Calibration of river models for the Flinders and Gilbert catchments

A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy

Julien Lerat[1], Chas Egan[2], Shaun Kim[1], Matt Gooda[2], Alex Loy[2], Quanxi Shao[3] and Cuan Petheram[1]

[1]CSIRO Land and Water, Canberra
[2]DSITIA, Brisbane
[3]CSIRO CMIS, Perth

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Flinders and Gilbert Agricultural Resource Assessment acknowledgments

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The Strategy was guided by two committees:

(i) the **Program Governance Committee**, which included the individuals David Crombie (GRM International), Scott Spencer (SunWater, during the first part of the Strategy) and Paul Woodhouse (Regional Development Australia) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; and the Queensland Government.

(ii) the **Program Steering Committee**, which included the individual Jack Lake (Independent Expert) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; the Etheridge, Flinders and McKinlay shire councils; Gulf Savannah Development; Mount Isa to Townsville Economic Development Zone; and the Queensland Government.

This report was reviewed by Dr Dushmanta Dutta (CSIRO), Mr Geoff Podger (CSIRO), Dr Peter Stone (CSIRO) and Dr Ian Watson (CSIRO).

Director's foreword

Northern Australia comprises approximately 20% of Australia's land mass but remains relatively undeveloped. It contributes about 2% to the nation's gross domestic product (GDP) and accommodates around 1% of the total Australian population.

Recent focus on the shortage of water and on climate-based threats to food and fibre production in the nation's south have re-directed attention towards the possible use of northern water resources and the development of the agricultural potential in northern Australia. Broad analyses of northern Australia as a whole have indicated that it is capable of supporting significant additional agricultural and pastoral production, based on more intensive use of its land and water resources.

The same analyses also identified that land and water resources across northern Australia were already being used to support a wide range of highly valued cultural, environmental and economic activities. As a consequence, pursuit of new agricultural development opportunities would inevitably affect existing uses and users of land and water resources.

The Flinders and Gilbert catchments in north Queensland have been identified as potential areas for further agricultural development. The Flinders and Gilbert Agricultural Resource Assessment (the Assessment), of which this report is a part, provides a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of agricultural development in these two catchments as part of the North Queensland Irrigated Agricultural Strategy. The Assessment seeks to:

- identify and evaluate water capture and storage options
- identify and test the commercial viability of irrigated agricultural opportunities
- assess potential environmental, social and economic impacts and risks.

By this means it seeks to support deliberation and decisions concerning sustainable regional development.

The Assessment differs from previous assessments of agricultural development or resources in two main ways:

- It has sought to 'join the dots'. Where previous assessments have focused on single development activities or assets – without analysing the interactions between them – this Assessment considers the opportunities presented by the simultaneous pursuit of multiple development activities and assets. By this means, the Assessment uses a whole-of-region (rather than an asset-by-asset) approach to consider development.
- The novel methods developed for the Assessment provide a blueprint for rapidly assessing future land and water developments in northern Australia.

Importantly, the Assessment has been designed to lower the barriers to investment in regional development by:

- explicitly addressing local needs and aspirations
- meeting the needs of governments as they regulate the sustainable and equitable management of public resources with due consideration of environmental and cultural issues
- meeting the due diligence requirements of private investors, by addressing questions of profitability and income reliability at a broad scale.

Most importantly, the Assessment does not recommend one development over another. It provides the reader with a range of possibilities and the information to interpret them, consistent with the reader's values and their aspirations for themselves and the region.

Peter Stone

Dr Peter Stone, Deputy Director, CSIRO Sustainable Agriculture Flagship

The Flinders and Gilbert Agricultural Resource Assessment team

Project Director	Peter Stone
Project Leaders	Cuan Petheram, Ian Watson
Reporting Team	Heinz Buettikofer, Becky Schmidt, Maryam Ahmad, Simon Gallant, Frances Marston, Greg Rinder, Audrey Wallbrink
Project Support	Ruth Palmer, Daniel Aramini, Michael Kehoe, Scott Podger
Communications	Leane Regan, Claire Bobinskas, Dianne Flett[2], Rebecca Jennings
Data Management	Mick Hartcher

Activities

Agricultural productivity	Tony Webster, Brett Cocks, Jo Gentle[6], Dean Jones, Di Mayberry, Perry Poulton, Stephen Yeates, Ainsleigh Wixon
Aquatic and riparian ecology	Damien Burrows[1], Jon Brodie[1], Barry Butler[1], Cassandra James[1], Colette Thomas[1], Nathan Waltham[1]
Climate	Cuan Petheram, Ang Yang
Instream waterholes	David McJannet, Anne Henderson, Jim Wallace[1]
Flood mapping	Dushmanta Dutta, Fazlul Karim, Steve Marvanek, Cate Ticehurst
Geophysics	Tim Munday, Tania Abdat, Kevin Cahill, Aaron Davis
Groundwater	Ian Jolly, Andrew Taylor, Phil Davies, Glenn Harrington, John Knight, David Rassam
Indigenous water values	Marcus Barber, Fenella Atkinson[5], Michele Bird[2], Susan McIntyre-Tamwoy[5]
Water storage	Cuan Petheram, Geoff Eades[2], John Gallant, Paul Harding[3], Ahrim Lee[3], Sylvia Ng[3], Arthur Read, Lee Rogers, Brad Sherman, Kerrie Tomkins, Sanne Voogt[3]
Irrigation infrastructure	John Hornbuckle
Land suitability	Rebecca Bartley, Daniel Brough[3], Charlie Chen, David Clifford, Angela Esterberg[3], Neil Enderlin[3], Lauren Eyres[3], Mark Glover, Linda Gregory, Mike Grundy, Ben Harms[3], Warren Hicks, Joseph Kemei, Jeremy Manders[3], Keith Moody[3], Dave Morrison[3], Seonaid Philip, Bernie Powell[3], Liz Stower, Mark Sugars[3], Mark Thomas, Seija Tuomi, Reanna Willis[3], Peter R Wilson[2]
River modelling	Linda Holz, Julien Lerat, Chas Egan[3], Matthew Gooda[3], Justin Hughes, Shaun Kim, Alex Loy[3], Jean-Michel Perraud, Geoff Podger

Socio-economics	Lisa Brennan McKellar, Neville Crossman, Onil Banerjee, Rosalind Bark, Andrew Higgins, Luis Laredo, Neil MacLeod, Marta Monjardino, Carmel Pollino, Di Prestwidge, Stuart Whitten, Glyn Wittwer[4]

Note: all contributors are affiliated with CSIRO unless indicated otherwise. Activity Leaders are underlined. [1] TropWATER, James Cook University, [2] Independent consultant, [3] Queensland Government, [4] Monash University, [5] Archaeological Heritage Management Solutions, [6]University of Western Sydney

Shortened forms

AEM	airborne electromagnetics
AHD	Australian Height Datum
APSIM	Agricultural Production Systems Simulator
AWRC	Australian Water Resources Council
CGE	Computable General Equilibrium
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	digital elevation model
GCMs	global climate models
GCM-ES	global climate model output empirically scaled to provide catchment-scale variables
IPCC AR4	the Fourth Assessment Report of the Intergovernmental Panel on Climate Change
IQQM	Integrated Quantity-Quality Model – a river systems model
Landsat TM	Landsat Thematic Mapper
MODIS	Moderate Resolution Imaging Spectroradiometer
NQIAS	North Queensland Irrigated Agriculture Strategy
NRM	natural resource management
NSE	Nash-Sutcliffe efficiency
NSELOG	Log Nash-Sutcliffe efficiency
ONA	the Australian Government Office of Northern Australia
OWL	the Open Water Likelihood algorithm
PAWC	plant available water capacity
PE	potential evaporation
RCP	representative concentration pathway
Sacramento	a rainfall-runoff model
SALI	the Soil and Land Information System for Queensland
SLAs	statistical local areas
SRTM	shuttle radar topography mission
TRaCK	Tropical Rivers and Coastal Knowledge Research Hub
WRON	CSIRO’s Water Resource Observation Network
WRP	Water Resource Plan

Units

MEASUREMENT UNITS	DESCRIPTION
GL	gigalitres, 1,000,000,000 litres
keV	kilo-electronvolts
kL	kilolitres, 1000 litres
km	kilometres, 1000 metres
L	Litres
m	Metres
mAHD	metres above Australian Height Datum
MeV	mega-electronvolts
mg	milligrams
MJ/m^2	megajoules per metre square
ML	megalitres, 1,000,000 litres

Preface

The Flinders and Gilbert Agricultural Resource Assessment (the Assessment) aims to provide information so that people can answer questions such as the following in the context of their particular circumstances in the Flinders and Gilbert catchments:

- What soil and water resources are available for irrigated agriculture?
- What are the existing ecological systems, industries, infrastructure and values?
- What are the opportunities for irrigation?
- Is irrigated agriculture economically viable?
- How can the sustainability of irrigated agriculture be maximised?

The questions – and the responses to the questions – are highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports must be read as a whole if they are to reliably inform discussion and decision making on regional development.

The Assessment is producing a series of reports:

- Technical reports present scientific work at a level of detail sufficient for technical and scientific experts to reproduce the work. Each of the 12 research activities (outlined below) has a corresponding technical report.
- Each of the two catchment reports (one for each catchment) synthesises key material from the technical reports, providing well-informed but non-scientific readers with the information required to make decisions about the opportunities, costs and benefits associated with irrigated agriculture.
- Two overview reports – one for each catchment – are provided for a general public audience.
- A factsheet provides key findings for both the Flinders and Gilbert catchments for a general public audience.

All of these reports are available online at <http://www.csiro.au/FGARA>. The website provides readers with a communications suite including factsheets, multimedia content, FAQs, reports and links to other related sites, particularly about other research in northern Australia.

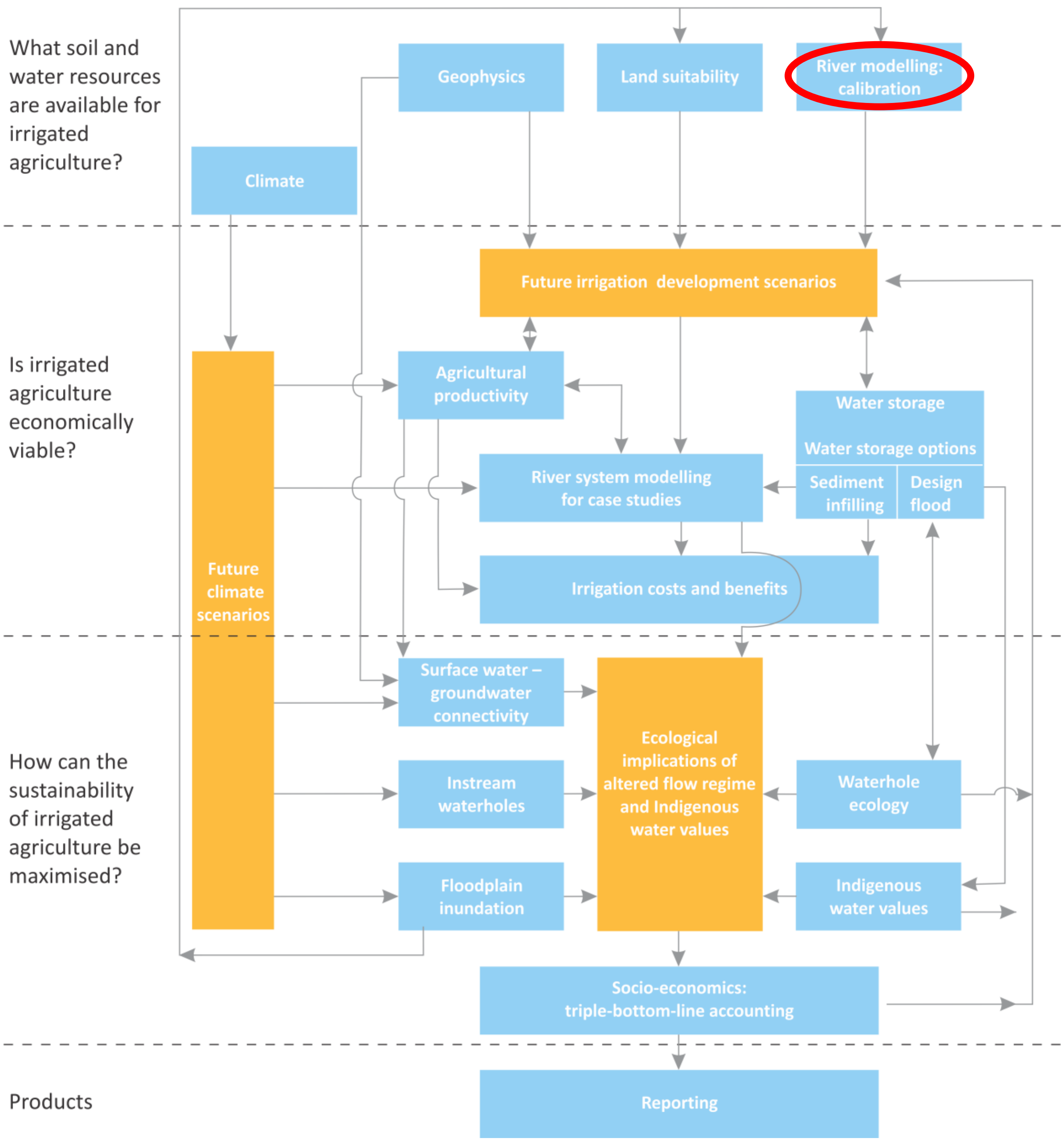
The Assessment is divided into 12 scientific activities, each contributing to a cohesive picture of regional development opportunities, costs and benefits. Preface Figure 1 illustrates the high-level linkages between the 12 activities and the general flow of information in the Assessment. Clicking on an ‘activity box’ links to the relevant technical report.

The Assessment is designed to inform consideration of development, not to enable particular development activities. As such, the Assessment informs – but does not seek to replace – existing planning processes. Importantly, the Assessment does not assume a given regulatory environment. As regulations can change, this will enable the results to be applied to the widest range of uses for the longest possible time frame. Similarly, the Assessment does not assume a static future, but evaluates three distinct scenarios:

- Scenario A – historical climate and current development
- Scenario B – historical climate and future irrigation development
- Scenario C – future climate and current development.

As the primary interest was in evaluating the scale of the opportunity for irrigated agriculture development under the current climate, the future climate scenario (Scenario C) was secondary in importance to scenarios A and B. This balance is reflected in the allocation of resources throughout the Assessment.

The approaches and techniques used in the Assessment have been designed to enable application elsewhere in northern Australia.



Preface Figure 1 Schematic diagram illustrating high-level linkages between the 12 activities (blue boxes)

This report is a technical report. The red oval in Preface Figure 1 indicates the activity (or activities) that contributed to this report.

The orange boxes indicate information used or produced by several activities. The red oval indicates the activity (or activities) that contributed to this technical report. Click on a box associated with an activity for a link to its technical report (or click on 'Technical reports' on <http://www.csiro.au/FGARA> for a list of links to all technical reports). Note that the Water storage activity has multiple technical reports – in this case the separate reports are listed under the activity title. Note also that these reports will be published throughout 2013, and hyperlinks to currently unpublished reports will produce an 'invalid publication' error in the CSIRO Publication Repository.

Executive summary

This report presents the methods for and results of the calibration of two river models developed for the Flinders and Gilbert Agricultural Resource Assessment (the Assessment), which is part of the North Queensland Irrigated Agriculture Strategy (NQIAS). These two models constitute the main tools that will be used in subsequent phases of the Assessment, to investigate the availability and reliability of water supply and to assess downstream perturbations of flow under historical and future climate scenarios and potential development storylines.

One of the key principles of the National Water Initiative (2004) was that water resource planning should be undertaken within a risk analysis framework. Theoretical and technical challenges make this challenging to undertake in an operational environment. This report details a new method of constructing a river system model that enables water resource planning to be undertaken within a risk analysis framework. To enable this, particularly innovative aspects of this study were i) the joint calibration of rainfall-runoff, routing and water loss components; which facilitated ii) an uncertainty analysis based on random perturbation of streamflow data, guided by the uncertainty in the streamflow to stage height relationships. The calibration of the river models was a collaborative effort between CSIRO and the Queensland Government. Based on an agreed calibration method, detailed in this report, the Flinders and Gilbert river system models were calibrated by CSIRO and the Queensland Government respectively.

The specific objectives of this technical report are to:

- Document the hydro-meteorological data used to develop the Assessment river system models for the Flinders and Gilbert catchments.
- Describe the methods by which the Assessment river models for the Flinders and Gilbert catchments were developed and calibrated.
- Document the Assessment river models' configuration and underlying assumptions.
- Assess and report the Assessment's river models' performance.
- Evaluate how much water is in the river at different locations and different times, under the historical climate and current levels of development.

Model set-up and calibration

The configuration of the eWater Source models was initially based on the Flinders and Gilbert Integrated Quantity-Quality Models (IQQM) (DRNM, 2006a and 2006b), which were developed by the Queensland Government to support the preparation of the Gulf Water Resources Plan. The IQQM configuration was subsequently translated into the eWater Source software package. The IQQM and the Source river models were run in parallel to ensure that the model was translated faithfully. Additional model nodes were incorporated in the models developed for the Assessment to improve their spatial resolution in key areas (particularly in the vicinity of potential irrigation areas and dam sites). The increased spatial resolution was desirable because it better captured rainfall gradients, and also allowed a wider range of development scenarios to be examined. Once the Source river models had been reconfigured, they were subsequently recalibrated using gridded SILO climate data (Jeffery et al. 2001) and observed streamflow data according to the agreed set of methods. Although only nine gauging stations are currently open in the Flinders catchment and only six are open in the Gilbert catchment, historical data from 22 and 19 gauging stations were used to calibrate the Flinders and Gilbert river models, respectively.

A split sample calibration method was adopted to quantify the calibration uncertainty. At each gauging station, a period was selected from the observed streamflow data that was thought most likely to be representative of long term streamflow (i.e. based on long term rainfall data). The model was calibrated over this period (calibration mode), using observed inflow data where possible, and then validated against the remaining observed streamflow data (validation mode). The bias, Nash-Sutcliffe efficiency (NSE) and log Nash-Sutcliffe efficiency (NSELOG) were computed under calibration and validation modes to indicate mass balance, high flow and low flow performance respectively. The performance metrics computed over the validation period provide some indication of model performance outside of the observed data period.

Due to the short duration of the observed streamflow record at most stations (less than 20 years), the model was subsequently re-calibrated over the full period of record to ensure that the most robust calibration was attained. Model performance was also assessed over this period.

Model calibrations were undertaken using an automated search algorithm that jointly calibrated rainfall-runoff, routing and loss model parameters. In the Gilbert catchment the search algorithm used an objective function that combined a bias constraint and the mean squared error on root square transform of the flow. In the Flinders catchment the highly ephemeral nature of the streamflow was particularly challenging to simulate and resulted in the use of an alternative objective function that combined a bias constraint, the mean squared error on root square transform of the flow and a constraint on the flow duration curve. The Sacramento model was used as the rainfall-runoff model and was chosen based on comparative assessments in similar catchments and previous use by the Queensland Government. The routing component used a three parameter lag and non-linear hydrologic routing scheme. Losses were modelled based on a two parameter Monod function. The Monod function was chosen based on its representation of loss with flow and because it provided a simplified approximation of the existing IQQM loss relationships. Note that IQQM loss relationships are piecewise monotonically increasing functions of flow. This approach to modelling losses was not adopted as it is not suited to automated calibration.

To better understand the influence of rating curve uncertainty on model calibration, 50 equally plausible streamflow replicates were generated. These replicates were generated using a regression model based on variation in the flow gauging measurements. The model was subsequently calibrated to each of the 50 replicates and results obtained. This innovative approach provides a means of understanding the uncertainty in the model so that modellers can advise whether the model is providing a meaningful answer within the context of the uncertainty that is inherent in the observed streamflow data. There was insufficient time to develop and implement a pragmatic method for assessing the uncertainty in simulated streamflow data as a result of temporally varying uncertainty in rainfall data.

Model performance and uncertainty

River model performance was assessed using a range of bias and Nash-Sutcliffe Efficiency (NSE) performance metrics, as well as visual inspection of the flood hydrographs and analysis of flow exceedance curves. Two additional performance metrics were developed to better assess the river model performance in low flow conditions.

In summary for the Flinders catchment.

- The river model accurately reproduced the mean annual flow at all gauging stations. Long term model bias (i.e. the difference between total observed and modelled flow) was below 5% at 20 stations and below 14% at the two remaining stations.
- When calibrated over the full period of streamflow records, the river model reproduced the historical monthly and annual streamflows well at most stations (NSE > 0.9) and in many cases the models performance was considered excellent (NSE > 0.95).
- The river model simulated large flood events reasonably well upstream of the lower Flinders floodplain area. Within the middle reaches of the lower Flinders floodplain, however, the model was unable to reproduce the shape of the largest flood hydrographs, especially the very large 1974 flood event. This is probably the result of poor quality streamflow data and the simplified representation of the lower floodplain in the river model. To overcome the limitations of depending upon a river model to simulate large flood events on a broad floodplain, a companion technical report on flood modelling (Preface Figure 1) describes the calibration of a hydrodynamic model in the lower Flinders and Gilbert catchments. The hydrodynamic models are complementary to the river models and will be used to assess the implications of perturbations to streamflow as a result of potential development upstream of the floodplain areas.
- The quality of low flow simulations was generally satisfactory with a good match between the observed and simulated flow exceedance curve at all stations. Model performance was less

satisfactory for certain stations when the simulated flow became close to the cease-to-flow conditions (flow below 1ML/d). The error on the frequency of cease-to-flow conditions was greater than 5% at 17 stations and greater than 10% at eight stations out of 22. This result is a consequence of the difficulty that conceptual rainfall-runoff models, which are used to simulate inflows to the river model, have at simulating high evaporation losses near cease-to-flow conditions. Hence, the river model may not be a robust tool for assessing how potential climate and development scenarios may perturb very low flow regimes.

- The uncertainty analysis further highlighted the large uncertainty associated with high flow in the lower parts of the Flinders catchment. The uncertainty range on simulated mean annual flows varied from ± 3% to ±29% of the flow at a 95% confidence level. This uncertainty range will provide a basis against which to compare the impact of potential climate and development scenarios on modelled flow. The impact of potential climate and development scenarios will be considered significant if they exceed a value greater than the model uncertainty range. This work is described in a companion technical report on river modelling climate and development scenarios (Preface Figure 1).
- When calibrated over half of the streamflow records (split-sample calibration), the average absolute bias in calibration mode across all reaches was 2.5%, the average NSE was 0.67 and the average NSELOG was 0.48. Under validation mode the average absolute bias was 24%, the average NSE was 0.37 and the average NSELOG was 0.5. Across individual reaches the bias under validation mode varied from 3.2% to 97%, NSE varied from of -0.8 to 0.77 and the NSELOG varied from 0.1 to 0.75.

In summary for the Gilbert catchment.

- The river model accurately reproduced the mean annual flow at all gauging stations. Long term model bias (i.e. the difference between total observed and modelled flow) was below 5% at 15 stations and below 9% at the three remaining stations.
- The river model reproduced the historical monthly and annual streamflows well at most stations (NSE > 0.9) and in many cases the models performance was considered excellent (NSE > 0.95). The four stations for which the model performed poorest (i.e. daily NSE between 0.53 and 0.68) were all gauged small headwater catchments. Since runoff in small headwater catchments is sensitive to localised rainfall, erroneous rainfall input data is one plausible explanation for the lower NSE scores recorded at these stations.
- The model generally performed better in the Einasleigh subcatchment than the Gilbert subcatchment. This is thought to be due to conceptual rainfall-runoff models generally performing better in wetter conditions and perennial rivers.
- Difficulties similar to the Flinders model were encountered in the simulation of low flow regimes. The model showed a tendency to overestimate low flows and the frequency of cease-to-flow conditions. Similarly to the Flinders model, the Gilbert model may not be suitable to analyse the impact of management scenarios on very low flow regimes.
- When calibrated over half of the streamflow records (split-sample calibration), the average absolute bias in validation mode was 14%, average NSE was 0.67 and the average NSELOG was 0.49. Across individual reaches the bias under validation mode varied from 0% to 38%, NSE varied from of -0.1 to 0.92 and the NSELOG varied from -0.26 to 0.84.

Water resources assessment

To assess the resources in the Flinders and Gilbert regions the models were run over the historical period of 1/7/1890 to 30/6/2011. In summary:

- The mean and median annual runoff spatially averaged across the Flinders catchment was 35 mm and 22 mm respectively. The mean and median annual runoff spatially averaged across the Gilbert catchment was 140 mm and 100 mm respectively.
- In the Flinders catchment the 20th and 80th percentile annual exceedance runoff was 52 mm and 7 mm respectively. In the Gilbert catchment the 20th and 80th percentile annual exceedance runoff was 196 mm and 47 mm respectively.

- The percentage of runoff occurring in the wet season in the Flinders and Gilbert catchments was 95% and 98% respectively.
- For the Flinders catchment, the mean annual flow in the Flinders River at Walker's Bend (gauging station 915003A - located 80 km upstream of the river mouth) was found to be 2543 GL/year with uncertainty bounds ranging from 2415 GL/year to 2685 GL/year at a 95% confidence level. The mean annual flow at Richmond (gauging station 915008A) was computed to be 405 GL/year with uncertainty bounds ranging from 377 GL/year to 414 GL/year at a 95% confidence level.
- For the Gilbert catchment, the mean annual flow at the most downstream gauging station (i.e. 917009A, Miranda Downs) was found to be 3719 GL/year with uncertainty bounds ranging from 3361 GL/year to 3927 GL/year at a 95% confidence level. The mean annual flow on the Einasleigh River at Minnie's Dip (gauging station 917111A) was found to be 2545 GL/year with uncertainty bounds ranging from 2448 GL/year to 2734 GL/year at a 95% confidence level.
- Under a full use of existing entitlements, the use of water relative to the mean annual flow at the outlet of the Flinders and Gilbert catchments is 3.5% and 1%, respectively.

A companion technical report on river modelling under climate and development scenarios (Preface Figure 1), will use the Assessment river models described in this report to examine how much water can be used under different climate, development and regulatory conditions and will assess the impact of climate scenarios and potential development storylines on modelled streamflow. A companion technical report on aquatic ecology (Preface Figure 1) will then describe how perturbations to modelled streamflow under climate scenarios and potential development storylines may impact in-stream, riparian and near shore ecology.

Comparison of Assessment and IQQM-NASY river models

The IQQM-NASY is identical to the IQQM model used to support the Gulf Water Resource Plan (WRP) except that the simulation period was extended up to 2008. The calibration methods adopted in this report and those used by the Queensland Government for IQQM-NASY (referred to as IQQM hereafter) are similar in terms of the rainfall-runoff and routing models used, but differ in terms of loss function, spatial resolution of the model, climate input data, calibration period and calibration method. As a result, the two models provide different estimates of the long-term mean annual flows. The differences were found significant for some stations in the Flinders catchment. For example, Petheram et al. (2009), based on the IQQM model and the reporting period 1930-2007, reported a mean annual flow at Walker's Bend of 1938 GL/y whereas the same flow is estimated to be 2543 GL/y in this report.

Detailed analysis was undertaken for the Flinders River model in order to explain these differences. The analysis compared several variants of the Assessment river model reproducing one or a combination of the IQQM set-ups including the use of the same calibration period, the same climate input data and similar loss functions. The analysis concluded that:

- The main factor explaining the difference between the two models is the use of different climate input data. The IQQM potential evaporation derived from point pan evaporation is considerably higher than the one used for the Assessment based on gridded Morton's wet environment areal potential evaporation. In addition, the data used for the Assessment showed a more consistent inter-annual variability across the reporting period.
- At Walker's Bend, the extension of the calibration period from 1970-2003 (IQQM) to 1970-2011 (Assessment) had a surprisingly large impact on model calibration parameters. This result was explained by the major flood that occurred in 2009 in the Gulf region that was captured by the Assessment calibration but not in the IQQM calibration.
- Both models obtained similar performance regarding bias and low flows (estimated with the NSE statistic computed on log-transformed flows) when comparing simulated and observed flow data.
- The Assessment river model performed better for the high flow regime as indicated by higher values of the NSE statistic.

Overall, the difference between the IQQM and Assessment river models was explained by the use of more recent data (potential evaporation and streamflow data) and the implementation of an automatic calibration method, which led to model improvement for the simulation of the high flow regime.

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1 Introduction

Access to reliable sources of water is a key factor in the development of irrigated agriculture in semi-arid environments. Hence the quantification of water resources and their variability is a core component of the Flinders and Gilbert Agricultural Resources Assessment (the Assessment). Previous studies (Petheram et al., 2009) have shown that large volumes of water (> 2000 GL/year) occur in both catchments. However, the spatial distribution of water within the catchments and their inter-annual and within-year variability imposes constraints on the availability of water and is an important consideration in the design of water storages and irrigation schemes. To better understand these opportunities and constraints this report describes a robust framework under which climate and potential development scenarios can be evaluated. At the heart of this framework are hydrological models, referred to as river models, that can simulate the spatial distribution of the water resources within a regulated river system. These models can simulate natural hydrological processes, including runoff generation, flow routing (i.e. the timing and attenuation of flow along a river reach), river reach evaporation and transmission losses. They are also capable of incorporating the effects on water flows of dams and weirs, extractions, diversions, irrigation return flows and complex operating rules and environmental flow conditions. In the context of the Assessment, river models can be used to help answer the following questions:

- How much water is in the river at different locations and different times, under the historical climate and current levels of development?
- How much water is available and at what reliability of supply for irrigated agriculture at different locations and different times, under current and future climate and potential development scenarios?
- How might potential development scenarios be optimised to maximise economic return?
- How may streamflow change downstream of potential development if the development went ahead?

The first step to answering these questions is to develop the river models. The method by which these models were developed is detailed in this report and an assessment of the models' performance is provided. In assessing the river models' performance, answers are also provided to the first of the above questions "How much water is in the river at different locations and different times, under the historical climate and current levels of development?" The remaining questions will be addressed in the companion technical report on river modelling: modelling under climate and development scenarios (Preface Figure 1).

Specifically the objectives of this report are to:

- Document the hydro-meteorological data used to develop the river system models for the Flinders and Gilbert catchments.
- Describe the methods by which river models for the Flinders and Gilbert catchments were developed and calibrated.
- Document the model configuration and underlying assumptions.
- Assess and report the models' performance.
- Evaluate how much water is in the river at different locations and different times, under the historical climate and current levels of development.

The calibration of the Flinders and Gilbert river models was a collaborative effort between CSIRO and the Queensland Government. After agreeing on a consistent calibration method, CSIRO calibrated the Flinders catchment river model and the Queensland Government calibrated the Gilbert catchment river model.

The remainder of the report is structured as follows. The model configuration and calibration methods are presented in Section 2. Section 3 describes the calibration of the Flinders model. Section 4 describes the calibration of the Gilbert model. Conclusions are presented in Section 5.

2 Method

This section describes the methods that were agreed between CSIRO and Queensland government to build and calibrate the river system models for the Flinders and Gilbert catchments. The summary statistics that are used in this report are presented in section 2.1. The components of the model are detailed in Section 2.2. Section 2.3 describes the calibration procedure, Section 2.4 describes metrics used for assessing model performance and Section 2.5 details the uncertainty analysis.

2.1 Expressing uncertainty in observed and modelled variables

River models consume and produce a large amount of data that need to be summarised by statistics. Assuming that a variable v takes n values $(v_1, v_2, \dots, v_n)$, the statistics that may be reported in this document are:

- The mean defined as

$$M = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (1)$$

- The exceedance percentiles computed from sorted values of v denoted $(v_1{}^*, v_2{}^*, \dots, v_n{}^*)$. For a given frequency $u < 1$ (say 5%), the corresponding exceedance percentile P is given by

$$P(u) = v^*{}_{(1-u)(n+1)} \quad (2)$$

  Note that the percentiles reported here are *exceedance* percentiles that decrease with u.

  When the sample size n is small, the quantity $(1-u)(n+1)$ cannot be approximated by an integer. In this case, the following interpolation is performed:

$$k_1 = \lfloor (1-u)(n+1) \rfloor \quad (3)$$

$$k_2 = k_1 + 1 \quad (4)$$

$$a = k_2 - (1-u)(n+1) \quad (5)$$

$$P(u) = a\, v^*{}_{k_1} + (1-a)\, v^*{}_{k_2} \quad (6)$$

Where $\lfloor (1-u)(n+1) \rfloor$ is the integer part of $(1-u)(n+1)$. In this case, u is always chosen so that k1>0 and k2<n+1, in other words, no percentiles can be reported outside of the range of v.

Two percentiles can be used to define a range with a given confidence level c (e.g. 95%) according to

$$R(c) = \left\{ P\left(1 - \frac{1-c}{2}\right), P\left(\frac{1-c}{2}\right) \right\} \quad (7)$$

2.2 Model component processes

River models are a genre of models that describe the movement of water along a regulated network. They can be used equally well to simulate the movement of water along non-regulated river systems, but their strength is in being able to handle complex river operating rules and regulations.

River models break a river system into several components that simulate individual processes such as rainfall-runoff or flow routing. The components are connected in a schematic form so as to capture the main characteristics of the river system. River models can be developed using a wide range of software packages such as IQQM (DWLC, 1995), REALM (Perera et al., 2005) and more recently eWater Source (Welsh et al., 2012). Each package offers a range of options to simulate the component processes. Different catchments may require different component processes. As a result, the selection of the most appropriate components to include in the model is the first step in a river modelling study (CRC, 2005).

The river models developed for the Assessment were built within the eWater Source modelling platform. The Assessment river models were initially configured on the existing IQQM models built by the Queensland Government to support the Gulf Water Resources Plan. The IQQM models were used within the Northern Australia Sustainable Yields (Petheram et al., 2009) project to estimate water yields under current and future climates and had been the main reference for river modelling in the Assessment area. As part of the Assessment the IQQM structure was transferred to the eWater Source software package. Additional model nodes were then incorporated in the Source models to improve their spatial resolution in key areas (particularly in the vicinity of the potential irrigation areas and dam sites). The models were subsequently recalibrated using gridded SILO climate data (Jeffrey et al., 2001) and taking advantage of the most recent streamflow data, provided by the Queensland Government

The following section describes the component processes that were selected for the Assessment's river models and how they relate to the structure of the existing IQQM models.

2.2.1 NODE –LINK NETWORK

The node-link network is a fundamental component of a river model. Nodes represent locations along the river where flow and water quality constituents enter, are stored, extracted, lost or measured. Links are used to model the movement of water and water quality constituents between nodes. Simple links connect two or more nodes without modifying the flow pattern. Routing links introduce lag and attenuation of flow, as well as fluxes of quality constituents. Routing links essentially mimic the effect that a river reach has on delaying flow and modifying the shape of the hydrograph.

Seven types of nodes are defined in a river model:

- Gauging stations are points where streamflow is monitored by measurement devices (see Section 3.3.2 and Section 4.3.2). In the case of gauging stations in the Assessment area they are maintained and operated by the Queensland Government. Streamflow observational data recorded at these stations are used to calibrate the river models and can also be used to assess the model results and performance.
- Inflow nodes define the location of headwater and residual inflows along a river system. Inflow nodes are associated with subcatchments that break the modelling area into homogenous sub-areas or sub-areas defined by specific points or items of interest such as an existing or potential dam. For example, the Flinders catchment was split into 43 subcatchments (see Section 3.2). Headwater and residual inflow are defined as follows:
    - Headwater inflows correspond to gauged flows entering the river system at the top most gauging stations in the catchment (e.g. Glendower inflow for the Flinders river model),
    - Residual inflows correspond to ungauged flows entering the river system between two gauging stations.
- Confluence and distributary nodes are used to schematically arrange the river system. Only the main rivers, their tributaries and the rivers with important management considerations (e.g. dams) are represented in the model.
- Storages correspond to water bodies capable of holding significant quantities of water. Storages can be natural (e.g. lakes and wetlands) or man-made (e.g. dams and weirs).
- Demand points include the locations where water is required to fulfil town water supply, irrigation and industrial demand, and environmental flow constraints.
- Diversion intakes and offtakes are the points where water is diverted to supply town water supply, industrial and irrigation water demand.
- Loss nodes account for the transmission losses due to surface water groundwater interactions, stream evaporation or unaccounted flow (e.g. bypass of gauged points by flood runners).

An example of a node-link network is presented in Figure 2.1. The Flinders and Gilbert node-link networks are presented in Sections 3.2 and 4.2, respectively.

For the purpose of model calibration, some of the nodes and links can be grouped together within larger entities referred to as reaches in the rest of the document. Two types of reaches can be found in a river model:

- Headwater reaches cover the areas located upstream of the top most gauging stations,
- Residual reaches cover the areas located between a set of upstream gauging stations and one downstream station.

The calibration method is detailed in section 2.3.

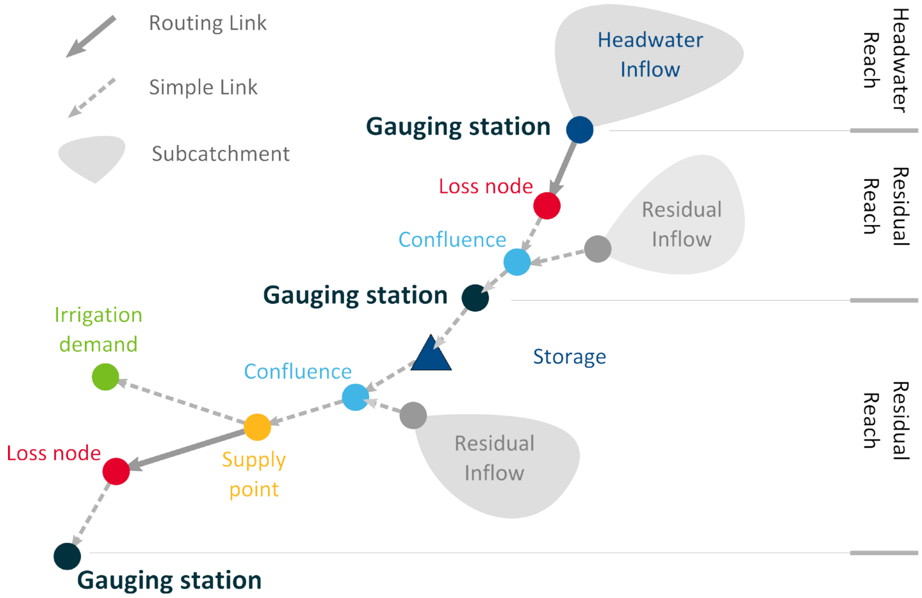

Figure 2.1 Example of a node-link network

2.2.2 RAINFALL-RUNOFF MODEL

Inflows constitute the main source of water in a river model. For those inflow nodes where flow measurements are available, they can be directly used as inputs to the model. However, flow measurements are costly and generally limited to a low density of sites within a catchment and short periods of record. Provided climate data can be obtained, conceptual rainfall-runoff models can be used to generate inflow time series for the river model in order to extend or infill the measured inflows, estimate inflow at nodes where no data are available or explore the impact of climate change on inflow. For the Assessment, rainfall-runoff models were first calibrated against observed streamflow records and subsequently used to generate inflow time series covering the reporting period 1890-2011. Details on the calibration procedure are provided in section 2.3.

The transformation of rainfall into runoff is a highly non-linear process that is heterogeneous in time and space. Many variables control this process including climate, topography, land cover, soil properties and connections between groundwater and surface water systems. Understanding and modelling these processes remains an active topic of research with numerous models available from the hydrological literature. Interestingly, complex models that include a representation of small scale physical processes do not simulate catchment scale runoff better than simpler conceptual models, largely because there are insufficient data available to parameterise a physically based model at the catchment scale. As a result, conceptual rainfall-runoff models, in which a catchment is represented by a small number of buckets, e.g. top soil, deep soil and groundwater, are generally preferred for operational use like flood forecasting and water resources planning, because their parsimony is generally more commensurate with the level of data available at the catchment scale. The Sacramento conceptual rainfall-runoff model (Burnash et al., 1973) was selected for use in the Assessment for the following reasons:

- The model operates at the subcatchment scale and only requires rainfall and potential evaporation inputs.
- It is a well-tested model and is in common use around the world.
- There is a historical precedent to using the model. The Queensland Government use the Sacramento model to provide inflows to their IQQM river models across the State, including the Flinders and Gilbert IQQM models.
- Previous studies conducted by CSIRO in South-East (Vaze et al., 2010) and northern Australia (Petheram et al., 2012) have shown that the Sacramento model performs better than similar models in a majority of catchments in Australia, particularly the semi-arid catchments.

The Sacramento model has 18 parameters as listed in Table 2.1. Following the approach taken by CSIRO during the Catchment Water Yield Estimation Tools project (CYWET, Vaze, 2011), the Rserv parameter was fixed in order to reduce the number of free parameters and better facilitate the search for optimal parameters during the calibration process. The fixed value is indicated in Table 2.1.

Table 2.1 Parameters of the Sacramento model

SACRAMENTO PARAMETER NAME	DESCRIPTION	UNIT	RANGE
Adimp	Proportion impervious area when tension requirements are met	-	1e-5 to 0.15
Lzfpm	Lower zone free water primary storage capacity	mm	1 to 300
Lzfsm	Lower zone free water storage capacity	mm	1 to 350
Lzpk	Lower zone primary drainage rate	-	1e-3 to 0.6
Lzsk	Lower zone supplemental drainage rate	-	1e-3 to 0.9
Lztwm	Lower zone tension water storage capacity	mm	10 to 600
Pctim	Permanently impervious fraction of catchment	-	0 to 0.11
Pfree	Proportion of percolated water going to lower zone storages		1e-2 to 0.5
Rexp	Exponential component for percolation		1 to 6
Rserv	Proportion of lower zone unavailable for transpiration (parameter is fixed to 0.3 during calibration)		0.3
Sarva	Proportion of basin covered by streams and lakes	-	0 to 0.11
Side	Proportion loss of baseflowr	-	0 to 0.1
Ssout	Loss in bed of river	mm/day	0 to 0.1
Lag	Lag time between rainfall and runoff	day	0 to 10
Uzfwm	Upper zone free water storage capacity		5 to 155
Uzk	Interflow drainage rate		0.1 to 1
Uztwm	Upper zone tension water storage capacity		12 to 180
Zperc	Percolation parameter		1 to 600

2.2.3 ROUTING MODEL

Flow routing models describe the transport, the lag and attenuation of streamflow hydrographs along a river system. Hydrodynamics provides the theory underlying the description of the routing process via a set of equations known as Saint-Venant equations. When the flow is mainly unidirectional and not influenced by significant backwater effects (e.g. effect of a weir on upstream flows), the equations can be replaced by conceptual routing models that capture the main physical features of the flow routing process. The most common model that is used in Australia for flood forecasting and water resource planning is the storage model, also referred to as Laurenson routing (Laurenson, 1959, Linsley et al. 1949, Mein et al., 1974), where the water stored in a river reach is related to the reach outflow as described in Equations 8 and 9:

$$\frac{dV}{dt} = I(t - LAG) - O(t) \tag{8}$$

$$V(t) = KO(t)^M \tag{9}$$

where V is the non-linear routing volume (ML), I and O the reach inflow and outflow (ML/d), respectively and t is time. LAG (day), M (dimensionless) and K ($m^{3(1-M)}.s^M$) are the three parameters of the conceptual routing model controlling the lag, attenuation and hydrograph shape, respectively. This model does not have a general solution unless M=1 or M=1/2, but can be solved with a numerical algorithm such as the one provided in the eWater Source software package (Welsh et al., 2012).

Table 2.2 Parameters of the routing model

ROUTING PARAMETER NAME	DESCRIPTION	UNIT	RANGE	COMMENT
Lag	Lag	Day	0 to 10	
K	Capacity of the routing store	$m^{3(1-M)}.s^M$	>1	The unit of K depends on the value of M
M	Exponent of the routing store	(dimensionless)	0.6 to 1	Range defined according to Mein et al. (1974)

The model described by Equations 8 and 9 remains valid as long as routing remains unidirectional and is not impacted by backwater effects. This is the case in the upper and intermediate parts of the Flinders and Gilbert catchments. It is expected, however, that this model may not be able to simulate flood hydrographs accurately in lower floodplain areas where considerable overbank flow leaves the main river channel. To improve this part of the model, the Assessment includes an activity devoted to the development of a hydrodynamic model for the floodplain areas of the Flinders and Gilbert catchments. This is discussed in more detail in the companion technical report about flood mapping (Preface Figure 1).

2.2.4 LOSS MODEL

The conceptual routing model described in Section 2.2.3 is based on the mass balance equation (1) that guarantees a conservation of mass during the routing process. This equation cannot represent the transmission losses that occur in most semi-arid stream networks due to evaporation and exchanges between surface and groundwater systems (Lange, 2005). Other types of losses can also occur including overbank flow leaving the river system, flow bypassing gauging stations during overbank events or, more generally, unaccounted losses that are related to an overestimation of streamflow by the model. As a result, a component process is required to remove water from the system.

There is no direct observation of transmission losses; rather, indirect estimation can be obtained by comparing the inflow and outflow from a particular reach. Consequently, the calibration of losses is subject to a high level of uncertainty. The traditional approach taken by the State agencies (DNRM 2006a, DNRM 2006b, Petheram et al., 2009, Van Dijk et al., 2008) is to undertake a staged calibration of the river models. In the first instance inflows are generated for each reach of the river system model, without consideration of a loss component. The loss functions are introduced in a second phase and take the form of Equation 10:

$$L(t) = f(Q(t)) \tag{10}$$

where Q is the flow immediately upstream of the loss node (ML/d), L is the loss (ML/d) and f is an increasing tabulated function. Figure 2.2 shows an example of a loss function that is implemented in the Flinders IQQM river models (DNRM, 2006a) upstream of Walker's Bend (gauging station 915003A). The flow immediately downstream of the loss node is given by Equation 11:

$$Q'(t) = Q(t) - L(t) \tag{11}$$

With this approach, the loss function is obtained by plotting the downstream flow Q' against the difference Q'-Q'_{obs} where Q'_{obs} is the flow measurement corresponding to Q'. The resulting relationship is then approximated by a look-up table.

This method for defining losses introduces a high degree of flexibility in the model because there is no restriction on the form of the tabulated relationship other than it must increase with flow. It can only be applied, however, where flow measurements are available. This restricts the application of a loss model to the vicinity of a gauging station. Moreover, without user judgement or verification of the data underpinning the function and the form of the function, the high flexibility offered by the function can lead to high loss values. This effect is not desirable because it indicates that a large part of the flow cannot be accounted for by the model and suggests that either the flow data or the model would require a revision.

Equation 10 is based on the rationale that losses are mainly driven by flow and therefore increase with river flow. The Assessment followed this approach, but the tabulated form of the loss function was replaced by the parametric form suggested by Monod (1949) as shown in Equation 12:

$$L(t) = A\frac{Q(t)}{1 + B\,Q(t)/Q_0} \tag{12}$$

where A (dimensionless) and B (dimensionless) are the two parameters of the Monod function, Q_0 (ML/d) is the mean annual flow upstream of the loss node. Table 2.3 summarises the characteristics of the parameters of the loss model.

Table 2.3 Parameters of the Monod loss model

ROUTING PARAMETER NAME	DESCRIPTION	UNIT	RANGE	COMMENT
A	Scaling factor	(dimensionless)	0 to 1	If A=0, the loss becomes null
B	Attenuation factor	(dimensionless)	0 to 200	

The Monod function has the following advantageous characteristics:

- It is strictly increasing, following the approach described in Equation 10.
- It is controlled by a small number of parameters (A and B). As a result, it can be calibrated simultaneously with other parameters of the river system model (e.g. conceptual routing model, rainfall-runoff model) with a limited increase in the total number of free parameters. This point is critical for a mathematical model because a high number of free parameters increases the risk of overfitting (i.e. matching the noise in the data) and decreases the model performance. This can be demonstrated theoretically for linear models (Johnston and DiNardo, 1972) or empirically by

comparing the performance of models with an increasing number of parameters (Jakeman and Hornberger, 1993, Perrin et al., 2001).

- Its parameters are dimensionless. As a result, the same parameter coefficients (i.e. values) can be applied to different loss nodes, reducing the total number of parameters requiring calibration and allowing a loss node to be used where no observed flow data are available. For example, this approach could be applied to simultaneously calibrate the three loss nodes shown in Figure 2.1. It is bounded towards infinity if B > 0. When Q becomes large in Equation 5, L becomes equivalent to Q_0 A/B. This characteristic can be used to ensure that the loss function will not take excessively large values, and reduces the risks of compensating the errors introduced by other components of the model. However, if large losses are expected in the system, e.g. in the case of break-out flow that by-passes the downstream gauging station, the parameter B can be set to 0 and the parameter A can be set to a value close to 1.

The main disadvantage of this loss model is the inability to capture sudden breaks in the flow-loss relationship. However, an analysis of the loss functions defined in the IQQM Flinders and Gilbert models suggested that most functions could be approximated by the form defined in Equation 12. Figure 2.2 shows the IQQM loss functions for the Flinders model upstream of Hughenden (Figure 2.2a) and Walker's Bend (Figure 2.2b). It can be seen that the IQQM loss function upstream of Hughenden is closely following the shape of the Monod function, with a linear behaviour close to the origin and an asymptote for large flow values. A large majority of the IQQM loss functions are similar to the one presented in Figure 2.2a. The loss function of Walker's Bend shown in Figure 2.2b is an exception with several breaks along the curve. However, the general shape of the curve remains close to a linear function, which can be approximated with the function defined in Equation 12.

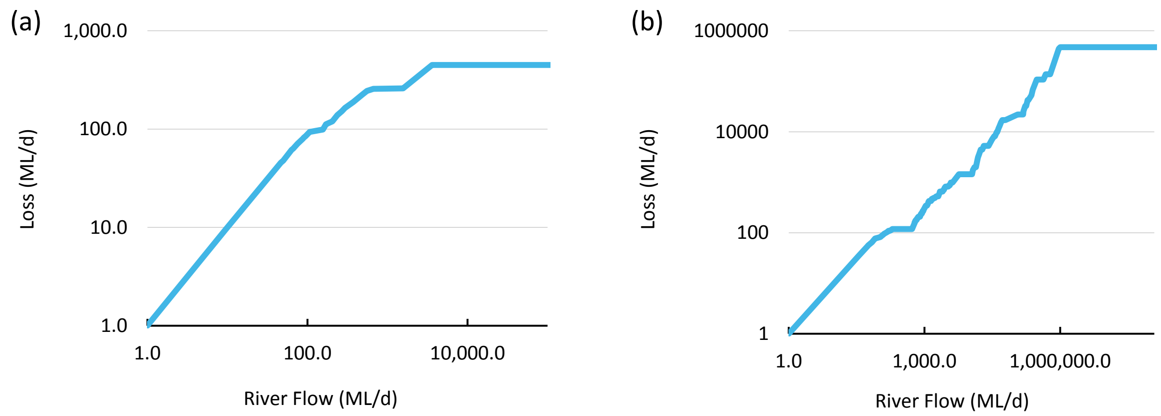

Figure 2.2 IQQM loss functions for the Flinders River upstream of Hughenden (915004A, IQQM node 003, see figure a) and Walker's Bend gauging station (915003A, IQQM node 059, see figure b)

2.2.5 DEMAND MODELS

Demand models estimate the quantity of water required to satisfy town water supply, irrigation and industrial water requirements. First, the models compute the demand for each demand node. Second, the demand is transferred to a supply point that diverts water from the river system based on pump capacity and availability of water in the river. If a dam exists upstream of the supply point, the demand might trigger a release. Finally, the water extracted at the supply point is sent back to the demand node, which may adjust the demand based on the amount of water received (e.g. crop demand will increase during shortage of water).

The simplest demand models are based on fixed patterns that are repeated every year. More complex models estimate demand based on estimates of crop requirements, climate conditions, antecedent soil moisture conditions, on-farm-storage and water allocation. The demand models representing the existing management scenarios in the Assessment were transferred from the IQQM river models developed by the

Queensland Government for input to the Gulf Water Resources Plan. The demand models were implemented as follows:

- All the demand nodes represented in IQQM were incorporated into the Assessment River models using the same water demands simulated in the IQQM scenario.
- In cases where IQQM utilised a fixed demand pattern, this was replicated in the Assessment River models.
- In cases where IQQM modelled demand using a crop model, these were replaced by a fixed demand pattern in the Assessment river model. This simplification was introduced based on the analysis of the crop requirements in IQQM. Figure 2.3 shows the annual time series of the total crop requirements and irrigation diversions for the Flinders and Gilbert IQQM models, respectively. The figure reveals that the inter-annual variation of crop requirements was negligible compared to the variation of diversions and can be approximated with fixed patterns. The patterns were computed in three steps:
    - For each irrigation demand node, the daily crop requirement time series was extracted from the IQQM model runs covering the period 1890-2003 (i.e. the simulation period used in the Gulf Water Resource plan).
    - The time series were processed to compute the mean value of the demand for each calendar day (e.g. mean demand on 1st January, 2nd January, and so forth).
    - The resulting daily demand pattern was repeated for each year of the historical period (i.e. 1 July 1890 to 30 June 2011) and input in the Assessment's river models.

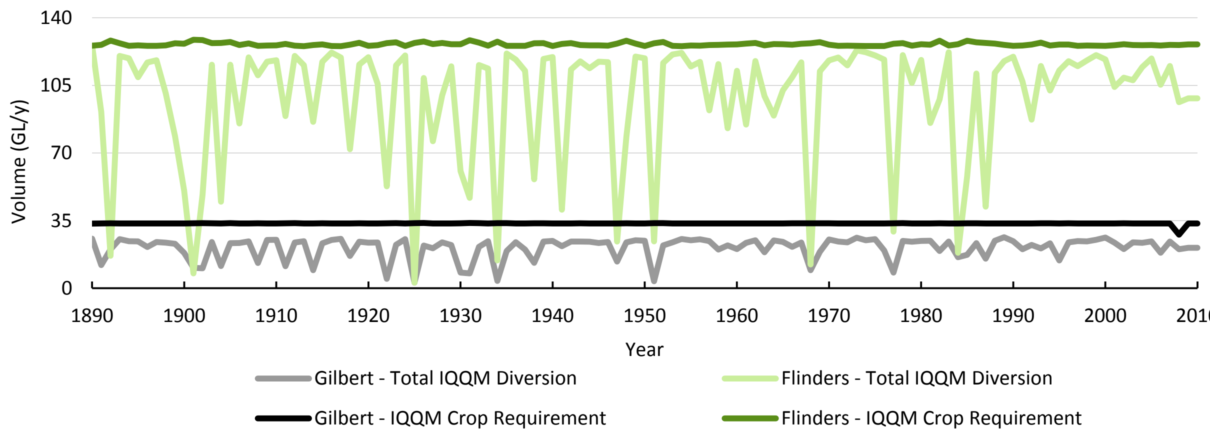

Figure 2.3 Simulated crop requirements and irrigation diversions from Flinders and Gilbert IQQM models

The simplifications introduced by using a fixed daily demand rather than modelling crop requirements are minor and limited to the modelling of Scenario A (i.e. current climate and levels of development and assuming full use of existing entitlements). As part of the Assessment, detailed crop models are being developed to compute crop requirements, yields and gross margins. These and other information will be used in the development storylines and case studies (Scenario D). This is discussed in detail in the companion technical report about agricultural productivity in the Flinders and Gilbert catchments (Preface Figure 1). The results from this crop modelling will be incorporated into the river models when evaluating potential development storylines.

2.2.6 STORAGE

River models distinguish large in-stream storages from small off stream storages, also referred as on-farm storages. In stream storages, such as the Kidston dam in the Gilbert catchment or Lake Corella in the Flinders catchment, are modelled with a great level of detail that includes information on the geometry of the reservoir, design of spillway and gates, evaporation, and defined operating rules that control the release of water from the dams. In-stream storages that were configured in the IQQM models were included in the Assessment river models, using an identical configuration to the IQQM. It should be noted that the bedsand aquifers were modelled as in-stream storages, again using the same configuration as the IQQM models.

Much less data are generally available to describe off-stream storages, which leads to simplified assumptions in the storage model. In the Flinders and Gilbert IQQM models, the modelling of off-stream storage is embedded in the irrigation demand model and based on a description limited to the pumping capacity and storage volume. Within this approach, pumping is triggered when river flow becomes available and stops when the off-stream storage is full. To speed-up the model execution, the pumping time series were replaced by fixed demand patterns equal to the licence volume and concentrated during the wet season.

2.3 Calibration and validation procedure

2.3.1 MODEL SET-UP FOR CALIBRATION, VALIDATION AND LONG-TERM MODEL RUN

Calibration and validation

The river models were calibrated in order to maximise the fit between the simulated and observed flows. This was undertaken for two periods:

- A first calibration period covering the full period of streamflow records available within each calibration reach.
- A second period was defined as the first half of the full period. The calibration on this period was undertaken to test the model on the second half of the period following the K-fold test approach advocated by Klemes (1986).

The calibration algorithm is described in section 2.3.3 and 2.3.4.

As indicated in Section 2.2.1, the calibration method was applied on two different types of areas including headwater reaches (upstream of the top most gauging stations), and residual reaches (located between upstream and downstream gauging stations). A specific model set-up was used for the calibration on residual reaches. For this type of reach, the flow at the upstream gauging stations was forced to the observed flow data. This approach was preferred to the use of simulated flows generated from model runs on upstream reaches. The use of observed flow data prevented model uncertainty propagating from upstream to downstream reaches.

Assessment of model performance

In order to assess model performance, the model was run without forcing the reach inflows to observed data. In other words, the model was run from the top to the bottom of the catchment based on simulated variables only. The simulated flow at each gauging stations was compared with the observed data and performance statistics were computed. The rationale behind this approach was to test the model in conditions that were similar to the long term simulation over the reporting period, where streamflow data are not longer available. This is considered to be the most robust test of model performance.

Long-term model run

Finally, the model was run for the entire reporting period (1890-2011) without forcing the reach inflows to the observed data. The variables presented in the water resources tables located in Appendix B and Appendix D were computed from this simulation.

2.3.2 CALIBRATED COMPONENTS

River models are characterised by a high number of parameters and limited observational data. As a result, the calibration is not a trivial exercise and can be greatly improved by breaking the whole system into smaller entities controlled by fewer parameters with more robust mathematical properties.

The first step towards that goal is to minimise the number of calibrated components. As documented in Section 3.3.3 and 4.3.3, the demand and storage models were not recalibrated. Rather, the Assessment river models replicated the demand and storage models configured in the IQQM models. River model calibration was restricted to the rainfall-runoff, routing and loss components. In addition, the three components were calibrated independently from the demand models by setting all diversions to zero. This approach constitutes an important assumption that was based on the following rationale:

- The current level of allocated water entitlement is low relative to the volumes of water in both the Flinders (5%; CSIRO, 2009a) and Gilbert (1%; CSIRO, 2009b) catchments. The actual volume of water diverted within each catchment is likely to be lower still, as not all allocated water is currently being used. CSIRO (2009a, 2009b) reports that the current usage is about 5 GL/year and 32 GL/year for the Flinders and Gilbert, respectively.
- For the majority of gauging stations in the Assessment area, the observed flow records extend from 1970 to 1990 (see Table 3.3 and Table 4.3). It is likely that the level of development over this period was lower than its current value.

These assumptions only affect the model run during the calibration period. The Assessment river model simulations used to evaluate the water resources in Section 3.7 and Section 4.6 incorporate the demand models described in Section 2.2.5.

2.3.3 PARAMETERISATION FOR HEADWATER AND RESIDUAL REACHES

To reduce the number of calibrated parameters, a single set of rainfall-runoff parameters was used for reaches having multiple subcatchments. A similar constraint was applied to the routing parameters of all routing links within a reach. Overall, 17 rainfall-runoff parameters are calibrated for each headwater subcatchment (see Section 2.2.2) and 22 parameters are calibrated for each residual reach:

- 17 parameters rainfall-runoff model (see Section 2.2.2),
- 3 routing parameters (see Section 2.2.3),
- 2 loss parameters (see Section 2.2.4)

2.3.4 SEARCH ALGORITHM AND OBJECTIVE FUNCTION

Historically, the calibration of hydrological model parameters relied on a trial-and-error procedure guided by visual inspection of observed and simulated streamflow hydrographs. This approach still constitutes the backbone of modern calibration techniques, but in recent decades the calibration process has been accelerated through the use of automated search algorithms that test a broader range of parameter combinations. The calibration of the Assessment river models was performed using a global optimiser, the Shuffle Complex Evolution algorithm (Duan et al., 1993).

Automated search algorithms are based on the minimisation of an objective function that quantifies the distance between the model output and the observed variable. The following function introduced by Coron et al. (2012) was selected:

$$F(\theta) = \underbrace{\left(\alpha \sum_{i=1}^{n} \left[{O_i}^{\lambda} - S_i(\theta)^{\lambda}\right]^2}_{\text{(I)}} + \underbrace{(1-\alpha) \sum_{k=1}^{n} \left[{O^*_k}^{\lambda} - {S^*}_k(\theta)^{\lambda}\right]^2\right)}_{\text{(II)}} \underbrace{\left(1 + \frac{\left|\sum_i O_i - \sum_i S_i(\theta)\right|}{\sum_i O_i}\right)}_{\text{(III)}} \qquad (13)$$

Where n is the number of simulation days, O_i is the observed flow on day i (ML/d), $S_i(\theta)$ is the simulated flow on the same day obtained by running the reach model with parameters θ, O^*_k and $S^*_k(\theta)$ denote the k^th value of the observed and simulated sorted flow series, λ is an exponent set to ½ and α a weighting factor set to 0.1 for the Flinders calibration and 1.0 for the Gilbert calibration. The function presented in Equation 13 combines three terms: the sum of squared errors on power transform of flow (I), the same sum on sorted flow values (II) and the relative simulation bias (III). The two coefficients α and λ are used to balance the three terms within the objective function $F(\theta)$. Using values of λ less than 1, the power transform has the effect of reducing the weight of the errors on high flows, where the flow data are known to be less accurate. Values of λ ranging from 0.05 to 1 were compared. The value λ=0.5 led to the best compromise between high and low flow performance. This result was also found by Petheram et al. (2012) on a study of over 100 high quality gauging stations from across northern Australia. The weighting factor α was used to reduce the impact of the timing errors on the objective function. This type of error can have a significant effect on the first term (I) in Equation 13, where a slight misalignment of observed and simulated peak flow timing can result in large amplitude errors. Conversely, the second term is based on sorted flow values, which remain unaffected by timing errors. The introduction of the term (II) in Equation 13 was found critical for the headwaters of the Flinders catchment where floods occur essentially at the sub-daily time scale. In this context, timing errors can be large and need to be balanced in the objective function, as in Equation 13.

Preliminary tests established that it would not be computationally feasible to calibrate the model within eWater Source, therefore each calibration reach was reconstructed outside Source, using custom C# .NET tools and R scripting language (R Development Core Team, 2012) to replicate Source functionality. Once the calibration was complete, the calibrated model parameters were applied to the Source model.

2.4 Assessing model performance

The prediction error, or model performance, is the most visible source of uncertainty. It can be quantified by comparing the modelled flows with corresponding observations obtained at gauging stations. The comparison can be based on a visual comparison of hydrograph and performance metrics. Sections 3.4 and Section 4.4 display plots of observed versus simulated hydrographs, focused on high flow, low flow and annual flow regimes in the Flinders and Gilbert catchments, respectively. Three metrics were used to assess model performance: the Nash-Sutcliffe efficiency (NSE, Nash and Sutcliffe, 1970), the NSE on log-transform flows (NSELOG) and the bias. The NSE on log-transform flows provides a measure of how well the model simulates low flow events. The metrics are described by Equations 14 to 16, using the same notations as Equation 13:

$$NSE = 1 - \frac{\sum_i [O_i - S_i(\theta)]^2}{\sum_i [O_i - \bar{O}]^2} \tag{14}$$

$$NSELOG = 1 - \frac{\sum_i [\log(O_i + \delta) - \log(S_i(\theta) + \delta)]^2}{\sum_i \left[\log(O_i + \delta) - \overline{\log(O + \delta)}\right]^2} \tag{15}$$

$$BIAS = \frac{|\sum_i O_i - \sum_i S_i(\theta)|}{\sum_i O_i} \tag{16}$$

where $\bar{O}$ is the mean daily flow (ML/d), $\overline{\log(O + \delta)}$ is the mean daily log-transform flow (-), and δ is a constant set to 1 ML/day. The three metrics are dimensionless. Table 2.4 indicates a set of reference values that are generally used by modellers (Van Dijk et al., 2008) to quantify the river model performance. The NSE and NSELOG were computed over the entire observed and simulated comparison period (this period varies from one gauging station to another, depending upon the start and end date of the observation period), over the comparison period but for the dry season months only, and at the daily, monthly and annual time steps. The metrics are discussed in greater detail in Section 3.4 and Section 4.4 for the Flinders and Gilbert river models, respectively.

Table 2.4 Reference values for the performance metrics

MODEL PERFORMANCE	DAILY NSE	DAILY NSELOG	BIAS
Excellent	>0.95	>0.8	<1%
Good	0.9-0.95	0.7-0.8	1% - 5%
Average	0.8-0.9	0.6-0.7	5% - 10%
Fair	0.5-0.8	0.4-0.6	10% - 20%
Poor	<0.5	<0.4	>20%

In addition to the above metrics, two alternative metrics were utilised for assessing model performance at low flows based on the streamflow exceedance curves. The first metric computes the difference between the observed and modelled exceedance at a streamflow equal to 1 ML/day. This streamflow value was selected on the basis that it is likely to correspond to the threshold at which measurement of low flows at sand and gravel controlled gauging stations is appropriate and for the purposes of the Assessment will be considered the cease-to-flow condition. The computation of this metric is illustrated in Figure 2.4. The second metric computes the streamflow threshold at which the discrepancies between the observed and simulated exceedance curves is greater than 0.05 exceedance frequency (Figure 2.4). For the purposes of the Assessment it is considered that at streamflow values below this threshold the model cannot provide an accurate simulation of low flows. These two criteria provide a rigorous test of model performance at low flows.

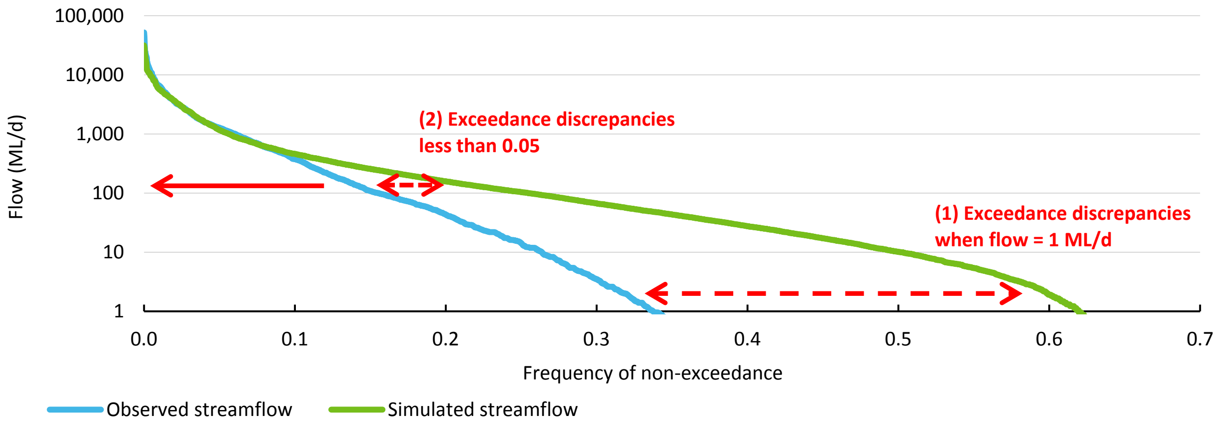

Figure 2.4 Computation of the criteria used to estimate the discrepancies between modelled and simulated streamflow exceedance curves

2.5 Uncertainty analysis

The uncertainty associated with hydrological models originates from a wide range of sources including the errors in the input and output data, the approximate model structure and the non-uniqueness of optimal parameter sets (Beven and Binley, 1992). How to most appropriately analyse the combined effects of multiple sources of uncertainty is still an area of active debate (Renard et al., 2010) and inevitably requires highly intensive computations (e.g. bootstrap analyses often require more than 10,000 model runs, Efron and Tibshirani, 1994). Due to the limited time frame of the Assessment and the complex nature of the models, the uncertainty analysis in this report was restricted to the analysis of model performance and the impact of the measurement uncertainty in the streamflow data. This is because the uncertainty in streamflow data was thought to be the primary source of uncertainty in the Assessment area.

The uncertainty arising from the errors in streamflow data was the second point investigated as part of the uncertainty analysis. Streamflow data were used to calibrate the rainfall-runoff, routing and loss components of the river model. They also provide a reference against which to assess the model as described above. However, many gauging stations in the Flinders and Gilbert catchments are located in remote areas with limited access during flood conditions. This can limit the opportunity to undertake streamflow measurements, which potentially introduces uncertainty in the streamflow data. As indicated in Appendix A , the uncertainty in modelled mean annual streamflow in the Flinders and Gilbert catchments ranged from +/-5% to +/-30% of the mean annual flow at confidence level of 95%. To quantify this type of uncertainty, a two-step method was devised as shown in Figure 2.5.The first step involved creating 50-equally statistically plausible time series of streamflow data for each gauging station by introducing a random perturbation in the original streamflow dataset. These new streamflow datasets are referred to herein as *replicates*. The second step involved repeating the calibration process described in Section 2.3 for each of the 50 streamflow replicates. This resulted in the generation of 51 calibrated parameter sets for each reach in the river model. These were:

- the *baseline model* run - obtained by using the parameters from the calibration against original streamflow data;
- 50 *ensemble runs* were obtained by using the parameters from the calibration against replicate streamflow data. The variables extracted from the ensemble runs were summarised with the 2.5% and 97.5% percentiles in order to generate uncertainty range with a 95% level of confidence (these are presented in Appendix A and Appendix B).

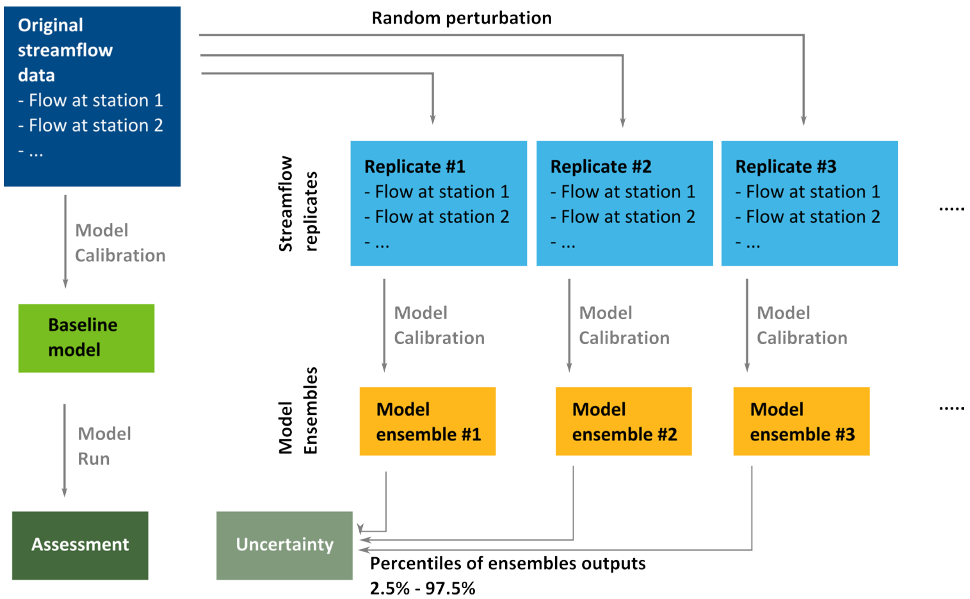

Figure 2.5 Flow chart of uncertainty analysis

The statistical method used to generate the streamflow replicates is documented in Appendix A . It is based on a regression between the streamflow staged - gauged discharge data and the streamflow discharge estimates produced by the rating curve. The gauging station on the Flinders River at Hughenden (915004A) is used in Figure 2.6 to illustrate this method. This figure shows the individual streamflow stage – gauged discharge data, as measured by the Queensland Government hydrographers, plotted against streamflow discharge estimates produced by the rating curve, for the range 0 to 20,000 ML/day. The figure illustrates that the discrepancies between the measured streamflow and rating curve generated streamflow can be large, with visible departures from the 1:1 line. This type of uncertainty can affect the calibration of the river model, which could have a considerable impact on the modelled results under different climate and potential development scenarios. As the gauged data were very sparse and irregular over time, the correlations in daily data cannot be modelled from the gauged data. Instead, we impose the correlation on the residuals as unknown and pre-determined in the ensemble generation. Further research on the correlation structure can surely improve the ensemble generation.

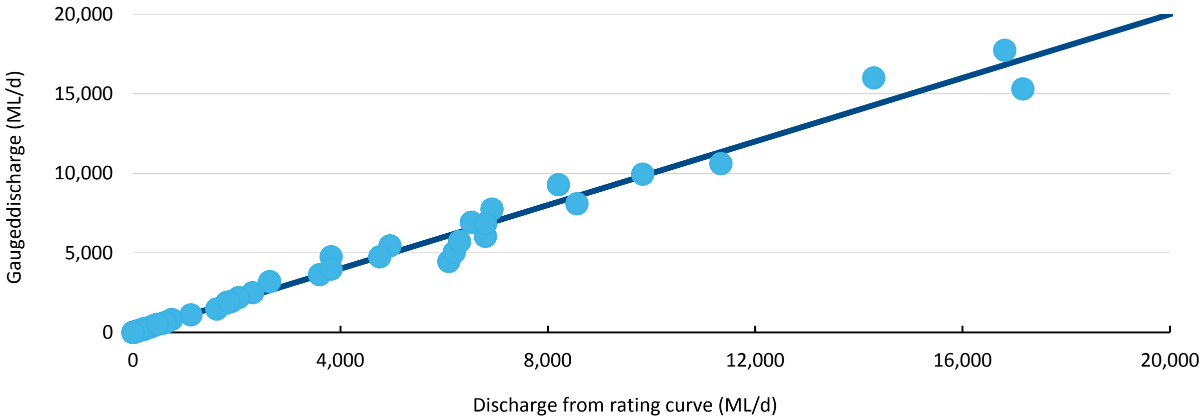

Figure 2.6 Flow from rating curve against gauged flow for the gauging station on the Flinders River at Hughenden (915004A)

Figure 2.7 provides a comparison of the original streamflow data used to calibrate the *baseline model* with the 2.5 and 97.5 percentiles of the streamflow replicates for the 1984 flood event at the gauging station 915004A, in the Flinders catchment.

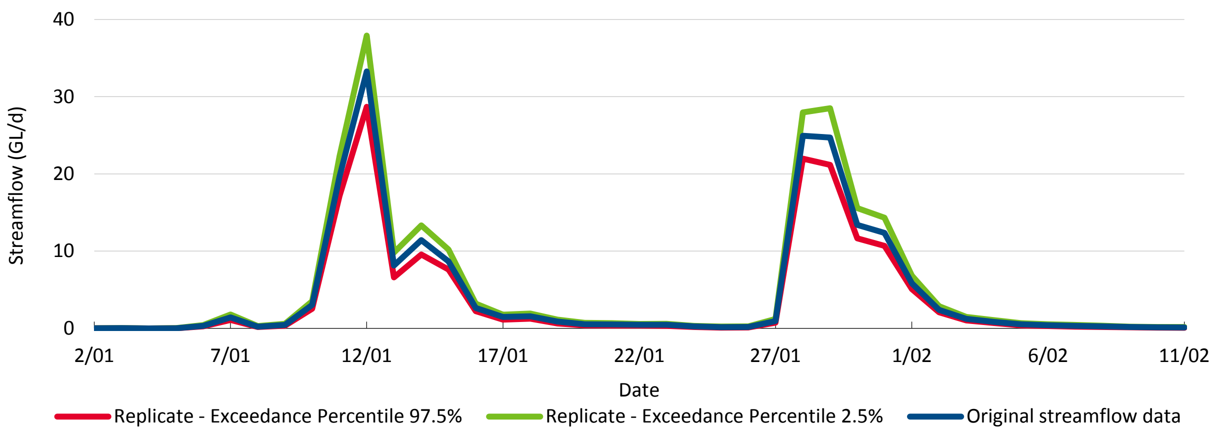

Figure 2.7 Baseline flow data and streamflow replicates for the 1984 flood on the Flinders River at Hughenden (915004A). The spread of the ensembles is represented by the 2.5% and 97.5% percentiles.

3 Calibration of the Flinders River model

This section describes the set-up, performance and uncertainty associated with the Flinders river model. The model set-up is described in Section 3.2. Section 3.3 describes the data used to build and calibrate the model and Section 3.4 details the performance of the model for different flow regimes.

3.1 Catchment description

3.1.1 FLINDERS RIVER CATCHMENT

The Flinders River catchment is located in the Gulf region of north-west Queensland and covers an area of 109,000 km^2. The catchment has a population of approximately 6000 with about two-thirds of the population residing in four towns: Cloncurry, Hughenden, Richmond and Julia Creek (Table 3.1). These towns are located along the Flinders Highway, which crosses the catchment in its southern section (Figure 3.2).

Table 3.1 Population of urban centres in the Flinders catchment

URBAN CENTER	POPULATION
Richmond	522
Hughenden	1,151
Cloncurry	2,313
Julia Creek	351

Source: Australian Bureau of Statistics (2011)

Figure 3.1 The Flinders River between Hughenden and Richmond. Source CSIRO

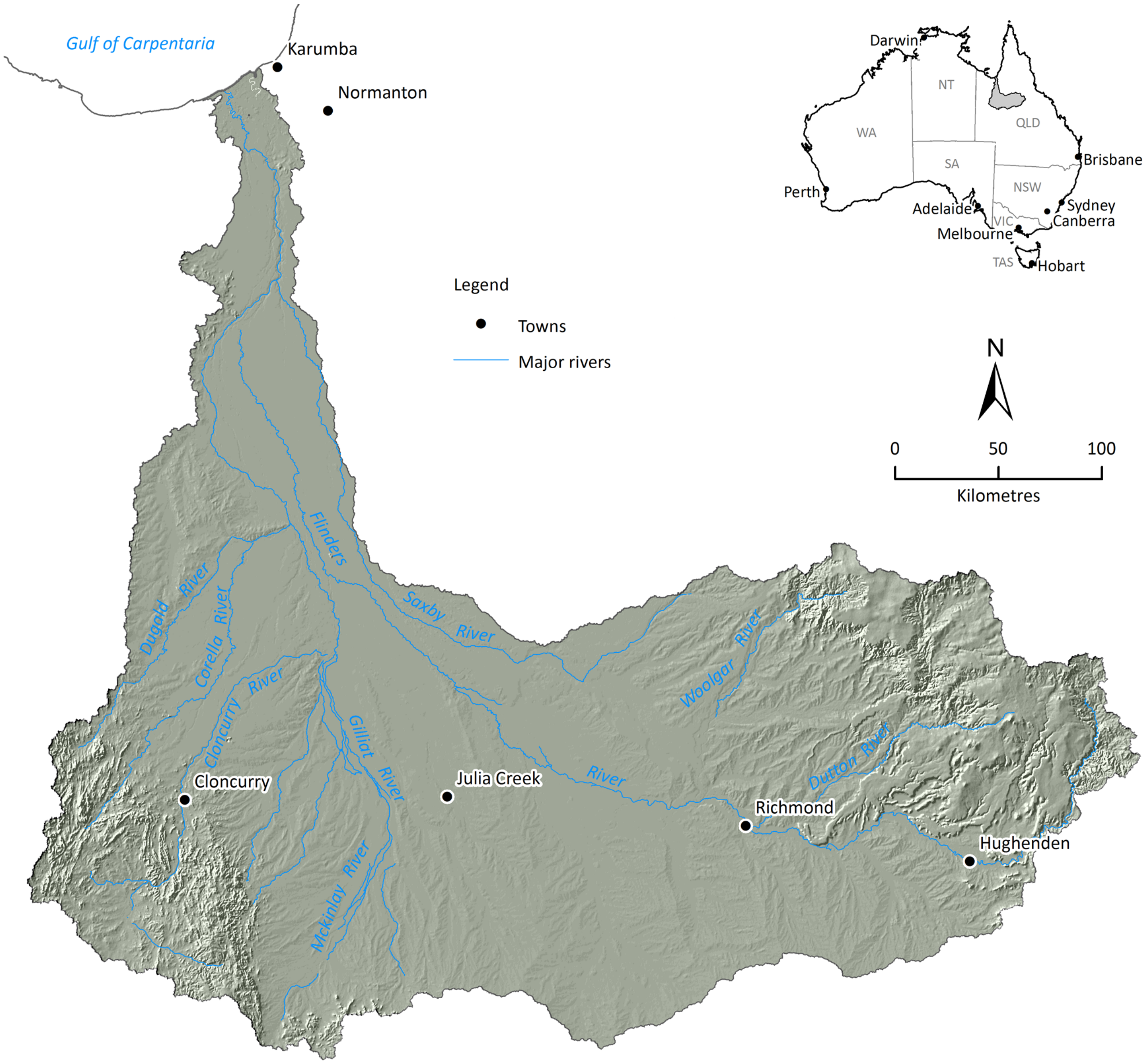

Figure 3.2 A shaded relief map of the Flinders catchment. Main rivers are named

The Flinders catchment has a semi-arid tropical climate. The mean and median annual rainfalls spatially averaged across the catchment are 492 mm and 454 mm, respectively. However, the historical annual rainfall series for the Flinders catchments shows considerable variation between years (Figure 3.3). The highest catchment average annual rainfall (1310 mm) occurred in 1974, nearly three times the median annual rainfall value. Spatially, mean annual rainfall varies from about 800 mm at the coast to about 350 mm in the south.

A defining characteristic of the climate of the Flinders catchment is the seasonality of rainfall, with 88% of rainfall occurring during the wet season (November to April inclusive) (Figure 3.4). The highest median monthly rainfall in the Flinders catchment occurs during the months of January and February (~100 mm). The months with the lowest median rainfall are July and August (~ 0.5 mm).

The Flinders catchment has a mean annual potential evaporation of 1862 mm. Mean wet and dry season potential evaporation are 1115 mm and 762 mm respectively. The majority of the Flinders catchment experiences a mean annual rainfall deficit of greater than 600 mm.

The climate of the Flinders catchment is described in more detail in a companion technical report by the climate activity (Preface Figure 1).

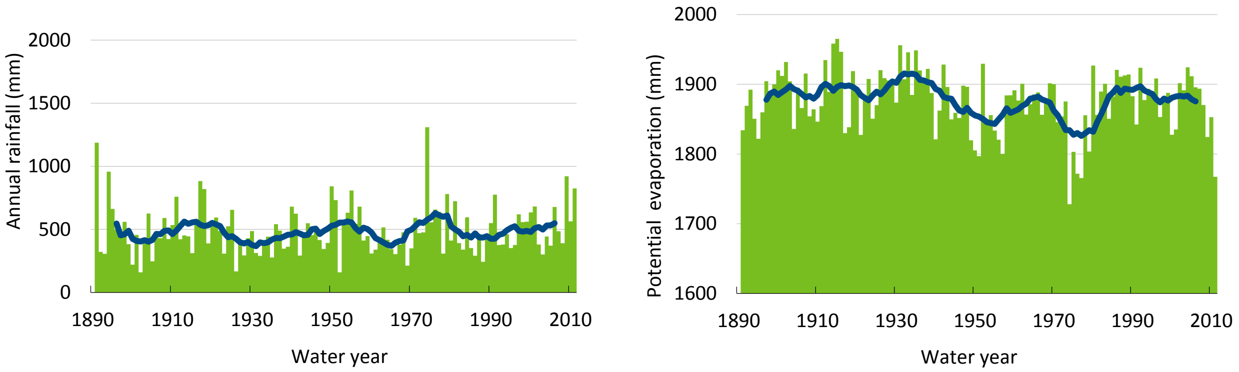

Figure 3.3 Historical mean annual rainfall and areal potential evaporation in the Flinders catchment

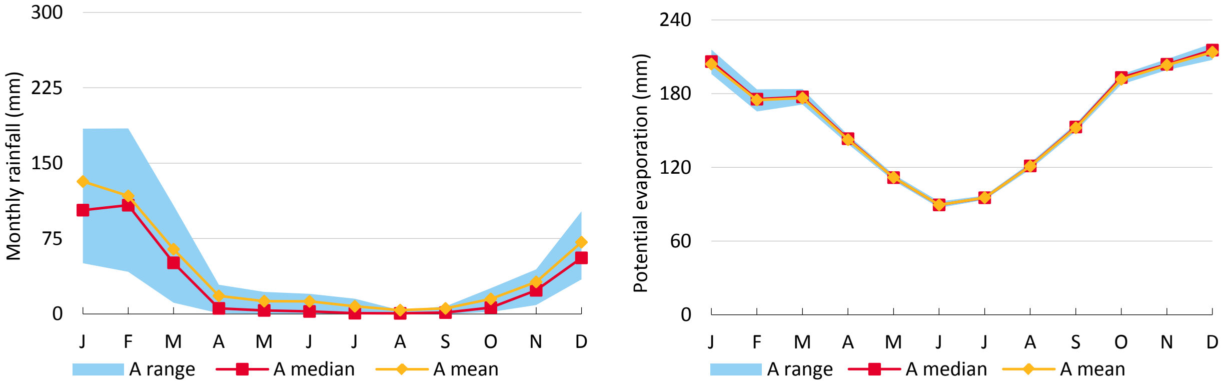

Figure 3.4 Historical monthly rainfall and potential evaporation averaged over the Flinders catchment (A range is the 20th to 80th percentile monthly rainfall) and potential evaporation)

The Flinders River is the main river in the Flinders catchment. It rises in the Great Dividing Range, 100 km north-east of Hughenden. The river flows from north to south, until it reaches Hughenden where it flows across the flat and treeless Mitchell grass plains to the west. After flowing through the town of Richmond, it continues towards the north-west before flowing north and draining into the Gulf of Carpentaria (Figure 3.2). Figure 3.5 illustrates the change in catchment area along the Flinders River from Glendower (upstream of Hughenden) to the river mouth. Large increases in catchment area occur where large tributaries join the Flinders River. The Flinders River has five major tributaries. These are the Dutton River, the Stawell River, Alick Creek, the Cloncurry River and the Saxby River (Figure 3.5). The largest tributary is the Cloncurry River, which accounts for half of the catchment area at the confluence between the Cloncurry and Flinders rivers.

Figure 3.6 illustrates the changes in catchment area along the Cloncurry River. The Cloncurry River has four main tributaries: the Malbon River, the Gilliat River, Julia Creek and the Dugald River.

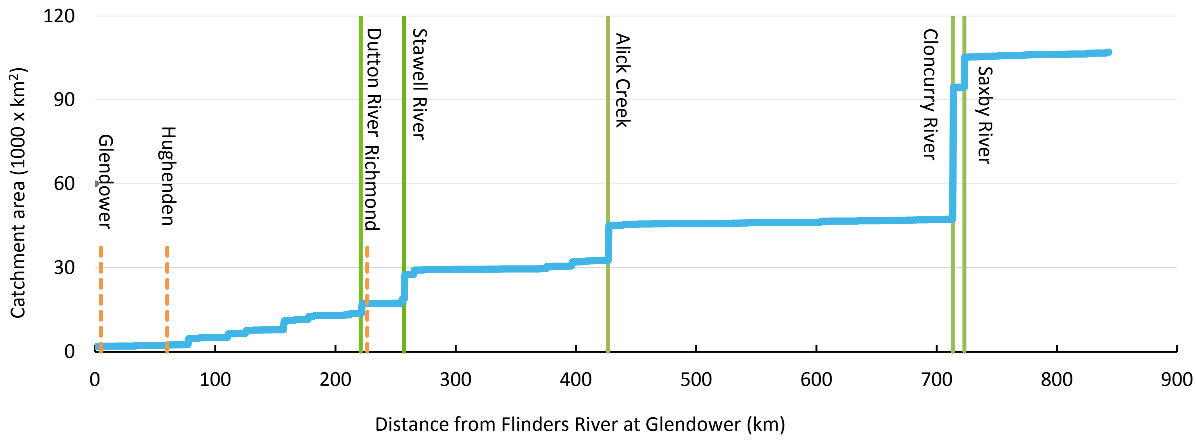

Figure 3.5 Change in catchment area along the Flinders River from Glendower to Flinder river mouth

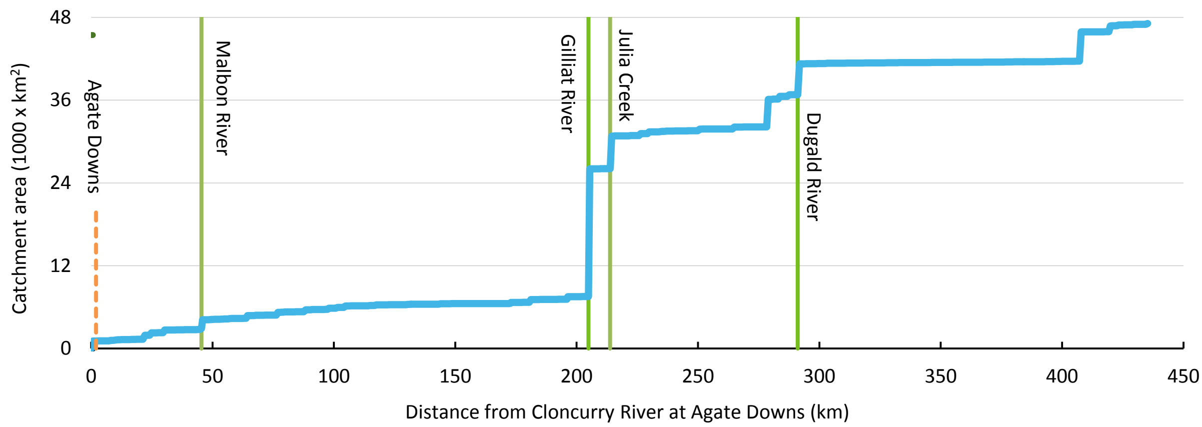

Figure 3.6 Change in catchment area along the Cloncurry River from Agate Downs to confluence with Flinders River

3.2 River models set-up

The Flinders River model developed for the Assessment was initially configured on the Flinders River basin full-utilisation IQQM Gulf Water Resources Plan model (DNRM, 2006a). The Assessment's Flinders River model extends from the headwaters of the Flinders catchment to the gauging station at Walker's Bend (915003A) (Figure 3.2). This station is located 80 km upstream of the river mouth, which flows into the Gulf of Carpentaria. The catchment area upstream of gauging station 915003A is approximately 100,000 km^2. The node-link network and the subcatchment boundaries in the Assessment Flinders River model are presented in Figure 3.7.

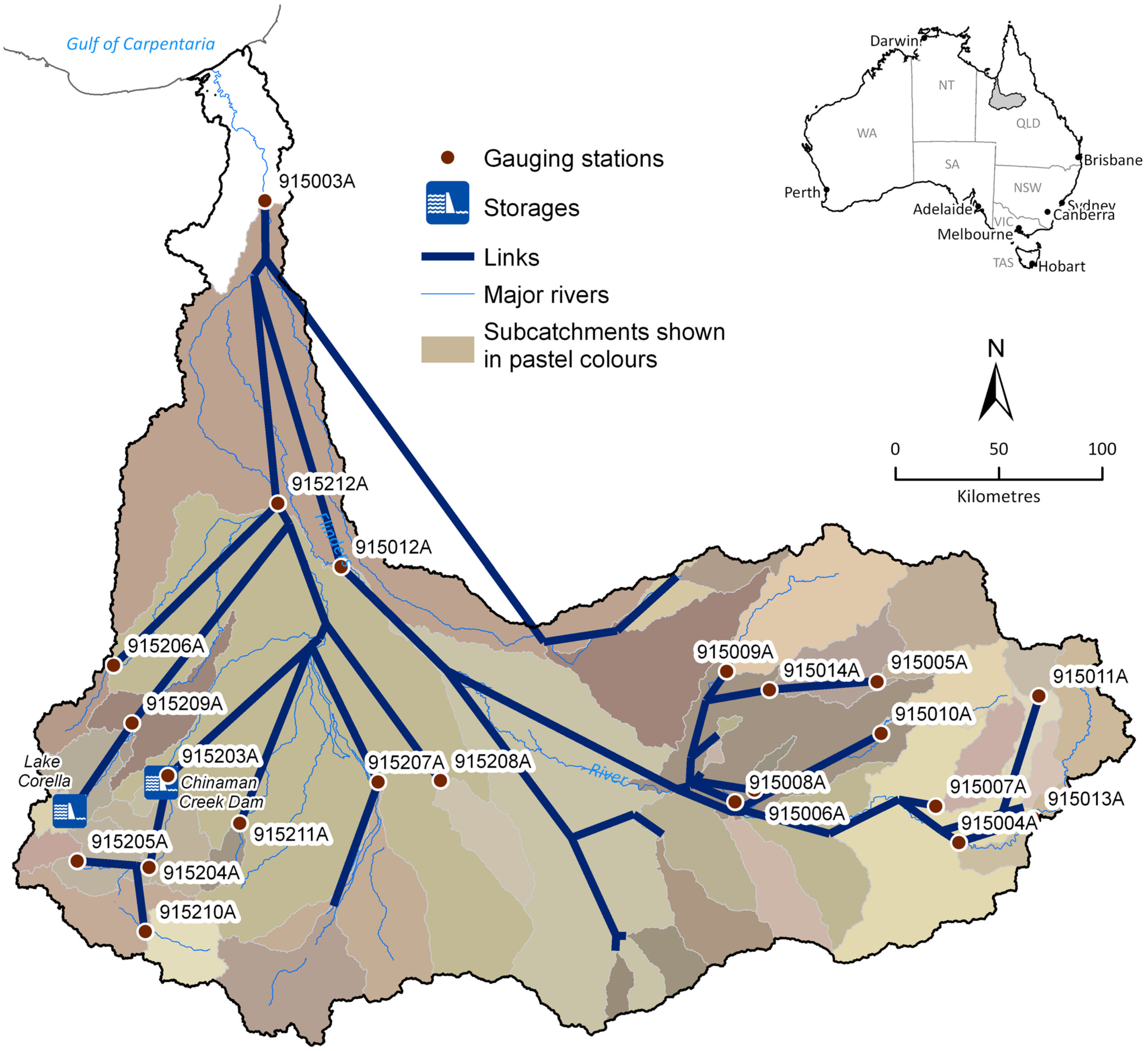

Figure 3.7 Schematic diagram of the Assessment Flinders river model configuration and gauging stations

The main features of the IQQM node-link network, the characteristics of the in-stream storages and the demand models were converted from IQQM to the eWater Source modelling framework (Welsh et al., 2012). The main changes that were introduced in the Assessment river model include:

- a finer spatial resolution, with the number of inflow nodes increasing from 32 in IQQM to 85 in the Assessment river model, and the number of routing links increased from 21 to 58;
- an extension of the input time series to cover the reporting period 1 July 1890 to 30 June 2011;
- a recalibration of the rainfall-runoff, routing and loss parameters.

Following the calibration procedure outlined in Section 2.3, the Flinders catchment was subdivided into 22 reaches based on the network of gauging stations. This resulted in 14 headwater areas and 8 residual reaches (Table 3.2). For each reach, the parameters of the river model were calibrated so as to minimise a single objective function equal to the product of the bias with the sum of square error on root square transform flows (see Equation 13).

A key characteristic of the Flinders river model is the difference in the spatial resolution of the model in the mid-headwater catchment areas and the floodplain area. As seen in Figure 3.7, the majority of the gauging stations are situated in the eastern and south-western mid-headwater catchments. Only three gauging stations are situated on the Flinders River floodplain; one at Etta Plains (915012A), one at Walker's Bend (915003A), and another on the Cloncurry River floodplain at Canobie (915212A). This difference is also evident in the area covered by the calibration reaches (Table 3.3). The three reaches upstream of Walker's Bend, Etta Plains and Canobie have the largest residual subcatchments with areas of 18,736, 23,358 and 25,695 km^2, respectively. The area of the subcatchments of the upstream reaches ranges from 199 km^2 to 9,571 km^2. This difference indicates that the model is more detailed and that it is likely to provide more accurate predictions in the upstream areas. The representation of the floodplain area in the Assessment river model remains highly simplified. To improve the manner in which the floodplain areas are simulated the Assessment includes an activity devoted to the development of a hydrodynamic model for the floodplain areas. This is discussed in more detail in the companion technical report about flood mapping (Preface Figure 1).

Table 3.2 Calibration reaches for the Flinders River model

REACH ID	DESCRIPTION	OUTLET	INLET(S)	REACH TYPE	SUB-CATCHMENT AREA (km^2)	TOTAL CATCHMENT AREA AT OUTLET (km^2)	FULL CALIBRATION PERIOD
1	Flinders River upstream of Glendower	915013A	NA	Headwater	1,910	1,910	09/1972-01/1992
2	Porcupine Creek upstream of Mount Emu Plains	915011A	NA	Headwater	550	550	09/1971-08/1991
3	Bett's Gorge Creek upstream of Alstonvale	915007A	NA	Headwater	1,070	1,070	10/1969-04/1979
4	Dutton River upstream of Perisher	915010A	NA	Headwater	1,430	1,430	10/1971-04/1980
5	Mountain Creek upstream of Revenue Downs	915006A	NA	Headwater	200	200	10/1970-10/1979
6	Stawell River upstream of Thirty Mile Hut	915005A	NA	Headwater	2,320	2,320	09/1971-03/1980
7	Woolgar River upstream of Patience Creek	915009A	NA	Headwater	3,330	3,330	09/1971-04/1980
8	Flinders River upstream of Hughenden	915004A	915013A	Residual	530	2,440	10/1969-04/1979
9	Stawell River upstream of	915014A	915005A	Residual	1,590	3,910	09/1972-09/1980

REACH ID	DESCRIPTION	OUTLET	INLET(S)	REACH TYPE	SUB-CATCHMENT AREA (km^2)	TOTAL CATCHMENT AREA AT OUTLET (km^2)	FULL CALIBRATION PERIOD
	Walker's Park						
10	Flinders River upstream of Richmond	915008A	915004A 915011A 915007A 915010A	Residual	10,200	15,690	09/1971-08/1991
11	Flinders River upstream of Etta Plains	915012A	915008A 915014A 915009A 915006A	Residual	21,910	45,040	09/1972-02/1992
12	Flinders River upstream of Walker's Bend	915003A	915012A 915212A	Residual	18,740	104,960	12/1969-09/1990
13	Cloncurry River upstream of Agate Downs	915210A	NA	Headwater	1,090	1,090	10/1970-09/1979
14	Malbon River upstream of Black Gorge	915205A	NA	Headwater	420	420	10/1970-10/1979
15	Dugald River upstream of Railway Crossing	915206A	NA	Headwater	660	660	10/1969-08/1990
16	Gilliat River upstream of Gilliat	915207A	NA	Headwater	5,790	5,790	10/1969-04/1979
17	Julia Creek upstream of Julia Creek	915208A	NA	Headwater	1,280	1,280	10/1970-02/1991
18	Corella River upstream of Main Road	915209A	NA	Headwater	1,590	1,590	10/1971-04/1980
19	Williams River upstream of Landsborough Highway	915211A	NA	Headwater	420	420	10/1970-02/1991
20	Cloncurry River upstream of Damsite	915204A	915205A 915210A	Residual	2,720	4,230	10/1968-11/1981
21	Cloncurry River upstream of Cloncurry	915203A 915203B	915204A	Residual	1,610	5,840	07/1958-10/1981
22	Cloncurry River upstream of Canobie	915212A	915209A 915203B 915211A 915207A 915208A 915206A	Residual	25,610	41,180	09/1972-02/1992

3.3 Available Data

3.3.1 CLIMATE DATA

The rainfall and potential evaporation data used to drive the model were extracted from the SILO data drill maintained by the Queensland Government (Jeffrey et al., 2001). The gridded data were interpolated from point measurements provided by the Bureau of Meteorology.

One of the limitations to hydrological and agricultural assessments in northern Australia is the availability of climate data. The distribution of rainfall data for three decadal periods in the Flinders catchment is shown in Figure 3.8.

The data include daily time series of rainfall, shortwave solar radiation, vapour pressure, minimum and maximum temperature covering the historical period 1890-2011. The last four variables were used to compute the Morton's wet environment Areal Potential Evaporation (APE). Rainfall and APE constitute the inputs to the rainfall-runoff and storage components of the river model.

The companion technical report by the climate activity (Petheram and Yang 2013) provides a detailed analysis of the characteristics and quality of the climate data.

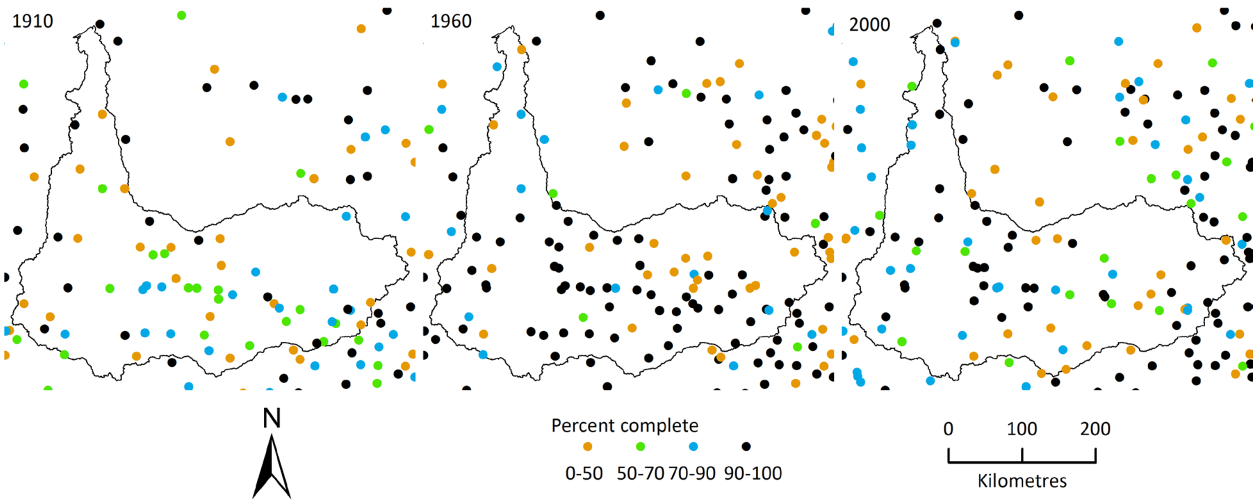

Figure 3.8 Decadal analysis of the location and completeness of Bureau of Meteorology stations measuring daily rainfall used in the SILO database. The decade labelled '1910' is defined from 1 January 1910 to 31 December 1919, and so on. At a station, a decade is 100% complete if there are observations for every day in that decade. The analysis for the decade starting in 2000 only extends to 2007

3.3.2 STREAMFLOW DATA

Streamflow data are central to the development of river models. Consequently data at all gauging stations were carefully scrutinised before and during model construction. Key characteristics of these stations are presented in Table 3.3 including the fraction of the flow above the maximum gauged level. This fraction compares the mean annual flow occurring above the highest gauged flow with the total mean annual flow. A ratio close to zero indicates that the extrapolation of the rating curve remains limited, and suggests a good quality of the flow records.

All stations except one (915203A) were open between 1968 and 1972. Nine stations are still open today, while the remaining stations except one (915204A) were closed in 1988. The duration of records is sufficient to calibrate the river model, although longer periods would greatly improve the calibration, especially in the subcatchments where the flow is highly intermittent. Table 3.3 indicates the river bed constitutes the control section for most gauging stations. In the absence of firm control structures, like weirs or rock bars that span the width of the river, the measurement of low flows (i.e. <1ML/d) remains of

limited accuracy. An example cross section is presented in Figure 3.9 for the Flinders River at Richmond (915008A).
Streamflow data are obtained by applying a rating curve to the water levels measured at the gauging station. Rating curves are based on the interpolation and extrapolation of point streamflow measurements. Consequently, the quality of the streamflow data is related to the quantity and range of the point streamflow measurements, also referred as gaugings. Table 3.3 indicates that the number of streamflow gaugings ranges from seven for Mountain Creek at Revenue Down (915006A) to 116 for the Flinders River at Walker's Bend (915003A). Seven stations have fewer than 20 streamflow gaugings. Rating curves at these stations are less likely to provide robust measurements of streamflow.

Another indicator of the quality of discharge data at a gauging station can be provided by computing the volume of streamflow that occurs above the maximum gauged level, and report this volume as a percentage of the total streamflow at the gauging station. When this ratio is close to 0, a limited amount of streamflow occurs at a level greater than the maximum gauged stage height. This is an indication that the gauging station has good quality streamflow data. Table 3.3 lists this ratio for the 22 gauging stations that have been open at some point in time in the Flinders catchment. A majority of stations in the Flinders catchment have a ratio greater than 50% with six stations having a ratio of between 50% and 80%, and at eight stations the ratio exceeds 80%. These high values indicate that the quality of streamflow data is poor at most stations in the Flinders catchment.

This analysis of the available streamflow data in the Flinders catchment indicates the quality of data is relatively low and it is likely that considerable improvements to the development of future river system models could be attained by further investment in the streamflow measurement network. In particular the following points may be considered:

- Re-opening of stations that were closed in 1988. The Flinders River at Hughenden (915004A and the Stawell River at Walker's Park (915014A) could be considered a priority.
- Increase in the frequency of gaugings on the Flinders River at Etta Plains (915012A) and on the Cloncurry River at Canobie (915212A).

Figure 3.9 The Flinders River at Richmond gauging station (915008A). Source CSIRO

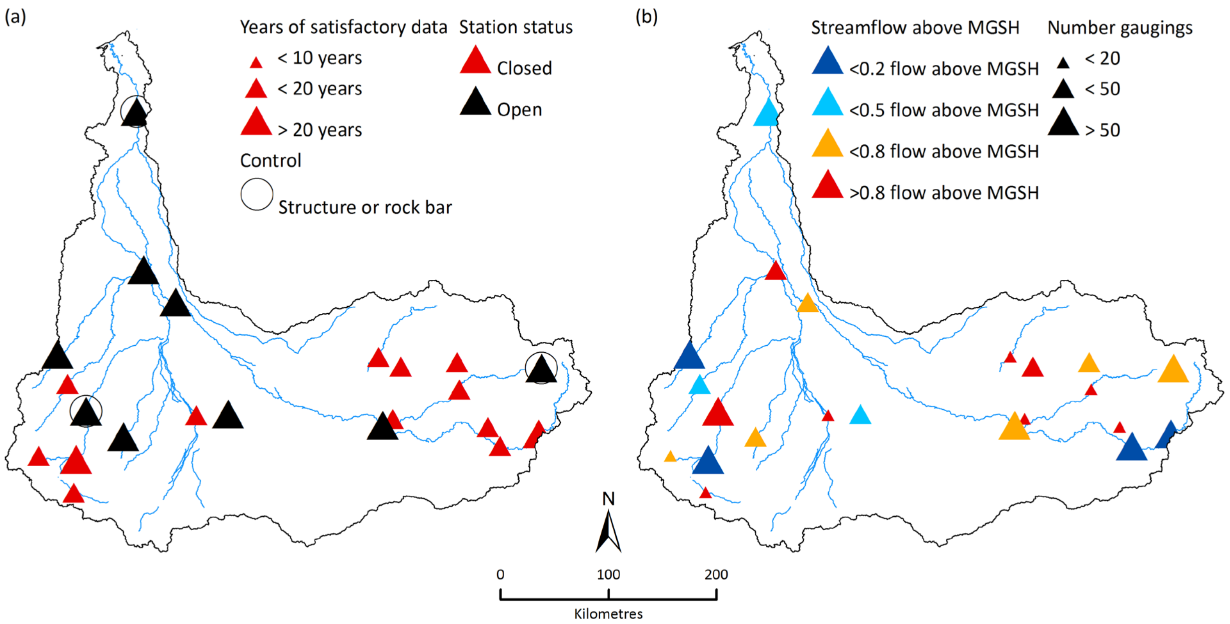

Figure 3.10 Quality of streamflow data in the Flinders catchment

Table 3.3 Key characteristics of gauging stations in the Flinders catchment

STATION ID	STATION NAME	START OF RECORDS	END OF RECORDS	CONTROL SECTION	NUMBER OF GAUGINGS WITH FLOW >0	MAX. GAUGED FLOW (ML/D)	FRACTION OF FLOW ABOVE MAX GAUGED FLOW (%)
915003A	Flinders River at Walker's Bend	12/12/1969	Current	Causeway	116	312,600	25
915004A	Flinders River at Hughenden	1/10/1969	1/10/1988	Sand	87	36,540	0
915005A	Stawell River at Thirty Mile Hut	22/09/1971	1/10/1988	Sand	33	1,550	65
915006A	Mountain Creek at Revenue Downs	1/10/1970	1/10/1988	Sand	7	370	81
915007A	Betts Gorge Creek at Alstonvale	1/10/1969	1/10/1988	Sand	9	110	98
915008A	Flinders River at Richmond	24/09/1971	Current	Sand	98	33,680	63
915009A	Woolgar River at Patience Creek	24/09/1971	1/10/1988	Sand	13	2,240	82
915010A	Dutton River at Perisher	1/10/1971	1/10/1988	Sand	14	920	83
915011A	Porcupine Creek at Mt Emu Plains	22/09/1971	Current	Control Weir	81	980	77
915012A	Flinders River at Etta Plains	3/09/1972	Current	Sand	41	32,830	71
915013A	Flinders River at Glendower	1/09/1972	16/06/201 1	Sand	63	25,890	13
915014A	Stawell River at Walker's Park	2/09/1972	1/10/1988	Sand	20	1,600	86
915203A 915203B	Cloncurry River at Cloncurry	28/07/1958	Current	Weir/ causeway	112	28,720	80
915204A	Cloncurry River at Damsite	1/10/1968	10/10/199 4	Sand Gravel	68	74,500	18
915205A	Malbon River at Black Gorge	1/10/1970	1/10/1988	Sand And Gravel	17	530	70
915206A	Dugald River at Railway Crossing	1/10/1969	Current	Gravel	58	25,170	12
915207A	Gilliat River at Gilliat	1/10/1969	1/10/1988	Soil	12	1,160	97
915208A	Julia Creek at Julia Creek	1/10/1970	Current	Mud Rock	33	8,690	37
915209A	Corella River at Main Road	1/10/1971	1/10/1988	Gravel	31	9,070	42
915210A	Cloncurry River at Agate Downs	1/10/1970	1/10/1988	Sand	16	830	89
915211A	Williams River at Landsborough Highway	1/10/1970	Current	Sand Gravel	44	2,360	68
915212A	Cloncurry River at Canobie	3/09/1972	Current	Gravel	21	7,350	94

3.3.3 DEMAND DATA

Historical diversion data were not collected for the Assessment. As indicated in Section 2.2.5, the demand models initially developed by Queensland Government as part of the Flinders IQQM model (DNRM, 2006a) were transferred to the eWater Source river models.

3.3.4 RESERVOIR DATA

Corella Dam is the only large in-stream storage in the Flinders catchment. The dam has a full supply capacity of 15,800 ML. Queensland Government provided time series of the water level and dam storage for the period between January 1973 and May 1983. The data were used to back calculate the dam inflow and outflow. The Sacramento model was then calibrated to dam inflow following the procedure described in Section 2.3.

The other large in-stream storage represented in the Flinders River model is the Chinaman Creek Dam that supplies water to Cloncurry. The reservoir has a full supply capacity of 2,750 ML. In the absence of accurate data on the characteristics of the reservoir, the storage was configured using the simplified geometry that was included in the Flinders IQQM model (DNRM, 2006a).

Ten minor in-stream storages with a total storage capacity of 5,073 ML are included in the model to represent the storage in bedsand aquifers.

3.4 Baseline model performance

3.4.1 GENERAL MODEL PERFORMANCE

The performance of the calibrated Assessment river model was investigated by comparing observed and simulated daily streamflow data at the 22 gauging stations in the Flinders catchment. For this exercise, the model was run with simulated inflow as indicated in section 2.3.1.

The performance of the baseline river model is summarised by the metrics reported in Table 3.4. The bias is low at all gauging stations, with a maximum absolute value of 13.5% computed for station 915004A at Hughenden on the Flinders River. The comparison indicates that the modelling of historical monthly and annual streamflows is good at most stations (NSE > 0.9) and in some cases excellent (NSE > 0.95). This is illustrated in Figure 3.11.

The river model NSE computed at the daily time step is acceptable (>0.5) at all stations except three (915011A, 915205A and 915209A). The daily NSE is generally lower in the Cloncurry catchment with a mean daily NSE of 0.61 for the stations 915203A-B, 915204A, 915205A, 915207A, 915208A, 915209A, 915210A, 915211A, 915212A, compared to 0.69 for the stations 915003A, 915004A, 915005A, 915006A, 915007A, 915008A, 915009A, 915010A, 915011A, 915013A and 915014A (Figure 3.7).

The NSE values are considerably lower during the dry season. The river model dry-season NSE exceeds 0.5 at only three stations on the Flinders Catchment; Mt Emu plains (915011A, 0.61), Glendower (915013A, 0.64), Etta Plains (915012A, 0.64). This is in part because NSE is a measure of relative error and, as a result, small absolute errors can result in a large relative error at low flows, and hence low NSE value. The NSE on log transform flow (another measure of the ability to simulate low flows) are generally higher but are less than 0.5 for 8 out of 22 stations. The low values obtained for these two performance metrics indicate that the relative error in simulating low flow is larger than when simulating mid to high flows. Figure 3.11 provides further elements to explain this point. The figure plots the NSE on log transform against the mean annual flow for the 22 gauging stations in the Flinders catchment. This figure shows that the performance score increases with mean annual flow. In other words, the model performance on low flow regimes remains acceptable for large subcatchments and wetter parts of the study area but degrades considerably in small and dry subcatchments. Again this is in part explained by the fact that NSE is a measure of relative error.

Table 3.4 Performance statistics of the Flinders River model. Superscript 1 designates those metrics that have most relevance to mid-high flows, superscript 2 designates those metrics that have most relevance to low flows.

STATION ID	BIAS (%) ALL PERIOD[1]	NSE DAILY[1] ALL PERIOD	NSE DAILY DRY[2] SEASON	NSE LOG[2] ALL PERIOD	NSE LOG DRY[2] SEASON	NSE MONTHLY[1] ALL PERIOD	NSE MONTHLY DRY[2] SEASON	NSE ANNUAL[1]
915003A	-6.7	0.78	0.27	0.46	-1.41	0.87	0.50	0.88
915004A	13.5	0.64	0.39	0.62	0.10	0.85	0.52	0.86
915005A	0.0	0.76	0.11	0.49	0.22	0.91	0.15	0.97
915006A	0.0	0.64	-0.63	0.33	-0.22	0.83	-0.98	0.82
915007A	0.0	0.55	0.10	0.40	-0.83	0.78	-1.42	0.76
915008A	4.5	0.81	-0.07	0.67	-0.18	0.93	-0.34	0.91
915009A	0.0	0.83	-9.44	0.56	-1.19	0.93	-7.60	0.95
915010A	0.0	0.67	-8.14	0.44	0.27	0.91	-6.26	0.95
915011A	0.0	0.46	0.61	0.52	0.09	0.84	0.70	0.83
915012A	1.1	0.82	0.64	0.73	0.09	0.91	0.66	0.94
915013A	0.0	0.59	0.64	0.56	0.29	0.82	0.68	0.81
915014A	-1.7	0.67	-0.79	0.53	-0.30	0.94	-1.44	0.98
915203AB	0.2	0.82	0.45	0.67	0.09	0.88	0.55	0.91
915204A	0.0	0.68	0.66	0.61	-0.44	0.80	0.61	0.80
915205A	0.0	0.24	-0.03	0.50	-0.52	0.71	-0.17	0.69
915206A	0.0	0.62	-0.73	0.54	-0.78	0.86	-3.04	0.90
915207A	0.0	0.76	-18.60	0.42	-2.56	0.96	-162.12	0.97
915208A	0.0	0.70	-0.16	0.26	-1.77	0.87	-0.98	0.92
915209A	-0.1	0.31	0.04	0.64	-0.47	0.74	-0.18	0.80
915210A	0.0	0.54	-1.31	0.53	-0.83	0.91	-2.36	0.95
915211A	0.0	0.63	0.06	0.52	-0.55	0.91	-0.61	0.88
915212A	5.1	0.75	-1.33	0.73	-0.55	0.88	-3.43	0.91

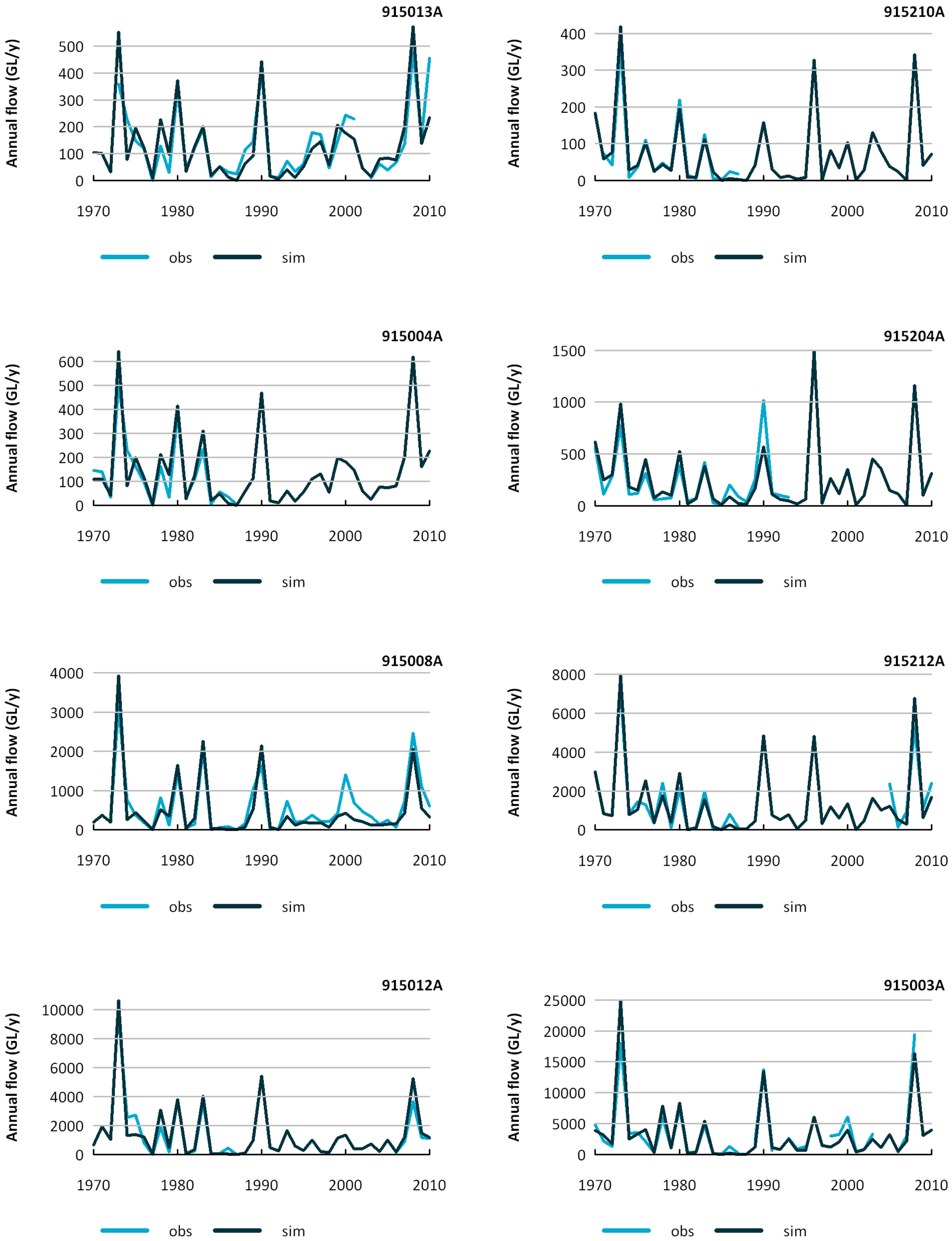

Figure 3.11 Observed (obs) and simulated (sim) annual streamflow for selected gauging stations in the Flinders catchment

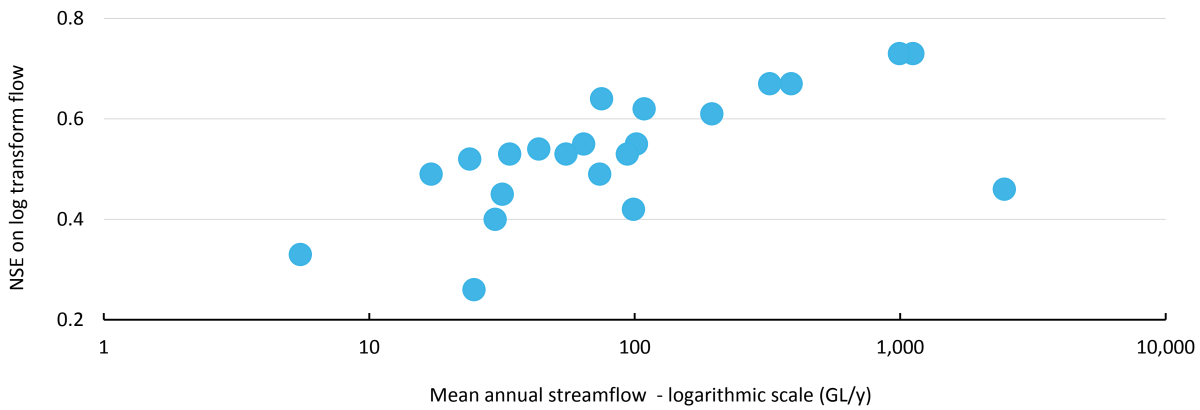

Figure 3.12 Nash-Sutcliffe Efficiency on log transform flow (Y-axis) plotted against mean annual flow (X-axis) for the 22 gauging stations in the Flinders catchment

3.4.2 PERFORMANCE IN HIGH FLOW CONDITIONS

The model performance in high flow conditions is best assessed using the daily NSE metric presented in Table 3.4. This performance metric, however, also encompasses model performance at mid-range flows, and hence is not solely a measure of the high flow performance. To complement the analysis of the NSE metrics, a visual inspection of the observed and simulated hydrographs was also undertaken. Figure 3.13 and Figure 3.14 show the observed and simulated daily flow hydrographs for the three largest flood events at eight gauging stations in the Flinders catchment. Additional plots of flood hydrographs are provided in Appendix E . These plots illustrate that the river model provides a satisfactory representation of the flood dynamic for six stations, with a good match between the observed and simulated flood peaks, peak timings and volumes. Of the two remaining gauging stations, at Walker’s Bend (915003A) the river model over predicted the largest flood event on record (i.e. in 1974) but simulated the second and third largest events well. Catchment scale rainfall and runoff during 1974 was considerably greater than all other years (see Section 3.7.1), yet the magnitude of the 1974 flood event was similar to the second and third largest recorded events. It is thought likely that during the 1974 event floodwaters may have by-passed the Walker’s Bend gauging station. Hence the simulated flood peak may be a better representation of reality than the observed flood peak.

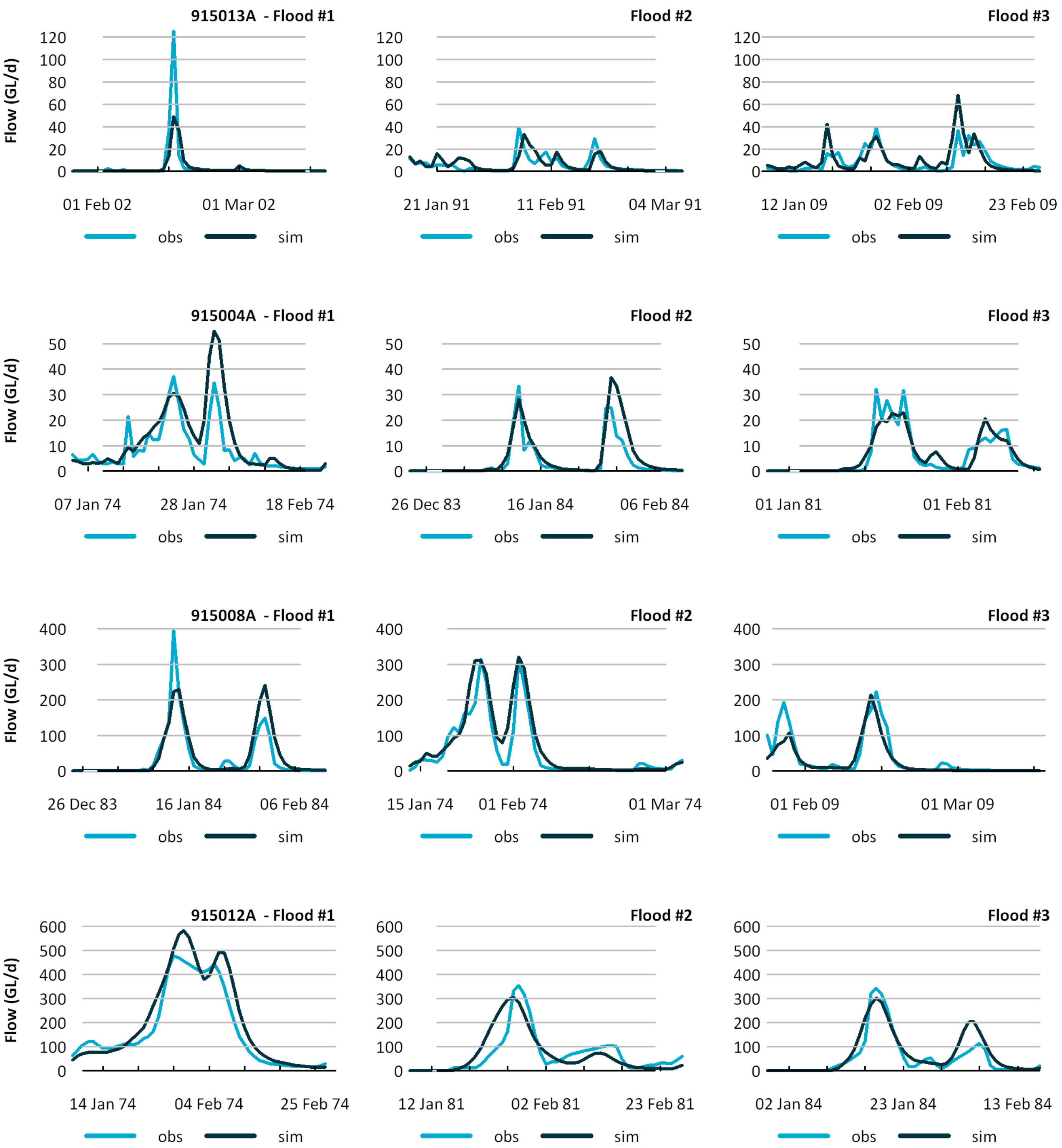

Figure 3.13 Observed (obs) and simulated (sim) flood hydrographs for the three largest streamflow events at selected gauging stations in the Flinders catchment

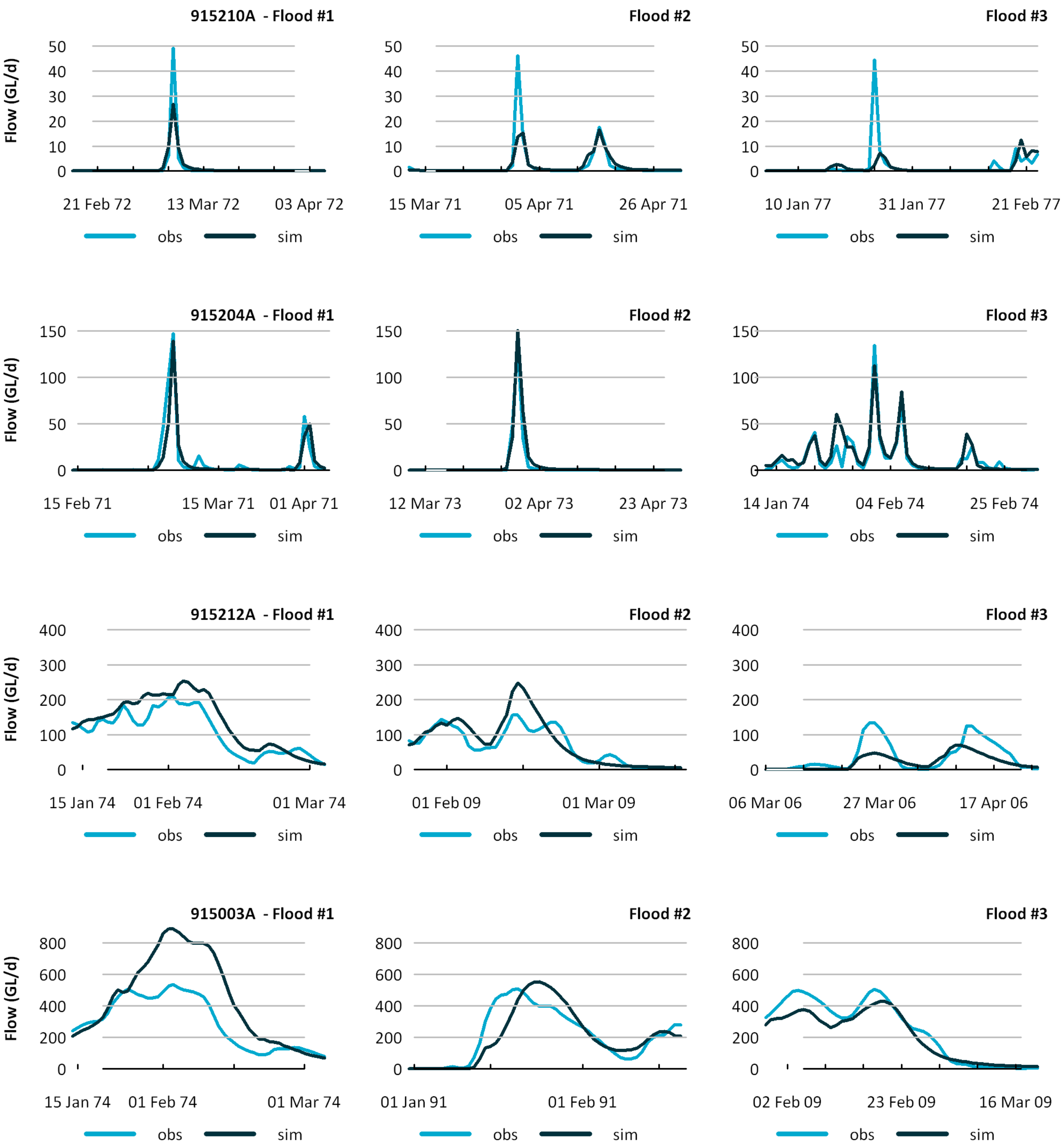

Figure 3.14 Observed (obs) and simulated (sim) flood hydrographs for the three largest streamflow events at selected gauging stations in the Flinders catchment (cont.)

3.4.3 PERFORMANCE IN LOW FLOW CONDITIONS

Low flow performance was assessed using the low flow related metrics listed in Table 3.4, as well as a visual inspection of the model outputs. The observed and simulated data were compared with the help of the flow exceedance curves shown (e.g. Figure 3.15). In this section the performance of the Assessment river model at simulating low flow conditions is presented. Figure 3.15 plots observed versus simulated flow exceedance curves, with streamflow plotted on a log-scale. The log-scale accentuates discrepancies between the observed and simulated exceedance plots at low flows and hence provides a robust test of model skill at low flows.

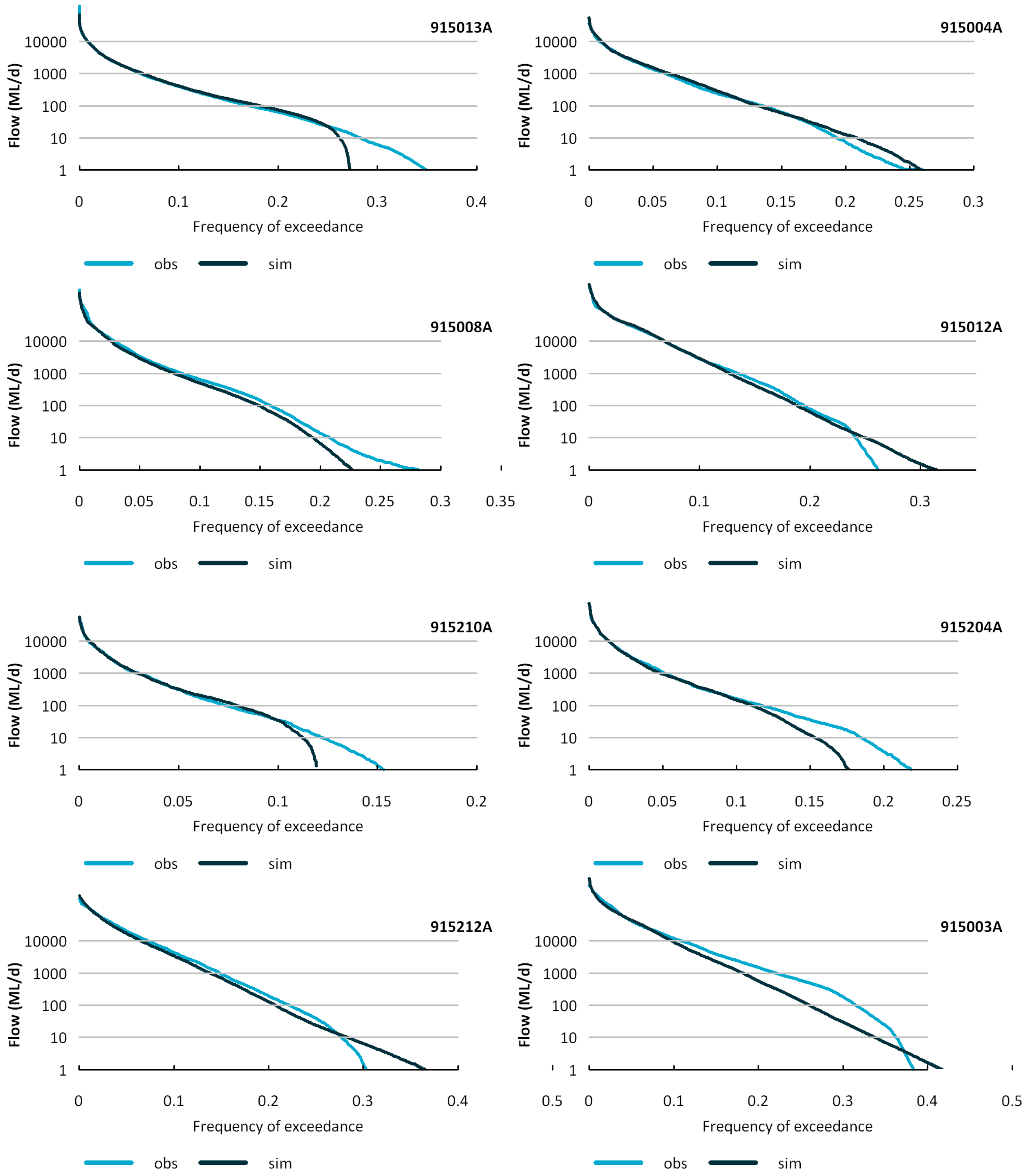

Figure 3.15 Observed (obs) and simulated (sim) flow exceedance curves in the Flinders catchment

Figure 3.15 illustrates that there is a close match between observed and simulated exceedance curves except for the very low flows (<10 ML/d). In order to précis this analysis, the two low flow criteria described in section 2.4 were computed for the 22 stations in the Flinders catchment. The first metric computes the difference between the observed and modelled exceedance at a streamflow equal to 1 ML/day. The second metric computes the streamflow threshold at which the discrepancies between the observed and simulated exceedance curves is greater than 0.05 exceedance frequency. The results are presented in Table 3.5. This table indicates that at five gauging stations the difference between the observed and simulated flow exceedance curve at 1 ML/day is lower than 0.05 (i.e. 5% error in the frequency of cease-to-flow conditions). It is between 0.05 and 0.1 at nine stations and greater than 0.1 at the remaining eight stations.

For the 17 gauging stations where the difference between the observed and simulated flow exceedance curve at 1 ML/d was greater than 0.05, the acceptable lower streamflow threshold ranged between 10.5 ML/day (at station 915004) and 736 ML/day (at station 915014).

Table 3.5 Summary of differences between observed and simulated flow exceedance curves

GAUGING STATION ID	EXCEEDANCE DISCREPANCY BETWEEN OBSERVED AND MODELLED FLOWS AT 1 ML/D (DIMENSIONLESS)	FLOW ABOVE WHICH EXCEEDANCE DISCREPANCIES ARE LESS THAN 0.05 (ML/D)
915003	0.12	51.5
915004	0.07	10.5
915005	0.12	59.7
915006	0.01	<1
915007	0.07	11.2
915008	0.09	102.3
915009	0.03	<1
915010	0.03	<1
915011	0.31	242.6
915012	0.16	110.5
915013	0.13	312.8
915014	0.09	736.0
915203	0.09	204.5
915204	0.07	41.1
915205	0.02	<1
915206	0.13	219.5
915207	0.04	<1
915208	0.06	11.2
915209	0.25	415.1
915210	0.07	23.9
915211	0.05	<1
915212	0.15	149.3

3.4.4 MODEL VALIDATION WITH K-FOLD TESTS

K-fold test (Klemes, 1986) were also undertaken to assess the performance of the river models. K-fold tests calibrate the model against one part of the observed streamflow time series and then test it on another part. Table 3.6 details the statistics obtained when the model was calibrated over the second half of the records and the resulting parameters were used to simulate runoff during the second half (calibration period) and the first half (validation period). This split was chosen in order to calibrate the model over a time period that had a similar mean annual rainfall to the reporting period. The value of the statistics was systematically worse during the validation than during the calibration period with an average increase of the absolute bias of 21.5%, a reduction of the NSE and NSELOG by 0.30 and 0.03, respectively. This drop of performance was expected due to the differences in climate conditions between the two sub-periods and the reduction of the length of the calibration period. As indicated in Table 3.5, at 16 stations out of 22, the K-fold calibration was performed with fewer than 10 years of flow data, which constitutes a very short duration for arid catchments with high inter-annual variability.

The significant bias increase between calibration and validation periods suggested that this statistic was largely influenced by the calibration period. The NSE exhibited an important drop, which was essentially occurring in the Cloncurry River (915204A) and Julia Creek (915208A). This can be explained by the arid conditions prevailing in these catchments, where the limited number of days with non-zero flow prevents the calibration algorithm from identifying a robust parameter set. By contrast, the NSELOG appeared relatively stable.

The impact of the model structure on K-fold statistics was investigated by comparing the baseline configuration with alternative approaches detailed in section 3.4.4, including a change of model inputs and the use of a different loss function. The K-fold performance of these configurations (not included in this report) did not bring significant improvement compared to the baseline approach presented here. This result suggested that the current model configuration has an appropriate level of complexity to simulate flows across the Flinders catchment.

Due to the longer calibration period that is used to derive the final parameters set, it is anticipated that the model will perform better than these statistics would indicate. Nonetheless, for some reaches the model uncertainty is quite large and can be explained by large uncertainty in rating curves and rainfall station coverage.

Table 3.6 K-fold validation results for the Flinders river model

	CALIBRATION					VALIDATION			
OUTLET STATION	PERIOD	NB OF VALID YEARS	BIAS (%)	NSE	NSELOG	PERIOD	BIAS (%)	NSE	NSELOG
915003	1990-2011	4.8	7.4	0.91	0.79	1969-1990	53.6	-0.30	0.61
915004	1979-1988	8.0	0.5	0.82	0.48	1969-1979	4.4	0.60	0.58
915005	1980-1988	8.5	-0.1	0.79	0.50	1971-1980	10.3	0.32	0.48
915006	1979-1988	9.0	0.0	0.76	0.00	1970-1979	16.0	0.42	0.10
915007	1979-1988	9.5	0.0	0.63	0.34	1969-1979	-54.4	0.49	0.43
915008	1980-1988	8.5	7.2	0.89	0.52	1971-1980	-3.8	0.77	0.64
915009	1980-1988	8.5	0.0	0.46	0.47	1971-1980	-7.8	0.62	0.42
915010	1980-1988	8.5	0.0	0.78	0.44	1971-1980	-4.9	0.40	0.46
915011	1991-2011	19.9	-0.6	0.34	0.60	1971-1991	18.8	0.40	0.55
915012	1992-2011	8.0	6.1	0.84	0.63	1972-1992	20.0	0.58	0.75
915013	1992-2011	19.2	0.0	0.60	0.49	1972-1992	18.1	0.50	0.59
915014	1980-1988	8.0	4.9	0.81	0.52	1972-1980	5.9	0.55	0.55

	CALIBRATION					VALIDATION			
OUTLET STATION	PERIOD	NB OF VALID YEARS	BIAS (%)	NSE	NSELOG	PERIOD	BIAS (%)	NSE	NSELOG
915203	1981-1994	12.8	-23.7	0.84	0.56	1958-1981	13.6	0.76	0.68
915204	1981-1994	13.1	-2.9	0.76	0.52	1968-1981	97.2	-0.02	0.65
915205	1979-1988	9.0	0.0	0.20	0.42	1970-1979	14.6	0.14	0.55
915206	1990-2011	19.8	0.0	0.60	0.53	1969-1990	-29.6	0.70	0.54
915207	1979-1988	9.5	0.0	0.69	0.29	1969-1979	60.1	-0.31	0.11
915208	1991-2011	20.4	0.0	0.49	0.24	1970-1991	48.5	-0.80	0.22
915209	1980-1988	8.5	0.1	0.64	0.58	1971-1980	-13.7	0.36	0.55
915210	1979-1988	8.9	0.0	0.67	0.54	1970-1979	14.6	0.58	0.44
915211	1991-2011	16.4	0.0	0.62	0.48	1970-1991	-3.2	0.68	0.53
915212	1980-1988	8.0	2.0	0.60	0.59	1971-1980	15.1	0.72	0.75

3.4.5 MODELLING RAINFALL-RUNOFF BELOW THE END OF SYSTEM GAUGING STATION IN THE FLINDERS FLOODPLAIN

The Flinders catchment is fortunate to have a good quality gauging station situated in the lower parts of the floodplain at Walker's Bend (915003A). This gauging station is the Flinders river model's end-of-system point.

For the purposes of modelling runoff in the small area below the Walker's Bend gauging station, Sacramento model parameters were adopted from the most immediate upstream reach (i.e. 915003A). This parameter set was chosen on the basis of its proximity and geomorphological similarity to the coastal region. Assigning model parameter sets on the basis of spatial proximity has been shown to be the best method of regionalising rainfall-runoff model parameters in northern Australia (Petheram et al. 2012). As this area is very small it has a very small impact on total runoff from the Flinders catchment.

3.5 Model uncertainty based on ensemble calibration

The calibration of the model ensembles was undertaken by repeating the calibration process 50 times as described in Section 2.3, using the 50 perturbed streamflow datasets. The perturbation of streamflow data was accomplished using a regression model described in Appendix A . Each calibration process led to a different set of parameters, which were used to generate 50 model runs and compute statistics on the outputs of the model, e.g. mean annual streamflow. The range of variation in the ensemble values gives an estimate of the uncertainty in the model results.

Figure 3.16 shows the ensemble time series for the largest flood at eight gauging stations. This figure mirrors the flood hydrographs shown in Figure 3.13 that were generated using the baseline model. Figure 3.16 confirms the conclusions drawn in Section 3.4.2; the uncertainty in the simulating flood events at gauging stations in the mid to upper catchment simulations is small relative to the simulations at gauging stations situated on the lower Flinders River floodplain area i.e. 915012A, 915212A and 915003A.

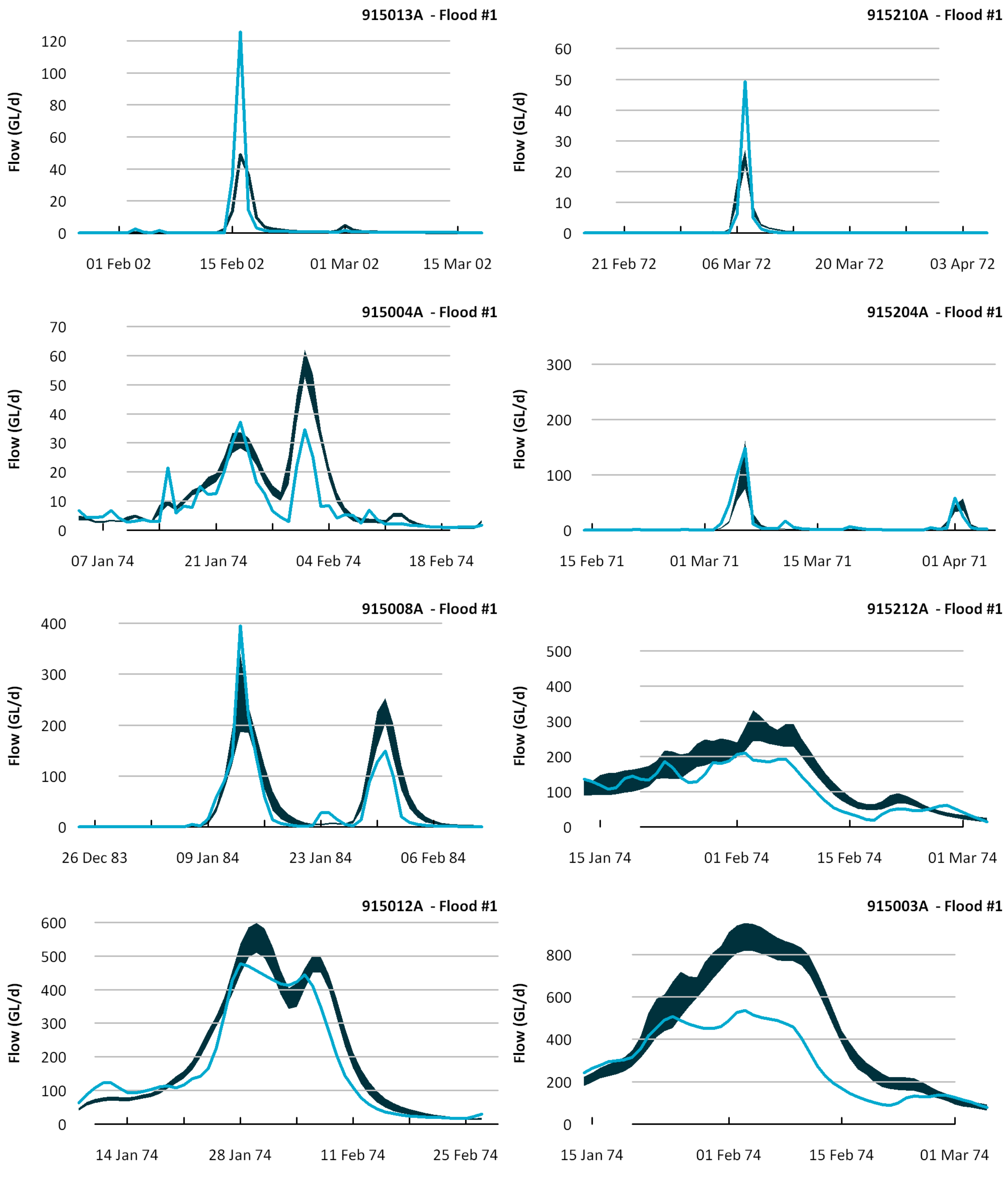

Figure 3.16 Ensemble simulations (dark blue band bounds the 97.5 and 2.5% exceedance daily flows) and observed flow (light blue) for selected gaugings in the Flinders catchment

The uncertainty in mean and median annual streamflow is presented in Table 3.7. The difference between the upstream and floodplain area is no longer evident. The uncertainty in mean annual streamflow varies from station to station with no clear spatial pattern. The results of Table 3.7 indicate that the relative uncertainty computed as the ratio between the range of the ensembles and the baseline value varies between 3% (for the station 915211A) to 28% (for station 915010A). On average, the relative uncertainty in the long term mean annual streamflow is 12%.

Table 3.7 Uncertainty in mean and median annual flow in the Flinders catchment computed over the Assessment reporting period 1890-2011

GAUGING STATION ID	MEAN ANNUAL STREAMFLOW (GL/y)			MEDIAN ANNUAL STREAMFLOW (GL/y)		
	ORIGINAL CALIBRATION	97.5% EXCEEDANCE ENSEMBLE	2.5% EXCEEDANCE ENSEMBLE	ORIGINAL CALIBRATION	97.5% EXCEEDANCE ENSEMBLE	2.5% EXCEEDANCE ENSEMBLE
915003A	2543.3	2415.3	2685.2	1241.2	1129.5	1384.4
915004A	109.9	104.8	115.4	60.2	55.0	63.9
915005A	78.7	66.9	81.7	52.0	39.8	52.7
915006A*	5.3	NA	NA	1.3	NA	NA
915007A	32.2	30.4	35.2	12.0	11.8	15.8
915008A	404.7	377.2	414.2	143.4	128.4	154.4
915009A*	64.6	NA	NA	33.1	NA	NA
915010A	34.5	28.2	38.1	15.3	10.7	17.3
915011A	25.8	21.4	25.6	13.1	10.6	14.4
915012A	1118.4	1042.4	1106.0	460.6	392.0	487.4
915013A*	110.5	NA	NA	62.6	NA	NA
915014A	98.5	92.0	107.9	53.0	44.0	55.7
915203AB	308.0	277.3	312.6	162.5	139.3	164.0
915204A	187.1	177.7	198.2	95.5	76.0	101.1
915205A	16.3	16.5	17.5	8.3	7.2	9.1
915206A	48.1	45.5	49.6	24.9	23.3	26.8
915207A*	106.7	NA	NA	<1	NA	NA
915208A*	26.9	NA	NA	2.6	NA	NA
915209A	72.3	70.5	74.7	27.1	23.3	31.6
915210A	54.8	50.5	54.1	23.7	21.8	25.0
915211A	34.4	33.4	34.6	16.3	15.6	17.7
915212A	1013.8	856.7	1089.2	515.4	349.3	563.9

* No ensemble calibration was performed for these stations

The generation of a large number of ensembles provides an opportunity to investigate the robustness of the performance scores that were computed in Section 3.4.1.Table 3.8 compares the scores obtained from the baseline model with the scores derived from ensemble simulations. This table reveals that the three metrics, bias NSE and NSELOG, are not associated with a high level of uncertainty, with limited variation of the scores across the ensemble simulations.

Table 3.8 Uncertainty in key performance metrics in the Flinders catchment

STATION ID	BIAS (%)			NSE DAILY			NSE LOG DAILY		
	BASELINE MODEL	97.5% EX. ENSEMBLE	2.5% EX. ENSEMBLE	BASELINE MODEL	97.5% EX. ENSEMBLE	2.5% EX. ENSEMBLE	BASELINE MODEL	97.5% EX. ENSEMBLE	2.5% EX. ENSEMBLE
915003A	-6.7	-7.8	-5.8	0.78	0.74	0.79	0.46	0.40	0.48
915004A	13.5	11.7	14.0	0.64	0.60	0.68	0.62	0.51	0.64
915005A	0.0	-0.5	0.1	0.76	0.64	0.76	0.49	0.43	0.50
915006A*	0.0	NA	NA	0.64	NA	NA	0.33	NA	NA
915007A	0.0	0.0	0.0	0.55	0.46	0.57	0.40	0.35	0.51
915008A	4.5	3.7	4.6	0.81	0.77	0.85	0.67	0.62	0.68
915009A*	0.0	NA	NA	0.83	NA	NA	0.56	NA	NA
915010A	0.0	-0.3	0.1	0.67	0.64	0.69	0.44	0.39	0.46
915011A	0.0	-0.3	0.0	0.46	0.41	0.50	0.52	0.52	0.58
915012A	1.1	0.8	2.3	0.82	0.80	0.82	0.73	0.70	0.76
915013A*	0.0	NA	NA	0.59	NA	NA	0.56	NA	NA
915014A	-1.7	-2.2	0.1	0.67	0.57	0.75	0.53	0.52	0.54
915203AB	0.2	-0.2	0.5	0.82	0.70	0.83	0.67	0.65	0.69
915204A	0.0	-0.1	0.0	0.68	0.47	0.71	0.61	0.58	0.63
915205A	0.0	0.0	0.0	0.24	0.23	0.30	0.50	0.48	0.55
915206A	0.0	0.0	0.0	0.62	0.51	0.69	0.54	0.52	0.55
915207A*	0.0	NA	NA	0.76	NA	NA	0.42	NA	NA
915208A*	0.0	NA	NA	0.70	NA	NA	0.26	NA	NA
915209A	-0.1	-0.3	0.1	0.31	0.30	0.38	0.64	0.62	0.67
915210A	0.0	0.0	0.0	0.54	0.54	0.61	0.53	0.51	0.54
915211A	0.0	-0.2	0.0	0.63	0.63	0.64	0.52	0.47	0.50
915212A	5.1	4.1	5.3	0.75	0.63	0.75	0.73	0.63	0.74

* No ensemble calibration was performed for these stations

3.6 Difference between Flinders IQQM and Assessment river models

As indicated in section 2.2, the Assessment river models were initially configured on the existing Flinders IQQM models built by the Queensland Government to support the Gulf Water Resources Plan and used within the Northern Australia Sustainable Yields (Petheram et al., 2009) project to estimate water yields under current and future climates. A comparison between the outputs from the Flinders IQQM and Assessment models was undertaken and concluded that significant differences existed between the two models at some gauging stations in the Flinders catchment. For example, the long term mean annual flows detailed in Table 3.7 (page 38, see also Appendix C for details about water balance tables) can be compared with the values published by Petheram et al. (2009). The comparison is not straightforward because Petheram et al. (2009) used a different reporting period (1930-2007) than the one used for the Assessment (1890-2011). Nonetheless, the difference between the IQQM and Assessment river models appeared significant at Hughenden (915004A), Richmond (915008A) and Walker's Bend (915003A). For those stations, Petheram et al. (2009) obtained a mean annual flow of 91.9, 347.7 and 1937.9 GL/y, respectively, whereas Table 3.7 indicates values of 109.9, 404.7 and 2543.3 GL/y for the same stations, respectively. This section details the analysis that was undertaken to explain these differences.

The IQQM and Assessment river models were built with similar approaches including the use of the same rainfall-runoff model (Sacramento), the same routing algorithm (non linear storage routing with lag) and the same location for the gauging stations. However, several elements differ between the two models:

- Spatial resolution: the Assessment models were developed using a finer spatial resolution than the IQQM models to better enable scenario modelling, using hypothetical storages and irrigation demands at various location across the catchments.
- Climate input data: rainfall and potential evaporation time series that were used to calibrate and run the two models were different. The IQQM climate data were averaged between point observation data. The Assessment model used gridded climate data extracted from the SILO data drill. In addition, the IQQM potential evaporation data were derived from pan evaporation data multiplied by a monthly pan-factor varying between 0.81 and 0.96. The Assessment used Morton's wet environment areal potential evaporation (see the companion report by Petheram and Yang, 2013).
- Loss functions: in IQQM, the losses were parameterised as tabulated loss functions determined at the end of the calibration process. In the Assessment, the losses were parameterised using the 2-parameter Monod function and calibrated jointly with the rainfall-runoff and routing components.
- Calibration procedure: The calibration approach differed between the two models, including:
    - Calibration period - the IQQM model was calibrated against streamflow data up to June 2003 whereas the Assessment calibration used streamflow data up to June 2011 where available. Although the majority of gauging station observations ceased in the early 1990s, some of the key stations (Glendower, Richmond and Walker's Bend) had records up to 2011.
    - Calibration algorithm - the IQQM model was calibrated manually whereas the Assessment model used an automatic search algorithm.
    - Objective function - the automatic search algorithm implemented in the Assessment calibration was driven by an objective function combining the model bias and the mean squared error on square root transform flow. Objective functions were not used in the calibration of the IQQM model calibration because the model was calibrated manually, using a combination of performance metrics and visual inspection of observed and simulated hydrographs and flow duration curves to assess model fit.
- Error correction algorithm (DMM) - the last stage of the IQQM calibration method introduces a correction of the ungauged inflows generated with the Sacramento rainfall-runoff model. This is done to improve the match between the simulated and observed streamflow at the gauges over the period for which there is observed streamflow data. This procedure was not implemented in the Assessment calibration method, because there is no means of suitably adjusting the error correction under future climate and development scenarios.

3.6.1 METHOD USED TO INVESTIGATE THE DIFFERENCES

In order to assess the impact of the differences listed in Section 3.6, the Assessment calibration was modified to reproduce certain aspects of the IQQM calibration. The original and modified Assessment calibration was compared with the IQQM results to provide a better insight into the differences between the two models. Table 3.9 presents the six configurations tested:

- The first two models correspond to the IQQM model. Configuration 1 (IQQM-NASY) is identical to the model used during the NASY project. This model is identical to the IQQM-WRP model except that its simulation period was extended up to 2008. Configuration 2 (IQQM-CAL) is identical to 1 except that the DMM procedure has been removed. The inflows used in this configuration are identical to the output of the Sacramento rainfall-runoff model. This configuration is used as the reference to be compared against the Assessment model configurations in the rest of this section.
- Configuration 3 (FGARA-R) corresponds to the model calibrated for the Assessment and is used to produce results in the rest of this document. The model was calibrated against flow data up to 2011 and uses the SILO climate inputs.
- Configurations 4 to 6 are identical to 3 except for one element:
    - Configuration 4 (FGARA-P) is calibrated on the same period as the IQQM, i.e. up to 2003. The difference between configuration 3 and 4 is due to the difference in calibration period.
    - Configuration 5 (FGARA-I) is identical to configuration 3 except that the model uses the IQQM climate inputs. It is important to note that the model was recalibrated with different inputs, not simply run with the same parameters as FGARA-R. This was undertaken to allow the model to adjust to the new input data set and better reflect the effect of those inputs to the model outputs.
    - Configuration 6 (FGARA-L) is identical to configuration 3 except that the Monod loss function is replaced by a tabulated function. The function is obtained in two steps. In the first step, the Assessment model (configuration 3) is run without the Monod Loss function by setting the Monod parameters to 0. A tabulated loss function is then fitted between the model simulated flow and the corresponding flow data by matching the flow percentiles in both time series following Hughes et al. (2012).
- Configuration 7 is a combination of configurations 4 to 6.

In order to facilitate comparison between the different models’ outputs and performance, the long term mean annual flow was computed over the period 1930-2007 for all the configurations listed in Table 3.9. This period is consistent with the one used in the NASY project but is different from the Assessment reporting period (1890-2011) used in the rest of the document. The Assessment period was not used because the IQQM simulations stop in 2008. For the same reason, the computation of performance statistics comparing modelled and observed flow was performed for the period up to 2008.

Table 3.9 List of model runs investigated for the comparison between the Assessment (FGARA) and IQQM river models

MODEL ID	MODEL NAME	CALIBRATION PERIOD	LOSS FUNCTION	CALIBRATION METHOD	CLIMATE INPUT DATA	COMMENTS
1	IQQM-NASY	Up to 2003-06 when flow data is available	Tabulated	Manual	IQQM	Parameters were provided by DSITIA. Model was identical to the one used for the NASY project including storage and diversions.
2	IQQM-CAL	Up to 2003-06 when flow data is available	Tabulated	Manual	IQQM	Same parameters as IQQM-NASY. The model was run without the DMM procedure.
3	FGARA-R	Up to 2011-06 when flow data is available	Monod	Assessment Objective function + SCE optimisation	Assessment	Model calibrated for Assessment and used in other sections of this report.
4	FGARA-P	Up to 2003-06 when flow data is available	Monod	Assessment Objective function + SCE optimisation	Assessment	Identical to Assessment model except that the calibration period is limited to the IQQM calibration period (prior to 2003).
5	FGARA-I	Up to 2011-06	Monod	Assessment	IQQM	Identical to Assessment model

MODEL ID	MODEL NAME	CALIBRATION PERIOD	LOSS FUNCTION	CALIBRATION METHOD	CLIMATE INPUT DATA	COMMENTS
		when flow data is available		Objective function + SCE optimisation		except that the model is run with IQQM climate inputs
6	FGARA-L	Up to 2011-06 when flow data is available	Tabulated	Assessment Objective function + SCE optimisation	Assessment	Identical to Assessment model except that the Monod loss function is replaced by a tabulated function
7	FGARA-PIL	Up to 2003-06 when flow data is available	Tabulated	Assessment Objective function + SCE optimisation	IQQM	Combination of FGARA-P, FGARA-I and FGARA-L

The results of this comparison are presented and discussed in the two following sections. A table listing the long term mean annual flows and performance scores for each station is provided in Appendix B .

3.6.2 DIFFERENCES IN MEAN ANNUAL FLOWS

This section compares the long term mean annual flows computed for the period 1930-2007 at the 22 gauging stations in the Flinders catchment and the seven configurations presented in Table 3.9. The values are shown in Figure 3.17 with details provided in Appendix B . The relative difference between the configurations FGARA-R, FGARA-I, FGARA-L, FGARA-PIL and IQQM-CAL is presented in Figure 3.18.The following comments can be made about these results:

- The difference between the IQQM and Assessment mean annual flow remains small for a majority of stations. More precisely, Figure 3.18 shows that the flow computed with the FGARA-R configuration remains within 15% of the flow computed with the IQQM-CAL configuration at all stations except 915003 (Walker’s Bend, difference of 23%), 915203 (Cloncurry at Cloncurry, difference of 19%) and 915204 (Cloncurry at Dam Site, difference of 25%).
- The change of calibration period (FGARA-P) and the use of a tabulated loss function (FGARA-L) produced nearly identical mean annual flows to the original Assessment configuration (FGARA-R). This can be seen in Figure 3.18 where the lines corresponding to the three configurations are indistinguishable. Walker’s Bend (915003), Hughenden (915004), Dugald River (915206) and Landsborough Highway (915211) are the only exceptions. FGARA-L produces higher flows than FGARA-R at 915003 (2735 against 2388 GL/y) and lower flows at 915004 (93 against 100 GL/y). FGARA-P produces lower flows than FGARA-R at 915003 (2049 against 2388 GL/y) and higher flows at 915206 (51 against 44 GL/y) and 915211 (37 against 34 GL/y).
- Among all the variants introduced in the calibration method, the change of climate inputs (FGARA-I) has the largest impact on the flow with a reduction of the mean flow by approximately 15%. As indicated in Figure 3.18, this reduction brings the mean annual flows produced with the FGARA-I configuration within 10% of IQQM-CAL for Mt Emu plains (915011), Glendower (915013), Walker’s Park (915014), Cloncurry (915203), Cloncurry River at Dam Site (915204), Black Gorge (915205), Agate Downs (915210) and Landsborough Highway (915211). In particular, the change of input data implemented in FGARA-I explains the large differences between FGARA-R and IQQM-CAL at 915003, 915203 and 915204.
- The combination of the three variants (FGARA-PIL) remains close to the configuration with modified climate inputs (FGARA-I). This result suggests that the change in input data dominates all other variants in regards to the mean annual flow.

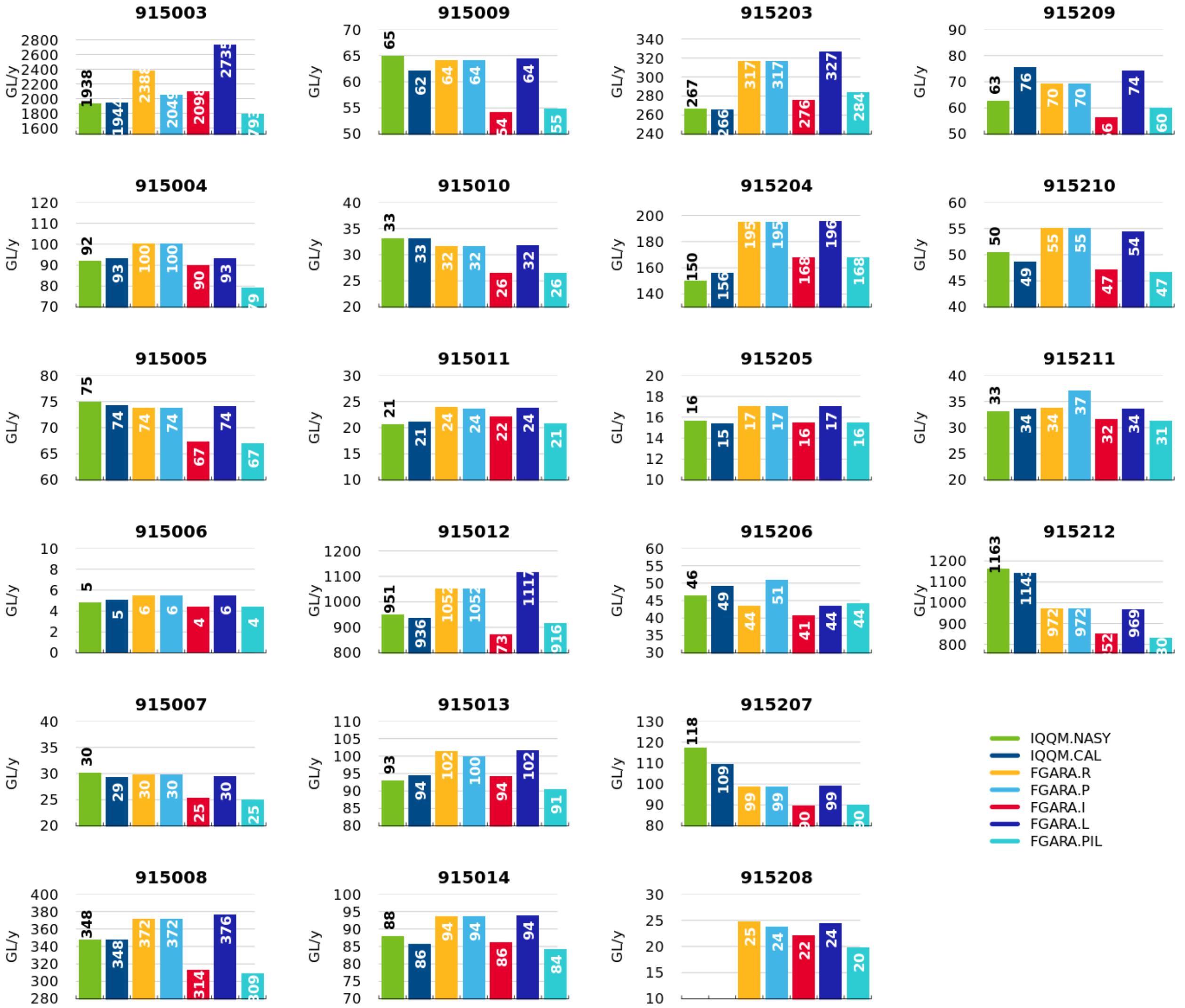

Figure 3.17 Mean annual flow over the period 1930-2007 for the six configurations listed in Table 3.9

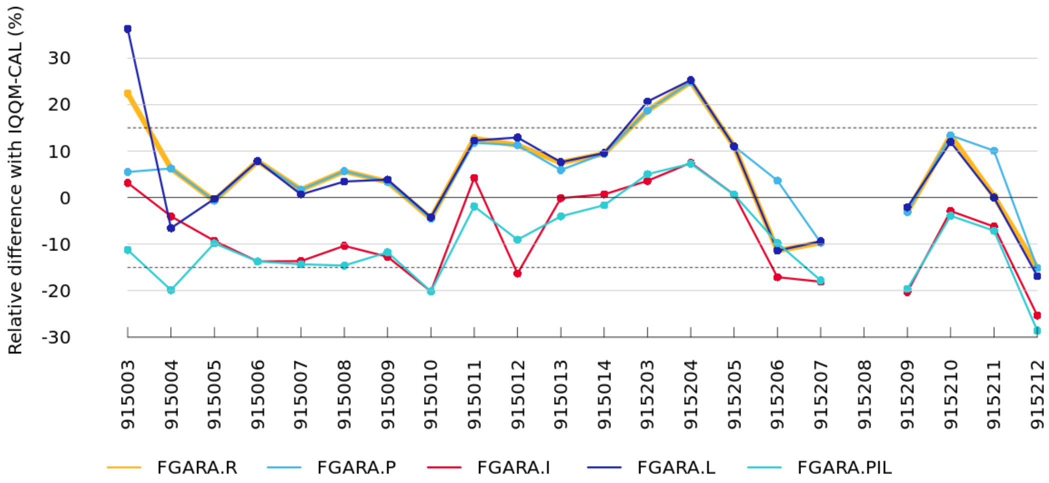

Figure 3.18 Relative difference between the mean annual flow computed with the IQQM-CAL configuration (IQQM model without the DMM procedure) and the four Assessment configurations (FGARA, FGARA-P, FGARA-I, FGARA-L, FGARA-PIL)

More specifically, the large differences observed at 915003, 915203 and 915204 between IQQM and FGARA-R can be explained by the following factors:

- Walker's Bend (915003): the change of the calibration period from 1970-2003 (IQQM) to 1970-2011 (FGARA) was the principal factor explaining the difference between the two models. The calibration of FGARA over the IQQM period (FGARA-P) leads to a mean annual flow of 2049 GL/y, which is comparable to the value of 1943.7 GL/y obtained with the IQQM-CAL model (+5%). The role of the calibration period at this station can be explained by the large flood that occurred in January and February 2009 in the Gulf Region. This flood was captured by the FGARA-R calibration but not in IQQM-CAL.
- Cloncurry at Cloncurry (915203) and Cloncurry River at Dam Site (915204): at these two stations, the change of input data was the principal reason for the difference between IQQM and FGARA results.

The previous results have revealed that the change of input data explains the differences between IQQM and Assessment models at most stations, with the other factors being of second order. To investigate this question further, Figure 3.19 shows the IQQM and Assessment climate input data for the residual catchment upstream of the Cloncurry River at Dam Site (915204). Data on other subcatchments show a similar pattern. Figure 3.19 reveals that

- The rainfall data are nearly identical between the two models.
- There is a significant difference between the PE used by the two models. The PE used in IQQM, which is based on pan evaporation data, appears much larger with an average of 2671 mm/y compared to 1847 mm/y for the Assessment. As a reference, the data published by Wang et al. (2001) suggest that the average areal potential evaporation can vary between 1500 and 1900 mm/y in this area.
- The annual variability of the IQQM evaporation data is not constant over time. During the recent period (1968-2010), it appears much larger than the annual variability in Assessment evaporation data. Conversely, the IQQM annual potential evaporation remains constant prior to 1968 whereas the Assessment data keep a similar variability than the one observed after 1968.

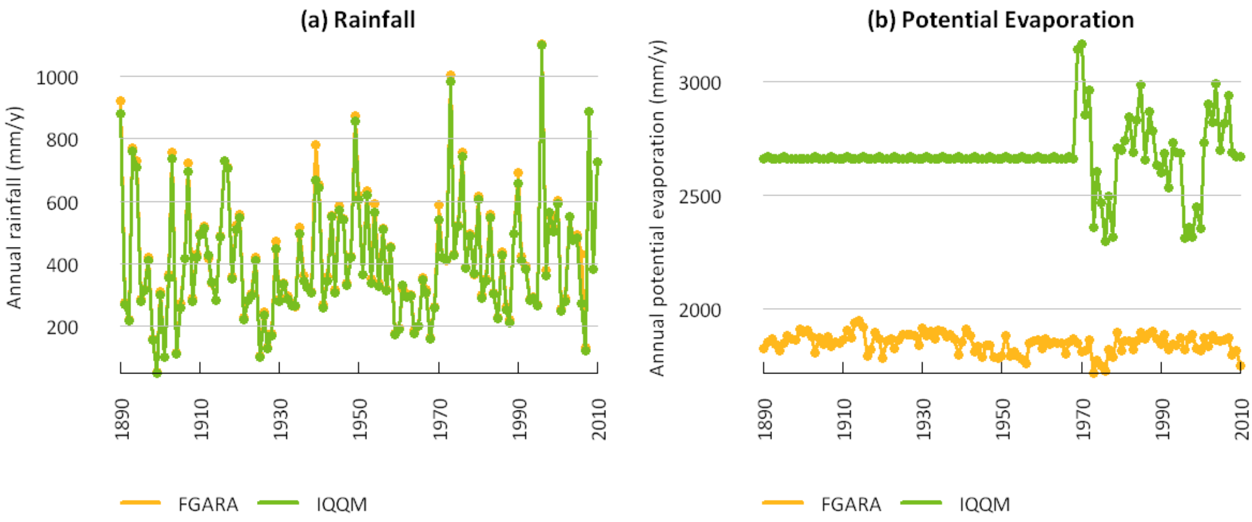

Figure 3.19 Annual time series of rainfall and potential evaporation for the residual catchment upstream of the Cloncurry River at Dam Site (915204).

3.6.3 DIFFERENCES IN MODEL PERFORMANCE

The comparison between long-term mean annual flows presented in the previous section was based on model outputs only, with no reference to observed flow data. This section investigates the performance statistics comparing the simulated and observed flow data.

Figure 3.20 and Figure 3.21 shows the model bias and Nash-Sutcliffe efficiency (NSE) introduced in section 2.4 and computed over the period of records up to 2008 for the 22 stations in the Flinders catchments. The NSE efficiency computed on log transformed flows is given in Appendix B Results for this statistic follow a similar pattern to the bias and were not included in this section. Figure 3.20 and Figure 3.21 can be commented as follows:

- The IQQM-NASY configuration obtains the best performance scores with bias remaining close to 0 and NSE close to 1 for nearly all the stations. This result was expected because the IQQM-NASY includes the DMM error correction procedure, which adjusts the ungauged inflows to match the simulated flows in the river system. As a result, the performance of IQQM-NASY cannot be compared with the Assessment model results, which do not include this type of correction.
- Regarding bias (Figure 3.20), the six configurations (excluding IQQM-NASY) show similar performance scores. The absolute bias remains below 10% for all models and all stations except at 915003 (Walker's Bend) and 915008 (Richmond) where all models tend to underestimate the mean flow with bias ranging from -21% (FGARA-PIL) to -4% (FGARA-R).
- Regarding NSE (Figure 3.21), FGARA-R obtains better scores than IQQM-CAL for all stations. The improvement is significant at 915007 (0.55 for the Assessment against 0.29 for IQQM-CAL), 915009 (0.83 against 0.57), 915012 (0.82 against 0.54) and 915207 (0.76 against 0.32).

The previous results indicate that the IQQM and Assessment model obtain similar performance scores regarding bias and NSELOG during the calibration period. Both models show a satisfactory goodness of fit to the observed flow data. However, the Assessment model provides significant improvement regarding the NSE statistic. This result indicates that the Assessment model better simulates the high flow regime across the Flinders catchment.

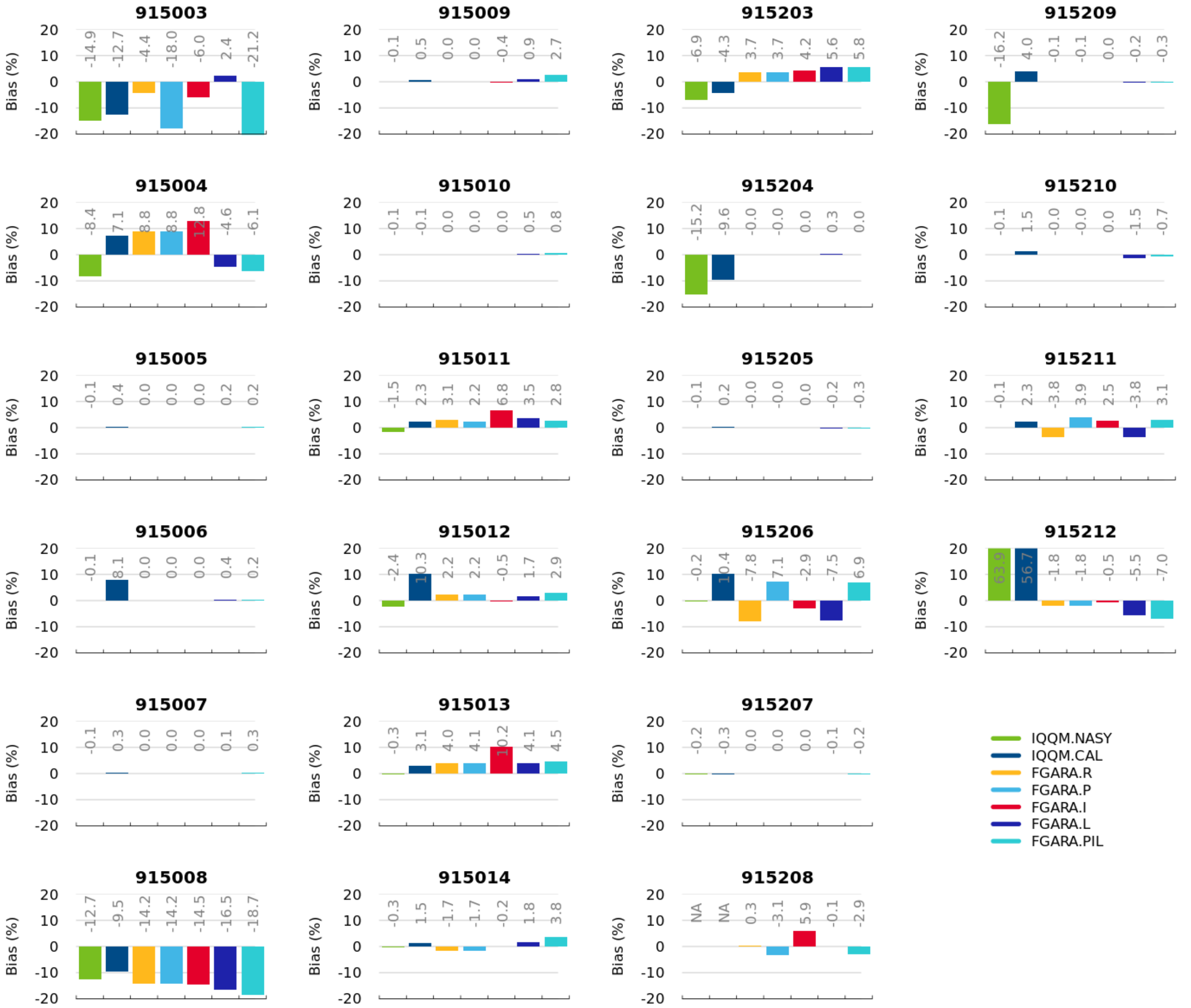

Figure 3.20 Model bias computed over the period of flow record up to 2008 for the IQQM and FGARA configurations

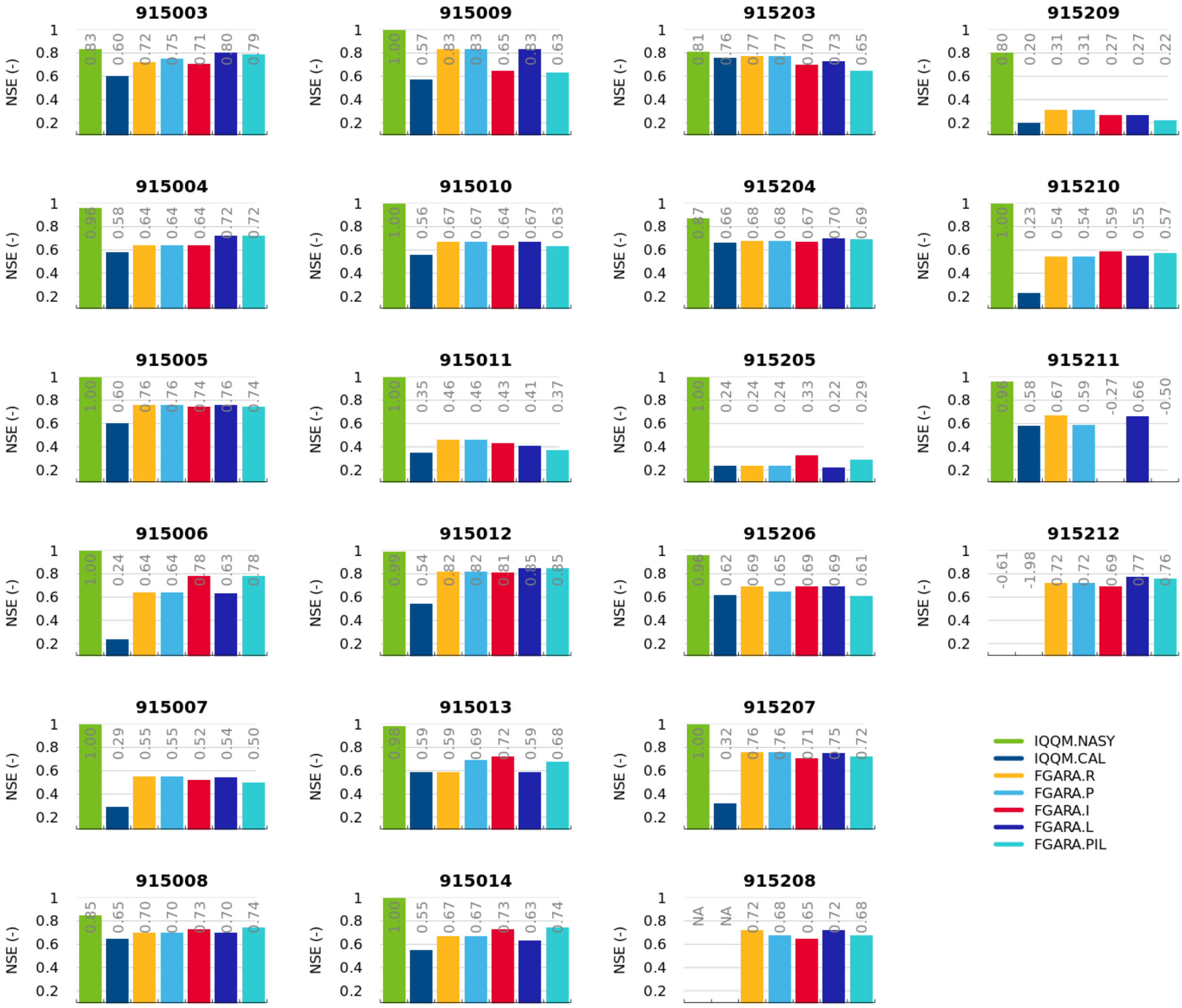

Figure 3.21 Model Nash-Sutcliffe efficiency computed over the period of flow record up to 2008 for the IQQM and FGARA configurations

3.6.4 CONCLUSION ON THE DIFFERENCES

Differences exist between the IQQM and Assessment river models developed for the Flinders catchment. A detailed comparison between the two models including variations in the Assessment calibration approach suggested that:

- The main factor explaining the difference between the two models is the use of different climate input data. The IQQM PE data were derived from pan evaporation data multiplied by a monthly pan-factor. The Assessment used Morton's wet environment areal potential evaporation.
- Both models show similar performance regarding bias and low flows (estimated with the NSELOG statistic).
- The Assessment river model performs better for the high flow regime as indicated by higher NSE values.

3.7 River water balance

This section presents the results obtained by running the Assessment Flinders river model under Scenario A over the Assessment reporting period (1890-2011). The model was run using the following set-up:

- Full use of the existing water entitlements,
- Historical climate,
- A single baseline run and 50 ensemble runs.
- Simulated inflows (see section 2.3.1).

3.7.1 CATCHMENT RUNOFF

Catchment runoff data presented in this section were simulated using the baseline Sacramento rainfall-runoff model parameters.

Figure 3.22 shows the spatial distribution of mean annual rainfall and runoff under Scenario A across the Flinders catchment. The mean annual rainfall and runoff averaged over the Flinders catchment is 492 mm (Petheram and Yang 2013) and 35 mm respectively. However, mean monthly and annual runoff data in northern Australia can be highly skewed. Consequently, Figure 3.23 shows the spatial distribution of the 20%, 50% and 80% annual exceedance runoff under Scenario A. The 20%, 50% and 80% annual exceedance runoff averaged across the Flinders catchment was 51 mm, 22 mm and 7 mm respectively. The largest runoff under Scenario A was 277 mm in 1974. The smallest catchment average runoff under Scenario A was 0.5 mm in 1902.

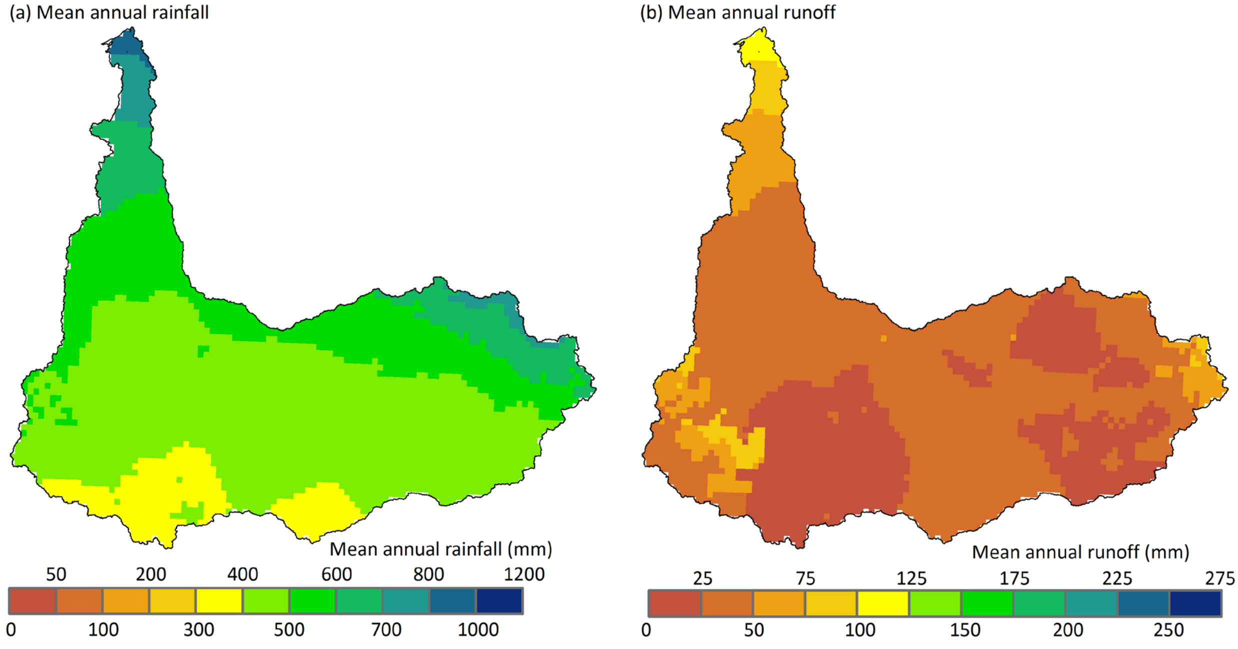

Figure 3.22 Mean annual modelled runoff in the Flinders catchment under Scenario A

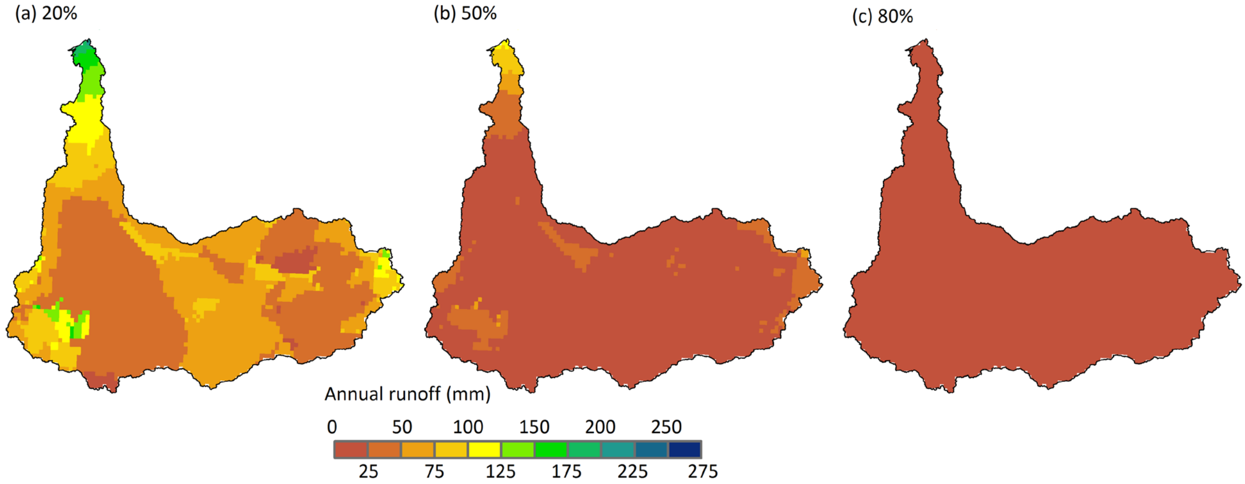

Figure 3.23 20th, 50th and 80th percentiles of modelled annual runoff in the Flinders catchment under Scenario A

Approximately 95% of runoff occurs during the wet season, with the majority of runoff occurring during the months January to March. Figure 3.24 illustrates the large monthly variability in runoff in the Flinders catchment.

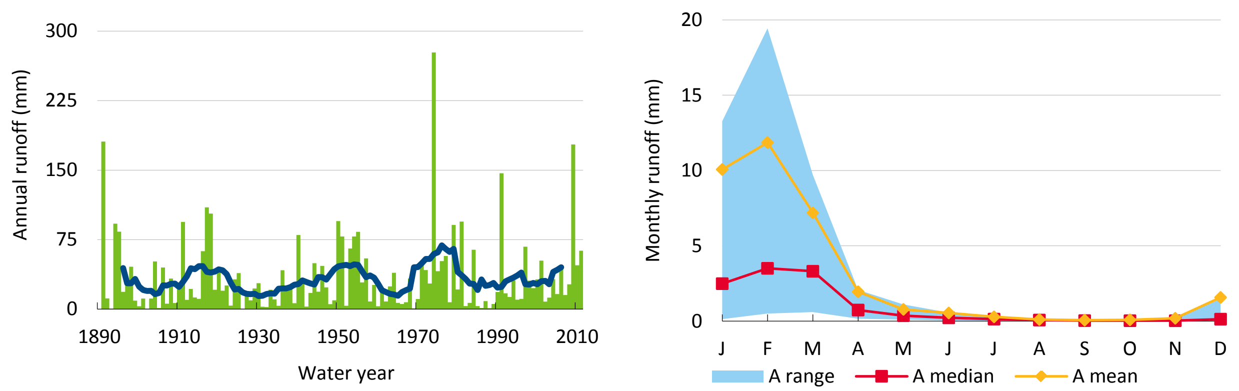

Figure 3.24 Annual runoff averaged across the Flinders catchment under Scenario A (left). Monthly runoff averaged across the Flinders catchment (right) under Scenario A

Figure 3.25 illustrates water years where runoff was above or below the median annual runoff. In this figure it can be seen that there were long runs of dry years around 1930 and 1990.

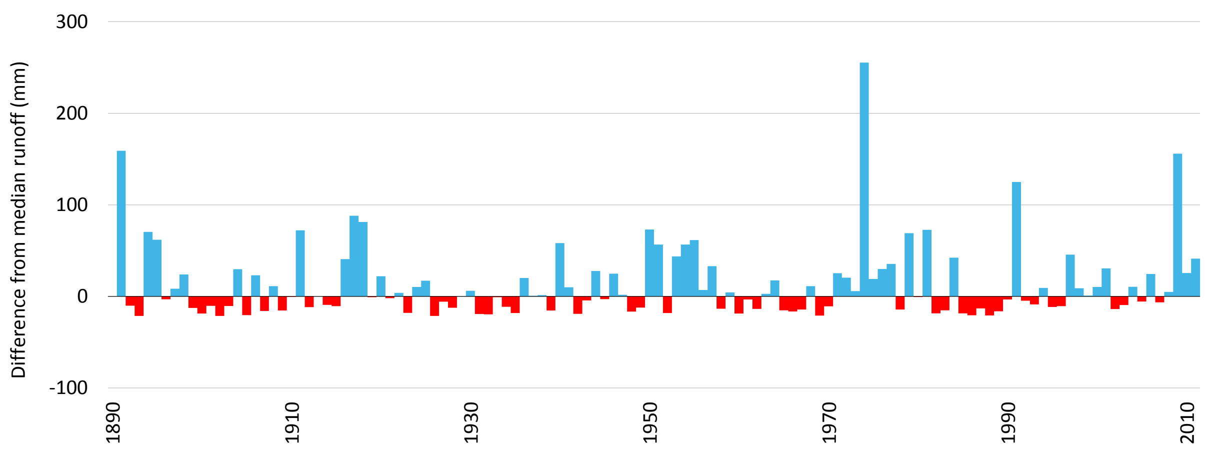

Figure 3.25 Runs of wet and dry runoff years averaged across the Flinders catchment under Scenario A

3.7.2 MEAN ANNUAL WATER BALANCE

This section presents the results obtained by running the baseline Flinders river model and the 50 river model ensembles under Scenario A. Table 3.10 shows the water balance table for the entire catchment including: the change in reservoir volume; the net evaporation from reservoirs; the catchment inflow computed as the total of simulated flow from the headwater reaches listed in Table 3.2; diversions; outflow at the end of the system (Walker’s Bend gauging station, 915003A) and losses. More detailed water balance tables are provided in Appendix C .

Table 3.10 Flinders river model mean annual water balance under Scenario A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0.0	0.0	0.0
	Net Rainfall on ponded area	0.9	0.8	0.9
	Net evaporation from ponded area	5.1	4.9	5.2
Inflows*	Subcatchments gauged	711.1	678.4	724.5
	Subcatchments ungauged	2448.3	2324.8	2568.8
	Sub-total	**3159.4**	**3006.3**	**3292.5**
Diversions	Agriculture – general security	12.4	12.1	12.5
	Agriculture – unsupplemented	70.6	68.6	70.6
	Water supply – High security	2.2	2.1	2.2
	Water supply – unsupplemented	0.1	0.1	0.1
	Other uses – High security	2.8	2.7	2.8
	Other uses – unsupplemented	1.0	1.0	1.0
	Sub-total	**89.2**	**86.7**	**89.2**
Outflows	**End of system flow (915003A)**	**2543.3**	**2415.3**	**2685.2**
	Reach losses	522.8	478.8	542.8

Figure 3.26 and Figure 3.27 illustrate the mean annual flow along the Flinders and Cloncurry rivers respectively.

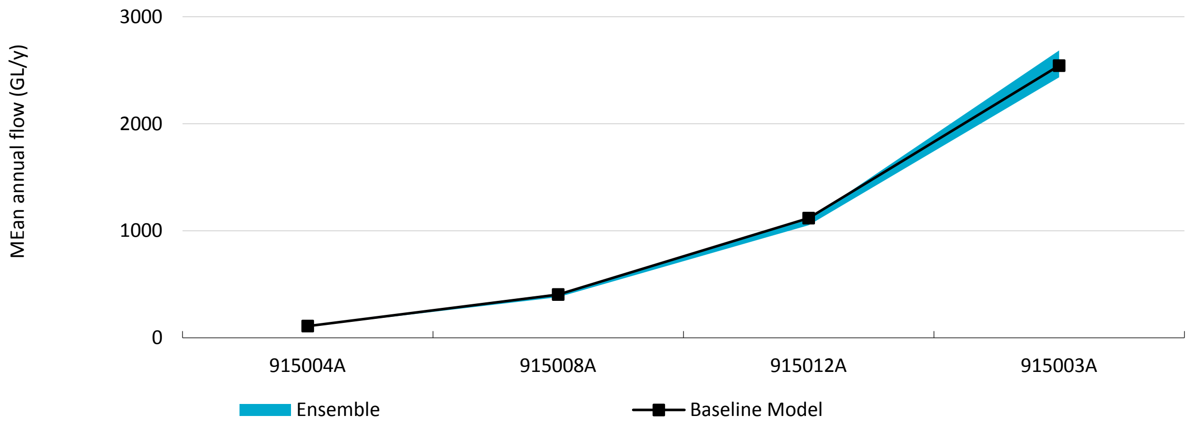

Figure 3.26 Mean annual streamflow along the Flinders River under Scenario A as simulated by the baseline river model (black line) and the 2.5% and 97.5% exceedance ensemble river models (shown by blue shading)

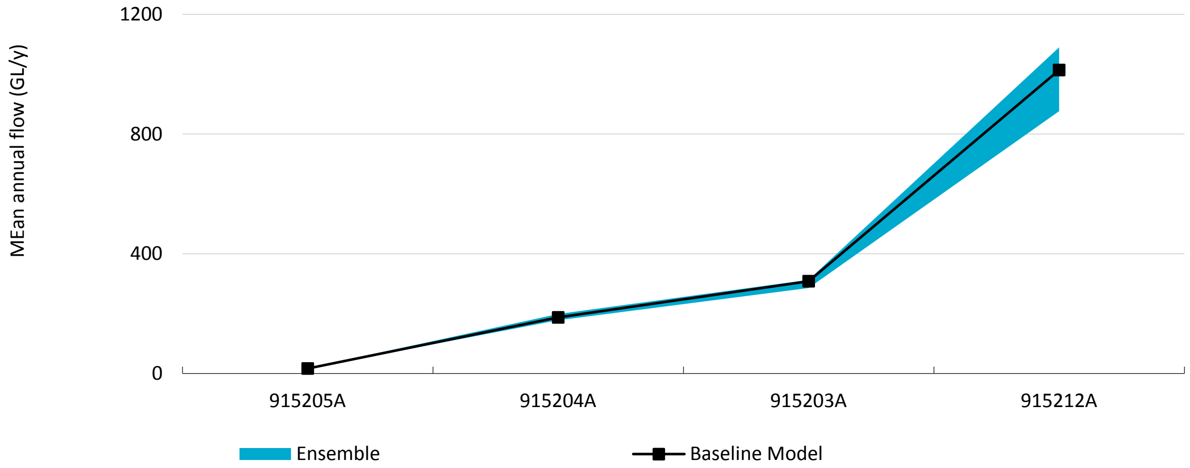

Figure 3.27 Mean annual streamflow along the Cloncurry River under Scenario A as simulated by the baseline river model (black line) and the 2.5% and 97.5% exceedance ensemble river models (shown by blue shading)

Figure 3.28 provides a spatial illustration of the mean annual streamflow in the Flinders catchment. This figure was generated by interpolating the mean annual streamflow between gauging stations and weighting the interpolation using upstream catchment area.

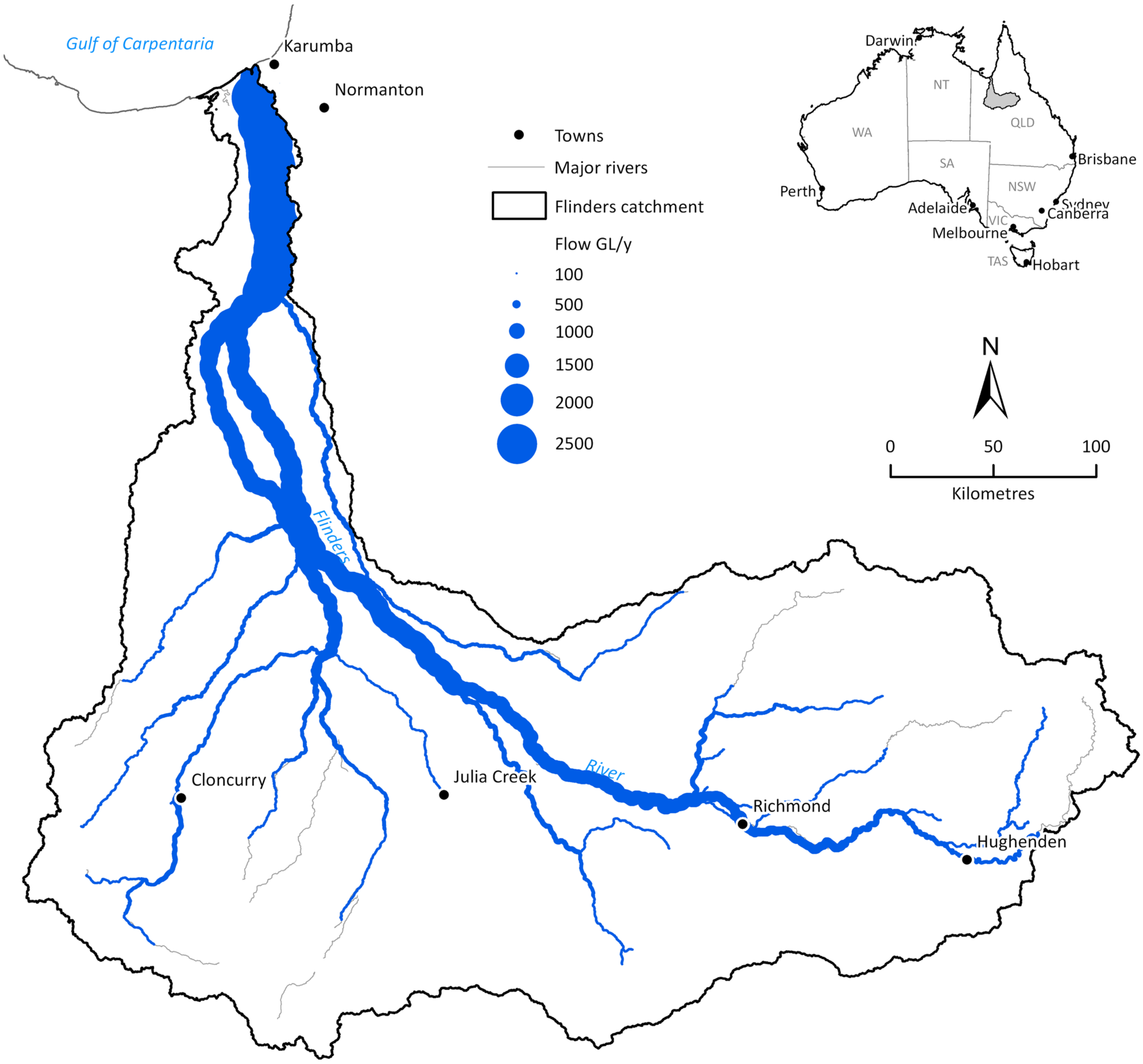

Figure 3.28 Mean annual streamflow in the Flinders catchment under Scenario A

3.7.3 STORAGE BEHAVIOUR

This section provides an analysis of the Corella and Chinaman creek storages. Table 3.11 presents the statistics associated with stored volume and reservoir spill.

Table 3.11 Summary of storage behaviour in the Flinders catchment under Scenario A

STORAGE		BASELINE MODEL	97.5% EXCEEDANCE ENSEMBLE SIMULATION	2.5% EXCEEDANCE ENSEMBLE SIMULATION
Corella dam	Minimum storage volume (GL)	0	0	0
	Average years between spills	0.81	0.83	1.12
	Maximum years between spills	14.76	14.72	15.78
Chinaman Creek dam	Minimum storage volume (GL)	0	0	0
	Average years between spills	0.55	0.45	0.68
	Maximum years between spills	3.5	3.49	3.5

3.7.4 CONSUMPTIVE WATER USE

This section details the model results associated with the diversion of water for consumptive use under Scenario A (which assumes full use of existing entitlements). Table 3.12 shows the mean annual diversions for the 22 calibration reaches of the Assessment river model. To compute the level of use, actual diversions were expressed as a percentage of the mean annual streamflow at the outlet of the Flinders catchment (Table 3.13). Table 3.14 details the reliability of supply computed as the ratio between the actual diversion and the licence volume.

Under a full use of existing entitlements, the use of water relative to the mean annual flow at the outlet of the Flinders catchments is 3.5% (Table 3.13).

Table 3.12 Total mean annual diversions in the Flinders catchment under Scenario A

OUTLET GAUGE	BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
915003A	0.6	0.6	0.6
915004A	8.2	8	8.3
915005A	0	0	0
915006A	0	0	0
915007A	0	0	0
915008A	9.7	9.4	9.9
915009A	0	0	0
915010A	0	0	0
915011A	0	0	0
915012A	49.8	48.5	50.2
915013A	0	0	0
915014A	0	0	0

OUTLET GAUGE	BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
915203A	5	4.7	5.1
915204A	0	0	0
915205A	0	0	0
915206A	0	0	0
915207A	0	0	0
915208A	0	0	0
915209A	2.8	2.7	2.8
915210A	0	0	0
915211A	0	0	0
915212A	13.1	12	13.3

Table 3.13 Relative level of surface water use in the Flinders catchment under Scenario A

	BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Total surface mean annual flow	2543.3	2415.3	2685.2
Total net diversions	89.2	86.7	89.2
Relative level of use (%)	3.5	3.6	3.3

Table 3.14 Average reliability of water supply in the Flinders catchment under Scenario A (fraction diverted per 1ML allocated)

		BASELINE MODEL	97.5% EXCEEDANCE ENSEMBLE SIMULATION	2.5% EXCEEDANCE ENSEMBLE SIMULATION
Town water supply	High security	0.83	0.79	0.85
	Unsupplemented	0.65	0.63	0.66
Agriculture	General security	0.62	0.6	0.62
	Unsupplemented	0.66	0.64	0.66
Other demands	High security	0.56	0.54	0.56
	Unsupplemented	0.69	0.67	0.69

4 Calibration of the Gilbert river model

4.1 Catchment description

4.1.1 GILBERT RIVER CATCHMENT

The Gilbert catchment is located in north-west Queensland and covers an area of 46,354 km^2. It has a population of approximately 1200 with one urban centre in Georgetown (population of 243, Australian Bureau of Statistics, 2011).

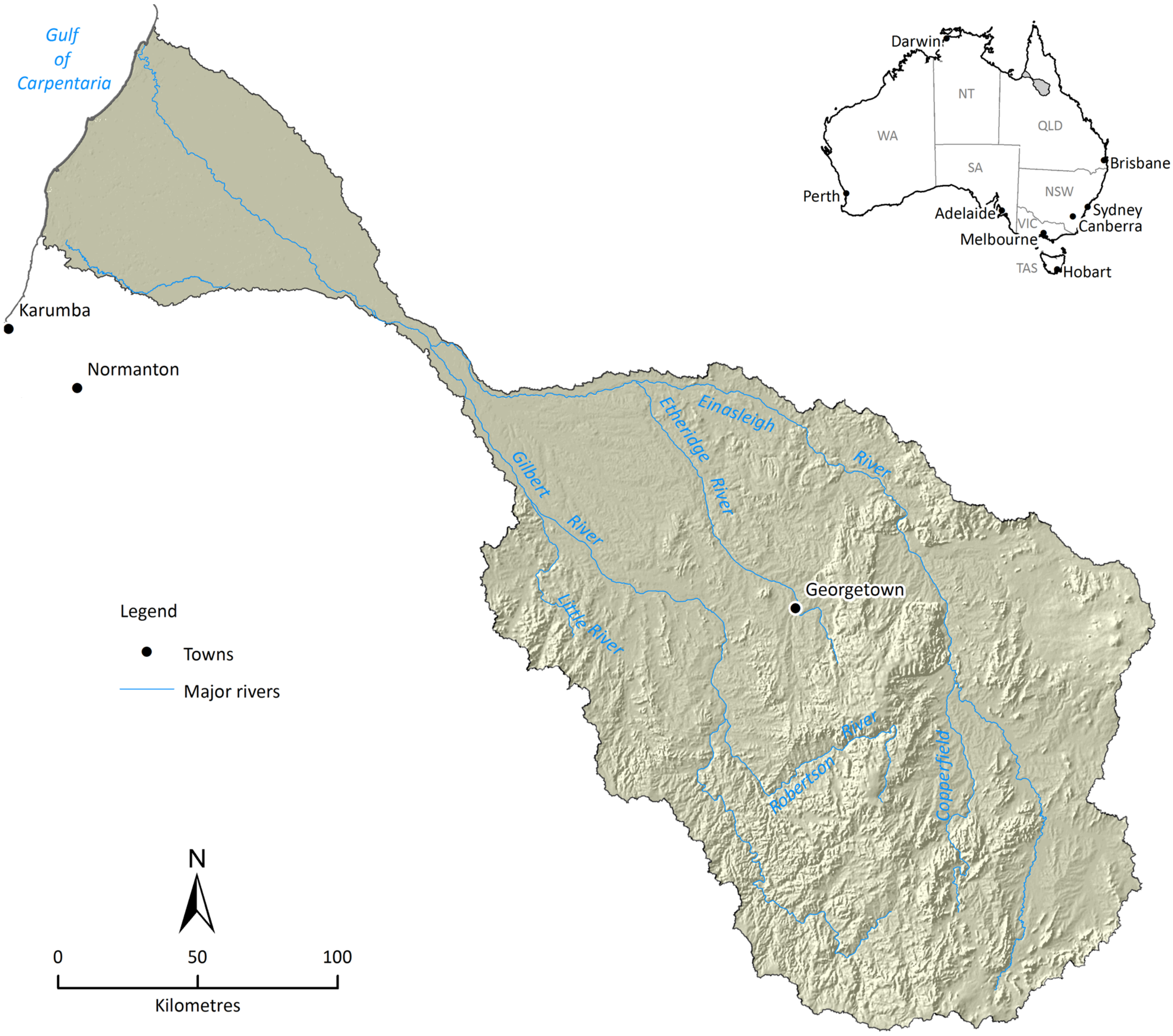

Figure 4.1 A shaded relief map of the Gilbert catchment. Main rivers named. Gilbert catchment and Gulf region shown in the small thumbnail map in top right corner

The Gilbert catchment has a semi-arid tropical climate. The mean and median annual rainfalls spatially averaged across the catchment are 775 mm and 739 mm respectively. However, the historical annual rainfall series for the Gilbert catchments shows considerable variation between years (Figure 4.2). The highest catchment average annual rainfall in the Gilbert (2187 mm) occurred in 1974, nearly three times the median annual rainfall value. Spatially, mean annual rainfall varies from about 1050 mm at the coast to about 650 mm in the south-east of the catchment. A defining characteristic of the Gilbert's climate is the seasonality of rainfall (Figure 4.3), with 93% of rainfall occurring during the wet season (November to April inclusive). The highest median monthly rainfall in the Flinders catchment occurs during the months of January and February (~200 mm). The months with the lowest median rainfall are July and August (~ 0.5 mm).

The Gilbert catchment has a mean annual potential evaporation of 1868 mm. Mean wet and dry season potential evaporation is 1067 mm and 815 mm respectively. The majority of the Gilbert catchment experiences a mean annual rainfall deficit of greater than 600 mm.

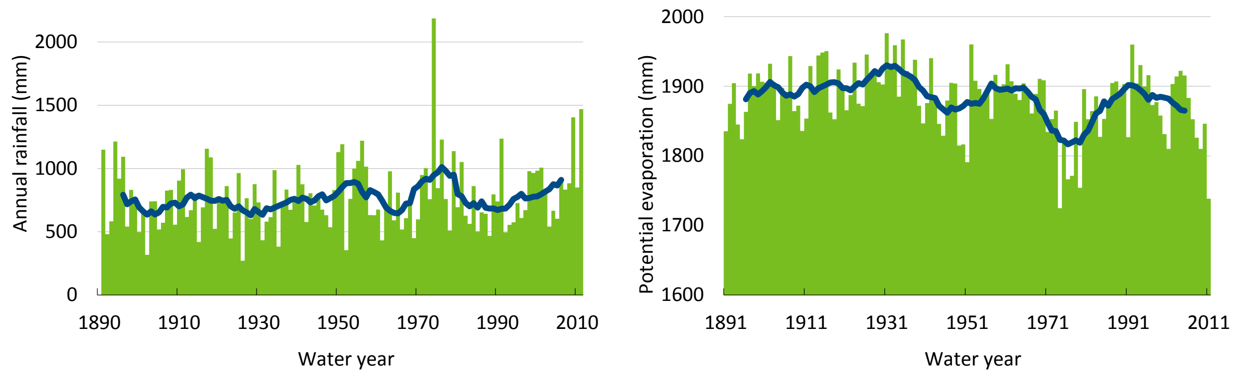

Figure 4.2 Historical mean annual rainfall and potential evaporation in the Gilbert catchment

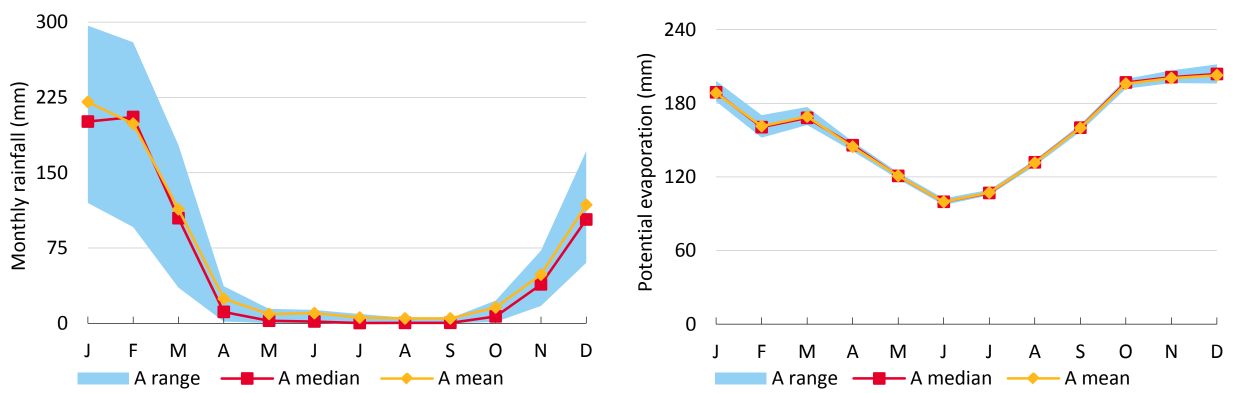

Figure 4.3 Historical monthly rainfall and potential evaporation averaged over the Gilbert catchment

The Gilbert catchment is comprised of two major rivers, the Gilbert and the Einasleigh (Figure 4.1). Although the Gilbert catchment shares a name with the Gilbert River (named after the explorer Gilbert), the Einasleigh is the larger of the two rivers. The flow characteristics of the two rivers are quite different, with the Einasleigh and some of its upper tributaries draining the basalt country in the eastern parts of the catchment. This results in extended flows during the dry season in some reaches of the Einasleigh River and its tributaries. In contrast the Gilbert River and the Etheridge, a major tributary of the Einasleigh, are highly ephemeral and do not flow for more than half the year on average. Downstream of Strathmore Station the Gilbert and Einasleigh rivers converge before entering the Gulf of Carpentaria.

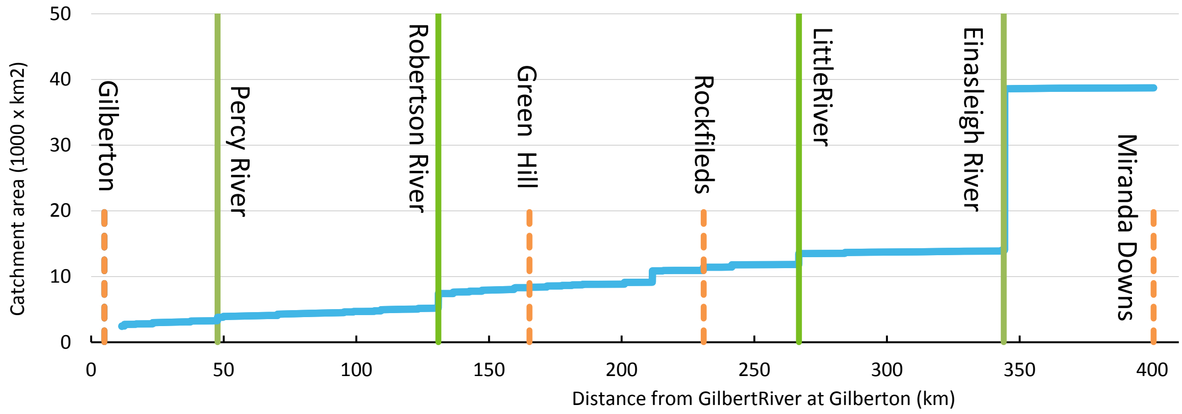

Figure 4.4 Change in catchment area along the Gilbert River from Gilberton

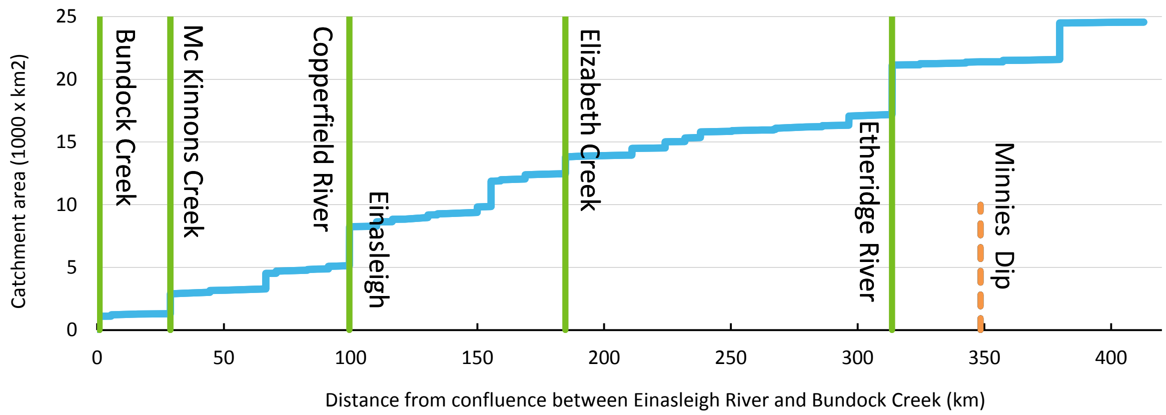

Figure 4.5 Change in catchment area along the Einasleigh River from the confluence between Einasleigh River and Bundock Creek

4.2 River model set-up

The Gilbert River model developed in this work was initially configured based on the Gilbert River Basin full-utilisation IQQM WRP model (DNRM, 2006). It represents the Gilbert River and its tributaries from the headwaters to the streamflow gauge 917009A at Miranda Downs (Figure 4.6).

The original IQQM node-link network, node properties, link properties and model input time series were translated into Source. The IQQM and Source models were then run in parallel, and the results were compared to ensure that the model was translated faithfully. The Source model was then elaborated to improve its spatial resolution. The number of inflow locations in the model was increased from 31 to 50, and between those inflow locations the number of streamflow routing links was increased from 14 to 57. This increased resolution is desirable from two points of view. Firstly, it allowed the use of more finely defined rainfall data (which would otherwise be averaged over larger areas). Secondly, the increased resolution will allow a wider range of scenarios to be considered in future scenario modelling work. The model is shown in Figure 4.6.

For calibration purposes, the model was divided into 19 major reaches which could be calibrated independently. Among these were 9 headwater reaches and 10 residual reaches (see Table 4.1). The calibration reaches were determined on the basis of available streamflow data, and closely correspond to those used by DNRM in the calibration of the IQQM WRP model. The calibrated baseline model was configured to run over the historical period (i.e. 1 July 1890 to 30 June 2011). Major storages in the Gilbert catchment are listed in Table 4.2.

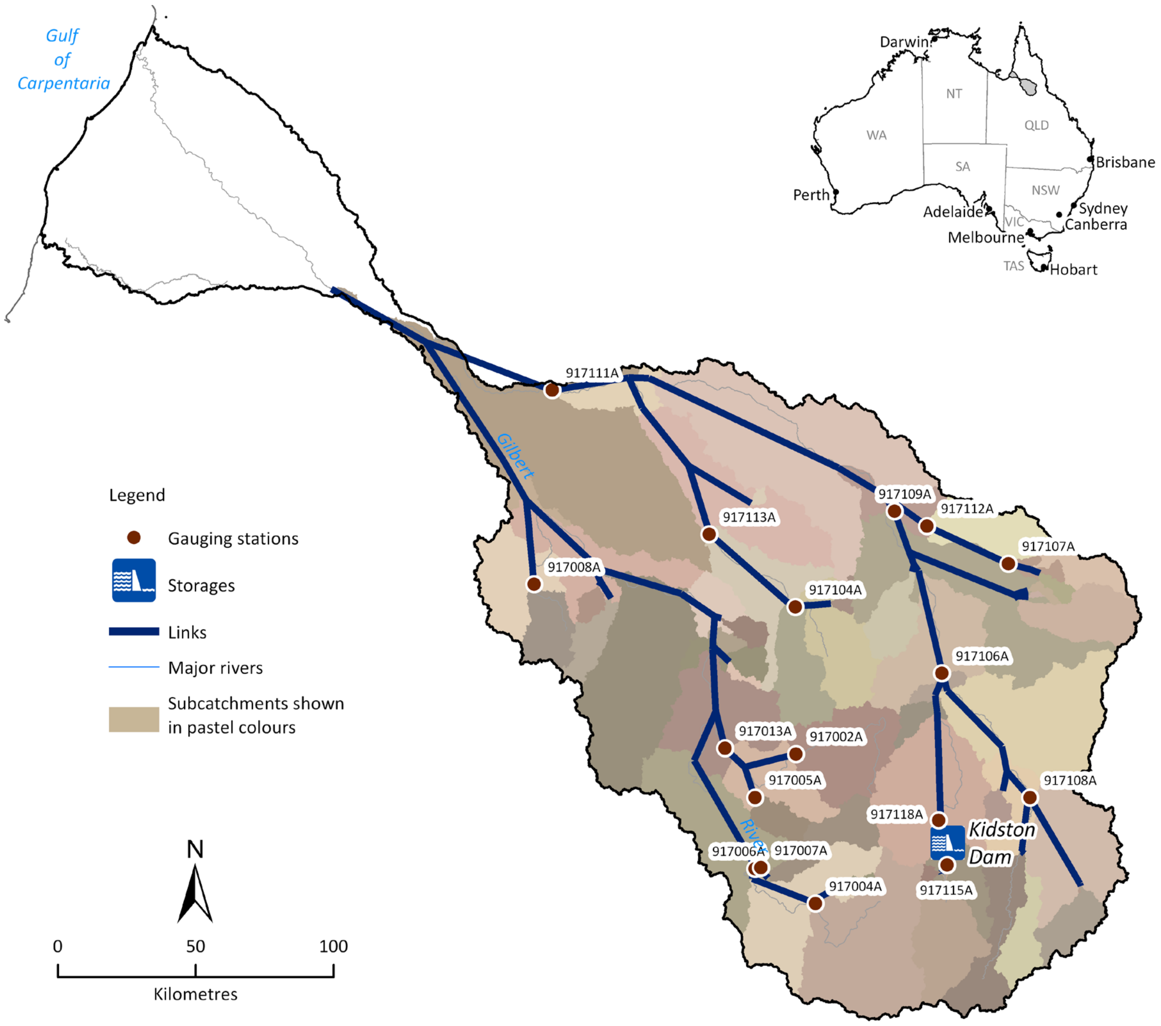

Figure 4.6 Schematic diagram of the Assessment Gilbert river model configuration and gauging stations

Figure 4.7 The Einasleigh River downstream of Einasleigh. Source CSIRO

Table 4.1 Calibration reaches in the Gilbert catchment

REACH ID	DESCRIPTION	OUTLET	INLET(S)	REACH TYPE	SUBCATCHMENT AREA (km^2)	TOTAL CATCHMENT AREA AT OUTLET (km^2)	FULL CALIBRATION PERIOD
1	Copperfield River upstream of Spanner Waterhole	917115A	NA	Headwater	1,200	1,200	12/1983-01/2005
2	Copperfield River from Spanner Waterhole to Kidston Dam	917118A	917115A	Residual	50	1,250	
3	McKinnon's Creek upstream of Possum Pad	917108A	NA	Headwater	1,570	1,570	06/1968-08/1978
4	Copperfield River at Kidston Dam to Einasleigh River at Einasleigh	917106A	917108A 917118A	Residual	5,420	8,240	12/1966-10/1976
5	Einasleigh River from Einasleigh to Cowana Lake	917109A	917106A	Residual	3,900	12,150	11/1968-12/1977
6	Elizabeth Creek upstream of Mount Surprise	917107A	NA	Headwater	650	650	07/1968-08/1987
7	Elizabeth Creek from Mount Surprise to Cabana	917112A	917107A	Residual	640	1,290	06/1972-08/1980
8	Etheridge River upstream of Roseglen	917104A	NA	Headwater	870	870	12/1972-03/1994
9	Etheridge River from Roseglen to Huonfels	917113A	917104A	Residual	1,491	2,360	12/1972-11/1980
10	Einasleigh River from Cowana Lake to Minnie's Dip	917111A	917109A 917112A 917113A	Residual	5,490	21,280	11/1971-09/1979
11	Gilbert River upstream of Gilberton	917004A	NA	Headwater	1,890	1,890	01/1967-01/1977
12	Gilberton River from Gilberton to Percy Junction	917006A	917004A	Residual	1,430	3,320	03/1970-05/1979
13	Robertson River upstream of Robin Hood	917002A	NA	Headwater	1,020	1,020	01/1967-12/1977
14	Agate Creek upstream of	917005A	NA	Headwater	220	220	01/1967-08/1976

REACH ID	DESCRIPTION	OUTLET	INLET(S)	REACH TYPE	SUBCATCHMENT AREA (km^2)	TOTAL CATCHMENT AREA AT OUTLET (km^2)	FULL CALIBRATION PERIOD
	Cave Creek junction						
15	Robertson River from Robin Hood to North Head	917013A	917002A 917005A	Residual	650	1,890	12/1972-11/1980
16	Percy River upstream of Ortana	917007A	NA	Headwater	530	530	03/1970-09/1979
17	Gilbert River from Percy Junction to Rockfields	917001D	917013A 917006A 917007A	Residual	5,260	10,990	01/1967-12/1974
18	Little River upstream of Inorunie	917008A	NA	Headwater	440	440	03/1970-04/1980
19	Gilbert River upstream of Miranda Downs	917009A	917001D 917111A 917008A	Residual	5,910	38,620	(no flow records)

Table 4.2 Major water storages in the Gilbert catchment

STORAGE NAME	RIVER	ACTIVE STORAGE (GL)	AVERAGE ANNUAL INFLOW (GL/y)	AVERAGE ANNUAL RELEASE	AVERAGE ANNUAL NET EVAPORATION	DEGREE OF REGULATION
Kidston Dam	Copperfield River	18.5	167.3	51.9	1.8	0.32

4.3 Available data

4.3.1 CLIMATE DATA

The rainfall and potential evaporation data used to drive the model were extracted from the SILO data drill maintained by the Queensland Government (Jeffrey et al., 2001). The gridded data are interpolated from point measurements provided by the Bureau of Meteorology.

One of the limitations to hydrological and agricultural assessments in northern Australia is the availability of climate data. The distribution of rainfall data for three decadal periods in the Gilbert catchment is shown in Figure 4.8.

The climate data include daily time series of rainfall, shortwave solar radiation, vapour pressure, minimum and maximum temperature covering the reporting period 1890-2011. The last four variables were used to compute the Morton's wet environment Areal Potential Evaporation (APE). Rainfall and APE constitute the inputs to the rainfall-runoff and storage components of the river model.

The companion technical report by the climate activity (Petheram and Yang 2013) provides a detailed analysis of the characteristics and quality of the climate data.

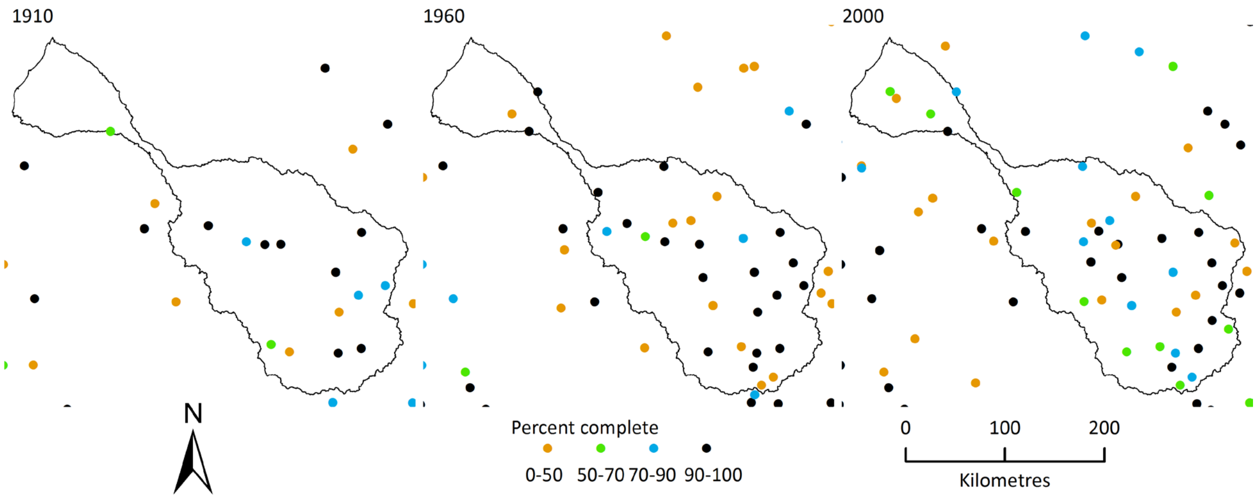

Figure 4.8 Decadal analysis of the location and completeness of Bureau of Meteorology stations measuring daily rainfall used in the SILO database. The decade labelled '1910' is defined from 1 January 1910 to 31 December 1919, and so on. At a station, a decade is 100% complete if there are observations for every day in that decade. The analysis for the decade starting in 2000 only extends to 2007

4.3.2 STREAMFLOW DATA

Historical streamflow gauge records underpin the model calibration process. Gauged streamflows downstream of each reach provide a target for the calibration of the reach, and gauged inflows from upstream reaches provide the best estimate of historical inflows into the reach. Streamflow records at 19 gauging stations were used to calibrate the Gilbert model. These stations are listed in Table 4.3.

The quality of recorded stream height data is considered good throughout the catchment, with the exception of a small number of gaps in the record. Missing records were omitted from the calibration.

The quality of recorded streamflow discharge data is limited by the gaugings that have been conducted and used to derive height-flow relationships. The ephemeral nature of the Gilbert catchment means that significant volumes of water flow above the highest gauging at each station, resulting in large uncertainty in the water availability. At Einasleigh River at Minnie's Dip for example, approximately 87% of the total streamflow volume occurs at a stage height that is greater than the highest gauging (refer to Table 4.3). This uncertainty is captured in the ensemble modelling as described in Section 3 and Section 5.4.

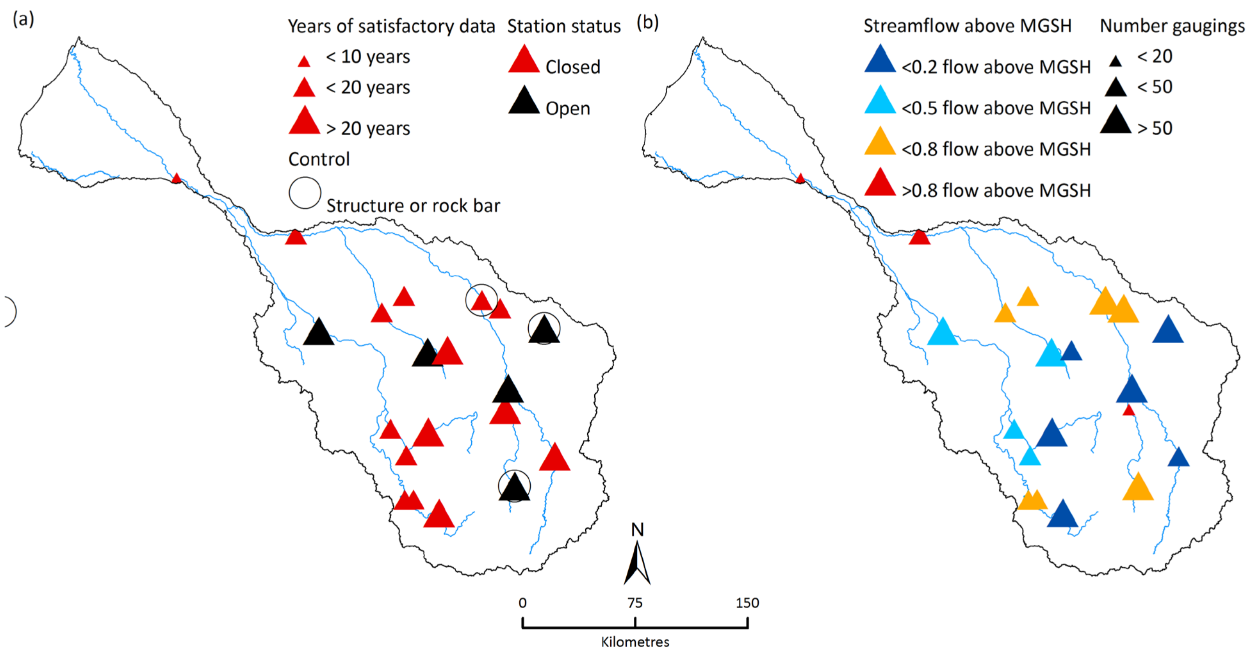

Figure 4.9 Quality of streamflow data in the Gilbert catchment. Stations 917115A and 917118A on Copperfield River shown by same symbol

Table 4.3 Gauging station characteristics in the Gilbert catchment

STATION ID	STATION NAME	START OF RECORDS	END OF RECORDS	CONTROL SECTION	NUMBER OF GAUGINGS WITH FLOW >0	MAX GAUGE FLOW (ML/d)	FRACTION OF FLOW ABOVE MAX GAUGED FLOW (%)
917001D	Gilbert River at Rockfields	14/01/1967	Current	Sand	159	103,248	19.5
917002A	Robertson River at Robin Hood	10/12/1966	30/09/1988	Sand	83	55,048	5.2
917004A	Gilbert River at Gilberton	26/07/1968	30/09/1988	Sand	68	116,188	7.3
917005A	Agate Creek at Cave Creek Junction	1/07/1969	30/09/1988	Sand	29	1,018	45.6
917006A	Gilbert River at Percy Junction	4/03/1970	30/09/1988	Sand	48	6,278	59.4
917007A	Percy River at Ortana	2/09/1969	30/09/1988	Sand	29	1,184	56.5
917008A	Little River at Inorunie	9/11/1971	10/01/1993	Rock	42	2,699	55.3
917013A	Robertson River at North Head	12/12/1972	1/12/1988	Sand and Gravel	36	9,603	45.6
917104A	Etheridge River at Roseglen	14/01/1967	Current	Sand	67	9,037	43.0
917106A	Einasleigh	10/12/1966	Current	Sand And	168	298,484	1.2

STATION ID	STATION NAME	START OF RECORDS	END OF RECORDS	CONTROL SECTION	NUMBER OF GAUGINGS WITH FLOW >0	MAX GAUGE FLOW (ML/d)	FRACTION OF FLOW ABOVE MAX GAUGED FLOW (%)
	River at Einasleigh			Rock			
917107A	Elizabeth Creek at Mount Surprise	23/07/1968	Current	Control Weir	191	8,243	7.2
917108A	McKinnon's Creek at Possum Pad	18/06/1968	30/09/1988	Rock Sand and Gravel	32	47,261	9.8
917109A	Einasleigh River at Cowana Lake	28/11/1968	20/10/1988	Rock	50	13,295	62.1
917110A	Copperfield River at Middle Creek Gap	6/01/1969	30/08/1988	Sand Gravel Rocks and Boulders	60	8,268	47.8
917111A	Einasleigh River at Minnie's Dip	9/11/1971	30/09/1988	Sand	45	6,533	86.9
917112A	Elizabeth Creek at Cabana	14/06/1972	19/10/1988	Sand Rock Outcrop	68	2,332	59.1
917113A	Etheridge River at Huonfels	13/12/1972	28/10/1988	Sand	31	6,595	65.0
917115A	Copperfield River at Spanner Waterhole	14/12/1983	Current	Sand And Rock	58	912	78.5
917118A	Copperfield River at Kidston Dam Tailwater	28/11/1984	Current	Control Weir	55	1,028	72.1

Most gauging stations in the Gilbert catchment were opened in the late 1960s or early 1970s, and then closed in 1988. Thus the period of record at most stations is about 20 years. While that length is satisfactory for calibration purposes, longer periods of record would improve the calibrations considerably.

Records from the gauging station 917110A (Copperfield River at Middle Creek Gap) were used to extend the period of record at 917115A (Copperfield River at Spanner Waterhole). A factor was applied to the 917110A flows, which was equal to the ratio of the catchment areas of the two gauges.

The streamflow station 917102A (Einasleigh River at Carpentaria Downs) has an inadequate period of record (i.e. < 2 years), and was not used in the calibration of the River model. This is reflected in the definition of Reaches 3 and 4.

The streamflow station 917009A (Gilbert River at Miranda Downs) has no gaugings and therefore could not be used to calibrate Reach 19 in the lower reaches of the Gilbert River, above the Gilbert fan. Source river modelling in this region will be compromised by this lack of data. A conservative approach has been adopted whereby residual inflows to Reach 19 have been neglected. A less conservative approach would be to include residual inflows based on a Sacramento model from a neighbouring reach (Reach 17 for example).

Satisfactory historical streamflow data were identified for the calibration of all reaches except for Reach 19. The streamflow data is generally of suitable quality and duration, although the calibration of the river model would benefit from records of longer duration.

4.3.3 DEMAND DATA

Historical diversion data were adopted from the DNRM Water Resource Plan (WRP) modelling. The only diversions recorded during the calibration period were extractions from Kidston Dam for the Kidston Gold Mine. Historical streamflow diversions were assumed to be zero throughout the rest of the model during the calibration.

Demands for this baseline scenario were adopted from the full-utilisation IQQM WRP model (DNRM, 2006). They represent the full-utilisation of water / irrigation entitlements existing when the IQQM WRP model was developed. Under this scenario the modelled level of use was 1.4% of mean annual flow (refer to Table 4.4) confirming that even at full-utilisation, extractions represent a small fraction of the catchment's total water balance.

4.3.4 RESERVOIR DATA

The Gilbert catchment contains just one major reservoir: Copperfield River Gorge Dam (also known as Kidston Dam) on the Copperfield River. Copperfield River Gorge Dam was constructed in 1985 to supply the Kidston Gold Mine. In addition to the dam, the catchment includes several bedsand aquifers along the Gilbert River which have formed from deposited coarse alluvial material. These are effectively aquifers (i.e. acting as natural reservoirs), and provide a reliable source of water during the dry season.

Copperfield River Gorge Dam has a full supply level of 24.9 m and 21,000 ML, including a dead storage of 10.1 m and 2,500 ML. The dam's storage characteristics, as well as the spillway and outlet rating curves were adopted from the Gilbert River Basin WRP IQQM model (DNRM, 2006).

A storage inflow derivation calculation was not performed for Copperfield River Gorge Dam. Instead, residual inflows to the 53 km^2 subcatchment surrounding the dam (Reach 2) were approximated using the Sacramento model for Reach 1, just 3 km upstream from the dam. Thus Kidston Dam's historical levels and extractions were not used in this modelling exercise.

The bedsand aquifers on the Gilbert River were assessed by PPK Environment & Infrastructure Pty Ltd. Their hydrologic properties have been incorporated into the Gilbert River model through the use of two passive storages: one just upstream of 917001D and one just downstream of 917001D.

4.4 Baseline model performance

4.4.1 GENERAL MODEL PERFORMANCE

To assess the performance and fitness for purpose of the calibrated Gilbert River model, the modelled flows and observed flows were compared at 17 gauging stations in the Gilbert catchment. The results are shown in Table 4.4. For this exercise, the model was run with simulated inflows as indicated in section 2.3.1.

The comparison of modelled and observed streamflow indicates that the model reproduced the historical monthly and annual streamflows well at most stations (NSE > 0.9) and in many cases the model's performance was considered excellent (NSE > 0.95). The simulation of daily flows was acceptable at all stations (< 0.5 NSE < 0.9). The bias discrepancy was less than 3% at most stations, and less than 10% at all stations, indicating that the total flow over the observed period is reproduced very well by the model.

Table 4.4 Performance statistics of the Gilbert River model

GAUGING STATION ID	BIAS (%) ALL PERIOD	NSE DAILY ALL PERIOD	NSE DAILY DRY SEASON	NSE LOG ALL PERIOD	NSE LOG DRY SEASON	NSE MONTHLY ALL PERIOD	NSE MONTHLY DRY SEASON	NSE ANNUAL
917001D	-7	0.87	-0.76	0.65	-0.10	0.96	-1.11	0.97
917002A	0	0.82	-2.18	0.42	-0.07	0.93	-0.26	0.99
917004A	0	0.71	-3.13	0.43	-0.64	0.92	-5.27	0.92
917005A	0	0.58	-0.29	0.39	-0.30	0.93	-0.53	0.97
917006A	2	0.70	-1.53	0.50	0.17	0.90	-1.75	0.96
917007A	-1	0.60	-1.12	0.36	0.09	0.86	-1.09	0.84
917008A	-3	0.53	-13.37	0.44	-1.61	0.80	-20.05	0.91
917013A	-3	0.80	-0.55	0.62	-0.34	0.95	0.13	0.97
917104A	0	0.68	0.45	0.60	0.16	0.86	0.66	0.89
917106A	-8	0.82	0.71	0.64	0.13	0.94	0.72	0.93
917107A	-1	0.75	0.75	0.61	0.33	0.91	0.68	0.97
917108A	0	0.76	0.61	0.62	0.18	0.92	0.84	0.96
917109A	-2	0.85	0.76	0.57	-0.01	0.96	0.85	0.96
917111A	2	0.69	0.82	0.81	0.61	0.81	0.96	0.74
917112A	-5	0.83	0.81	0.67	0.41	0.96	0.91	0.99
917113A	-3	0.85	0.63	0.74	0.57	0.99	0.70	1.00
917115A	0	0.71	0.55	0.57	-0.66	0.96	0.66	0.97
917118A	9	0.68	0.22	0.32	-0.23	0.90	0.08	0.86

The four gauging stations at which the river model performed worse were 917008A (daily NSE = 0.53), 917005A (daily NSE = 0.58), 917007A (daily NSE = 0.60) and 917104A (daily NSE = 0.68). These stations are all situated in headwater reaches with relatively small catchment areas. Since runoff from small headwater catchments is sensitive to localised rainfall, erroneous rainfall input data is one plausible explanation for the lower NSE scores recorded at these stations.

The four gauging stations at which the Assessment river model performed best were 917001D (NSE = 0.87), 917113 (NSE = 0.85), 917109 (NSE = 0.85) and 917112A (NSE = 0.83). All four of these stations reside below residual reaches.

Figure 4.10 compares the modelled and historical flows on an annual basis at six selected streamflow gauges.

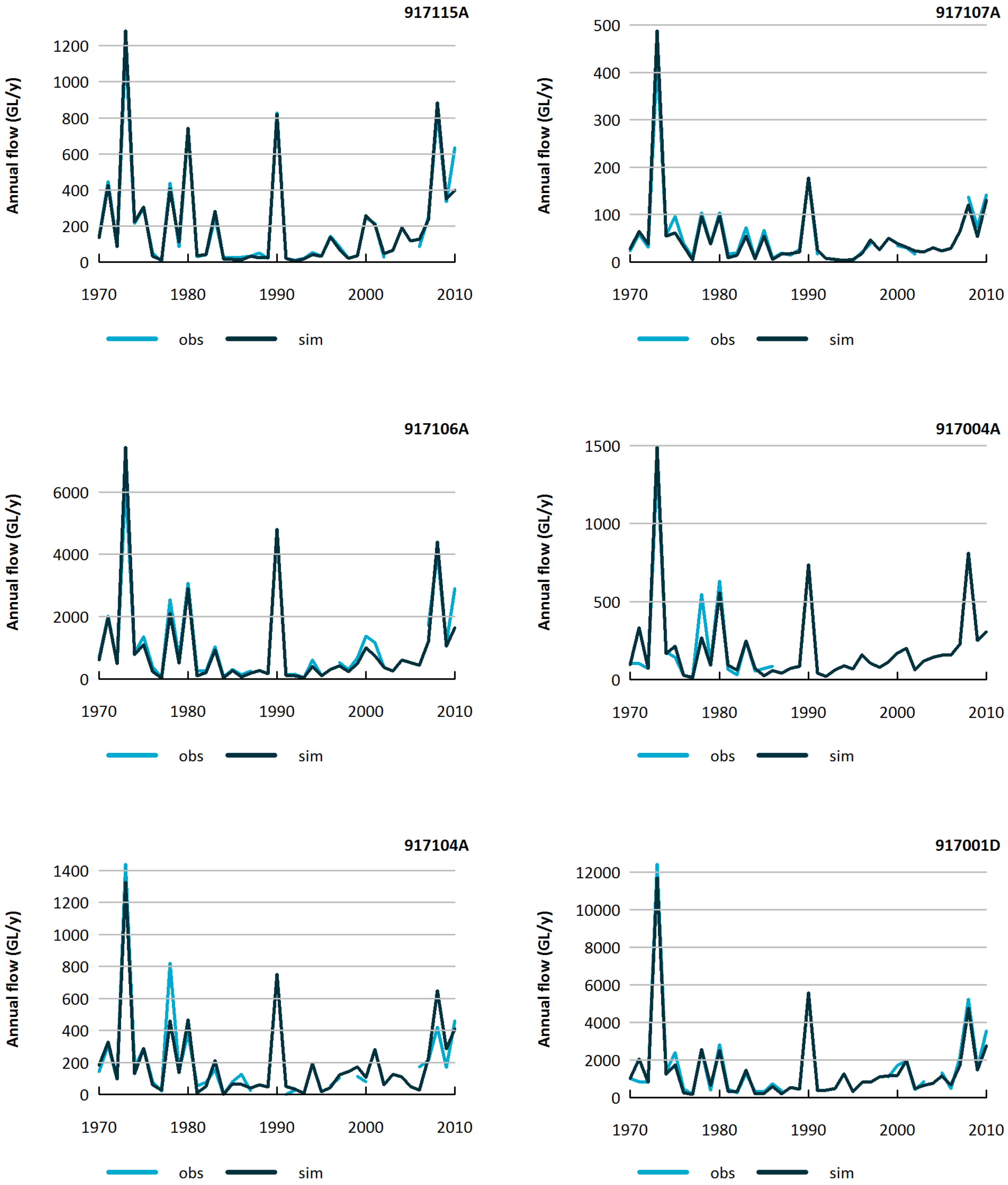

Figure 4.10 Time series of observed and simulated annual flows for selected gauging stations in the Gilbert catchment

4.4.2 PERFORMANCE IN HIGH FLOW CONDITIONS

Good performance in the high flow regime is important for the modelling of flood events, relevant to development planning and environmental management. The high flow performance is quantified by the NSE daily and NSE monthly statistics (Table 4.4) and ranges from poor (NSE < 0.50) to good (NSE > 0.90) across the catchment, as discussed previously in Section 5.3.1.

Figure 4.11 compares the modelled and observed flows over the three biggest events on record. The largest event at all stations was registered in January 1974, corresponding to the 1974 floods that affected much of the east coast of Australia.

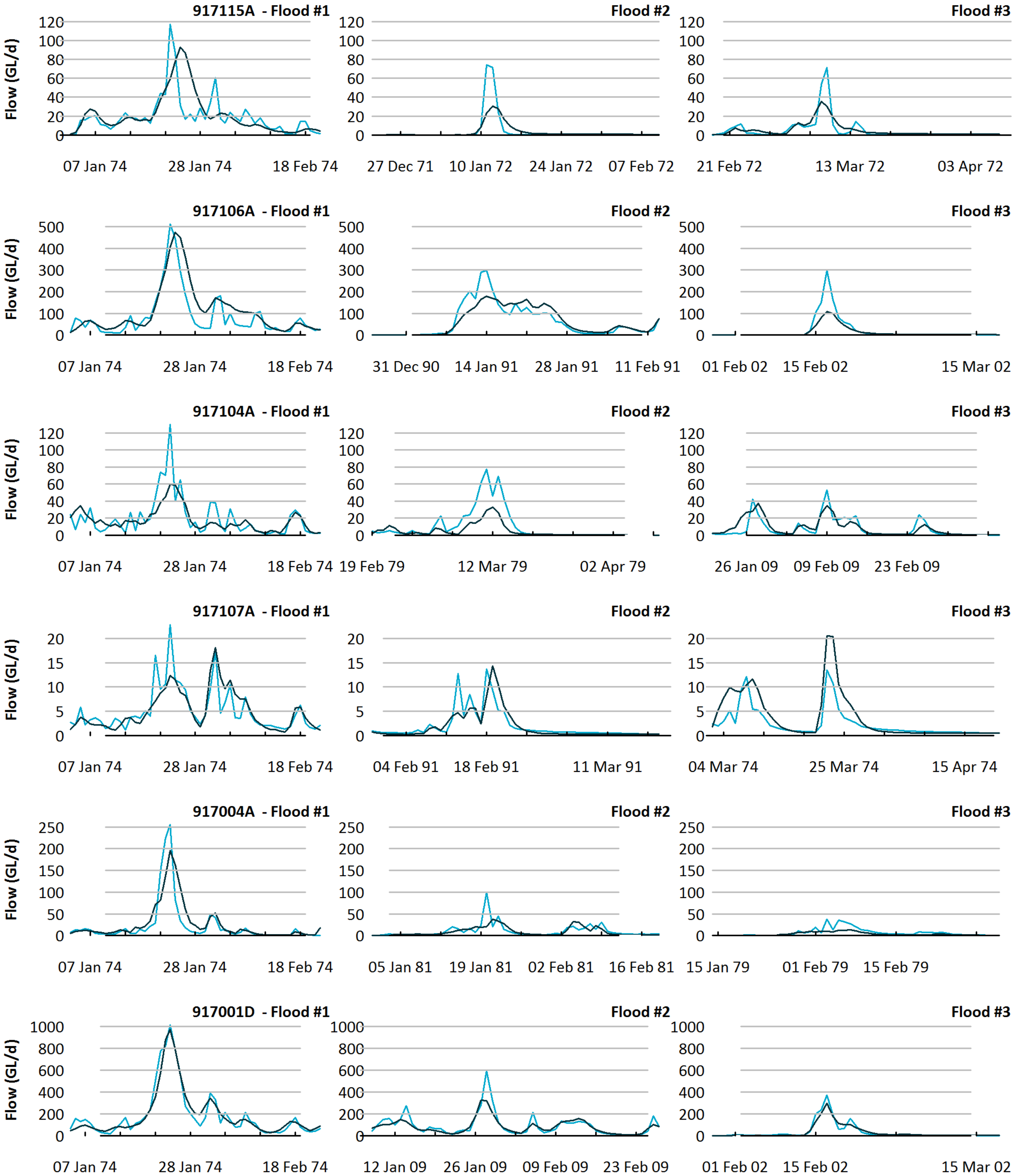

Figure 4.11 Observed (light blue) and simulated (dark blue) flood hydrographs in the Gilbert catchment

Generally the overall shape of the flood hydrographs is reproduced reasonably well by the model. The rising and falling limbs match observed events well, although some peaks are not captured.

Performance is very good in both primary investigation areas: 917001D in the Gilbert investigation area and 917106A in the Mid Einasleigh investigation area. Performance is fair in both secondary investigation areas: 917108A in the Upper Einasleigh investigation area and 917111A in the Lower Einasleigh investigation area.

4.4.3 PERFORMANCE IN LOW FLOW CONDITIONS

The low flow performance is not generally as good as the medium or high flow performance. Perhaps the most straightforward quantification of this is that during the dry-season half of the sites have daily NSE scores less than 0.5 (very poor) whereas none have NSE scores less than 0.5 over the full-period (Table 4.4).

Table 4.4 presents several other indicators of the low flow performance detailed in section 2.4:

- NSE monthly – dry season
- NSE log transform – all period
- NSE log transform – dry season

Figure 4.12 shows the observed and modelled flow exceedance curves at six selected sites. These figures provide an excellent indication of the relative performance across different flow regimes. The good performance seen at higher flows is broken at low flows (below about 10-100 ML/day depending on location).

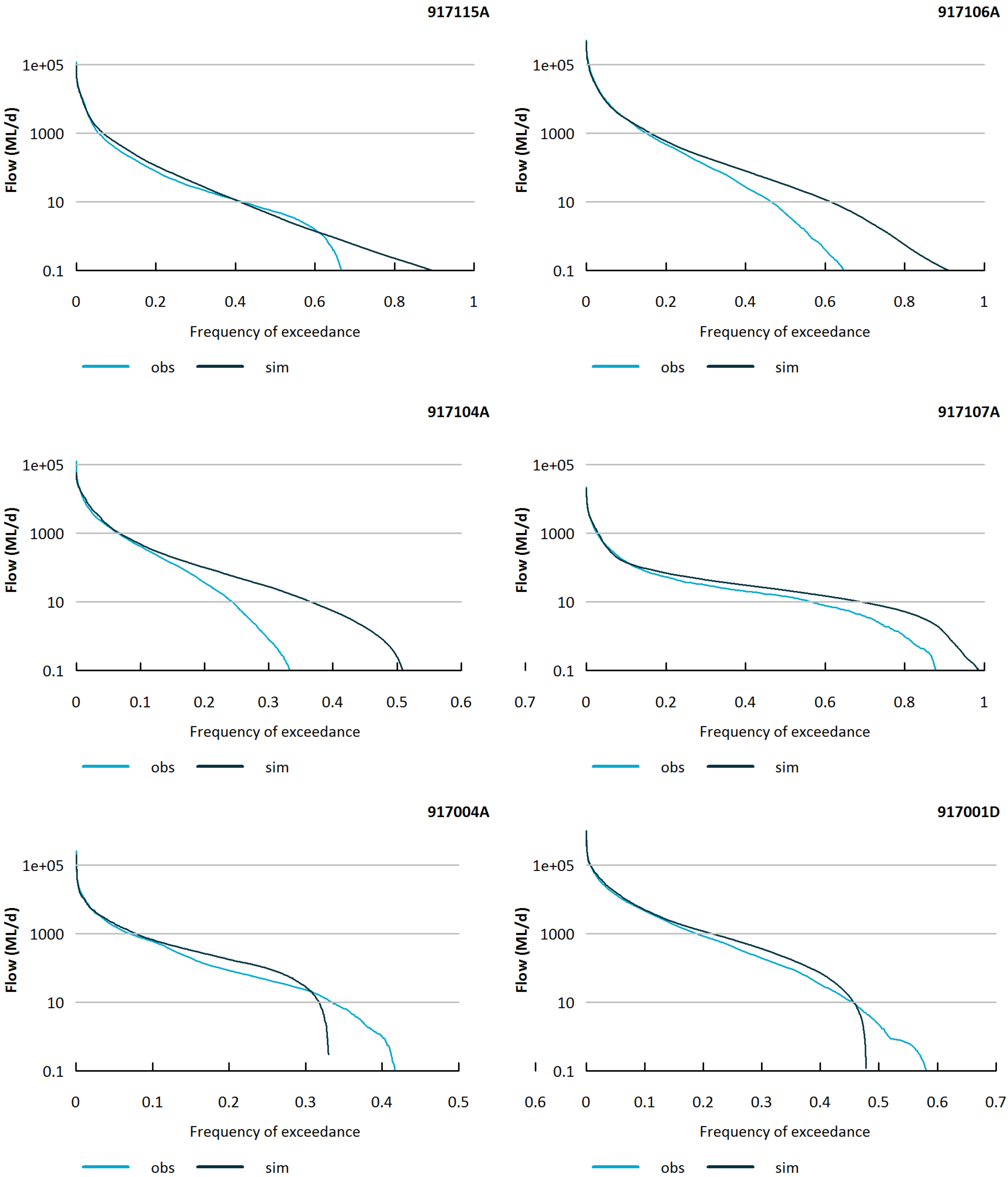

Figure 4.12 Observed and simulated exceedance curves for six selected sites in the Gilbert catchment

Discrepancies in the lower part of the flow exceedance curve are likely to manifest in other model results related to low flows, such as the frequencies and durations of cease-to-flow events. As an example, consider the percentage of zero-flow days at 917104A (we regard all flows < 1 ML/day as zero flow). Observed data indicates that 917104A has zero-flows on about 69% of days, but modelled data indicates zero-flows on only 54% of days over the same period. At this gauge there is a discrepancy between the observed and modelled 1 ML/day exceedance probabilities of 0.15 (i.e. 15% of days).

Table 4.5 summarises the discrepancies between the observed and modelled 1ML/day exceedance probabilities for streamflow stations across the catchment. The table also shows the flow rate above which exceedance discrepancies are less than 0.05 (i.e. 5% of days).

Table 4.5 Summary of differences between observed and simulated flow exceedance curves

STATION ID	EXCEEDANCE DISCREPANCY BETWEEN OBSERVED AND MODELLED FLOWS AT 1ML/d	FLOW ABOVE WHICH EXCEEDANCE DISCREPANCIES ARE LESS THAN 0.05 (ML/d)
917001D	0.08	4
917002A	0.15	40
917004A	0.07	155
917005A	0.03	31
917006A	0.13	8
917007A	0.04	<1
917008A	0.06	166
917013A	0.15	25
917104A	0.15	49
917106A	0.19	114
917107A	0.00	48
917108A	0.11	4
917109A	0.07	4
917111A	0.23	68
917112A	0.07	26
917113A	0.20	11
917115A	0.01	<1
917118A	0.20	30

It may be possible to improve the low flow performance by using a revised calibration objective function. The objective function described in Equation (6) is the product of two terms, the first term targeting the observed flows on a daily basis, and the second targeting the observed flows on an aggregated basis. For further improvements it may be necessary to add another term that specifically targets low flow performance.

It may also be possible to improve the low flow performance by adopting a multistep calibration approach such as the MACS method described by Hogue et al. (2003). The MACS approach for Sacramento model calibration involves calibrating prescribed parameter subsets in isolation, and is purported to result in more finely tuned parameters (particularly the lower-zone Sacramento parameters, which regulate low flow behaviour).

In summary, the daily dry-season performance ranges from poor (NSE < 0.5) to average (NSE ≥ 0.8) at different sites across the catchment. This will have little or no impact on the amount of water released for irrigation. Statistics related to low flow or cease-to-flow periods should be understood to contain large systematic error but may still be valuable for comparing modelled scenarios. Some recommendations have been made that might improve the low flow performance in future work.

4.4.4 MODEL VALIDATION WITH K-FOLD TESTS

K-fold tests (Klemes, 1986) were also undertaken to assess the performance of the river models. K-fold tests calibrate the model against one part of the observed streamflow time series and then test it on another part. Table 4.6 details the statistics obtained when the model was calibrated over the second half of the records and applied to the second half (calibration period) and the first half (validation period). This split was chosen in order to calibrate the model on a period that had a similar mean annual rainfall to the reporting period. The value of the statistics was systematically worse during the validation than during the calibration period with an average increase of the absolute bias by 9.9%, a reduction of the NSE and NSELOG by 0.32 and 0.007, respectively. This drop of performance was expected due to the differences in climate conditions between the two sub-periods. The significant bias increase between calibration and validation periods suggested that this statistic was largely influenced by the calibration period.

Due to the longer calibration period that is used to derive the final parameters set, it is anticipated that the model will perform better than these statistics would indicate. Nonetheless, for some reaches the model uncertainty is quite large and can be explained by large uncertainty in rating curves and rainfall station coverage.

Table 4.6 K-fold validation result for the Gilbert river model

REACH ID	OUTLET STATION	CALIBRATION PERIOD	BIAS (%)	NSE	NSELOG	VALIDATION PERIOD	BIAS (%)	NSE	NSELOG
1	917115	1997-2011	2.26	0.85	-0.11	1983-1997	-1.63	0.68	-0.26
3	917108	1978-1988	3.2	0.66	0.63	1968-1978	-0.27	0.76	0.53
4	917106	1989-2011	0	0.93	0.68	1966-1989	-12.84	0.87	0.57
5	917109	1979-1988	0.03	0.93	0.77	1968-1977	-15.49	0.73	0.79
6	917107	1990-2011	-0.15	0.75	0.5	1968-1990	0.46	0.77	0.34
7	917112	1980-1988	0.07	0.86	0.65	1972-1980	-5.87	0.85	0.83
8	917104	1980-1988	0.11	0.69	0.57	1972-1980	21.88	0.67	0.54
9	917113	1980-1988	7.47	0.85	0.19	1972-1980	-13.41	0.82	0.55
10	917111	1980-1988	26.53	0.72	0.81	1971-1980	-25.14	0.78	0.81
11	917004	1989-2011	0	0.58	0.55	1967-1989	-32.84	0.46	0.35
12	917006	1979-1988	0.08	0.83	0.62	1970-1979	38.01	0.73	0.44
13	917002	1989-2011	0	0.79	0.48	1967-1989	-10.79	0.8	0.41
14	917005	1989-2011	0.04	0.54	0.32	1967-1989	-15.62	-0.12	0.32
15	917013	1981-1988	0.12	0.78	0.54	1972-1980	-6.49	0.87	0.62
16	917007	1979-1988	-0.01	0.58	0.34	1970-1979	-21.86	0.36	0.31
17	917001	1989-2011	4.1	0.86	0.73	1967-1989	-11.6	0.92	0.84
18	917008	1979-1988	1.04	0.29	0.01	1970-1979	-4.59	0.5	0.47

4.4.5 MODELLING RUNOFF IN THE GILBERT RIVER FLOODPLAIN

The Gilbert floodplain exists downstream of the model's end-of-system point (Miranda Downs, GS 917009A) and is not included in the Gilbert hydrologic model.

There are no historical gauged flow records in the Gilbert floodplain, and the direct calibration of a Sacramento rainfall-runoff model for the floodplain was not possible. To model the runoff, Sacramento model parameters were adopted from a nearby catchment, 918002A, chosen for its proximity to the

Gilbert floodplain and similar geomorphic characteristics. This approach introduces some uncertainty which could be estimated by adopting other Sacramento parameter sets from catchments in the region.

Upcoming hydrodynamic modelling could be used to derive level-flow relationships for level-gauging stations in the floodplain. This would allow the derivation of historical flow time series in the floodplain, which could be used to refine the calibration of the Sacramento rainfall-runoff model used there.

4.5 Model uncertainty based on ensemble calibration

Hydrologic modelling inherently contains a degree of uncertainty. Three key sources of uncertainty are:

- Uncertainty in the historical gauged flow records. This results in calibrations that misrepresent reality by overestimating or underestimating streamflows. In highly ephemeral systems, such as the Gilbert, much of the total volume can occur at very high flows where reliable gaugings may be lacking. This source of uncertainty has been addressed in the present work by using an ensemble of modified streamflow records to produce a distribution of calibrations spanning a range of possible realities. The ensemble can be used to quantify the consequences of streamflow gauge uncertainty on any modelled results.
- Uncertainty in the historical climate records. Since rainfall records are based on measurements at one, or a few, stationary rainfall gauges, it is possible for weather systems to contribute catchment inflows without appearing in the rainfall records. In some cases, local topological features can cause a pluviograph to systematically over- or under-represent the rainfall in the catchment. No attempt has been made to account for this source of uncertainty in the present work, however compared to the Gilbert Basin IQQM WRP model (DNRM, 2006) the present work uses a finer subcatchment definition to help reduce the problems of using spatially averaged rainfall.
- The conceptual nature of the numerical models. The Source and Sacramento models used in this work employ simplistic mathematical representations to approximate what are actually very complicated physical processes. No attempt has been made to account for this source of uncertainty.

Figure 4.13 shows the observed flow and the 2.5% - 97.5% distribution in ensemble modelled flows resulting from uncertainty in the historical gauged flows. To a large degree, the distribution of modelled flows encompasses the observed flows in these figures. That they do not completely encompass the observed flow indicates that other sources of uncertainty (besides historical gauged flows) are still significant.

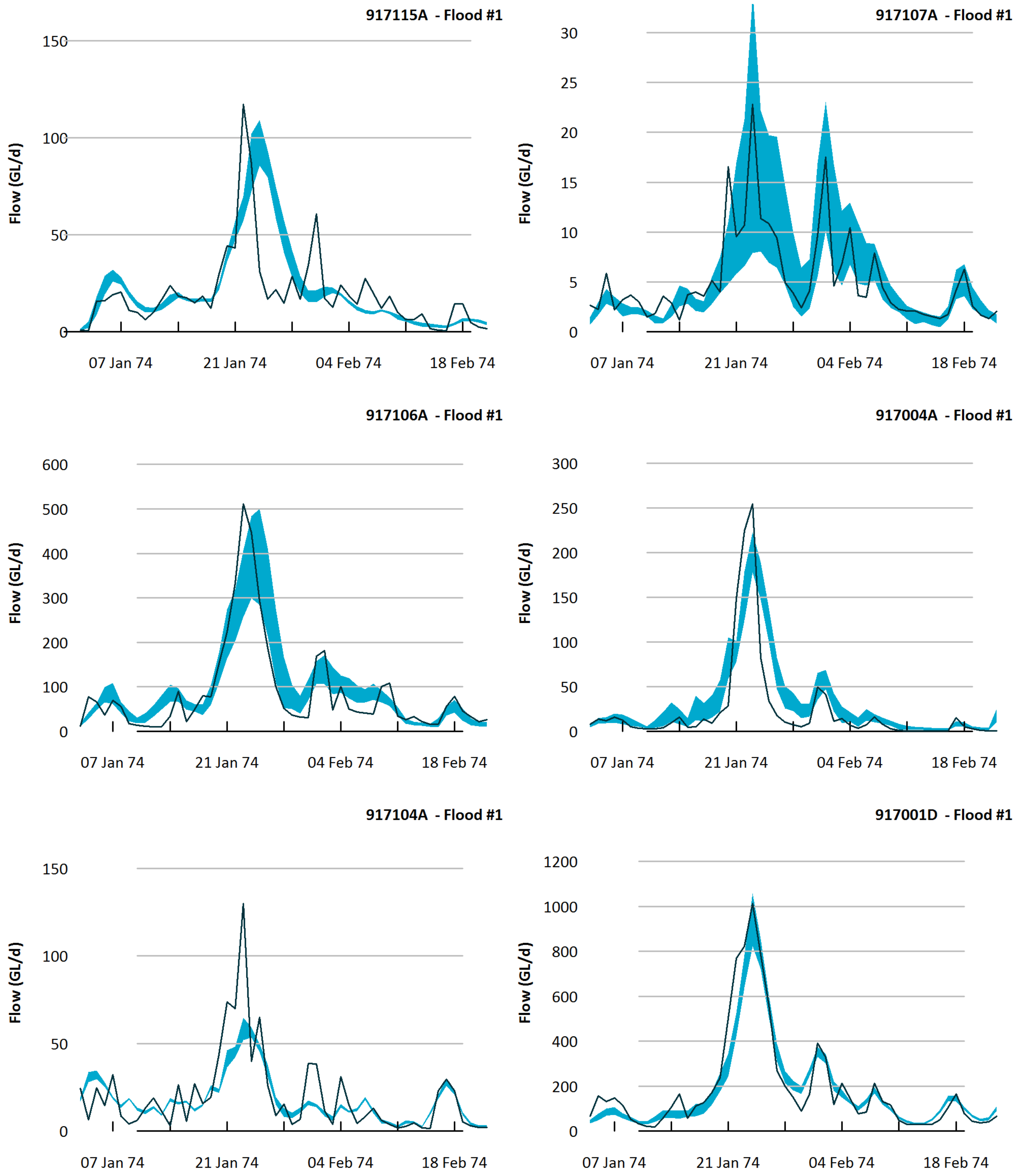

Figure 4.13 Example ensemble flows (blue band bounds the 2.5% and 97.5% daily flows) and the observed flow time series (dark blue) for selected gauging stations in the Gilbert catchment

Table 4.7 shows that there is significant uncertainty in the mean and median modelled flow at each gauge resulting from uncertainty in the historical gauged flows. Sites that are particularly uncertain include 917005D (a headwater to the Gilbert), and 917115A and 917118A (in the upper Copperfield River).

Table 4.7 Uncertainty in mean and median annual streamflow in the Gilbert catchment computed over the Assessment reporting period 1890-2011

GAUGING STATION ID	MEAN ANNUAL FLOW (GL/y)			MEDIAN ANNUAL FLOW (GL/y)		
	BASELINE MODEL	97.5% EX. ENSEMBLE	2.5% EX. ENSEMBLE	BASELINE MODEL	97.5% EX. ENSEMBLE	2.5% EX. ENSEMBLE
917001D	1058.7	809.4	1093.4	643.8	529.6	679.0
917002A	138.5	132.9	146.3	73.0	71.0	84.6
917004A	159.4	138.2	191.1	103.8	81.2	110.4
917005A	20.4	21.8	42.0	14.2	11.8	33.7
917006A	334.4	281.5	333.5	180.4	163.1	210.5
917007A*	42.0	NA	NA	25.7	NA	NA
917008A	86.7	77.7	89.3	69.1	57.7	73.5
917013A	210.2	198.3	220.7	117.5	103.9	135.0
917104A	155.1	149.4	165.6	98.0	90.5	113.8
917106A	728.7	682.2	775.1	416.5	329.5	457.8
917107A	40.3	38.0	42.9	25.5	19.9	29.3
917108A	136.5	122.4	143.8	67.4	55.0	71.3
917109A	1006.8	908.3	1126.8	653.6	527.0	699.3
917111A	2545.1	2447.9	2733.8	1796.0	1754.6	1952.0
917112A	118.4	115.2	124.8	81.5	74.0	90.9
917113A	386.8	293.2	400.7	269.8	201.0	288.3
917115A	160.6	149.7	192.0	75.4	59.7	118.8
917118A	161.0	149.7	193.6	70.4	53.7	114.4

* No ensemble calibration was performed for this station

Table 4.8 shows uncertainty in the bias, NSE daily and NSE log daily performance indicators. These uncertainties were estimated by comparing the ensemble modelled flows with the historical observed flows. The results show that uncertainty in the streamflow records has little impact on the quality of the calibration as measured by the NSE daily. By comparison the NSE log daily statistic, which is more sensitive to low flow performance, varies a lot (typically 10-15%) across the ensemble.

There is moderate uncertainty in the bias (Table 4.8). This is expected given the variance in the mean annual flows across the ensemble (Table 4.7).

Table 4.8 Uncertainty in key performance metrics in the Gilbert catchment

STATION ID	BIAS (%)			NSE DAILY (-)			NSE LOG DAILY (-)		
	BASELINE MODEL	97.5% EX. ENSEMBLE	2.5% EX. ENSEMBLE	BASELINE MODEL	97.5% EX. ENSEMBLE	2.5% EX. ENSEMBLE	BASELINE MODEL	97.5% EX. ENSEMBLE	2.5% EX. ENSEMBLE
917001D	7.30	3.40	27.50	0.873	0.801	0.879	0.649	0.468	0.684
917002A	0.10	-3.90	4.10	0.819	0.792	0.839	0.423	0.395	0.539
917004A	0.00	-22.80	6.20	0.706	0.598	0.758	0.430	0.428	0.529
917005A	0.00	-82.20	-3.10	0.583	-0.310	0.596	0.394	0.230	0.472
917006A	-1.50	-2.40	11.80	0.697	0.692	0.755	0.496	0.348	0.623
917007A*	1.20	NA	NA	0.601	NA	NA	0.363	NA	NA
917008A	3.50	1.20	10.90	0.531	0.525	0.573	0.443	0.380	0.514
917013A	2.70	-0.40	8.80	0.798	0.754	0.841	0.625	0.555	0.700
917104A	0.10	-6.00	3.10	0.680	0.658	0.689	0.596	0.558	0.613
917106A	8.50	6.20	15.90	0.824	0.814	0.911	0.636	0.532	0.726
917107A	1.00	-5.60	6.20	0.746	0.529	0.804	0.605	0.563	0.744
917108A	0.10	-3.30	10.40	0.756	0.709	0.763	0.617	0.457	0.681
917109A	1.60	-9.00	12.50	0.846	0.783	0.855	0.573	0.487	0.725
917111A	-1.70	-7.90	4.10	0.693	0.667	0.699	0.810	0.782	0.833
917112A	4.70	-0.10	6.80	0.832	0.791	0.847	0.669	0.504	0.759
917113A	3.40	-0.90	25.50	0.850	0.795	0.858	0.743	0.659	0.795
917115A	0.30	-15.50	5.80	0.711	0.660	0.713	0.571	0.415	0.733
917118A	-9.20	-32.60	-1.20	0.684	0.600	0.681	0.319	0.097	0.353

* No ensemble calibration was performed for this station

It was noted that the small headwater reach 917005A (Reach 14) has very poor NSE values for some of its ensemble members. This may indicate inconsistencies between the rainfall data and some of the replicate streamflow datasets. Poor performance in this reach is not expected to significantly affect performance (or the amount of water allocated for irrigation) in the Gilbert investigation area due to the isolation and small size of the reach.

4.6 River water balance

This section presents the results obtained by running the FGARA Gilbert model over the reporting period 1890-2011. The model was run with the following set-up:

- Full use of the existing water entitlements,
- Historical climate,
- A single baseline run and 50 ensemble runs.
- Simulated inflows (see section 2.3.1).

4.6.1 CATCHMENT RUNOFF

Catchment runoff data presented in this section were simulated using the baseline Sacramento rainfall-runoff model parameters.

Figure 4.16 shows the spatial distribution of mean annual rainfall and simulated runoff under Scenario A across the Gilbert catchment. The mean annual rainfall and runoff averaged over the Gilbert catchment is 775 mm (Petheram and Yang 2013) and 140 mm respectively. However, mean monthly and annual runoff data in northern Australia can be highly skewed. Consequently Figure 4.15 shows the spatial distribution of the 20%, 50% and 80% annual runoff under Scenario A. The 20%, 50% and 80% annual runoff averaged across the Gilbert catchment are 196 mm, 100 mm and 47 mm respectively. The largest runoff under Scenario A was 1231 mm in 1974. The smallest catchment average simulated runoff under Scenario A was 4 mm in 1935.

Mean annual runoff varies from over 200 mm in the lower reaches of the Gilbert catchment to less than 75 mm in the south. Runoff in the Gilbert catchment is highly variable from one year to the next. The coefficient of variation of annual rainfall and runoff averaged over the Gilbert catchment are 0.34 and 1.1 respectively.

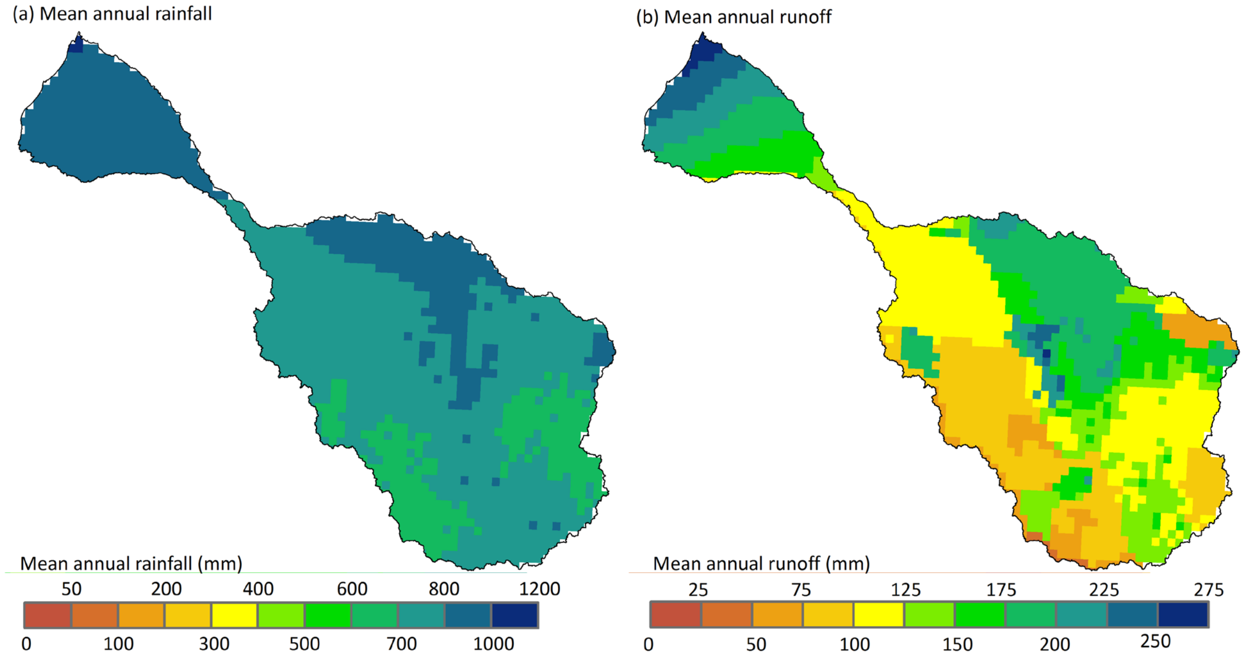

Figure 4.14 Mean annual runoff in the Gilbert catchment

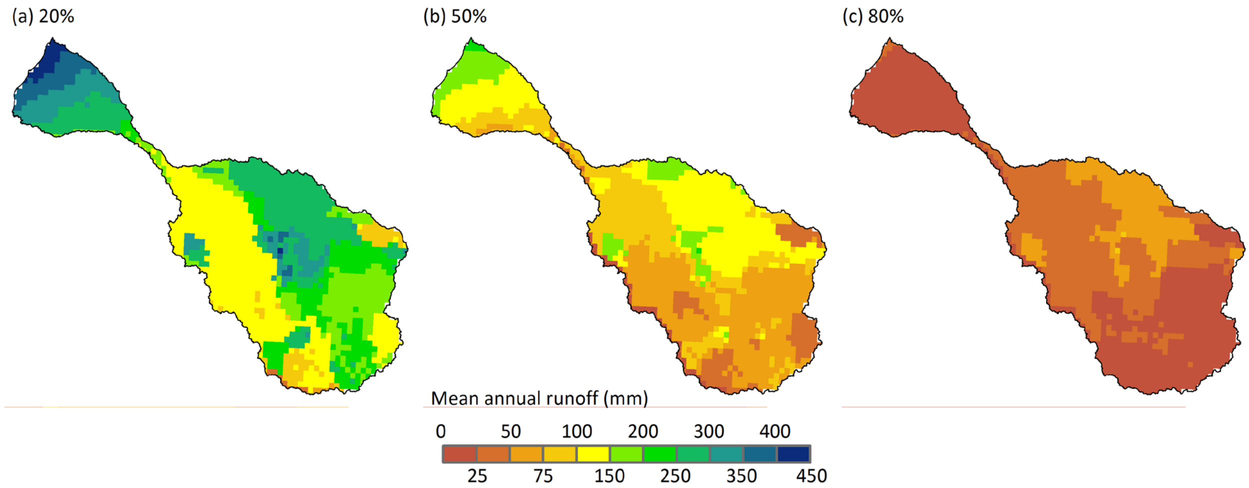

Figure 4.15 20%, 50% and 80% exceedance annual modelled runoff in the Gilbert catchment

Approximately 98% of runoff occurs during the wet season, with the majority of runoff occurring during the months January to March. Figure 4.16 illustrates the large monthly variability in runoff in the Gilbert catchment.

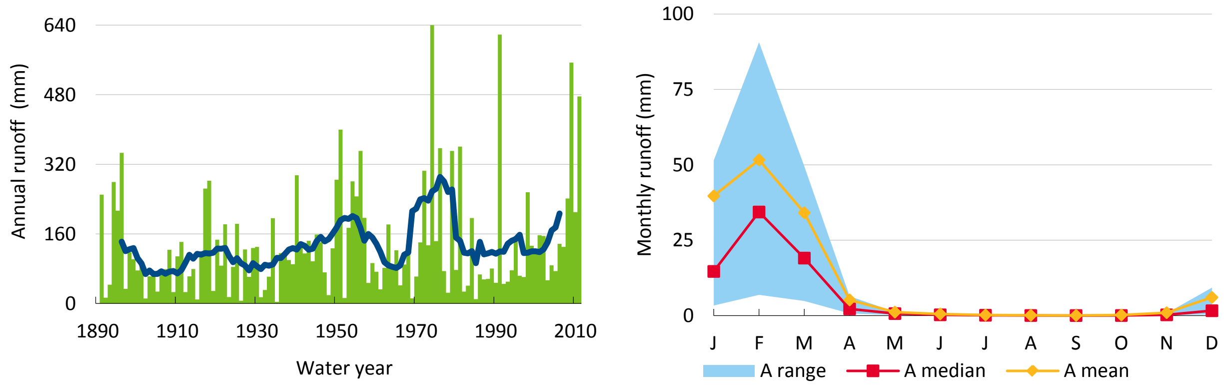

Figure 4.16 Historical annual runoff averaged across the Gilbert catchment (left). Catchment average runoff in 1974 was 1231 mm. Monthly runoff averaged across the Gilbert catchment (right) under Scenario A

Figure 4.17 illustrates water years where runoff was above or below the median annual runoff. In this figure it can be seen that there were long runs of dry years around 1905 and 1990.

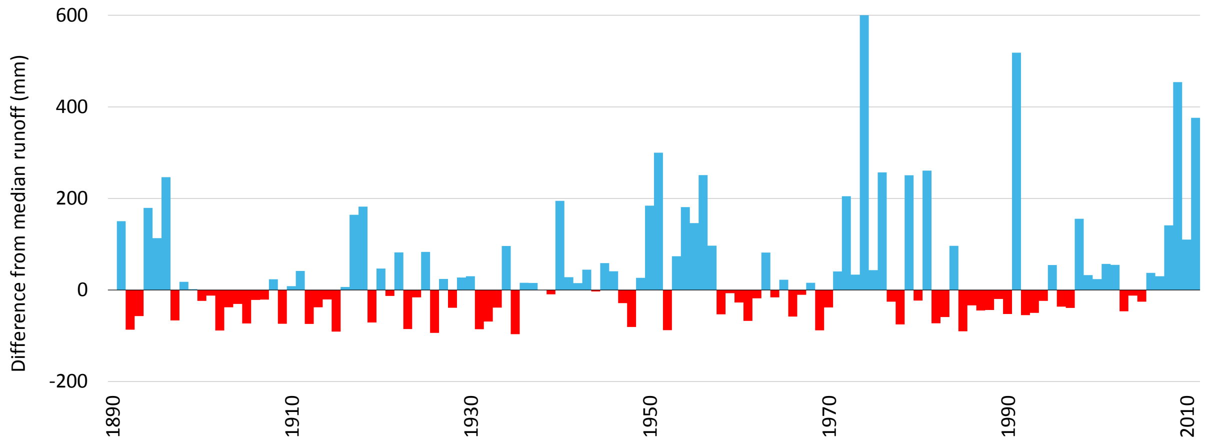

Figure 4.17 Runs of wet and dry runoff years averaged across the Gilbert catchment under Scenario A

4.6.2 MEAN ANNUAL WATER BALANCE

This section presents the results obtained by running the baseline Gilbert river model and the 50 model ensembles over the reporting period 1890-2011. Table 4.9 shows the water balance table for the whole catchment including: the change in reservoir volume; the net evaporation from reservoirs; the catchment inflow; diversions; outflow and losses. More detailed water balance tables are provided in Appendix D .

Table 4.9 Gilbert River mean annual water balance under Scenario A

		BASELINE MODEL (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/ y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/ y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	1.4	1.4	1.5
	Evaporation from ponded area	3.3	3.1	3.4
Inflows	Subcatchments gauged	602.1	573.4	668.4
	Subcatchments ungauged	3631.0	3398.7	3907.6
	Sub-total	**4233.1**	**4049.8**	**4538.9**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	21.5	20.8	22.1
	Water supply – general security	0	0	0
	Water supply – unsupplemented	29.9	29.1	30.0
	Sub-total	**51.4**	**50.4**	**52.0**
Outflows	End of system flow (917009A)	3719.1	3361.0	3926.8
	Reach losses	460.8	189.8	867.9
Unattributed fluxes	Unattributed loss	0.1	0.0	0.1

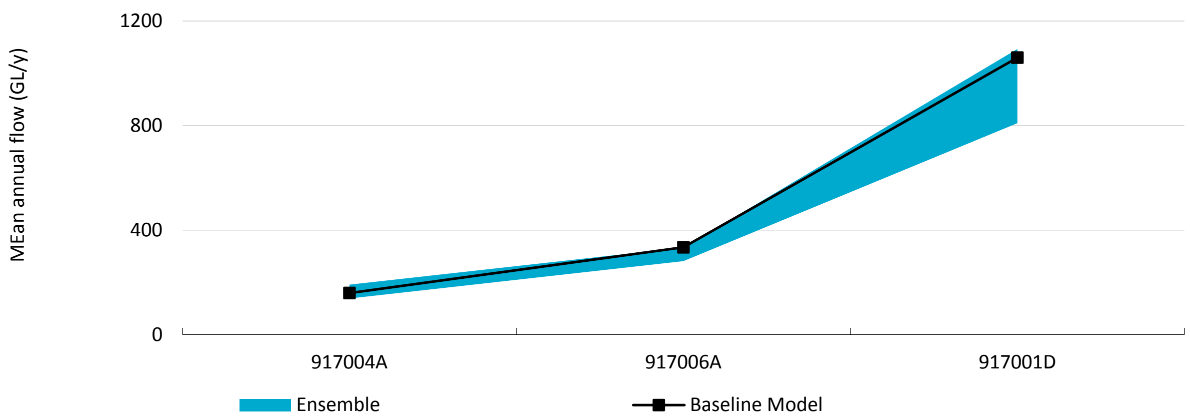

Figure 4.18 Observed (dark blue) and modelled (light blue band) mean annual flow along the Gilbert River and the 2.5% and 97.5% exceedance ensemble river models (shown by blue shading)

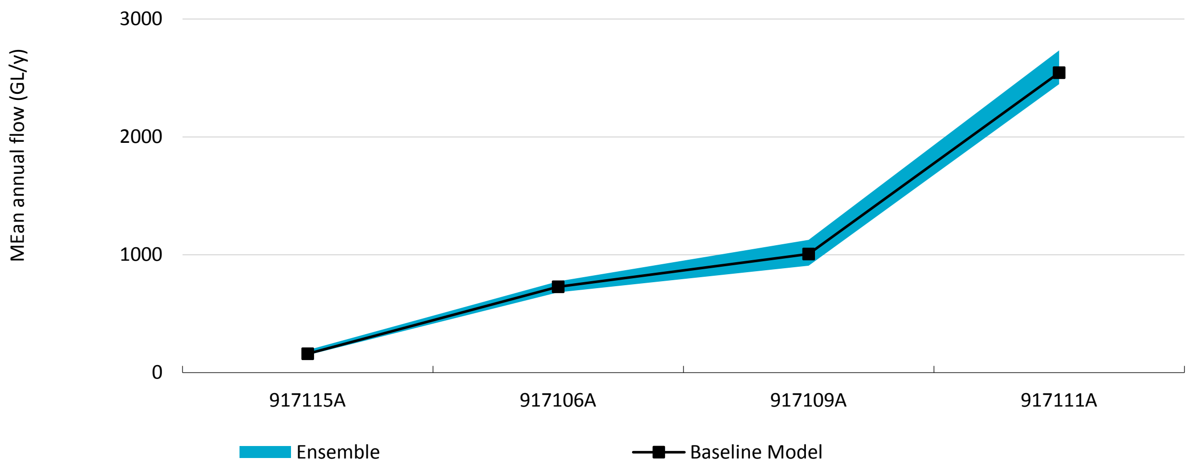

Figure 4.19 Observed (dark blue) and modelled (light blue band) mean annual flow along the Einasleigh River and the 2.5% and 97.5% exceedance ensemble river models (shown by blue shading)

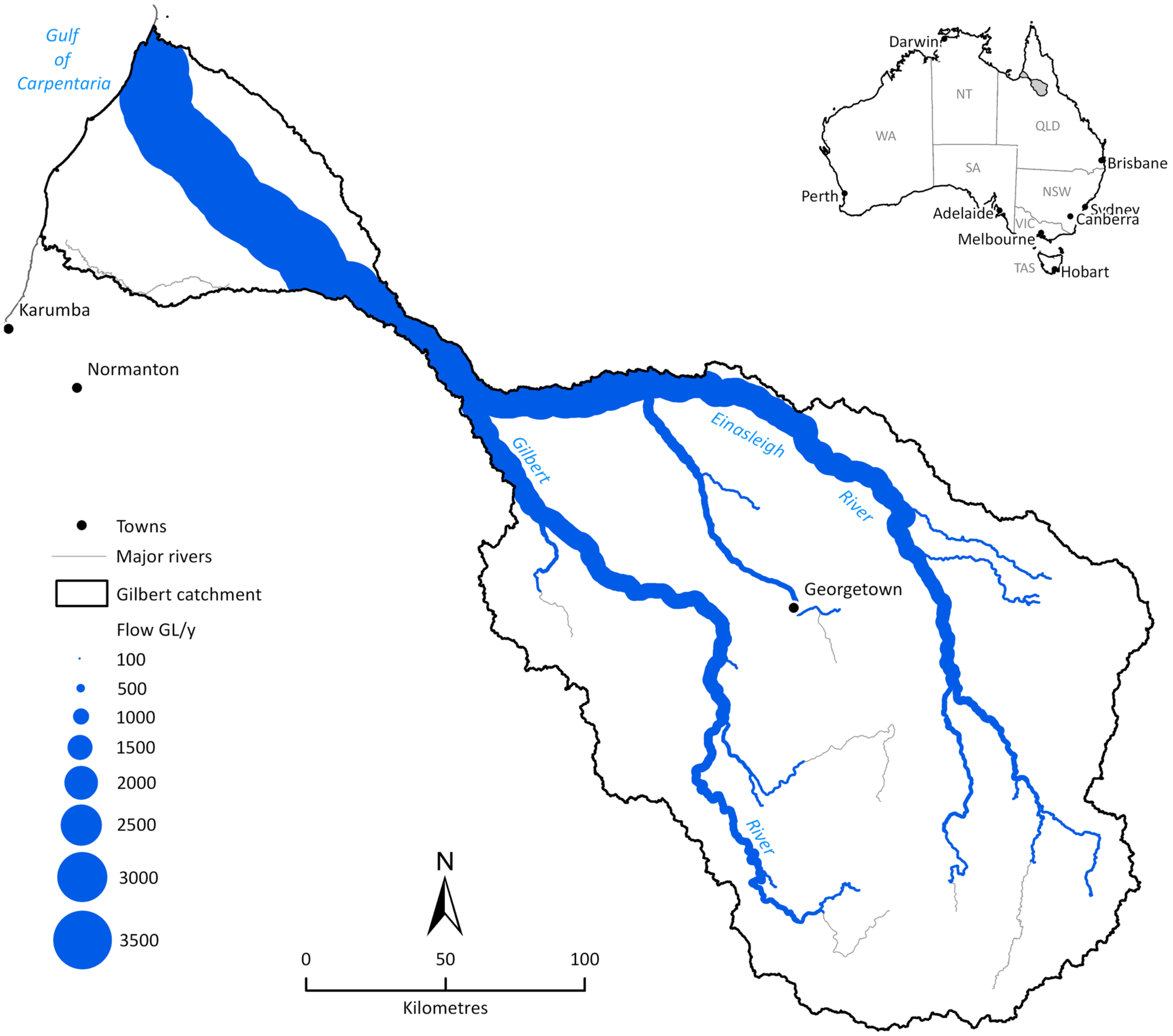

Figure 4.20 Mean annual flow in the Gilbert catchment. The flow downstream of the confluence between the Gilbert and Einasleigh rivers is indicative of the total catchment flow. The image does not represent the distributary flow leaving the main stem.

4.6.3 STORAGE BEHAVIOUR

This section provides an analysis of the Copperfield River Gorge Dam. Table 4.10 presents the statistics associated with stored volume and reservoir spill.

Table 4.10 Detail of dam behaviour in the Gilbert catchment

STORAGE		BASELINE MODEL	97.5% EXCEEDANCE ENSEMBLE SIMULATION	2.5% EXCEEDANCE ENSEMBLE SIMULATION
Kidston Dam	Minimum storage volume (GL)	1.7	1.6	1.8
	Average years between spills	0.7	0.5	0.8
	Maximum years between spills	6.8	3.9	6.8

4.6.4 CONSUMPTIVE WATER USE

This section details the model results associated with the diversion of water for consumptive use under Scenario A (which assumes a full use of existing entitlements). Table 4.11 shows the mean annual diversions for the 19 calibration reaches. The actual diversions were compared with the mean annual flow at the outlet of the catchment to compute the level of use. Results are presented in Table 4.12. Finally, Table 4.13 indicates the reliability of supply computed as the ratio between the actual diversion and the licence volume.

Under a full use of existing entitlements, the use of water relative to the mean annual flow at the outlet of the Gilbert catchments is 1%.

Table 4.11 Total mean annual diversions in the Gilbert catchment

REACH	OUTLET GAUGE	BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
1	917115A	0	0	0
2	917118A	4.6	4.5	4.6
3	917108A	0	0	0
4	917106A	3.8	3.4	4.3
5	917109A	0.7	0.5	0.8
6	917107A	0.5	0.4	0.5
7	917112A	3.1	2.3	3.2
8	917104A	0	0	0
9	917113A	0.2	0.2	0.2
10	917111A	1.0	1.0	1.0
11	917004A	0	0	0
12	917006A	0	0	0
13	917002A	0	0	0
14	917005A	0	0	0
15	917013A	0	0	0
16	917007A	0	0	0

REACH	OUTLET GAUGE	BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
17	917001D	28.8	28.7	28.8
18	917008A	0	0	0
19	917009A	8.1	7.4	8.8

Table 4.12 Relative level of surface water use in the Gilbert catchment

	BASELINE MODEL (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Total surface mean annual flow	3719.1	3361.0	3926.8
Total net diversions	51.4	50.4	52.0
Relative level of use (-)	0.014	0.013	0.015

Table 4.13 Average reliability of water supply in the Gilbert catchment

		BASELINE MODEL	2.5% EXCEEDANCE ENSEMBLE SIMULATION	97.5% EXCEEDANCE ENSEMBLE SIMULATION
Town water supply	High security	NA	NA	NA
	Unsupplemented	0.97	0.97	0.98
Agriculture	General security	NA	NA	NA
	Unsupplemented	0.70	0.69	0.72
Other demands	High security	NA	NA	NA
	Unsupplemented	NA	NA	NA

5 Conclusions

River system models were successfully created for the Flinders and Gilbert catchments. An innovative aspect of the calibration method was the joint calibration of rainfall-runoff, routing and water loss components of the model. To enable these three components to be jointly calibrated a two parameter parametric function was used to describe the water loss term. This approach streamlined the calibration method and limited the degree of flexibility of the model under calibration, resulting in a robust model for undertaking scenario simulations.

An uncertainty analysis was undertaken. It assumed that the greatest source of uncertainty in simulating streamflow in the Flinders and Gilbert catchments was uncertainty in streamflow measurements. The analysis firstly involved generating an ensemble of 50 equally plausible streamflow replicates using a regression model based on the variation in the streamflow gauging measurements. Using the 50 streamflow replicates, the calibration procedure was repeated 50 times to generate 50 additional calibrated parameter sets. Under scenario analysis, running the river model using all 51 calibrated parameter sets enables the variability in the 51 model results to be explored. When undertaking scenario simulations using the Assessment river models the results of the uncertainty analysis can be interrogated to provide guidance about which results contain useful information and in which results the uncertainty in model output is too large to be conclusive.

The Assessment river models for the Flinders and Gilbert catchments accurately reproduced the historical monthly and annual streamflows well at most stations (NSE > 0.9) and in several cases the models' performance was considered excellent (NSE > 0.95). Long term model bias was small at all gauging stations and never exceeded 14% in the Flinders catchment and 9% in the Gilbert catchment. In both catchments large flood events were reasonably well simulated.

Low flow regimes were satisfactorily simulated in most subcatchments of the Flinders and Gilbert, but as is the case with most conceptual hydrological models they did not simulate low flows as well as mid to high flows.

Under Scenario A the mean and median annual runoff spatially averaged across the Flinders catchment was 35 mm and 22 mm respectively. The mean and median annual runoff spatially averaged across the Gilbert catchment was 140 mm and 100 mm respectively.

In the Flinders catchment the 20% and 80% annual exceedance runoff under Scenario A was 52 mm and 7 mm respectively. In the Gilbert catchment the 20% and 80% annual exceedance runoff was 196 mm and 47 mm respectively.

The percentage of runoff occurring in the wet season in the Flinders and Gilbert catchments was 95% and 98% respectively.

For the Flinders catchment, the mean annual flow of the Flinders River at Walker's Bend was found to be 2543 GL/year with uncertainty bounds ranging from 2415 GL/year to 2685 GL/year. The mean flow at Richmond was found equal to 405 GL/year with uncertainty bounds ranging from 377 to 414 GL/year.

For the Gilbert catchment, the mean annual flow at the gauging station of Miranda Downs was computed to be 3719 GL/year with uncertainty bounds ranging from 3361 GL/year to 3927 GL/year. The mean annual flow on the Einasleigh River at Minnie's Dip was computed to be 2545 GL/year with uncertainty bounds ranging from 2448 GL/year to 2734 GL/y.

The calibration methods adopted in this report and those used by the Queensland Government for IQQM are similar in terms of the rainfall-runoff and routing models used, but differ in terms of loss function, spatial resolution of the model, climate input data, calibration period and calibration method. As a result, the two models provide different estimates of the long-term mean annual flows. The difference was found significant for some stations in the Flinders catchment. For example, Petheram et al. (2009), based on the

IQQM model and the reporting period 1930-2007, reported a mean annual flow at Walker's Bend of 1938 GL/y whereas the same flow is estimated as 2543 GL/y in this report.

Detailed analysis was undertaken to investigate the differences between the long-term mean annual flow computed with the Flinders IQQM model and the Assessment river model. The analysis concluded that the main factor explaining the difference between the two models is the use of different climate input data. The IQQM potential evaporation derived from point pan evaporation is significantly higher than the one used for the Assessment based on gridded Morton's wet environment areal potential evaporation. In addition, the data used for the Assessment showed a more consistent inter-annual variability across the reporting period. At Walker's Bend, the extension of the calibration period from 1970-2003 (IQQM) to 1970-2011 (Assessment) had a significant impact on mode output. This result was explained by the major flood that occurred in 2009 in the Gulf region that was captured by the Assessment calibration but not in the IQQM calibration.

Both models showed similar performance regarding bias and low flows (estimated with the Nash-Sutcliffe performance statistic computed on log-transformed flows) when comparing simulated flows with observed streamflow data. The Assessment river model performed better for the high flow regime as indicated by higher values of the Nash-Sutcliffe performance metric.

Overall, the difference between the IQQM and Assessment river models was justified by the use of more recent data (potential evaporation and calibration period) and automatic calibration method, which led to model improvement for the simulation of the high flow regime.

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Appendix A Generation of streamflow replicates

Streamflow data are produced by applying a rating curve to a continuous record of water level. The curve is obtained by interpolating and extrapolating the flow gaugings to produce a smooth curve covering the range of water levels expected at the station. This process introduces a high level of uncertainty if the curve cannot capture the relationship between water level and flow (e.g. backwater effects), or if the extrapolation goes far beyond the maximum observed flow.

To quantify this type of uncertainty, a regression model between the estimated flow obtained from the rating curve, noted Q_e, and the gauged flow, noted Q_g, was developed. The regression has the following form:

$$B(Q_g, \gamma) = B(\alpha {Q_e}^{\beta}, \gamma) + \varepsilon \tag{17}$$

where α and β are the parameters of the regression, ε a residual term assumed to be identically and independently distributed, B the Box-Cox transform (Box and Cox, 1964) and γ the Box-Cox parameter. The Box-Cox transform is given by

$$B(x, \gamma) = \begin{cases} \dfrac{x^{\gamma} - 1}{\gamma}, & \gamma \neq 0 \\ \log(x), & \gamma = 0 \end{cases} \tag{18}$$

It is used to reduce the weight of high flows in the regression and stabilise the variance of the residual ε. This type of regression model is discussed in details by Carroll and Ruppert (1988). The parameters were obtained by a bootstrap procedure (Li and Shao, 2010) based on the following steps

1. For each station, the pairs of gauged and estimated flows were obtained from the Queensland Government. The pairs with zero flows were excluded. For example, there are 87 gaugings available for the Flinders River at Hughenden (see Table 3.3).
2. A first estimate of the parameters α, β and γ was obtained by minimising the sum of squared residuals $\sum_{i=1,..n} {\varepsilon_i}^2$ with n the number of pairs in the sample.
3. The residuals (ε_i) were resampled to form a new series of residuals $({\varepsilon_i}^*)$.
4. A new series of observations was generated by adding the resampled residuals to the transform data using ${Q_{g,i}}^* = B^{-1}(B(Q_{e,i}) + {\varepsilon_i}^*)$ with $Q_{g,i}$ and $Q_{e,i}$ the i^{th} gauged and estimated flow, respectively.
5. Step 2 was repeated using the new series of observation ${Q_{g,i}}^*$ to calibrate the parameters of the regression.

This procedure was repeated 50 times to generate 50 sets of parameters. Finally, the regression was applied to the daily time series of original streamflow data to produce the replicates. Apx Table A.1 gives the parameters of the regression obtained for 41 gauging stations in the Flinders and Gilbert catchments. The procedure led to acceptable replicates for 31 stations. For the 10 remaining stations, the gauged data did not provide enough information for the algorithm to converge (due to the limited sample size with only gauged data at lower end of rating curves). The corresponding replicates were discarded from the analysis.

The procedure described in the previous paragraph does not account for the correlation between upstream and downstream flows. When a river model is calibrated for a residual reach (see Table 3.2 and Table 4.1), this may introduce inconsistencies in the calibration if upstream and downstream replicates are randomly selected. For example, an upstream replicate with a large mean annual flow might be paired with a downstream replicate having a much smaller mean annual flow. To avoid this issue, the replicates were ranked according the mean annual flow. Upstream and downstream replicates with the same rank were paired to form the calibration dataset.

Furthermore, given that the gauged data were very sparse and irregular over time, the correlations in daily data cannot be modelled from the gauged data. However, it is widely known that the daily streamflows are correlated and the correlation can be complicated and cannot be ignored. We impose the correlation on the residuals as unknown and pre-determined in the ensemble generation. It is the best we can do in the current dataset. Further research will surely improve the ensemble generations.

Apx Table A.1 Characteristics of the replicate streamflow data

STATION ID	COMMENT	PARAMETERS OF THE REGRESSION				DRY SEASON FLOW (GL/SEASON) PERIOD OF RECORDS			MEAN ANNUAL FLOW (GL/y) PERIOD OF RECORDS		
		α	β	γ	σ	ORIGINAL DATA	REPLICATES PERCTL. EXCEED.		ORIGINAL DATA	REPLICATES PERCTL. EXCEED.	
							97.5%	2.5%		97.5%	2.5%.
915003A		1.11	0.99	0.15	0.42	32.7	32.5	36.2	3350.6	3228.7	3537.5
915004A		1.002	0.997	0.192	0.205	4.6	4.4	4.8	120.6	116.0	127.4
915005A		0.97	0.99	-0.08	0.11	2.5	2.2	2.6	103.4	85.4	105.8
915006A	Insufficient gaugings	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
915007A		1.009	1.001	-0.20	0.025	0.6	0.6	0.7	44.2	41.7	47.9
915008A		1.02	1.00	0.02	0.19	17.0	15.7	17.8	573.4	539.4	587.7
915009A		0.86	0.97	-0.38	0.68	NA	NA	NA	NA	NA	NA
915010A		1.01	0.98	0.28	0.09	0.5	0.5	0.5	49.8	41.7	55.4
915011A		0.96	0.98	0.10	0.13	0.9	0.8	0.9	32.7	26.8	32.1
915012A		0.99	1.00	0.18	0.07	13.4	12.8	13.3	1476.0	1380.0	1447.4
915013A	Unreliable replicates	1.01	1.00	-0.68	0.22	NA	NA	NA	NA	NA	NA
915014A		0.99	0.99	0.13	0.04	1.2	1.1	1.2	138.9	127.3	139.4
915203B	Unreliable replicates	0.92	0.98	-0.18	0.45	NA	NA	NA	NA	NA	NA
915204A		0.91	1.02	0.18	0.27	4.0	3.6	4.4	200.9	192.9	214.1
915205A		1.01	1.01	0.53	0.02	0.4	0.4	0.4	19.6	19.6	20.8
915206A		0.98	1.00	-0.08	0.11	0.5	0.5	0.5	57.3	53.7	58.9
915207A	Unreliable replicates	1.17	0.99	0.05	0.44	NA	NA	NA	NA	NA	NA
915208A	Unreliable replicates	0.75	0.96	0.05	0.98	NA	NA	NA	NA	NA	NA
915209A		1.03	1.00	0.18	0.05	0.8	0.8	0.9	77.3	75.6	80.0
915210A		1.03	0.99	0.60	0.02	0.5	0.5	0.6	71.7	66.9	71.0
915211A		1.01	1.00	0.70	0.05	0.6	0.6	0.6	43.6	42.4	43.7
915212A		1.02	1.00	-0.10	0.07	5.9	5.3	6.4	1271.7	1101.0	1372.3
917001D		1.17	0.97	0.20	0.52	12.3	12.8	14.3	1250.3	991.4	1241.1

STATION ID	COMMENT	PARAMETERS OF THE REGRESSION				DRY SEASON FLOW (GL/SEASON) PERIOD OF RECORDS			MEAN ANNUAL FLOW (GL/y) PERIOD OF RECORDS		
		α	β	γ	σ	ORIGINAL DATA	REPLICATES PERCTL. EXCEED.		ORIGINAL DATA	REPLICATES PERCTL. EXCEED.	
							97.5%	2.5%		97.5%	2.5%.
917002A		0.99	1.00	0.25	0.22	1.7	1.7	1.8	172.5	168.1	179.3
917004A		1.03	1.01	0.08	0.19	1.6	1.5	1.8	190.6	178.8	234.4
917005A	Unreliable replicates	1.03	1.01	-0.30	0.19	NA	NA	NA	NA	NA	NA
917006A		0.99	0.99	0.13	0.08	4.2	4.0	4.3	406.3	358.7	416.6
917007A	Unreliable replicates	0.62	0.90	-0.15	1.25	NA	NA	NA	NA	NA	NA
917008A		0.90	1.01	0.25	0.28	0.2	0.2	0.3	104.8	93.8	122.8
917013A		1.00	1.00	0.55	0.10	2.5	2.5	2.6	301.0	300.3	310.4
917104A		0.95	1.02	0.53	0.11	0.8	0.8	0.8	168.7	172.0	179.0
917106A		0.93	1.01	0.25	0.29	17.1	16.0	17.2	964.5	953.6	986.4
917107A		1.01	0.99	0.40	0.11	4.4	4.4	4.7	49.7	47.5	50.8
917108A		0.99	1.00	200.00	0.14	1.8	1.7	1.9	166.3	161.8	172.3
917109A		0.96	1.00	0.38	0.41	47.8	42.5	50.2	1338.5	1173.4	1516.8
917110A	Unreliable replicates	1.07	1.05	0.10	0.36	NA	NA	NA	NA	NA	NA
917111A		0.99	1.00	0.33	0.10	78.8	77.0	82.1	3491.9	3297.7	3815.0
917112A		1.00	1.00	0.63	0.11	8.1	7.9	8.4	170.5	167.7	177.6
917113A		0.96	0.99	-0.10	0.16	4.7	3.2	5.2	515.9	409.7	559.4
917115A	Unreliable replicates	0.00	1.00	0.20	0.02	NA	NA	NA	NA	NA	NA
917118A	Added at the end of the study	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Appendix B Details on the comparison between the IQQM and FGARA river model

This appendix provides the values of the metrics used for the comparison between the IQQM and Assessment river models described in section 3.6. **In order to compare the model outputs with the ones from IQQM, the mean annual flow and performance statistics were computed for a different period than the reporting period of the Assessment. As a result the numbers indicated in the following table may differ from the numbers indicated in the rest of this document.** As indicated in section 3.6, the values indicated in the following table are computed for the following periods:

- The long term mean annual flow was computed over the period 1930-2007. This period is consistent with the one used in the NASY.
- The performance statistics comparing modelled and observed flow were computed for the period of records up to 2008.

		ALTERNATIVE RIVER MODEL CONFIGURATION						
STATION ID	VARIABLE	IQQM. NASY	IQQM.CAL	FGARA-R	FGARA.P	FGARA.I	FGARA.L	FGARA.PIL
915003	Mean Ann Flow (GL/y)	1937.7	2016.3	2467.6	2127.4	2080.2	2747.8	1789.4
	Bias (%)	-14.91	-12.65	-4.44	-18	-5.99	2.38	-21.2
	NSE (-)	0.83	0.6	0.72	0.75	0.71	0.8	0.79
	NSELOG (-)	0.79	0.6	0.43	0.41	0.38	0.37	0.38
915004	Mean Ann Flow (GL/y)	91.9	102.1	108.5	108.5	98	95.4	81.8
	Bias (%)	-8.4	7.12	8.83	8.83	12.8	-4.57	-6.14
	NSE (-)	0.96	0.58	0.64	0.64	0.64	0.72	0.72
	NSELOG (-)	0.81	0.46	0.64	0.64	0.62	0.65	0.64
915005	Mean Ann Flow (GL/y)	74.9	74.3	73.8	73.8	67.4	74.1	67
	Bias (%)	-0.06	0.42	0	0	0	0.16	0.23
	NSE (-)	1	0.6	0.76	0.76	0.74	0.76	0.74
	NSELOG (-)	1	0.46	0.49	0.49	0.48	0.5	0.48
915006	Mean Ann Flow (GL/y)	4.8	5.1	5.5	5.5	4.4	5.5	4.4
	Bias (%)	-0.07	8.05	0	0	0	0.37	0.23
	NSE (-)	1	0.24	0.64	0.64	0.78	0.63	0.78
	NSELOG (-)	1	0.44	0.33	0.33	0.38	0.36	0.38
915007	Mean Ann Flow (GL/y)	30.2	29.3	29.8	29.8	25.3	29.5	25.1

	Bias (%)	-0.06	0.27	0	0	0	0.15	0.33
	NSE (-)	1	0.29	0.55	0.55	0.52	0.54	0.5
	NSELOG (-)	1	0.57	0.4	0.4	0.44	0.41	0.46
915008	Mean Ann Flow (GL/y)	347.6	367.4	388.3	388.3	329.3	380.1	313.7
	Bias (%)	-12.74	-9.53	-14.15	-14.15	-14.46	-16.49	-18.7
	NSE (-)	0.85	0.65	0.7	0.7	0.73	0.7	0.74
	NSELOG (-)	0.74	0.51	0.65	0.65	0.64	0.66	0.67
915009	Mean Ann Flow (GL/y)	65	62.1	64.2	64.2	54.2	64.5	54.8
	Bias (%)	-0.06	0.53	0	0	-0.42	0.86	2.7
	NSE (-)	1	0.57	0.83	0.83	0.65	0.83	0.63
	NSELOG (-)	1	0.43	0.56	0.56	0.62	0.56	0.62
915010	Mean Ann Flow (GL/y)	33.2	33.2	31.7	31.7	26.5	31.8	26.5
	Bias (%)	-0.06	-0.12	0	0	0	0.49	0.81
	NSE (-)	1	0.56	0.67	0.67	0.64	0.67	0.63
	NSELOG (-)	1	0.43	0.44	0.44	0.47	0.46	0.48
915011	Mean Ann Flow (GL/y)	20.6	21.2	23.9	23.7	22.1	23.8	20.8
	Bias (%)	-1.5	2.31	3.07	2.21	6.76	3.48	2.77
	NSE (-)	1	0.35	0.46	0.46	0.43	0.41	0.37
	NSELOG (-)	0.99	0.59	0.5	0.57	0.57	0.51	0.6
915012	Mean Ann Flow (GL/y)	951.2	1003.1	1116.1	1116.1	839.3	1132.8	912.2
	Bias (%)	-2.39	10.28	2.19	2.19	-0.48	1.72	2.89
	NSE (-)	0.99	0.54	0.82	0.82	0.81	0.85	0.85
	NSELOG (-)	0.86	0.53	0.72	0.72	0.72	0.73	0.73
915013	Mean Ann Flow (GL/y)	93	94.4	101.5	100	94.3	101.6	90.6
	Bias (%)	-0.35	3.06	4.02	4.1	10.24	4.06	4.52
	NSE (-)	0.98	0.59	0.59	0.69	0.72	0.59	0.68
	NSELOG (-)	0.98	0.41	0.54	0.46	0.56	0.54	0.55
915014	Mean Ann Flow (GL/y)	88	85.7	93.8	93.8	86.3	93.9	84.3
	Bias (%)	-0.3	1.47	-1.67	-1.67	-0.16	1.8	3.8
	NSE (-)	1	0.55	0.67	0.67	0.73	0.63	0.74
	NSELOG (-)	0.82	0.38	0.53	0.53	0.52	0.58	0.58

915203	Mean Ann Flow (GL/y)	266.7	271.6	322.4	322.4	281.4	327.7	285.3
	Bias (%)	-6.87	-4.32	3.73	3.73	4.16	5.57	5.76
	NSE (-)	0.81	0.76	0.77	0.77	0.7	0.73	0.65
	NSELOG (-)	0.77	0.61	0.6	0.6	0.64	0.62	0.65
915204	Mean Ann Flow (GL/y)	149.9	156.3	195.2	195.2	168	195.8	167.7
	Bias (%)	-15.17	-9.63	-0.01	-0.01	0	0.32	0.04
	NSE (-)	0.87	0.66	0.68	0.68	0.67	0.7	0.69
	NSELOG (-)	0.83	0.56	0.61	0.61	0.63	0.6	0.61
915205	Mean Ann Flow (GL/y)	15.7	15.4	17.1	17.1	15.5	17.1	15.5
	Bias (%)	-0.07	0.22	-0.02	-0.02	0	-0.24	-0.29
	NSE (-)	1	0.24	0.24	0.24	0.33	0.22	0.29
	NSELOG (-)	1	0.52	0.5	0.5	0.49	0.52	0.53
915206	Mean Ann Flow (GL/y)	46.5	49.1	43.5	50.9	40.7	43.5	44.3
	Bias (%)	-0.19	10.4	-7.8	7.12	-2.93	-7.51	6.88
	NSE (-)	0.96	0.62	0.69	0.65	0.69	0.69	0.61
	NSELOG (-)	0.98	0.46	0.51	0.49	0.52	0.51	0.51
915207	Mean Ann Flow (GL/y)	117.6	109.5	98.9	98.9	89.7	99.2	90
	Bias (%)	-0.18	-0.29	0	0	0	-0.11	-0.2
	NSE (-)	1	0.32	0.76	0.76	0.71	0.75	0.72
	NSELOG (-)	1	0.47	0.42	0.42	0.47	0.41	0.48
915208	Mean Ann Flow (GL/y)	NA	NA	24.8	23.8	22.2	24.5	19.9
	Bias (%)	NA	NA	0.3	-3.15	5.94	-0.11	-2.85
	NSE (-)	NA	NA	0.72	0.68	0.65	0.72	0.68
	NSELOG (-)	NA	NA	0.15	0.24	0.07	0.13	0.3
915209	Mean Ann Flow (GL/y)	62.6	77.4	75	75	61.7	75.8	62.2
	Bias (%)	-16.2	3.95	-0.05	-0.05	0	-0.21	-0.27
	NSE (-)	0.8	0.2	0.31	0.31	0.27	0.27	0.22
	NSELOG (-)	0.85	0.6	0.64	0.64	0.62	0.66	0.63
915210	Mean Ann Flow (GL/y)	50.5	48.6	55.1	55.1	47.2	54.4	46.7
	Bias (%)	-0.06	1.46	-0.02	-0.02	0	-1.47	-0.69
	NSE (-)	1	0.23	0.54	0.54	0.59	0.55	0.57

	NSELOG (-)	1	0.49	0.53	0.53	0.57	0.53	0.57
915211	Mean Ann Flow (GL/y)	33.2	33.7	33.8	37.1	31.6	33.7	31.3
	Bias (%)	-0.14	2.31	-3.76	3.92	2.5	-3.8	3.09
	NSE (-)	0.96	0.58	0.67	0.59	-0.27	0.66	-0.5
	NSELOG (-)	0.99	0.5	0.5	0.53	-0.06	0.51	0.06
915212	Mean Ann Flow (GL/y)	1163.1	1170.4	993.4	993.4	873.6	972.8	835.8
	Bias (%)	63.87	56.74	-1.83	-1.83	-0.53	-5.54	-6.97
	NSE (-)	-0.61	-1.98	0.72	0.72	0.69	0.77	0.76
	NSELOG (-)	0.82	0.56	0.72	0.72	0.74	0.7	0.69

Appendix C Water balance tables for the Flinders catchment

This appendix provides water balance tables for the principal river reaches of the Flinders river model.

Apx Table C.1 Water balance for reach 8, upstream of gauging station 915004A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0.0	0.0	0.0
	Net Rainfall from ponded area	0.0	0.0	0.0
	Net Evaporation from ponded area	0.1	0.1	0.1
Inflows	Subcatchments gauged	110.5	110.5	110.5
	Subcatchments ungauged	21.9	12.4	27.2
	Sub-total	**132.5**	**122.9**	**137.8**
Diversions	Agriculture – general security	0.0	0.0	0.0
	Agriculture – unsupplemented	7.8	7.6	7.9
	Water Supply – high security	0.0	0.0	0.0
	Water Supply – unsupplemented	0.0	0.0	0.0
	Other uses – high security	0.0	0.0	0.0
	Other uses – unsupplemented	0.4	0.4	0.4
	Sub-total	**8.2**	**8.0**	**8.3**
Outflows	**End of system flow**	**109.9**	**104.8**	**115.4**
	River losses	14.3	2.6	18.0

Apx Table C.2 Water balance for reach 9, upstream of gauging station 915014A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0.0	0.0	0.0
	Net Rainfall from ponded area	0.0	0.0	0.0
	Net Evaporation from ponded area	0.0	0.0	0.0
Inflows	Subcatchments gauged	78.7	66.9	81.7
	Subcatchments ungauged	21.5	19.7	39.7
	Sub-total	**100.3**	**93.4**	**109.5**
Diversions	Agriculture – general security	0.0	0.0	0.0
	Agriculture – unsupplemented	0.0	0.0	0.0
	Water Supply – general security	0.0	0.0	0.0
	Water Supply – unsupplemented	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**
Outflows	**End of system flow**	**98.5**	**92.0**	**107.9**
	River losses	1.8	1.4	1.8

Apx Table C.3 Water balance for reach 10, upstream of gauging station 915008A

		BASELINE MODEL (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Net rainfall from ponded area	0.0	0.0	0.0
	Net evaporation from ponded area	0.0	0.0	0.0
Inflows	Subcatchments gauged	202.5	185.9	214.2
	Subcatchments ungauged	235.4	222.8	252.6
	Sub-total	**437.9**	**409.5**	**448.4**
Diversions	Agriculture – general security	0.5	0.5	0.5
	Agriculture – unsupplemented	8.8	8.5	9.0
	Other uses – unsupplemented	0.3	0.3	0.3
	Sub-total	**9.7**	**9.4**	**9.9**
Outflows	**End of system flow**	**404.7**	**377.2**	**414.2**
	River losses	23.5	22.0	26.3

Apx Table C.4 Water balance for reach 11, upstream of gauging station 915012A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0.0	0.0	0.0
	Rainfall on ponded area	0.2	0.2	0.2
	Net Evaporation from ponded area	1.8	1.8	1.8
Inflows	Subcatchments gauged	573.1	541.6	585.2
	Subcatchments ungauged	702.9	636.9	675.6
	Sub-total	**1276.0**	**1200.0**	**1252.2**
Diversions	Agriculture – general security	11.3	11.0	11.3
	Agriculture – unsupplemented	38.2	37.2	38.5
	Other uses – unsupplemented	0.4	0.3	0.4
	Sub-total	**49.8**	**48.5**	**50.2**
Outflows	**End of system flow**	**1118.4**	**1042.4**	**1106.0**
	River losses	106.2	85.4	110.6

Apx Table C.5 Water balance for reach 12, upstream of gauging station 915003A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0.0	0.0	0.0
	Rainfall on ponded area	0.0	0.0	0.0
	Net Evaporation from ponded area	0.0	0.0	0.0
Inflows	Subcatchments gauged	2132.2	1901.6	2195.2
	Subcatchments ungauged	644.4	680.8	783.6
	Sub-total	**2776.6**	**2656.1**	**2927.1**
Diversions	Agriculture – general security	0.0	0.0	0.0
	Agriculture – unsupplemented	0.6	0.6	0.6
	Other uses – unsupplemented	0.0	0.0	0.0
	Sub-total	**0.6**	**0.6**	**0.6**
Outflows	**End of system flow**	**2543.3**	**2415.3**	**2685.2**
	River losses	232.7	220.8	262.8

Apx Table C.6 Water balance for reach 21, upstream of gauging station 915203AB

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0.0	0.0	0.0
	Net Rainfall on ponded area	0.0	0.0	0.0
	Net Evaporation from ponded area	0.1	0.0	0.1
Inflows	Subcatchments gauged	187.1	177.7	198.2
	Subcatchments ungauged	125.9	103.2	124.2
	Sub-total	**313.1**	**282.3**	**317.1**
Diversions	Agriculture – general security	0.0	0.0	0.0
	Agriculture – unsupplemented	2.8	2.7	2.9
	Water Supply – high security	2.2	2.0	2.2
	Sub-total	**5.0**	**4.7**	**5.1**
Outflows	**End of system flow**	**308.0**	**277.3**	**312.6**
	River losses	0.0	0.0	0.4

Apx Table C.7 Water balance for reach 20, upstream of gauging station 915204A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0.0	0.0	0.0
	Net Rainfall on ponded area	0.0	0.0	0.0
	Net Evaporation from ponded area	0.0	0.0	0.0
Inflows	Subcatchments gauged	71.2	67.0	71.4
	Subcatchments ungauged	116.0	110.1	126.9
	Sub-total	**187.1**	**177.7**	**198.2**
Outflows	**End of system flow**	**187.1**	**177.7**	**198.2**
	River losses	0.0	0.0	1.8

Apx Table C.8 Water balance for reach 18, upstream of gauging station 915209A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0.0	0.0	0.0
	Net Rainfall on ponded area	0.6	0.6	0.6
	Net Evaporation from ponded area	3.1	3.0	3.2
Inflows	Subcatchments gauged	0.0	0.0	0.0
	Subcatchments ungauged	77.6	75.7	81.0
	Sub-total	**77.6**	**75.7**	**81.0**
Diversions	Other uses – high security	2.8	2.7	2.8
	Other uses – unsupplemented	0.0	0.0	0.0
	Sub-total	**2.8**	**2.7**	**2.8**
Outflows	**End of system flow**	**72.3**	**70.5**	**74.7**
	River losses	0.0	0.0	2.5

Apx Table C.9 Water balance for reach 22, upstream of gauging station 915212A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0.0	0.0	0.0
	Rainfall on ponded area	0.0	0.0	0.0
	Net Evaporation from ponded area	0.0	0.0	0.0
Inflows	Subcatchments gauged	596.4	560.7	605.1
	Subcatchments ungauged	573.0	436.6	644.3
	Sub-total	**1169.3**	**998.7**	**1246.8**
Diversions	Agriculture – general security	0.7	0.7	0.7
	Agriculture – unsupplemented	12.4	11.3	12.6
	Sub-total	**13.1**	**11.9**	**13.3**
Outflows	**End of system flow**	**1013.8**	**856.7**	**1089.2**
	River losses	142.4	117.3	146.9

Appendix D Water balance tables for the Gilbert catchment

This appendix provides water balance tables for the principal river reaches of the Gilbert river model.

Apx Table D.1 Water balance for Reach 1, upstream of gauging station 917115A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	0	0	0
	Subcatchments ungauged	160.6	149.7	192.0
	Sub-total	**160.6**	**149.7**	**192.0**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	0	0	0
	Water supply – general security	0	0	0
	Water supply – unsupplemented	0	0	0
	Sub-total	**0**	**0**	**0**
Outflows	**End of system flow**	**160.6**	**149.7**	**192.0**
	Reach losses	0	0	0

Apx Table D.2 Water balance for Reach 2, upstream of gauging station 917118A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	1.4	1.4	1.5
	Evaporation from ponded area	3.3	3.1	3.4
Inflows	Subcatchments gauged	160.6	149.7	192.0
	Subcatchments ungauged	6.7	6.3	8.0
	Sub-total	**167.3**	**156.0**	**200.0**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	0	0	0
	Water supply – general security	0	0	0
	Water supply – unsupplemented	4.6	4.5	4.6
	Sub-total	**4.6**	**4.5**	**4.6**
Outflows	**End of system flow**	**161.0**	**149.7**	**193.6**
	Reach losses	0	0	0

Apx Table D.3 Water balance for Reach 3, upstream of gauging station 917108A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	0	0	0
	Subcatchments ungauged	136.5	122.4	143.8
	Sub-total	**136.5**	**122.4**	**143.8**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	0	0	0
	Water supply – general security	0	0	0
	Water supply – unsupplemented	0	0	0
	Sub-total	**0**	**0**	**0**
Outflows	**End of system flow**	**136.5**	**122.4**	**143.8**
	Reach losses	0	0	0

Apx Table D.4 Water balance for Reach 4, upstream of gauging station 917106A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	297.4	282.1	334.7
	Subcatchments ungauged	435.2	382.1	711.4
	Sub-total	**732.7**	**704.7**	**1036.6**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	3.8	3.4	4.3
	Water supply – general security	0	0	0
	Water supply – unsupplemented	0	0	0
	Sub-total	**3.8**	**3.4**	**4.3**
Outflows	**End of system flow**	**728.7**	**682.2**	**775.1**
	Reach losses	0.1	0.3	266.7

Apx Table D.5 Water balance for Reach 5, upstream of gauging station 917109A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	728.7	682.2	775.1
	Subcatchments ungauged	640.5	362.7	671.1
	Sub-total	**1369.2**	**1091.6**	**1432.8**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	0.7	0.5	0.8
	Water supply – general security	0	0	0
	Water supply – unsupplemented	0	0	0
	Sub-total	**0.7**	**0.5**	**0.8**
Outflows	**End of system flow**	**1006.8**	**908.3**	**1126.8**
	Reach losses	361.7	1.0	496.2

Apx Table D.6 Water balance for Reach 6, upstream of gauging station 917107A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	0	0	0
	Subcatchments ungauged	40.8	38.5	43.4
	Sub-total	**40.8**	**38.5**	**43.4**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	0.3	0.3	0.4
	Water supply – general security	0	0	0
	Water supply – unsupplemented	0.2	0.1	0.2
	Sub-total	**0.5**	**0.4**	**0.5**
Outflows	**End of system flow**	**40.3**	**38.0**	**42.9**
	Reach losses	0	0	0

Apx Table D.7 Water balance for Reach 7, upstream of gauging station 917112A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	40.3	38.0	42.9
	Subcatchments ungauged	82.7	79.1	88.3
	Sub-total	**123.0**	**120.2**	**129.3**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	0	0	0
	Water supply – general security	0	0	0
	Water supply – unsupplemented	3.1	2.3	3.2
	Sub-total	**3.1**	**2.3**	**3.2**
Outflows	**End of system flow**	**118.4**	**115.2**	**124.8**
	Reach losses	1.5	0.6	4.8

Apx Table D.8 Water balance for Reach 9, upstream of gauging station 917113A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	155.1	149.4	165.6
	Subcatchments ungauged	298.0	157.5	343.0
	Sub-total	**453.1**	**317.9**	**504.8**
Diversions	Agriculture – high security	0	0	0
	Agriculture – unsupplemented	0.2	0.2	0.2
	Water supply – high security	0	0	0
	Water supply – unsupplemented	0	0	0
	Sub-total	**0.2**	**0.2**	**0.2**
Outflows	**End of system flow**	**386.8**	**293.2**	**400.7**
	Reach losses	66.1	0.2	168.1

Apx Table D.9 Water balance for Reach 10, upstream of gauging station 917111A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	1511.9	1327.2	1636.5
	Subcatchments ungauged	1040.3	1066.7	1174.5
	Sub-total	**2552.2**	**2461.1**	**2758.4**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	0	0	0
	Water supply – general security	0	0	0
	Water supply – unsupplemented	0	0	0
	Sub-total	**0**	**0**	**0**
Outflows	**End of system flow**	**2545.1**	**2447.9**	**2733.8**
	Reach losses	7.0	0.6	49.3

Apx Table D.10 Water balance for Reach 12, upstream of gauging station 917006A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	159.4	138.2	191.1
	Subcatchments ungauged	190.8	127.8	149.4
	Sub-total	**350.2**	**283.3**	**335.9**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	1.6	1.5	1.7
	Water supply – general security	0	0	0
	Water supply – unsupplemented	0	0	0
	Sub-total	**1.6**	**1.5**	**1.7**
Outflows	**End of system flow**	**334.4**	**281.5**	**333.5**
	Reach losses	14.2	0.0	9.2

Apx Table D.11 Water balance for Reach 15, upstream of gauging station 917013A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	158.9	156.1	188.2
	Subcatchments ungauged	52.0	36.5	106.1
	Sub-total	211.0	202.3	291.7
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	0	0	0
	Water supply – general security	0	0	0
	Water supply – unsupplemented	0	0	0
	Sub-total	0	0	0
Outflows	**End of system flow**	**210.2**	**198.3**	**220.7**
	Reach losses	0.7	0.1	82.1

Apx Table D.12 Water balance for Reach 17, upstream of gauging station 917001D

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	586.7	527.7	583.9
	Subcatchments ungauged	510.2	321.1	567.1
	Sub-total	**1097.0**	**851.3**	**1130.5**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	6.7	6.7	6.7
	Water supply – general security	0	0	0
	Water supply – unsupplemented	22.1	22.0	22.1
	Sub-total	**28.8**	**28.7**	**28.8**
Outflows	**End of system flow**	**1058.7**	**809.4**	**1093.4**
	Reach losses	9.5	0.4	71.0

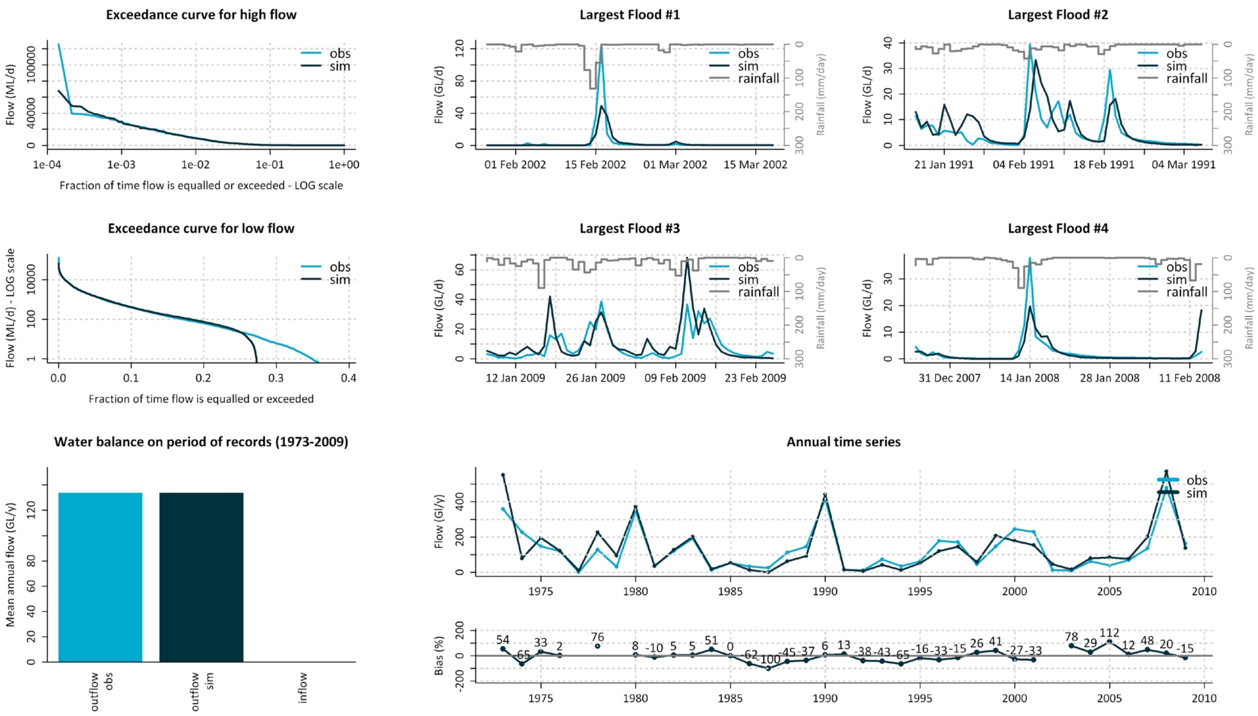
Apx Table D.13 Water balance for Reach 19, upstream of gauging station 917009A

		BASELINE MODEL (GL/y)	97.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)	2.5% EXCEEDANCE ENSEMBLE SIMULATION (GL/y)
Storages	Change in volume	0	0	0
	Rainfall on ponded area	0	0	0
	Evaporation from ponded area	0	0	0
Inflows	Subcatchments gauged	3690.5	3345.9	3896.9
	Subcatchments ungauged	36.7	22.7	40.5
	Sub-total	**3727.1**	**3368.7**	**3934.7**
Diversions	Agriculture – general security	0	0	0
	Agriculture – unsupplemented	8.1	7.4	8.8
	Water supply – general security	0	0	0
	Water supply – unsupplemented	0	0	0
	Sub-total	**8.1**	**7.4**	**8.8**
Outflows	**End of system flow**	**3719.1**	**3361.0**	**3926.8**
	Reach losses	0	0	0

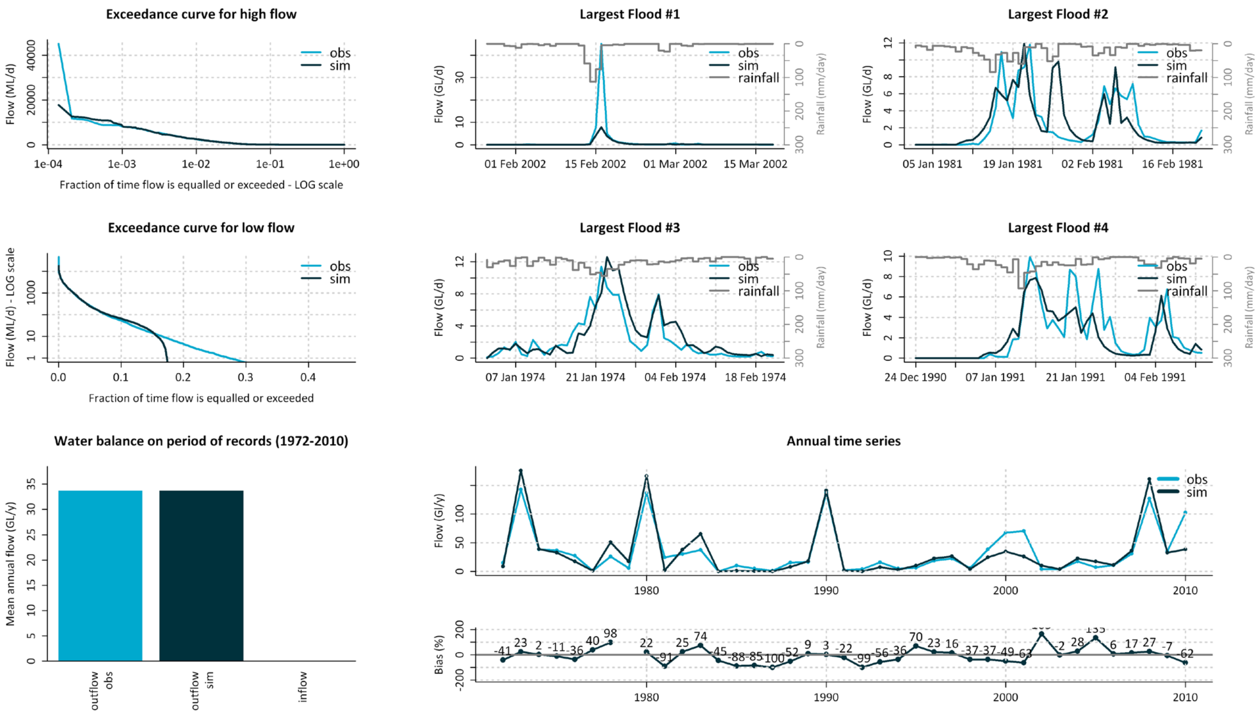
Appendix E Performance report cards for the Flinders river model

This appendix provides summary information on the performance of the Flinders river model for each individual river reach.

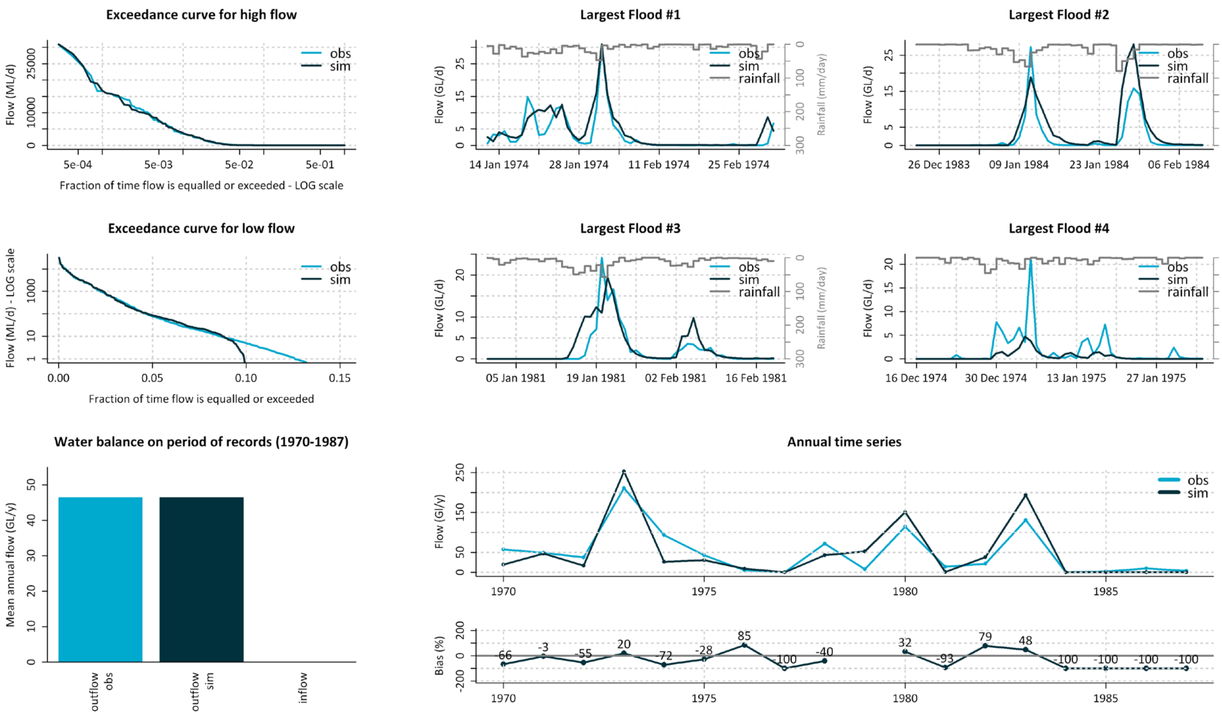
Reach 1 - upstream of station 915013A



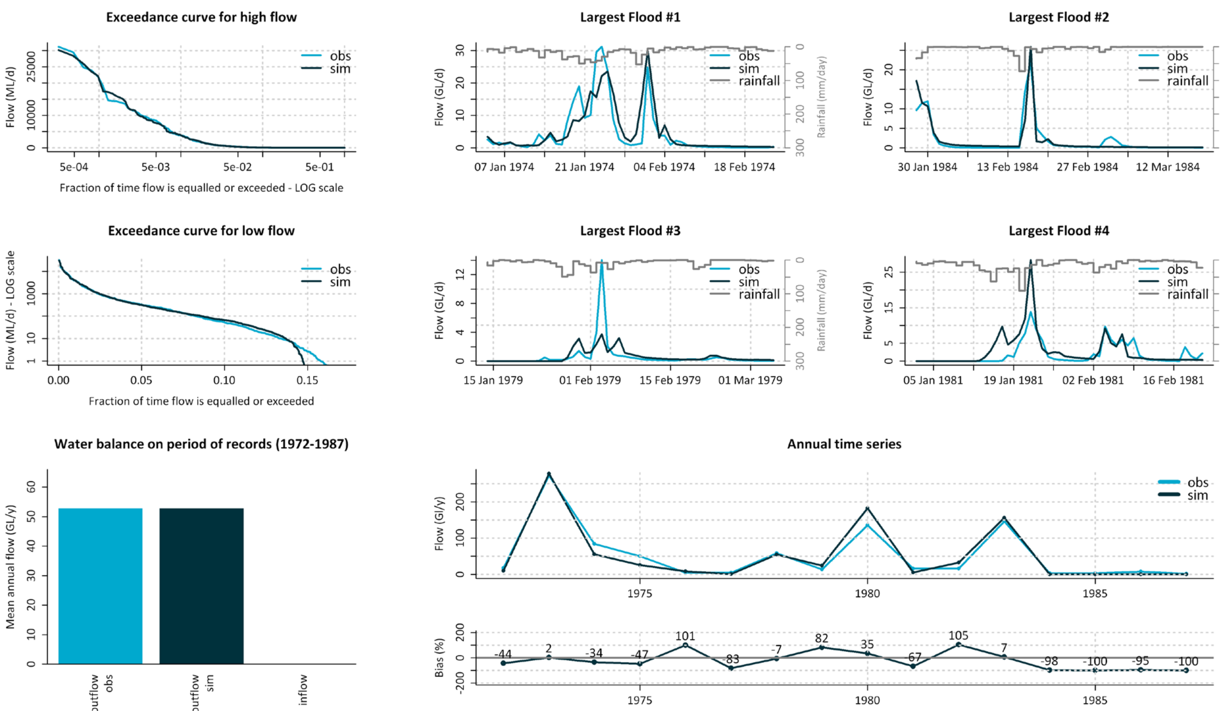
Reach 2 - upstream of station 915011A



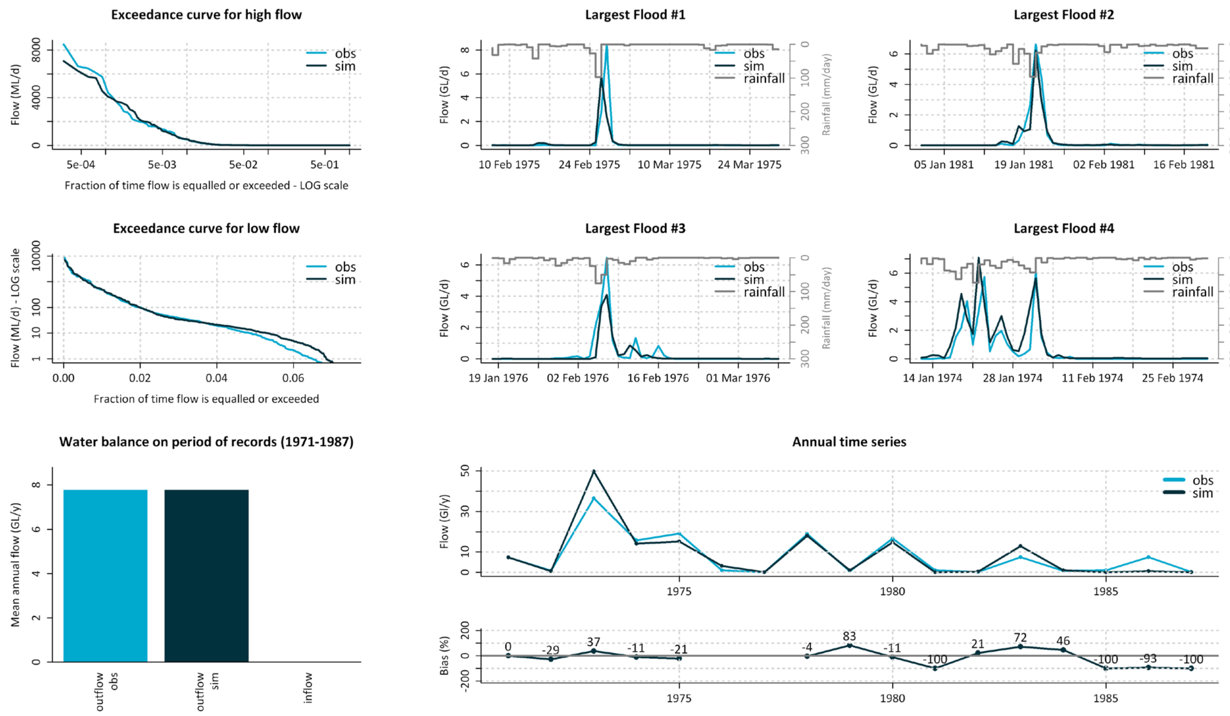
Reach 3 - upstream of station 915007A



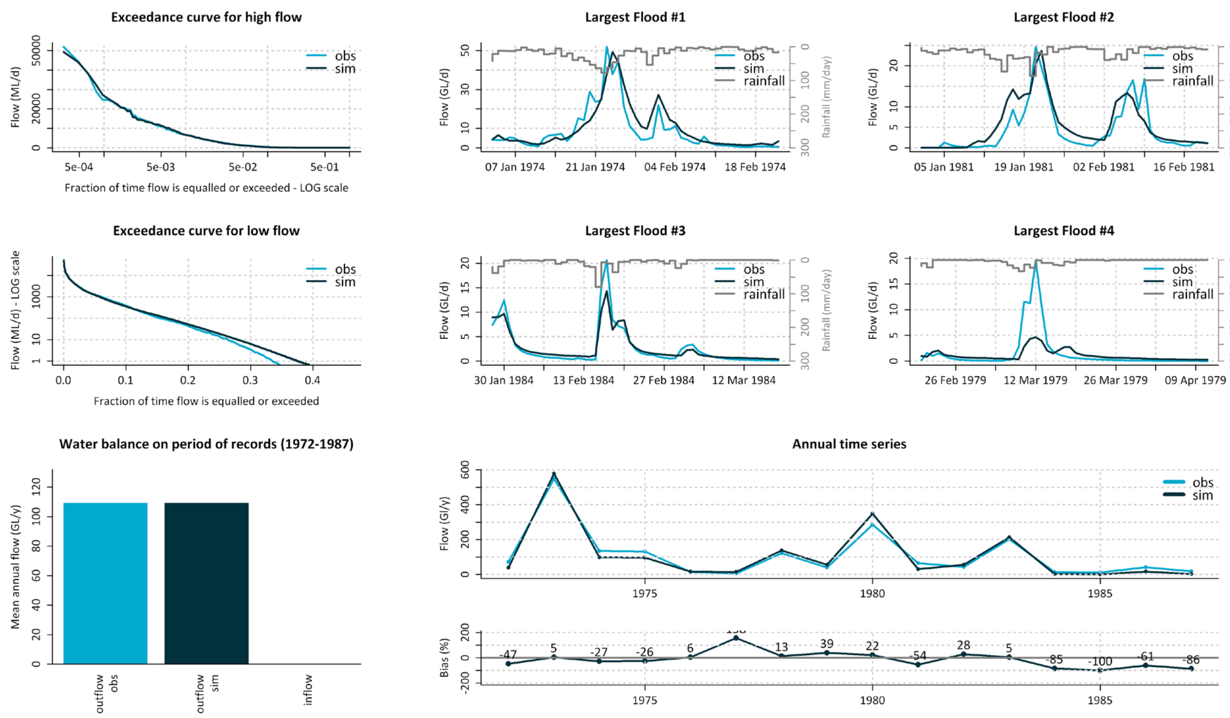
Reach 4 - upstream of station 915010A



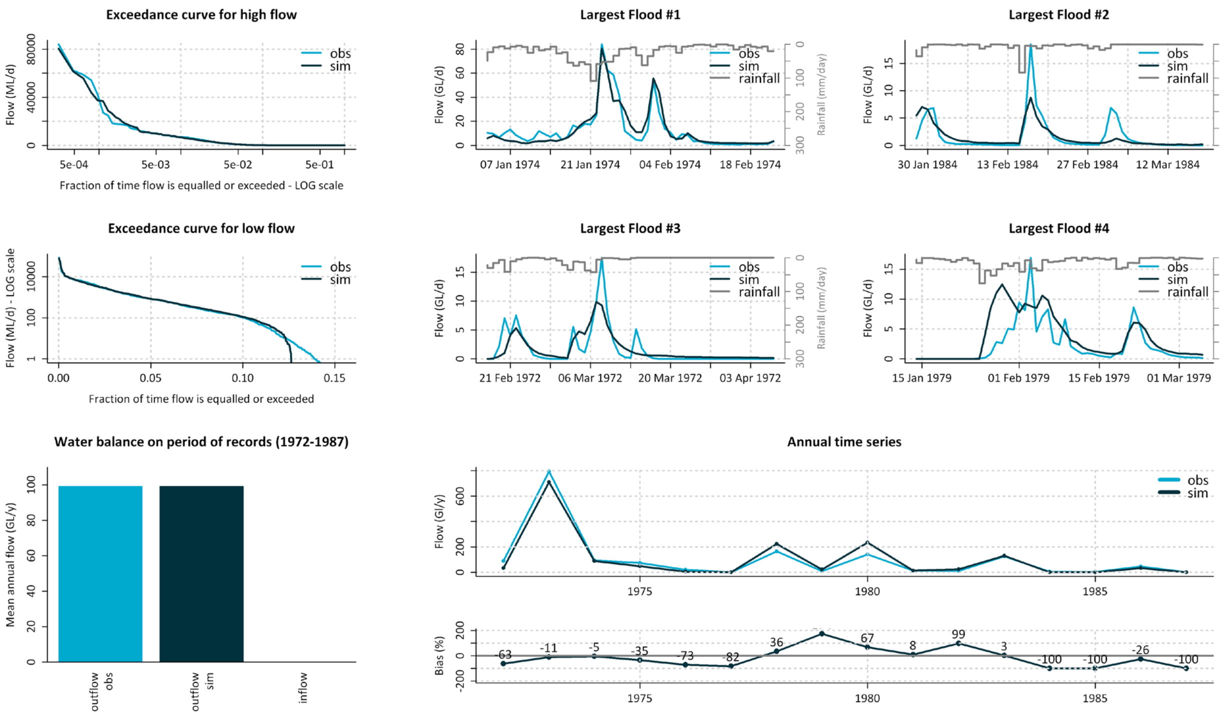
Reach 5 - upstream of station 915006A



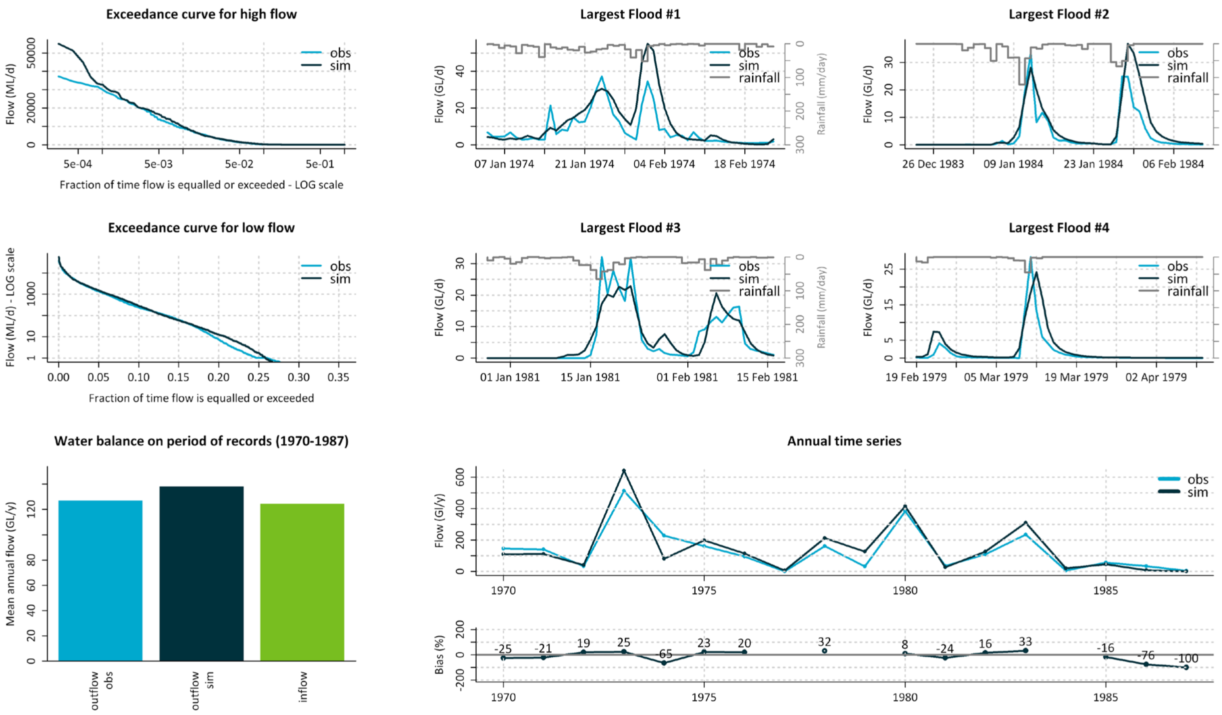
Reach 6 - upstream of station 915005A



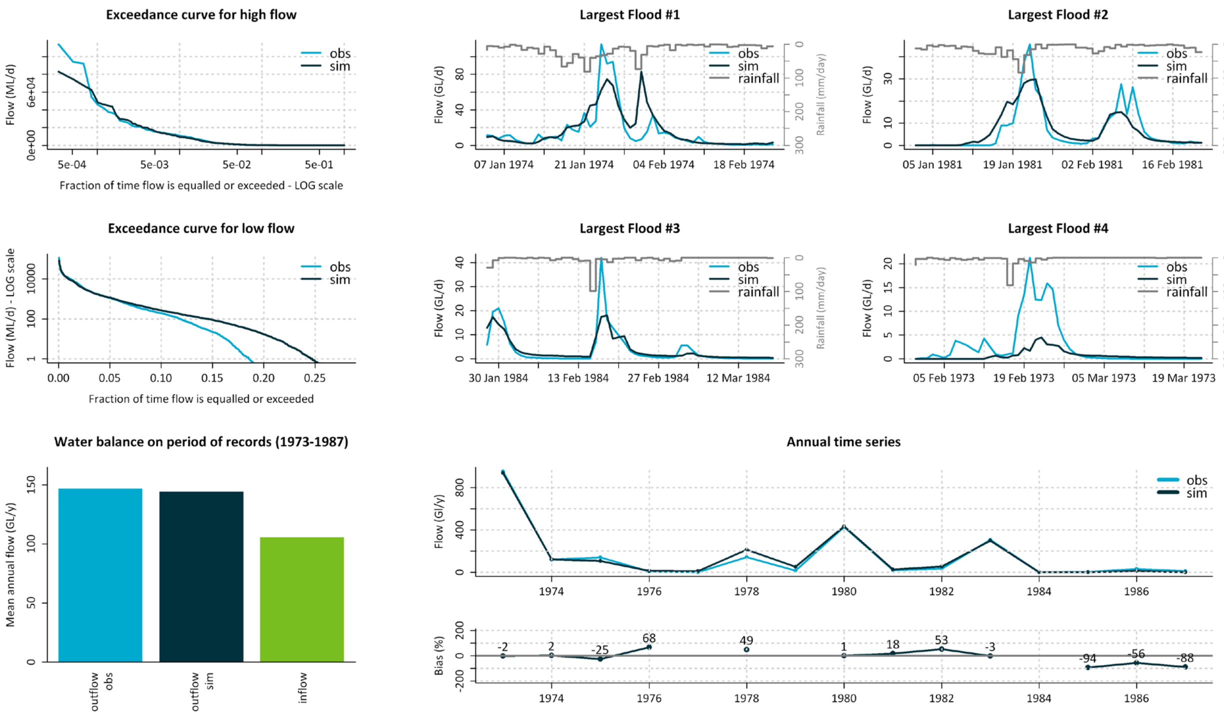
Reach 7 - upstream of station 915009A



Reach 8 - upstream of station 915004A



Reach 9 - upstream of station 915014A



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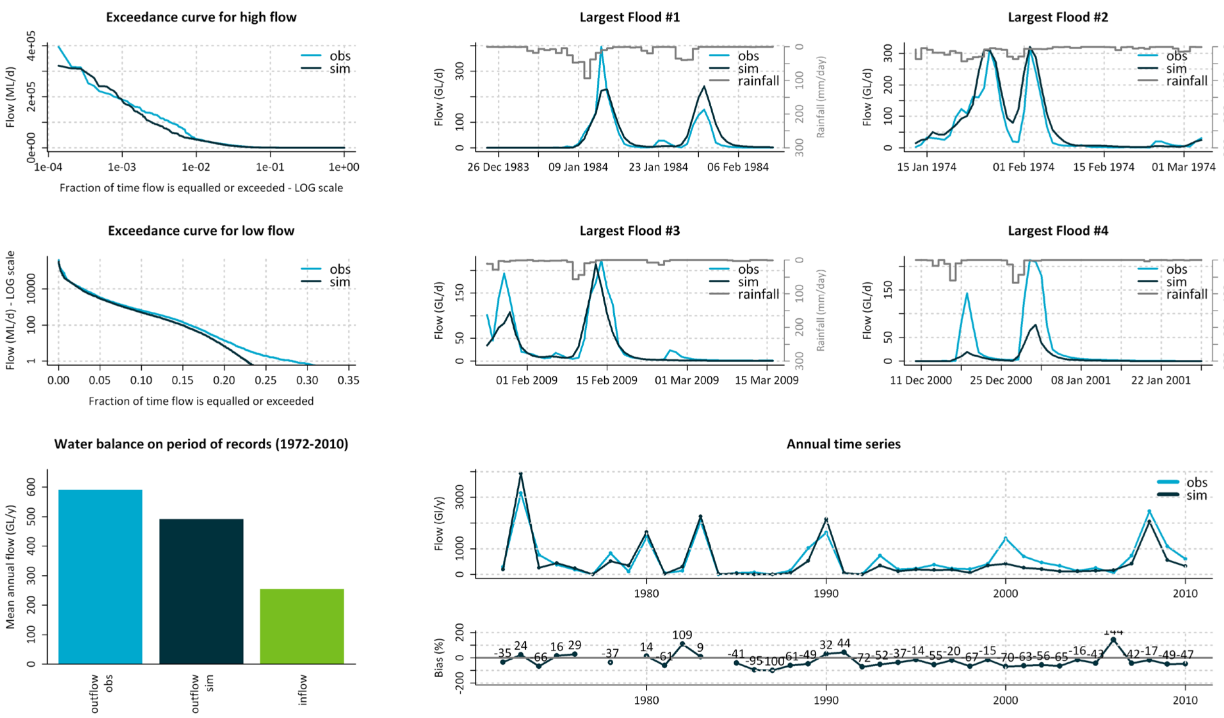

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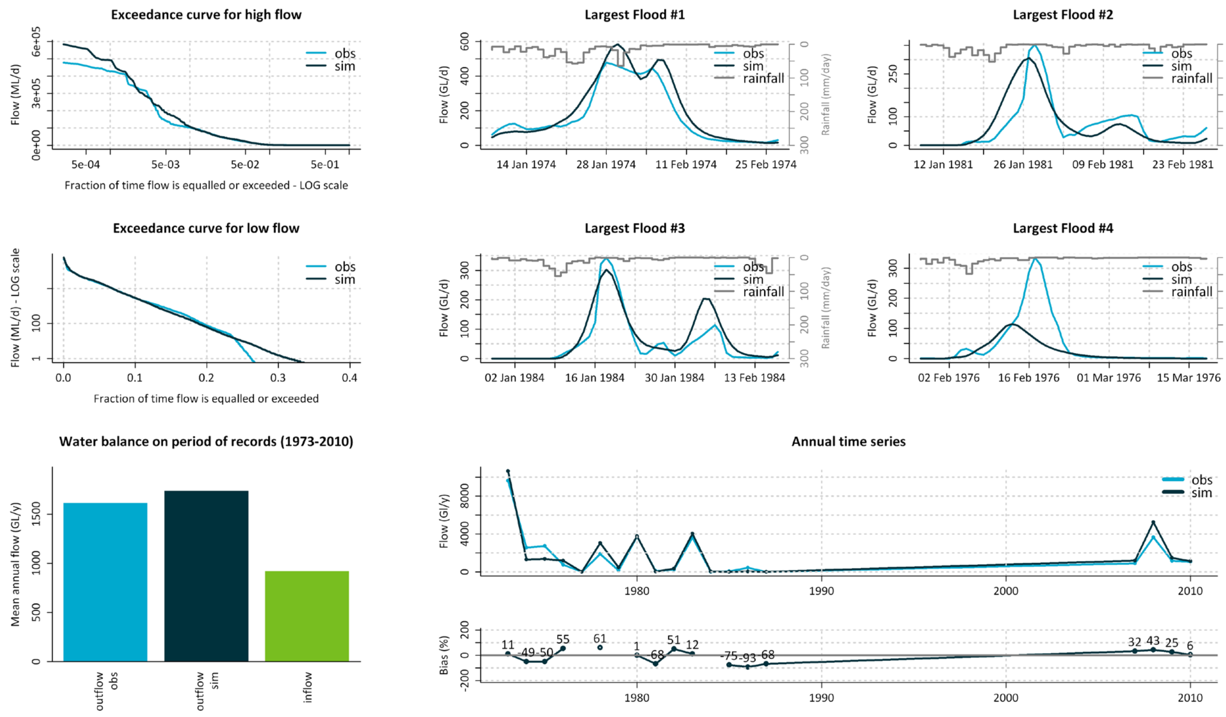

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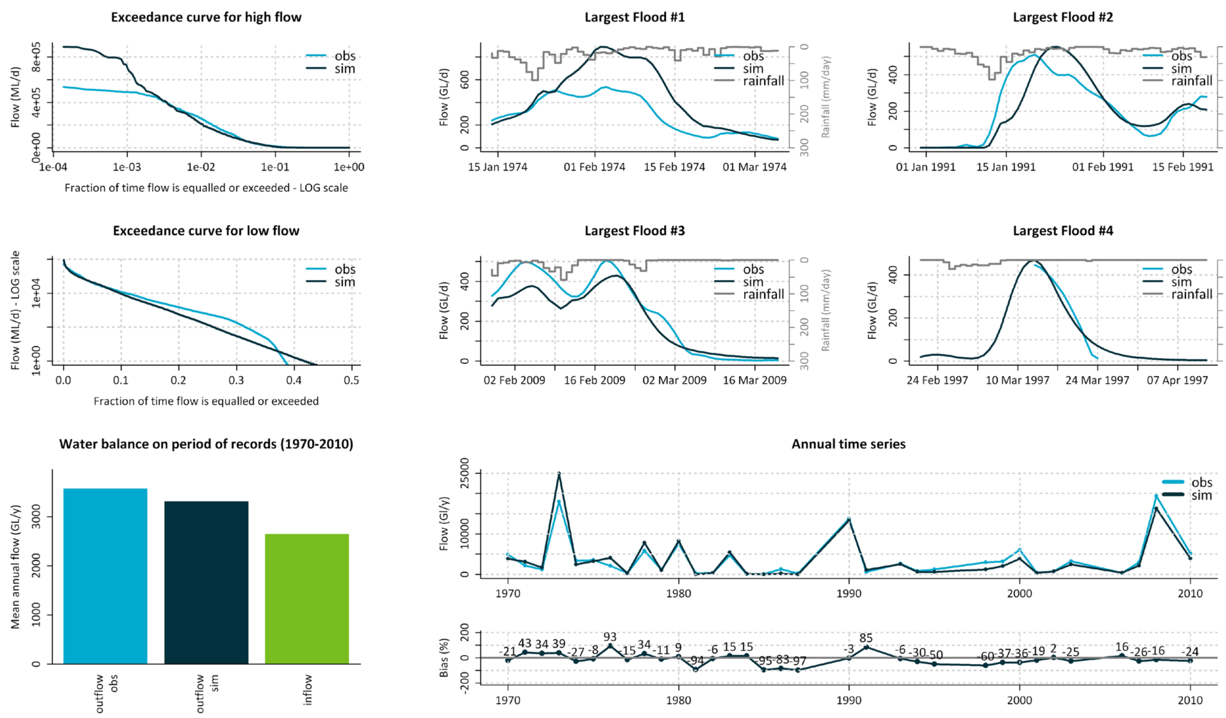

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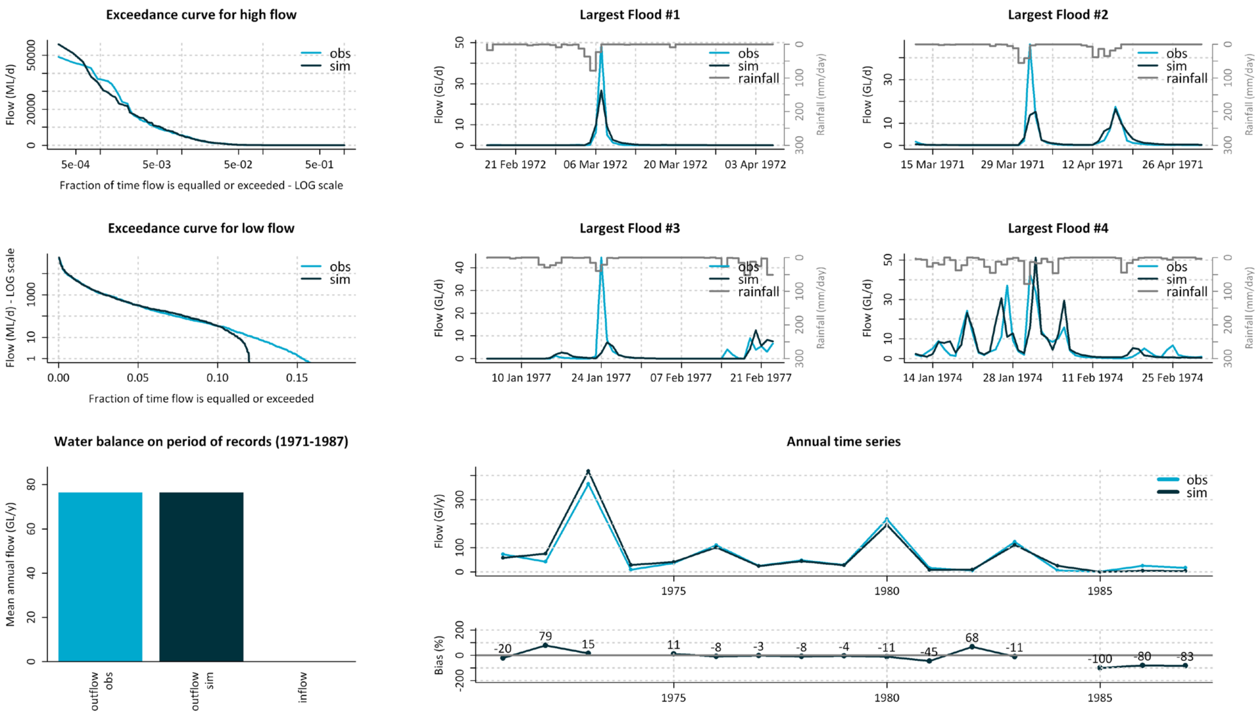

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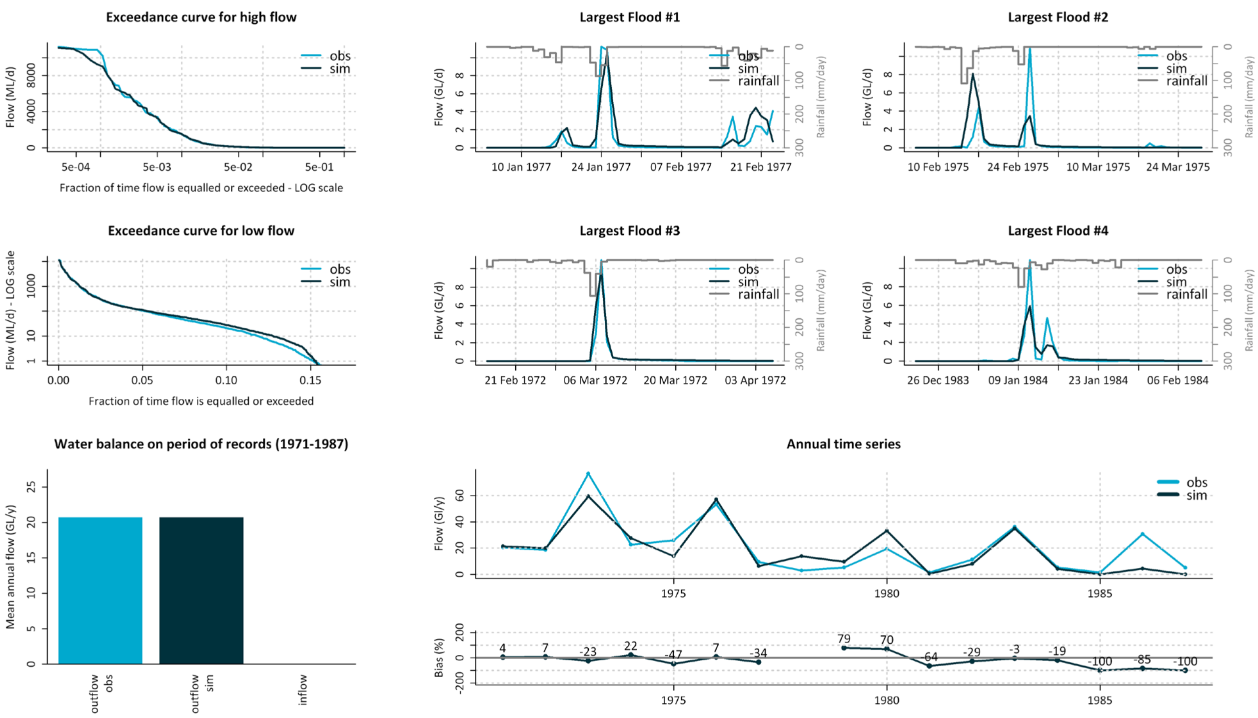

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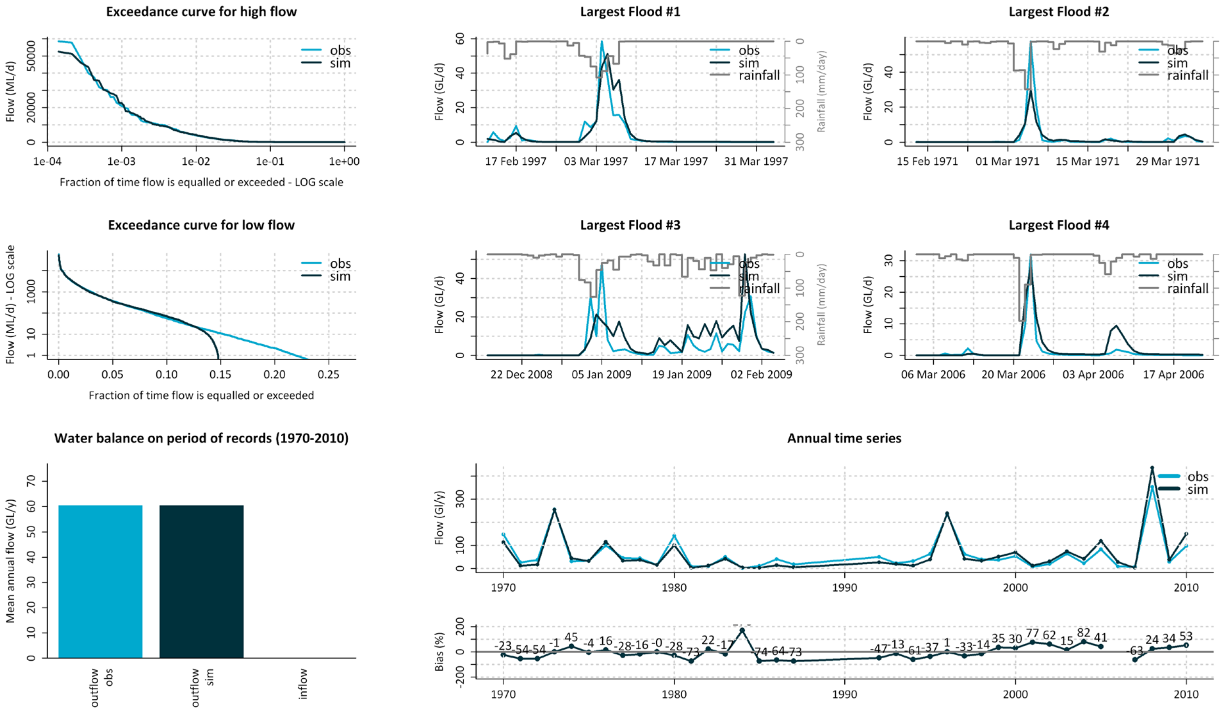

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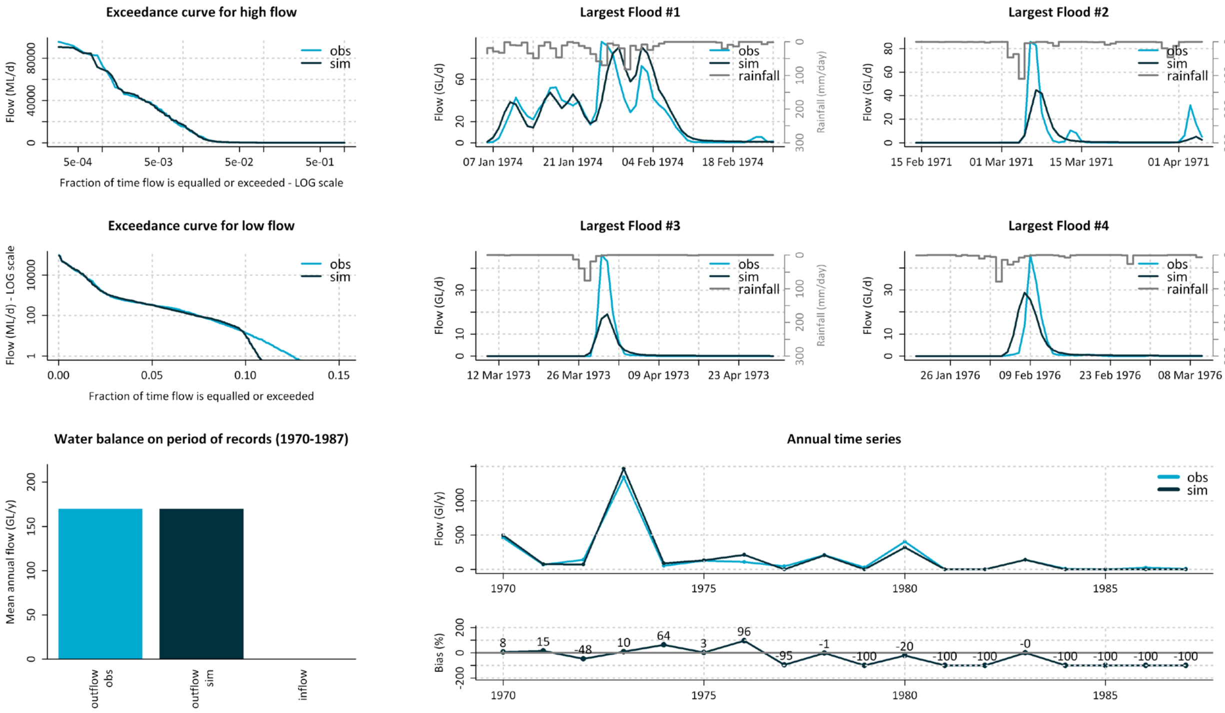

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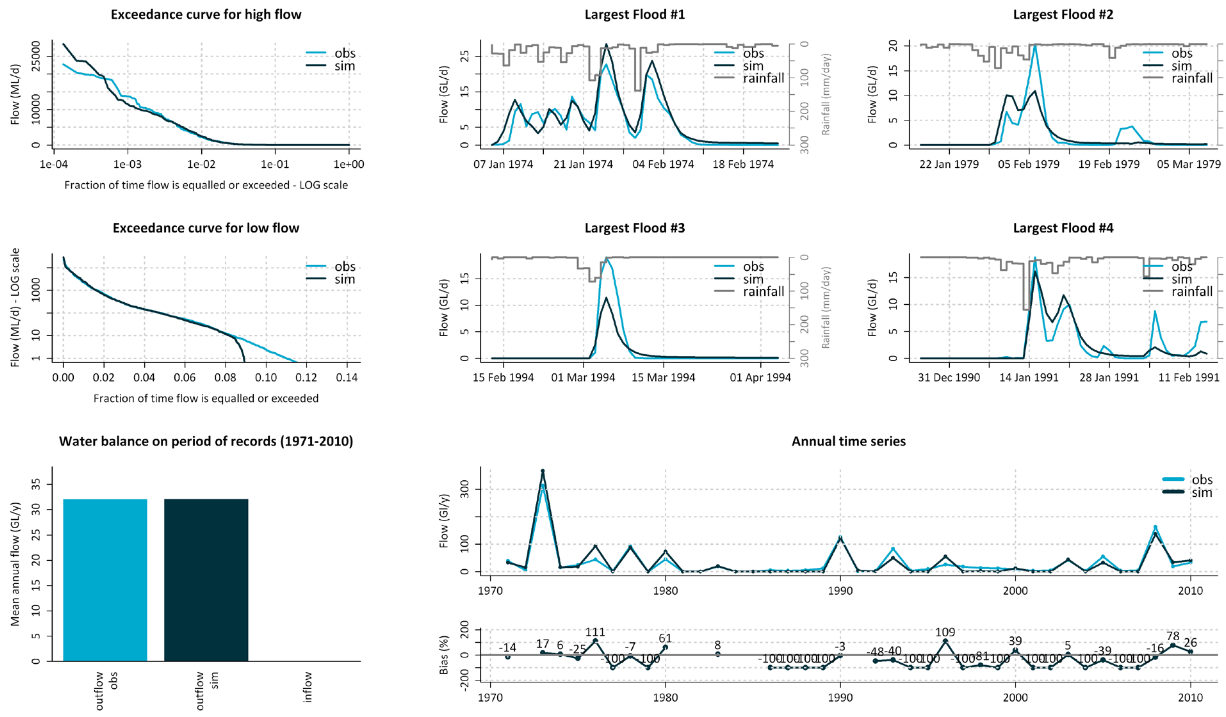
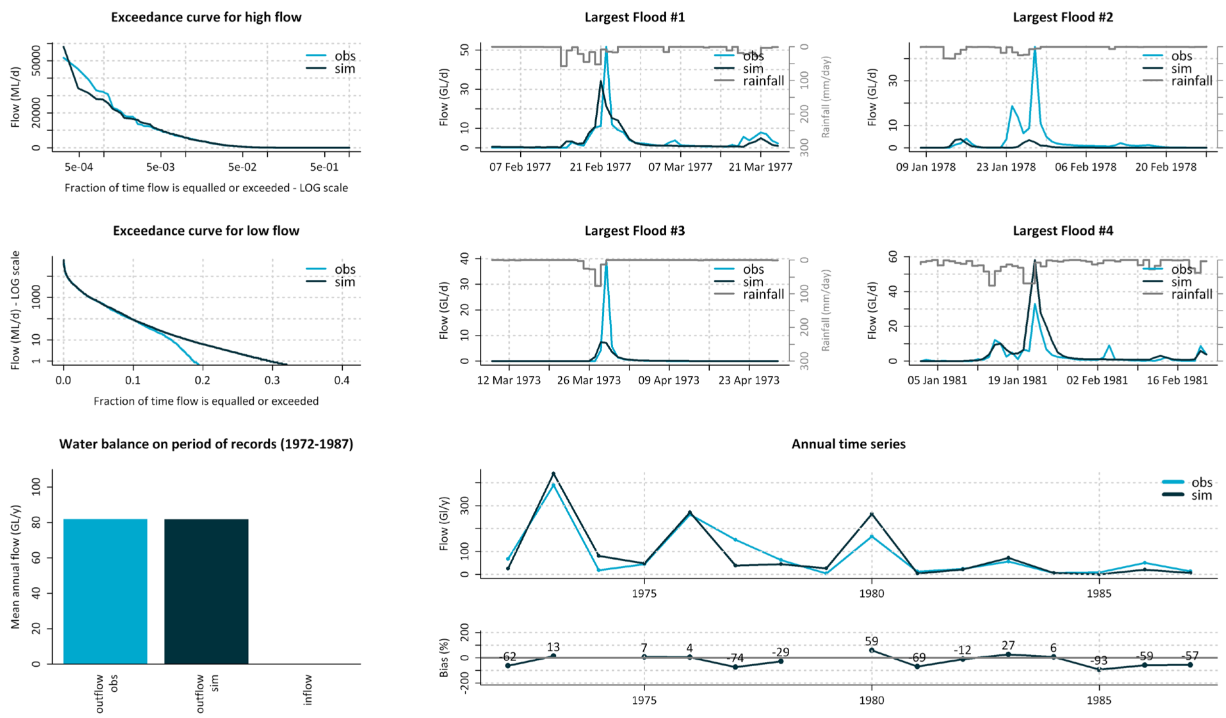
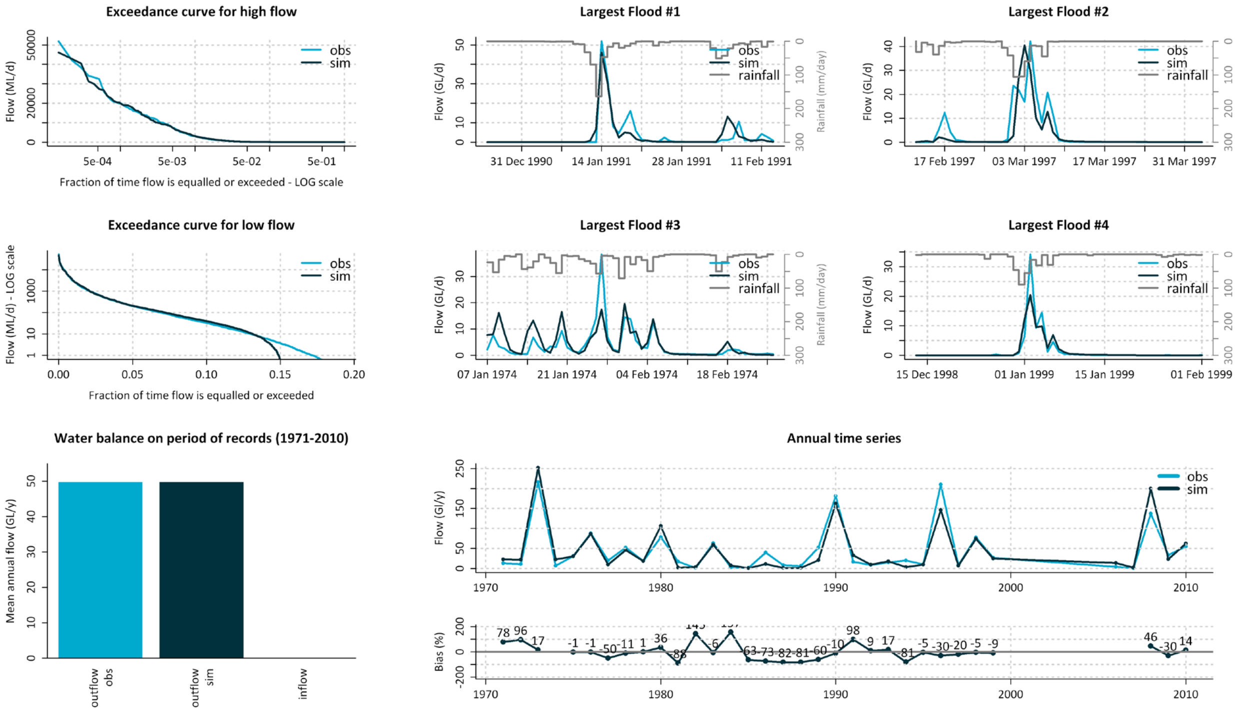


Reach 18 - upstream of station 915209A



Reach 19 - upstream of station 915211A



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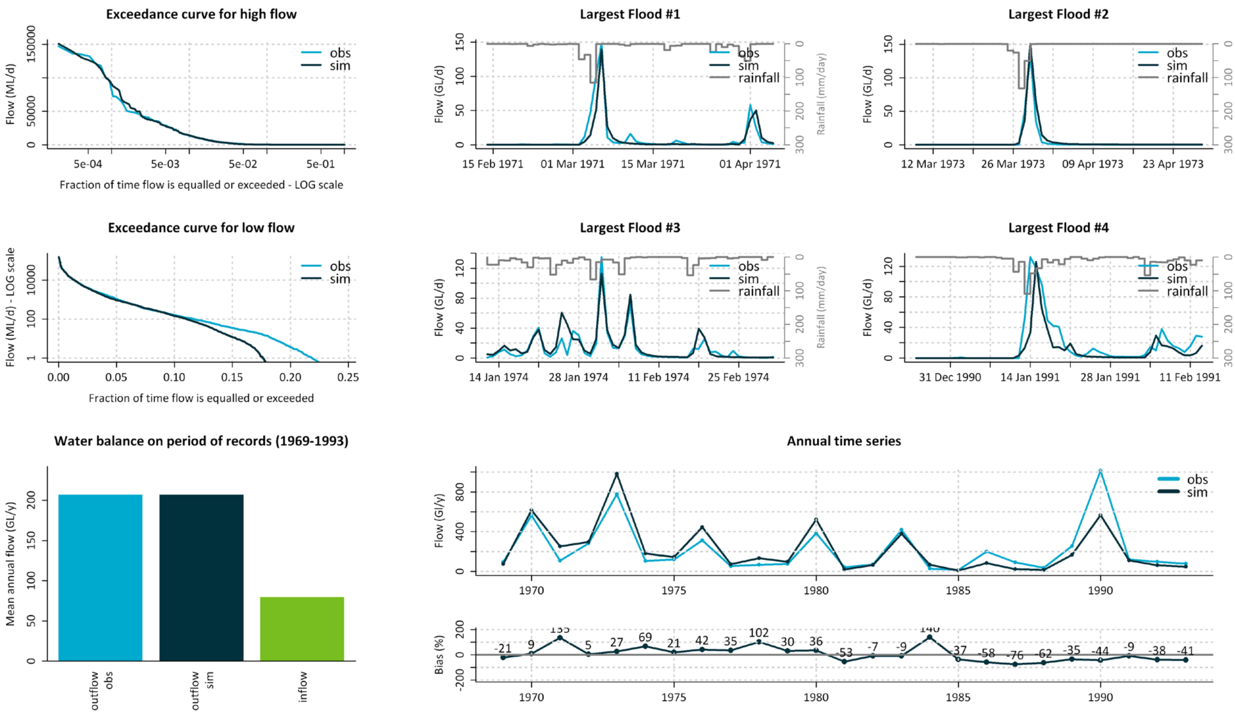

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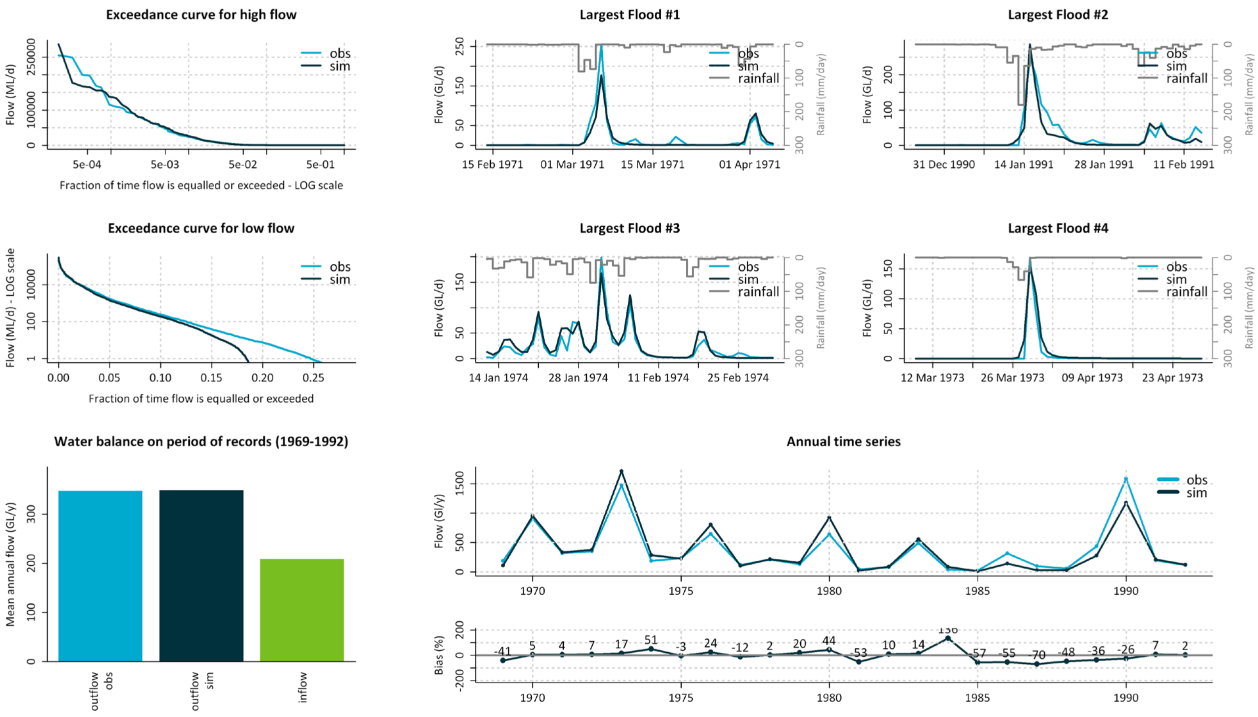
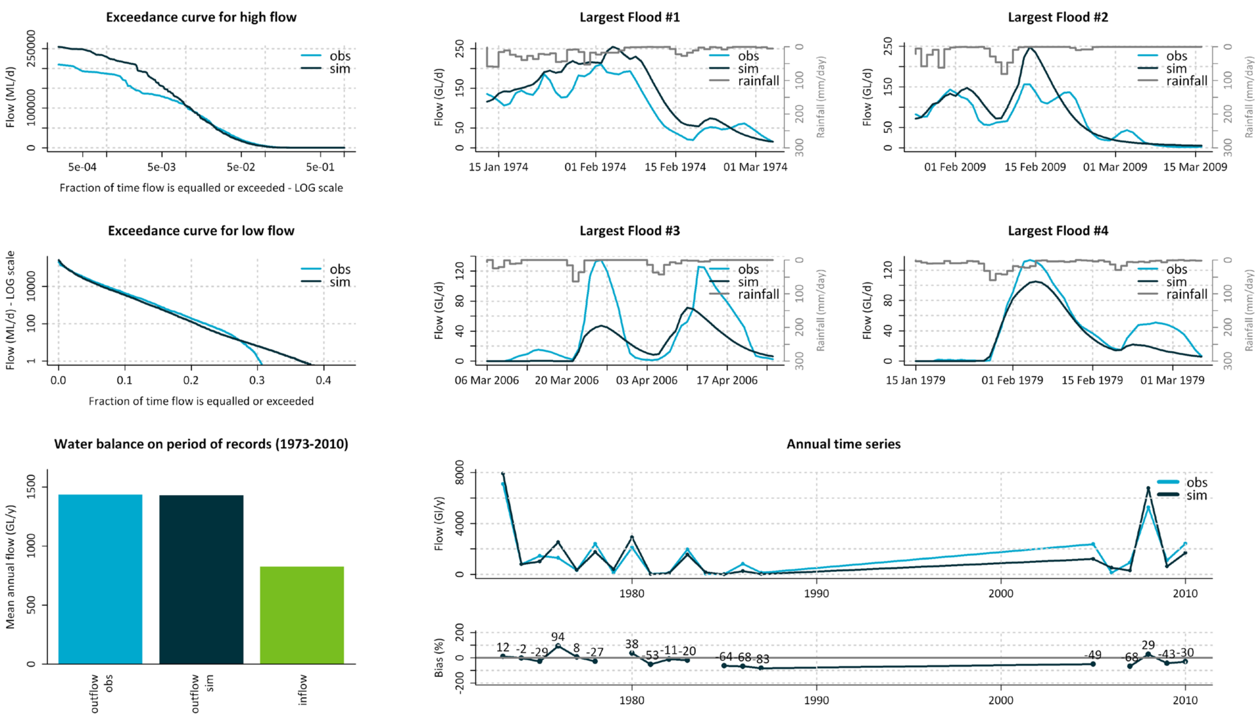


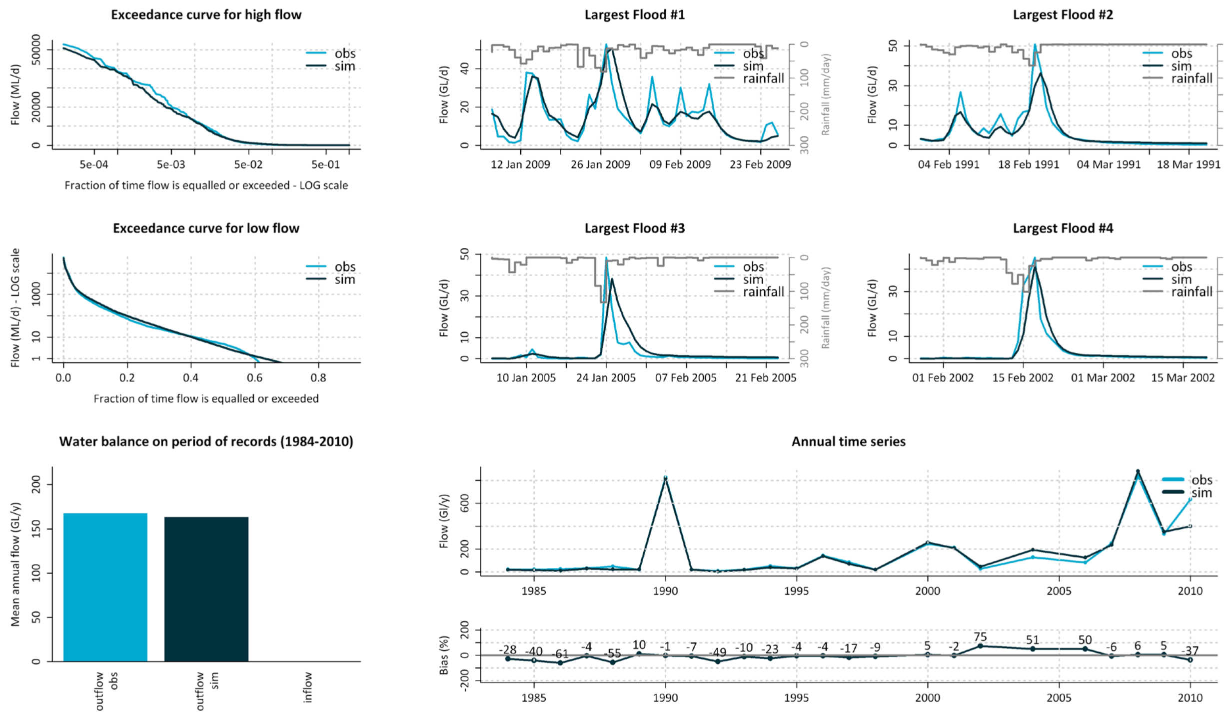
Reach 22 - upstream of station 915212A



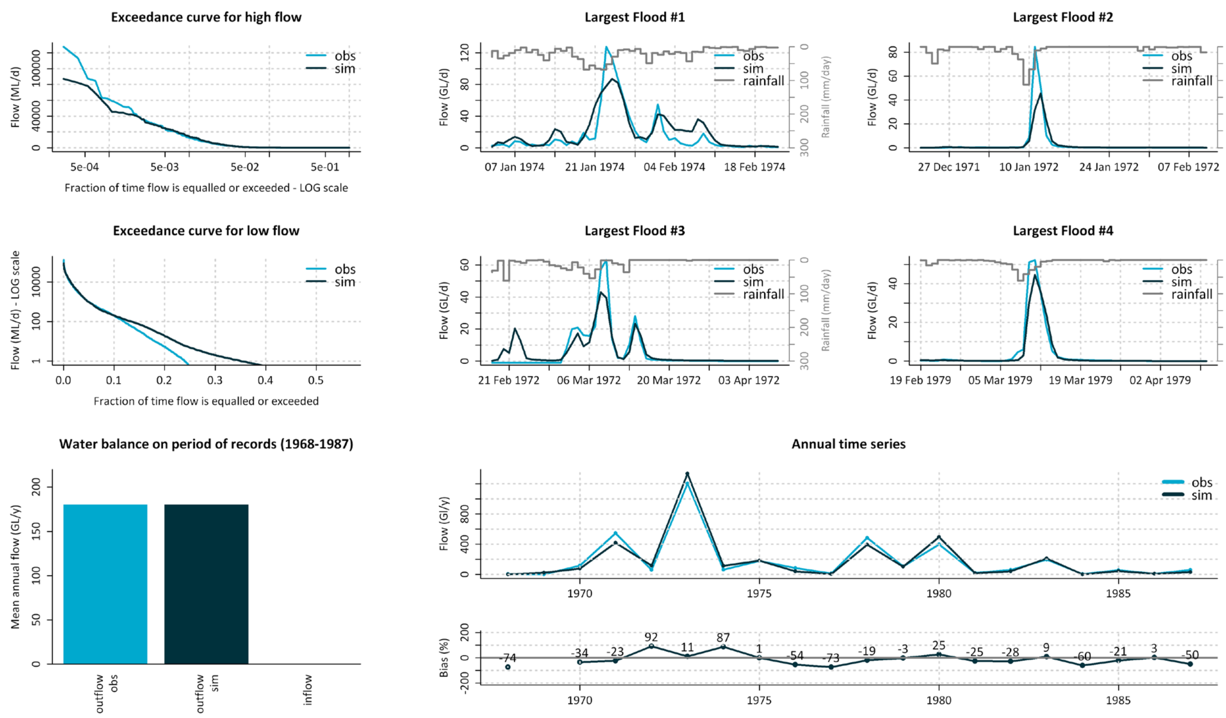
Appendix F Performance report cards for the Gilbert river model

The appendix provides summary information on the performance of the Gilbert river model for each individual river reach.

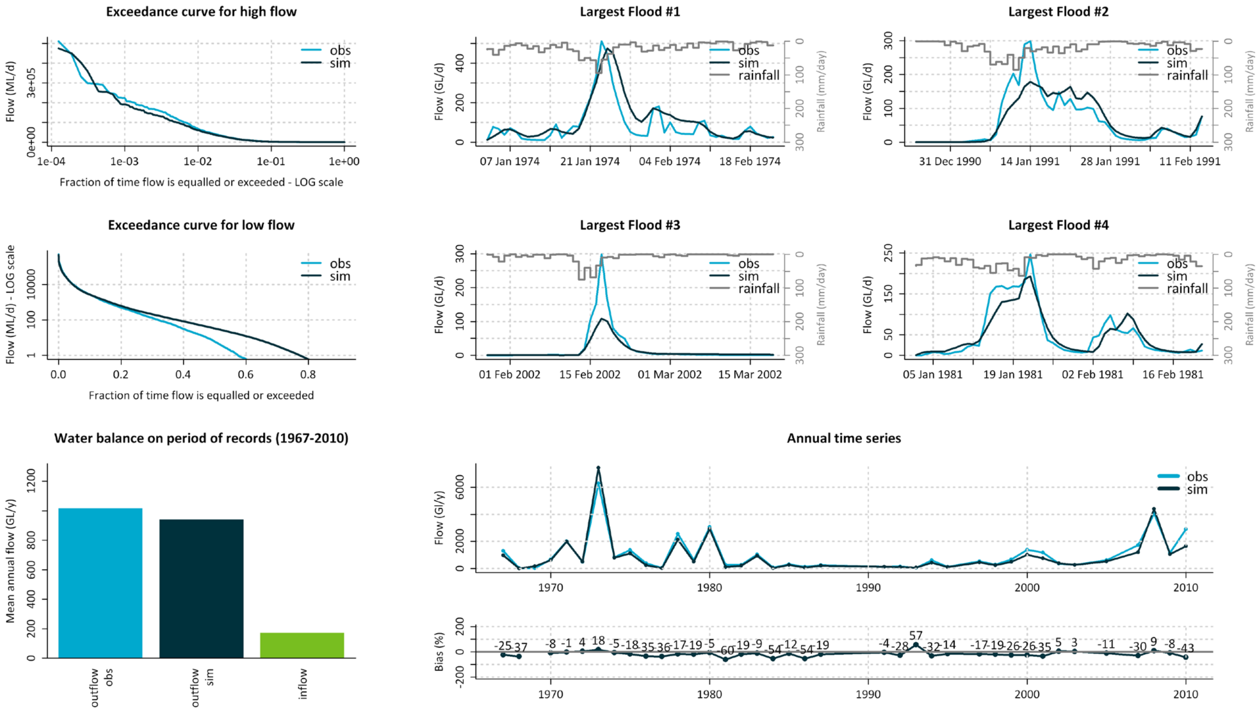
Reach 1 - upstream of station 917115A



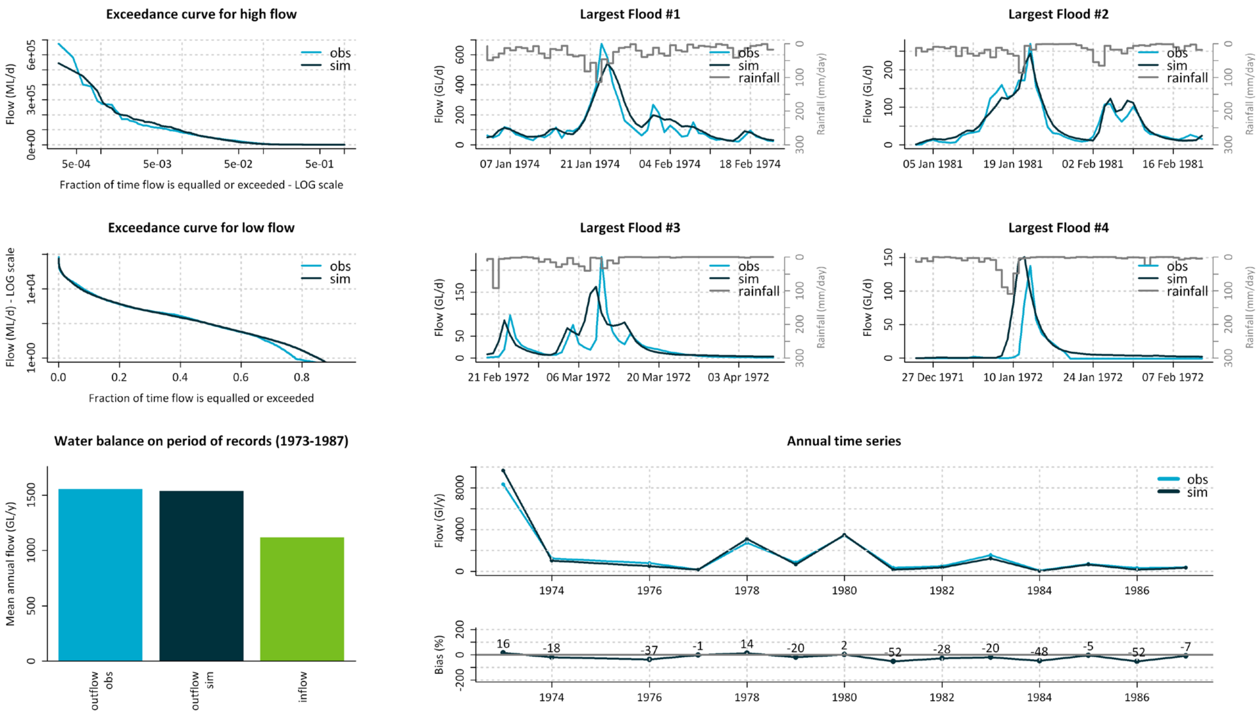
Reach 3 - upstream of station 917108A



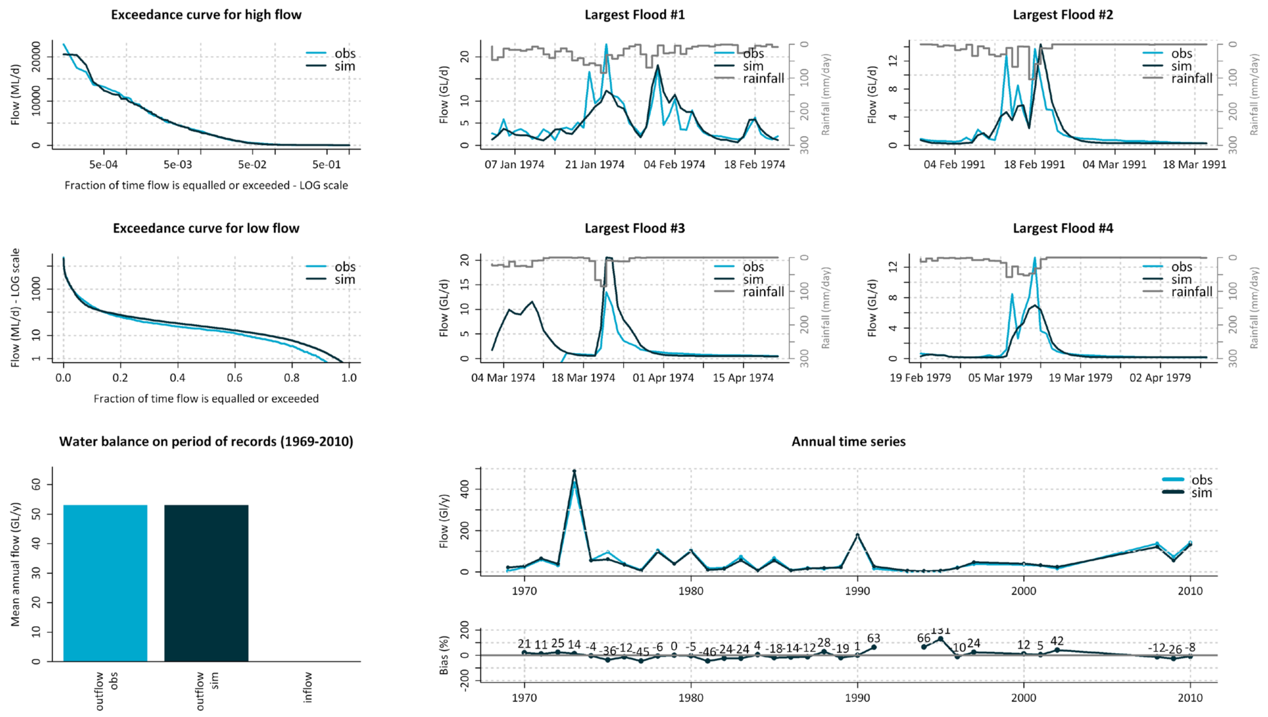
Reach 4 - upstream of station 917106A



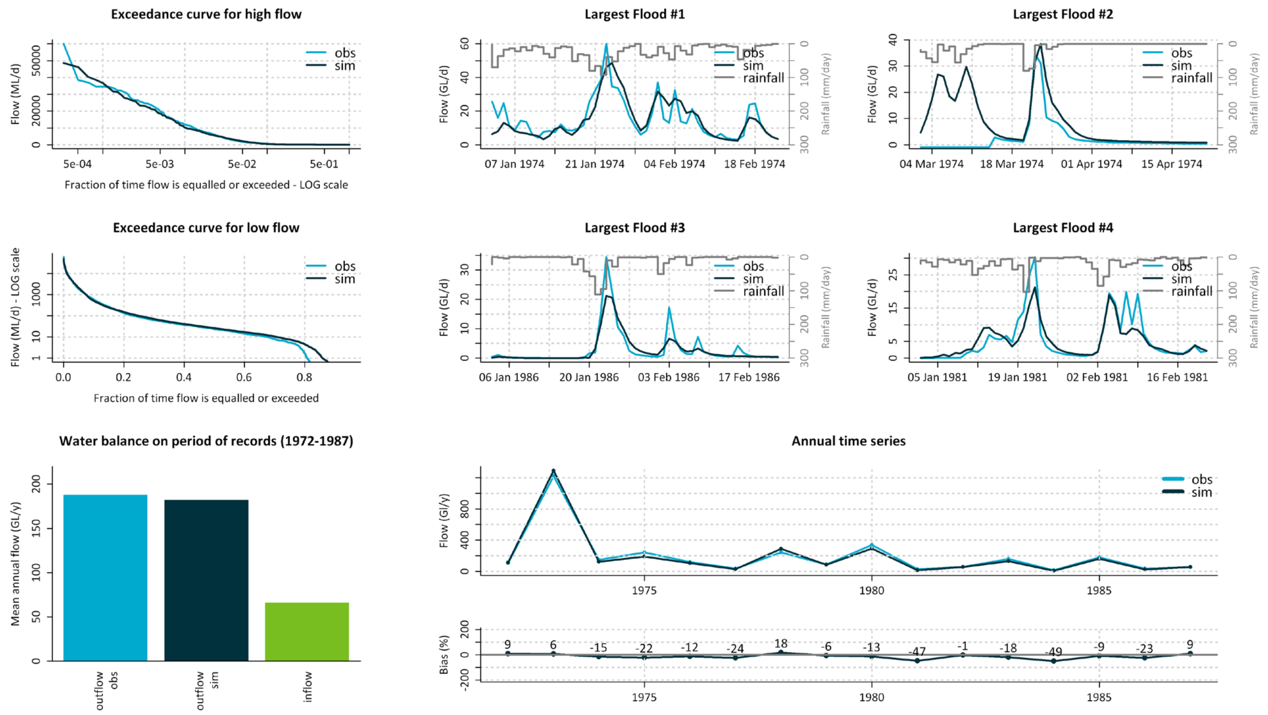
Reach 5 - upstream of station 917109A



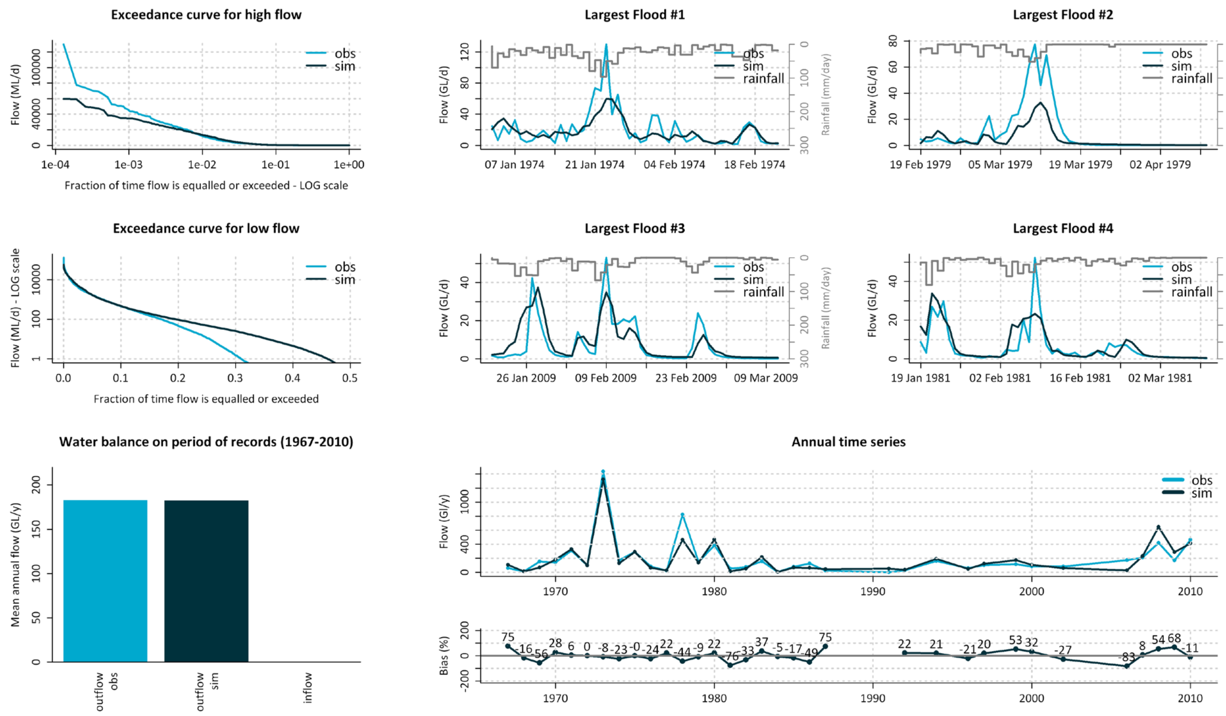
Reach 6 - upstream of station 917107A



Reach 7 - upstream of station 917112A



Reach 8 - upstream of station 917104A



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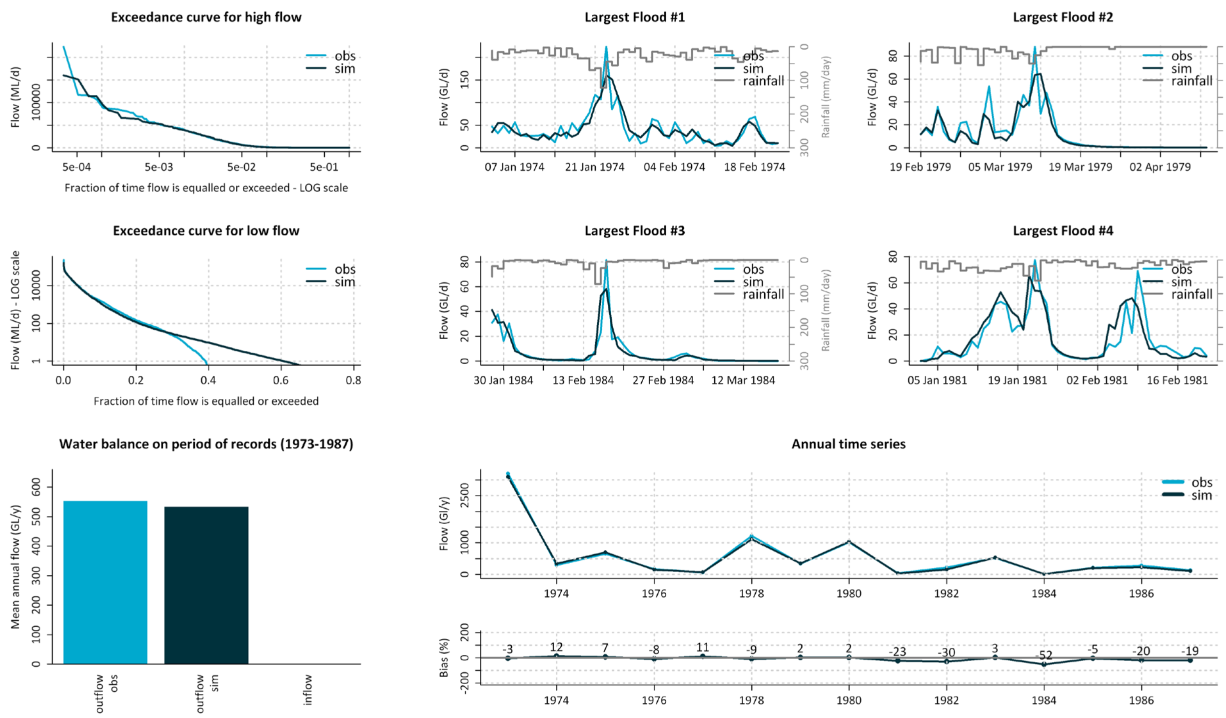
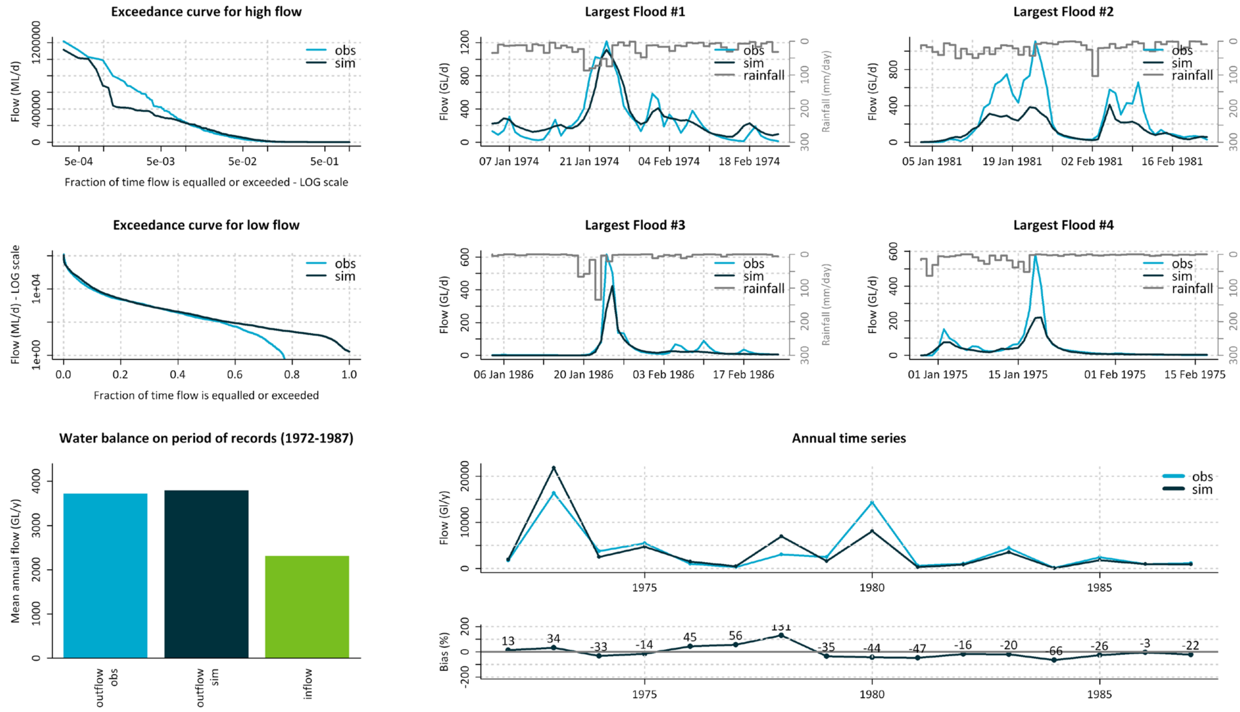
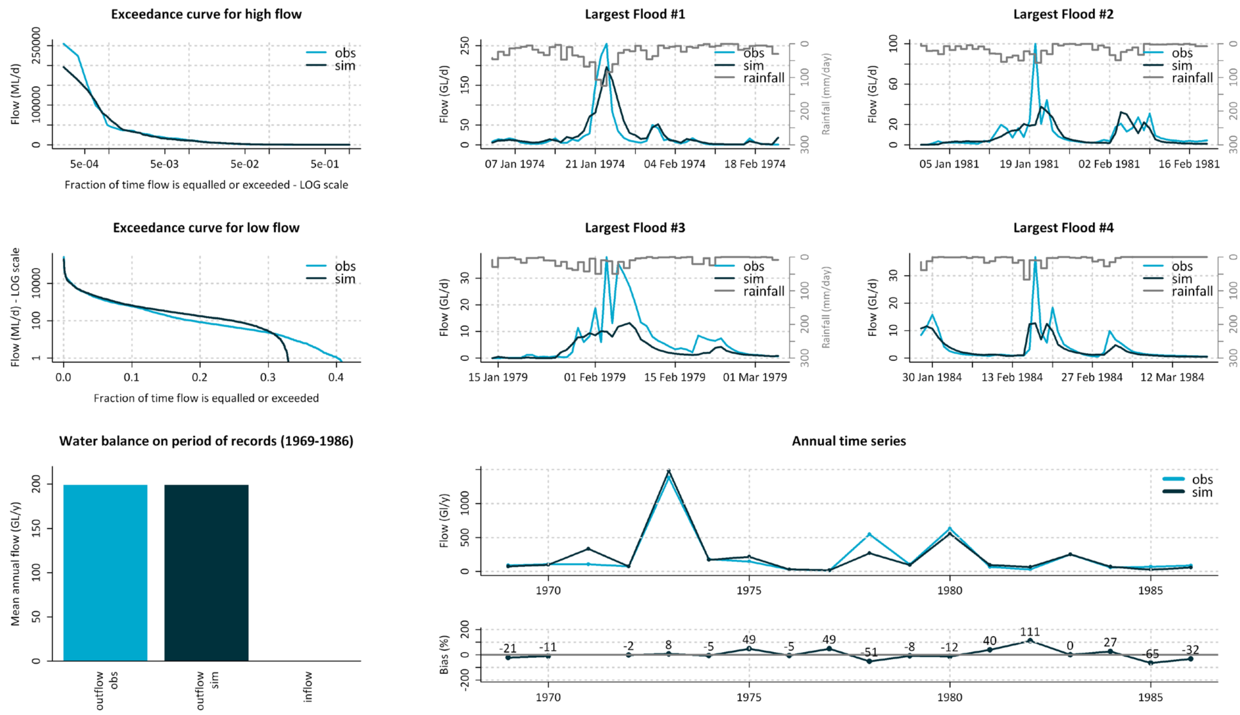


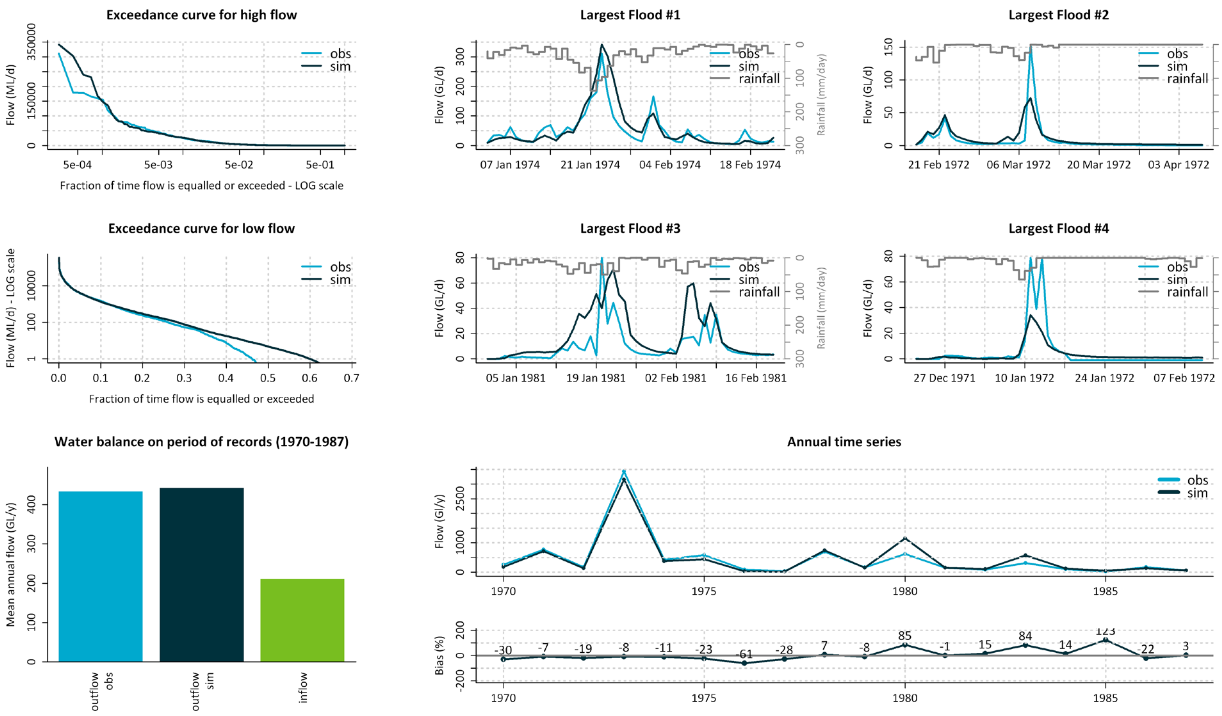
Reach 10 - upstream of station 917111A



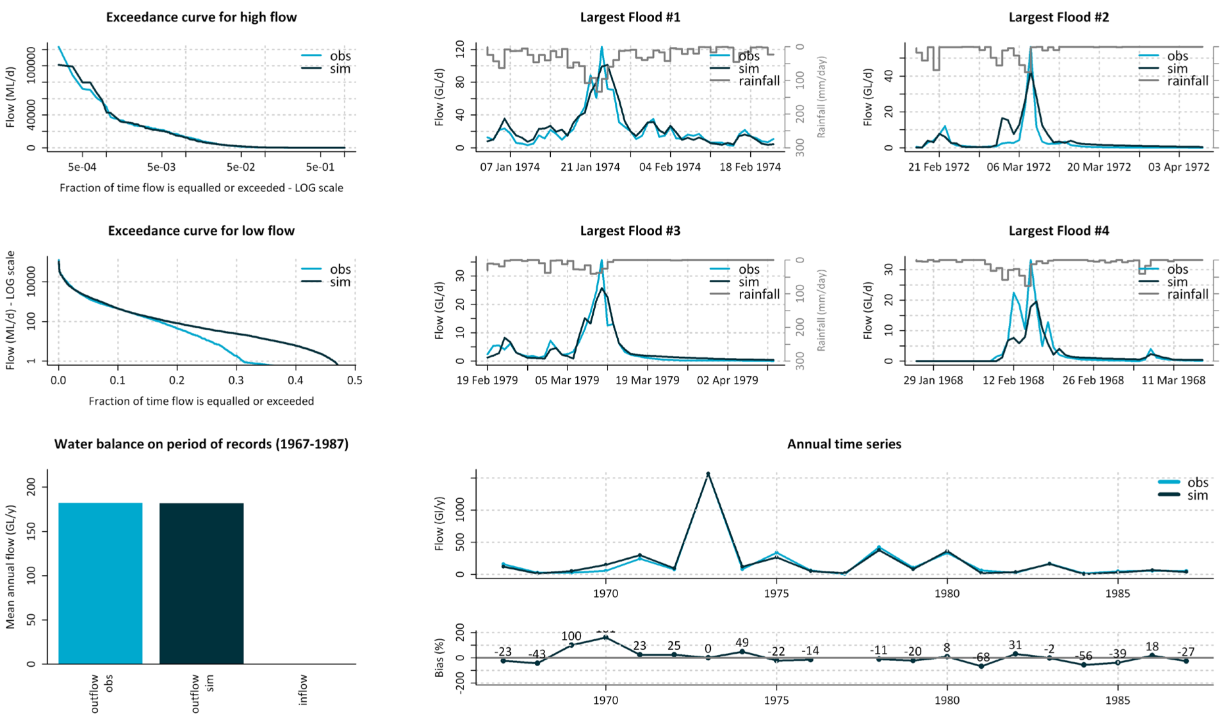
Reach 11 - upstream of station 917004A



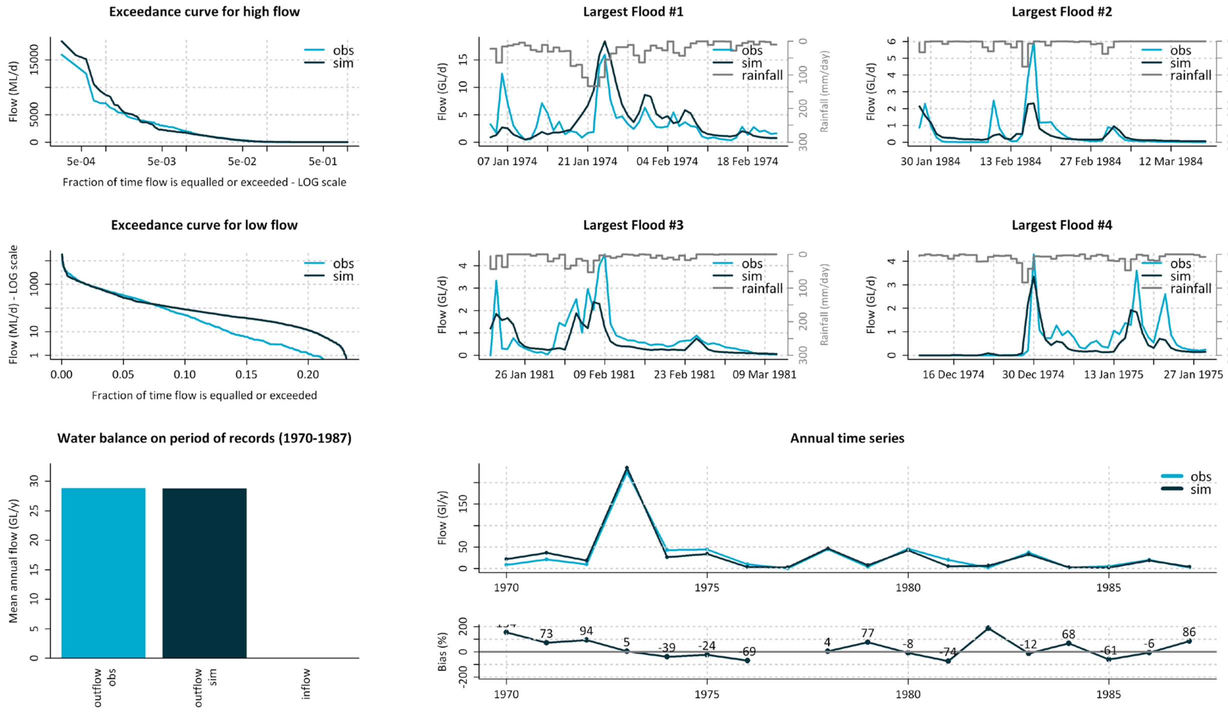
Reach 12 - upstream of station 917006A



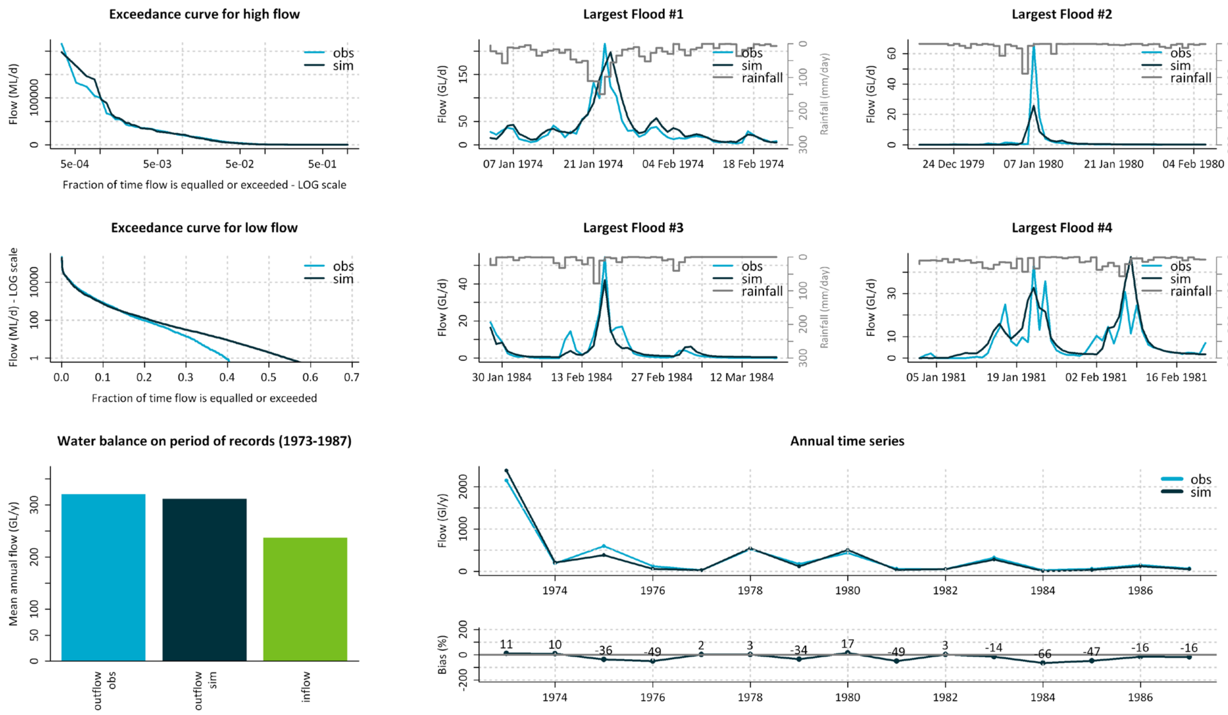
Reach 13 - upstream of station 917002A



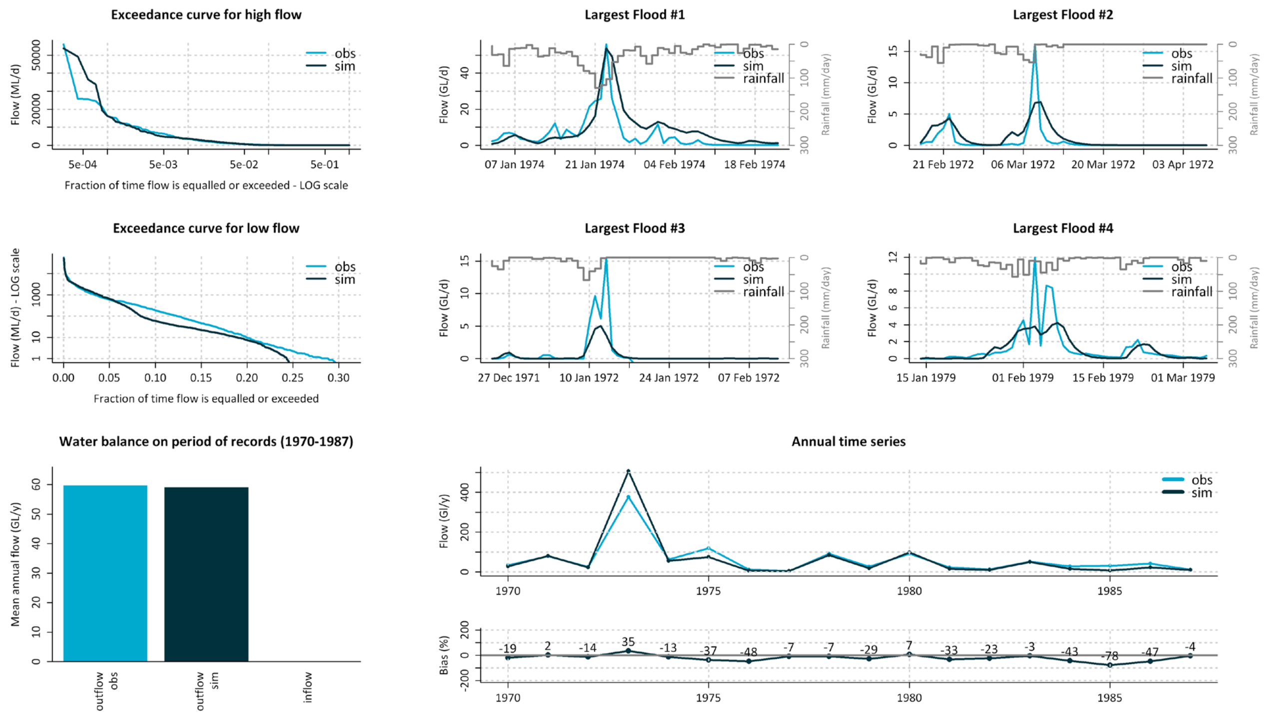
Reach 14 - upstream of station 917005A



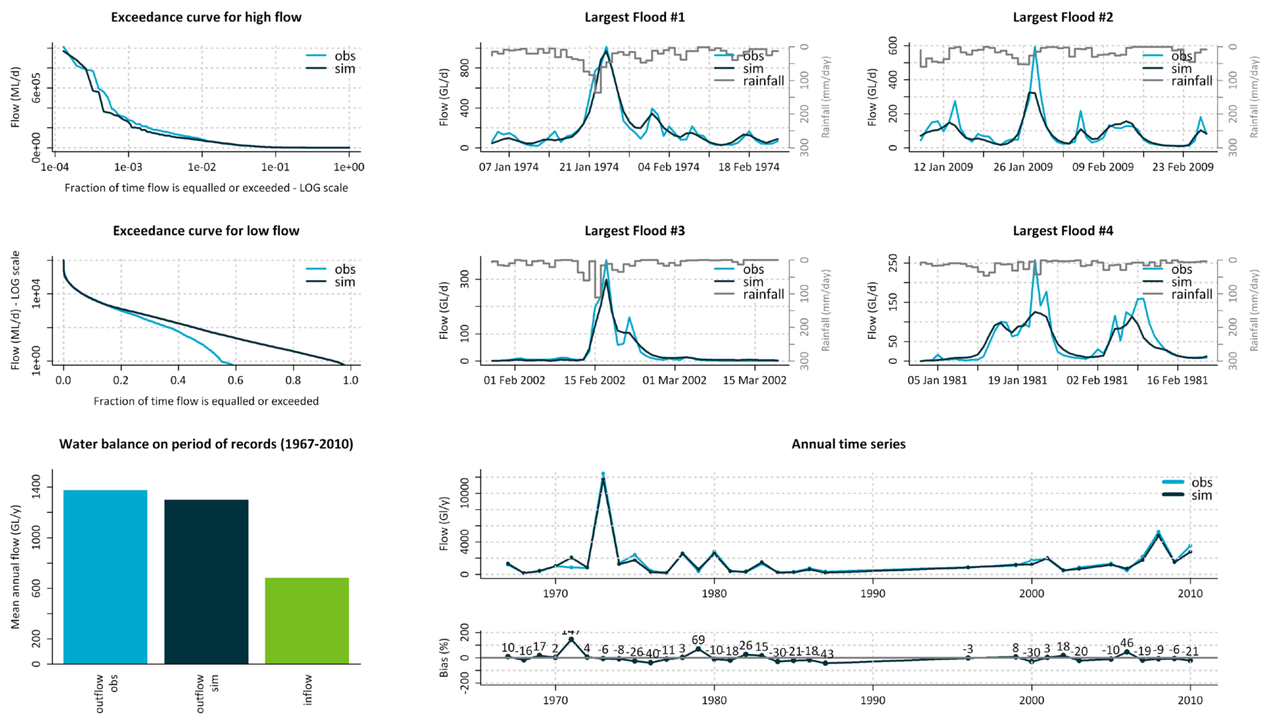
Reach 15 - upstream of station 917013A



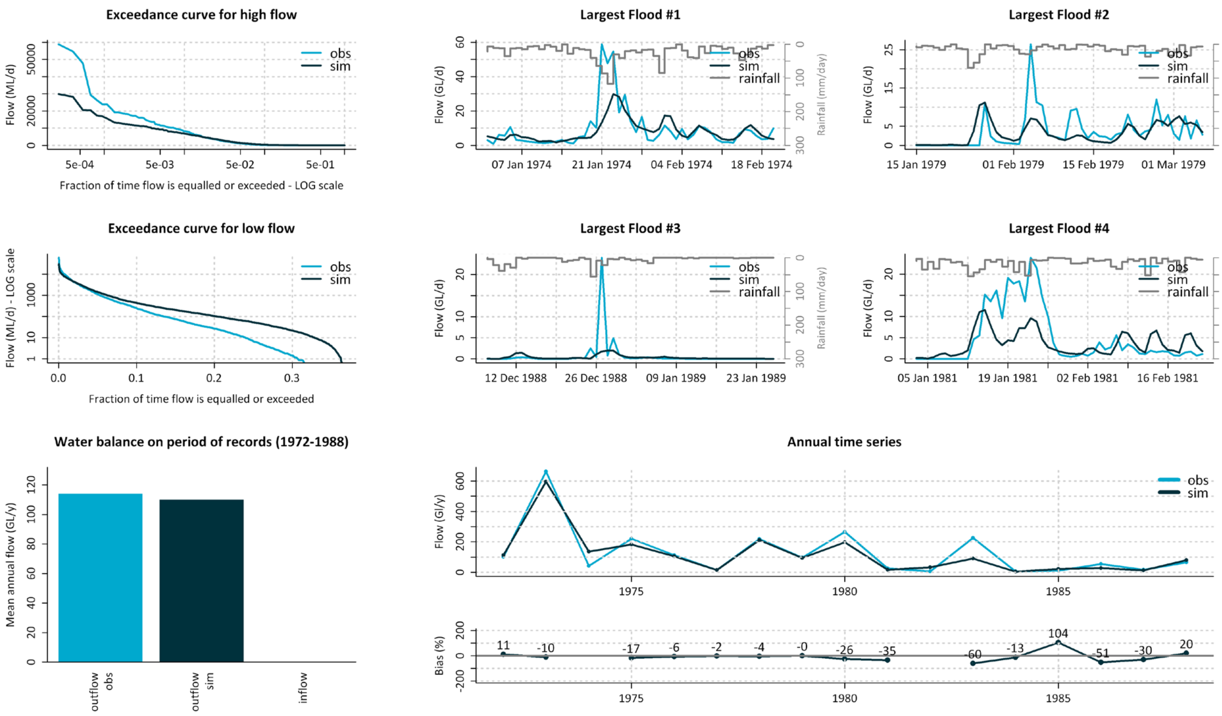
Reach 16 - upstream of station 917007A



Reach 17 - upstream of station 917001D



Reach 18 - upstream of station 917008A



CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

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Water for a Healthy Country Flagship
Julien Lerat
t +61 2 6246 5647
e julien.lerat@csiro.au
w http://www.csiro.au/Organisation-Structure/Flagships/Water-for-a-Healthy-Country-Flagship.aspx