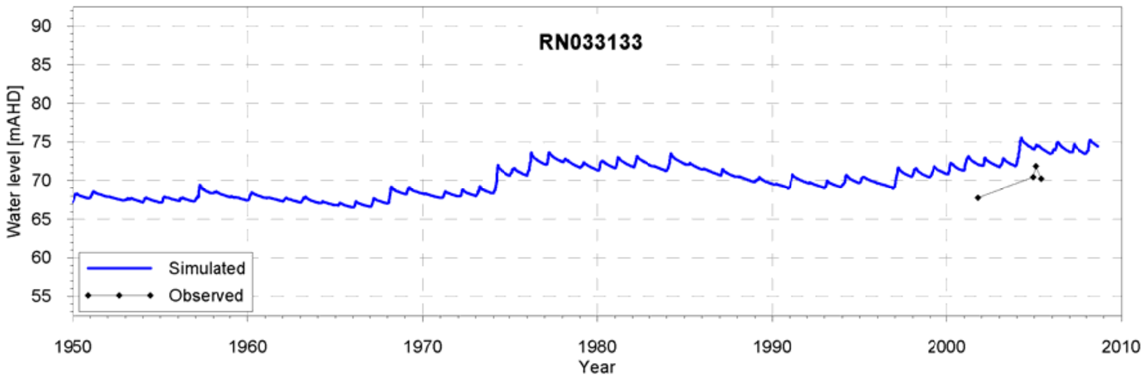
RN033130
Water level [mAHD]
Year
Simulated
Observed

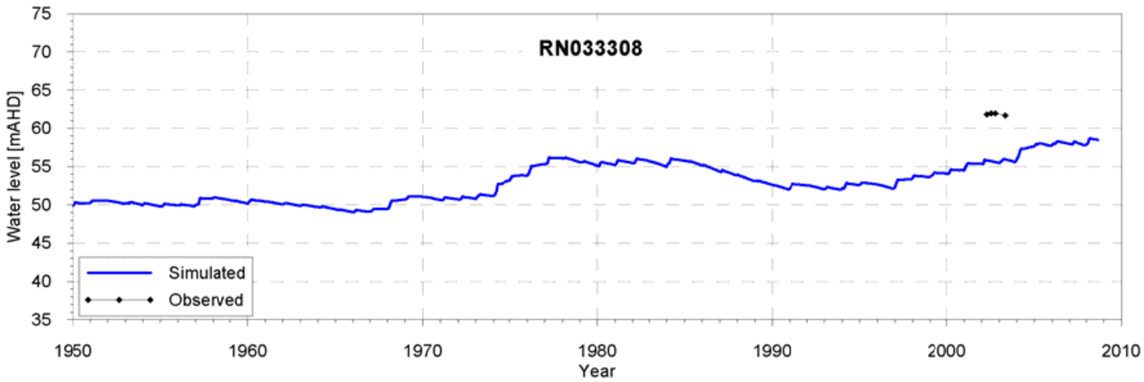


RN033131
Water level [mAHD]
Year
Simulated
Observed

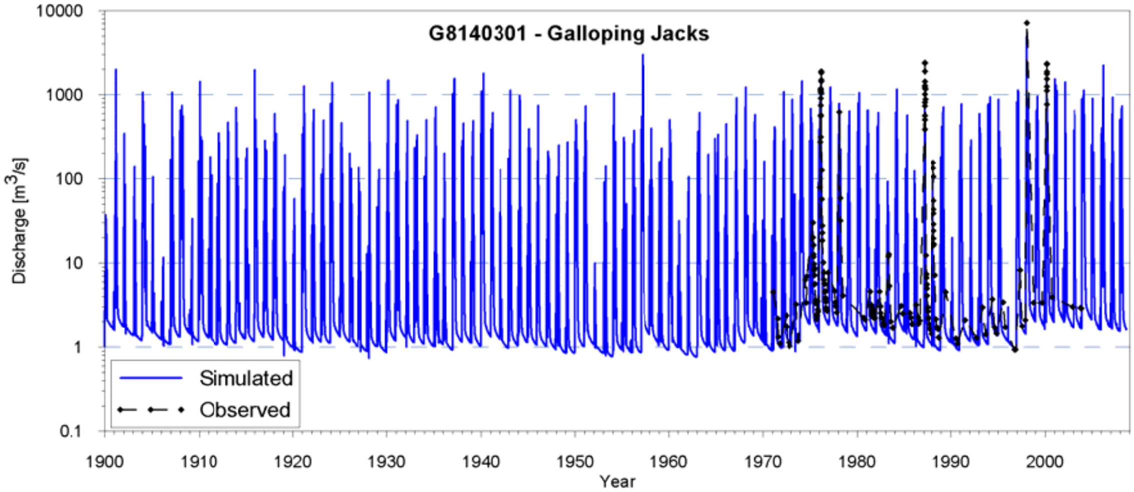


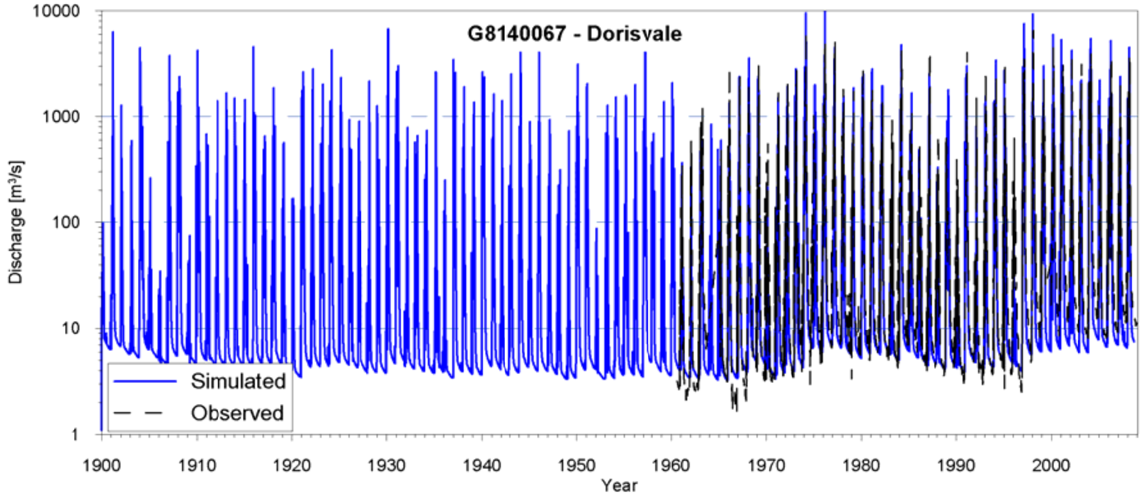
RN033132
Water level [mAHD]
Year
Simulated
Observed

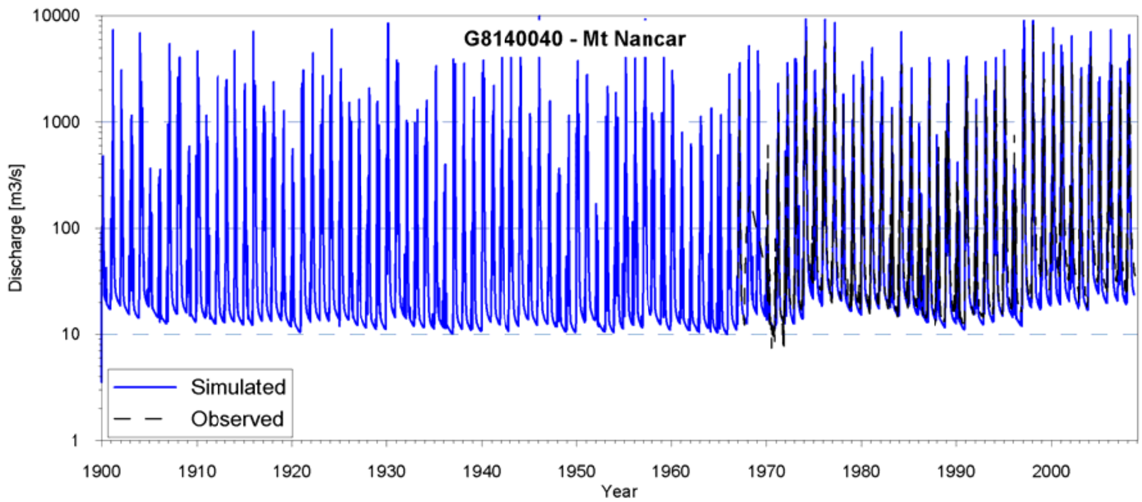

RN033133
Water level [mAHD]
Year
Simulated
Observed
90
85
80
75
70
65
60
55
1950
1960
1970
1980
1990
2000
2010


RN033308
Water level [mAHD]
Year
Simulated
Observed
75
70
65
60
55
50
45
40
35
1950
1960
1970
1980
1990
2000
2010

APPENDIX B – CALIBRATED GROUNWATER DISCHARGES







Northern Territory Government

DEPARTMENT OF
NATURAL RESOURCES, ENVIRONMENT, THE ARTS AND SPORT