Building the river system model for the Border Rivers Valley regulated river system

Report

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Executive summary

Water management in NSW (and globally) relies on (numerical simulation) models to provide robust and reliable estimates of what water is available, how much is needed, and how the resource can be equitably shared. The Department of Industry, Planning and Environment Water manages the river system models that have been developed for this purpose. A model exists for each of the regulated valleys in NSW. These models are being extended (or rebuilt) to determine volumetric entitlements for floodplain harvesting consistent with the *NSW Floodplain Harvesting Policy*.

This report describes the rebuild of the Border Rivers Valley river system model – its conceptualisation, construction and calibration. It includes sections that describe the valley (section 3), and how it has been represented in the model. This extends beyond the physical components of the river system (section 4) to water licensing (section 5), water users (section 6) and water management (section 7). The model developers describe their approach to the modelling, following, and adapting, contemporary, industry-standard modelling practices (section 2).

Model results that report the performance of the model are presented in section 8. In all cases, the model developers provide comment on the results including implications for overall model performance. Where uncertainty in the result has been assessed as being of significance, sensitivity tests have been developed and run, and the results of these tests are reported in section 9. Section 10 concludes the report by summarising (a) how the model has addressed (and met) the design criteria (established in section 1) required to meet the modelling objective of being able to determine floodplain harvesting entitlements using an extended river system model; and (b) recommendations for further data collection to reduce residual uncertainty in the model. Extensive supporting material is provided in 14 appendices. Key findings and messages from the model build process are now described in some more detail.

Modelling approach

The Border Rivers Valley river system model is designed to support contemporary water management decisions in the Border Rivers, whether it is a rule change in the water sharing plan, or estimating long term average water balances for components such as diversions for compliance purposes. It has two overarching objectives, being to: support traditional water policy, planning and compliance uses, such as implementing the Basin Plan and estimating plan limits; and to determine volumetric entitlements for floodplain harvesting. Six design criteria were established to realise these objectives (in section 1): represent key processes affecting water availability and sharing; use a sufficiently long period of climate data to capture the climate variability; have detailed spatial resolution to allow system analysis and reporting at multiple spatial scales; use a daily time step to enable flow variability assessment and reporting at multiple time scales; represent historical usage on a seasonal basis and enable robust estimates of annual water use; and provide a pathway to update and improve accuracy (i.e. be update-able and extensible).

Building the model in the Source modelling platform[1] provided the architecture and functionality required to simulate water availability and management and meet the design criteria. The model was built by connecting Source node and link components (in-built or coded by the model developers) to represent a full river system, including its floodplains. These components were then populated (parameterised) with data, in most cases specific to the Border Rivers, but

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[1] https://ewater.org.au/products/ewater-source/

where local data were not available, from other parts of NSW and/or the literature. The model enables a water balance assessment accounting for inflows and outflows at multiple scales (daily, seasonal, annual; property, river reach, whole-of-valley).

Simulating a perfect water balance at individual property scale is only possible with fine temporal and spatial data on water movements to and from floodplains and property management practices. These data are not yet available – to compensate, we undertook a multiple lines of evidence approach to assessing floodplain harvesting. We used a **capability assessment** to consider the physical infrastructure used for floodplain harvesting and also the opportunity irrigators may have to access floodplain flows based on their location and climatic variability. We also used a water balance assessment given historical crops grown and the estimated water requirements. This assessment focuses on the reach and valley scale to ensure that the total volume of water including historical metered use and estimated floodplain harvesting is representative of the estimated historical water use.

Modelling flows

Rainfall–runoff models have been used to simulate the conversion of rainfall into streamflow. The Border Rivers has an extensive network of climate and river gauge stations and 32 models (one for every reach in the model) were built and calibrated to reproduce historical flows. **Effluents** (i.e. rivers/streams that flow out of a river, often only at high flows) and **breakouts** (i.e. the points where the river spills over onto its floodplains) provide the water for properties to access floodplain harvesting. Breakouts and effluents are modelled explicitly using relationships estimated from multiples lines of evidence including surveys, hydraulic modelling, remote sensing, gauged flows and advice from river managers. Modelling of the three major **water storages** (Coolmunda, Glenlyon and Pindari dams) and Boggabilla Weir simulate physical processes (e.g. effect of evaporation on the storage volume) and operating rules.

Modelling water sources and licensing

The main licence categories of high security, general security A and B and supplementary access licences are configured for relevant water users, and regulate access to the water sources in the valley. Water sources are then labelled as regulated, supplementary, floodplain harvesting, unregulated and ground water. Modelling of these components is very complex and involves the sharing of water between states, the allocation of water to licences, staged flow threshold rules, together with the ordering and delivery of water through the system. The water available for **floodplain harvesting** for NSW water users is simulated through the breakouts and rainfall–runoff. Harvesting of **rainfall–runoff** water is embedded in the crop water model included for each property which calculates runoff based on soil moisture and rainfall. **Unregulated diversions** are mostly recognised inherently in the gauged inflow data and/or flow-loss relationships. **Groundwater** is not included in the Border Rivers Valley river system model as no use was identified for any of the floodplain harvesting properties on the regulated river system.

Modelling water users

Water users includes urban areas, irrigators, the environment, and water for stock and domestic supply. **Town water supply** volumes are represented using fixed monthly patterns. The volumes are very small in relation to other water users and are not included in the results.

The largest water users are (mainly cotton growing) **irrigation properties** in the floodplain areas between Goondiwindi and Mungindi, downstream of the junction of the Dumaresq River to upstream of the junction with the Darling River. Those properties assessed as eligible for floodplain harvesting entitlements are represented as individual Irrigator water users in the model. The remaining, generally smaller, properties are aggregated within the river reach where they are located. The most contemporary and detailed sources of information were used to parameterise each Irrigator water user. These included information on farm infrastructure such as on farm storages, pumps, areas developed for irrigation, area planning decisions and irrigated crops for the period 2003/04 to 2013/14. These data sets were made available through the Floodplain Harvesting Property farm surveys and from the Natural Resource Access Regulator (NRAR); and ground survey and LIDAR data to derive on-farm storage volumes and surface areas. The modelling can be split into 5 components: a) modelling of on-farm storages and their use for irrigation, simulated based on demand; b) modelling of crop area planting, simulated based on a relationship with water availability; c) modelling of crop water use using embedded crop models that order water based on crop growth and soil moisture balance; d) harvesting of rainfall–runoff simulated from fallow, irrigated crop and undeveloped areas, using the same soil water balance component of the crop model; e) overbank flow harvesting into the on farm storage.

Until more information is available on how **Held Environmental Water** is to be used, it has been modelled as a consumptive use that assumes an irrigation demand pattern. **Stock and domestic** replenishment flows are represented as a demand at the Boomi River offtake.

Modelling water management rules

Source’s ownership system provides functionality to assign and track the ownership of water throughout the model network and is used in the model with two owners, NSW and Qld, to model state ownership and sharing arrangements. The 3 resource assessment systems used in the Border Rivers – NSW continuous accounting, Qld continuous accounting and Qld continuous sharing (Macintyre Brook) – are modelled to represent operational practice as closely as possible.

While **water trading** is not explicitly represented in the model, it is taken into account when assessing model results. **Environmental flow** rules to represent environmental releases are configured in the model.

The operations of major storages, including harmony operation between Pindari and Glenlyon dams, and Boggabilla Weir and other regulators (e.g. Newinga) are all represented in the model.

Model performance

Results have been selected to report on the calibration of the model, and the performance of the overall model. For flow calibration, this focussed on being able to replicate important parts of the flow regime. Overall performance is measured by comparing to recorded data such as flows, metered diversions and irrigated areas.

Statistics and plots for key model components under conditions as at 2008/09 give confidence that the structure and parameterisation of the model are sufficiently capturing the physical and management processes necessary to meet modelling objectives.

Mean annual and inter-annual variability of flows are well reproduced for headwater inflows and main river flows.

Simulation of irrigation water use was tested against other models or data sources (e.g. Australian Bureau of Statistics). These sources all provided estimates similar to the model, providing confidence in the model.

Simulation of **rainfall–runoff harvesting** is based on a relatively simple daily soil moisture model. Long-term averages and annual depths show a clear (and expected) relationship between runoff depth and rainfall. Data collection is required at farm scale to confirm assumptions used in the modelling to reduce what is an area of significant uncertainty in the model.

Overbank flow (for harvesting) depends in part on modelling of frequency and volume of events. Simulation of the number of moderate flood events and events above the commence-to-break flows closely match observed.

Farm water balance (i.e. total irrigation water use) was checked at 3 spatial scales. At valley scale, metered diversion results closely match observed. Reach scale indicates that the distribution between reaches is reasonable – again the results match well. At property scale, there can be many variations in water use and efficiency so water balance assessment at this scale was used with caution. We undertook sensitivity testing to understand whether farm scale assumptions caused a significant impact on floodplain harvesting results and generally found low sensitivity.

Planted areas agree well with those reported in the farm surveys. Seasonal variability in area planted in response to water availability was particularly well captured.

Metered diversions from the river agree well with observed data, with small differences (over-estimations) attributable to small variations between observed and simulated crop areas.

Total **storages volume** patterns over time match reasonably well with observed. Differences could be due to variation in planted areas, management practices, simulated floodplain harvesting or account management transfers, the nuancing of which are not captured in the model.

Summary

This report captures the considerable body of intellectual effort and modelling expertise that sits behind the construction of the Border Rivers Valley river system model. It reports on the modelling approach adopted, how the component parts were put together, and reports outcomes. Significant effort went into understanding how sensitive model results were to uncertainties in climate and flow data, diversion data, model assumptions and simplifications, and model parameters; with the aim of reducing these uncertainties where possible, either through access to better data, improved parameterisation, or re-configuration of the model.

The results show that the most significant diversions in terms of long-term averages in the Border Rivers are general security, followed by supplementary access, then overbank flow harvesting and lastly on-farm rainfall–runoff harvesting.

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1 Introduction

The Department of Planning Industry and Environment Water (the department) has developed a new river system model of the Border Rivers Valley in collaboration with the Qld Department of Environment and Science. The model is a complete rebuild of an earlier departmental model. It has been developed using eWater Source[2] and the redevelopment has enabled improvements due to significant new data sources. Whereas NSW and Qld previously used separate river system models, the Source model will be used by both states.

We use river system models for many policy, planning and compliance uses. One key use is that we are using the new model to determine floodplain harvesting entitlements[3] consistent with the *2013 NSW Floodplain Harvesting Policy* (the policy) as revised September 2018.

1.1 Report objectives

Communities in the Border Rivers and regulators need to be confident that the modelling underpinning the determination of floodplain harvesting entitlements has been undertaken using best available information and modelling practices. They also need confidence that the model is the best available for other intended purposes such as assessing compliance to water sharing plan limits. This report has been written to underpin that confidence.

The Border Rivers Valley river system model provides support to more than floodplain harvesting. Floodplain harvesting takes place within the context of all other processes operating within the Border Rivers; including climate conditions, streamflow generation, water storage, water sharing rules, diversions, accounting. The report describes how, and how well, the model represents all these processes.

1.2 Report structure

The report structure follows the modelling steps. It provides detail on how the model was built, starting with a description of the Border Rivers Valley, the information available to inform the model, our design approach to building these river system models, and model results relevant to assessing model performance (Figure 1).

Section 2 describes the modelling approach that we have adopted – the objectives for the modelling, the software that we have used, and overviews the modelling phases.

Section 3 introduces the valley to provide the context for how we have characterised the valley for modelling.

Sections 4 to 7 contain the details of the modelling, grouped to make for consistent navigation into the valley's:

- physical environment affecting flows
- water sources and licensing
- water users
- water management.

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[2] https://ewater.org.au/products/ewater-source/

[3] An access licence entitles its holder to specified shares in the available water within a specified water source, known as the share component. The shares specified in an access licence can also be referred to as an entitlement and are expressed as share components or megalitres per year. You will see both 'licence' and 'entitlement' used in this report.

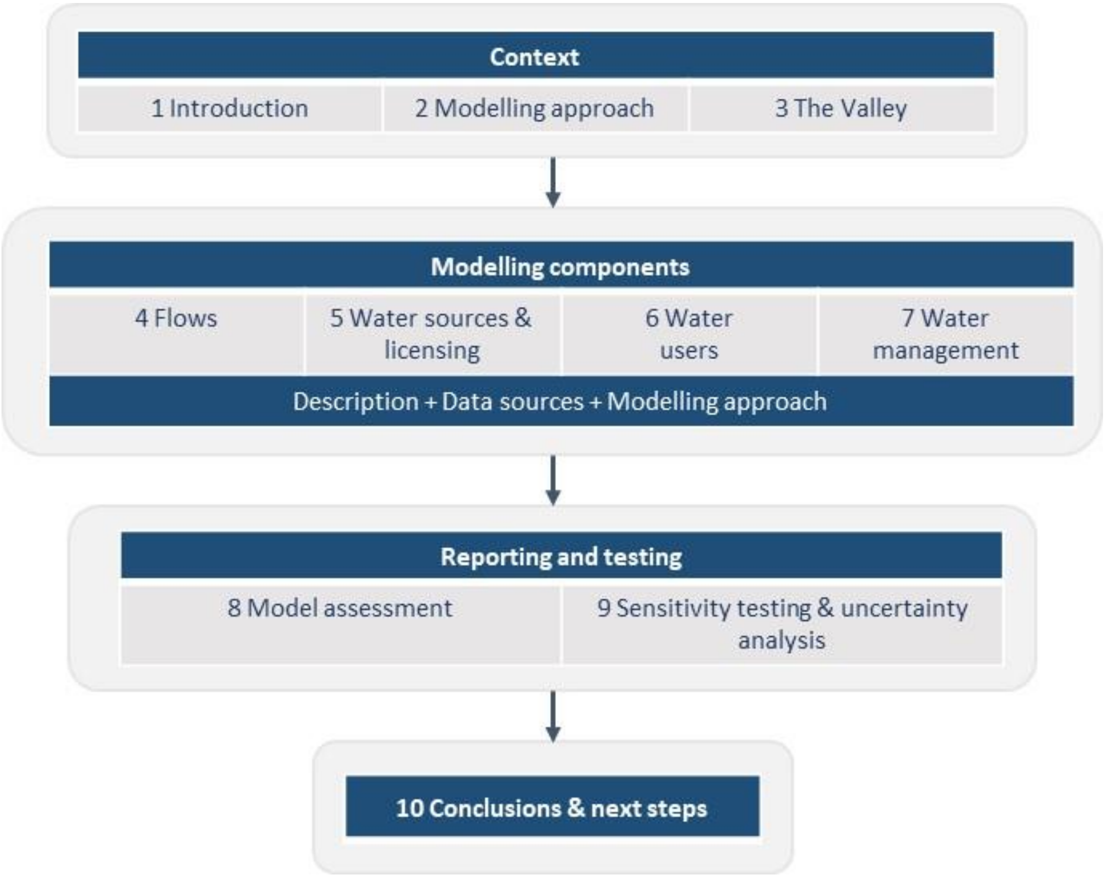

Figure 1 Report structure

These sections detail the data available to describe the key components of the valley, how we assessed what data to use and how it was used in the modelling.

In section 8, we present the results of the modelling, focussed on simulation of headwater inflow and main river flow, water use and Plan Limit Scenario results.

Uncertainty analysis and sensitivity testing of key parameters, input data and modelling assumptions is an important step in modelling practice. This is discussed in section 9.

Section 10 concludes the report with an overall assessment of the model suitability, and limitations, against its specific objective of floodplain harvesting entitlements determination. The section includes recommendations for further work to improve the accuracy and capability of the model, particularly the need for more suitable data.

The report contains a large set of appendices to support the report content. These include descriptive information (e.g. identification of rainfall and gauging stations used for the modelling) through to detailed modelling results. They provide extensive documentation and demonstrate the complexity and extent of work involved in building the model.

It is our intention that this report demonstrates our understanding of the river system being modelled, that we have collected the best, readily available and suitable data to build a model that meets the specified objectives, and that our approach to develop the model was sound. Our goal is to provide full transparency. We welcome further enquiries on this work, allowing our stakeholders to have confidence in our work and results.

1.3 Companion reports

This report describes the building of a baseline river system model for the Border Rivers Valley regulated river system.

How the model has been used to update the water sharing plan limit and calculate floodplain harvesting entitlements to bring total diversions back within that limit is described in companion report *Floodplain Harvesting entitlements for NSW Border Rivers Valley regulated river system: model scenarios* (DPIE Water 2020a).

The use of the model results for predicting potential environmental outcomes is described in companion report *Environmental outcomes of implementing the Floodplain Harvesting Policy in the Border Rivers Valley* (DPIE Water 2020b).

The three reports together serve to describe how the modelling meets the objectives of the policy.

2 Modelling approach

This section describes the modelling approach used to construct a Border Rivers Valley river system model. While the modelling steps are set out here sequentially, some of the steps can run in parallel, and they are of course iterative as insights or limitations encountered in a step can result in re-working previous steps. The overarching goal is to ensure the model is only as complex as it needs to be to meet its purpose. The modelling described in this report needed to provide information at both a valley scale and irrigation property scale. Assumptions and presumptions are made in this process and we have attempted to document those to the best of our ability in this report.

The model has been developed collaboratively with the Qld Department of Environment and Science (DES 2018). We each have our own set of modelling practice guidelines; these are constantly refined over time and we also contribute to broader modelling guidelines[4]. Where our guidelines differed, we agreed on the approach to be followed for the Border Rivers. Our practice, particularly in regard to assessing data quality, is described in Appendix A .

2.1 Modelling objectives

River system models have been used for several decades to determine water availability, flows and diversions under varying climate conditions, as a critical step in informing the development of water sharing arrangements. The Border Rivers Valley river system model is designed to support contemporary water management decisions in the Border Rivers, whether it is a rule change in the NSW Border Rivers water sharing plan or estimating long term average water balances for components such as diversions for compliance purposes. It has two overarching objectives, being to:

- support traditional water policy, planning and compliance uses, such as implementing the Basin Plan and estimating Plan limits
- determine volumetric entitlements for floodplain harvesting.

Six criteria were established for the design of the model to enable it to meet these objectives. How well these are met is reported in section 10.1.

Table 1 Model design criteria to meet modelling objectives

	The model must:
1	**Represent the key physical and management processes that affect water availability and sharing within the river system, at a sufficient spatial scale to estimate floodplain harvesting volumes and entitlements at irrigation property level** Essential to enable the conceptualisation and model execution to meet the other design criteria

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[4] https://wiki.ewater.org.au/display/SC/Australian+Modelling+Practice

	The model must:
2	**Run over years that capture the climate variability (wet and dry periods)** This is required to be able to understand how the water balance varies in wet and dry periods, and so demonstrate that the valley meets statutory diversion limits (SDLs) as set out in the Basin Plan. Modelling using long periods of climate records that captures a wide range of wet and dry periods is an important way of understanding the effects of Australia's particularly variable climate on river flows and water management arrangements. The Basin Plan requires the assessment of diversions from 1895 to 2009 for calculating SDLs and Baseline Diversion Limit (NOTE: The Border Rivers Valley river system model has been built in a way that enables consideration of impacts from climate change scenarios, however this was not needed for this project, nor for current statutory requirements.)
3	**Report at multiple spatial scales (river reach up to whole-of-valley)** Simulate processes at a suitable spatial resolution to allow checking of performance and behaviour of individual components, to allow aggregation to report on up to whole-of-valley outcomes, and to support equitable sharing of floodplain harvesting volumes and entitlements at farm scale
4	**Report at multiple time scales (daily to annual)** Simulate model processes on a daily basis so as to properly represent flow variability at a resolution important for ecosystem processes, water management rules, water access (e.g. to high flows for irrigated farms) and other statutory reporting requirements; and to allow aggregation to report on up to annual outcomes
5	**Capture historical usage on a seasonal basis, at reach and valley scale** Simulate annual water use under a range of climatic conditions to support statutory requirements. This is required for Annual Permitted Take assessment as part of Basin Plan reporting requirements
6	**Be update-able and extensible** that is the model can be updated and new functionality added as and if new and better data and methods become available

In the case of the Border Rivers Valley river system model, meeting these objectives and criteria required extensive redevelopment and enhancement of the earlier departmental model (IQQM, DNRM & DLWC, 1998) which was built for a different purpose, primarily to model in-channel diversions.

2.2 Type of model and modelling platform used

The models that are used by the department to underpin water management in NSW are quantitative, simulation models. Simulation models are widely used in water resources management to improve understanding of how a system works and could behave under different conditions.

The department, along with other Australian water agencies, uses or is migrating to use the Source software platform which has been adopted as Australia's National Hydrological Modelling Platform. Source was developed by a consortium of Australian research and industry partners to provide a consistent hydrological and water quality modelling and reporting framework to support integrated planning, operations and governance at urban, catchment to river basin scales. Use of a common platform facilitates collaborative and consistent modelling, analysis and policy development across the Murray Darling Basin, including the accreditation of water resource plans under the Basin Plan.

Source is designed to simulate flows through a system, whether those flows are water, sediment, contaminants, water accounts or water trade. It provides sufficient functionality to simulate the process of water moving out onto floodplains.

Source models are built from components which are linked, through adding nodes and links, to represent the system to be modelled. There are many types of nodes to represent places where water can be added, diverted, stored, and recorded (for reporting) in a model, including:

- water sources (supply), such as inflows, storages
- water users (demand), such as crops, towns, industries, the environment
- reporting points, such as gauges and environmental assets.

Links connect, store and route water passing between nodes.

Source also contains models (hereinafter referred to as component models) that can run together to simulate multiple processes within the system. For floodplain harvesting modelling, these include:

- rainfall–runoff models that converts rainfall into runoff across the landscape
- irrigated crop models that simulate the crop growth cycle, and thus water demand
- storage models that simulate the management of storage water.

These models are mentioned here because the choice of model dictates the amount and type of data that must be collected.

Additionally, the Source platform supports the coding of functions to dynamically calculate values based on other values during a model run. An example in the Border Rivers Valley river system model is the function that dynamically calculates crop area planted as a function of water availability (ref section 6.2.2).

2.3 Modelling steps

After we understand key aspects of the river system through model conceptualisation and assess the available information, a model of the system can be constructed. The Source software platform contains a variety of model components that represent different processes, such as inflows, water storage, water movement, crop demands and environmental flow rules, that can be connected together, progressively, to represent a full river system.

These components all have many attributes that are configured to represent the relevant aspect of the river system, a process known as parameterisation. The parameterisation process is described in section 2.3.4.

The model build process requires the model inflows and outflows to be accounted for at all scales. The model is built systematically using a number of stages. The concept of a water balance, stages of model building and scales of model building are described in section 2.3.1 to section 2.3.3.

2.3.1 Water balance

A water balance is a common approach in hydrology based on the conservation of water in a particular river system. This means that all the inflows, outflows, or changes in water stored must balance over a given time step, whether one day or one hundred years. This is useful when we know most of the inflows and outflows and have one unknown that can be solved to make the system balance each time step.

Water balance assessments are used to estimate various model components such as ungauged inflows to storages or river reaches and unmetered water use. Components of the water balance at irrigation farm, river section (known as a reach) and valley scale are visualised in Figure 2, Figure 3 and Figure 4 respectively.

2.3.2 Stages of model building

As the total number of parameters in the model is large, a systematic, multi-stage process is used to progressively parameterise valley-scale surface water models. Many stages can be completed independently from each other, but they are subsequently combined together in an assembly sequence that is outlined in Table 2. This sequence recognises which stages rely on the results of previous stages. As recorded data are progressively replaced with simulated data during the model assembly process, simulation results are re-checked at each stage, and adjustments made to parameters where necessary.

The river system is divided geographically into river reaches for the initial four stages for practical and methodological reasons. The practical reasons are the sheer complexity of the whole river system and the computing time for this. This subdivision also allows more people to work concurrently on the model.

This approach manages uncertainty by firstly setting observed data as a boundary condition for most of these stages, and varying parameter values of the component models to calibrate their response to match observed data, whether this is matching observations, a prior estimate, or system behaviour more generally. Once parameter values have been calibrated, the observed data are progressively replaced with calibrated parameters, and outputs validated.

Table 2 Stages of model assembly

Stage number	Process	Modelling approach section
1	Climate	sections 4.2.2 and 4.3.2
2	Directly gauged inflows	subsection in section 4.4.2
3	Indirectly gauged inflows and losses	subsection in section 4.4.2
4	Irrigation diversions	subsection in section 6.2.2
5	Irrigated planting areas	subsection in section 6.2.2
6	Supplementary access diversions	subsection in section 5.3.2
7	Water management	subsection in section 7.1.7
8	Storage operation	subsection in section 7.6.2

2.3.3 Scales of model building

Farm scale

The farm scale is the computational unit with the greatest complexity, combining several physical and management processes. The main water balance components of the farm scale water balance are illustrated in Figure 2 for the 4 principal areas of an irrigation farm – the permanent on-farm storage, the irrigated and non-irrigated developed areas, and the non-developed farm area. The focal point for most of these irrigation properties are the on-farm storages which regulate the water at this scale. Most of the water that enters the farm is stored, before being used later to meet crop water requirements. The exception to this is rain that infiltrates into the soil.

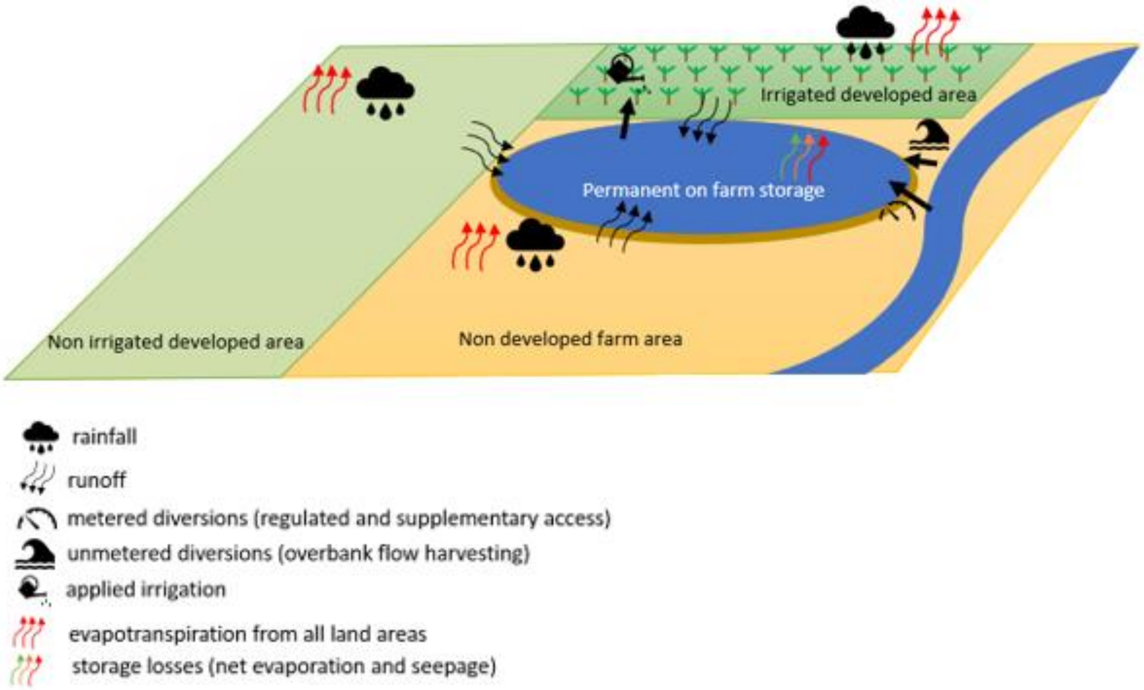

Figure 2 Farm scale water balance components

Modelling the on-farm water balance provides an understanding of the **total volume** of water required to meet irrigation demands based on the area of crops planted.

When unmetered diversions are not actually a significant component of the on-farm water balance, metered diversions can be assumed to represent the surface water diversions for irrigation purposes.

Where unmetered diversions such as floodplain harvesting are a significant component of the on-farm water balance, modelling the total irrigation demand (referred to as crop modelling) allows us to estimate the additional unmetered diversions through subtraction of metered diversions. This estimate of total irrigation demand using crop models provides an estimation of the take from rainfall–runoff harvesting and floodplain harvesting.

We would not expect a perfect water balance to be achieved at all individual properties due to a number of uncertainties (such as different management practices) at that scale. We place more emphasis on ensuring that the reach and valley scale results make sense in terms of historical production. We use multiple sources of information to configure floodplain harvesting access, rather than relying on perfect water balance at individual properties.

The estimation of these components is described in section 6.2.2.

Reach scale

The reach scale allows for the combining of the sources of water availability (principally inflows) with the largest source of consumptive water demand – the irrigation farms. The reach water balance is illustrated in Figure 3. Note that depending on the physical characteristics of the reach, some components may be negligible or zero, e.g. in upper reaches breakouts or irrigation diversions may not exist.

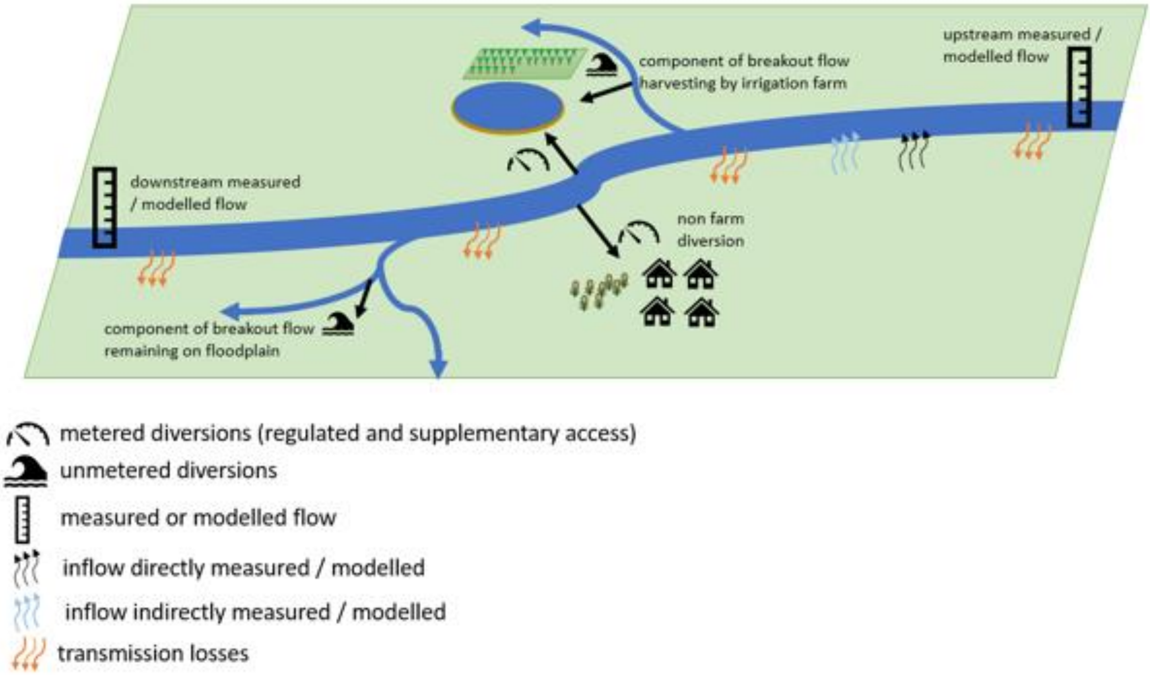

Figure 3 Reach scale water balance components

Valley scale

The complete river system is an assemblage of the reach calibrations, to which is added the management arrangements operating in the river system. In the upper reaches, especially on unregulated reaches, the inflow components dominate. Downstream of the major headwater storages all components become increasingly important (Figure 4).

The assemblage of all the river reaches allows the processes that operate at a river system scale to be configured, specifically Stages 5 to 8 (irrigated planting areas, supplementary access diversions, water management, storage operation) in Table 2.

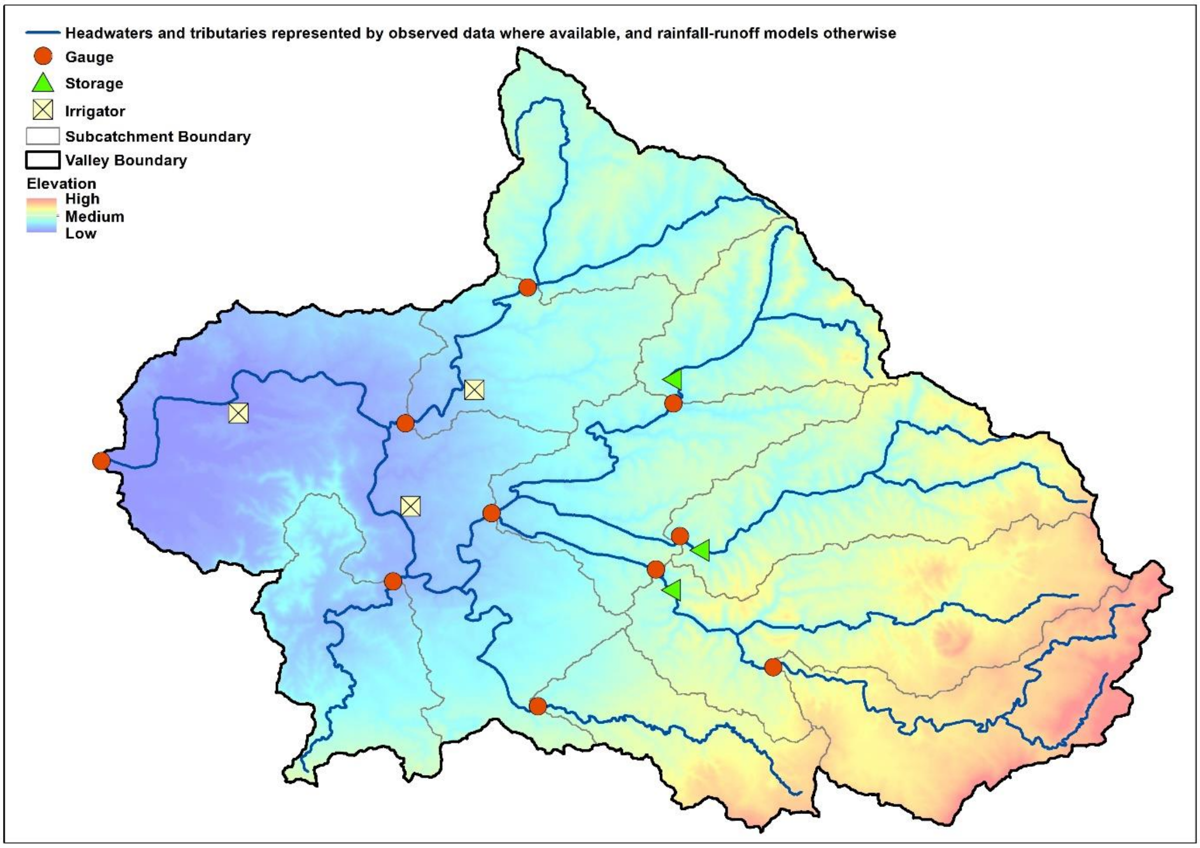

Figure 4 Valley scale water balance components

2.3.4 The parameterisation process

Most river system model software (including Source) is developed to be generic, with parameter values configured within the software to describe the system being modelled. Parameter values are estimated using one or a mix of the following methods:

- assigned directly, based on measured data, such as where we have surveyed or LIDAR data of on-farm storages
- assigned based on published advice from industry or research
- calibrated by systematically adjusting to match recorded data at the site or of system behaviours – this method iteratively checks how well model outputs match recorded data and parameters are adjusted to improve performance.

Model calibration with climate data as the primary inputs is conducted on a reach-by-reach basis using available recorded data such as gauged flows, metered diversions, infrastructure, and crop areas. These individual calibrations are then combined and validated at a whole of river system scale.

The method used to parameterise each of the component models varies depending on the availability of good quality data. Data availability also determines time periods available for calibration. It is good practice to use the longest period possible to represent natural system behaviour for a range of different climatic conditions. For some components such as water demand, the data should reflect the period of time most appropriate (e.g. for cap modelling, need data for that period); for a model to represent current behaviour, the most recent data should be used.

Where possible, a number of parameters are pre-defined based on research or industry data. This approach streamlines the calibration process by reducing the number of parameters to be calibrated at the same time, which runs the risk of unrealistic parameters that may not result in the model being robust when simulating outside the calibration period.

2.3.5 Model assembly and data extension

Model components are progressively and systematically assembled to represent the total river system, from headwater inflows, indirectly gauged inflows, through regulating structures, water demands and end-of-system flows. These processes are worked together along each section of the river, i.e. each reach.

As we assemble the model, observed data are progressively replaced with modelled data. The last two stages of model calibration listed in Table 2, water management and storage operation, are parameterised only when the model is assembled. The whole assembled model is shown in Figure 5 to highlight the geographic scope and detail.

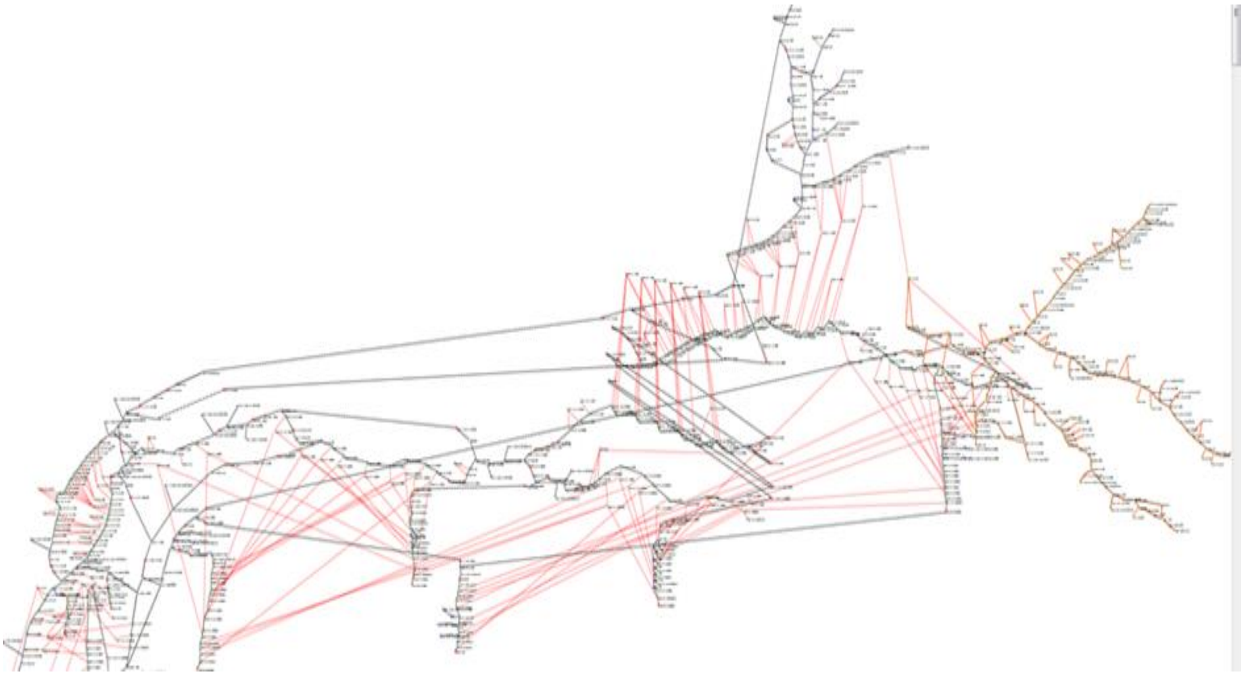

Figure 5 Assembled node-and-link model (as represented in Source). The model includes a node for every irrigation property assessed as eligible for a floodplain harvesting entitlement

2.3.6 Data periods

The last step is required to enable use of the model for scenario analysis and to extend all the input data to its fullest temporal extent. During earlier build stages, the component models and the fully assembled models were simulated for shorter climate periods depending on data availability. The scenarios need to be simulated for at least the climate period 1895 to 2009 for Basin Plan Sustainable Diversion Limit compliance purposes, and for longer to account for more recent data. The full climate period for all rainfall and evaporation stations was input directly to the model, as well as used to generate inflows at all points for input to the model.

Table 3 Time periods using in the Border Rivers Valley river system modelling

Period term	Period	Note
Long term record	1/7/1889–30/6/2014	1889–1895 is model warm-up period; reporting commences from 1895
Reference climate period for reporting	1/7/1895–30/6/2009	Basin Plan reporting period. Period used for long-term averages. Water years 1895/86–2008/09; short form 1895–2009
Available climate data period	1/1/1890–30/6/2020	SDL compliance process required extension to current conditions
Period for calibration and validation of flow modelling	various	Based on data availability
Assessment period for diversions and water management using fully configured model	1/7/2003–30/6/2014	Water years 2003/04 to 2013/2014; short form 2003–2014 Covers key benchmark years for the NSW Floodplain Harvesting Policy and the Basin Plan and was based on data availability at time of model development
Base model conditions	2008/09	Represents development conditions from 1 July 2008 to 30 June 2009

2.3.7 Validating the model

The assembled model is then tested to evaluate its performance by comparing model results with observed data. We use different tests to validate the model:

- The last step in the flow calibration process was to develop a validation model by amalgamating the individual reach models. The validation model is used to confirm the performance and accuracy of the model run as a complete system and provides a foundation for the development of scenario models.
- The diversions and water management components have been compared over the period 2003 to 2014, which includes key benchmark years for the policy and the Basin Plan. We also evaluate how well the model performs during two sub-periods.

These tests are further described in section 8.

2.3.8 Scenario development

The fully assembled model with the full period of available climate data are now ready to simulate scenarios. A scenario for managed river systems includes the following characteristics:

- fixed development conditions: including catchment and land use, headwater and re-regulating storages, areas developed for irrigation, on-farm storage volumetric capacity, and pump capacity
- fixed management arrangements, including all rules, resource assessment and allocation processes, and accounting as set out in the WSP, as well as on-farm decision making regarding crop mix, crop area planting as a function of water availability, and irrigation application rates.

With these development conditions and management arrangements set in the scenario model, the model is simulated for the full climate period and results are analysed and compared. This is described in more detail in the companion Scenarios report (DPIE Water 2020a). The scenarios developed for the Border Rivers are listed in Table 4.

Table 4 Scenarios used in the Border Rivers Valley river system model

Scenario name	Description
2008/09 Scenario	Represents the conditions in the valley, licences and diversions, as at 2008/09[5]
Cap Scenario	Generally based on 1993/94 conditions however an allowance was made for enlargement of Pindari Dam which means some development levels are based on November 1999
Plan Limit Scenario	Cap on diversions – uses development levels as at 2001/02 and management arrangements and share components as at 1 July 2009
Baseline Diversion Limit (BDL) Scenario	Equivalent to Plan Limit Scenario

2.4 Sources of data for river system modelling

Modellers rely on a range of sources of data – some are directly measured such as rain, flow or licensed diversions; some are indirectly estimated such as crop areas from remote sensing, or breakout relationships from hydraulic models. Table 5 describes the primary sources of data that are used in river system models, tailored to provide examples for the Border Rivers Valley.

Table 5 Primary sources of data relevant to river system modelling and their uses for components: river network, climate, flows, regulating infrastructure, water users, farm infrastructure, crop areas, water management (X = used for this purpose; o = not used for this purpose)

Input / parameter	Primary data sources	Use – configure model	Use – direct input	Use – calibrate model	Use – validate model
Component: river network					
Model (node-link) structure	Maps, data layers in GIS	X	o	o	o
Effluents, breakouts	Farm surveys[6], State Emergency Service (SES), flow gauges, hydraulic modelling, remote sensing imagery of flood events	X	o	o	o
Component: climate					
Rainfall, evaporation	Bureau of Meteorology /SILO	o	X	o	o

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[5] This scenario is configured with all eligible storages, which includes one storage built post 2008.

[6] Farm surveys refer to the Irrigator Behaviour Questionnaire

Input / parameter	Primary data sources	Use – configure model	Use – direct input	Use – calibrate model	Use – validate model
Component: flows					
Observed flows and storage volumes	NSW flow gauging network (Hydstra database)	o	X	X	X
Simulated flows	Rainfall–runoff modelling	o	X	o	o
Component: regulating infrastructure					
Dams, weirs, and regulators	WaterNSW	X	o	o	o
Component: water users					
Licences, water sources, metered water use	NSW government (WaterNSW) Water Accounting System (WAS) and Water Licensing System (WLS)	X	o	X	X
Component: farm infrastructure					
Pump capacities, crop areas, developed areas, on-farm storage capacities	Farm surveys, remote sensing (LIDAR), site inspections	X	o	o	X
Component: crop areas					
Crop type and area planted each year	Farm surveys, remote sensing, survey records (WaterNSW, ABARE, ABS, industry groups)	X	o	X	X
Component: water management					
Water sharing, announcing allocations and supplementary access, planned environmental water requirements	NSW Border Rivers Water Sharing Plan, BRC Standing Operating Procedure (2009), NSW-Qld IGA (2008), Operational procedures	X	o	o	o

3 Overview of the Border Rivers Valley

3.1 Physical description

The Border Rivers Valley comprises the catchments of the Dumaresq, Severn, Macintyre and Barwon Rivers. These catchments drain from the Great Dividing Range between Inverell in far northern NSW and Warrenbayne in Southern Qld (Figure 6). It has an area of approximately 49,500 km^2, of which just under half (about 24,500 km^2) is in NSW. Grazing and dryland cropping are the major agricultural land uses in the valley, covering about 90% of the area, with irrigated agriculture, mainly cotton, covering less than 3% of the NSW Border Rivers Valley area.

The valley sits in a sub-tropical climate zone. Average annual rainfall across the valley decreases from east to west, from over 1000 mm in the eastern ranges around the Great Dividing Range to around 500 mm in the west at Mungindi. The rainfall is strongly seasonal with the highest volumes during the summer months occurring through summer storm activity. Annual evaporation has a strong east-west gradient across the valley, with average Class A pan evaporation exceeding the average rainfall across the entire valley. Annual evaporation is around 1200 mm in the eastern ranges and over 2000 mm in the far west of the catchment at Mungindi. Mean daily evaporation at Inverell ranges from 2 mm /day in winter to 6.5 mm/day in summer.

The river network is made up of the main river and its tributaries, effluents[7] and breakouts[8], with a complex series of branching channels at the lower end of the valley. The main tributaries entering NSW draining from Qld are:

- Pike Creek and Macintyre Brook, which enter the Dumaresq River
- the Weir River which enters the Macintyre River.

The junction of the Weir and Macintyre Rivers marks the start of the Barwon River, and the town of Mungindi on the Barwon River marks the downstream end of the Border Rivers Valley. Approximately 450 km of the border between NSW and Qld is formed by (from upstream to downstream) sections of the Dumaresq, Macintyre and Barwon Rivers.

Climate (rainfall and evaporation) and geography directly affect the volume of runoff generated within the valley, and how, when and what crops are grown. The characteristics of the river network affect how runoff accumulates as streamflow through the system, including how some flow breaks out of the main channel into the floodplain zones, where most of the irrigation farms are located. This requires representing how water flows through the system, including the large volumes stored behind headwater dams and released in response to downstream demands.

3.2 Regulation

Water in the valley is regulated through three major public water storages (Glenlyon Dam on Pike Creek (Qld), Coolmunda Dam on Macintyre Brook (Qld), and Pindari Dam on the Severn River (NSW)) and several weirs that regulate the flow pattern and availability of water in the system. The construction of these major dams and the regulation of river flows have enabled

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[7] Effluents are rivers/streams that flow out of a river and may have their own local catchment. Some effluent rivers/streams only start flowing when the flows in the main river reach higher levels. They are also called effluent systems, effluent offtakes, effluent rivers, effluent streams

[8] Breakouts are points where the river spills over onto the floodplains.

the NSW and Qld governments to deliver water to water users, and issue licences for the supply of water according to their respective legislations.

Access to regulated water is through licences and usage is metered. Unregulated water (e.g. in tributaries and headwater streams) can be accessed under certain conditions as can groundwater and water that floods out onto the flat plains. Under natural conditions, the river system would exhibit high flow variability in response to climate variability. However, regulation of the river has reduced this variability.

3.3 Water users

Water users includes urban areas, irrigators, the environment, and water for stock and domestic supply.

The largest water demands are from the irrigation farm properties in the floodplain areas between Goondiwindi and Mungindi, downstream of the junction of the Dumaresq River to upstream of the junction with the Darling River. These areas are principally cotton growing. A map of the primary irrigation areas is provided at Figure 7.

3.4 Legislation, policies and operating procedures

The New South Wales–Qld Border Rivers Act 1946 and the Continuous Accounting of the State's Shares of the Inflows to Glenlyon Dam and the Border Rivers Regulated Flows: Standing Operating Procedure 2009 (referred to herein as the BRC Standing Operating Procedure) establish the sharing of water between the two states.

The New South Wales–Qld Border Rivers Intergovernmental Agreement 2008 (the IGA) is an agreement between NSW and Qld to manage their respective shares of the river flows to ensure key environmental outcomes are achieved and to provide a consistent approach to managing water use and trade. Other NSW policies/legislation that are referred to in this report are:

- *Water Management Act 2000 No 92*
- Water Sharing Plan for the NSW Border Rivers Regulated River Water Source 2009 (the NSW Border Rivers WSP)
- *Natural Resources Access Regulator Act 2017*
- Water Sharing Plan for the NSW Border Rivers Unregulated and Alluvial Water Sources 2012 (the NSW Border Rivers Unregulated and Alluvial Water Sources WSP)
- (Draft) Floodplain Management Plan for the Border Rivers Valley Floodplain 2018
- NSW Floodplain Harvesting Policy 2013 (revised 2018) (the policy).

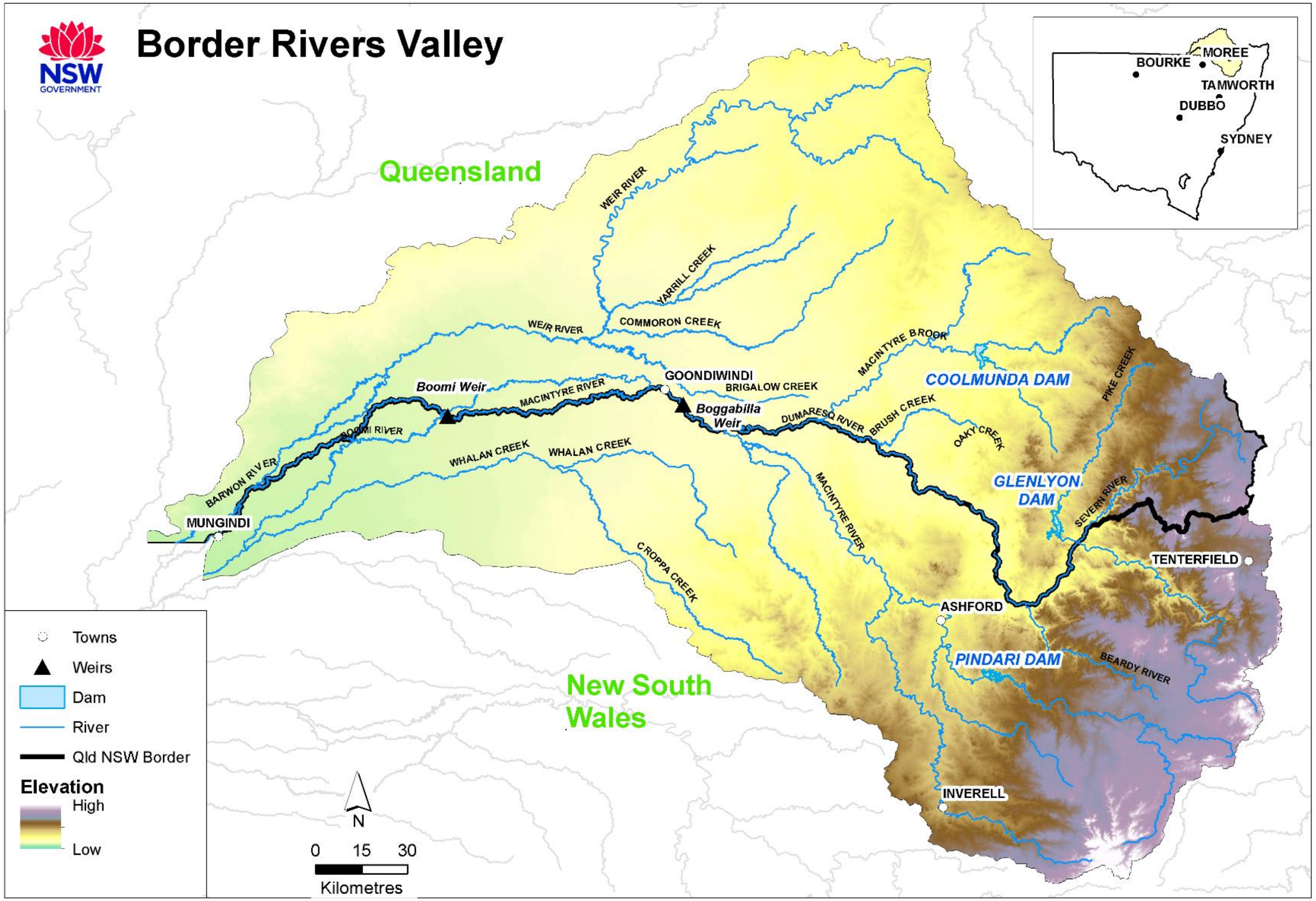

Figure 6 River network (main channel and tributaries) and locations of main towns and water storages in the Border Rivers Valley

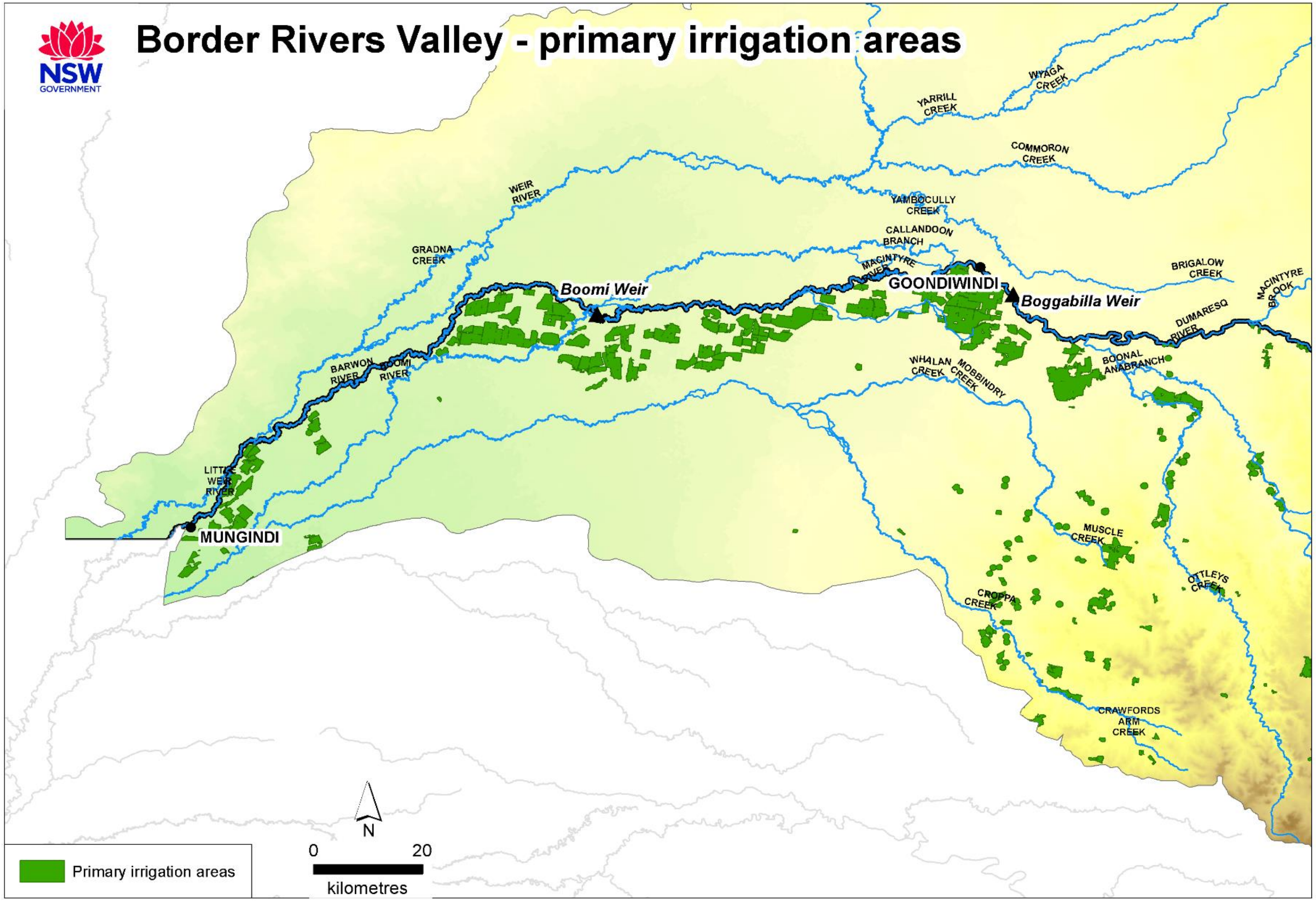

Figure 7 Primary irrigation areas in the NSW Border Rivers Valley

Qld legislation and/or planning documents referred to in this report are:

- *Water Act 2000*
- Border Rivers Resource Operations Plan 2008
- Water Plan (Border Rivers and Moonie) 2019
- Border Rivers and Moonie Water Management Protocol 2019
- Qld Border Rivers–Moonie Water Resource Plan 2019.

The NSW Border Rivers WSP applies to all regulated river sections in the NSW area of the Border Rivers Valley and regulates sharing and use of NSW's share of the water in the Border Rivers. The management components described in this report closely reference key provisions of the NSW Border Rivers WSP and their practical implementation, as well as how water users in the NSW Border Rivers choose to use their water based on water availability.

3.5 Summary

This section has provided an overview of the valley which translates into a suite of components for modelling. The next 4 sections (sections 4 to 7) describe each of the components, including the sources of data selected to best characterise them for the purposes of modelling floodplain harvesting. Typical sources of data for these components have already been listed in Table 5. For ease of navigation through this report, the components are grouped into:

- flows (section 4)
- water sources and licensing (section 5)
- water users (section 6)
- water management (section 7).

4 Modelling flows

This section describes the data sources and adopted modelling approach for the key physical components of the valley that affect flows along the river system.

4.1 River network

The main rivers and tributaries are listed in section 3 and shown in Figure 6.

The river network is used to define the spatial relationship of components that cause changes in water balance, and of the movement of water along the river system from headwater tributaries to the end of the river system. To simulate this movement of water, the valley has been broken up (discretised) into 32 modelling units (catchments and sub-catchments (sub-reaches)) (Figure 8).

Reaches are defined as discrete sections of the river with a flow gauge at the downstream end, and in many cases at the upstream end. These gauges must have good available observed streamflow data. Reach types are headwater reaches which do not receive inflows from upstream reaches; and mainstream reaches which receive flows from one or more upstream reaches.

4.1.1 Data sources

Locations of climate stations (Appendix B) and flow gauges (Appendix C), maps and a digital elevation model were available to delineate the valley at multiple scales for modelling.

Information on the river network is readily available from mapping maintained by NSW Spatial Services and digital modelling maintained by the NSW government. Much of this information was collated for earlier modelling of the Border Rivers (e.g. the now-replaced IQQM Border Rivers model).

4.1.2 Modelling approach

Data availability and design criteria of being able to report at multiple scales (property, reach and whole-of-valley) informed the number of discrete modelling areas needed.

Reaches for the Border rivers models are show in Figure 8. The downstream end of the headwater reaches are the inflow gauges listed in Appendix C . The mainstream reach upstream and downstream gauges are defined in Appendix J .

Models are developed for each reach representing each significant component of the water balance (see Figure 3) and then progressively linked to form the final aggregated catchment model.

The catchment areas and stream lengths were derived from direct measurement, using standard GIS routines.

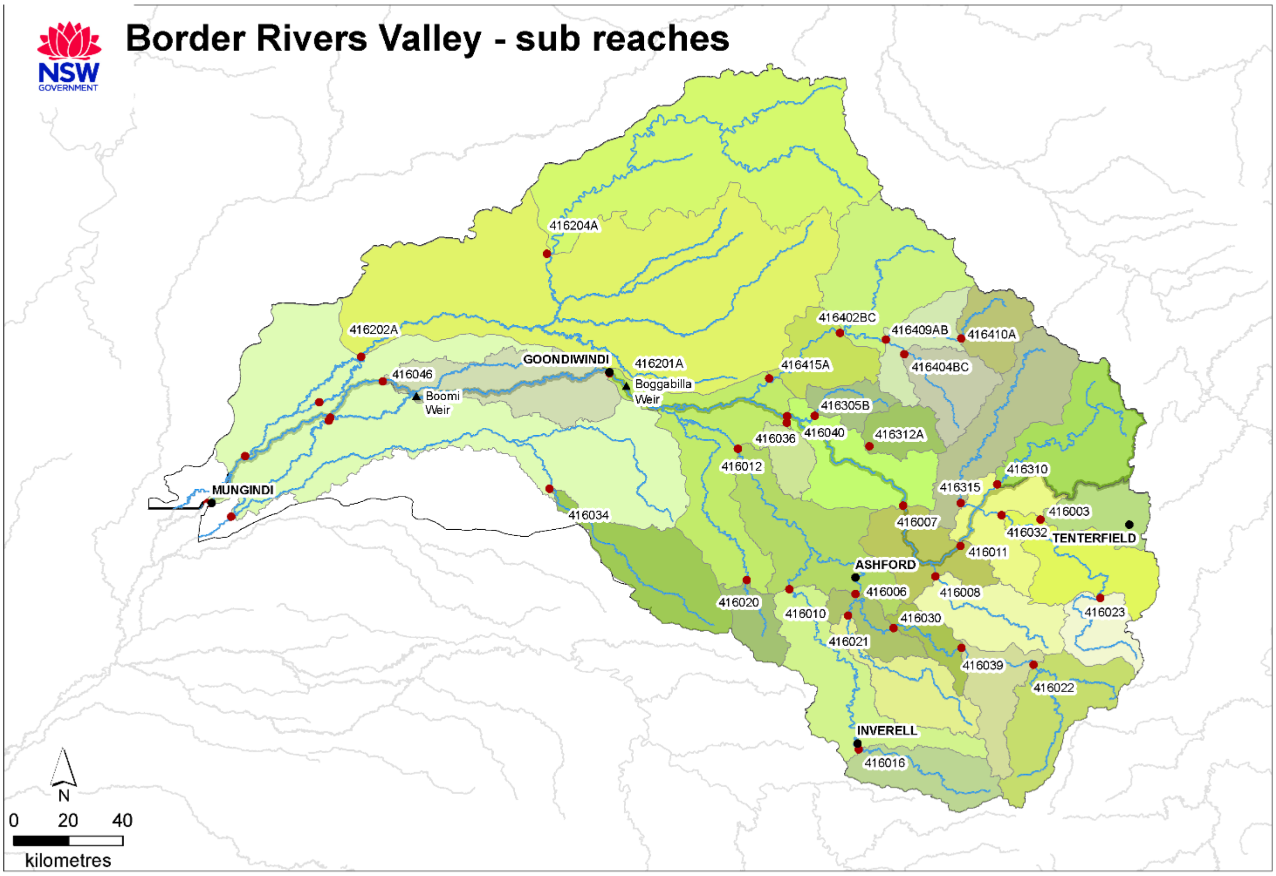

Figure 8 Map of modelling units of the Border Rivers Valley

4.2 Rainfall

Average annual rainfall across the Border Rivers Valley decreases from east to west, from over 1000 mm in the eastern ranges around the Great Dividing Range to around 500 mm in the west at Mungindi (Figure 9). The rainfall is strongly seasonal with the highest volumes during the summer months occurring through summer storm activity.

4.2.1 Data sources

Rainfall data are used extensively through the model, as input for rainfall–runoff modelled inflows, storage water balance, and crop water demands. Departmental guidelines recommend the use of the Qld Government's SILO patch point data[9]. These data are based on official Bureau of Meteorology datasets with well documented routines to infill missing data at stations. The SILO datasets extend back past the period required for our statutory reporting under the Basin Plan. We have also found point data more suitable for rainfall–runoff modelling.

We chose the rainfall stations for each reach based on their location, length and quality of the record. We also used correlation with observed reach inflows during flow calibration. The departmental guideline is to adopt the SILO infilling, however Qld prefer to generate their own infill where possible. Gaps in data were infilled using raw data from nearby stations as available, and otherwise using SILO Patched Point data, to create records that are complete over the full

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[9] These data are always referred to as SILO, which stands for Scientific Information for Land Owners. Available at https://www.longpaddock.qld.gov.au/silo/

modelling period. Any significant periods of infilled data were checked for introduction of bias in the data.

The rainfall stations used within the Source river system model are shown at Figure 9. In addition to these stations, a larger number of rainfall stations are used in rainfall–runoff modelling which is used to generate inflow time series data for the Source model. This modelling occurs separately to the Source river system model. A full list of rainfall stations including spatial coordinates and long-term annual average is included in Appendix B .

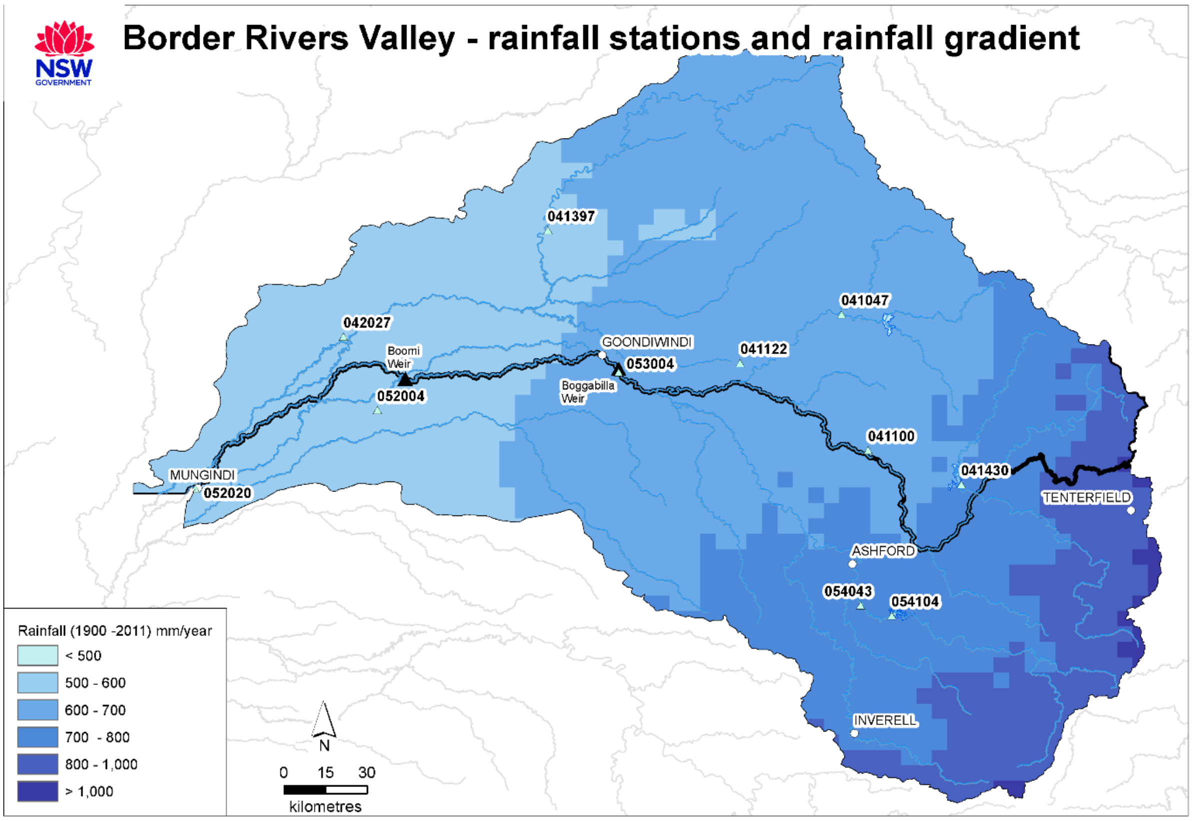

Figure 9 Map showing the rainfall gradient (1900 to 2011) across the Border Rivers Valley and location of rainfall stations used within the model

4.2.2 Modelling approach

Corresponding to stage 1 of the stages of model assembly (Table 2), rainfall data are used as an input to rainfall–runoff modelling, simulation of rainfall on storages and river surfaces and the modelling of irrigation demands.

We adopt the nearest suitable climate station in each part of the model. Sensitivity testing indicated that long term results for each irrigation property are relatively insensitive to choice of climate station, with less than 5% change in floodplain harvesting with change between the nearest two climate stations.

4.3 Evaporation

Annual evaporation has a strong east–west gradient across the valley (Figure 10), with average Class A pan evaporation exceeding the average rainfall across the entire valley. Annual evaporation is around 1200 mm in the eastern ranges and over 2000 mm in the far west of the catchment at Mungindi. Mean daily evaporation at Inverell ranges from 2 mm /day in winter to 6.5 mm/day in summer.

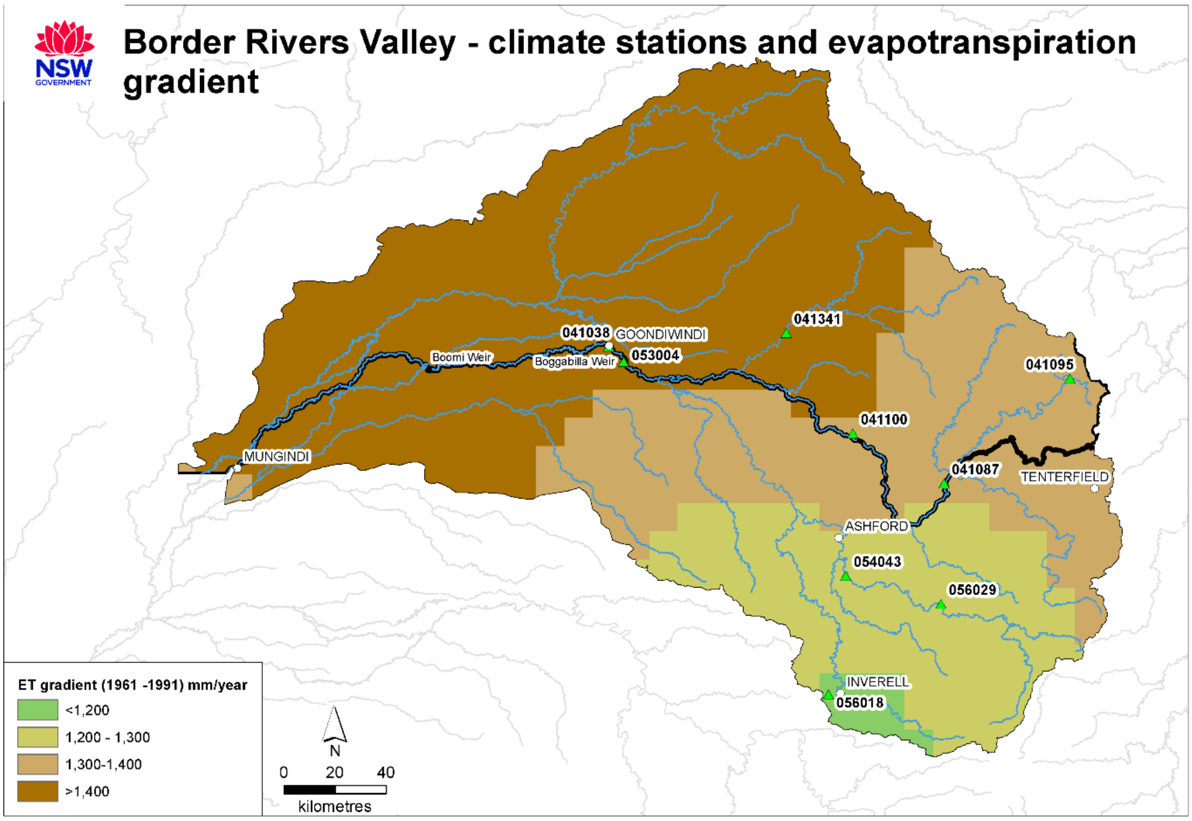

Figure 10 Map showing the evaporation gradient (1961 to 1990) across the Border Rivers Valley and the location of climate stations used for rainfall–runoff modelling

4.3.1 Data sources

Evaporation data are used as input for rainfall–runoff inflow models, storage water balance, simulation of stream losses, and estimating crop water demands.

Estimates of daily potential evapotranspiration were obtained from evaporation stations in and around the Border Rivers Valley from the SILO database which provides Morton's estimated potential evapotranspiration data. We used two forms of potential evapotranspiration:

- Morton's Wet evapotranspiration (MWet) data to estimate potential evapotranspiration for rainfall–runoff inflow modelling. MWet represents the potential evapotranspiration from a wet environment, such as catchment or soil moisture stores after rainfall. We smoothed the MWet data using a 7-day centred moving average to remove spurious daily variations.
- Morton's Lake evaporation (MLake) data to estimate evaporation from the surface of water bodies, including reaches and storages.

The evapotranspiration station locations used for the flow calibration components of the river system modelling are shown in Figure 10 and listed in Appendix B . Additional evapotranspiration data were used for crop modelling, using the SILO data for FAO56 method. These are the same as the climate stations shown in Figure 9.

4.3.2 Modelling approach

When choosing evaporation stations for rainfall–runoff modelling, stations with significant cloud okta records were preferentially chosen, as this is typically the limiting observational ingredient to the Morton's calculations. When choosing evaporation stations for all other purposes, nearby stations were preferred, as local effects may be important.

4.4 Streamflow

As with many northern NSW inland tributaries, the Border Rivers system experiences high flow variability in response to climate variability. A long-term modelled flow is shown graphically for the Macintyre River @Goondiwindi (Station 416201A, Figure 11) demonstrating this. This is a modelled (pre-development) flow, and is used here in preference to observed flow which, due to regulation, does not give an indication of natural flow variability. This data shows that while the annual average is around 900 GL/year, it is highly variable with extended low flow periods particularly in the period 1920 to 1948, and wet periods particularly in the 1950s and the 1970s.

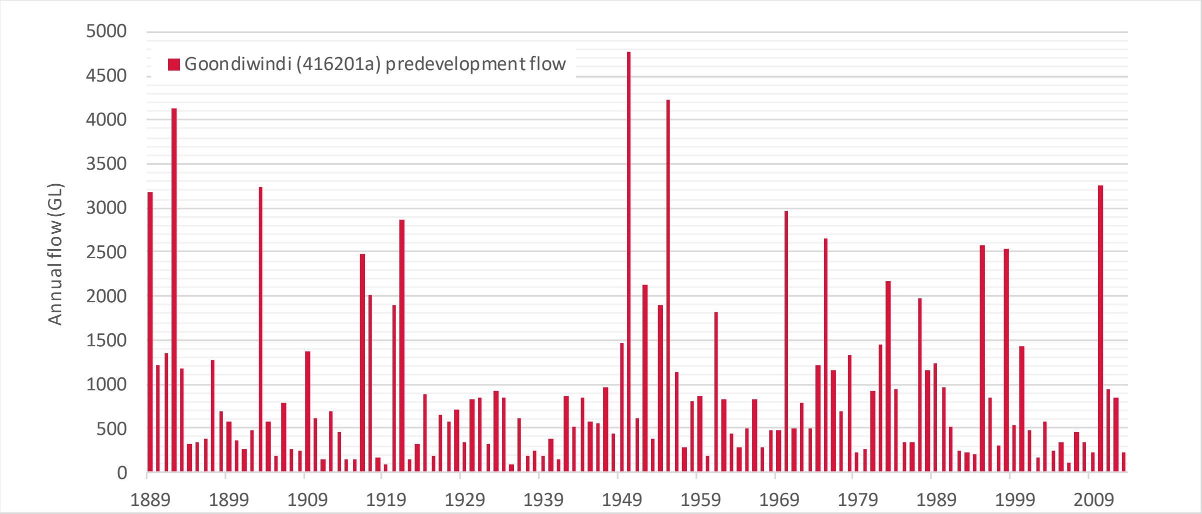

Figure 11 Modelled historical annual flow (GL) at Macintyre River @ Goondiwindi (416201A) for the period 1889 to 2013

As well as the annual flow variability, daily flow variability also matters. A large event in an otherwise low volume year can still provide significant runoff. The largest flood in terms of peak flow at most stations was recorded in the valley in February 1976, resulting from short but intense tropical cyclone rainfall event. The frequency and occurrence of such daily events plays a big part in floodplain harvesting behaviour.

4.4.1 Data sources

NSW and Qld maintain a network of river flow gauging stations across the Border Rivers Valley to support water management activities. Data for each station are archived in the Department’s Hydstra hydrometric database (Kisters Pty Ltd, 2010). These continuous flow records are the foundation of the river system modelling.

Flow gauging stations are operated and maintained by trained hydrographic staff who estimate flow based on established procedures and standards. Most flow gauging stations consist of a water level measurement device with a continuous data logger that continually records the output. These water levels are converted to flows using a height–flow relationship (known as a rating table) developed by hydrographic staff using flow gaugings over a period of time.

There are 51 flow gauging stations currently operating in the Border Rivers Valley (including storage level gauges, with a further 34 stations that have operated in the past and have some flow records. Storage level gauges can be used to estimate inflows to that storage using daily mass balance calculations of changes in volume, rainfall and evaporation, and known outflows.

The stations used to calibrate flow in the model are listed in Appendix C . Data from 20 stations were used to calibrate headwater inflows from 16 catchments that cover about 15,500 km^2 area, about 40% of the total Border Rivers Valley to Mungindi. A further 15 stations were used to calibrate reach flow at 14 sites. Location of these stations is illustrated at Figure 12.

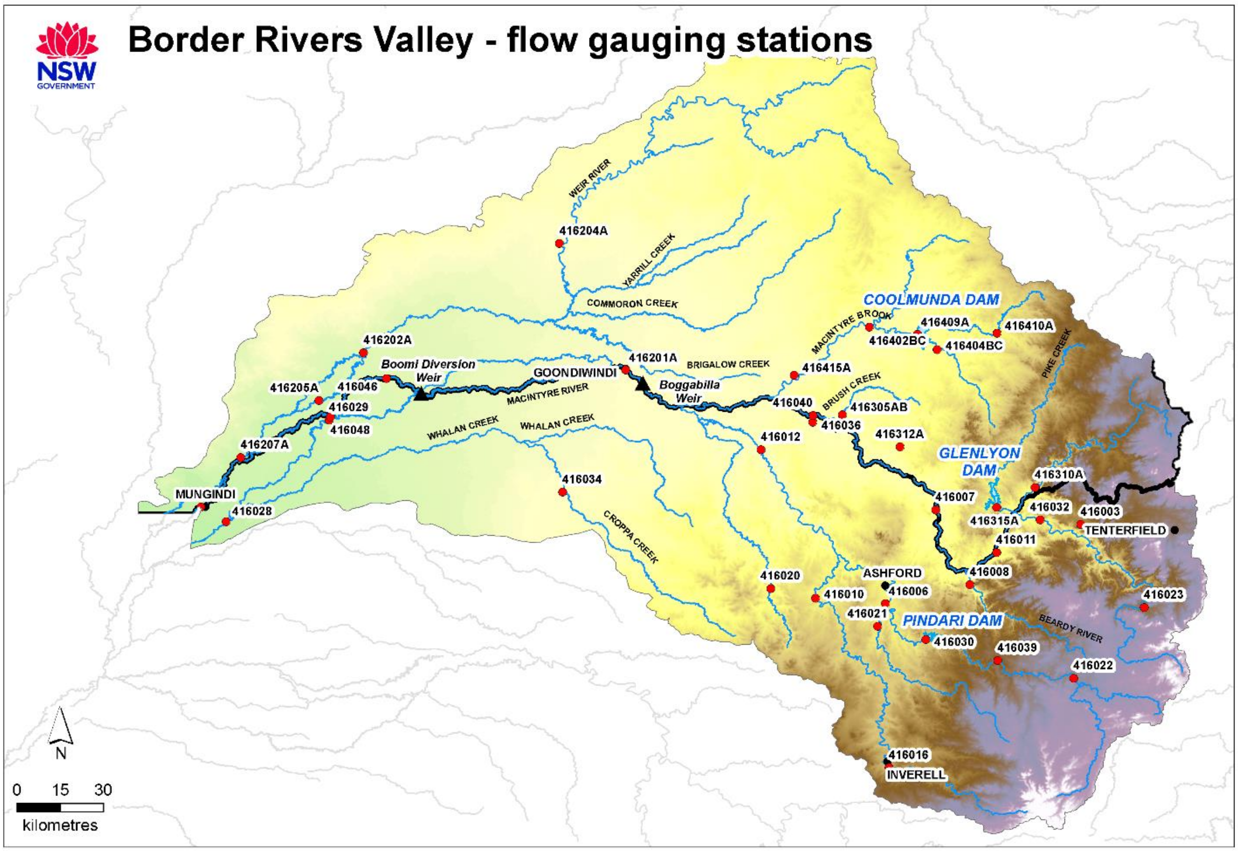

Figure 12 Map showing location of flow gauging stations in the Border Rivers Valley

4.4.2 Modelling approach

A summary of the parameters used for the tributary inflows and main river reaches flow calibration is described in Table 6.

Note that directly gauged inflows are for catchment areas where all the flow generated from that catchment has been recorded at a single point, for example the most upstream gauge on a tributary. Indirectly gauged inflows are from catchment areas where the flow generated needs to be estimated based on the difference between an upstream and a downstream gauge.

Table 6 Calibration approach for tributary inflows and main river flow

Step	Fixed input data	Target	Parameters
Tributary inflow	Rainfall Potential evapotranspiration Catchment area	Directly gauged catchment inflows	16 Sacramento model parameters describing soil storage components and flux rates

Step	Fixed input data	Target	Parameters
Main river flow	Rainfall Potential evapotranspiration Gauged flow at reach's upstream gauges and tributaries Metered diversions	Downstream gauged flow in river reach	Routing parameters Indirectly gauged catchment inflows Effluent relationships (including flood outbreaks) Instream losses

Directly gauged tributary inflows

Corresponding to stage 2 of the stages of model assembly (Table 2), inflows are estimated for the gauged headwater tributaries with significant catchment areas. The flow gauging station network does not cover all tributaries for the full simulation period. We use gauged flows directly as input wherever possible, and calibrated modelled inflows elsewhere.

Rainfall–runoff models simulate the conversion of rainfall into streamflow from a catchment (see Figure 13 for an example).

Use of these types of model enables us to take advantage of the more extensive rainfall records to fill gaps and extend the period of record for the tributary inflow gauges, and to explicitly represent sub-catchments that may not have a flow gauge on them. We use the Sacramento rainfall–runoff model for this purpose because we have found it performs well, and we have considerable experience and skills in obtaining good calibrations with this rainfall–runoff model.

A Sacramento rainfall–runoff model was built for every reach in the model (i.e. 32 models). Each Sacramento model was calibrated to reproduce the flows for the recorded period. For headwater reaches the calibration target was the recorded flow at the gauge or a derived storage inflow sequence.

Calibration

We calibrated the Sacramento model firstly by setting it up with the local climate station data and catchment areas as input, and then applying an automated calibration process using software developed by the Qld Government.

Rainfall can be quite spatially variable, and a single rain gauge may not be representative of the rainfall received across a catchment area. This can be an important issue for rainfall–runoff modelling, and rainfall at individual stations in a catchment are weighted initially based on how representative they are of rainfall across the catchment.

This calibration systematically adjusts model parameters to get the best overall match of modelled flows with recorded flows for the period of flow record. This method aims to match certain statistical characteristics of the flow record, including matches of daily values, flow distributions, and overall volume.

The optimised parameter set is checked by manually comparing the modelled and observed flows over the full flow range using time series flow plots at daily, monthly and annual time steps, flow-duration curves, cumulative mass and residual mass curves. Summary statistics, including statistics associated with daily flows and peak flow discharges, are produced and checked. Report cards are produced which summarise the comparison between modelled and observed flow sequences. These results can be found in Appendix K .

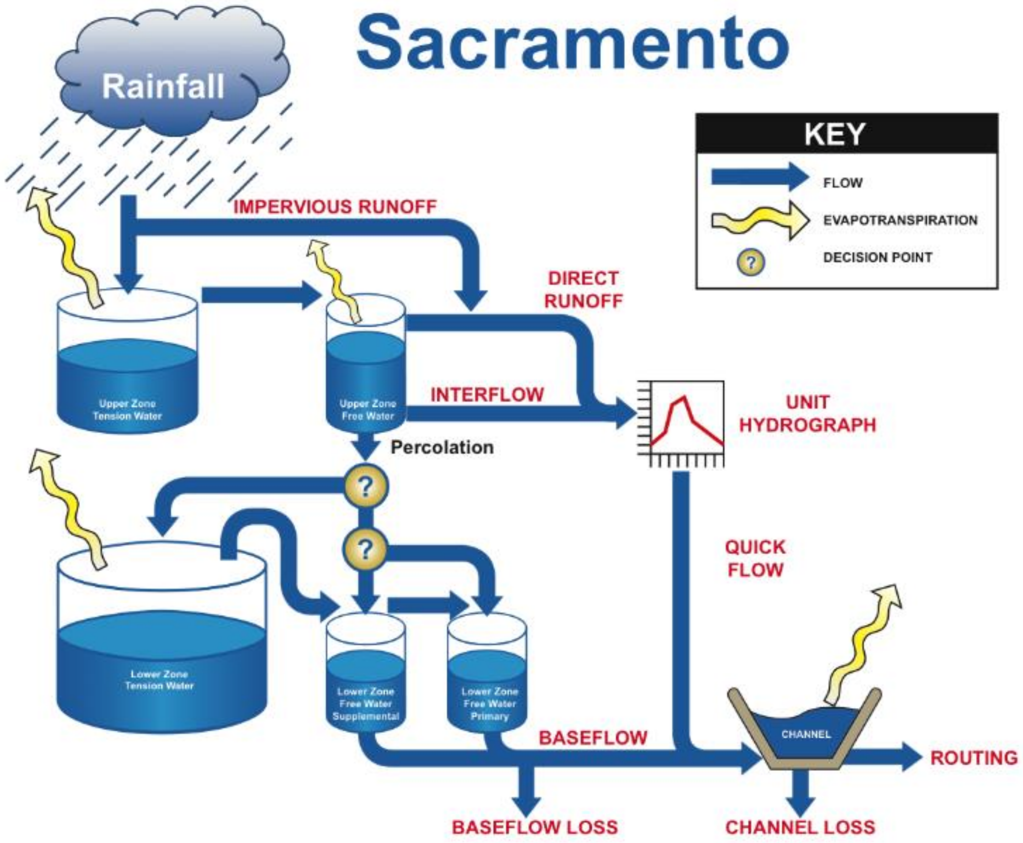

Figure 13 Conceptual diagram of the Sacramento rainfall–runoff model [Source: eWater, 2016]

Indirectly gauged inflows and regulated river system flows

Estimation of indirectly gauged inflows is stage 3 of the stages of model assembly (Table 2). This step is undertaken iteratively with estimating transmission losses.

Once headwater inflows enter the regulated river network, either from tributaries or as releases from the major storages, the model must route the flows down the river network. Flow routing simulates the time taken for water to move through the river, and the change in the shape of the hydrograph because of channel and floodplain storage effects.

The model must also simulate the river transmission losses and the indirectly gauged catchment inflows. These processes are configured in the model using a structured series of steps at a reach scale, considering the components shown in Figure 3.

Sacramento rainfall–runoff models were also set up and calibrated to represent the residual inflows for each river reach to infill and extend the observed inflow sequences to cover the full period of model simulation. Flow was calibrated at the downstream gauge in a structured series of actions, in the process estimating routing parameters, ungauged tributary inflows, transmission losses, net evaporative losses, and in some cases breakout relationships:

1. Use recorded inflows at the upstream gauge and any gauged inflow tributaries as inputs to the model, as well as any known outflows such as metered diversions
2. Systemically adjust routing parameters to reproduce key characteristic of timing and shape of hydrographs at the downstream gauge
3. Estimate net evaporation from the river by inputting climate data and defining a flow v surface area relationship

4. Estimate transmission and other unaccounted losses based on flow rate with an emphasis on drier periods where residual inflows are not significant
5. Calculate initial water balance difference between simulated flow and observed flow at downstream gauge as first estimate of indirectly gauged catchment inflows, with an emphasis on wetter periods
6. Calibrate Sacramento model to a smoothed time series of the water balance difference. An alternative approach was also tested where the Sacramento model was tested as part of a full reach simulation; in this case the calibration target is the downstream flow, rather than the water balance difference. The two methods were compared, and best performing method chosen.
7. Revise the loss estimate in Step 4.

As a final step, we link all the individual calibrated river reach models to the full flow network, run the full model and check that this has not significantly changed simulated flows at all gauges.

4.5 Effluents, breakouts and floodplains

Several effluent rivers/streams leave the main Macintyre River, sometimes with other smaller rivers and streams joining them at various points. The main effluent systems – the Boomi River and the Qld effluent river systems and the Weir River – both re-join the main river channel further downstream.

Boomi River effluent

The Boomi River is a natural stream from the lower Macintyre River on the NSW side. With the exception of high flow events, flows into the Boomi River are controlled by a dropboard regulator constructed across it adjacent to the Macintyre River.

The nearby Boomi Weir constructed across the main Macintyre River creates a deep pool of water that helps divert water into the Boomi River. The Boomi River is joined downstream by the ephemeral Whalan Creek before re-joining the Barwon River below Mungindi.

While there are no regulated licensed water users along the Boomi River, regulated water is released by WaterNSW to replenish water for stock and domestic supply for landholders along the Boomi River. These releases are known as replenishment flows.

Qld effluent systems and the Weir River

There are several effluent offtakes on the Qld side of the Macintyre River. These include:

- Newinga Creek
- Callandoon Creek
- Dingo Creek (an ephemeral creek).

These effluent offtakes join together and flow into the Weir River in Qld, which then re-enters the Macintyre River near the lower end of the regulated river system.

Other than the Newinga Creek offtake, these effluent streams generally only receive water during higher flows. The Newinga offtake has a dropboard regulator to contain regulated flows within the regulated Macintyre River.

Breakouts and floodplain areas

As the water level rises from within the channel, the most common points through which inundation initially occurs are low areas where the stream can spill over onto its floodplain. These flow breakouts can extend across many properties, sometimes flowing along indistinct flow paths that can inundate large areas of the floodplain. Some breakout flow paths only get water flowing in very high flows, and others happen more frequently. Local rainfall–runoff can also contribute to flow in this region.

Breakouts include NSW and Qld floodplains, Whalan Creek (NSW), Callandoon Creek (Qld), Dingo Creek (Qld), Coomonga Creek (Qld), Boomi River (NSW), Weir River (Qld), Little Barwon Creek (NSW), and Boomangera Creek (NSW). A map of key breakout locations and breakout paths is presented in Figure 14, noting that how and when they 'break out' depends on river levels.

4.5.1 Data sources

Some of the major effluent offtakes have flow gauges and follow well-defined channels.

A number of significant effluents were defined in previous IQQM modelling on the basis of operator advice and gauged flows. These relationships were also adopted, with some refinement where additional flow gauging allowed. These are noted in Appendix D .

High flow breakouts are well-known locally by river operators, State Emergency Service personnel, and landholders. However, there is no direct measurement of flow rates. We used a combination of local knowledge (e.g. operators, hydrographers, local emergency services, and landholders), remote sensing and flow gauges to assist in representing where the breakouts occur, and the main channel flow rate at which breakouts commence.

In reality overland flow paths are very complex. Where appropriate, simplifications were made by amalgamating some flow paths and connections. Generally, two or more flow paths were amalgamated where they:

- flow in the same direction
- have significant connections along the length of the flow paths
- do not appear to be accessed by floodplain harvesters, or
- they do not carry a significant volume of water.

The flow paths for these breakouts, and the properties that have access to them, have been identified using multiple sources, including satellite imagery, modelling of floodplain flows, and information from the farm surveys. Figure 14 shows the identified breakouts in the models overlaid on overland flow paths derived from results of the TUFLOW model which was developed for the (draft) Floodplain Management Plan for the Border Rivers Valley Floodplain 2018. Further information on these breakouts is given in Appendix D .

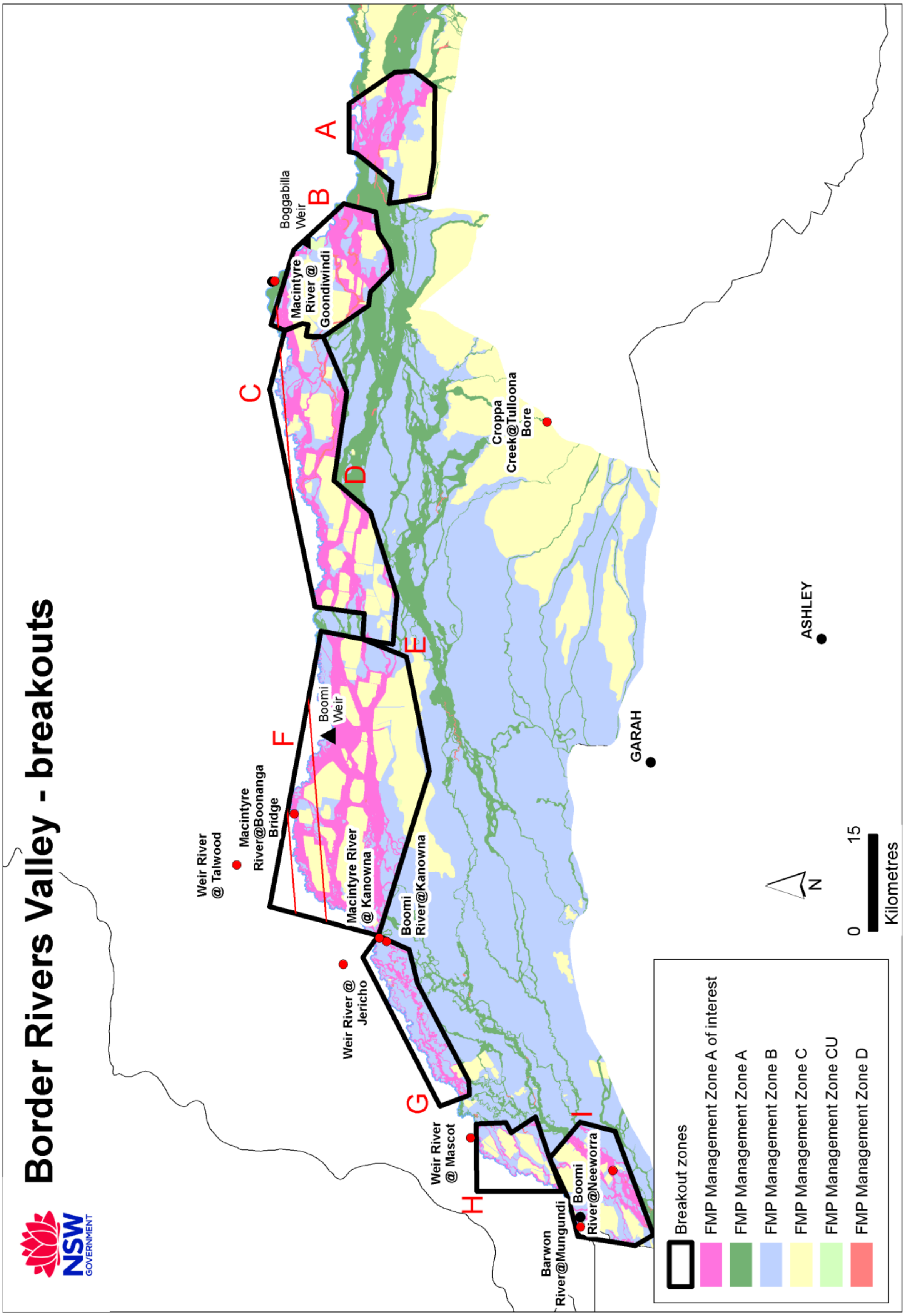

Figure 14 Floodplain Management Plan (FMP) zones and key breakout locations in the Border Rivers Valley; A Boonal, B Boggabilla, C Goondiwindi, D Whalan, E Tarpaulin (Croppa/Whalan), F Terrewah, G Boomangera, H Yarrowee, I Boomi/Whalan

The rate at which flow enters the breakouts was derived using:

1. cross-section and rating information at flow gauges
2. Healthy Floodplain Irrigator Behaviour Questionnaires (farm surveys)
3. Bureau of Meteorology flood warning levels
4. Landsat data to compare historical flood extent along reaches to recorded flows
5. a regional hydraulic TUFLOW model developed for the Floodplain Management Plan
6. water balance methods by comparing upstream and downstream flow rates (described in section 4.4.2).

The breakout relationships from these information sources were reviewed by assessing the frequency of harvesting compared to survey data where available. Where a consistent bias between simulated and observed reach water balance components was detected, the breakout relationships were reviewed.

Detailed TUFLOW modelling information was not available until after the Border Rivers Valley river system model was developed. As a consequence, rather than use the TUFLOW results to inform the initial model development, they were used to verify previous estimates and adjust them where required. Further detail is in Appendix D .

The breakout zone, or area of interest, was then further refined by using ArcGIS (10.3.1) to select environmental assets and values for the environmental outcomes analyses. This process is described in the companion Environmental Outcomes report (DPIE Water 2020b).

4.5.2 Modelling approach

We use a relationship between river flow and breakout flow to represent each effluent or floodplain breakout; these are implemented using the *Regulated Splitter Node* in Source. This node type can be used to represent both unregulated flows and channels with regulators. Further information on how we represent regulation is in section 7.6.

The breakout relationships are an estimate using the available gauged data on the river and effluents.[10]

The locations and flow conditions for breakouts in the model provide the water for properties to access floodplain harvesting (see Figure 14). The Border Rivers Source model includes 8 high flow breakouts that were configured in the previous Border Rivers IQQM, and 9 additional high flow breakouts. The flow rates at which they breakout from the main channel were determined from a range of sources (as described in section 4.5.1 Data Sources above). Where these were determined from flow calibration is indicated in Appendix D . Previous modelling treated flow onto the floodplain as a loss to the system. This Source model represents floodplain breakouts explicitly, i.e. as an effluent. This means that the remaining loss node has smaller losses, which better reflects within channel losses[11].

Once flow has broken out of the river the routing, loss and extraction of flows can be simulated. For the main effluents, this is estimated as part of the flow calibration using gauged flow data

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[10] Should further data analysis suggest that a change is required, then other parts of the model will most likely also need to be changed to ensure that the downstream flow calibration is still acceptable. For example, if flow down Dingo Creek were found to be greater than modelled, then adjustments to other loss relationships would be required to match flow at Terrewah.

[11] The remaining loss relationships can also be compensating for measurement errors so should be interpreted as unaccounted change in flow rather than literally the within channel losses

either on the effluent or downstream of where they return to the main river. For floodplain breakouts, we adopt a very simple approach to represent water moving across the floodplain. We use a storage node to represent temporary storage of flows on the floodplain and losses. This is described further in section 6.2.2.

The model includes returns from effluents to the main river. The extent to which water returns from floodplains to the main river is not sufficiently understood and has only been partially represented in the model. This is further discussed in section 6.2.2 and also in the recommendations for future work.

We do not explicitly represent inundation of floodplain assets. The impact of floodplain harvesting on these areas has been estimate using the nearest breakout flow relationship and the simulated floodplain harvesting in that part of the model. This is described further in the companion Environmental Outcomes report (DPIE Water 2020b).

4.6 Regulating infrastructure – dams and re-regulating storages

Flows in the Border Rivers are regulated by three major public storages – Glenlyon Dam on Pike Creek (Qld), Coolmunda Dam on Macintyre Brook (Qld), and Pindari Dam on the Severn River (NSW) (see Figure 6 for locations). Basic details of these storages are summarised in Table 7.

Table 7 Major headwater storages in the Border Rivers Valley

Storage	River	Commissioned	Capacity (GL)	States supplied
Glenlyon Dam	Pike Creek	1976	254	NSW & Qld
Coolmunda Dam	Macintyre Brook	1968	69	Qld
Pindari Dam	Severn River	1995[12]	312	NSW

These storages were constructed primarily to store and release water to downstream licensed water users (including for environmental flows) and have ungated spillways that cannot actively manage spills during major floods. However, these storages still provide passive flood mitigation as they take time to fill and discharge over spillways.

There are several smaller weirs within the regulated Border Rivers river system. Boggabilla Weir is a gated weir commissioned in 1991 on the Macintyre River near the NSW township of Boggabilla, approximately 9 km upstream of Goondiwindi. The weir has a storage capacity of 5850 ML and re-regulates releases from Pindari Dam and Glenlyon Dam and conserves unregulated tributary inflows.

Other water management infrastructure in the regulated Border Rivers river system include:

- three fixed crest weirs along the system upstream of Boggabilla Weir
- two fixed crest weirs across the Macintyre River downstream of Boggabilla Weir, at Goondiwindi and Mungindi
- the Boomi Weir across the Macintyre River (see section 4.4)
- a dropboard regulator at the Newinga breakout.

4.6.1 Data sources

Major water management infrastructure such as dams, weirs, and regulators are maintained and operated by state owned corporations, WaterNSW in NSW and SunWater in Qld. WaterNSW manages releases of water from the major storages to meet environmental and licensed water user requirements, and SunWater operates and maintains the regulating infrastructure, including keeping records of key parameters such as the storage capacity, volume-surface area relationships, and maximum release rates at each structure.

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[12] Pindari Dam was originally commissioned in 1969 with a capacity of about 40 GL. The work to enlarge it to 312 GL capacity was completed in 1995.

4.6.2 Modelling approach

Major dams

The three major water storages were configured based on the relevant engineering parameters provided by SunWater. Capacities are listed in Table 7 and storage curves are provided in Appendix E .

The Source storage node in the model simulates a range of physical processes at the storage, including the effect of rainfall and evaporation on storage volumes, and seepage. It also includes simulation of key management actions, including releases of water to meet downstream demands and other operating rules.

Re-regulating storages

Boggabilla Weir was configured as a re-regulatory weir that captures surplus flows and releases water to meet downstream demands (see Table 34 in section 7.6 Storage and weir operation for more details). In the model, it is configured as a Source storage node. The model simulates the key operational features; a storage volume at the weir, and operation rules such as target range and capture and release of unregulated inflows.

The smaller fixed crest weirs do not have significant volumes of water in storage and releases from them are not controllable by the river operator and are not configured in the model. To the extent that these weirs will affect flow travel times and river transmission losses, the calibration of river flows for that reach implicitly includes these effects with the overall flow travel time and losses for that river reach. Regulation of the effluent flow is represented at Boomi Weir and for the Qld effluent systems. Further information on this, and on all parameters related to operation of storages and weirs, can be found in section 7.6 Storage and weir operation.

5 Modelling water sources and licensing

Water can only be taken from rivers and streams in NSW under a licence or a right. Water sources as listed in the NSW Border Rivers WSP are:

- regulated water source
- supplementary water source
- floodplain harvesting water source
- unregulated water source
- groundwater source.

5.1 Water licences

The main licence types to access surface water sources are listed in Table 8. Some water can be taken without the need for a licence under basic landholder rights as described in the *Water Management Act 2000* and the NSW Border Rivers WSP.

Table 8 Surface water access licence types in the NSW Border Rivers

Licence type (NSW)	Licence type (Qld)	Note
High security	High priority allocations	Includes local water utilities, horticulture, permanent plantings, stock and domestic
General security Class A	Medium priority allocations	Supplemented water
General security Class B	Medium priority allocations	
Supplementary water access	Unsupplemented allocations	Water not reliant on infrastructure for storage or distribution Referred to as off allocation in Source
Unregulated river	Unsupplemented allocations	These are defined through supply point nodes in Source and named as unreg in NSW and WH for water harvesting in Qld

Higher security (water utilities, stock and domestic) licence categories receive full allocations of water each year except in extreme drought conditions.

There are a small number of high priority licences issued to towns (local water utility licences), and high-security water access licences for some agricultural purposes, such as horticulture or permanent plantings (e.g. orchards or vineyards). The majority of irrigators hold general security water access licences, larger volumes of water designed to support irrigation of annual crops such as cotton and winter cereals. Water allocation varies from year to year with the prevailing climatic conditions and the resulting inflows to the regulated river system.

NSW issues water access licences with volumetric share components and an associated water account. When water is assessed as becoming available in the regulated river system, typically following inflows, the department makes an allocation announcement (as a percentage of each share component) for each licence category that indicates how much individual water licences receive. This water is credited to each licence's water account for subsequent ordering and extraction from the river. Water access licences must be linked to a works approval to take water from a river. The works approval describes the type of authorised works at a particular location (e.g. pumps or a gated regulator and associated channel) and any conditions on the use of those works.

Under the *NSW Water Management Act 2000*, extraction of water for basic stock and domestic rights from a property with river frontage (basic landholder rights), and for native title rights, does not require a water access licence. There are currently no extractions for native title rights in NSW.

5.1.1 Data sources

Licences in NSW are issued by the department who maintains a database of all surface and groundwater access licences and works approvals. This database, known as the Water Licensing System (WLS) is linked to the formal public register of licences maintained by NSW Land Property Information.

All information used in our models regarding the category and number of water access licences, the shares they hold, the works (pumps, etc) they are attached to, and the location of those works are taken from the WLS. For some scenarios that are historical (e.g. cap on diversions which requires some 1993/94 data), prior records within the department are used. The total number of share components issued for each licence category is shown in Table 9.

Table 9 Share components in the NSW Border Rivers regulated river system (as at 30 June 2019)

Category	Consumptive	Environmental water	Total
Domestic and stock	1,001	0	1,001
Local water utility	640	0	640
Regulated river (high security)	1,500	0	1,500
Regulated river (general security A class)	22,007	0	22,007
Regulated river (general security B class)	238,405	2,806	241,211
Supplementary water access	118,564	1,437	120,001
Total	382,117	4,243	386,360

No information is available on water use under basic landholder rights, other than the estimate in Part 4 in the NSW Border Rivers WSP.

5.1.2 Modelling approach

Licences are configured for all of the individual water user nodes in the model representing each irrigation property, and all groups of properties. Representation of licences in the model has been simplified to represent the main licence categories; high security, general security A and B and also supplementary access licences.

For the purposes of model calibration, the volume of entitlements for Qld licence categories is based on the moratorium level of development as per the IGA and the (Qld) Border Rivers Resource Operations Plan 2008. For the purposes of water resource plan scenario modelling, the scenario is based solely on the (Qld) Border Rivers Water Resource Operations Plan.

Water use under basic landholder rights is not explicitly included in the model but are implicitly accounted for in the calibration of flow loss relationships.

5.2 Regulated water

Regulated water is that water made available through the resource assessment process (section 7.2) to supply the various access categories. Water can be ordered from the river operator (WaterNSW), up to the limit of the water in each licence's account. During wet periods, river operators may make use of tributary inflows downstream of the major dams to deliver these water orders. During very dry periods, the river operator may defer delivery of individual water orders until there is a large enough volume, and release water during a specific period (known as a block release) to reduce transmission losses. Water meters measure the take of water by the majority of regulated water.

5.2.1 Data sources

Water users in major regulated river systems measure water use via flow meters installed and maintained at pump sites for all significant sources of surface water, with the exception of floodplain harvesting and unregulated diversions. Very small water users are not currently required to order water or measure their diversions. WaterNSW and SunWater each maintain a database of water orders and use (in NSW this is the Water Accounting System – WAS) and arrange for meters to be read at varying intervals. Larger water users may have meter readings undertaken monthly or quarterly, whereas smaller water users have meter readings undertaken less frequently.

When the Border Rivers Source model was initially developed, these records were available for the reaches below Glenlyon Dam and Pindari Dam from 01/01/1985 to 30/06/2014. Operational data collected and used for daily management of releases from the major storages, such as flows and water use (e.g. meter readings communicated to the river operator by irrigators), are available from the river operator (WaterNSW) and can be used where data are unavailable from the WAS.

Accuracy of meter readings varies depending on the type of meter, and the nature of the installation. Meter manufacturers have layout requirements (usually the length of straight pipe either side of the meter) for meters to operate accurately. Each state also periodically undertakes verification tests on meters to ensure they are being maintained in reasonable condition and are operating correctly. Testing in the NSW Border Rivers has been limited in the last 10 years. Over time, propeller type meters have been progressively replaced with more accurate electro-magnetic or ultrasonic meters. The national standard for non-urban water measurement is intended to ensure measurement errors are within 5% of the volume diverted. NSW now requires meters and installations to meet these standards, with a phase-in period up to 2020.

Recorded water usage at monthly time steps or longer needs to be disaggregated to a daily time step for use in the model for simulating water use and estimate water losses.

Records for the period 1985–1996 were previously disaggregated for the Border Rivers IQQM build and have been re-used for the current work. Records for 1997–2014 were disaggregated to daily time steps as follows:

- for Qld, quarterly data were disaggregated to daily time steps based on flow at a downstream gauge and an appropriate flow threshold
- for NSW, the data from 1997 to mid-2009 were disaggregated using a similar method as Qld. The availability of water order data from mid-2009 to 2014 meant that diversions from this time were disaggregated using this information.

The total metered diversions over the period used to calibrate water use in the model are shown in Figure 15. The available diversion data does not adequately account for water use associated with temporary trade with Qld. This is a quality issue that the department are examining to improve data records for future model refinements.

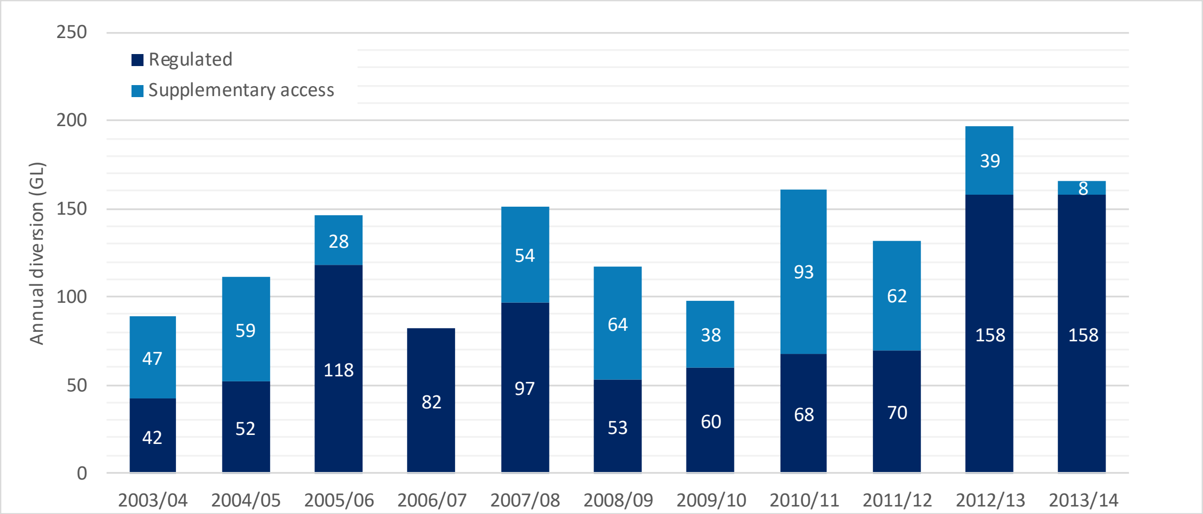

Figure 15 Total metered diversions in the NSW Border Rivers Valley

5.2.2 Modelling approach

The supply of regulated water involves the sharing of water between the states, the allocation of water to licences, together with the ordering and delivering water in the regulated river system. Water orders are generated by the simulation of irrigation demands. The simulation of water sharing, the allocation of water, and the delivery of water by river operators using water management infrastructure are described in section 7 Modelling water management rules.

5.3 Supplementary water

When there are rainfall events resulting in significant inflows from tributary streams downstream of headwater storages, or spills from major storages, river flows may exceed requirements for water orders.

These excess flows are referred to as uncontrolled flows. When these flows become large and exceed the agreed triggers in the *IGA*, the Dumaresq-Barwon Border Rivers Commission (BRC) announce water available for supplementary water access in NSW and unsupplemented diversions in Qld. The *IGA* gives the two states equal access to this volume. Further information on these rules can be found in section 7.5.

In NSW, supplementary water access licences allow water to be taken during these flows up to the limit of the water in each licence's account. Qld has also issued similar licences called unsupplemented water licences. Water meters measure the take of water by the majority of supplementary water access licences.

The river operator usually manages access unless the event is sufficiently large that there is more than enough flow for all of the supplementary access licence holders. Within the NSW Border Rivers, supplementary water access is a significant source of water supply for irrigators.

5.3.1 Data sources

Supplementary access periods announced by the BRC are recorded in each state's water use database. Diversions during these periods are measured from meter readings using the same meters as for regulated water use and is recorded in WAS as a total volume for that event, or a set period of time (e.g. monthly). As with regulated diversions, where possible recorded supplementary diversions are disaggregated based on flow, announced supplementary access periods and pump capacity.

5.3.2 Modelling approach

Access to water from the river is permitted for supplementary water access licences in NSW (and the equivalent in Qld) when flows are more than required for regulated water in the river, and exceed the thresholds set in the 2008 *IGA*. There are different rules for various parts of the river system, and we have reflected these as detailed in Table 10.

For NSW water users, the supplementary access licence accounts for each water user node are configured so that water access is shared based on the number of share components for that licence relative to the other licences in that river reach. Qld water user nodes have been configured so that water access is shared according to pump capacity in each river reach.

The simulation of supplementary water access is summarised in Table 10 with licence flow thresholds listed in Table 11.

Table 10 Simulation of the components of supplementary water access

Component	Modelling method
Sharing between states	Ownership rules are 50:50 for off allocation; 57:43 otherwise During uncontrolled flow events, flow above regulated requirements is redefined as 50:50 share by using the feature 'reset ownership' at gauge nodes
Uncontrolled flow reach definition	5 reaches are modelled: • Pindari to Macintyre-Dumaresq confluence. There are actually 2 reaches however the reach from Pindari Dam to Ashford is ignored as all irrigation in this area is combined with the downstream reach. For direct use on crops only. • Glenlyon to Macintyre-Dumaresq confluence. For direct use on crops only. • Macintyre-Dumaresq confluence to Goondiwindi. Rules are the same as the downstream reach from Goondiwindi. • Goondiwindi to Newinga 2 • Newinga 2 to end of system
Reserves for downstream	A 25% reserve was defined for each uncontrolled flow reach as per IGA rules for the two reaches from the Macintyre-Dumaresq confluence to Newinga 2
Thresholds	Event starts if: Flow > 'threshold volume' + Orders Event ends if: Flow < 'threshold volume' + Orders Threshold volumes are based on NSW Border Rivers WSP rules as summarised in Table 11 For the lower reaches, the threshold volume and orders are assessed as two separate steps rather than jointly: this achieved an acceptable frequency / calibration result so was not adjusted Supplementary water access is not declared in the reach from the confluence to Newinga if Pindari is spilling more than 1000 ML/day to reduce over-simulation of supplementary access. It is assumed that during large flood events most irrigators would plan to fill storages with floodplain harvesting instead. We also use Execution Order Rules in Source so that the model takes floodplain harvesting prior to other forms of available water.
Cap on usage	NSW: 1 ML/share usage limit is defined on a reach basis ('Annual usage limit'). Qld: the calibration model did not include any caps. These have been added to subsequent Qld water resource plan scenarios.

Table 11 Supplementary water access licence flow thresholds

Reach: reference gauge	Start flow trigger (ML/day)	End flow trigger (ML/day)
Pindari to confluence: Holdfast	1,000 (summer) 150 (winter)	250 (summer) 50 (winter)
Glenlyon to confluence: Glenarbon	750 (summer) 150 (winter)	250 (summer) 50 (winter)
Confluence to end of system: Goondiwindi	2-day period: 10,000 ML	2-day period: 3,650 ML

The IGA and the NSW Border Rivers WSP state additional triggers for events originating from inflows downstream of Goondiwindi (e.g. from the Weir). The model includes an approximate representation of these rules.

5.4 Floodplain harvesting water

In addition to the regulated and supplementary licence categories described above, many irrigation properties can harvest water flowing across the floodplain that has either broken out from the main river (overbank flow) through breakouts, or which is the result of rainfall–runoff.

Floodplain harvesting is inclusive of both overbank flow harvesting (water from breakouts) and rainfall–runoff harvesting from local areas and within the properties. Floodplain harvesting has not been directly measured to date; individual irrigation property studies and other anecdotal evidence indicate that irrigators can and do take significant volumes of water in this way.

The regulation of harvesting of overland flows is being implemented through the issuing of Floodplain Harvesting Licences. These licences limit the amount of water that water users can take from the floodplain either as the result of overbank flows or rainfall–runoff that enters or is generated upon the licence holder's property.

Figure 14 shows the area potentially covered by overland flow from breakout locations. Major irrigation properties are shown in Figure 7.

5.4.1 Data sources

Overbank flow

Water harvested from overbank flow is not as yet officially recorded. A small number of respondents for the farm survey included estimated overland flow harvesting volumes. Many properties indicated the timing of the overland flow harvesting events, while few provided estimates of volumes harvested. This part of the farm survey data was treated only as indicative.

Due to the absence of recorded data, we undertook a multiple lines of evidence approach to assessing floodplain harvesting. We used a capability assessment to consider the physical infrastructure used for floodplain harvesting and also the opportunity irrigators may have to access floodplain flows based on their location and climatic variability. We also used a water balance assessment given historical crops grown and the estimated water requirements. This assessment focuses on the reach and valley scale to ensure that the total volume of water including historical metered use and estimated floodplain harvesting is representative of the estimated historical crop water use.

Runoff harvesting

The farm survey requested information on rainfall–runoff harvested from within properties. Harvesting occurs from areas developed for irrigation as well as other non-developed areas within the property. The non-developed areas within farm which were reported as contributing to rainfall–runoff harvesting were smaller; around 55% of the developed area. In some instances there is the ability to directly intercept runoff from local areas outside of the farm; in some cases this is accounted for through the overbank flow harvesting estimated and in other cases it is represented as rainfall harvesting by adding additional area to the undeveloped area model.

Six properties provided estimates of runoff volumes harvested which ranged from 0–20% for the same annual rainfall, with an average of 9%. These estimates were analysed to estimate what percent of annual rainfall these volumes represented: however, no positive trend with increasing rainfall was discerned. There was uncertainty in these estimates as to what area of land this runoff was from, and whether these separated out rainfall–runoff from outside of the property. To improve our confidence in runoff rates, alternate lines of evidence were considered as detailed in Appendix F . Further data collection is required to confirm the runoff patterns and volumes under different cropping conditions.

5.4.2 Modelling approach

Overbank flow harvesting

The water available for floodplain harvesting for NSW water users is simulated through the breakouts (as described in section 4.5). The extraction of this water is simulated through supply point nodes; these use the overbank pump capacity to represent the floodplain harvesting capacity. This capacity, or intake rate, was generally set to the total capacity of on-farm storage pumps for the property. This data was obtained from NRAR as part of the licensing process. Where there is eligible harvesting of localised rainfall–runoff, this is either added to the overbank flow or the rainfall–runoff modelling within the property. Further information is in section 6.2.2.

Qld overland flow diversions are modelled through supply point nodes on the main river, with access conditions tied to flow rates as per the previous IQQM.

Runoff harvesting

The upgraded models for floodplain harvesting use the best available information on rainfall–runoff, and account for differences in runoff rates between undeveloped, developed and irrigated areas. A separate rainfall–runoff model embedded in the crop water model is included for each property, continuously tracking the soil moisture of undeveloped, developed and irrigated areas. This enables the calculation of different rates of runoff from these areas based on soil moisture and rainfall. We calibrated these property area models to produce a long-term average rate consistent with available data as outlined in section 6.2.2. Rainfall–runoff harvesting generally refers to harvesting within the property; in a few instances eligible access to localised runoff from outside of the property has been incorporated into the property area model and reported as part of the rainfall–runoff harvesting result.

5.5 Unregulated water

NSW has issued licences on rivers and streams that are not regulated by major infrastructure. These typically allow access when flows at a nearby river flow gauging station reach certain levels, but does not guarantee that flows will be available at any time.

A small number of irrigators that access regulated water also have water access licences on a nearby unregulated watercourse. Most of the unregulated licences for water access on unregulated rivers and streams are either upstream of the regulated river reaches or for conveyance only. Conveyance licences allow the holder to take water from the river using their regulated river licence and then transfer the water to their fields or storage through an unregulated channel. The conveyance licence only allows them to take the volume which was extracted under the regulated river license and not any additional water which may occur at the extraction point due to unregulated inflows.

The diversion of water by the majority of unregulated water access licences is not measured. However, larger water users will be required to install meters by the NSW metering policy.

5.5.1 Data sources

A small number of regulated water users also have unregulated water licences that access another nearby unregulated water source. There is generally no metering data available for these few cases.

A few properties have unconverted[13] unregulated licences which are in the process of being converted (by WaterNSW). While most of these are for conveyance of water taken under a regulated access licence, some may receive an unregulated licence entitlement once converted. At the time of writing, there was only three properties which were eligible for floodplain harvesting which also held a converted licence with an unregulated licence entitlement. Two of these properties do not hold regulated licences and are not assessed through the use of the Border Rivers Valley river system model. Prior to finalising the floodplain harvesting entitlements the status of each conversion will be confirmed.

5.5.2 Modelling approach

Unregulated flow access refers to water access under licences that are in an unregulated water source. The Border Rivers Valley river system model has generally been configured to represent the regulated Border Rivers system. However, the water use in the unregulated Weir River and the effluent streams flowing from the Macintyre to the Weir River can affect the inflows at the lower end of the regulated Border Rivers, and water use is simulated in these areas as described in the following subsections. Some other areas of unregulated flow access are also represented as described below.

Lower Weir unregulated flow access

Lower Weir users have access to unregulated flows commencing when the flows at Jericho (416205A; upstream of the users) exceed 1192 ML/day and ending when the flows at Mascot (416207A; downstream of the users) recedes below 100 ML/day. A function is used to assess these conditions and control the corresponding users simultaneously.

Unregulated diversion caps

Two types of diversion caps are used in modelling the Qld unregulated flow access. Annual caps limit the total diversions that can be made via a supply point in any water year. Carryover caps limit the rolling average diversions via a supply point. These have been configured at the water user supply points according to the user’s licence conditions. Note: where and how these caps are applied depends on the scenario and will be discussed in separate reporting.

Other unregulated use

Unregulated flow access in the upper parts of catchments is not explicitly represented. The effect of these diversions are recognised inherently in the gauged inflow data and hence the inflows (observed and modelled) are net of any such usage.

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[13] The majority of unregulated licences in NSW have been converted from area-based licences to volumetric licences.

The only significant effluent river on the NSW side is the Boomi River, which does not re-join the Barwon River until below the regulated system. Diversions from here are not explicitly represented, rather they would be included as part of the flow-loss relationship which was defined to replicate flows at Boomi River at Neeworra (416028).

Conveyance licences do not need to be modelled since they just enable transfer of water. There are three properties in NSW where licenced unregulated flow access was explicitly modelled. The model will need to be revised in future to account for new converted licences with an unregulated licence entitlement.

5.6 Groundwater

NSW and Qld have issued licences that allow taking of water from the alluvial aquifers that underlie the Border Rivers for irrigation and town water supply. NSW has issued approximately 17,000 ML/year of aquifer access licences, but water use is limited to an average of approximately 8600 ML/year under the NSW Border Rivers Unregulated and Alluvial Water Sources WSP. Some irrigators that access regulated water also have groundwater access licences.

5.6.1 Data sources

A small number of regulated water users also have groundwater water licences. There is some metering data available for larger groundwater users. No groundwater usage information was reported in the farm surveys, and no usage data for these properties has been recorded.

5.6.2 Modelling approach

In NSW, none of the floodplain harvesting properties on the regulated river system have been identified as accessing significant volumes of water from a groundwater bore. Groundwater is not modelled as a water source.

6 Modelling water users

6.1 Urban water supply

NSW has issued local water utility access licences to Ashford (on the Severn River), Boggabilla (on the Macintyre River) and Mungindi (on the Barwon River). These are very small licences compared to the larger licences used for irrigation but have the highest priority of supply.

6.1.1 Data sources

A small number of urban water utilities take water from the Border Rivers regulated river system to supply domestic, commercial, and industrial users in the town. In all cases diversion estimates used in the previous IQQM were adopted for modelling purposes. These are sufficiently accurate for most model uses considering the much larger volumes used for irrigation. However, they are being reviewed to assess whether refinements are required to support any future urban water supply reliability analysis.

6.1.2 Modelling approach

The very small volumes of town water supply in the NSW Border Rivers are represented as fixed monthly patterns with an annual use equivalent to the entitlement, as per previous modelling in IQQM. The results in this report do not include these diversions.

6.2 Irrigators

Diversions in the regulated part of the Border Rivers are predominantly due to irrigated agriculture, which accounts for over 95% of the total water use on average. These water users have access to a range of water sources: high and general security, supplementary access and floodplain harvesting. Some regulated water users also have access to unregulated flows and groundwater; however, there are relatively few of these users in the NSW Border Rivers. Some irrigators also have licences for stock and domestic use.

Most irrigated agriculture is cotton, with varying amounts of winter cereal grown depending on seasonal conditions, and only a very few permanent plantings in the NSW Border Rivers.

Numbers and distribution

There are 433 individual licences as at July 2019, with most being in general security (232 licences) and supplementary (129 licences) categories. The smaller licences that generally do not have on-farm storages are typically located in the upper parts of the regulated system, and only relatively small volumes of water are taken for irrigation. High security licence holders are mostly concentrated in the single river reach between Ashford and Holdfast. The majority of larger water users are located on the floodplains below the confluence of the Macintyre and Dumaresq Rivers. The locations and areas covered by these larger water users are shown in Figure 7.

6.2.1 Data sources

Diversion of water by irrigation enterprises is a major component of the water balance in a regulated river system. Information on metered diversions, private irrigation infrastructure and the areas of crops irrigated in the Border Rivers each year are essential for configuring our model and for calibrating the modelled demand and water use patterns by irrigators. A summary of data sources is presented in Table 12.

Table 12 Data sources for data types used for parameterisation of irrigation property modelling

Data type	Data source	Model use
Diversions	Water Accounting System (WAS) where available, internal records otherwise	Flow calibration and diversion calibration. Not used as an input during model simulations
Licences	Water Licencing System (WLS). During initial model development we also corrected for permanent and temporary trades. The final model uses licences fixed to a point in time depending on which scenario is being run	Configuring Resource Assessment which links the licence to an individual Water User node
Farm infrastructure (storages, developed area, additional rainfall harvesting areas, pumps)	Permanent on-farm storage capacity initially based on farm survey and updated based on NRAR advice which was based on a combination of LIDAR and survey data. On-farm storage losses modelled through Morton’s Lake evaporation data and seepage based on 2mm/day based on data from Wigginton (2012a)	Configuring permanent on-farm storage geometry for relevant Water User nodes
Area on farms developed for cropping, and undeveloped area contributing to rainfall–runoff	Farm survey for individually modelled water users. For other relatively small water users estimated based on either earlier survey data (e.g. 2001/02) as per the existing IQQM Water Sharing Plan model or estimated based on the year of maximum diversions and an assumed rate of 7 ML of river extractions per hectare	Configuring upper limit to planted areas, and contributions to rainfall–runoff for relevant Water User nodes
River pumping capacity	Farm survey Users upstream of Macintyre-Dumaresq confluence are based on earlier survey data (e.g. 2001/02) as per the existing IQQM Water Sharing Plan model	Configuring rate of water diversions from the river for regulated and supplementary access for all Water User nodes

Data type	Data source	Model use
Floodplain harvesting rate	FPH rate was generally set to the combined on-farm storage lift rate. This was initially based on farm survey data: however, the final model was based on NRAR data. In a couple of instances, the FPH rate was set higher or lower than the on-farm storage pump rate: Reduced rate if the total FPH intake into the developed area is restricted due to pipe capacities Allowance for higher rates where properly constructed temporary storages confirmed by NRAR allow for a higher rate of intake to property before transfer to permanent storage NRAR supplied pump rates, using standard conversions for pump type and size (Appendix G). They also supplied estimated rates for pipes; in general, these rates were not important to the model as the pump rates were lower, hence the pipe rates were not used	Configuring rate of water harvesting from floodplains and rainfall–runoff for relevant Water User nodes
Crop watering efficiency	Efficiency factor (30% loss) based on industry advice and research Note that tailwater returns are not explicitly modelled – efficiency and hence application rates are net of returns	Configuring rate of on-farm losses during irrigation watering for relevant Water User nodes. Some allowance for channel losses was included in this parameter
Crop factors and soil parameters	Crop factors and root depth based on FAO56, however specific values derived in consultation with agronomists from Department of Agriculture for different climatic zones in NSW (DLWC, 2000). Some refinement of the cotton crop factors was implemented after more recent consultation with DPI Agriculture. Adopted values listed in Table 19. Total available water is defined based on root depth for each crop type (DLWC, 2000) and also for fallow and undeveloped areas. Soil moisture capacity (20%) based on industry advice (MDBA, 2018)	Configuring crop models for relevant Water User nodes to simulate total crop water requirements
Crop planting dates each year	Planting date based on farm survey data where available (preferred date) and NSW Dept Agriculture advice (DLWC 2000) otherwise	Configuring crop models for relevant Water User nodes
Climate data	SILO patch point sites data (Morton Lake for on-farm storage evaporation, Penman Monteith for crop modelling)	Input to crop models that drives simulation of crop water requirements for relevant Water User nodes

Regulated and supplementary metered diversion data are described in sections 5.2 and 5.3 respectively. Information on entitlement distribution is maintained in the WaterNSW's Water Licensing System (WLS). Information on some on farm infrastructure has been collected in the past by WaterNSW. The IBQ farm survey represents a significantly expanded and updated dataset and has undergone various verification checks.

These structured farm surveys undertaken for the Floodplain Harvesting Project for every property that registered interest are the most contemporary and detailed source of information on farm infrastructure, area planting decisions, irrigated crops for the period 2003/04 to 2013/14 (NOW, 2016a). The participants in the farm survey represented approximately 90% of the licensed entitlement to water and over 90% of the annual NSW's water use in the valley. Infrastructure information in these surveys was verified as far as possible by NRAR staff. However, other data gathered in the surveys were sometimes incomplete.

The farm survey data were reviewed using other lines of evidence and updated or supplemented for missing data where appropriate. The principal alternate lines of evidence considered were the results of farm inspections by NRAR staff, and the use of remote sensing data to estimate on-farm storage volumes and verify date of construction. The various lines of evidence used to supplement the farm survey are discussed in the following sub-sections on irrigator infrastructure, crop areas, and floodplain harvesting.

Numbers and distribution

Data relating to numbers and distribution of irrigators and the licences they hold were obtained from the Water Licensing System (WLS).

Infrastructure

On-farm infrastructure such as areas developed for irrigation, storages and pump capacities allow us to model likely water harvesting and usage volumes in the model. Current levels of infrastructure were well documented from the farm surveys, however, information on historical development for many surveyed farms was either incomplete or uncertain because of change in ownership and gaps in recordkeeping.

On-farm storage volumes and surface areas were derived using LIDAR data. Where good quality survey data was provided this was used instead. In both instances a 1m freeboard was assumed for permanent storages. Either of these methods provide an objective basis to determine capacity. Remote sensing methods were also used to validate history of development of storages. This is explained further in Appendix G .

River pump capacities were based on information from farm surveys. On-farm storage pumps were initially based on information in the farm survey, however the final model is based on NRAR data for pump size and type, and NRAR advice on the associated capacity and intake restrictions if any (Appendix G). Allowance was also made for higher rates where NRAR staff confirmed that properly constructed temporary storages allow for higher intake rates prior to transfer to a permanent storage. Standard rates for pipe size and intake rate were also used to review the rate at which overland flow can be brought into the property (Appendix G).

Historical on-farm storage pump capacity was determined at key dates based on which storages were constructed at that date. This means that if the storage did not exist, we assumed the pumps associated with that storage did not exist. In some instances, storages are a collection of cells attached to each other with one pump station; if one of the cells existed at the scenario date then we assumed that all the pumps existed at that date.

Areas developed for irrigation were primarily based on information from the farm survey and verified by NRAR staff. We also compared the developed area to maximum historical cropping, which was also verified using remote sensing.

The latest data for on-farm infrastructure for different parts of the NSW Border Rivers Regulated River system are set out in Table 13. The developed area and river pump capacities are from IBQ farm survey so represent 2014 levels of development. The permanent on-farm storage capacity and pumps represent a more contemporary estimate of capacity. LIDAR data was obtained in 2013 but was supplemented by photogrammetry in 2019 and also by many professional surveys obtained in 2020 as part of the floodplain harvesting farm scale validation process. Comparative levels at prior dates used in scenario development are summarised in Table 14.

Table 13 Latest estimates for on-farm irrigation infrastructure

Reaches	Developed area (ha)	Permanent on-farm storage capacity (ML)	River pump capacity (ML/day)	On-farm storage pump capacity (ML/day))
Upper reaches to Dumaresq-Macintyre confluence	4,700	9,024	683	360
Dumaresq-Macintyre confluence to Goondiwindi	10,541	25,303	1,360	3,123
Goondiwindi to Kanowna	27,135	135,800	5,015	13,314
Kanowna to Mungindi	6,921	32,073	1,120	2,601
Total	49,297	202,200	8,178	19,398

Table 14 On-farm irrigation infrastructure estimates at prior dates

Infrastructure	2002	2008	Latest estimate
On-farm storage capacity (GL)	166	190	202
On-farm storage pump capacity (ML/d)	16,771	18,558	19,398
Installed river pump capacity (ML/d)	7,434	7,984	8,178
Maximum irrigable area (ha)	6,338	48,799	49,297

Irrigated crops and crop water use

Having access to the history of crop areas and types planted is important. It improves the ability of the model to simulate the planting of crops under a range of climate and water availability situations, providing a more robust estimate of water requirements and diversions from rivers and floodplains over the longer term.

About 70% of the surveyed irrigators provided complete or partial irrigated cropping records for the 11-year period covered in the farm surveys. Remote sensing was used to validate the provided information and to provide information on historical valley totals. This work is described in Appendix H .

The remote sensed dataset compares well to the survey data, and together provides a relatively contemporary dataset of irrigated crop area for most of the NSW Border Rivers water users.

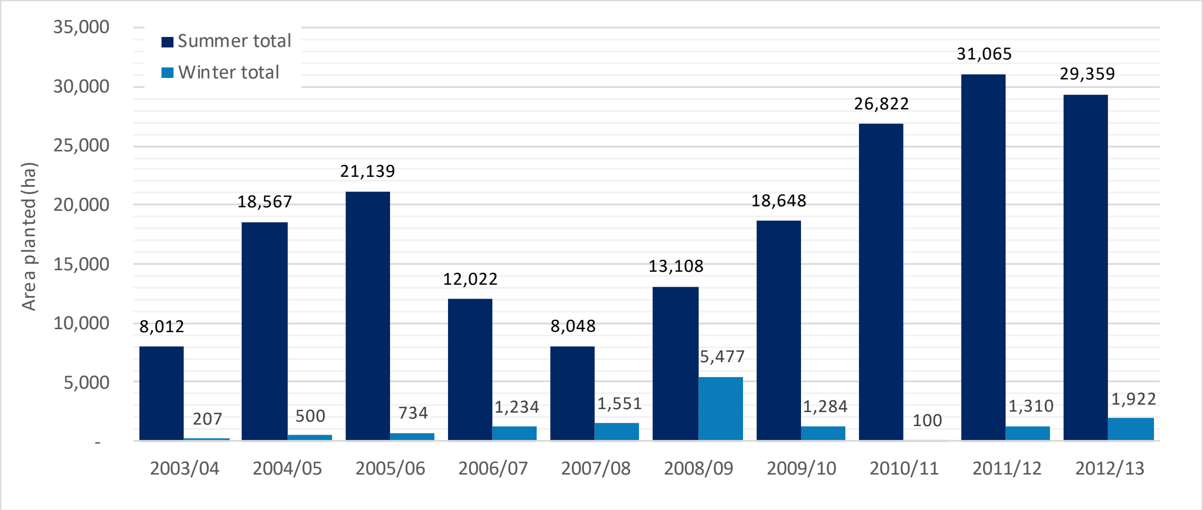

Figure 16 Reported summer and winter planted crop areas from 2003/04 to 2012/13 [Source: IBQ farm surveys]

Analysis of crop types shows it is dominated by cotton with a small amount of cereal and oilseeds also grown in summer. Wheat is also grown in the winter growing season on an irregular basis (Figure 16). Small areas of a few other crop types were grown.

The farm surveys indicated that areas planted in summer were strongly related to water availability, whereas for winter crops this was not as significant a factor. The decision on how much crop to plant based on water availability varied between individual properties in the range of 3–10 ML/ha for cotton. The farm survey did not provide planting decision information for other crop types so these were estimated as is described in the following section.

The farm surveys included estimates of rates of water use by crops, including pre-watering and tailwater return flows. Analysis of this information indicated a large range of water use rates reported, varying from 3.6–11.5 ML/ha for cotton. The reasons for this wide range of water use was difficult to reconcile, there was no geographic basis for this. Potential reasons for this wide range include different periods this may have been calculated over, whether this factored in pre-watering and efficiency, possibly different approaches to recordkeeping and different practices.

The estimate of total water use by irrigation is critical for the water balance on a reach basis and to develop confidence that the total water inflows to the farms are sufficient to irrigate crops. Further lines of evidence were required to arrive at a robust set of parameters, and included data from the Australian Bureau of Statistics, WaterSched Pro software, remote sensed data from the IrriSAT platform and parameters prescribed by the FAO crop model method. These sources are discussed in Appendix I . Using these evidences, a common set of parameters (apart from climate station and planting decision and date) were adopted for all properties.

6.2.2 Modelling approach

This section deals mainly with stage 4 (Irrigation diversions) and stage 5 (Irrigated planting areas) of the stages of model assembly (Table 2).

Irrigation farms are modelled concurrently within the context of a reach as they rely on the volumes of water breaking out from the river as a source of water.

Modelling of irrigation water use is based on a water balance approach as described in section 2.3.1 and illustrated at Figure 2, where all of the water that enters a farm (metered and unmetered diversions, rainfall on the land), and the water that leaves the farm (evapotranspiration from land and storages, and seepage) must balance each other. We use the irrigator model within the water user node in Source for this purpose. We refer to this below as the irrigator node.

Overview

The representation of each irrigator node has used the best available data and methods for long term simulation modelling as outlined in Table 15. In the model, all processes operate on a daily time step.

Table 15 Steps in the simulation of irrigation diversions and irrigated planting areas

Component	Modelling process
On farm infrastructure	On-farm storages along with pump capacity simulate diversion and storage of multiple water sources, including regulated water and floodplain harvesting Evaporation and seepage losses and rainfall on the storage are explicitly modelled Usage for irrigation is simulated based on demands On-farm infrastructure also includes areas of land developed for irrigation
Crop area planting	For calibrating parts of our model, we can use actual planted areas as advised by farm survey and supplemented by remote sensing. However, in long term simulation modelling, the crop areas are simulated based on a relationship with water availability. This enables the models to be representative of the planting and diversion behaviour over diverse climatic periods
Crop models	Source provides crop models that simulate total irrigation demand for a given area and type(s) of crops. This is done by simulating the soil moisture balance, based on the of use climate data (rainfall, and evapotranspiration) to estimate the water use by each crop type. When the soil moisture falls below configured trigger levels the crop model orders water
Rainfall–runoff harvesting	Simulates rainfall–runoff from within the property boundaries from fallow, irrigated crop and undeveloped areas In a few instances is also used to simulate localised rainfall–runoff harvesting from outside of the farm
Overbank flow harvesting	Simulates the diversion into storage of water on the floodplain outside of the property and can include localised rainfall–runoff

The parameter summary for the simulation of water demands is given in Table 16.

Table 16 Water demands calibration approach

Step	Fixed input data	Target to meet	Parameters
Demand	Climatic data Cropped area Infrastructure	Metered diversions Published data on crop requirements	Crop requirements (a set of a model parameters, either calibrated or pre-set to defined values, are derived to achieve crop requirements in line with literature and reported application rates, i.e. ABS, IrriSAT) On-farm storage operation (discussed further below)
Crop areas	Water available at planting decision date (simulated)	Reported crop areas and checked against remotely sensed data	Planting decision function

The Source model includes a number of different scenarios representing development at different points in time. The default model (default Scenario Input Set) has development set at 2008/09 levels.

Each irrigation farm or group represented in the model was initially parameterised as described in the following sub-sections. Further assessment and refinement occurred in subsequent stages of the model building process, when system operation and management rules were simulated. Adjustments made during these later stages are noted in relevant sections. While the period 2003/04 to 2013/14 was used as a calibration period for some components of the model, many components were configured or calibrated using other periods of time as is noted throughout this report. For example, rainfall–runoff rates were calibrated using a longer period of time to match published data. We therefore refer to the period 2003/04 to 2013/14 as an assessment period for the final model performance. This period was chosen for the following reasons:

- best available relevant data at the time of model development
- sufficiently long enough period to represent climatic range in the region (Table 17). This is important to ensure that the model is robust during different periods of water availability
- includes key benchmark years for the policy and the Basin Plan.

Table 17 Comparison of rainfall statistics (average, minimum and maximum) over the assessment period (2003 to 2014) to long term record (1889 to 2014)

Metric	Long term (mm) (1889–2014)	Short term (mm) (2003–2014)
Average	557	582
Maximum	1078	944

Numbers and distribution

Those Irrigation farms that were assessed as eligible for floodplain harvesting entitlements have been represented individually in the model. The remaining, generally smaller, farms have been aggregated in the model within the reach they are located. This resulted in 50 irrigator nodes, of which 36 represent individual eligible properties (or eligible enterprises consisting of several properties with one owner). There are 4 additional individual farm nodes in the model; one is not eligible and 3 are unregulated and the model is not used for their floodplain harvesting assessment.

Farm infrastructure

Each irrigator node has been configured to represent the key relevant infrastructure, including: pump capacities for regulated and supplementary access, the rate at which any floodplain harvesting access can be taken, the capacity and volume-surface area of on-farm storages, the total area developed for irrigation, and any undeveloped areas that contribute to rainfall–runoff harvesting.

The model generally only includes one on-farm storage for each irrigator node. This represents all on-farm storages. The volume-surface area relationship has been defined based on the assumption of storages being filled sequentially, generally from most to least efficient. This means that it is able to reflect smaller surface areas when held volumes are low and not all storages or cells would be in use. We tested the sensitivity of the model to this assumption (section 9) and found that the simulated floodplain harvesting had low sensitivity to this assumption.

Crop area planting

For long-term simulation of planted areas, the model needs to simulate the crop areas to be planted each year for irrigation. The planting decision determines the crop area planted as a function of water availability. Other socio-economic variables which in reality affect the area planted in any one year are not taken into account as data are not generally available for this, and the objective is to provide a reasonable representation over a long climatic period.

A ‘risk factor’ is used to define the planting decision. This is the volume of water required to be available before a water user would plant one hectare of a given crop (i.e. megalitres required per hectare).

In previous river system modelling, planting decisions were estimated using independent data analysis relating crop areas to water availability at the time of planting. This approach is no longer suitable for much of the Border Rivers because floodplain harvesting are significant components of water availability and we do not have recorded data for these. This means that water availability needs to be simulated.

The planting decision application rate for cotton was based on risk values reported in the farm surveys and varied between 3–10 ML/ha between properties with the average being 6.8 ML/ha. In some cases, the reported value was adjusted slightly to achieve a better match between simulated and historical planted areas. The survey data did not include risk values for crops other than cotton. A default risk value was assumed for other crops and calibrated if required. These are summarised in Table 18.

Table 18 Adopted crop planting decision rates, i.e. the volume of water required to be available before an irrigator decides to plant 1 ha of a given crop

Crop	Upstream of Dumaresq–Macintyre junction (ML/ha)	Dumaresq–Macintyre junction to Mungindi (ML/ha)
Winter wheat	1	4.2
Summer maize	3–6	–
Cotton	5	3–10 (average of 7 used if no information provided)
Perennial pasture	3–4	–
Lucerne	variable: fixed areas or range of risk functions used to calibrate demand	–
Soybeans	–	8.1

As noted in section 6.2.1 Data sources, winter crops are planted irregularly and do not appear to be related to water availability. The model was configured to replicate average winter diversions rather than replicate the time series of planted areas by calibrating a maximum winter crop area such that the average winter diversions match recorded over the assessment period.

For properties with one summer and one winter crop type the planting decision for each crop is relatively simple:

1. A Source function was defined to calculate water availability as the sum of the volume currently stored in on-farm storages and licence account balances
2. This is then divided by the ‘risk factor’ which defines how many hectares to plant per ML of water available, constrained by a maximum area
3. The total area planted cannot be larger than the developed area. Where required, a smaller maximum area was specified for example if the maximum area historically planted was less.

For winter crops, the maximum area was calibrated to match historical winter diversions over the 2003/04 to 2013/14 period.

For farms with more than one crop type per season, the planting decision takes into account the water required to finish the existing crop and also ensures that the total area planted does not exceed the developed area. For areas where floodplain survey data were available, the crop mix was simplified to the crops which were planted in more than two years. This reduced the crop mix to largely cotton and winter wheat, with minor exceptions.

Crop water use

Crop models simulate the total water requirement of the crops being irrigated and are the core of the irrigator nodes in the model. The crop model uses recorded climate data and either recorded crop areas (for calibration) or simulated crop areas (validation and long-term scenario simulations) as primary inputs and simulates the water requirements of those crops. These water requirements are used by the irrigator node in the model to either take water already stored on farm, or to order water from the major dams. Fallow areas are also simulated as a crop type to allow for the continuous simulation of the soil moisture through to the next crop planting.

Crop models simulate a soil moisture balance on a daily basis using climate data (rainfall, and evapotranspiration) to estimate the water use by each crop type (e.g. cotton, wheat) and need for irrigation. To ensure irrigation requirements vary with climate appropriately, the nearest climate station (rainfall, evapotranspiration) is used for each irrigator node. When the soil moisture falls below the trigger levels configured in the model, it will order water (Figure 17). In the right-hand figure, the bottom line represents the target level at which irrigation is triggered; this represents irrigation scheduling in practice.

Rather than attempting to represent discrete irrigation events, the model simulates smaller volumes of water being applied more frequently such that soil depletion is maintained around a specified target value[14]. A new method has been added to Source which might be used to represent irrigation scheduling; we trialled this method but did not adopt it in the final model as the added complexity resulted in some poor outcomes when compared to historical data.

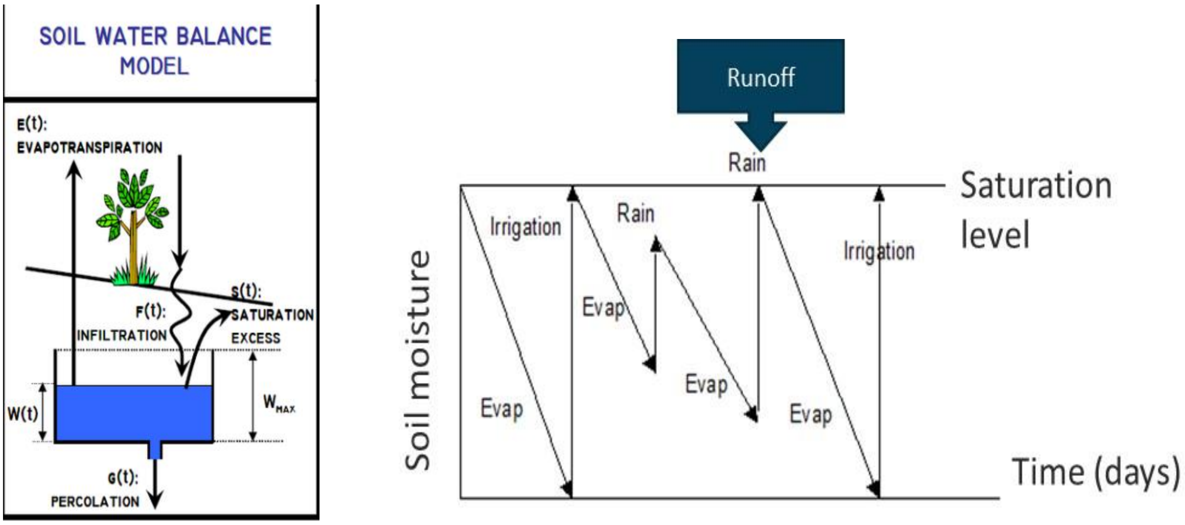

Figure 17 Soil water balance model (left) with accounting for evapotranspiration, rain, and irrigation (right)

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[14] This is the same approach used in IQQM.

Parameters in the crop model were pre-defined or narrowly bounded where possible based on research and industry values or expert knowledge, some of which have already been detailed in Table 12. This was done to avoid inappropriate calibration of parameters in the model, and to ensure the overall calibration is robust outside of the calibration period.

The delivery of water to the crops is subject to an ‘efficiency factor’ that represents delivery and application loss; a value of 30% has been adopted as defined in Table 12. Surface water irrigation efficiency can vary widely. Gillies, 2012 application efficiency results (cited in Wigginton, 2013, p26) were based on data collected from 2000/01 to 2011/12. The average was 76% with tailwater recycling but efficiencies up to 90% were recorded. As the industry improves efficiency over time, this dataset may under-estimate efficiency for the more recent period. Gillies highlighted that an optimised irrigation approach results in average application efficiency of around 85% with tailwater recycling. We assume that this is likely to more representative of most irrigation enterprises over the recent period. The following application losses have been adopted:

- 30% application loss for all scenarios. This is based on Gilles average result plus some allowance for channel losses.
- We propose that a 15% application loss be adopted for future versions of the Current Conditions Scenario*;* however, this will need to be considered along with other lines of evidence of contemporary water use and assessment of model performance before being implemented.

Tailwater return flows from a crop after watering are not explicitly modelled; rather the crop demands and efficiency have been defined to be net of these returns.

Soil moisture capacity for crop and fallow crops are not defined directly in Source; they are a function of root depth and soil moisture capacity (%) as referenced in Table 12. The multiplication of the two equals the total available water (TAW); 176 mm and 120 mm respectively for cotton and fallow areas. Actual TAW will vary depending on soil type and farm management practices; however, the adopted values appear to be within a reasonable rage for clay-based soils (e.g. 140-200 mm for 1m of soil as cited in Larsen and Weir (2012)). While this is an averaged approximation, it is used in combination with other parameters to ensure that the generated demand is reasonable. This reduces the sensitivity of the results to this one parameter (further described in Appendix I). Similarly, the TAW will affect the rates of rainfall–runoff; again, it is used in combination with other parameters to produce realistic overall runoff rates (discussed in the next section).

The basis for the crop model parameterisation is the method set out in the Food and Agriculture Organisation of the United Nations Irrigation and drainage paper 56 (FAO56, Allen et al., 1998). This method uses crop factors (Kc) to convert potential evapotranspiration to crop evapotranspiration. The FAO56 method provides a range of values for the coefficients (Kc) used to estimate evapotranspiration by each crop from the reference evapotranspiration values calculated at the nearest climate station. These factors change as the crop develops over time from planting to harvest or between seasons for perennial crops (Figure 18).

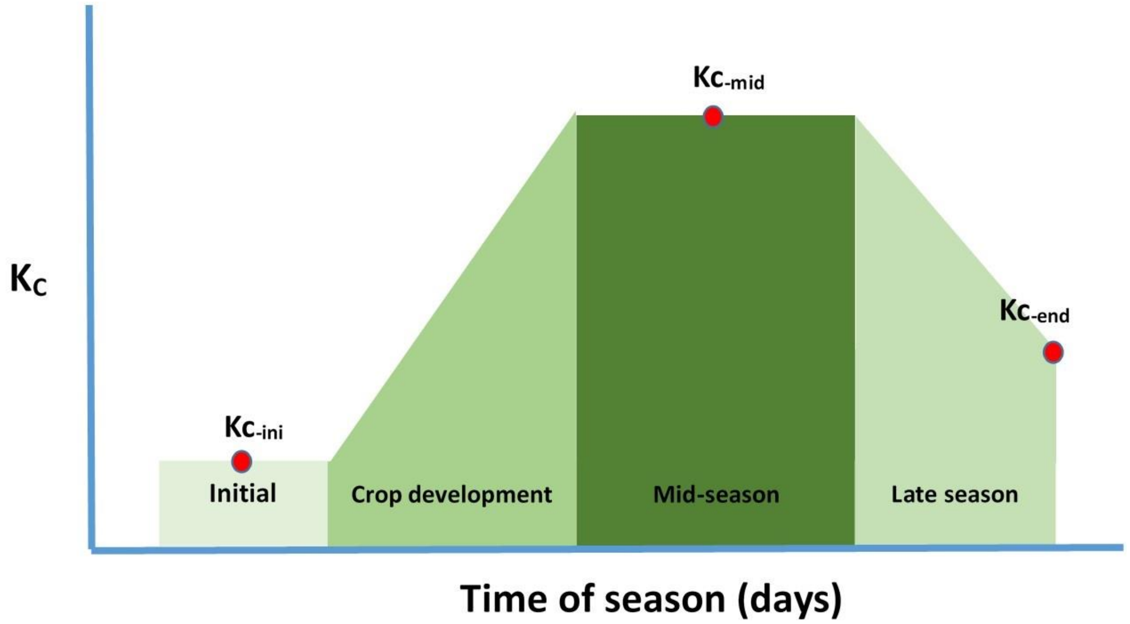

Figure 18 The relationship of Kc crop factors to time of season [adapted from Fig 34, Allen et al. 1998]

Derivation of crop factor values, soil parameters and crop planting dates is provided in Table 12 and values summarised in Table 19. In Table 19, note that the late season cotton period is shorter than the likely actual period. This has been done to enable the simulation of depletion of soil moisture at the end of the season.

Table 19 Crop parameters used in the model: crop factors (Kc), length of period in season (days), periods and planting date

Crop class	Winter cereal	Summer cereal	Cotton	Summer oilseeds	Pulses	Perennial/ summer pasture	Lucerne
Crop factors							
Kc-ini	0.30	0.30	0.35	0.40	0.50	0.40	0.40
Kc-mid	1.15	1.20	1.20	1.15	1.15	0.75	0.95
Kc-end	0.25	0.50	0.60	0.50	0.30	0.75	0.90
Length of period in season (days)							
Initial	16	30	30	20	90	120	10
Development	31	40	50	30	45	62	30
Mid season	67	50	60	60	40	120	150
Late season	41	30	20	25	60	63	35
Planting decision date	15 May	15 Oct	Late Sep to end Oct	01 Dec	05 May	01 May	01 Sep

Rainfall–runoff harvesting

Individually represented water users in the model that are capable of floodplain harvesting simulate rainfall–runoff harvesting based on the same soil water balance component of the crop model (Figure 17). In this model, the soil moisture profile is simulated separately for areas developed (planted and fallow), and areas undeveloped for irrigation. The model continuously tracks the soil moisture of cropped, fallow and non-irrigable areas separately, enabling calculation of runoff following a rainfall event with consideration of antecedent conditions.

Runoff occurs when the soil is saturated. Given that the soil water balance model is a much-simplified representation of runoff generation, as this was not its prime intent, these simplifications of processes and associated parameterisations require a simple basis to calibrate. Rather than explicitly represent other processes, percentage return efficiency parameter is applied to calibrate available runoff to pre-calculated long-term averages. The results were also checked for annual variability compared to nearby gauged inflows. This simulated runoff is then collected into an on-farm storage; in some instances, the runoff is not captured as either the runoff rate is greater than the pump rate or the storage is full.

The parameters used for runoff are summarised in Table 20. The supporting literature is further described in Appendix F .

No rainfall–runoff harvesting has been configured for the non-floodplain harvesting farms represented in the lumped *Irrigator Nodes* in each river reach. There is only a small volume of on-farm storage capacity on these farms, and hence rainfall harvesting is expected to be relatively small.

Table 20 Calibration of parameters which control rainfall–runoff harvesting

Parameter	Adopted value	Comment
Fallow crop factor (for both developed and undeveloped areas)	0.6	Estimated and in conjunction with the other parameters produces the expected runoff response (Appendix F)
Rainfall–runoff return efficiency for fallow and winter irrigated areas	40–50%	Assumption that winter crops are often not fully irrigated. 50% was adopted for Boggabilla climate to ensure the resulting runoff was within expected range (Appendix F)
Rainfall–runoff return efficiency for summer irrigated areas	100%	Assumption of highest efficiency due to elevated soil moisture
Rainfall–runoff return efficiency for undeveloped areas	20–30%	30% was adopted for Boggabilla climate to ensure the resulting runoff was within expected range. Defined as lower than fallow rates, but within the bounds suggested by the Budyko framework (Appendix F) on the basis that the efficiency of collecting from these areas is likely to be lower Where these areas become more significant, or there is evidence of significant unaccounted for volumes, this assumption will be reviewed

Overbank flow harvesting

The breakouts described in section 4.5 and Appendix D and verified through flow calibration, deliver water onto the floodplain when their flow thresholds are exceeded. This outflow is simulated as a permanent loss from the river system. In some instances, the breakouts are flood runners that may return a portion of that water to the river.

This portion is difficult to determine in practice. If the breakout and return flows are localised to the same river reach, the returning flows will be included in the observed flows measured at the bottom of the river reach. The flow calibration process seeks to simulate the flows as measured at the downstream flow gauge, and this may result in the overbank flow relationship more closely representing the net breakout of water from the river.

The accumulated volume of water above this threshold that leaves the river is held in a conceptual floodplain storage, which functions as a source of water for harvesting by one or more properties that are hydraulically connected to that storage, as illustrated in Figure 19.

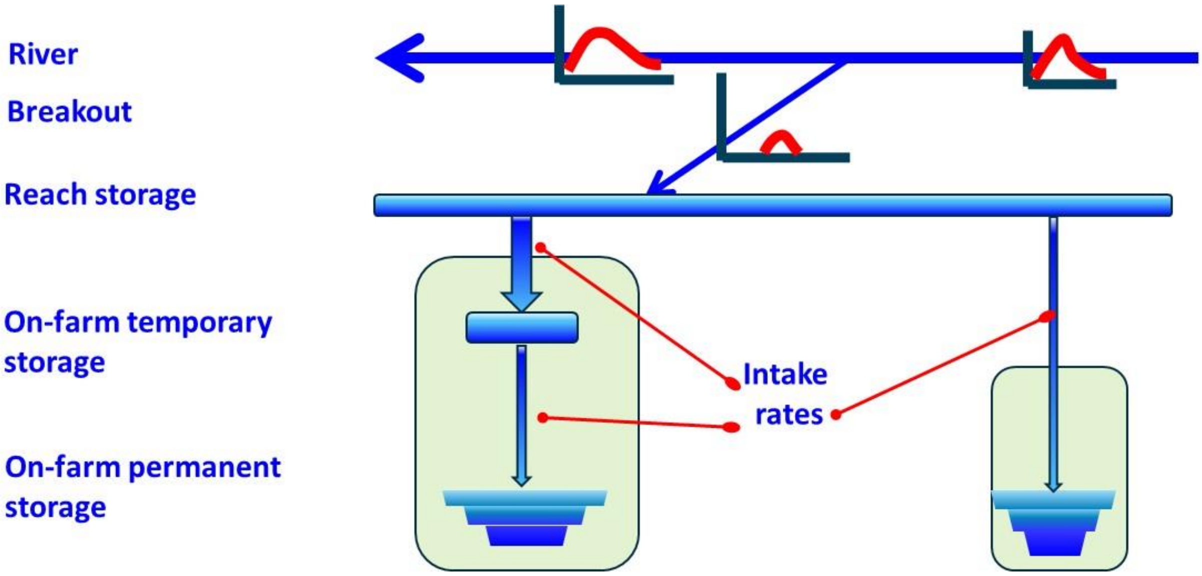

Figure 19 Relationship between breakouts, floodplain storages and overbank flow harvesting

The conceptual storage size is based on the estimated number of days over which harvesting can occur. This is a simple approach to representing routing and temporary storage of flows on the floodplain. Choice of values and rationale for these choices is given in Table 21.

Table 21 Setting of parameters which affect modelling of Irrigator overbank harvesting

Parameter	Adopted value	Rationale
Days over which harvesting occurs	10 days	Selected in an attempt to replicate routing that is occurring on the floodplain. This information is not available from gauged river flow data and sensitivity testing indicated that it was not a source of significant uncertainty. The 10-day access means that in addition to the first day of breakout flow, an additional maximum of 9 days access is required, meaning that the virtual storage is sized based on 9 times the total of all downstream floodplain harvesting intake rates[15]. Likely to be an overestimate in the upper reaches

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[15] This is the rate at which the water user node pumps water onto the property

Parameter	Adopted value	Rationale
Release of water from the floodplain storage	Rate equal to 1 day's pumping for properties with access to that storage. Spills also occurring when the storage is filled	This means that in a small event, the water held in on-farm storage may be released quickly
Daily loss for water held in floodplain storage	10%	There are no data available to inform this assumption

Multiple properties that access water from the same floodplain storage are modelled with their order of access to the breakout flow represented. Some areas required a more distributed approach to access, and this was based on advice from hydraulic modelling, farm survey information and Landsat data. The rate of filling of eligible on-farm storages was initially based on farm survey data; however final rates were based on NRAR data for pump size and type and recommended rates.

Appendix section G.5 provides an example of how we configured the breakout, floodplain storage and individual farm works.

Storage operation and water balance

The combined on-farm storages on a property are configured to allow for sequential filling or emptying of the cells. It is assumed that the emptying order is the reverse of the filling order. The filling sequence of permanent storages adopted for each property has been estimated based on a number of assumptions; that the most efficient (deepest) storages are filled first and checked based on an assessment of whether they are likely to be the primary storage (based on largest, order presented in farm survey, and proximity to water extraction point).

The combined storages are filled by all sources of water diversions that each farm has access to. The total rate of filling the storage is based on the combined rate of filling each individual storage.

Access to floodplain harvesting was configured with intake rates from the floodplain storage. These rates were generally the same as the total storage pump rate. Some variations occurred, for example if intake pipes restrict harvesting, or if higher rates of intake occur into temporary storages and have verified history of use. Where temporary storages are known to have operated such that they allow for a large intake rate and later slower transfer to permanent storage, this has been accounted for in the model where considered significant. This was configured by assuming a change in the floodplain harvesting rate into the permanent storage rather than explicitly modelling temporary storages.

Seepage from storages was not captured in the survey, and an industry average of 2 mm/day is used based on results from Wigginton (2012a).

The model software includes the ability to define a target reserve volume to hold in the storage during the cropping period. The size of this reserve was defined based on farm survey data. However, during model calibration, the start date of the reserve was changed to December to achieve a better monthly match of simulated and recorded diversions. The reserve is modelled in the cell which is filled first and emptied last. In all cases the capacity of the storages has been defined such that it excludes a 1m freeboard (airspace at the top of a storage).

This information is summarised in Table 22.

The recorded data also indicated that 'account management' diversions occurred during the wet periods of 2011 and 2012, with significant volumes of diversions occurring in June of both years. These diversions occurred when headwater storages and / or accounts are full and farmers transfer water into on-farm storages to create space in their account such that they are able to receive additional allocations. By transferring water into on-farm storages, these irrigators are able to make use of unallocated water in headwater storages and may also be taking advantage of unregulated flows to meet orders.

These diversions have been represented by defining a function which increases the target on-farm storage volume when account balances are high. These functions initially resulted in transfers occurring too frequently, hence further restrictions were added such as: time of year; or including an on-farm storage volume threshold in the trigger.

Table 22 Setting of parameters which affect modelling of Irrigator on-farm storage and water balance

Parameter	Adopted value	Rationale
Storage capacity	variable	Based on NRAR data which excludes 1m freeboard
Storage intake rate	variable	Set at total storage pump rate using NRAR data
Storage seepage	2 mm/day	Industry average from Wigginton (2012a)
Reserve volumes of storage	Variable	Based on farm survey data, with start date moved to December Where relevant, also includes a function to approximate account management diversions

Non harvesting properties

Each river reach has an *Irrigator Node* to represent smaller farms that did not participate in the farm survey. The irrigated crop areas outside of the individually represented farms are predominantly in the upper reaches and are relatively small. There are no crop areas available for these properties in the assessment period, and a planting decision was developed to achieve a match to recorded diversions only. These *Irrigator Nodes* have been configured as set out in Table 23.

Table 23 Setting of parameters which affect modelling of non-harvesting properties (Irrigator groups)

Parameter	Adopted value	Rationale
Crop model parameters	As used for individual farm simulation	Consistency
Crop mix	Based on prior 2001/02 survey data	Used in previous IQQM modelling
Developed area	Estimated on 2001/02 survey data OR on year of maximum diversions	Initially based on 2001/02 survey data Where larger developed areas were required to match recorded diversions, the developed area was estimated on the basis of the year of maximum diversions
Rate of river extractions	Based on prior 2001/02 survey data	Used in previous IQQM modelling

6.3 Held environmental water

Held environmental water refers to any water access licence that is held and used to achieve environmental outcomes. It is not a separate category of licence, just a different type of use. These licences are generally used to improve the health of rivers and their environs through re-introduction of some natural variability in river flows to reconnect with the river's floodplains and wetlands.

Under the Basin Plan, the Commonwealth Government has purchased water licences to use for environmental outcomes. The management of these water licences is undertaken by the Commonwealth Environmental Water Holder (CEWH).

6.3.1 Data sources

The department maintains a register of Held Environmental Water (HEW) licences linked to the NSW WLS. At 31 May 2020, total NSW Border Rivers holdings held by the Commonwealth Environmental Water Holder[16] comprise of 2,806 unit shares of general security B licences and 1,437 unit shares of supplementary licences. This represents around 1% of the total licences in the NSW Border Rivers. Larger volumes of Qld entitlements have been purchased for Held Environmental Water; 15,540 medium priority and 19,986 unsupplemented shares as at 31 May 2020.

6.3.2 Modelling approach

Not enough is known regarding exactly how Held Environmental Water (HEW) is going to be used. The HEW portfolio has been modelled as a consumptive use that assumes an irrigation demand pattern. This issue has been addressed in other reporting for *Basin Plan* compliance. We plan to explicitly represent how HEW is used in future versions of the model.

6.4 Stock and domestic use

Landholders in the NSW Border Rivers can access water for stock and domestic purposes through either:

- basic landholder rights for properties with river frontage
- a specific purpose access licence
- replenishment flows diverted into the Boomi River (see section 7.6).

6.4.1 Data sources

The department maintains records of stock and domestic water use in WAS.

Operational records of stock and domestic replenishment flows are maintained by WaterNSW. Flows diverted into the Boomi River are measured at the gauging station on the Boomi River at the offtake and stored in WaterNSW Hydstra database.

No data is available on water use under Basic Landholder Rights. The NSW Border Rivers WSP estimates water requirements of holders of domestic and stock rights at 8GL/year.

6.4.2 Modelling approach

Stock and domestic replenishment flows are represented in the model, as a demand at the Boomi River offtake. This is described as part of the overall operation of the Boomi River offtake described in section 7.6.

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[16] https://www.environment.gov.au/water/cewo/about/water-holdings

The relatively small volumes of diversions by Basic Landholder Rights and other stock and domestic licences are not measured and are not explicitly represented in the model. However, the effect of such water use is captured in the estimated volumes of water lost as river transmission losses (transmission losses are described in section 7).

7 Modelling water management rules

Qld and NSW enacted legislation in 1946 and 1947 with agreed arrangements for sharing the waters of the Border Rivers, including the formation of an independent commission, the Dumaresq-Barwon Border Rivers Commission (BRC), to manage this sharing, and the delivery of water from Glenlyon Dam to licensed water users in both NSW and Qld down to Mungindi.

WaterNSW is contracted by the BRC to undertake river operations for the regulated Border Rivers system, and for Sun Water to operate and maintain shared infrastructure assets.

Management rules are implemented for:

- sharing: sharing of water and infrastructure between NSW and Qld as defined by the IGA and the 2009 BRC Standard Operating Procedure
- resource assessment: allocation to accounts based on continuous accounting framework (continuous sharing in the Macintyre Brook)
- off allocation rules: used to represent unsupplemented (Qld) and supplementary (NSW) diversions
- unregulated flow access: licensed access to surface water on unregulated tributaries is subject to conditions including flow conditions; also the operation of Boomi Weir for unregulated flows
- planned environmental water: environmental flow rules to represent environmental releases described in NSW Border Rivers WSP and Qld Resource Operations Plans.

7.1 State sharing

The IGA sets out the high level arrangements for managing each state’s share of the water resources of the Border Rivers. The BRC developed the *Continuous Accounting of the State's Shares of the Inflows to Glenlyon Dam and the Border Rivers Regulated Flows: Standing Operating Procedure* in 2009 to give effect to the legislative requirements for sharing between the states. It accounts each state’s sovereignty over a share of the water resources in the catchment. The IGA sets out the high level arrangements agreed by NSW and Qld to manage their respective share of the water resources to provide environmental outcomes and to provide a consistent approach to managing water use and trade.

Within each state, the state’s share of the water resources is made available through statutory water sharing plans.

Sharing rules are established for:

- inflows
- storages and storage spills
- breakouts
- transmission losses.

7.1.1 Inflows

NSW and Qld generally share the inflows to Glenyon Dam and inflows downstream of Glenyon and Pindari Dam in a 57:43 ratio. Table 24 provides further details on the sharing arrangements.

Table 24 Ownership of inflows

Inflows	NSW share	Qld share
[1] Pike Creek upstream of Glenlyon Dam	57%	43%
[2] Macintyre River upstream of Pindari Dam	100%	0%
[3] Macintyre Brook upstream of the Dumaresq Junction	0%	100%
[4] Weir River and its tributaries	0%	100%
[5] NSW creeks downstream of the Macintyre River including Whalan Creek, Croppa Creek, Boomi Creek	100%	0%
[6] All other inflows: unregulated inflows to the Dumaresq including Tenterfield Creek, Mole River, Pike Creek downstream of Glenlyon Dam, Beardy River, Oaky Creek, Brush Creek, Campbells Creek; unregulated inflows on the Macintyre River downstream of Pindari Dam	57%	43%

While inflows into the Macintyre Brook and Weir River systems are initially assigned to Qld ([3] and [4] in Table 24), they are reassigned to NSW and Qld in the proportion 57:43 respectively at the points where they discharge into the Border Rivers. In the case of Macintyre Brook, there is a regulated component designated for Qld irrigators on the Macintyre River which retains 100% Qld ownership.

7.1.2 Storage capacity

The capacities of the major storages are shared as outlined in the 2008 *IGA* and are the same as each State’s share of inflows to that storage (inflow shares are given in Table 24).

Table 25 Ownership of storages

Storage	Capacity (ML)	NSW share	Qld share
Glenlyon Dam	254,320	57%	43%
Pindari Dam	312,321	100%	0%
Coolmunda Dam	69,061	0%	100%
Boggabilla Weir	5,850	57%	43%

If either State’s share in any storage is full before the storage is physically full, additional inflows spill into the share of the State with remaining airspace and become part of the resources of that State.

7.1.3 Storage spills

Physical spills from storages may occur when shares of both States are full. The 2008 *IGA* stipulates that spills from Coolmunda Dam (Qld) and Pindari Dam (NSW) belong to their respective States until they flow into the Border Rivers at which point NSW and Qld share them in the ratio 57:43.

Whenever downstream tributary inflows or storage spills result in flows that exceed downstream requirements for licensed water use of other system needs, these uncontrolled flows on the Macintyre River are announced by the BRC and are subsequently made available for supplementary water access in NSW and water harvesting in Qld, with States given equal access to these flows.

7.1.4 Breakouts

States concede breakouts of higher flows to the State of destination. Breakouts include NSW and Qld floodplains, Whalan Creek (NSW), Callandoon Creek (Qld), Dingo Creek (Qld), Coomonga Creek (Qld), Boomi River (NSW), Weir River (Qld), Little Barwon Creek (NSW), and Boomangera Creek (NSW). Any flows returning to the Macintyre River, notably including those returning from Callandoon Creek (Qld), Coomonga Creek (Qld) and the Weir River (Qld), are shared between NSW and Qld in the ratio 57:43.

7.1.5 Transmission losses

Ownership of transmission losses is accounted in proportion to the ownership of flows at that location in the system, as set out in the BRC Standard Operating Procedure.

The BRC Standard Operating Procedure also provides for the delivery of water to Qld users from the NSW Pindari Dam. This provision helps reduce transmission and operation losses and improves the amount of water that can be regulated by reducing spills from Pindari Dam. In return, an amount equivalent to 130% (to account for the delivery losses) of the Pindari release attributable to satisfying Qld orders is ceded from Qld to NSW in Glenlyon Dam.

7.1.6 Data sources

Within the context of the state sharing arrangements described under the BRC Standard Operating Procedure, WaterNSW maintains bulk accounts of water for each State on a monthly basis, which are regularly reviewed by the BRC Management Committee. These accounts describe how inflows, water in storage, and flows along the Border Rivers have been shared between the States, and how much water use is attributable to each State.

7.1.7 Modelling approach

Source’s ownership system provides functionality to assign and track the ownership of water throughout the model network. This system is used in the model with two owners, NSW and Qld, to model state ownership and sharing arrangements as prescribed in the 2008 IGA and BRC Standard Operating Procedure. This means that the volume of water in storages and within each river reach at any point in time is accounted as either NSW or Qld water, depending on the source of inflows, or which water users have ordered the releases from storage. The ownership system manages borrow and payback between the states and supports the ordering and resource assessment systems within the model.

Ownership of inflows

Ownership of inflows is assigned in accordance to Table 24.

Ownership in storages

The storages have been configured so that each State’s share of the water in storage is limited to their maximum share of the storage (Table 25), as has the ownership of spills from each dam. In the case of Coolmunda Dam ownership of physical spills is modelled explicitly. In the case of Pindari Dam it has been assumed that spills will coincide with the announcement of supplementary water access periods and that the sharing rule for supplementary water access takes precedence.

Contributions from Pindari Dam used by Qld

The model simulates the supply of water from Pindari Dam for Qld by passing Qld orders to Pindari Dam instead of Glenlyon Dam when conditions are suitable (the Glenlyon-Pindari harmony rule is discussed in section 7.6).

The BRC Standard Operating Procedure specifies that contributions from Pindari Dam for Qld are accounted net of losses and repaid in Glenlyon Dam at a rate of 130% to cover delivery losses. However, limitations in Source's ordering and ownership systems entail that Qld orders generate borrows at the Pindari Dam wall rather than the point of take and are therefore inclusive of associated losses. Accordingly, the model is configured to repay 100% of these borrowed volumes from Qld to NSW in Glenlyon Dam.

The borrow-and-payback feature of Source's ownership system is active throughout the model and allows water users to borrow surplus water (that belonging to another state or water user in excess of their regulated requirements) and repay it at the end of the timestep by an internal transfer within an appointed storage. The Border Rivers Valley river system model is configured with Glenlyon Dam appointed as the storage for reconciliation.

Although systemwide borrow-and-payback is not described explicitly in the BRC Standard Operating Procedure, it is consistent with efficient and coordinated operation of the system by the river operators (WaterNSW).

The BRC Standard Operating Procedure specifies that these borrowed volumes be reconciled in Glenlyon Dam once per month, 21 days after the assessment date of each month. Source's ownership system reconciles borrows at the end of each model timestep (i.e. daily). The continuous reconciliation is not anticipated to have any significant effects.

Ownership and uncontrolled flows

Uncontrolled flow access is represented using the five river reach groups listed in Table 10. Ownership of uncontrolled flows available for supplementary access in NSW and water harvesting in Qld are modelled by overriding the state-based ownership of flows at the start of each uncontrolled flow reach, whenever off-allocation access has been announced, such that supplementary access is shared 50:50 between NSW and Qld water users.

Ownership of streamflow losses, breakouts, and return flows

The ownership of streamflow losses including evaporative losses, within-bank losses, and floodplain breakouts are accounted in the model in proportion to the ownership of flows at that location in the system. This is consistent with section 12 of the BRC Standard Operating Procedure.

Breakout flows into either state are conceded to the State of destination. Flows returning to the Macintyre River from Qld are shared between NSW and Qld in the ratio 57:43.

Ownership at water users

All water users in the model are associated with either NSW or Qld depending on where their licence is held. Any flows diverted by a water user come from the share of the streamflow owned by their associated state.

7.2 Resource assessment

The volume of water controlled by the three major dams is assessed each month, and the share of available water for new allocation announcements is assessed for both NSW and Qld.

WaterNSW undertakes a resource assessment every month to formally assess any improvements in water available, either through a substantive inflow or lower than forecast river transmission losses. When approved by the BRC, WaterNSW credits improvements to each State in the accounts it maintains on behalf of the BRC.

7.2.1 Available water determination

When there is an improvement in water available to NSW, the department undertakes an available water determination (AWD), as set out in the NSW Border Rivers WSP, of the volume of that improvement and announces allocations in the form of a percentage of the total shares in each licence category.

The AWD considers the need to set aside water to cover additional river transmission and operational losses, evaporation from dams, and any other requirements such as minimum flow rates or environmental water requirements as set out in the NSW Border Rivers WSP and the BRC Standard Operating Procedure. Unlike some southern NSW systems, the resource assessment system used in the Border Rivers does not make any assumptions about minimum inflows when determining available water.

Announced AWDs in NSW are gazetted when made, and the results subsequently incorporated in the WAS. Records of water set aside for transmission and operating losses are maintained by WaterNSW.

The history of the announced allocations for general security class licences is shown in Table 26 (announced allocations for local water utility, stock and domestic, and high security entitlements are not included as they were 100% for all years).

The effects of drought in allocations can be seen in the years 2013/14 to 2015/16, and again from 2017/18.

Table 26 NSW Border Rivers announced allocations (%) for general security licences

Year	General security class A	General security class B
2009/10	96%	10%
2010/11	98%	104%
2011/12	70%	37%
2012/13	52%	60%
2013/14	90%	5%
2014/15	98%	2%
2015/16	84%	27%
2016/17	97%	106%
2017/18	96%	16%
2018/19	32%	0%

Source: NSW water register, as at 9 July 2019

7.2.2 Modelling approach

Resource assessments are simulated on a daily timestep in the model. There are 3 resource assessment systems in the model:

- NSW continuous accounting
- Qld continuous accounting
- Qld continuous sharing (Macintyre Brook).

These are described in section 7.3.

Additional unallocated water is assessed for each State and credited to individual water accounts according to the volumes available via the sharing arrangements set out in section 7.1 (summarised in Table 24), and the water accounting parameters described in section 7.3.

7.3 Water accounting

All regulated water licences have an associated water account to manage their share of available resources. These accounts are managed differently in each State, and also between access licence categories.

Between NSW and Qld

WaterNSW maintains accounts of each State’s share of the major storages on behalf of the BRC. These accounts are maintained continuously from one year to the next according to the rules set out in the Standard Operating Procedure approved by the BRC.

Within NSW

For NSW water users, water accounting rules are set out in the relevant Water Sharing Plan (WSP).

NSW uses a **continuous accounting** system to allocate the water available for diversion by all licensed water users and transmission and operation losses.

- Water is allocated to a bulk account for higher priority licence categories (local water utilities, domestic and stock, and high security) and a separate bulk account for general security licences. Individual licences then receive a share of the water in these bulk accounts according to their licence category and then according to the proportion of the licence shares they have.
- Whenever water is allocated to the bulk accounts for water users, water must also be allocated to a separate bulk account to cover the transmission and operation losses incurred when delivering water along the river to water users. These transmission and operational Loss (TOL) accounts receive 30% of the volume credited to the water user bulk accounts.
- If losses incurred exceed 30%, any further improvements must be used to first top up the TOL accounts to reach 30% of the water in the water user bulk accounts before allocating any further water to both accounts in the required proportions.

Individual licences in the higher priority categories are managed under an **annual accounting approach**, where they receive annual allocations each year, and cannot carry over water from one year to the next. Individual water accounts cannot exceed 100% of the share component for that licence.

General security class B licences are managed under a **continuous accounting approach**, where allocations can be carried over (continuously) from one year to the next, subject to the water account limit for each licence of 100% of the share components for that licence. To deliver water as efficiently as possible, general security class A and class B licences operate under a water order debiting system, with the greater of the water ordered or the metered water use debited from individual water accounts.

Within Qld

Qld uses a similar **continuous accounting system** (to NSW) in the Border Rivers to manage its supplemented water licences (analogous to general security in NSW) that are set out in the Qld Water Plan (Border Rivers and Moonie), and the Border Rivers and Moonie Water Management Protocol 2019.

In the Macintyre Brook tributary system, Qld uses a **continuous sharing** system.

7.3.1 Data sources

Between NSW and Qld

Accounts of each State's share of the major storages are maintained by WaterNSW, on behalf of the BRC.

Within NSW

Individual water accounts are maintained within the WAS, including all account transactions and balances. Individual account holders can view accounts online, and the WAS provides a variety of reports that describe water in accounts and the various types of transactions that have occurred. Prior to 2009, a continuous accounting database was used to record account balances, but only a limited set of data were maintained.

Three key information sources were used to inform the modelling:

- BRC Continuous Accounting of the State's Shares of the Inflows to Glenlyon Dam and the Border Rivers Regulated Flows: Standing Operating Procedure
- Water Sharing Plan for the NSW Border Rivers Regulated River Water Source
- resource assessment spreadsheets.

Within Qld

Accounting for water licences in Qld is maintained by SunWater.

Key information sources were reviewed to inform the modelling:

- BRC's Continuous Accounting of the State's Shares of the Inflows to Glenlyon Dam and the Border Rivers Regulated Flows: Standing Operating Procedure
- Qld Border Rivers Resource Operations Plan 2008.

7.3.2 Modelling approach

NSW continuous accounting

The modelled continuous accounting system has been developed to represent operational practice as closely as possible. Key parameters are summarised in Table 27.

Table 27 Key parameters for modelling of NSW continuous accounting

Component	Comment
Debiting type	Water order
Timestep	Daily
Assigned storages	Pindari and Glenlyon. Boggabilla Weir is not included in the resource assessment; however, use out of Boggabilla Weir will be picked up in the apparent inflows as part of the monthly reconciliation
Transmission & operational loss (TOL) share	General security A and B licences – 30% High security licences – 60%
Usage limits	General security A and B licences – 1 ML/year
Account limits	General security A and B licences – 1 ML/share account limit
Allocation limit	General security A licences – 1 ML/year (incl. carryover)
Storage loss reserve	As per storage reserve calculations used in water allocation determinations

Component	Comment
NSW essential supplies reserve (including delivery)	41.1 GL (This is a reduced requirement as noted in the BRC Standard Operating Procedure)

Qld continuous accounting

The model has been configured to represent operational practice as closely as possible. Key parameters are summarised in Table 28.

Table 28 Key parameters for Qld continuous accounting (Border Rivers)

Component	Comment
Debiting type	Water order
Timestep	Daily
Assigned storages	Glenlyon Dam. Boggabilla Weir is not included in the resource assessment but capture of unregulated water is accounted for as part of Boggabilla Weir operation
TOL share	Medium priority – 30% Essential supplies – 60%
Usage limits	Medium priority – 1 ML/share per water year
Account limits	Medium priority – 0.85 ML/share account limit
Storage loss reserve	Qld's share of Glenlyon storage loss reserve, up to a maximum of 7740 ML, calculated as per water allocation determinations
Qld essential supplies reserve (incl delivery)	9590 ML

Qld continuous sharing (Macintyre Brook)

Continuous sharing in the Source modelling platform is designed according to the specific requirements of the Macintyre Brook and St George (Condamine-Balonne) schemes and was tested by the Macintyre Brook Continuous Accounting Trial Application project17. It is therefore ideally suited for the present purpose.

The maximum active storage capacity in the Macintyre Brook irrigation scheme is 68,849 ML (being the active capacity of Coolmunda Dam) of which 13.5% is High Priority storage associated with the Inglewood Town Water Supply account, and 86.5% is Medium Priority storage associated with the 6 medium priority user accounts.

Key parameters are summarised in Table 29.

Table 29 Key parameters for modelling Qld continuous sharing (Macintyre Brook)

Component	Comment
Debiting type	Water order
Timesteps	Daily
Water year	1 Jul –30 Jun

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[17] https://ewater.org.au/casestudies/rivers-case-studies/the-macintyre-brook/

Component	Comment
Assigned storages	Coolmunda Dam
Active capacity	68,849 ML
High priority allocation	13.5% (9309 ML)
Medium priority allocation	86.5% (59540 ML)
Medium priority threshold	1,400 ML (these accounts are not given a share of the inflows until the system storage is above this threshold)
Maximum cap carryover	20% (at most 20% of a user's annual cap can be carried over into the following water year)

The high priority and medium priority user accounts have been configured with shares, share factors, and annual caps reflecting the details of their licences.

7.4 Water trading

Trading within NSW of licence shares (known as permanent trade) and account water (known as temporary trade) has been permitted since the 1980s. Before 2009, formal interstate trade arrangements did not exist. An informal arrangement existed for properties held by a single owner in both States to use water associated with their licences in the other State.

The 2008 IGA includes provisions for interstate trade between NSW and Qld, which began as a trial in 2009/10. Two methods have been trialled: (1) interstate traded water is counted against the licence from which the water was purchased; (2) the traded water is counted against the licence which purchased the water.

The accounting arrangements are being reviewed and updated as part of Water Resource Plan development under the Basin Plan.

7.4.1 Data sources

Records for all water trading are maintained by WaterNSW in the Continuous Accounting database prior to 2009, and in the WAS from 2009 onwards.

Figure 20 shows the number of permanent trades and the number of shares transferred within NSW from 2009/10 to 2015/16. Figure 21 shows temporary trading within NSW, as well as interstate trade. All licence categories (including supplementary) are included. In all years there is a net trade out to Qld. From Figure 21, it can be seen that the general direction of temporary trade is from NSW to Qld.

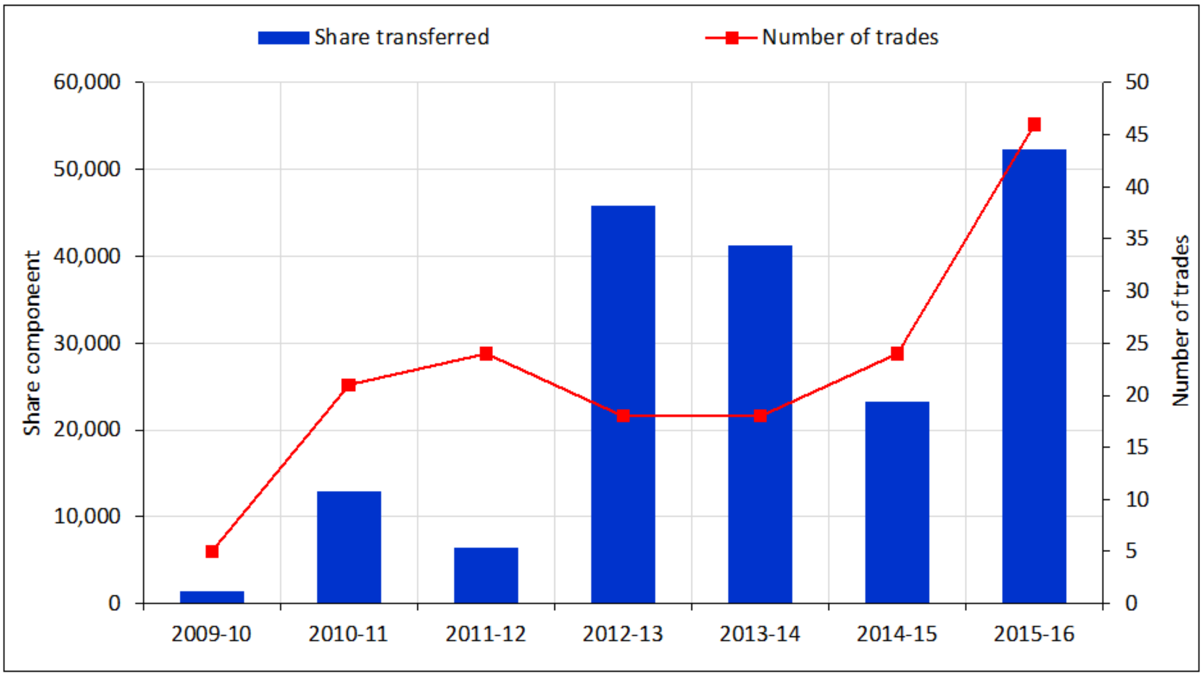

Figure 20 Annual permanent trade of licence shares (permitted within NSW only) from 2019/10 to 2015/16

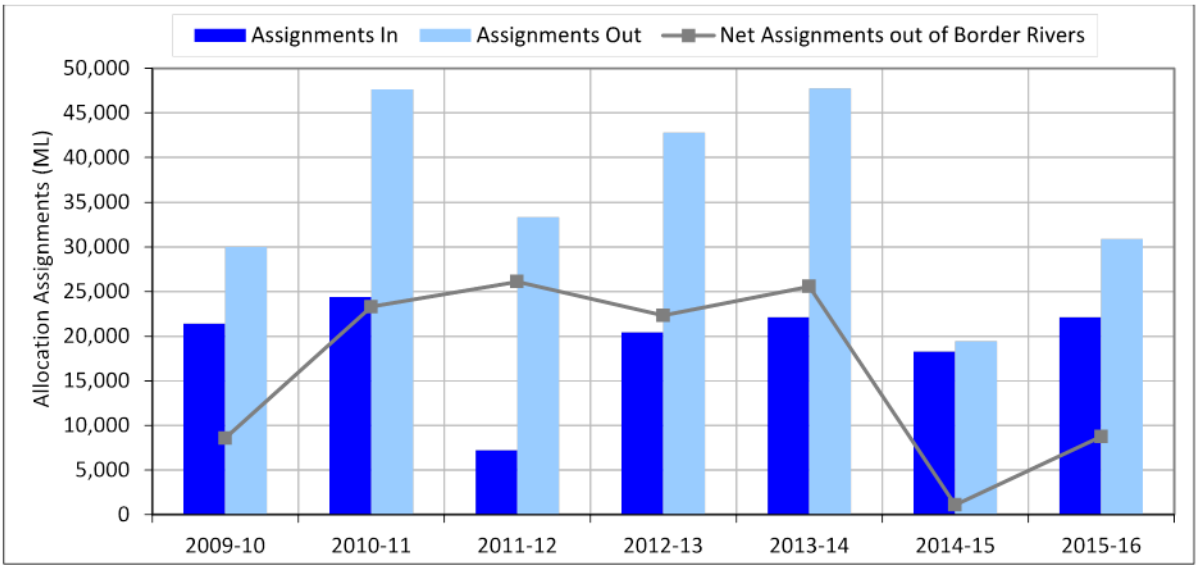

Figure 21 Annual temporary (including interstate) trade of allocations (volumes) from 2009/10 to 2015/16

Prior to 2009, trade data are incomplete for individual licences, with no date of trade recorded.

7.4.2 Modelling approach

Water trading is not explicitly represented in the model. When assessing the results of the model (section 8), any water trading that was occurring is taken into account. Temporary trades have been approximated in the initial model development by treating them like a change in permanent entitlement. This was necessary due to data limitations (no date of trade prior to 2009) and also software limitations. While assessing the results of individual farms, the effect of error in representation of temporary trade was considered.

7.5 Planned environmental water

Under the 2008 IGA, NSW and Qld use their State shares of water to provide for environmental flows as specified in their respective statutory water plans, including additional environmental flow requirements at Pindari Dam and Coolmunda Dam. These provisions and how they are implemented are summarised in Table 30.

Table 30 Key environmental flow provisions and how they are implemented

Environmental flow provision	Description
Minimum flow thresholds that must be exceeded before announcing access under supplementary water access licences (NSW) and unsupplemented allocations (Qld)	Seasonal minimum flow rates or volumes are set below: Pindari Dam, Glenlyon Dam, and the confluence of the Macintyre and Dumaresq Rivers (see section 5.3)
Minimum flow at Mungindi during uncontrolled flow periods to improve low flows at the end of the Border Rivers system to support a healthy riverine environment	Access to flows under supplementary water access licences (NSW) and unsupplemented allocations (Qld) must be restricted to ensure a minimum flow of 100 ML/day at Mungindi during uncontrolled flow periods between 1 September and 31 March
Translucent releases from Coolmunda Dam	Inflows to Coolmunda Dam will be released up to a limit of 100 ML/day
A minimum flow requirement below Pindari Dam to maintain connectivity between downstream pools and riffles	A minimum daily volume of 10 ML must be released from Pindari Dam
Translucent releases from Pindari Dam	Limit on release of inflows to Pindari Dam: September to May: <= 50 ML/day June to August: <= 200 ML/day
‘Stimulus flow’ release from Pindari Dam	4000 ML is set aside each year to be used for a ‘stimulus’ flow release from Pindari Dam, which may be made between August and December, with the aim of providing a flow in the river that mirrors a naturally occurring hydrograph, targets pre-season cues to fish breeding and to regularly wet and inundate interconnected riparian areas A stimulus flow must be released when inflow is greater than 1200 ML on any day between April and August – otherwise the water set aside may be carried over once only and used in the following year. The height and peak of stimulus flows released have varied from year to year, to target specific environmental outcomes. The Commonwealth also holds licences to use for environmental purposes in the Border Rivers (as described in section 6.3.2) and, on occasion, the stimulus flow has been released in conjunction with this Commonwealth held water.

Water released under the Pindari Dam minimum release rules described in Table 30 are protected to the confluence of the Severn River and Frazers Creek but may be used, in part or full, to meet orders from water users downstream of the confluence.

If there were an inflow into the dam greater than 1200 ML/day on any day between April and August, then a stimulus flow must be released from Pindari Dam in that year, but the water set aside may otherwise be carried over once only and used in the following year. The height and peak of stimulus flows released have varied from year to year, to target specific environmental outcomes. The Commonwealth also holds licences to use for environmental purposes in the Border Rivers (as described in section 6.3.2) and, on occasion, the stimulus flow has been released in conjunction with this Commonwealth held water.

7.5.1 Sources of data

WaterNSW prepares reports on compliance with environmental flow rules set out in the 2008 IGA for the BRC on an event basis (for supplementary flow sharing), and on an annual basis. These reports set out the volumes of flow for individual events, how much of that water was diverted by licensed water users, and how much water flowed out of the regulated river system.

WaterNSW also prepares reports on compliance with the Pindari Dam environmental flow rules as part of the annual compliance review undertaken by the department. These reports describe the releases made to satisfy the environmental flow rules, and any departures from the required releases for operational reasons.

7.5.2 Modelling approach

Environmental flow rules to represent environmental releases described in NSW Border Rivers WSP and Qld Resource Operations Plan have been configured into the model as described in Table 31.

Table 31 Configuration of key environmental flow provisions in the model

Environmental flow provision	Configuration
Minimum flow thresholds that must be exceeded before announcing access under supplementary water access (NSW) / unsupplemented allocation (Qld) licences	The IGA requirement limits access to any supplementary flow event based on flows over a 2-day period at Goondiwindi. The 2-day flow at Goondiwindi has been configured as: • Today's flow + 1.09*[flows at Booba Sands + flows at Roseneath + flows at Holdfast] This relationship was derived using recorded data and further checked by comparing simulated periods to actual announcements. Details on the flow triggers were described in section 5.3. These rules are all defined at off allocation nodes in Source
Minimum flow at Mungindi during uncontrolled flow periods	Based on advice from river operators, Boggabilla Weir releases are the minimum of tributary inflows and 200 ML/day during uncontrolled flow periods Set via a non-extractive demand (1802 D SP Environmental Demand[18]) below Boggabilla Weir in the model
Translucent releases from Coolmunda Dam	Modelled using a splitter node upstream of Coolmunda Dam, which redirects the appropriate inflows around Coolmunda Dam. These flows re-join the Macintyre Brook directly below Coolmunda Dam
A minimum flow requirement below Pindari Dam	This rule is included in the minimum flow requirement which also covers the translucent release rules from Pindari

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[18] This is the label of the demand node in the Source model

Environmental flow provision	Configuration
Translucent releases from Pindari Dam	Defined in the model through a Minimum Flow Requirement Node (2029 P Translucency Demand[18]). This approach means that if regulated releases for downstream demands are greater than the translucency requirement, then no additional release is required
'Stimulus flow' release from Pindari Dam	Configured from April to August, when dam inflow exceeds 1200ML/day, by making an order based on the 2013 stimulus event. The event volume has been set to equal the account balance, which is typically 4000 ML, but can be up to 8000 ML. As there are currently no prescribed rules to determine what kind of release should be made in any one year, a single release type has been assumed in the modelling[19]. The model assumes the following logic for stimulus releases: • releases only occur if the Pindari inflow trigger is met • the shape of the 2013 proposed release has been used with a start date of 1 October (Table 32) • if carryover has occurred in the previous year, the release is scaled up to release the account balance i.e. up to 8000 ML release.

Table 32 Assumed hydrograph shape for environmental flow release

Date	Release (ML/d)
01 Oct	125
02 Oct	250
03 Oct	500
04 Oct	1000
05 Oct	500
06 Oct	325
07 Oct	625
08 Oct	375
09 Oct	200
10 Oct	100

7.6 Storage and weir operation

Releases from Glenlyon and Pindari dams and access to water for licensed water users and other statutory purposes are managed by WaterNSW who, every day, set a release rate from each major storage to meet downstream water requirements. The releases are optimised to meet downstream demands for water without any unnecessary flows passing out the end of the regulated system (referred to as operational surplus). There are many factors to take into account when setting these daily releases, including water orders, other flow requirements,

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[19] This review was developed in consultation with departmental officers involved in stimulus release decisions at the time of calibration.

short-term forecasts of weather and inflows; and that the travel time for flows to reach the lower end of the regulated river system can take up to 2 weeks. Releases are particularly sensitive to operational forecasts of inflows from downstream tributary streams.

Releases (known as harmony operations) of water from Glenlyon Dam and Pindari Dam are coordinated to:

- minimise the likelihood of one dam filling before the other, and leading to spills of water owned by NSW that could be avoided or reduced
- ensure that each storage can meet supply commitments in the river reaches where it is the sole source of supply.

Releases from Coolmunda Dam are managed separately by SunWater.

The BRC has also developed standing operating procedures for Boggabilla Weir to capture unregulated tributary inflows when possible while maintaining the weir pool within a target operating range. This target operating range is set to balance the ability to capture tributary inflows with the ability to supply downstream requirements and stay within local operating limits. Unregulated tributary inflows are allowed to pass through the weir once the water level has reached the upper bound of the target range. The exception is when an unregulated inflow occurs within a month of the start of the irrigation season – in this case operators can store water in the Weir above the target range. From April to August each year, the weir pool level may be allowed to fall to low levels during periods of low or no flows.

The rate of the drawdown of the Boggabilla Weir pool is also managed to ensure it does not exceed 0.5 m/day.

7.6.1 Data sources

In addition to the volumes in storage and the releases made at each Dam and Weir that are recorded with other flow information, WaterNSW maintains a spreadsheet-based decision support system known as Computer-Aided River Operations (CAiRO), which has an associated database of the water orders and flow requirements that were used to determine target releases from each storage, and any target storage level at Boggabilla Weir. The CAiRO database records the various elements used to inform the release from the major storages each day, including forecasts of tributary inflows and transmission losses.

The operational staff at each major dam also maintain ancillary records, such as which valves or outlets were used to make the target releases each day.

At Boggabilla Weir, the gate openings, upstream and downstream water levels are continuously logged. Storage levels are also stored in Hydstra.

7.6.2 Modelling approach

Storage operation

Use of tributary inflows

The model takes into account forecasted inflows when determining how much water needs to be released from Pindari Dam or Glenlyon Dam to meet orders, reflecting operator practice. This part of the model is based on the IQQM parameters, which were configured using advice from WaterNSW river operators.

The model allows us to forecast a rate of inflow from an unregulated tributary based on the previous timestep flow. The forecasted inflow is defined as yesterday’s inflow multiplied by a factor. The adopted values are summarised in Table 33. For headwater inflows, the forecast rate was generally 1, which means inflows are assumed to be 100% of yesterday’s flow when determining how much regulated water should be released. The factors adopted in the model are listed in Table 33. Confluences with a forecast inflow of zero are not shown in Table 33.

Table 33 Adopted tributary recession factors to forecast rate of inflow from unregulated tributaries

Node name	Tributary recession factor (trend forecast rate)
0158 G Severn Dumaresq Confluence	1
0160 G Mole Dumaresq Confluence	1
0428 B Beardy Dumaresq Confluence	1
0435 D Oaky Dumaresq Confluence	1
0441 D Brush Dumaresq Confluence	1
0446 D Campbells Dumaresq Confluence	1
1807 D Macintyre Brook Dumaresq	0.5
0175 P Severn Frazers Confluence	0.5
0177 S Severn Macintyre Confluence	0.3
0180 S Ottleys Macintyre Confluence	0
0092 M Callandoon Return Confluence	1
0169 M Weir Macintyre Confluence	1

Harmony rules

The model uses a harmony rule at the Macintyre-Dumaresq confluence to control whether NSW water orders are sent to Pindari Dam or Glenlyon Dam. This rule was derived through prior modelling to minimised spills from both dams and is illustrated in Figure 22. The harmony line defines the target; for example, if there is currently ‘too much water in Pindari’ then orders will be sent to Glenlyon Dam.

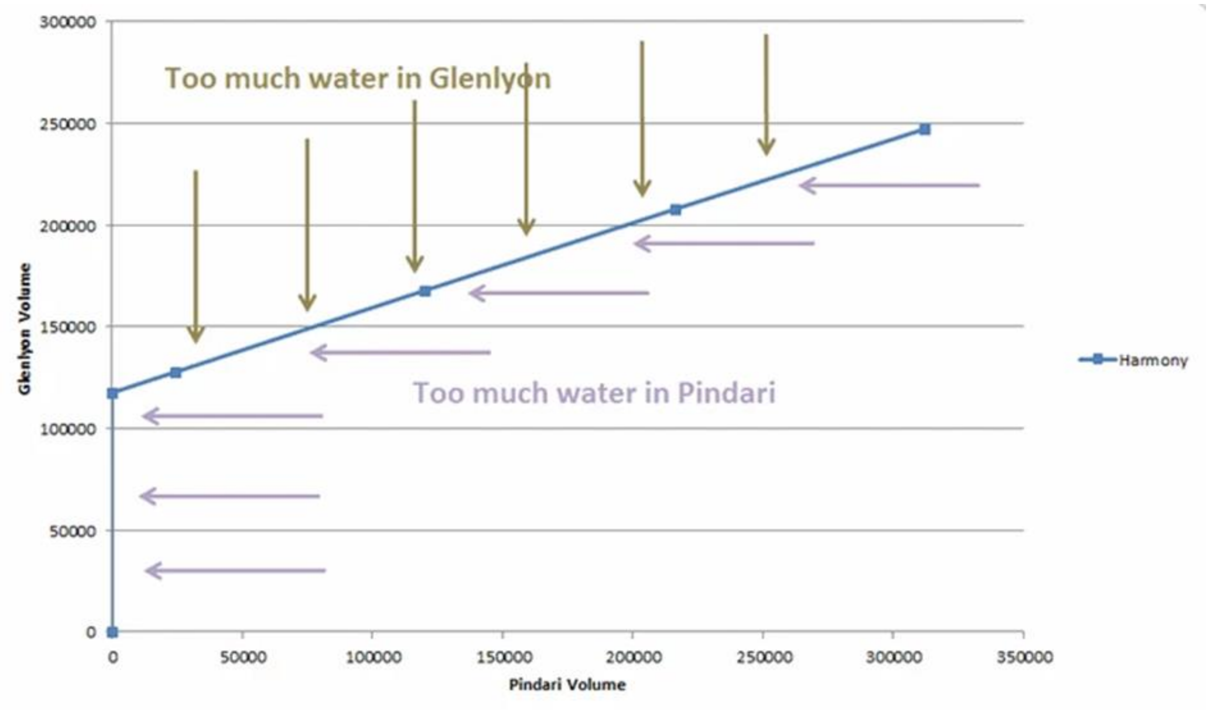

Figure 22 Adopted storage harmony rule at the Macintyre-Dumaresq confluence

Weirs and regulators operation

The configuration of the operation of Boggabilla Weir under the BRC Standing Operating Procedures is described in Table 34.

Table 34 Model representation of Boggabilla Weir operations

Component	Model representation
Target operating range in irrigation season	Simplified monthly pattern is used based on typical operations
Target range in winter / flood operations	Maximum operating constraint defined by a simplified monthly pattern Target increased to FSL in August to better reflect history of operation
Use of unregulated tributary inflows	Can fill up to the maximum operating constraint Releases are set via a downstream Node (1803 D Environmental Demand M12) to the minimum of tributary inflows and 200 ML/day
Rate of drawdown	Not represented, as it is not expected to be significant for long-term simulations

Boomi regulator operation

The Boomi River is a natural effluent of the Macintyre River, with a regulator constructed across it adjacent to the Macintyre River. This regulator is represented through a regulated splitter node. These nodes include a minimum and maximum flow relationship compared to the simulated flow into the Boomi Weir pool upstream of the Node.

The maximum flow relationship represents flows down the effluent when the dropboards have been removed from the regulator. The maximum flow relationship is normally used to represent infrastructure limitations for delivering regulated water where ordered down an effluent. However, for the Boomi no such restrictions are applied as the only targeted diversions into the Boomi River are for the stock and domestic replenishments each year made at relatively low rates. The minimum flow relationship represents uncontrolled flows down the effluent when the dropboards are in place. This relationship has been established by deriving a relationship between simulated flows upstream of the Boomi effluent and gauged flows at Boomi River at Offtake (416037).

Operation of the regulator is only simulated where water is ordered on the effluent. Orders for stock and domestic replenishment flows have been represented through a minimum flow requirement node. The operation of the Boomi offtake is modelled in accordance with the IGA rules as summarised in Table 35.

Table 35 Model representation of operation of Boomi regulator

Rule	Model parameterisation
Water may be diverted from regulated flows into the Boomi River for domestic and stock replenishment as part of NSW share of flows.	Based on observed replenishment flows, a Minimum Flow Requirement Node (0145'Boomi Replenishment 1) was configured as follows: order water if Boomi offtake flows < 2000 ML in the last 140 days • Dec–Mar, order 110 ML/day • Aug–Oct, order 80 ML/day • cap annual orders at 10 GL
All boards will remain in place to maintain the Mungindi target flows (100 ML/day in prescribed circumstances)	No explicit modelling as boards are modelled as being in place
When flows in the Macintyre River are in excess of those required to maintain the Mungindi target flow, but less than those required for supplementary access, water may be diverted at the Boomi Offtake up to 25% of the flow in the Macintyre River at Boomi Weir	Based on observed flows, a minimum flow requirement node (0124 M Boomi Unreg Flow MFR) orders 7% of the flow upstream of the Boomi offtake outside of supplementary flow events. If there are Boomi replenishment orders, this volume is subtracted from the unregulated flow order
WaterNSW have advised that during a declared supplementary event they do not remove the boards at the regulator, so flows won't enter the Boomi until 1100–1200 ML/day is reached and they are then overtopped	The overtopping of boards is represented through the breakout minimum flow relationship which starts at 1100 ML/day A very small breakout has been defined below this based on recorded data

Other regulators

Callandoon and the Lower Weir below Newinga are both configured as unregulated branches. The Newinga regulator has generally been operated with the boards out so the model reflects the history of operation. The delivery of water to Callandoon users is represented as a direct connection upstream of the Callandoon breakout. The breakout relationship therefore just represents overtopping of the regulator.

8 Model assessment

8.1 Overview

This section reports the results of:

- the calibration of the component models, i.e. how well the modelled flow matched observed flows
- the fully assembled Border Rivers Valley river system model.

For flow calibration, it is important to replicate various parts of the flow regime, especially medium to high flow events that break the banks and flow overland onto the floodplain.

We measured whether there is sufficient water from all sources, including floodplain harvesting, to irrigate the historical crops, at valley, reach and property scale (some variation is allowed for given known differences in irrigation behaviour, potential inaccuracy of metered diversions and historic ineligible harvesting).

Appendix M details which version of the model has been used to report results in this section.

8.1.1 Model assessment criteria

We have designed a suite of numerical and graphical indicators to evaluate how well the component models and the complete model have met objectives and design criteria (as set out in section 2.1). They were selected on their ability to:

- meaningfully determine the relative performance of the model, i.e. ability to be confident that, based on the metric, can determine whether model performance is better or worse than an alternate model
- measure how well the model reproduces system behaviour – e.g. inflows, diversions, flow distribution – necessary to meet the modelling objectives, i.e. its ‘goodness-of-fit’.

There are many that meet these requirements, including comparisons of means, or some goodness of fit metrics for sets of corresponding data pairs. However, we have found that some standard goodness-of-fit metrics can be misleading in determining relative performance, e.g. where getting a model right during dry periods, for example, is more important than during wet periods and the metric measures across the whole model. A possible solution to this shortcoming is using more than one metric, e.g., one for wet and one for dry, or try to customise a metric that satisfactorily describes both. Often having multiple metrics describing an aspect of model performance can be beneficial, and we have taken this approach where necessary.

As well as getting the ‘big terms’ (i.e. average annual inflows, diversions, and end of system flows) correct, getting their distributions correct is equally important, i.e. we want our models to reproduce inflows, diversions and outflows well in wet and dry periods. It is not possible to replicate every historical flow event; however, the overall characteristics such as frequency of low, medium and high flows as well as replicating wet and dry periods are important.

We have selected graphical techniques which implicitly factor in multiple model metrics. Some examples include time-independent distributions such as comparisons of modelled v observed results as either; an exceedance graph; and/or a time series at daily or longer time steps; and/or the spatial distribution of results. For modelling practitioners, this is a more intuitive way to assess model performance, but not as simple to describe the conclusions from these assessments without including significant background information learned from modelling experience. In these cases, we include key graphs indicating model performance and describing relevant characteristics.

The assessment criteria/methods are summarised in Table 36.

Table 36 Overview of assessment criteria

Component	Performance test	Metrics and/or visuals
Flow simulation for headwater inflow and main river	How well long-term average volumes are replicated, especially medium to high flow events, as well as daily and interannual variability	Summary statistics listed in Table 37)
Water use simulation		
Crop water use	How well total irrigation water use is estimated	Model configured to 2 availability conditions to allow comparison to 4 other data sources
Runoff harvesting	How well runoff from developed and undeveloped areas on farm is simulated	Rainfall–runoff rates from fallow and irrigated areas Interannual variability in runoff depth
Overbank flow harvesting	How well frequency and volume of overbank flows are simulated	Observed vs modelled commence to flood and moderate flood events
Total irrigation water use (farm water balance)	How well metered diversions are reproduced at valley and reach scale and how well historic irrigation areas are reproduced	Observed vs modelled & measure of model bias (%) Sensitivity testing to variations in simulated crop water demand
Planted areas	How well historic irrigated areas are simulated	Annual total crop area compared to 2003–2014 farm survey data; filtered to exclude gaps in survey record
Metered diversions	How well general security and supplementary access metered diversions are simulated	Total, general security & supplementary access diversions over full 2003/04 to 2013/14 period (and first 4 and second 6 years of this period) compared to observed, model bias (%) metric
Supplementary access diversions	How well announced periods of supplementary access	Graphical comparison to announced periods
Storage operation & harmony management	How well storage volumes are simulated	Daily time series of storage volumes compared to observed
Weirs and regulators operation	How well flows into Boomi River are simulated	Monthly average flows compared to recorded lows

8.1.2 Model validation

The last step in the flow calibration process was to develop a validation model by amalgamating the individual reach models. The validation model is used to confirm the performance and accuracy of the model run as a complete system and provides a foundation for the development of scenario models.

The validation model is configured to simulate the historical behaviour of the system, such that model flows can be meaningfully compared to historical streamflow gauge records throughout the system. To achieve this, releases from headwater storages are forced to recorded data and diversions are also forced using metered data.

For headwater gauges, the Sacramento results are compared to recorded flows. For main river gauges, the results are generally based on using the final flow data inputs, which are a combination of gauged flows and Sacramento flows to extend and fill gaps. Appendix I also includes a second type of validation test for these gauges, where inputs are based on Sacramento model results only.

The model that we have assembled using various calibrated model elements has been configured as a scenario that is representative of the assessment period. This allows us to evaluate the overall model performance by comparing model results with observed data over the period of calibration. For this Border Rivers Valley river system model, the diversions and water management components have been assessed over the period 2003 to 2014, which is a period that also includes key benchmark years for the policy and the Basin Plan. To ensure that our assembled model is able to simulate all of the key processes (flows, diversions, water management), a scenario has been configured to represent the 2008/09 level of development[20]. We refer to this as the 2008/09 Scenario.

The 2008/09 water year was selected for this validation scenario as it is in the middle of the assessment period for many of the model components, and it represents a key date for the issuing of floodplain harvesting licences (only floodplain harvesting works constructed or applied for by 3 July 2008 are eligible for consideration) and the Basin Plan (1 July 2009 is the baseline point from which the requirements of the Basin Plan were set).

We know that there were some changes in irrigation infrastructure development over the period 2003 to 2014. However, in the NSW Border Rivers, there was very little change in irrigation development levels between 2008/09 and 2015/16. Whilst there was some irrigation infrastructure development between 2003/04 and 2008/09, mainly for floodplain harvesting activities, there are only small volumes of floodplain harvesting simulated in the first few years, and it is likely that water availability, rather than infrastructure, is the constraint in this period.

We considered any changes in irrigation infrastructure and water management rules that actually occurred over the comparison period when reviewing results[21].

8.2 Flow simulation assessment

The quality of the calibration of simulated flow influences the overall model performance. Several characteristics of the flow regime are important, overall volumes, distribution across the full flow range from low to high, daily variability, and interannual variability in particular. The methods to calibrate the models are intended to reproduce those characteristics.

The department and Qld have developed a workflow to standardise the reporting of results for all flow comparisons. The results include multiple metrics as no single metric alone can inform the suitability of a model result for a particular purpose. Key metrics are listed in Table 37. A subset of results from the workflow reporting is described below and summarised in Appendix K for all flow calibrations.

These multiple lines of evidence are presented as a report card (Figure 23) and show the degree to which the model has reproduced the quantity, distribution, and variability of streamflow that affects water availability for allocation, as well as instream variability for supplementary access, overbank flow harvesting, and environmental flows.

Further information on events is presented at section 8.3.1 for a key location at Goondiwindi that demonstrates how well daily variability relevant to overbank flows has been reproduced.

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[20] This scenario is configured with all eligible storages, which includes one storage built post 2008.

[21] Early calibration models forced infrastructure changes over time.

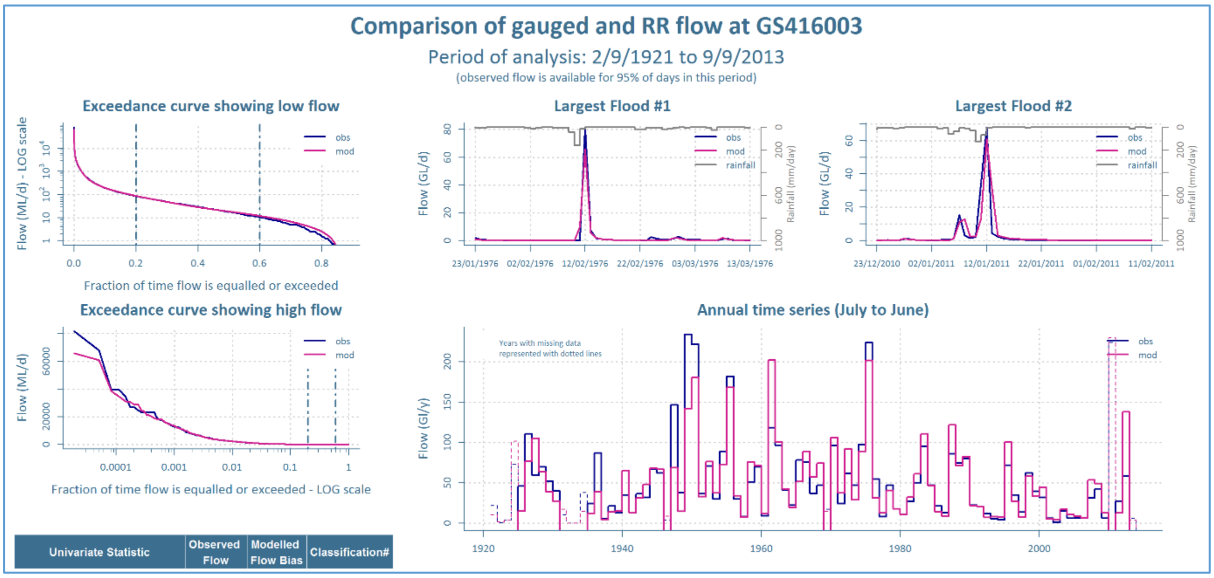

Figure 23 Example of graphical comparison of flow calibration reported in Appendix K

Table 37 Flow metrics used to assess flow calibration

Metric	Importance
Tabular metrics	
Station Number	Identifier and location
Mean Annual Flow (MAF)	Relative importance to total flow. For comparative purpose, values in Appendix J are over the full simulated period and not the observed data period. Other comparisons are modelled v observed
Runoff % of rainfall	Confidence in water balance if spatially coherent and within published ranges for rainfall v evaporation
Daily Nash Sutcliffe	Goodness of fit modelled to observed – sensitive to high values and timing offsets
Flow bias – full range	Overall volume match – important for storage filling and overall water balance
Flow bias – low range	Volume match in low flow range (upper threshold defined in flow exceedance graph)
Flow bias – medium range	Volume match in medium flow range (between high and low flow ranges)
Flow bias – high range	Volume match to in high flow range (threshold defined in flow exceedance graphs)
Graphical metrics	
Flow exceedance – full	Distribution of flows – indication of degree of match for all flow ranges
Flow exceedance – high	Distribution of highest flows – indications for flood events
Flood hydrographs	Shapes of hydrographs well represented – flow components work together
Annual time series	Wet and dry years appropriately simulated for flood and drought sequences

8.2.1 Headwater inflow rainfall–runoff modelling

These results refer to Appendix K with reference to the flow metrics listed in Table 37.

Mean annual flows for the catchments range from 8–96 GL/y, and collectively account for 724 GL/year of inflow, with runoff coefficients in the range 3.2–9.5%. These runoff coefficients have a west–east increasing trend, reflecting the rainfall gradient. The spatial coherence of these demonstrates the robustness of the rainfall–runoff modelling process, as the major water balance components of rainfall and evapotranspiration are varying in a structured way.

Daily Nash-Sutcliffe values ranged from 0.5 to 0.85, with the exception of one small catchment (416312a) which had a result of 0.39[22]. These results are influenced most of all by the representativeness of the rainfall data used, which may mean that individual events are not well represented. What is important however, is that the distribution of flows is well represented. In the case of gauge 416312a the flow distribution and inter-annual variability have a close match to gauged data with the exception that the extreme events are over-estimated. The importance of this result varies depending on the location of the station, and main purpose within the model calculation. In the case of 416312a, given that it is a small catchment below the headwater storages, this over-estimate is not likely to be significant.

Flow biases across the full flow range are in most cases 0.0%, with two exceptions the largest being 2.5% of observed in total. This close match is not surprising as flow bias has a high weighting in the automated process. The distribution across the flow ranges varies considerably more, with in most cases overestimates of 10–30% for the low flow range. The discrepancies are much less for the medium flow range (mostly less than +/- 7%) and for the high flow range (mostly less than +/- 2%). The larger discrepancies in the low flow range are not a great concern in the context of the model suitability. In the worst case, this describes flows less than 2 ML/day for a tributary in the lower reaches and would not affect operational decisions or water availability calculations.

There is a close match of the **flow exceedance** graphs however some divergence does occur for extreme high and flow flows (Figure 48 to Figure 63). The matching of the highest flows is difficult as it is particularly sensitive to rainfall totals on rare events. The inter-annual variability also matches closely in most cases, where the patterns of high and low observed total flows are matched by the simulated flow.

8.2.2 Main river flow simulation

These results refer to Table 59 and Figure 64 to Figure 77 in Appendix K with reference to the flow metrics described in Table 37. The results are for the fully assembled flow calibration model. This is referred to as the Validation model as described earlier.

Mean annual flows at these gauging locations vary in the range 103 to 856 GL/year. These values are higher than for headwater inflows but represent larger catchment areas as flow accumulates along the system, as well as the effect of transmission losses and effluents in the reaches from just upstream of Goondiwindi.

Daily Nash Sutcliffe values range from 0.7–1.0, with mean value of 0.80. These high values are one line of evidence that provides us with confidence that mainstream flows are simulated well.

Overall **flow bias** ranges from -10% to +16% and reflect the bias in the high flow range. Examination of the related **graphs** indicate that this is heavily weighted to a few days. For example, the negative (underestimated) high flow bias at Mungindi at the end of the system can

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[22] While this is a low NSE, it is very small catchment so has negligible influence on overall result. The catchment does have a gravel control which may be the contributing factor.

be attributed to 0.02% of days, particularly the February 1976 flood. Consideration should also be given to the uncertainty in the measured high flow rating, with the highest gauging at Mungindi only 33% of the high recorded flow. The annual time series shows the inter-annual variability is reproduced, with a few high volume years in the late 1950s and 1976 underestimated compared with gauged flows. The rest of the flow distribution matches observed well above 100 ML/day (flow bias -1%), but overestimates below that.

The **medium range flow** results indicate significant overestimation for Macintyre Brook @ Inglewood (416402B/C) and Macintyre River @ Boonanga Bridge (416046). The Boonanga data were only compared over a 3 year period, which would affect the reliability of this comparison. The Inglewood result warrants some further investigation however it is not likely to have an influence on NSW results as this gauge is in the Macintyre Brook.

The graphical comparisons in Figure 64 to Figure 77 provide a summary of model performance. **Interannual variability** is closely reproduced in all cases. There is also close match of the **flow exceedance** graphs, except at the extremes which diverge in some cases. On examination of the hydrographs and gauging records, some of this divergence can be attributed to flow breakouts, some to rating table uncertainty, and some can be attributed to rainfall representativeness in the rainfall–runoff models used. The **low flows** most affected are those at less than 10 ML/day. This may be important for some applications and scenarios, however, not for overbank flow diversions.

8.3 Water use simulation assessment

8.3.1 Irrigation

Modelled crop water use

Our approach to estimating irrigation water use was described in section 6.2.2. The many parameters in the crop models used to simulate irrigated water demand were consistently configured to established values from industry and research advice. This was done in preference to calibrating to highly uncertain data for each individual property or group.

The available literature on average irrigation requirements uses variable definitions (i.e. whether it includes some or all losses) which makes comparison difficult. Publications which include data from large areas and over short periods of time also make it difficult to compare as different climatic conditions in each season need to be taken into account in order to compare to model assumptions. These comparisons are briefly made in the remainder of this section, with further detail in Appendix I .

Four independent data sources or methods have been used to assess the model estimates; farm surveys, WaterShed Pro software, IrriSAT remote sensed data, and Australian Bureau of Statistics (ABS) data. The model was configured to two different water availability conditions to enable comparison with these:

- with no restrictions
- with restrictions as estimated within the Border Rivers Valley river system model.

The first test allows for comparison of the theoretical irrigation water use to WaterSched Pro. In practice, full irrigation may not occur during dry years. The second test allows comparisons to be made to published data on actual application rates (e.g. ABS and IrriSAT).

Test 1: comparison with WaterSched Pro

In the first test, a simple model was set up with 1ha of cotton crop area and water use was simulated using a long term period of climate data. This test model has been used to calculate the simulated irrigation water use as a volume of water per hectare (ML/ha). The modelled application rates were defined as follows:

- includes application losses
- excludes rainfall, on-farm storage losses and tailwater returns.

Using climate data for Boomi, from 1950–2014, an average of 8.7 ML/ha irrigation water is applied to cotton using this test model. The model assumes that 30% of this water is lost between the water source and the crop water use. Removing the 30% loss means that cotton uses 6.1 ML/ha of irrigation water on a long-term average basis, in addition to effective rainfall.

This test was compared to WaterSched Pro. This is an industry developed tool that provides an estimate of crop water use, assuming an unrestricted water supply and FAO crop method.

The results for cotton (test 1) compare well to the modelled results after adjusting for pre-watering.

Test 2: comparison with ABS data

In the second test, average irrigation application for cotton is 7.4 ML/ha over the period 2005/06 to 2013/14. This has been compared to ABS data in this period for cotton irrigation application rates across the Gwydir and Border Rivers. Modelled results are higher than ABS data in some years, which is not surprising given the large areas covered in the ABS reporting region.

Test 3: comparison with farm survey data

The farm surveys resulted in a range of reported application rates, from 3.6–11.5 ML/ha with an average of 7.9 ML/ha. Further detail is discussed in Appendix I . It is difficult to compare the survey data to modelled given this wide range and given that the relevant period these reported figures were averaged over is not known.

Test 4: comparison with IrriSAT

The IrriSAT website[23] publishes estimates of crop factors and actual ET, and the data can be assessed down to a paddock scale. Some sample areas have been assessed and compared to modelled data for the 2017/18 year. Kc values estimated by IrriSAT near Goondiwindi closely approximate those values used in the Border Rivers Valley river system model. Sample estimates of actual ET were also obtained from IrriSAT and compared to the model results for 2017/18 year, indicating that the modelled ET estimate compares well around Goondiwindi and Mungindi, but is possibly underestimating by about 10% around Boomi.

All methods described above have their own sources of uncertainty as truly representing both long-term averages. These sources all provided estimates similar to that of the modelled values and provide confidence that this is a robust estimate. The dynamic representation of water availability from both climate and management provides an advantage for the Border Rivers Source model for the interannual variability.

Runoff harvesting

Runoff from developed and undeveloped areas on farm were simulated with climate variability and irrigation as inputs to a soil moisture accounting component model of the same crop water model used to determine irrigation application rates. This was described in section 5.4.2.

There is significant uncertainty in the simulation of rainfall–runoff from developed areas because:

- rainfall–runoff rates vary depending on site specific soil, land, and irrigation management practices (e.g. Haghnazari, 2015)

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[23] https://IrriSAT-cloud.appspot.com/#

- the simple daily model for simulating rainfall–runoff does not account for many factors which affect runoff, such as rainfall intensity.

Our simple model does not consider these factors. Soil moisture content appears to be the primary predictor of runoff response to after rainfall in areas with high water holding capacity (e.g. Freebairn et al., 2009), which is the case for most of the study area. Soil moisture is accounted for in the crop water model as it tracks changes resulting from rain, evapotranspiration, and irrigation on a daily basis. Therefore, limitations in the ability to account for rainfall intensity does not appear to be a significant issue for a long-term simulation period. These considerations led to our decision to match these to long term averages to the best available data sources available.

Simulated **rainfall–runoff rates** are summarised in Table 38. The runoff rates from both fallow and irrigated areas are in line with the results from the literature review described in Appendix F .

The **interannual variability in runoff depths** from climate variability is well represented (Figure 24). As well as reinforcing the relative rates of runoff response summarised in Table 38, this also shows a clear relationship of higher annual runoff depths with more annual rainfall for each land use type. Results for other gauges can be found in Appendix F .

Table 38 Rainfall–runoff rates for Boomi climate (calculated as total runoff over the period divided by total rainfall. The same parameters are applied for other climate stations however a small amount of variation occurs due to differences in rainfall characteristics)

Area	1950 to 2000
Summer irrigated + winter fallow	8.8%
Continuous fallow	4.1%
Undeveloped	2.1%

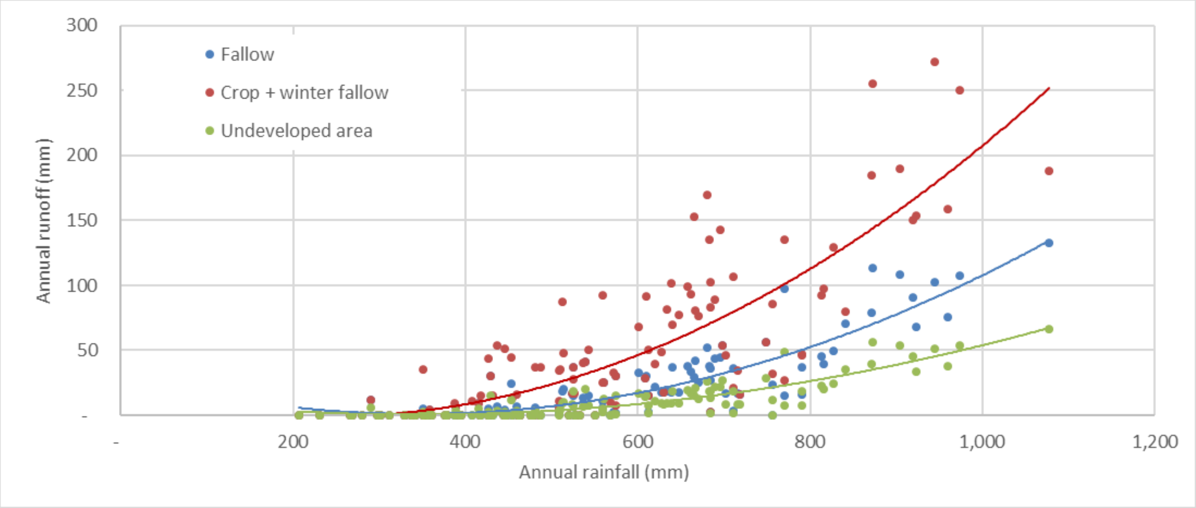

Figure 24 Annual runoff depth (mm) compared to annual rainfall (mm) for 3 on-farm land area types: fallow, crop + winter fallow, and undeveloped area

While the runoff depths are the best available, we acknowledge there is considerable uncertainty around this, and this uncertainty is largely because there is a paucity of data to indicate what the true value is.

Further data collection would be desirable to confirm the assumptions used noting that:

- data collection should be from properties with representative management practices
- collection should be over a number of years to compare to modelled estimates. The runoff coefficient can be very high in individual years (Figure 24). An average obtained over a short-term period is likely to have a different average runoff coefficient compared to the long term.
- bias in rainfall–runoff rates may be in part offset by a bias in overbank harvesting estimates. Any revision should consider data for both sources.

Overbank flow harvesting

The simulated volumes of overbank flow harvesting are affected by the simulation of flow breakouts as described in section 4.5 and the harvesting of those breakouts are described in section 6.2. The opportunity to harvest overbank flows depends in part on their frequency and volume. This ability of the model[24] to reproduce these is shown at Figure 25, with summary statistics reproduced at Table 39.

These show that the modelled **frequency of overbank flow events** closely matches the observed behaviour, particularly for the more recent 32 years. The number of **moderate flood events** since 1981 is close to observed and the number of **events above the commence to break flow** is the same as observed (Table 39). Prior to this period the modelled data has less events than observed flow data would indicate, however more weighting would be given to the more recent behaviour as there are better data for this period.

The analysis depends on what assumption is made about how to define separate events; this analysis used a 5 day interval (i.e. if 5 days separate flow above the threshold, they are defined as separate events). If two events occur within a few weeks of each other, it may make no difference to results as the storages may have already been filled. If a larger interval between events were assumed in this analysis, then the simulated and observed results would be a closer match.

Volumes above the commence to break threshold are close, with a -1% bias overall.

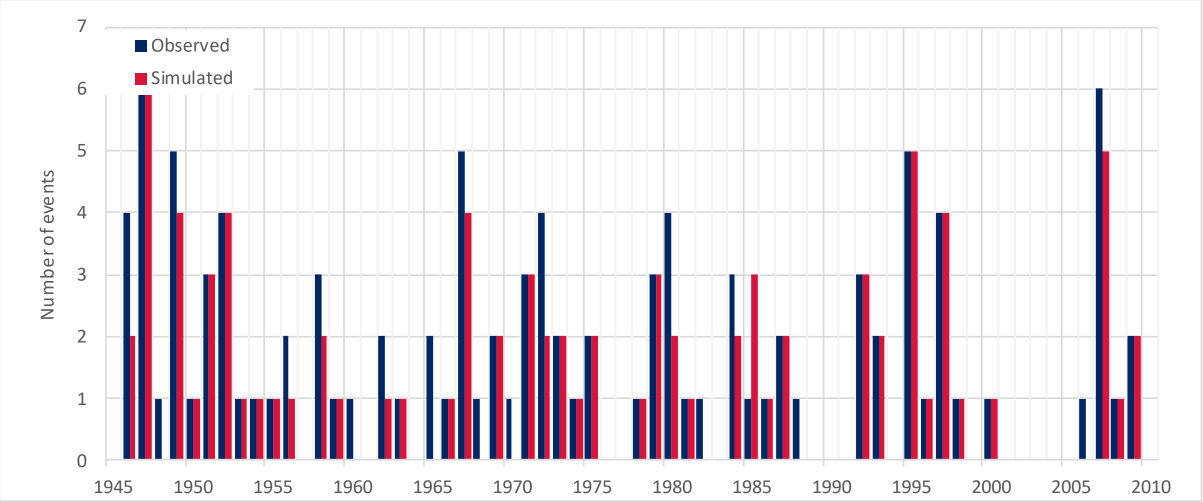

Figure 25 Annual modelled vs observed events @ Goondiwindi above moderate flood threshold

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[24] The flow validation model is used for this purpose as described in Appendix M

Table 39 Total observed vs modelled events @ Goondiwindi above breakout threshold

Periods	Observed	Modelled
Commence to flood events (>9,000 ML/day)		
1948–1980	132	120
1981–2013	67	67
Moderate flood events (>27,000 ML/day)		
1948–1980	71	53
1981–2013	35	33

Apart from the data that was analysed to form the breakout relationships, there is no further data that can be used to validate the volume on the floodplain during an event[25]. We have investigated whether it will be possible to use remote sensing data to estimate change in on-farm storage volumes over an event. This type of data could provide much more confidence in the estimates than simply looking at volumes on the floodplain, as not all water can be and is diverted[26]. Very high-resolution data are required to undertake this analysis and we found insufficient historical data to undertake this assessment immediately prior and post a floodplain harvesting event.

Irrigation water balance check

There was limited information from the surveys to compare total harvesting. The following summarises the comparison with commentary:

- Upstream of Goondiwindi, we simulated harvesting to within 10% of one property. The other two properties are under-estimated however they both have minimal access to overland flow. One of these properties has had historic ineligible unregulated flow access and the other reported rainfall harvesting which would require very high runoff coefficients.
- For six properties between Goondiwindi and Boomi, the model has a reasonable match to farm survey data in most instances during the wet period from 2010 to 2013. There was some under-estimation during dry years, however most of these properties have had ineligible historic access to within channel flows. Two properties reported very high harvesting in 2010/11 which did not appear feasible given the available infrastructure to store the reported harvesting. For one property, we estimate significantly more harvesting than reported, however the farm survey acknowledges their estimates for two years as ‘rough’. In several cases the final storage capacity estimate was significantly lower than reported in the farm survey and this may also account for some of the differences in estimates.

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[25] We have considered whether remote sensing might be used to estimate volumes of water on the floodplain. However given the uncertainties involved, and the need for volumes over the course of an event rather than on a single day, the method was not pursued. Remote sensing has been used however via the use of data from floodplain hydraulic models, as these have been calibrated using aerial photography and satellite imagery.

[26] Our long term model results indicate that the proportion of breakout water harvested ranged from 3-61% in each region. These results indicate that the breakout relationships are not a limiting factor in determining overall volumes harvested.

- One property downstream of Boomi reported harvesting. This was the longest period of reporting obtained from all farm surveys. We had some yearly differences in estimates however over the whole period (1996–2013) we estimated within 2% of the survey data.

Further checks of the overall water balance results are now discussed in more detail.

Farm water balance check

As an overall check for each individually represented irrigation enterprise, the simulated water balance in the model was checked against diversions. This checks how well the metered diversion components are reproduced. The remainder of the water taken by the farms is floodplain harvesting, combining rainfall–runoff harvesting and overbank flow harvesting.

The premise of this farm water balance check is that where the model simulates a realistic crop irrigation demand such as was reported earlier, then the combined metered diversions and floodplain harvesting should be sufficient to water the reported crop areas, to the extent that they were in practice. The crops may not always be fully irrigated and this is evident in the comparison between the two test models described earlier.

This test was completed using the 2007/08 to 2012/13 water years. Earlier years and the 2013/14 year were not included due to gaps in cropping data in the IBQ.

These checks were performed at 3 scales:

- whole-of-valley scale
- reach scale
- property scale.

Valley scale results should match observed metered diversion data well to provide confidence in the estimates of total floodplain harvesting, and therefore established whether the model can reliably update diversion limits for long term baseline scenarios. Table 40 shows that valley total results are close to the observed data, with no overall bias in estimating diversions.

Some of the properties have incomplete crop areas and one property had a large change in storage capacity; when these are filtered, the model bias is +2% as reported in the Revised total row in Table 40. Further detail on metered diversion components is discussed in section 8.3.3.

Table 40 Total metered diversions for floodplain harvesting properties (GL) (7/2007–6/2013)

Sub-region	Observed (GL)	Simulated (GL)	Model bias (%)
upstream Goondiwindi	187	190	+2%
Goondiwindi to Kanowna	490	486	-1%
Kanowna to Mungindi	118	116	-1%
Total	796	798	0%
Revised total	667	688	+2%

Reach scale results should be reasonable to indicate that the distribution between reaches is consistent. Table 40 shows that the bias is very similar between all reaches, hence there do not appear to be any distribution issues.

This water balance check at individual **property scale** was undertaken at various stages of calibration. In early stages of the calibration model components were forced to observed values over the comparison period (e.g. supplementary diversions), and at later stages these were replaced with simulated values.

Simulation of individually modelled irrigators was reviewed to check the following:

- the simulated metered diversions against metered diversion records
- farm survey information regarding periods and volumes of harvesting
- remote sensing information (e.g. cropping, water in on-farm storages)
- any recorded temporary trading of water (not simulated in the model) which may account for some properties running out of water in their account within the model.

These individual results are assessed for large anomalies, and if so whether there is a reasonable explanation. Other supporting information is also assessed; comparison to IBQ farm surveys, nearby properties, remote sensing etc.

We would not expect a perfect water balance to be achieved at all individual properties. There are several reasons for this. The method to parameterise the crop model uses assumptions about average irrigation water use to ensure that the valley scale results are robust. Given the reported variation in individual water use efficiencies, allowance was permitted for some variation in water balance results at individual properties. The accuracy of metered water use is also expected to vary and this may also cause differences in the water balance result as will any ineligible historic harvesting.

Individual results were interpreted as being good if the simulated diversions directly from the river (general security and supplementary) was within 10% of the recorded volumes over the 2007/08 to 2012/13 period. Approximately 70% of the individual results fell into this category. Individual results outside of this range were associated with a reasonable explanation such as temporary trading of water, account management transfers which were not well accounted for, or incomplete area records.

Around 30% of properties have modelled results which exceed observed by more than 10%. In these cases, the results could be indicative of the model under-estimating floodplain harvesting, however, in all these cases there was either a known issue[27], or other checks were acceptable (e.g. they compared closely to information in farm survey estimate or to reliability of nearby properties).

Some sensitivity testing was undertaken to confirm the sensitivity of the simulated floodplain harvesting to variations in the simulated crop water demand (see section 9). This found that if the irrigator is set up to use more water through either greater area planted or less efficiency, this increases airspace in on-farm storages and subsequently increases floodplain harvesting. However, the increase is relatively small (e.g. 0.6% increase in total harvesting as described in section 9). By using multiple sources of information to configure floodplain harvesting access, rather than relying on perfect water balance at individual properties, the determination of entitlements is not highly sensitive to individual differences in water use.

8.3.2 Planted areas

The Border Rivers Valley river system model estimates the area planted on the basis of water availability. Other factors such as markets also affect planting decisions, hence some variability between years is expected.

The crop areas from the final fully assembled Source calibration model using 2008/09 conditions were compared to the observed data over the 2003–2014 period.

The modelled **planted areas for individual properties** are in reasonable agreement with those reported in farm survey data (Figure 26). There are some gaps in the farm survey record and it is not clear whether no irrigated crop was grown or whether the area was unknown. For this

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[27] For example, temporary trading of water, account management transfers which were not well accounted for, incomplete area records or historic ineligible take

reason, the modelled data have been presented for both total crop area and for area filtered to exclude gaps in farm survey records.

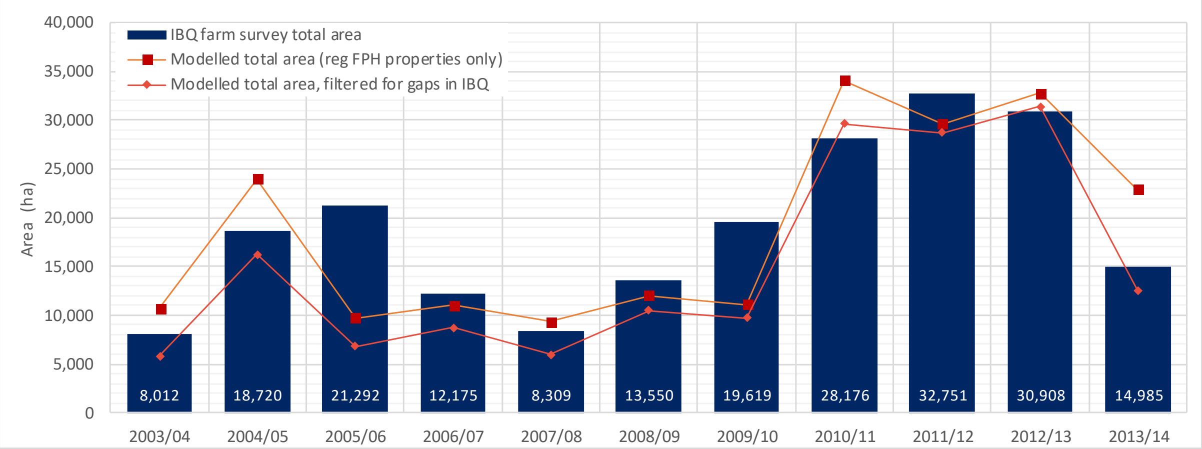

Figure 26 Observed (farm survey total) and modelled total and total filtered for gaps in the farm survey day for summer crop areas for floodplain harvesting properties

The calibrated model represents well the **seasonal variability in the area planted** in response to water availability. The biggest difference in summer planted areas occurs in 2005/06, which is due to carryover of water from the previous season. In some of the dry years, it appears that the model is under-estimating planted areas. This may be offsetting possible over-estimating of application rates in those years.

8.3.3 Metered diversions

Results of simulated diversions from the fully assembled, calibrated model for the 2008/09 validation scenarios were compared with recorded diversions. This scenario simulates all system operations and management rules such as supplementary announcements and general security allocations. The totals for the 2003/04 to 2013/14 comparison period are illustrated in Figure 27 with summary results reported in Table 41.

Table 41 Total simulated and observed metered diversions from 2003/04 to 2013/14

Diversion type	Observed diversions (GL)	Simulated diversions (GL)	Bias (%)
General security	957	933	-2%
Supplementary access	490	617	26%
Total	1,447	1,550	7%

The model over-simulates **total diversions** from the river by 7% which is around 103 GL over the assessment period. The model under-simulates **general security diversions and** over-simulates **supplementary access diversions.** After accounting for observed trade of water in accounts from NSW to Qld that is not simulated in the model, the model under-simulates diversions from the river by 5%.

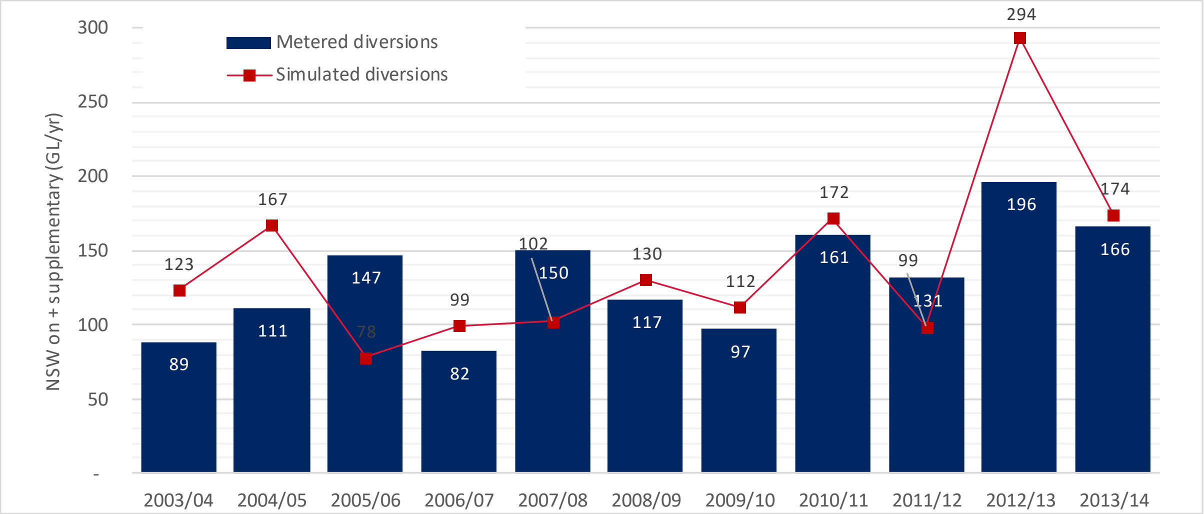

Figure 27 Annual NSW simulated and observed (metered) diversions from 2003/04 to 2013/2014

We have also examined how well the model performs during the first five years and the second six years of this period. The results of this are reported in Table 42. The model under-estimates general security diversions in the early period and a low bias in the later period. This result is acceptable given the year to year variability in irrigation behaviour shown in Figure 27. The model has a reasonably consistent bias for supplementary diversions across the two periods.

Table 42 Split period simulated vs observed total generally security and supplementary access diversions (GL) comparison

Type/period	Observed diversions (GL)	Simulated diversions (GL)	Bias (%)
General security			
01/07/2003–30/06/2008	391	337	-14%
01/07/2008–30/06/2014	566	596	5%
Supplementary access			
01/07/2003–30/06/2008	188	233	24%
01/07/2008–30/06/2014	302	384	27%

Supplementary access diversions

Simulating supplementary access is inherently difficult, as it is more sensitive to mismatches between the observed and simulated timing and size of flows and water orders on a daily basis. There is also an element of variability to forecasting orders and flows made by river operators when assessing whether flows will be supplementary to requirements.

The results of the supplementary access diversions were reported as part of metered diversions in the previous section and show a consistent over-estimation of around 25%. This section examines more closely the announced periods of supplementary access in the model compared with data. The corresponding graphs have been placed in Appendix L .

Announced periods are compared from 2010 to 2014 by defining an announced period as value 1 and any other period as value zero. The graphs show respectively the timing of announcements, and the cumulative announced days. Key features of these results are as follows:

- Pindari Dam to confluence: The model simulates slightly more days with supplementary access than observed (Figure 78 and Figure 79)
- Glenlyon Dam to confluence: the model simulates more days with supplementary access than observed. (Figure 80 and Figure 81)
- Goondiwindi to Kanowna: the model simulates slightly fewer days of supplementary access than recorded. (Figure 82 and Figure 83)
- downstream of Kanowna: The modelled and recorded number of days of supplementary access are very similar (Figure 84 and Figure 85).

The **total** modelled compared with observed supplementary access diversions were over-estimated as reported in Table 41.

The **annual** modelled compared to observed are shown in Figure 28. These results show that **inter-annual variability** is reproduced. This result is a great improvement on the results from the previous model used for Border Rivers.

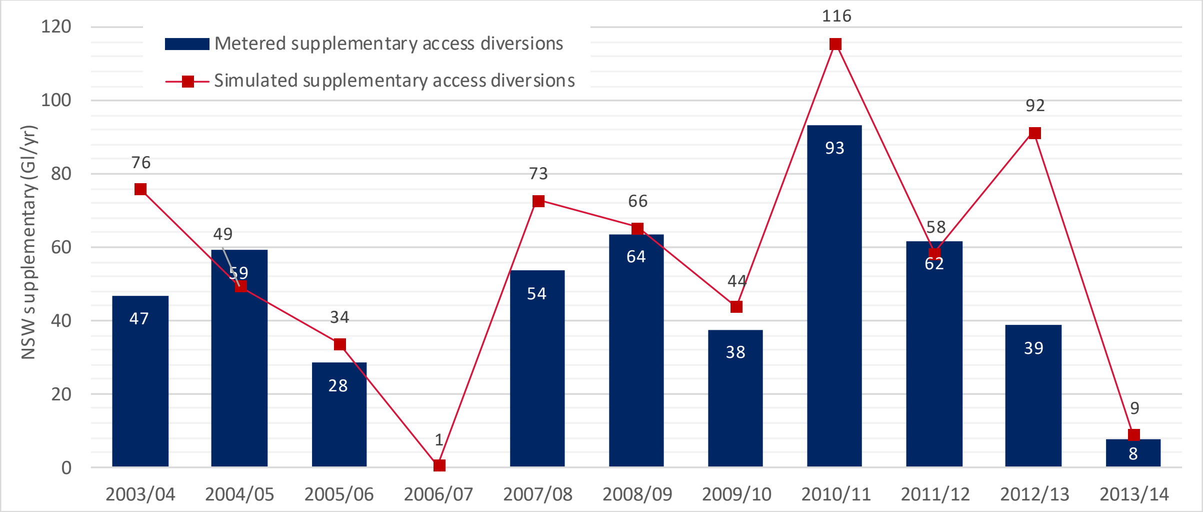

Figure 28 Annual simulated and observed (metered) supplementary access diversions from 2003/04 to 2013/14

8.4 Water management rules

8.4.1 Storage and weir operation

Storage operation

The simulated total storage volume from the freely simulating 2008/09 Scenario calibrated Border Rivers river system model is compared to the observed storage volumes in Figure 29. There are some differences to observed data. The general behaviour of storage volumes is similar to Current Conditions results using the previous model of Border Rivers developed using the IQQM platform.

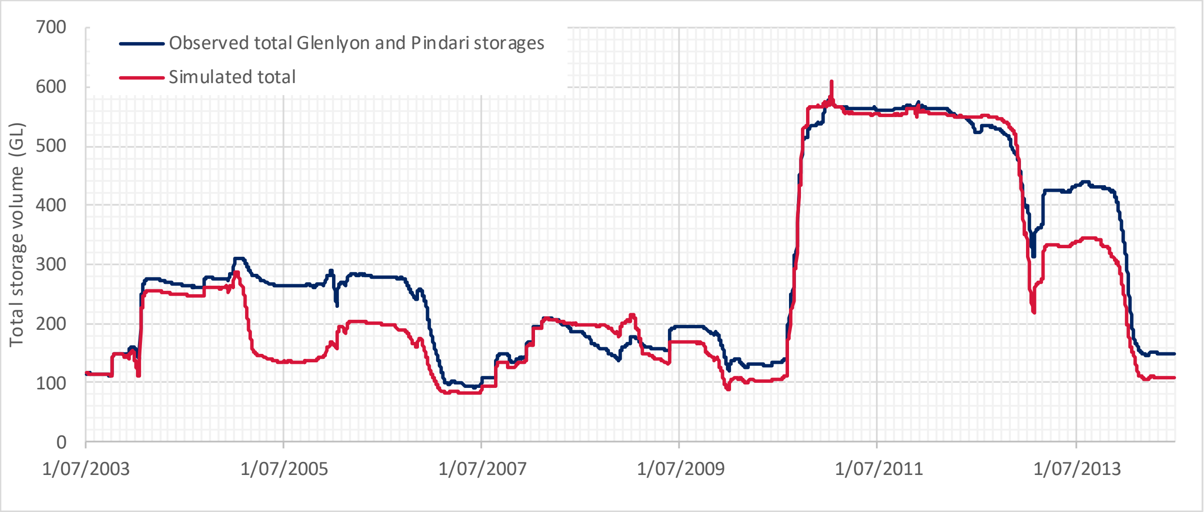

Figure 29 Time series of observed vs simulated total storage volume at Glenlyon and Pindari Dams from 2003/04 to 2013/14

There can be multiple causes for variations in headwater storage volumes, including variations in modelled Qld water use compared to observed. Other issues may include variation in annual planted areas, differences in management rules (e.g. supplementary announcements or block releases), and differences in inflows and in estimates of unmetered water use including floodplain harvesting.

The 2004/05 year had the biggest mismatch in storage behaviour, with too great a drawdown of storage levels. Some potential causes include overestimation of area planted (Figure 26) and underestimation of supplementary access diversions (Figure 28). The 2012/13 year also had a mismatch with higher than observed draw-downs in December 2012, consistent with the over-simulation of metered diversions in that year (Figure 29). The model under-simulates general security diversions in the 2011/12 year by around 30GL and over-simulates in the 2012/13 year by around 44GL. It is assumed that the under-simulation in 2011/12 is due to account management transfers that appear to have taken advantage of unregulated tributary inflows / Pindari spills. This would mean that more water was in on farm storages at the start of the 2012/13 water year than was simulated. This likely accounts for a significant part of the mismatch in headwater storage volumes in 2012/13. Other potential causes include differences in Qld water use and in planting behaviour[28].

Periodic differences in headwater storage volumes are to be expected, however if systematic issues emerge in future assessments, this will require amendment to be suitable for planning and compliance purposes.

Storage harmony management

The simulation of storage volumes at each storage have also been compared to observed storage levels over the comparison period. The harmony rules appear to be favouring draw down of Pindari Dam: Glenlyon dam volumes are over-simulated during some periods when Pindari is under-simulated as shown in Figure 30 and Figure 31.

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[28] One of the larger irrigators has indicated that they have used short season varieties in past years. Remote sensing indicates that cotton may have germinated later in 2012, with possibly short season varieties of cotton grown in this year

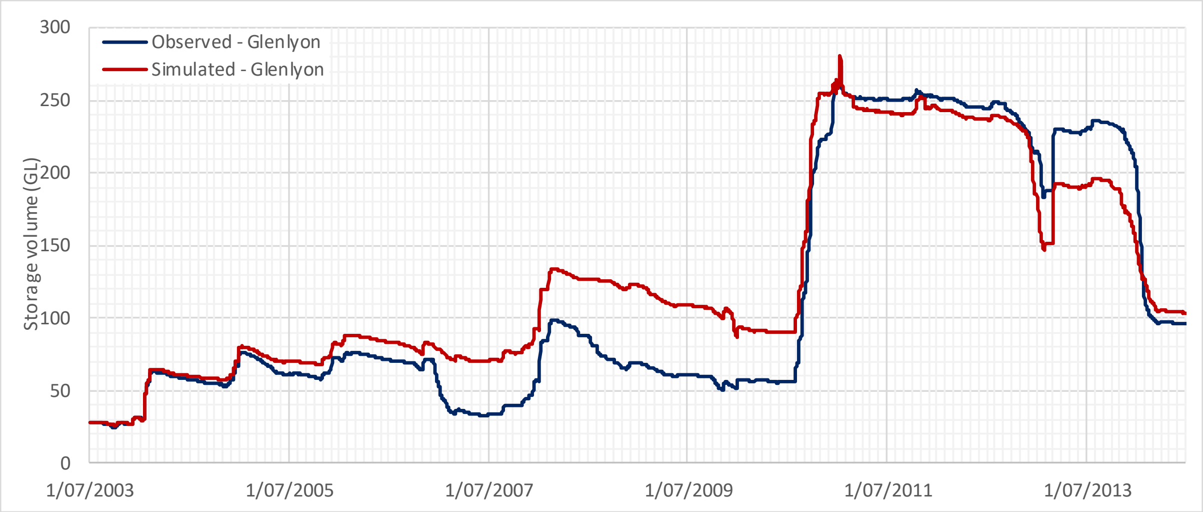

Figure 30 Time series of Glenlyon Dam observed and simulated storage volumes from 2003/04 to 2013/14

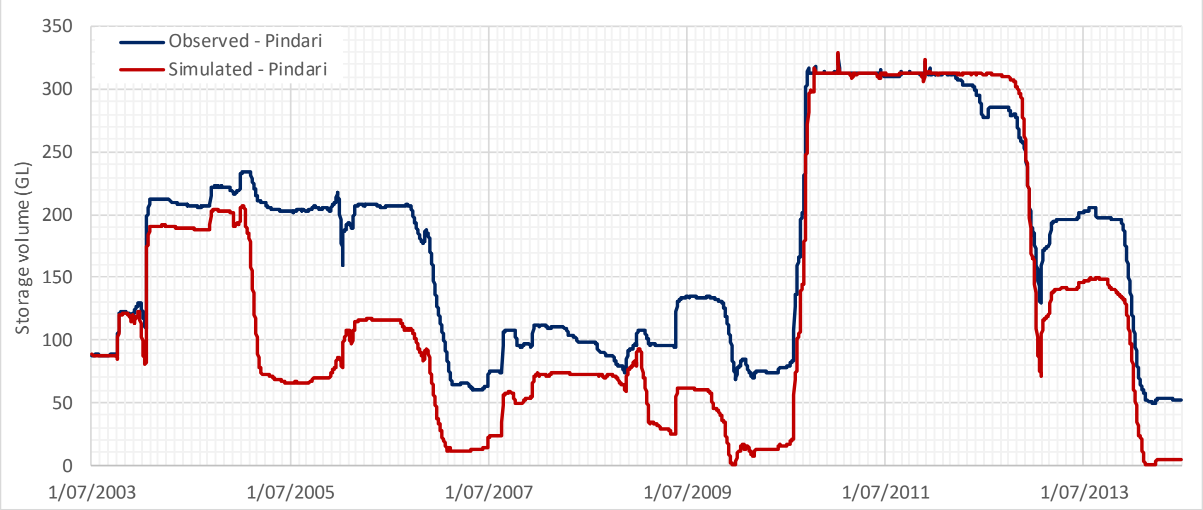

Figure 31 Time series of Pindari Dam observed and simulated storage volumes from 2003/04 to 2013/14

The **harmony rule** does not appear to represent all aspects of operator practice. An attempt was made to adjust the rule to better reflect history of operation. However, this significantly increased spills, and was discontinued. Future work should include a review of the harmony rules with the operator, with potential benefits for both the representativeness of the model and long-term operational performance.

8.4.2 Weirs and regulators operation

Boomi River flows

Diversion of water into the Boomi River is controlled by the operation of the regulator at the offtake. To show how well the model reproduces flows into the Boomi River, the simulated **monthly average flows** at the Boomi River offtake (416037) are compared to recorded flows in Figure 32. This shows the simulated flows are close to the recorded flows over the calibration period (+1.5% bias). The match between the simulated and recorded **daily flow** time series are illustrated in Figure 33.

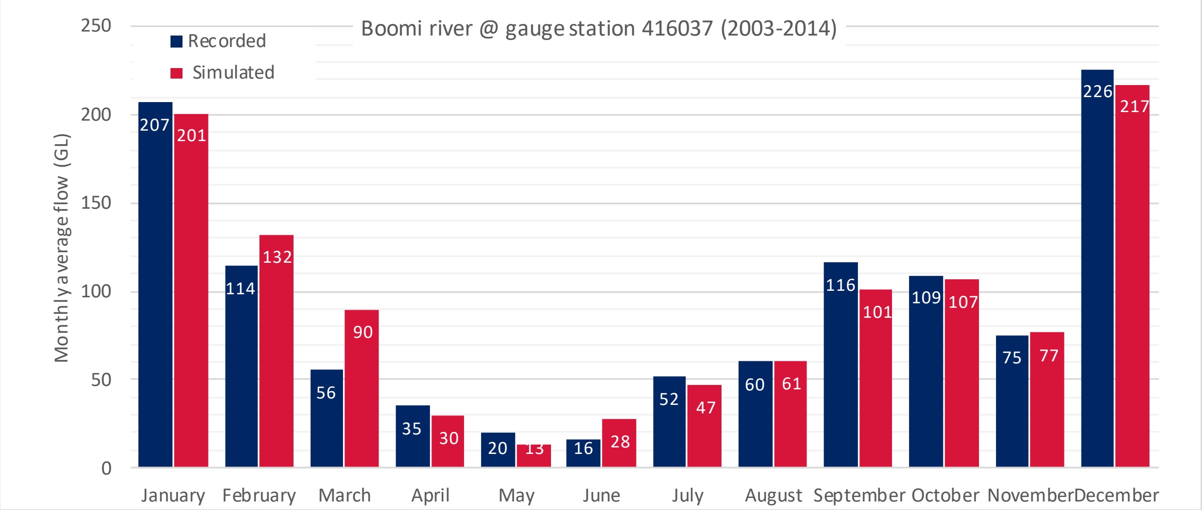

Figure 32 Monthly average Boomi River flows 2003–2014

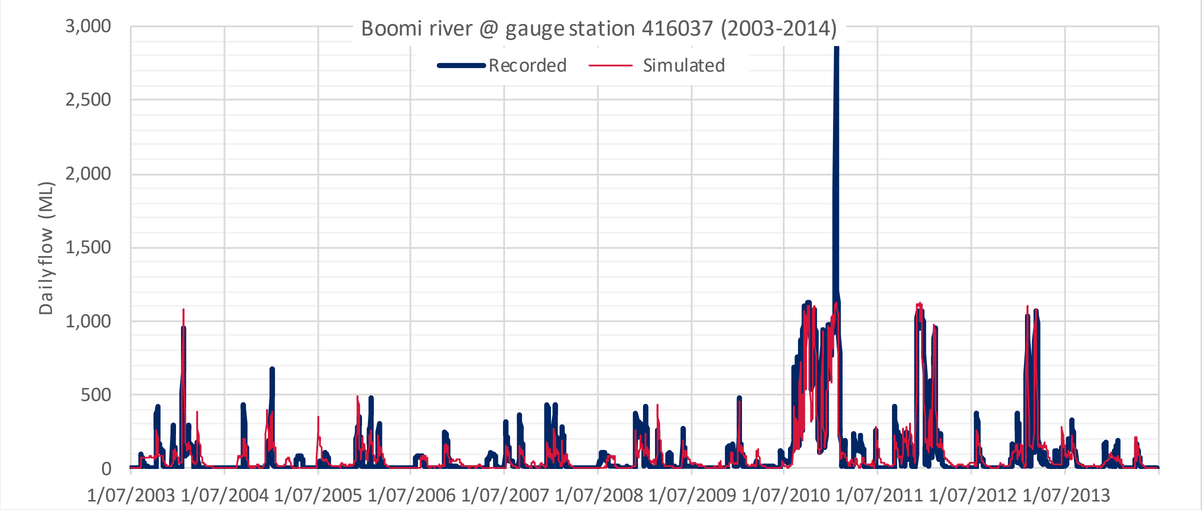

Figure 33 Daily time series of Boomi River flows 2003–2014

8.5 Long term annual diversions

River system models are used to create a number of scenarios, which reflect different levels of development and management rules in the river system. For example, the *NSW Border Rivers WSP* describes two scenarios which are used to determine the Plan Limit. We have described how we have updated the Plan Limit estimate in the companion Scenarios report (DPIE Water 2020a). The report describes how we modified the baseline 2008/09 Scenario to create the scenarios required under the policy.

We have included here some long-term results from the updated Plan Limit Scenario (Figure 34) purely for illustration of the relative magnitude of the components and how they vary over time. The results show the most significant diversions in terms of **long-term averages** are general security, followed by supplementary access, then floodplain harvesting excluding within farm rainfall harvesting (referred to as overbank flow harvesting below), and lastly on-farm rainfall–runoff harvesting. **General security diversions interannual variability** reflects the impacts of climate and headwater storage. **Supplementary diversions interannual variability** are lower due in part to the annual limit on diversions, as well as other factors related to the inter-seasonal dynamics of water use and availability. **Overbank flow harvesting** has the greatest interannual variability and corresponds with the occurrence of flow breakout events as shown in Figure 25. **Rainfall–runoff harvesting** has a similar pattern, albeit at a lot reduced scale.

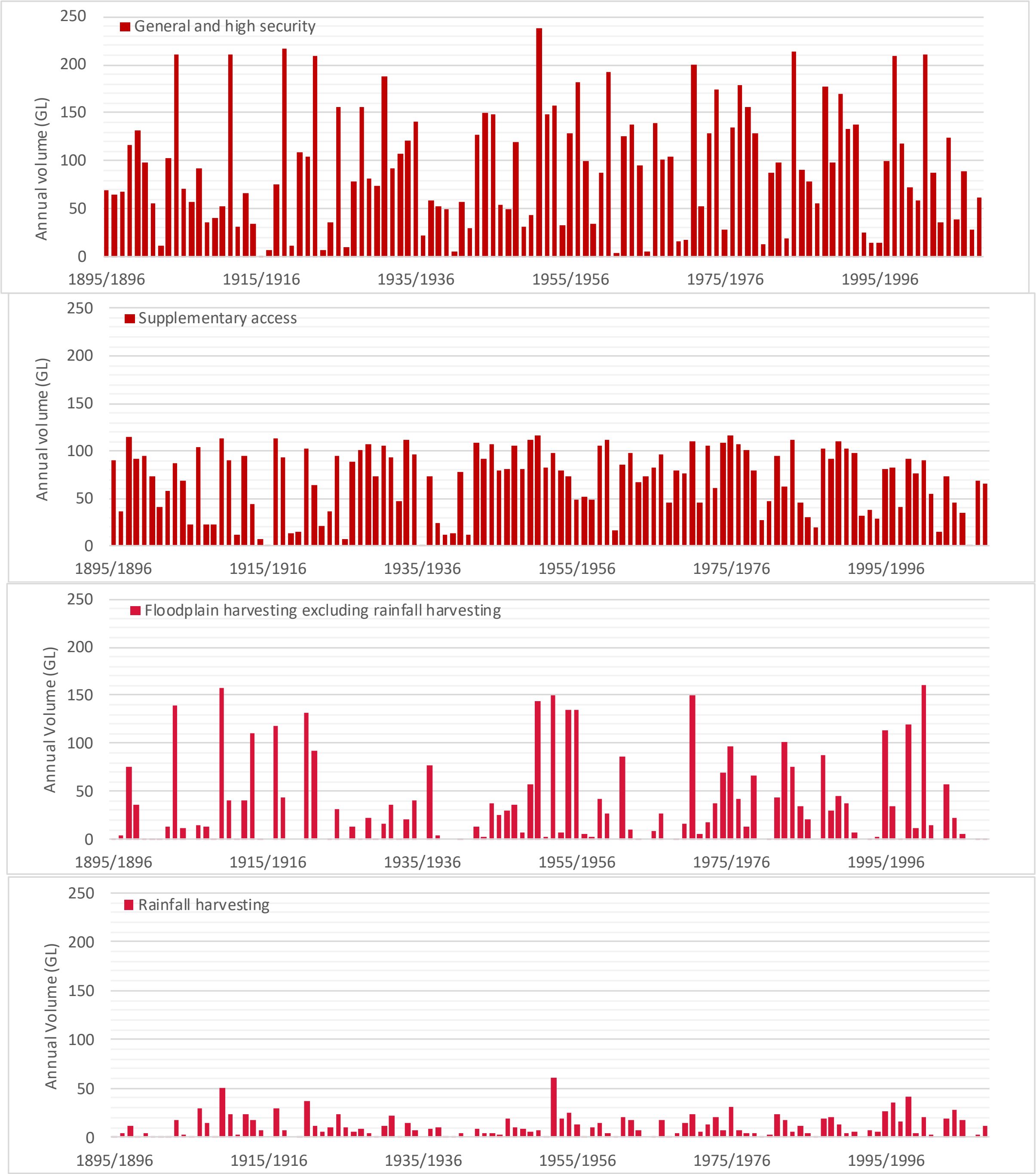

Figure 34 Simulated annual volumes of high and general security, supplementary access, floodplain and rainfall harvesting flow diversions over the period 1895 to 2009

9 Sensitivity testing and uncertainty analysis

This section considers:

- key sources of uncertainty in the models
- measures put in place to reduce the uncertainty
- sensitivity of modelled floodplain harvesting outputs compared to the remaining significant uncertainty
- measures required to reduce uncertainty in the future.

Specifically, this section responds to recommendations below from the *Independent Review of NSW Floodplain Harvesting Policy Implementation* (Alluvium 2019) for a qualitative assessment of uncertainty.

> "Document an assessment of model uncertainty and suitability for application, including where future improvements should be made to reduce that uncertainty, in the model."
>
> "We believe that a more qualitative assessment of uncertainty is still required, combined with an analysis of parameter sensitivity, in order to document where the major uncertainties may lie and how they can be addressed through further model improvements".

9.1 Approach

The two main model outputs (in terms of the policy) are the impacts of modelled floodplain harvesting outputs on:

- **total diversion limit**, as specified in a water sharing plan, and **annual compliance** with the limit
- the **distribution** of floodplain harvesting entitlements **between individual properties.**

These two criteria can be used to assess the impact of uncertainty on these modelled outputs.

Future refinements to models and adaptive management tools will enable changes to the total valley limits. However, these changes will not enable changes to the distribution of individual floodplain harvesting entitlements. In accordance with the policy, the distribution of entitlements is based on a capability assessment of eligible works capable of floodplain harvesting and access to water flowing across a floodplain. Further, the policy states that information relating to history of use will not be used to determine entitlement. Further information on the capability assessment, and how our methodology addresses this component of the policy, is discussed later in this section.

In summary, we consider the:

- key sources of uncertainty in the models
- measures we put in place to reduce the uncertainty
- sensitivity of modelled floodplain harvesting outputs compared to the remaining significant uncertainty
- measures we need to take to reduce uncertainty in the future.

9.2 Sources of uncertainty

The key sources of uncertainty in the models are as follows:

- input and calibration data

- model representation of processes including physical processes and management arrangements
- model parameter values.

We considered these issues during model development and took a number of actions to minimise uncertainty as described in Table 44 below. The following risk management approach has been used to consider uncertainty:

- If our confidence in the parameter or model component is high, model uncertainty has low significance
- If our confidence in the parameter or model component is not high, sensitivity testing is used, where possible, to assess the sensitivity of model results to the parameter or model component (i.e. how much it matters).

We have devised a qualitative rating criteria to identify the largest impact on the ability of the model to accurately determine diversion limits and distribution of floodplain harvesting entitlements. The rating is for indicative purposes only.

Table 43 Qualitative uncertainty significance rating system, with sensitivity test results examples

Significance rating	Description	Example
Low	Either the uncertainty in the parameter is low or the impact of the uncertainty on floodplain harvesting outputs is low	Sensitivity test using a plausible scenario results in: • less than or equal to 5% change, or • the issue is not relevant, or • the issue is well researched / analysed
Medium	Uncertainty in the parameter and impact on floodplain harvesting outputs is larger, but they are not considered as primary issues	Sensitivity test using a plausible scenario results in: • change greater than 5% and less than or equal to 15%
High	Primary issues affecting the accuracy of floodplain harvesting outputs in a long-term model assessment	n/a

Table 44 Sources of uncertainty and their significance for modelling floodplain harvesting estimates

Source of uncertainty	Comment	Significance rating
Climate and flow data		
Long term climate stations used in modelling are significant distances apart and may not match rainfall on an individual farm on specific days	Large rainfall events may make it difficult to calibrate for a specific area if it is not representative of rain on that day. However, the long term modelled results have low sensitivity to changes in assignment of climate station to each property (see Table 45, Test 1).	Low

Source of uncertainty	Comment	Significance rating
Use of historical climate data means that climate change is not accounted for	Use of historical climate data is consistent with the data specified for the limit specified in water sharing plans (1895–2009)	Low
Data accuracy – error in measurement of historical climate data	We implement a suite of methods to review data to ensure that we identify and filter out poor quality climate stations or data at these stations, particularly those with missing data that has been infilled	Low
Data accuracy – availability of and error in flow data	Short periods of flow records, sparsity of flow gauges and data quality issues all contribute to uncertainty in flow behaviour and representation in river system models. We use mitigation measures, including ensuring inflow estimates are a plausible ratio of rainfall, avoiding poor quality gauges, having regard to periods of and ranges of flow record with higher uncertainty, and using supplementary information such as remote sensing and hydraulic modelling to understand flow behaviour	Medium
Diversion data		
Accuracy of river diversions	Meters used to measure regulated and supplementary diversions have known uncertainties of ±1–25%. A key consideration in our method was to assess the overall water balance to meet irrigation requirements for historical crop areas. Uncertainty in the measured component of the water balance would be offset through estimates for the other components, such as floodplain harvesting. Noting the significance of metered diversions, a systematic 5% underestimate or overestimate in metered diversions would result in a 10–20% compensatory overestimate or underestimate respectively in floodplain harvesting diversions. This uncertainty will be reduced in the future by further meter testing and validation data through the Metering Framework and on-farm storage monitoring data through the Floodplain Harvesting measurement requirements	High
Sparsity of records on harvested volumes	There is a lack of reliable records on actual volumes harvested from overbank flow events or rainfall–runoff. Whilst other lines of evidence have been used, such as information gathered through farm surveys (Irrigator Behaviour Questionnaires), the lack of data makes it difficult to validate both the valley total and individual variability in floodplain harvesting. This is the principal cause of uncertainty in modelling floodplain harvesting. However, the data provided through the measurement requirements for floodplain harvesting properties will reduce this uncertainty over time.	High

Source of uncertainty	Comment	Significance rating
Model assumptions / simplifications		
Property scale rainfall–runoff model operating on a daily timestep does not account for rainfall intensity	Research indicates that the primary predictors of rainfall–runoff in areas with high water holding capacity are rainfall and soil moisture content. Our model continuously tracks soil moisture content. Therefore, in most areas, any limitations in accounting for rainfall intensity would not be a significant issue for a long term simulation period	Low
Evaporation and seepage loss from storages is based on assumed sequential filling rather than simultaneous filling of storages	This assumption relies on this being the most efficient mode of operation to minimise losses. Long term results have low sensitivity to changes in this assumption (see Table 45, Test 2). We can further reduce this uncertainty in time through analysis of monitoring data and of multi-date satellite imagery	Low
Hydraulic characteristics of intake pipes are not represented	Intake pipe flow rates depend on the difference between intake and outlet water levels. This intake or environmental information is not available. However, in most situations this limitation is not an issue as the total rate of floodplain harvesting is limited by the on farm storage pumps. Sensitivity testing for the intake rate shows that valley wide totals are not sensitive to our assumptions. The majority of individual results also have low sensitivity (see Table 45, test 3). The sensitivity may be higher when considered in conjunction with other issues, as is further discussed in Table 45. Reducing this uncertainty further would require significant new datasets and investment in model refinements (which we are not planning to undertake)	Low
Model parameters		
On-farm storage capacity	We identified at an early stage of this work that the floodplain harvesting results were very sensitive to on-farm storage capacities. Significant effort has been put into improving the accuracy by using LIDAR or photogrammetry data with verification against a sample of surveyed storages (Morrison and Chu, 2018). These data indicate the results are reasonably reliable (generally around 2% difference in volume at a given level) but the assumptions around freeboard can have a larger impact on the assumed full supply capacity. Due to the latter, we have assigned Medium significance. Overall, we consider our approach to be robust due to a standardised approach for calculating freeboard (1m for constructed permanent storages which is in line with industry best practice)	Medium
On-farm storage seepage	Seepage rate estimates for on-farm storages are based on data published in Wigginton (2012a). Sensitivity testing indicates our floodplain harvesting outputs are not sensitive to seepage estimates (see Table 45, test 4)	

Source of uncertainty	Comment	Significance rating
Crop model parameters	Uncertainty in total irrigation water use has a significant impact on the assessment of the diversion limit but has less of an impact on the distribution of individual floodplain harvesting entitlement. Irrigation water use is estimated using historical crop area data, and a crop model that is parameterised to match published crop water requirement information, including application rates. This assumption is important to the assessment of the valley total floodplain harvesting. We explicitly account for annual variation in irrigation water use due to climate, however, individual differences in application rates and efficiency cannot be verified and accounted for. We have managed this uncertainty by using multiple sources of information to represent floodplain harvesting access, rather than relying on highly accurate water balance at individual properties without data to validate harvested volumes. We have found, through sensitivity testing of irrigation efficiency post calibration, that the determination of entitlements is not highly sensitive to individual differences in water use (see Table 45, test 5). In the future, we will use data from the floodplain harvesting measurement requirements to review and verify our assumptions about application rates and reduce the uncertainty in total valley estimates	Medium for valley total Low for distribution
Rainfall–runoff parameters for within farm runoff model	We have relied on best available data to characterise differences in runoff between undeveloped, developed and irrigated areas. However, this data is limited, and it is not possible to verify and account for individual variation in irrigation practice and runoff generation. In response to recommendations of the Independent Review (Alluvium, 2019), we have also undertaken another independent review of the assumptions for runoff from irrigation areas (Barma Water Resources, 2019). This found that: • the estimates were uncertain due to limited available data • the adopted approach represents a step forward compared to other approaches reviewed • harvesting of rainfall–runoff is likely to be a fairly small component of total valley diversions. In the future, data from the floodplain harvesting measurement requirements will be used to review and verify our assumptions.	generally Medium may be High for some properties where rainfall–runoff is the dominant form of take

Source of uncertainty	Comment	Significance rating
Relationships between river flow and overbank flow and access to that flow	We have based overbank flow relationships where possible on hydraulic models of floodplain flow developed for Floodplain Management Plans[29]. These models were calibrated to several flood events against gauged flows, remotely sensed flood inundation extents, and previous flow distribution calculations and estimates. Where this was not available, we have used other lines of evidence such as long term flow records at upstream and downstream gauges, flood records, farm survey information and remote sensing. The relationships between river flow and overbank flow are important for determining the volume of water on the floodplain available to harvest. We have managed uncertainty in this by assessing the overall farm water balance at a reach scale. Individual property access to overbank flow has been assessed using a range of information such as irrigator behaviour questionnaire data and remote sensing analysis. In larger floods, the model is less sensitive to overbank flow and access assumptions as there is an excess of water compared to airspace in storages. However, in small to medium floods the actual volume harvested will be sensitive to the breakout relationship and access to this flow. This will be reviewed using information from the floodplain harvesting measurement requirements.	Medium
Rate of take of floodplain water into permanent on-farm storages	All on-farm storage pump capacity values are based on expected flow rates from well-designed pump stations. Gravity fill of storages is only represented where this is the only eligible intake into the storage, or in exceptional circumstances, where high rates can be used to fill to a high level. Comparisons have been made between farm survey (IBQ) data, industry advice and pump charts to inform the expected flow rate for a given type and size pump, within a range of around 30%. This range was derived through discussion with field operators and industry consultants. Sensitivity testing shows that valley wide totals are not sensitive to these assumptions. The majority of individual results also have low sensitivity (see Table 45, test 3). Adopting a standard set of rates is considered to be the most equitable approach that also enables a robust review of eligible and historical works.	Low

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[29] The FMP models are described in technical appendices for each valley. https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/plans

9.2.1 Sensitivity testing

The 6 sensitivity tests referred to throughout Table 44 are described in Table 45.

Table 45 Sensitivity tests, results and discussions for the Plan Limit reporting period 01/07/1895 to 30/06/2009

Test	Test completed	Result and discussion
Choice of long-term climate stations used in modelling farm water balance	For 6 properties in the Border Rivers, we changed the climate station used in the Irrigator component model to the second closest climate station	2 properties had around a 3% reduction in FPH. The other properties had a smaller change. Given that these properties sit half-way between the two climate stations, the actual climate is somewhere in between, hence the difference between modelled and actual is less than 5% difference
Assumptions around sequential filling of storages	Two tests have been completed: 1) Assume that the storage losses are based on all storages being at maximum surface area at all times. This is not physically possible; however, it provides an indication of upper bounds of sensitivity. This test was completed for all properties in the Border Rivers. 2) Assume that least efficient storages are filled first. This test was completed for 3 properties in the Border Rivers.	1) Total floodplain harvesting increased by about 1%. Note that this scenario is not physically possible and therefore the actual impact will be less than this. All individual properties had less than 5% change 2) The maximum change was a 1.1% increase in FPH
Change intake rate assumptions	30% increase in each of the following: 1) intake of FPH 2) on-farm storage pump rates 3) rate of release from the virtual storage This test was completed for all properties in the Border Rivers	1) Total FPH had less than a 1% increase. 2) The majority of properties had less than 5% change. 7 properties had large increases with the maximum being a 10% increase. 3) The model has low sensitivity as the rate of release from the virtual storage is matched to the assumed take rates. If more detailed information were known about conveyance of water across the floodplain and represented in the model, then the assumed take rates would likely be more significant
OFS seepage	On-farm storage seepage rate was doubled from 2mm to 4mm per day. This test was completed for all properties in the Border Rivers	Total FPH increased around 3% All properties had a change of around 5% or less with the exception of one property which had a 6.5% increase.

Test	Test completed	Result and discussion
Irrigation efficiency assumptions	Irrigation component model changed to assume less efficient operation; from 30% loss to 40% loss (i.e. 33% relative increase in loss). This test was completed for all properties in the Border Rivers.	Total FPH increased 0.6% in the Border Rivers In the Border, a few properties had a reduction, but the majority had an increase in total floodplain harvesting with the maximum being a 4.7% increase.

9.3 Total uncertainty estimates

There is an understandable interest in total uncertainty in a quantitative sense. This type of rigorous analysis has been tested for simple models where good quality observed data exist to be able to use automated calibration techniques. The complexity of the river system models, the large number of parameters and insufficient data mean that confidence intervals cannot be provided for floodplain harvesting model outputs.

Methods used to provide a quantitative analysis of uncertainty require good observed data to either undertake model error analysis (e.g. McInerney et al., 2018) or assess parameter, structure and data errors (e.g. Beven and Binley, 1992; Kavetski et al., 2006). We do not have sufficient observed data for floodplain harvesting or knowledge of parameter distributions to undertake any of these approaches.

Simple sensitivity testing, where random combinations of parameters are assessed, is not suitable to quantify uncertainty in results. This is because it is entirely likely that many of the tests created in this way result in models that are not plausible

Rather than attempting to quantify overall uncertainty, the purpose of this report is to communicate what we have done to manage (and minimise) uncertainty. We also take the opportunity to recommend the key data collection and future work needed to significantly improve confidence in floodplain harvesting estimates.

9.4 Impact of uncertainty on distribution of entitlements

The policy states that the determination of share components will not be based on any history of use information. Instead, a capability assessment is to inform the distribution of individual entitlement. This assessment is intended to allow consideration of both the physical infrastructure used for floodplain harvesting, and the opportunities that irrigators may have to access floodplain flows based on their location and climatic variability. The key components of the capability assessment are detailed in Table 46. The appropriateness of the adopted methodology in addressing each criteria relies on the conclusions made in Table 45.

Table 46 Capability assessment criteria and confidence to inform the distribution of individual entitlements

Capability assessment criteria	Confidence in modelled approach
Know with some confidence	
Capacity to store and use water	The use of independent and verified methods such as LIDAR and standard assumptions around freeboard result in a robust approach to determining storage capacity. However, there are a few examples of unusual storage construction where the method is less reliable. In these instances, it is assumed that the information supplied by the applicants in the submissions process will improve the confidence

Capability assessment criteria	Confidence in modelled approach
Existing water access licences	Department database data as at 2008 has been used in determining individual shares
Know with less confidence. However, sensitivity testing indicates a minimal impact on distribution of individual floodplain harvesting entitlements	
Irrigation behaviour	Differences in irrigation efficiency have been shown to have little impact on individual estimates. Other aspects of behaviour such as planting decisions have been defined in line with information provided in irrigator behaviour questionnaires and historical cropping
Configuration of the works	Sensitivity testing was undertaken to examine different scenarios for the sequence of storage use. This shows that there is low sensitivity
Know with less confidence and distribution of individual floodplain harvesting entitlements is sensitive to assumptions	
Extraction capability and location specific frequency, magnitude and duration of flood events	Sensitivity testing has been undertaken which shows the model has low sensitivity to the assumed extraction rates. However, we propose that, in combination, these issues are a larger cause of uncertainty. Some of these issues are structural in nature such as routing and water depth on the floodplain, making it difficult to complete a sensitivity test. Sensitivity tests could be undertaken for other components, such as individual property access to overbank flow. We have already attempted to use multiple lines of evidence to inform the individual property access, such as farm survey data, remote sensing analysis and, in some cases, relevant information from floodplain management plan hydraulic models. A review of the modelled approach can be undertaken when sufficient data are obtained from the floodplain harvesting measurement requirements

In summary, uncertainty in the distribution of individual floodplain harvesting entitlements has been managed through the following:

- incorporating all aspects of the capability criteria into the modelling approach. Importantly, the modelling which informs the distribution of entitlements, is based on eligible works which have been identified by the Natural Resource Access Regulator (NRAR)
- undertaking checks on the relative distribution of the floodplain, such as comparisons with storage capacity, to check trends
- undertaking checks of farm water balances. Tests of farm water balance can be used as a check of modelled estimates. These checks have been completed, primarily at valley and reach scale. There can be large errors for individual properties, for example, if differences in irrigation behaviour and the accuracy of existing meters are not known and accounted for. Therefore, this test should be used with caution at an individual property scale. Initial assessments of water balance calculations have shown that, in some cases, results can become implausibly large and the distribution less reliable. This result is supported by previous work undertaken by the Murray-Darling Basin Authority which compared a farm water balance calculation to ground-truthed data and found a large scatter in estimates and some bias (Prasad, 2010).

9.5 Adaptive management approach

Adaptive management is a principle of the *Water Management Act 2000.*

There are two primary areas where adaptive management is used in modelling of floodplain harvesting:

- The first relates to the on-going improvements made to models in response to increased availability of data. These improvements allow for better calibration and understanding of processes on the floodplain.
- The second relates to the crucial role that modelling plays in assessing compliance with diversion limits specified in water sharing plans. By bringing floodplain harvesting into the licensing framework, a targeted growth in use response can be undertaken for floodplain harvesting or other forms of licensed take. The use of models that are regularly updated and improved is crucial in assessing current conditions against diversion limits to determine if a growth in use response is required.

9.6 Summary

This section has provided information on the sources of uncertainty and their significance on the modelling of floodplain harvesting, what we have done to reduce these uncertainties, and some recommendations for future work to further reduce these uncertainties. Where possible, sensitivity testing has been used to support the discussion.

The work undertaken as part of implementing the policy has already substantively reduced uncertainty in the models. We have more confidence in the estimates due to updated detailed datasets, and we now established a framework to better understand causes of uncertainty and their impacts. Despite this substantive improvement, uncertainty remains in our estimates that we can improve with acquisition of better information.

What measures have we already put in place to reduce uncertainty?

We have reduced the uncertainty in the models by undertaking an extensive review of all datasets to ensure the best quality available data are used. We have used multiple lines of evidence where possible such as remote sensing and hydraulic modelling, as well as comparing datasets to published literature.

Where there is significant residual uncertainty, how sensitive is the modelling of floodplain harvesting outputs to this?

We have undertaken a number of sensitivity tests to show the relative sensitivity of different issues. The principal causes of uncertainty are the lack of records on actual volumes taken by floodplain harvesting and inaccurate measurement of regulated river diversions.

Where standard values are used rather than farm specific values, how sensitive are individual floodplain harvesting results to potential variability in these values?

We have assessed 5 cases where standardised values were used: the choice of long term climate stations; on-farm storage seepage rates; crop model parameters; rainfall–runoff long term averages; and the rate of take of floodplain water into on-farm storages.

We found that our use of long-term climate stations, on-farm storage seepage rates and rate of take were of Low significance for total valley floodplain harvesting diversions and distribution of entitlements. Crop model parameters have a Medium significance to total valley diversions, with a Lower significance for the individual floodplain harvesting entitlement distribution.

Rainfall–runoff assumptions have been independently reviewed and concluded that harvesting of rainfall–runoff is likely to be a fairly small component of total valley diversions and that the department’s approach represents a step forward compared to other approaches adopted.

Proposed rainfall– runoff harvesting partial exemption should reduce the significance of uncertainty in these values. This should mean that these assumptions have Low to Medium significance to individual entitlements, however it may have Higher significance for some properties where rainfall–runoff is the dominant form of take.

What are the key actions required to improve floodplain harvesting modelling in future?

The key information required to make significant improvement in estimates of floodplain harvesting will be data obtained through the floodplain harvesting measurement requirements.

The models are under continuous improvement in response to availability of better data, information and lines of evidence. Modelling of floodplain harvesting will be reviewed and improved after sufficient floodplain harvesting measurement data are available following implementation of the policy.

10 Conclusions

Two modelling objectives and 6 design criteria were established in section 2.1 for the model to be fit for the purposes of: informing water planning; establishing floodplain harvesting entitlements, and of compliance with statutory annual diversion limits. Section 10.1 provides a qualitative assessment of how well these were met.

The Border Rivers Valley river system model is the primary tool that will be used for the NSW Government to provide the technical information about the NSW Border Rivers regulated river system. The model will be used for a range of purposes some of which are known and likely some that will emerge over time in response to future water management challenges. This model has known uncertainties that inform how fit it is for current purposes. Recommendations for addressing this are set out in section 10.4.

10.1 Meeting objectives

The Border Rivers Valley river system model represents the key physical and management processes that affect water availability and sharing within this managed river system. This model is proposed as the best available model to estimate flow and water use for water planning purposes and estimating floodplain harvesting entitlements. The two objectives were that it would:

- support traditional water policy, planning and compliance uses, such as implementing the Basin Plan and estimating Plan limits
- determine volumetric entitlements for floodplain harvesting.

We have reported on the enhancements to the model to meet the second objective, while not compromising the ability of the model to deliver against the first objective. Based on the model assessment results, we contend that the model is suitable to be used for entitlement estimation, with two caveats: (1) the model is best suited to modelling at whole-of-valley and river reach scale, and increasing the spatial resolution to farm-scale requires very detailed understanding and characterisation of flow pathways and farm management at that scale; and (2) that the lack of actual harvested volumes data reduced our ability to minimise uncertainty in the model and thus our ability to verify the accuracy of the modelling.

10.2 Meeting design criteria

Six design criteria to serve the dual role of informing the model development and evaluating the resultant model, set in section 2.1 (and paraphrased below), were that the model must:

- 1) represent key processes affecting water availability and sharing
- 2) use a sufficiently long period of climate data to capture the climate variability
- 3) have detailed spatial resolution to allow system analysis and reporting at multiple spatial scales
- 4) use a daily time step to enable flow variability assessment and reporting at multiple time scales
- 5) represent historical usage on a seasonal basis
- 6) provide a pathway to update and improve accuracy (i.e. be update-able and extensible).

A qualitative assessment of how well these modelling objectives and criteria have been met is discussed in the following sections. Meeting the design criteria was a critical requirement to be able to meet the objectives. The six criteria, and how they were met is discussed below.

10.2.1 Criteria 1: key physical and management processes represented

The processes that have the greatest effect on water availability at a valley scale and are represented explicitly in the model can be characterised as either a physical or management process.

In summary, the physical processes represented in the model are described primarily in section 4 Modelling flows and include:

- climate (rainfall and potential evapotranspiration)
- inflow generation
- flow aggregation
- flow routing
- transmission losses
- flow outbreaks
- on-farm evapotranspiration
- evaporation from and rainfall on water surfaces.

The management processes are those that relate to the storage, regulation and diversion of water, and are a combination of infrastructure and policy. These are described in section 5 Modelling water sources and licensing, section 6 Modelling water users and section 7 Modelling water management rules and include:

- headwater storages
- instream storages
- irrigation farms, including developed areas, infrastructure, and pump capacity
- water access entitlements
- resource assessment
- irrigation crop planting decisions
- interstate water sharing
- diversions, both metered and unmetered
- water accounting
- environmental watering.

10.2.2 Criteria 2: period of data sufficient to capture climate variability

The reference climate period over which statutory diversion limits are calculated is water years 01/07/1895 to 30/06/2009. These limits are used to calculate entitlements. The period of climate data in the model extends from 01/01/1890 to 30/06/2019 and includes this period.

The calibration period varies depending on the component. The flow calibration uses the period of flow record. Various components of the farm scale models were calibrated over different periods of time e.g. rainfall–runoff rates were calibrated using a long period of time to match published information while winter cropping was calibrated using an 11-year period from 2003/04 to 2013/14. Floodplain harvesting was initially assessed using a shorter period of time (2007/08 to 2012/13 based on sufficient crop area data). While the period 2003/04 to 2013/14 was used as a calibration period for some components of the model this is referred to as an assessment period for the fully configured model (e.g. diversions and headwater storage volumes).

The inclusion of climate records to represent climate change has been raised. This is not necessary for the purposes of estimating Sustainable Diversion Limits under the 2012 *Basin*

Plan, nor for estimating entitlements which use the same reference climate period for calculations.

Climate change is of broader interest and will be addressed in other departmental programs such as the Regional Water Strategies, and later for the 2026 Basin Plan review. A climate risk dataset has been developed for that purpose which includes: a stochastic element derived from historical climate observations, and a paleological climate signal; and combines this with future climate projections from dynamically downscaled climate models.

10.2.3 Criteria 3: spatial resolution sufficient for multi-scale analysis

The spatial detail in the Border Rivers Source model is best illustrated by the node-link diagram (Figure 5 in section 2), indicating several hundred computational points. The highest number of points represent where water:

- enters (inflows)
- leaves (diversions, breakouts, and transmission loss)
- is measured (gauging stations).

For **inflows and measurements**, the spatial resolution makes the use of all available gauged flow data of reasonable quality. This combined with the 90+ rainfall stations allow for coverage of the spatiotemporal variability of water availability from climate, upstream and downstream of the major headwater storages. The resultant flow variability enables representation of regulated water access, as well as for Supplementary Access and Floodplain harvesting. The checking of flow variability as both inflows and mainstream flow was covered in detail in section 8.2.

The detail reporting and assessment of diversions was with reference to available data. These models have previously been used primarily to report aggregated diversion at a valley scale. In contrast, this model needs to provide results at a **farm scale**. Hence the model includes a separate calculation point for each and every farm that was assessed as eligible for a floodplain harvesting entitlement. The detailed data collected from farm surveys and other sources for each farm was used to undertake a capability assessment of each farm. The model configuration of river network, breakout relationships, and individual farm detailed representation allows for the type of calculations that would enable an **individual farm water balance** to be estimated under different scenarios. We used eligible works information to estimate how the allowable total floodplain harvesting volume is shared between individual properties.

The model includes all significant breakouts based on multiple lines of evidence, and the flow rates down these breakouts are based on local knowledge, farm surveys, flow change analysis, hydraulic modelling and remote sensing.

The uncertainty in this regard still remains significant. This is not necessarily because of spatial detail. What is missing in fully meeting this potential of equitable distribution of entitlements is lack of information on actual volumes harvested as either rainfall–runoff, or from overbank flow, as well as incomplete management detail on each farm, including application rates specific to that farm, and on-farm water management.

The model uncertainty is much better resolved where there are data to inform the parameterisation of the model. For this reason, the uncertainty around volumes harvested is lower at a reach scale, where flow gauges, breakout volumes, and reach water balance can be assessed.

10.2.4 Criteria 4: report at multiple time scales (daily to annual)

The standard time step for calculation in the Source Model is **daily**, as is the climate data and inflow data used for these models. This enabled the replication of flow variability as discussed in section 8.2, with results show in detail in Appendix I.

The model was configured with the hydrology, infrastructure and management arrangements to simulate climatically dependent inflows at multiple points in the river system, as well as the development and management conditions at defined points in time that affect the interannual water use. The ability to aggregate to **annual use** was demonstrated in the results of the calibration in sections 8.3 and 8.4 and in the **long-term annual** simulation results in section 8.5 This capability will be further tested in the annual diversion compliance for the Basin Plan.

10.2.5 Criteria 5: supports replication of historical usage

The replication of historical usage has been undertaken using both crop areas forced to historical data (section 8.3.1) and simulation of crop areas (section 8.3.3). Both tests show that historical **metered usage** is well represented. Total simulated metered diversions had a +2% bias when using historical crop areas and a +7% bias when using planting decision. The model replicated inter-annual variability well.

The fully assembled model with simulated crop areas generates General Security diversions which are close to metered diversions as discussed in section 8.3.3. Overall bias was -2%, with underestimation during the earlier drier periods. Some potential reasons for the under-estimation in the earlier period include variations in planted area, efficiency and application rates and limitations in rainfall data.

Supplementary access diversions were over-estimated, and this was attributed to difficulties representing the periods of access announced by river operators. The annual patterns of access were well replicated. Despite the over-estimate, the results represent a huge improvement compared to the previous model of Border Rivers developed using the IQQM platform.

The balance of diversions from unmetered sources, i.e. **floodplain harvesting**, was inferred from farm infrastructure and management. We also evaluated this estimate by reviewing reach and valley scale water balance results using known crop areas and industry standardised crop application rates. There are insufficient data to represent variations in efficiency at property scale, however sensitivity testing shows that the determination of entitlements is not highly sensitive to changes in this parameter. In the future, we will use data from the floodplain harvesting measurement requirements to review and verify our assumptions about application rates and reduce uncertainty in floodplain harvesting estimates.

10.2.6 Criteria 6: pathway for upgrades

River system models in the department have been and will continue to be used as ongoing tools to inform water management in NSW, and in the case of the Border Rivers Valley river system model, also in Qld. The previous models are about two decades old, and it is foreseeable that the Border Rivers Valley Source model will likewise be around for at least a generation. The Source platform has been designed for models built with it to be easily updated and extended, through inclusion of more data and/or new or improved component models. Additionally, it has a nice facility (input datasets*)* to describe scenarios and run them quickly through the model.

Good modelling practice requires that the models are continuously improved, both in terms of their accuracy and their capability. Improved accuracy increases confidence for existing purposes, and improved capability provides for broader application and increased confidence. These improvements arise from the inclusion of additional data, particularly where previously sparse, better methods, and more time.

In the case of the Border Rivers Valley river system model, of these three factors, additional on farm water harvesting and use data will allow the department the greatest scope to improve the models, as the on-farm water balance is where there is the greatest uncertainty. These data should be provided as an output from implementing the policy. The additional data can be used within the existing model framework to better parameterise components of the farm models. The

Source software platform has sufficient onboard capability to customise components where needed.

The other significant limitation of the Border Rivers Valley river system model is the estimation of the proportion of overbank flows that return to the river. This will require additional data collection and method development, and additional detail in the model, rather than a new model.

10.3 Conclusion

The updated Border Rivers Valley river system model represents floodplain harvesting much better than previous models and is capable of providing more detailed results at a finer spatial resolution. Significant effort has gone into detailed data collection and model conceptualisation under the Healthy Floodplains Project. The model has been developed using multiple lines of evidence and best available industry data to ensure that the assessment of floodplain harvesting capability at each farm is realistic. We also used a water balance assessment given historical crops grown and the estimated water requirements. This assessment focuses on the reach and valley scale to ensure that the total volume of water including historical metered use and estimated floodplain harvesting is representative of the estimated historical water use.

In brief we would argue there is sufficient evidence to conclude with low uncertainty that the model meets design criteria 1–4. Meeting these is important for the model to meet the remaining design criteria and objectives.

With respect to criteria 5, we could reasonably conclude that the model produces sufficiently accurate results where we have accurate direct observations to compare against, for example metered diversions. The calibrated model provides a good representation of the area planted in each season in response to water availability, and a good representation of both total and monthly average metered diversions.

There are some significant differences in monthly and annual time series of diversions. These differences are considered acceptable as they can largely be attributed to yearly differences in irrigation behaviour. It may be possible to better capture some of this behaviour in future refinements, however, some issues such as the influence of markets are not able to be captured in river system modelling. The model also provides a more realistic representation of supplementary access diversions in comparison to the previous IQQM.

In conjunction with more accurate infrastructure data, the model is now able to provide a more robust estimate of floodplain and rainfall harvesting diversions. However, for components with only surrogate data such as on farm water balance, we can only conclude that we have made the best available estimate given the data available. Despite the improvements to our models, there is still uncertainty in the estimates for floodplain harvesting. However, we are better able to understand the sources of uncertainty, and their impact on both total valley diversions and individual shares. We intend to make further improvements in the future through adaptive management to reduce the impacts of these sources of uncertainty.

Another known limitation is in estimating the location of and extent to which floodplain flows return to the downstream channel system. This could be concluded to be implicit as part of the flow calibration but presents a limitation when estimating the flow impacts of changes to diversions, e.g., as part of the entitlement derivation. This limitation is picked up in recommendations.

We would argue that the model is suitable to upgrade for accuracy and capability (design criteria 6). The model has sufficient process and spatial description, however, has been constrained by availability of data. As these data become available, methods can be refined and models re-parameterised to improve the accuracy and capability. Over the course of this model build, we have gone to great lengths to develop methods and datasets, for example, the hydraulic models and satellite data. Additional analysis of this data, as well as the consideration of data from the floodplain harvesting monitoring program, will improve accuracy and capability of the model.

10.4 Recommendations for future work

This modelling work has benefitted greatly from the feedback from stakeholders and especially the Independent Reviewers. While we contend that the model as described in this report meets the objectives and design criteria, models are under continuous evolution as better data and methods become available. We propose the 10 recommendations listed in Table 47 as priorities to evolve the model to increase its functionality and improve model results. These recommendations reflect external feedback and the insights of the modelling team.

Table 47 Recommendations for future work to improve model results

	Recommendation
1	Comparison to data that will be obtained through the floodplain harvesting monitoring program. Revise rainfall–runoff and overbank flow take assumptions if required, noting that several years of data will be required before this can be done with any confidence
2	Improved recording of diversions, entitlements and account balances to enable future calibrations of the model to be undertaken more efficiently and accurately, including: better recording of usage associated with temporary interstate trading; changes are required so that we can more accurately report both physical NSW usage and usage associated with interstate trade recording diversions separately for each pump through a unique ESID, rather than sharing ESID across multiple pumps changes to WLS structure and maintenance to ensure historical entitlements and temporary trades can be more readily generated for each property
3	Better representation of return flows from floodplains to river channels. This will require further research to develop a methodology for addressing this limitation in the models. Similarly, stakeholders are concerned about changes in flows breaking out into Qld and this will also likely require additional data to monitor and understand.
4	Investigate reasons and solutions for over-estimating supplementary access
5	Determine the impacts of future climate on diversion and flows for consideration during 5 yearly reviews of NSW water sharing plans and the development of the department’s regional water strategies
6	Review and refine the account management transfer functions including opportunistic placement of orders to take advantage of tributary inflows
7	Including stock and domestic entitlements and usage within the model (where significant)
8	Determine whether any refinement in either the planting decision or under-irrigation behaviour during wet and dry periods can be quantified by the available data. In particular this may be required to update the Current Conditions Scenario
9	Review the harmony rules with the operator and refine where appropriate, especially the low volume section to ensure Pindari Dam retains sufficient water to supply Pindari users
10	The efficiencies of the model’s ordering system (with borrow-and-payback) should be compared with operational records and discussed with operators in future work

11 References

11.1.1 NSW legislation and policies

(NSW) *Water Management Act 2000* No 92. Last updated 2020. https://legislation.nsw.gov.au/~/view/act/2000/92/

NSW Floodplain Harvesting Policy. First published May 2013, updated September 2018. http://www.water.nsw.gov.au/__data/assets/pdf_file/0012/548499/floodplain_harvesting_policy.pdf. Referred to in this report as the policy

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Border Rivers specific

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Appendix A Quality assurance

A.1 Quality assurance practices

The department and the Qld Department of Environment and Science each have our own set of in-house modelling practice guidelines for the development of river system models. These are based on the collective application of modelling over many decades and the broader modelling community of practice across the Murray-Darling Basin and internationally. These guidelines cover recommended data sources, extraction, validation and preparation techniques. They are regularly reviewed to capture new learnings including those circumstances which deviate from the expected, and to improve the department's modelling practice. As they are a 'living' document, i.e. they continue to evolve, they are not published in report form. However, many of the principles and practices are published through contributions to other initiatives, most recently with eWater[30] and MDBA (2017–2019).

The department's approach to selection and review of data is further detailed below.

Another important part of our quality assurance process is to undertake peer review of our final work. This includes both internal and external reviews. The department together with the Murray Darling Basin Authority (MDBA) commissioned an independent peer review of implementation of the policy in northern NSW. The key objective of the review is to provide transparency around the technical information and to provide stakeholders with confidence that the technical rigour and supporting processes are suitable to support policy implementation. For further information on this review and our action plan to respond to the recommendations, refer to our website[31].

One of the recommendations of the independent peer review was that we undertake a farm scale validation process. This was to ensure "*that the chosen parameters relating to particular farms or enterprises are realistic in relation to farm activity and are discussed with landholders*". We have undertaken this review process as is further described below.

A.2 Data review and prioritisation of data sources

Selection of data source is informed by its:

- completeness
- consistency
- accreditation, e.g. official sources with quality assured processes
- verifiability

Available data are first reviewed and checked for completeness, and to ensure that the quality of the data are understood and acceptable for the intended use. Much of the flow and climate data used in these river system models are collected using procedures that are documented and well understood. These procedures provide a basis for assessing the accuracy of the data and are taken into account when undertaking calibration and validation

A typical review process for a set of data are to search for any gaps or missing records, for example, when a flow gauging station malfunctions or a rainfall gauge was discontinued for some time. Where possible we check data against independent information or with data for nearby sites. We check for consistency in the data and to identify anomalies or changes in the statistical properties of the dataset over time.

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[30] https://wiki.ewater.org.au/display/SC/Australian+Modelling+Practice

[31] https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/harvesting

A body of practice has developed for techniques to infill missing data for many data sources. The techniques can include establishing relationships between climate (rainfall and evaporation) at one site (where there is a gap in the data) and other sites nearby (where there is no gap in the data), either directly, or via models. Where these techniques have been used to improve data for this model, relevant sections of the report describe the approach and results.

To adequately model floodplain harvesting, we required more detailed information about on-farm processes than was previously available. We have collected data from several new sources, including an extensive survey of irrigators, site inspections, remote sensing, and advice from research and industry bodies. We, therefore, needed to prioritise between the use of different data sources.

We applied the following rationale when making data choices:

1. Follow the department's model development guidelines where possible. These have been developed based on the collective body of knowledge through the development and application of models over many years, including from other agencies within NSW and interstate.
2. Base modelling on Natural Resources Access Regulator (NRAR) datasets.
    - In particular, NRAR site inspection data helped to review assumptions around the rate of floodplain harvesting. Their knowledge and data of farm operations and data on infrastructure such as pipes and pumps were used to estimate rates of take.
    - NRAR also determined on-farm storage capacities using a combination of LIDAR and survey data
    - When using the models to determine floodplain harvesting licences, some existing infrastructure is excluded as it has been deemed ineligible by NRAR for entitlement determination. Conversely, some proposed future works were deemed eligible and need to be accounted for in the entitlement determination process. Further information is provided in the companion Scenarios report (DPIE Water 2020a).
3. Prioritise verifiable data sources. For example, official government records, published data or data derived from appropriate use of remote sensing technology.

A 'multiple lines of evidence' approach is embedded throughout river system modelling. It is considered in initial data reviews as well as throughout the calibration process from flow calibration through to the final model. For example, we undertook comparisons between IBQ farm survey information as well as other supplementary material such as gauged flows and remote sensing data.

A.3 Farm scale validation and review

The floodplain harvesting program has a number of data collection and review steps which are completed prior to finalisation of entitlements. One of these steps is referred to as the farm scale validation process. We sent letters to all eligible properties in the NSW Border Rivers, outlining some key information that we would use to determine floodplain harvesting entitlements for their property. This includes a letter from NRAR with details on their works that are eligible for consideration in determining the floodplain harvesting entitlement. Landholders were able to make a submission, with supporting evidence, to an independent Floodplain Harvesting Review Committee.

In conjunction with NRAR, we reviewed all submissions and presented the results of the review to the Review Committee. Where submissions supported changes to the model, the proposed changes were presented to the Review Committee for endorsement before inclusion in the final Border Rivers Valley river system model used to determine floodplain harvesting entitlements.

Further information on the function of the review committee, and the overall implementation of the policy, can be found in the 2020 *Guideline for the implementation of the NSW Floodplain Harvesting Policy* (NSW DPIE 2020).

A.4 Report review process

This report has gone through an extensive review and editorial process. A key finding of the Alluvium (July 2019) *Independent Review of the NSW Floodplain Harvesting* Implementation was the lack of documentation of the model development process, in particular with respect to:

- the rainfall–runoff component
- how matters raised in the Independent review were responded to
- compliance with good modelling practice
- documentation of assessment of model uncertainty and suitability for application.

In response, the department prepared the first draft of this report for review (again by Alluvium, 2020). Overall, the review team supported the documentation of the model development, calibration results, and assessment of suitability, while drawing attention to areas where more detail was required. In all they listed 18 issues to be addressed, some of these being structural, some requesting further detail, and some requesting addition of new material such as Lessons Learnt, worked examples of derivation of entitlements, uncertainty analysis and sensitivity testing. This report addresses those review comments, either through adding more explanatory material to this report, or through adding material to the companion Scenarios report (DPIE Water 2020a).

An external editor was engaged in June 2020 to work with the model development team to prepare the final report. The final report was again externally reviewed to ensure all of the issues had been satisfactorily addressed.

Appendix B Climate stations

Table 48 Rainfall stations used in headwater inflow calibration, their station numbers, location (latitude/longitude) and mean annual rainfall. Asterisk (*) against a station # identifies those shown in Figure 9

Station #	Station name	Lat (°S)	Long (°E)	Mean annual rainfall (mm)
041033	Carawatha	28.76	151.99	826
041034	Glenelg	28.40	151.47	676
041038	Goondiwindi Post Office	28.55	150.31	619
041047*	Inglewood Post Office	28.41	151.08	651
041058	Kindon	28.09	150.74	587
041064	Willowvale	28.72	151.19	611
041066	Maidenhead	29.20	151.55	657
041079	Passchendaele	28.54	151.84	827
041095	Stanthorpe Leslie Parade	28.66	151.93	759
041100*	Texas Post Office	28.85	151.17	662
041110	Turallin	27.83	151.20	665
041116	Wallangarra Post Office	28.92	151.93	784
041122*	Yelarbon	28.57	150.75	601
041128	Wondalli	28.50	150.59	610
041152	Langley TM	27.98	150.92	672
041189	Warahgai	28.24	151.54	679
041340	Inglewood Forestry	28.42	151.07	656
041349	Mundagai	27.73	150.58	606
041360	Bengalla	28.66	150.67	628
041365	Pikedale TM	28.65	151.63	690
041370	Yagaburne	28.12	150.54	573
041371	Melva	28.46	151.68	699
041373	Calm Downs	28.88	151.51	676
041376	Warroo Station	28.54	151.35	665
041377	Tummurrami	28.34	151.54	609
041384	Lesbrook	28.48	151.23	584
041388	Murralah	28.06	151.33	637
041389	Pikes Creek	28.68	151.58	696
041391	Woodspring	28.36	151.15	641
041397	Burilda	28.14	150.13	579

Station #	Station name	Lat (ºS)	Long (ºE)	Mean annual rainfall (mm)
041408	Glen Etive	28.50	151.23	649
041413	Hunters Hill	28.36	151.56	632
041415	Warahgai TM	28.24	151.53	668
041428	Wobur	28.73	151.67	716
041430*	Glenlyon Dam	28.97	151.47	722
041457	Coolmunda Dam	28.42	151.21	605
041521	Goondiwindi Airport	28.52	150.33	621
041545	Dunmore Exchange Tm	27.65	150.91	692
041554	Talinga	27.78	150.46	592
042027*	Talwood State School	28.49	149.47	567
042030	Bungunya School	28.43	149.65	534
042104	Surrey TM	28.38	149.67	655
042116	Arden Downs Tm	28.23	149.56	540
052004*	Boomi (Barwon St)	28.72	149.58	557
052020*	Mungindi Post Office	28.98	148.99	507
053018	Croppa Creek (Krui Plains)	28.99	150.02	586
053041	Tulloona (Coolanga)	28.87	150.09	582
053042	Garah (Ulinga)	28.90	149.54	534
053047	North Star Post Office	28.93	150.39	619
053076	North Star (Bonanza)	28.95	150.26	588
054007	Bonshaw (Campbell St)	29.05	151.28	673
054012	Coolatai (Orana)	29.25	150.75	716
054016	Delungra (Craigmore)	29.44	150.79	681
054029	Warialda Post Office	29.54	150.58	688
054031	Graman (Willowie)	29.40	150.98	708
054032	Coolatai (Willunga)	29.20	150.61	651
054035	Yetman (Warialda Street)	28.90	150.77	657
054036	Wallangra (Wallangra Station)	29.24	150.89	735
054043*	Ashford (Beaumont)	29.36	151.14	704
054048	Graman (Maneroo)	29.36	150.92	707
054049	Graman (Ulupna)	29.41	150.90	700
054053	Ashford (Coolendoon)	29.45	151.17	680
054057	Cherry Tree Hill (Kulki)	29.52	150.96	728
054065	Nullamanna (Silverdale)	29.61	151.27	756

Station #	Station name	Lat (ºS)	Long (ºE)	Mean annual rainfall (mm)
054073	Nullamanna (Belmore)	29.64	151.24	753
054082	Kings Plains (Croye)	29.64	151.41	845
054104*	Pindari Dam	29.39	151.24	716
054122	Warialda (Croppa)	29.34	150.58	648
054124	Crooble Station	29.27	150.27	579
054129	Croppa Creek (Rawdon)	29.21	150.37	616
054130	Croppa Creek (Belford Street)	29.13	150.30	615
054135	Beebo (Mauro)	28.72	150.93	608
054161	Caroda (Paleroo)	30.12	150.13	690
056001	Sapphire (Argyle)	29.72	151.36	764
056008	Deepwater Post Office	29.44	151.85	793
056009	Emmaville Post Office	29.44	151.60	825
056013	Glen Innes Ag Research Stn	29.70	151.69	864
056018	Inverell Research Centre	29.78	151.08	786
056029	Emmaville (Strathbogie)	29.46	151.48	773
056032	Tenterfield (Federation Park)	29.05	152.02	861
056033	Tingha Post Office	29.95	151.21	806
056050	Tenterfield (Aberfeldie)	29.02	151.75	775
056052	Tenterfield (Mole Station)	29.10	151.74	704
056055	Mole River (Trenayr)	29.02	151.62	666
056094	Dundee (Wattle Dale)	29.55	151.99	933
056098	Dundee (Karinga)	29.58	151.95	816
056123	Elsmore (Paradise Station)	29.88	151.47	870
056128	Swan Vale (Numeralla)	29.83	151.52	837
056129	Stonehenge (Hazelwood)	29.83	151.73	826
056207	Maryland	28.54	151.99	823
057123	Kookabookra	30.01	152.01	878

Table 49 Evapotranspiration stations used in headwater inflow calibration, their station numbers, location (lat/long), mean potential evapotranspiration (PET) and mean lake evaporation. Asterisk (*) against a station # identifies those shown in Figure 10

Station #	Station name	Lat (ºS)	Lon (ºE)	Mean PET (Mwet) (mm/y)	Mean lake evap (MLake) (mm/y)
041038*	Goondiwindi Post Office	28.55	150.31	1,647	1,675
041087*	Riverton	29.03	151.49	1,482	1,507
041095*	Stanthorpe Leslie Parade	28.66	151.93	1,351	n/a
041100*	Texas Post Office	28.85	151.17	1,555	1,582
041341*	Inglewood Tobacco Research	28.50	150.93	1,575	1,602
053004*	Boggabilla Post Office	28.60	150.36	1,635	1,663
054043*	Ashford (Beaumont)	29.36	151.14	1,489	1,515
056018*	Inverell Research Centre	29.78	151.08	1,430	1,455
056029*	Emmaville (Strathbogie)	29.46	151.48	n/a	1,380
056032	Tenterfield (Federation Park)	29.05	152.02	1,303	1,322
054104	Pindari Dam	29.39	151.24	n/a	1,484
052020	Mungindi Post Office	28.98	148.99	1,616	1,695
041038	Goondiwindi Post Office	28.55	150.31	1,647	1,675
041087	Riverton	29.03	151.49	1,482	1,507

Appendix C Streamflow gauges

Table 50 Inflow headwater gauges used in Border Rivers Valley river system model, their station number and name, catchment area (CA), start and end dates of gauge, highest recorded and highest gauged flows. – in End date indicates that the station is still active

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m3/s)	Highest gauged flow (m3/s)
416003	Tenterfield Creek @ Clifton	550	11/07/1921	-	1,981	90.9
416008	Beardy River at Haystack	890	10/08/1934	-	738	77.5
416016	Macintyre River at Inverell	749	1/06/1962	-	1,544	1505
416020	Ottleys Creek at Coolatai	384	28/02/1967	-	562	57.0
416021	Frazers Creek at Westholme	822	3/03/1967	-	919	60.5
416022	Severn River at Fladbury	1,127	8/03/1967	-	650	82.5
416023	Deepwater River at Bolivia	531	10/03/1967	-	593	40.1
416034	Croppa Creek at Tulloona Bore	1,192	29/06/1972	16/02/1989	289	13.2
416036	Campbells Creek near Beebo	314	2/04/1973	6/05/1996	103	46.2
416204 A	Weir River at Gunn Bridge	4,424	1/07/1999	-	459	360
416305 B	Brush Creek at Beebo	323	1/10/1968	-	211	68.3
416309 A	Pike Creek at Dam Site	1,315	1/11/1960	15/02/1973	545	29.3
416309 B	Pike Creek at Glenlyon Dam T/W	1,317	5/07/1973	-	477	222
416310 A	Dumaresq River at Farnbro	1,296	14/09/1962	-	1,600	215
416312 A	Oaky Creek at Texas	395	19/04/1969	-	585	183
416315 A	Pike Creek at Glenlyon Dam Headwater	1,315	30/03/1977	-	267	222
416404 B	Bracker Creek at Terraine	675	1/10/1952	12/06/1967	2,115	332

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m3/s)	Highest gauged flow (m3/s)
416404 C	Bracker Creek at Terraine	676	1/10/1966	2/07/2002	1,051	197
416410 A	Macintyre Brook at Barongarook	537	15/06/1967	1/07/2002	756	319
416410 B	Macintyre Brook at Barongarook	537	2/07/2002	-	-	-

Table 51 Stream gauges used for reach calibration in Border Rivers Valley model, their station number and name, catchment area (CA), start and end dates of gauge, and highest recorded and highest gauged flows. – in End date indicates that the station is still active

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m3/s)	Highest gauged flow (m3/s)
416001	Barwon River @ Mungindi	38,924	01/12/1889	-	2,250	742
416006	Severn River @ Ashford	3,302	22/11/1933	-	3,264	903
416007	Dumaresq River u/s Bonshaw Weir	7,249	9/08/1934	-	4,210	568
416010	Macintyre River at Wallangarra	2,139	20/12/1936	-	1,744	993
416011	Dumaresq River at Roseneath	5,505	22/01/1937	-	5,687	486
416012	Macintyre River at Holdfast	6,976	5/06/1950	-	2,612	1,383
416028	Boomi River at Neeworra	28,705	4/04/1968	-	68	798
416032	Mole River at Donaldson	1,582	10/07/1969	-	1,659	267
416040	Dumaresq River at Glenarbon Weir	9,054	5/06/1996	-	1,903	697
416046	Macintyre River at Boonanga Bridge	24,050	15/01/1981	-	270	912
416049	Dumaresq River at Mauro	8,632	30/09/1985	4/06/1996	777	589
416201 A	Macintyre River @ Goondiwindi	22,743	20/09/1917		1,767	589
416202 A	Weir River at Talwood	12,179	1/05/1949	-	606	249
416402 B	Macintyre Brook at Inglewood	3,426	1/10/1953	2/02/1981	5,291	1,776
416402 C	Macintyre Brook at Inglewood	3,426	3/02/1981	-	1,398	672

Appendix D Sources of flow breakout information

Multiple sources of information have been used to define within channel breakouts to creeks and also overland flow breakouts as noted below. Detailed information from the TUFLOW model, which was developed for the (draft) Floodplain Management Plan for the Border Rivers Valley Floodplain 2018, was not available until late in the development of the Source model. Peak overland flow rates were obtained for a small flood event approximating the 2000 flood (Nov/Dec) around Goondiwindi and a 2013 flood at Mungindi. These data were used to cross check the modelled floodplain breakouts in the Border Rivers Valley river system model. In some areas there was no flow in this event. Cross-checking found that some breakouts were over-estimated and some were under-estimated; where possible these were addressed. More details on the TUFLOW model are provided in the (draft) Floodplain Management Plan for the Border Rivers Valley Floodplain 2018).

Table 52 Border Rivers Basin known effluents and breakouts: their name, location (reach) and downstream gauge. Those with an ID are the NSW breakouts that are depicted in Figure 14

Reach No.	Downstream gauge	Effluent name in model	ID in Figure 14	Comments
27	416201A	Ottleys FPH	A	Consistent with TUFLOW results
		Boonal FPH		Initial estimate revised based on TUFLOW data
		Whalan Creek		Based on IQQM results
		Boggabilla FPH	B	Based on SES flood records End of system connects to Whalan FPH
28	416046	Callandoon Creek		Starting estimate from IQQM recalibrated using gauged flows, including at Oonavale
		Dingo Creek		Starting estimate from IQQM recalibrated using gauged flows, including at Oonavale
		Goondiwindi FPH	C	Commence to flow based on BOM flood warning[32] for Crops and Grazing and farm survey data for the property with first access Breakout rate revised based on TUFLOW data End of system connects to Terrewah FPH (E)

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[32] http://www.bom.gov.au/qld/flood/brochures/border_rivers/border_rivers.shtml

Reach No.	Downstream gauge	Effluent name in model	ID in Figure 14	Comments
28	416046	Terrewah FPH	F	Commence to flow consistent with BOM minor flood warning and farm survey data for the property with first access[33]. Breakout rate was revised during diversion calibration. However, comparison to TUFLOW data indicates this still under-estimates breakout flows
		Coomonga Creek		Based on IQQM results
		Boomi River		Derived during flow calibration using gauged flows at Boomi River @ Offtake (416037)
29	416204A	Breakout 2 Low Breakout 2 High		Based on previous IQQM results
30	416202A	Billa Breakout Breakout 3 Low Breakout 3 High Floodplain Storage Yarrilwanna Creek		Based on previous IQQM results
32	416001 & 416028	Whalan FPH	D	Consistent with TUFLOW cross check
	416001 & 416028	Croppa Whalan FPH	E	Update made to ensure catchment inflows are appropriate[34] Compared to TUFLOW model, rate of breakout is over-estimated [35]
	416001 & 416028	Newinga Breakout I		Based on river operator advice
	416001 & 416028	Newinga Breakout II		Derived during flow calibration using observed streamflow records at downstream gauges
	416001 & 416028	Little Barwon Creek		Based on previous IQQM with some recalibration using gauged flow data.

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[33] Two properties report a slightly lower trigger (4.5m) however lowering the trigger did not result in significant difference in results.

[34] Indirectly gauged catchment inflows in this reach were partially repositioned based on catchment areas along the reach to represent inflows above Croppa Whalan FPH breakout.

[35] Downstream of Terrewah the TUFLOW model indicates more breakout flow originating from the Macintyre and less flow originating from the Whalan. On balance there is an under-estimate in total floodplain flow access by properties in this region. This section of the model cannot be readily updated to reflect the TUFLOW data as it is a complex reach. The existing results simulate the filling of all storages in the area during the 2000 event, except for 3 properties which have relatively small on-farm storage pumps and require more than 10 days to fill.

Reach No.	Downstream gauge	Effluent name in model	ID in Figure 14	Comments
		Boomangera Creek		Based on previous IQQM and consistent with farm survey
		Boomangera FPH	G	TUFLOW data indicates the rate may be under-estimated however this has not been further revised as the primarily property intercepting flow is not eligible for FPH End of system connects to Yarrowee FPH
		Yarrowee FPH	H	Commence to break based on BOM minor flood level at Mungindi Breakout rate revised during diversion calibration. Comparison to TUFLOW data indicates this still under-estimates breakout flows36
		Boomi Whalan FPH	I	Compares well in TUFLOW cross check End of system connects to Whalan creek
		Little Weir River		Based on previous IQQM results, recalibrated using gauged flow data.
		Unnamed (on Whalan Creek)		Based on previous IQQM results

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[36] Downstream of Yarrowee the TUFLOW model indicates more breakout flow than is simulated in the Source model. The model has not been updated as better representation of returns is needed to address the shortfall. The existing results do simulate the filling of all storages in the area during the 2013 event, except for one property with limited flood access for this size event.

Appendix E Major storage characteristics

Table 53 Pindari storage curves (level, volume, surface area relationships)

Level	Volume (ML)	Surface area (km2)
443	0	0
444	15.1	0.00947
446	67.6	0.0423
449	400	0.189
451	925	0.334
454	2,298	0.581
458	5,387	0.984
464	13,913	1.89
473	36,581	3.15
481	65,978	4.21
487	93,638	5.06
495	138,967	6.3
502	187,142	7.51
516	312,321	10.48
529	469,075	13.79
540	638,537	17.14

Table 54 Glenlyon storage curves (level, volume, surface area relationships)

Glenlyon level	Volume (ML)	Surface area (km2)
365.2517	0	0
365.64	0.0001	0.0001
369	185	0.157273
370	345	0.185
371	555	0.241
372	827	0.3075
373	1,170	0.3865
374	1,600	0.47
375	2,110	0.56

Glenlyon level	Volume (ML)	Surface area (km2)
376	2,720	0.66
377	3,430	0.77
378	4,260	0.895
379	5,220	0.963636
379.8	6,090	1.15
380.6	7,070	1.3
381.3	8,030	1.45
382.0	9,120	1.65
382.6	10,160	1.85
383.1	11,100	1.95
383.6	12,110	2.05
384.1	13,190	2.2
384.5	14,100	2.3
384.9	15,040	2.4
385.3	16,020	2.5
385.7	17,050	2.6
386.1	18,120	2.7
386.5	19,230	2.85
386.8	20,110	2.95
387.5	22,260	3.25
388.1	24,270	3.5
388.6	26,050	3.65
389.2	28,330	3.9
389.7	30,340	4.1
390.1	32,010	4.25
390.6	34,180	4.4
391.1	36,430	4.6
391.5	38,280	4.7
391.9	40,200	4.85
392.3	42,170	5.05
392.7	44,210	5.15
393.1	46,330	5.4
393.5	48,520	5.65
393.8	50,240	5.8

Glenlyon level	Volume (ML)	Surface area (km2)
394.6	55,080	6.3
395.4	60,310	6.75
396.1	65,180	7.15
396.8	70,290	7.45
397.5	75,610	7.75
398.1	80,350	8
398.7	85,250	8.35
399.3	90,340	8.6
399.9	95,600	8.95
400.4	100,140	9.25
401	105,770	9.55
401.5	110,620	9.85
402	115,620	10.15
402.5	120,780	10.5
402.9	125,020	10.75
403.4	130,480	11.1
404.3	140,730	11.7
405.1	150,300	12.25
405.9	160,290	12.75
406.7	170,660	13.25
407.4	180,040	13.7
408.2	191,280	14.3
408.8	200,040	14.9
409.5	210,710	15.65
410.1	220,260	16.2
410.7	230,150	16.8
411.3	240,390	17.3
411.9	250,930	17.8
412.09	254,320	18
412.5	261,730	18.25
413	270,950	18.65
413.5	280,370	19
415	309,900	20.38
415.5	320,210	20.86

Glenlyon level	Volume (ML)	Surface area (km2)
416.5	341,560	31.84
417	362,600	31.84

Appendix F Irrigation farm runoff: data review

F.1 Background

The irrigator nodes in the Source model include runoff from rain falling on developed areas, irrigated and un-irrigated, as well as undeveloped areas. The model continuously tracks the soil moisture based on rainfall, irrigation, and evapotranspiration, allowing for antecedent conditions when calculating runoff following rainfall. Quantifying this runoff is important for the farm water balance. Data to quantify this was collected and reviewed as part of our modelling.

Long term monitoring data are available for natural catchments in the region. However, there is not as yet a comparable dataset for farmed irrigated areas. An analysis of data from all calibrated gauged rainfall–runoff models in northern river systems shows runoff rates increasing with rainfall, with 2–4% of long term average rainfall becoming runoff for catchments with less than 600 mm/year average annual rainfall, the range most representative of irrigated areas. The comparative rates for higher rainfalls are 4 to 8% for average annual rainfall from 600 to 800 mm/year, and 8–16% for average annual rainfall from 800–1100 mm/year.

Two gauged catchments in the Border Rivers Valley have been evaluated to understand how much the rainfall–runoff coefficient might vary from year to year; this is shown as an exceedance graph in Figure 35 While runoff from individual rainfall events may be very high, especially for high rainfall events on a wet soil, the long-term average will be much lower. For example, annual runoff from these gauged inflows can be up to 18% of annual rainfall volume with a long term average of about 4%.

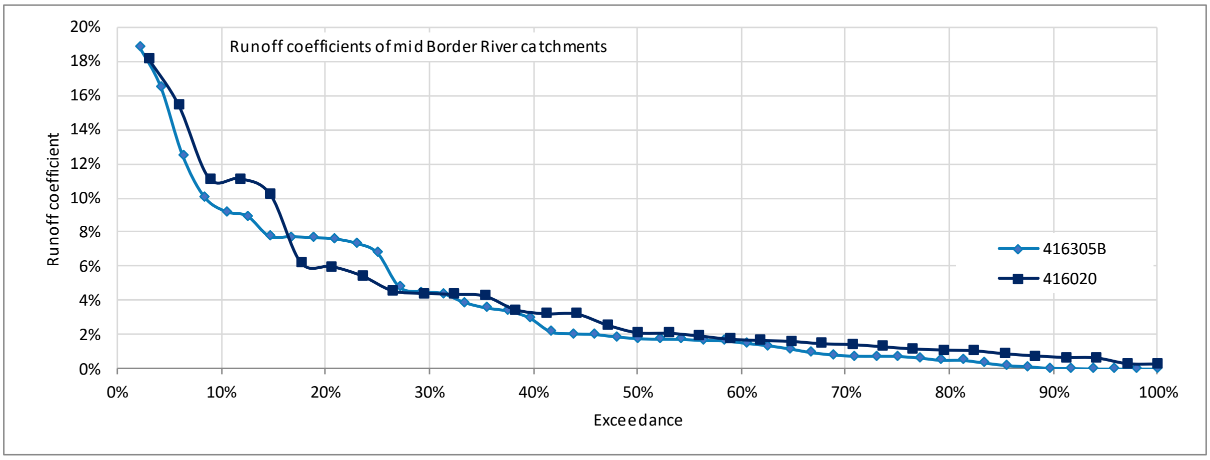

Figure 35 Comparison of mid system gauged inflow annual runoff coefficients

Long term mean annual rainfall–runoff rates are useful to develop trends for different climate zones. The Budyko framework is one such assessment method that can be used to estimate lower and upper bounds for runoff coefficients. These bounds can be used to test that inflow estimates are within the expected range at the mean annual timescale given the climate characteristics for the site. This is the recommended approach adopted by the good modelling practice guideline[1] developed by modellers across the MDB jurisdictions. Neumann et al. (2017) have demonstrated the approach using 213 catchments in the basin over the 1965 to 2009 period. Their results have been used to characterise the expected and range of runoff values for a given climate.

The expected runoff rates derived by Neumann et al. (2017) in the more arid regions is also consistent with property level runoff data and modelling for a number of cotton properties as is detailed in the following section. This gives us some confidence that the farm scale runoff results for fallow and undeveloped land should be within the bounds suggested by Neumann et al. (2017).

Runoff rates for irrigated land are expected to be higher than the fallow and undeveloped rates due to elevated soil moisture. In response to recommendations of the Independent Review, we have undertaken another independent review of the assumptions for runoff from irrigation areas (Barma Water Resources, 2019). This found that:

- the estimates were uncertain due to limited available data
- the adopted approach represents a step forward compared to other approaches reviewed
- harvesting of rainfall–runoff is likely to be a fairly small component of total valley diversions.

A small amount of relevant farm scale data was available and is summarised below.

- In field data for furrow-irrigated cotton fields was collected by Connolly et al. (2001) to calibrate a daily water balance model (GLEAMS). This has been used to assess runoff values from both un-irrigated and irrigated areas over a relatively long period (eg 30 year simulation in Connolly et al. (2001). They measured 16 mm runoff for a dryland cotton site on black vertisols in Emerald, Qld with 600 mm rainfall (~3% of rainfall), whereas an irrigated field with the same rainfall generated 42 mm of runoff (as quoted in Silburn et al., 2012). Their results indicate for a site near Warren in NSW with 625 mm of rainfall, that rainfall–runoff under conventional irrigation is around 8.5% of rainfall and that under dryland conditions it is approximately half this rate.
- The farm survey data indicated a large range of rainfall–runoff values, however the quality of the reported data (in particular the separation from other forms of floodplain harvesting) is uncertain. The overall average is a little higher than our adopted approach. Six properties provided estimates on rainfall–runoff harvesting in the farm surveys. The estimates had ranges from 0– 20% for the same annual rainfall, with an average of 9%. There was no discernible positive trend with increasing rainfall as would be expected. We assumed that the reported rainfall harvesting was from developed areas. If some of the harvesting were also from undeveloped areas, then the runoff coefficient would be lower.
- MDBA commissioned a study (FSA Consulting and Aquatech Consulting, 2011) which included field data collection over a three year period from 2008 to 2011 from six representative sites in the northern basin (three in NSW). These data was used to inform calibration of farm water balance models, including rainfall–runoff harvesting from within the irrigation property. This included runoff from both fallow and irrigated areas. The study period was relatively short but covered both dry and wet periods. An average and median rainfall–runoff of 2.5% and 1.3% respectively were reported across all properties and across both the calibration and verification period; however some correction to these rates has now been proposed by one of the authors, which would make the results closer to around 10% runoff.

F.2 Further information on Border Rivers Valley river system model development

The parameter for the rainfall–runoff model in the Border Rivers Valley river system model were developed using Boomi rainfall. The same parameters were initially adopted for other regions with the climate data changed as applicable. For Boggabilla, this resulted in runoff rates a little lower than might be expected so the parameters were adjusted slightly. The final fallow and undeveloped area runoff rates appear to be reasonable compared to the median values in the Budyko framework (Figure 2).

The parameters were defined such that runoff from fallow areas were greater than undeveloped areas. The undeveloped runoff rates were assumed to be lower, in part as the efficiency of harvesting runoff from these areas is not known. The models have adopted the undeveloped farm catchment areas claimed in the farm surveys generally without review, which in most instances was considered acceptable as the runoff volumes are relatively small. The adopted approach is that where these areas become more significant, or there is evidence of significant unaccounted for volumes, the assumptions for undeveloped areas would be reviewed. A small number of properties upstream of Goondiwindi were found to have a significant source of direct capture of regional inflow and a higher rate was adopted for this inflow (runoff coefficient of 0.04 or 4%).

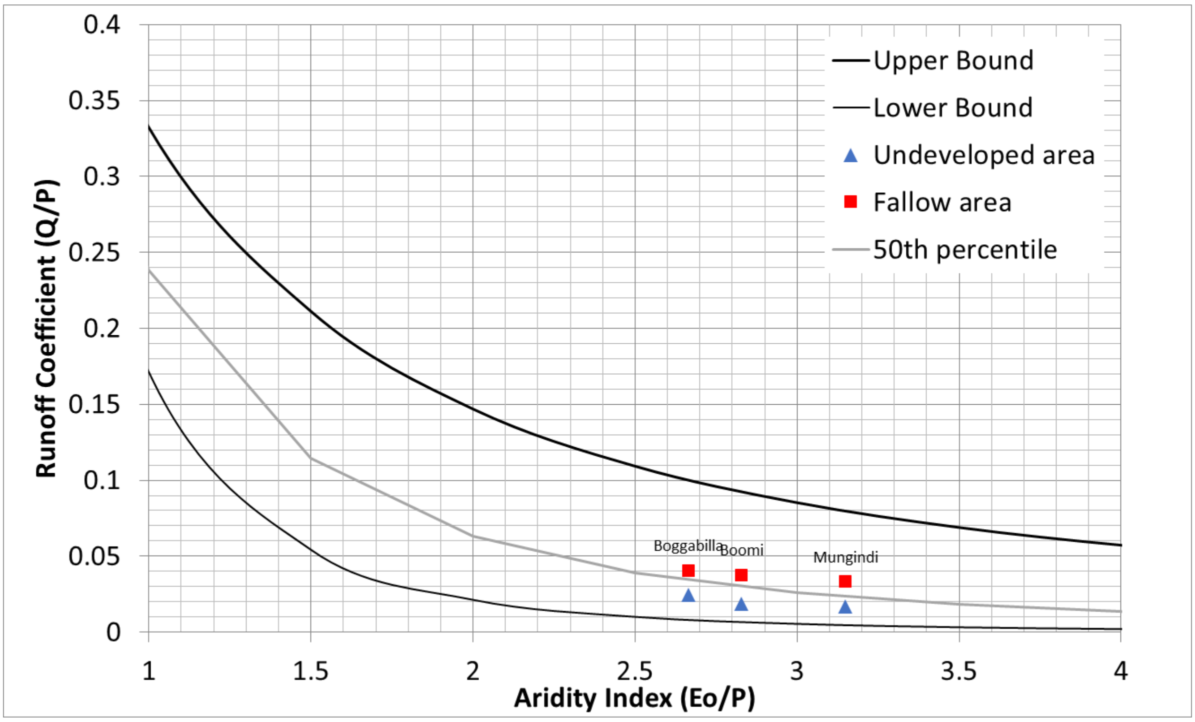

Figure 36 Runoff and aridity results for Border Rivers (1965–2009 as per Neumann et al. (2017))

As mentioned, the runoff coefficient in any one year can be quite variable. A check has also been made to ensure that the range of annual values and general pattern are reasonable, when compared to a nearby gauge (Figure 37).

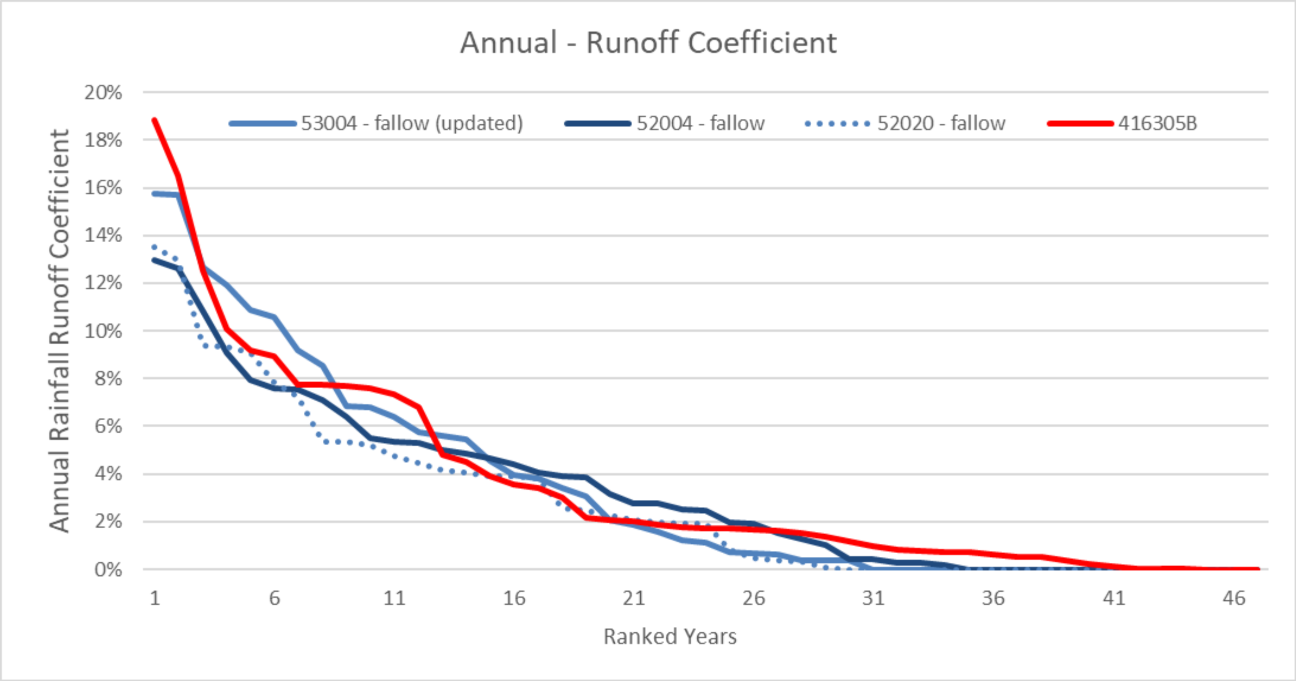

Figure 37 Range of annual runoff coefficients compared to gauged inflows; ranked data from 1969–2015

Appendix G On-farm storage and pump rate verification and worked examples

As part of implementing the policy, there has been unprecedented investment in data and modelling to improve modelled estimates of floodplain harvesting. The farm surveys collected a range of data, including information on permanent and temporary on-farm storages. The model was initially developed using the permanent storage and pump information in the farm survey. Because of the sensitivity of model results to this infrastructure, we further validated this information from a combination of remote sensed data and detailed surveys.

G.1 Storage volume and surface area

While indicative information of storage volume(s) and height(s) was provided as part of the farm surveys, more accurate information was needed. Only a few properties provided storage geometry data from a qualified surveyor and these datasets were also of variable quality.

Storage capacities have been reviewed using LIDAR data. In a few instances where these data were not available, photogrammetry has been used. LIDAR is a remote sensing method that can be used to measure relative elevations of the land surface. LIDAR was used to provide a detailed survey of significant areas in the five northern valleys for the Healthy Floodplains Project. The elevation data were used to generate a high-resolution digital elevation model. This was accurate enough to develop water level versus volume curves for on-farm storages that were empty during the time of survey.

The LIDAR survey cannot penetrate below water in partially full storages. This limitation was overcome by synthesising the area below water level using a storage bathymetry model (SBM), and computing the volume vs level relationship from this synthesis. An initial SBM was based on 5 empty storages with a range of volumes and surface areas. The SBM was validated using an additional 6 on-farm storages for which a conventional land survey was available.

The average difference in volume between the storage curves derived from the land survey and the SBM survey was less than 2% at full supply level. However, the accuracy is lower for on-farm storages with small surface areas and high bank heights. The SBM model was then refined using information from an additional 27 empty storages. Further information on the method and verification can be found on the department's website[37]. A 1m freeboard has been assumed for all permanent storages.

The spatial maps of storages were combined with Landsat data to confirm the date on-farm storages were built, which was used to estimate levels of development for scenarios.

G.2 Verification and representation of temporary storages

As part of the detailed survey data collected from all farms, many landholders indicated significant historical use of irrigation fields, surge areas, and supply channels, as temporary water storages. The extent of this was verified using Landsat data from 30 Jan 2011. A very large event occurred prior, peaking at Goondiwindi on 15 January. Assuming a depth of 1m, it is estimated that less than 1.5GL was held in temporary storages on 30 January.

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[37] https://www.industry.nsw.gov.au/__data/assets/pdf_file/0010/271936/Storage-bathymetry-model-update-and-application-gwydir.pdf

Temporary storages have only been accounted for in the model where NRAR advise that they should be included. The policy position is that temporary storages are not to be included in the storage capacity assessment for the farm. However, where temporary storages such as Surge areas and sacrificial fields allow for a fast intake of water and then transfer to permanent storages (within 14 days), this buffering effect can be accounted for. It is only the water transferred to permanent storage which counts as eligible floodplain harvesting.

We include these in the model where:

- the storage is either a property constructed buffer storage mapped by NRAR or remote sensing evidence prior to 2008 confirms that it was used to hold overland flow
- the storage is significant; it is greater than 20 ML and greater than 5% of eligible OFS capacity.

Small surges, or surges that do not allow a much faster intake rate compared to the on-farm storage pumps, will have little impact on modelling results. Adding the temporary storages adds significant complexity to the modelling (particularly in IQQM) and hence we developed this approach to avoid unnecessarily complicating the modelling.

G.3 On-farm storage pump rate

NRAR have undertaken a comparison of IBQ data, industry advice and pump charts to provide information to the modelling team on the expected flow rate for a given type and size pump. A flow range has also been provided.

The actual flow rate can vary for a number of reasons:

- capacities can change by 20–30% depending on head
- all values are based on expected flows from reasonably designed pump stations. Variations in design may affect flow rates.
- some irrigators run pumps harder (higher speed / higher tolerances) than others for greater output. In particular this may occur for short periods when floodplain harvesting.

We have adopted the expected flow rate; however, sensitivity testing has also been undertaken to assess the impact of variable pump rates on the floodplain harvesting estimate.

Pump rate analysis

The adopted flow rate and expected range are illustrated in Figure 38 and Figure 39. The adopted flow rates have also been compared to check for reasonably consistency (Figure 40).

The adopted flow rate has good consistency with average flow rate information obtained from a combination of IBQ and other industry advice.

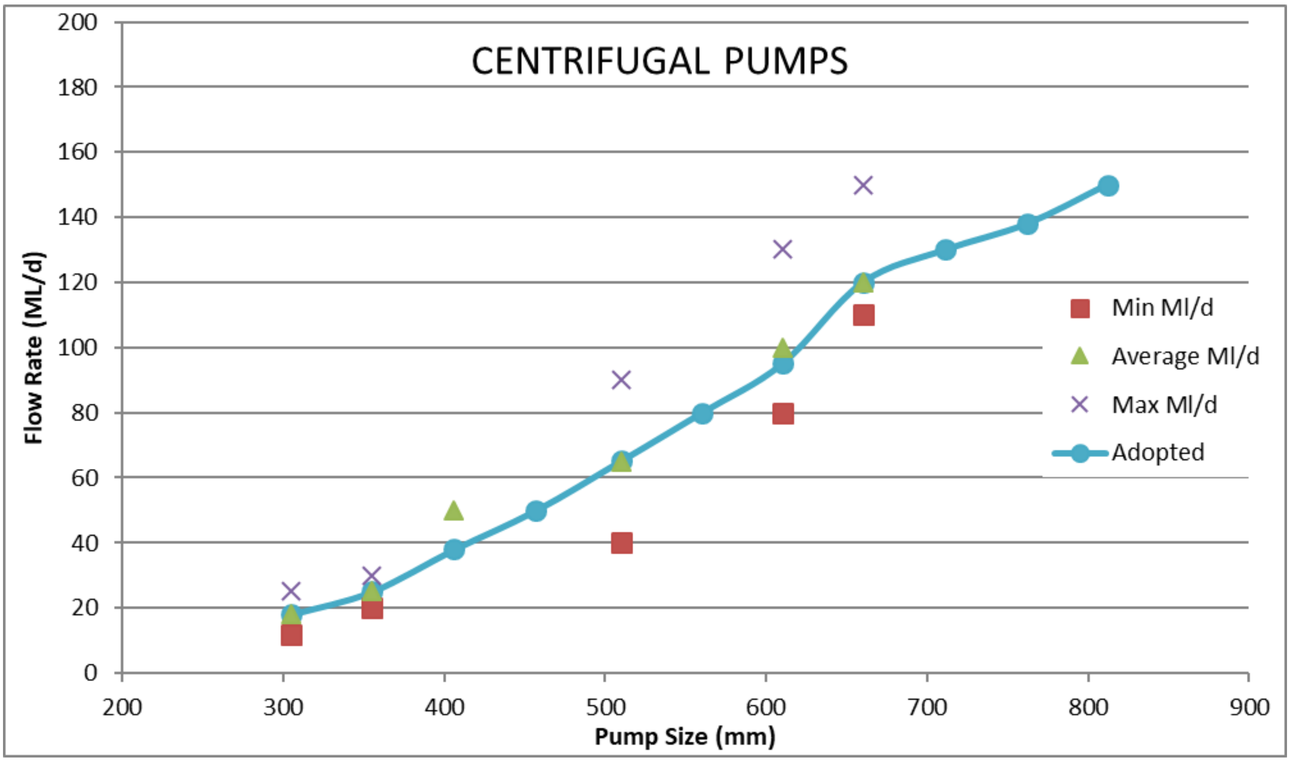


Figure 38 Centrifugal pumps flow rate analysis

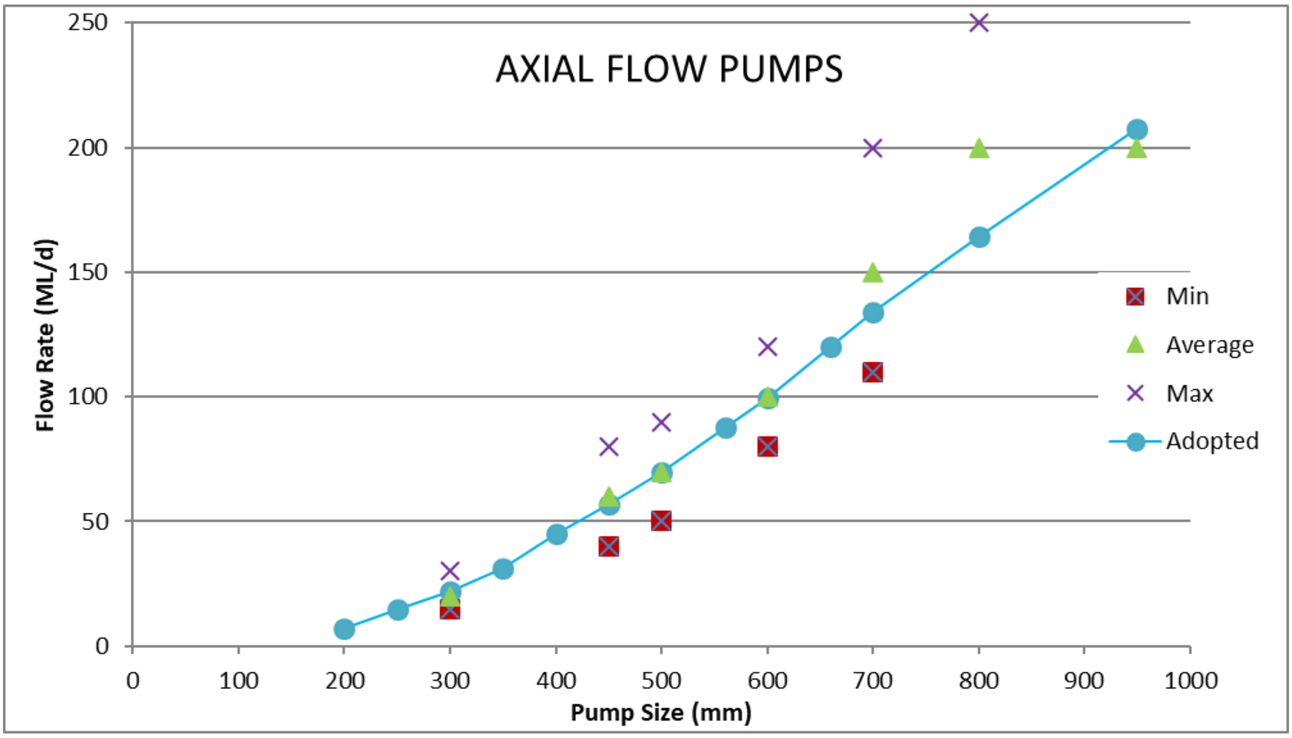


Figure 39 Axial flow pumps flow rate analysis

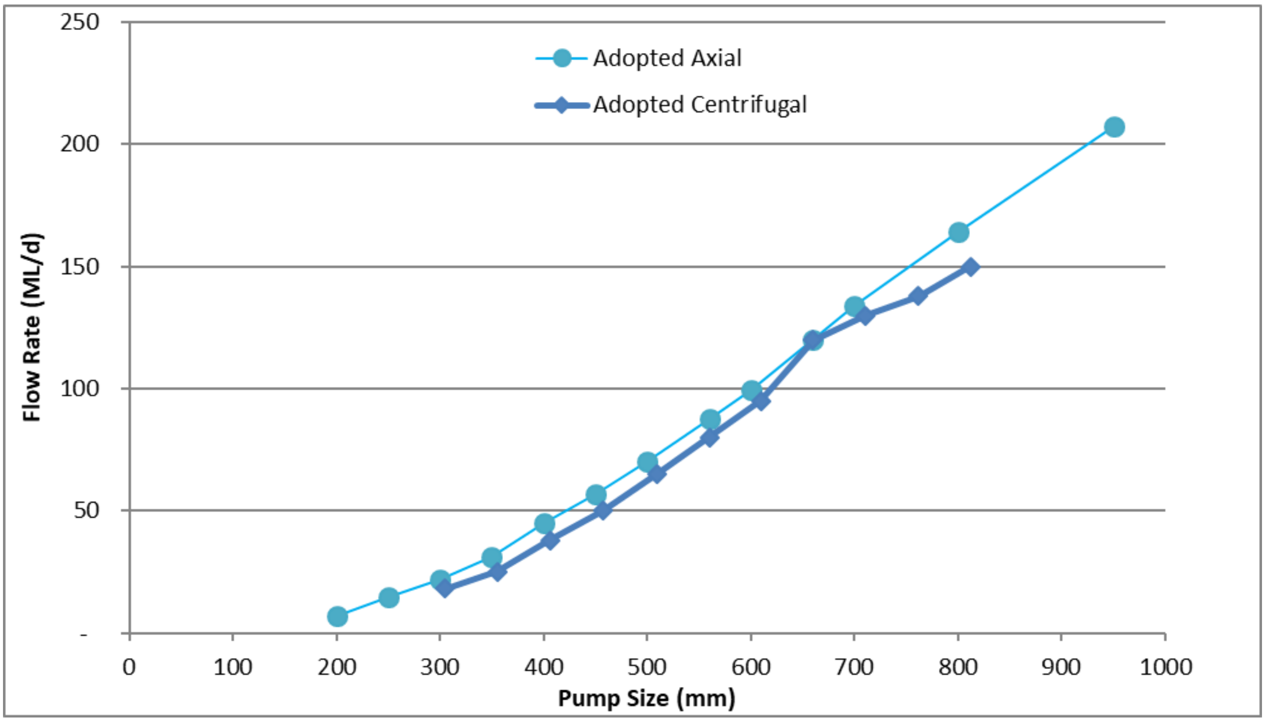


Figure 40 Comparison of adopted centrifugal and axial flow rates

G.4 Intake infrastructure

There are typically a number of pipes which bring water in from the floodplain to the area developed for irrigation. In some cases, regulators and pumps also serve this function. These were all assessed to estimate the capacity of 'intake' into the property. In general, the total 'intake capacity' was more than the total on-farm storage pump capacity. This means that the on-farm storage pumps were considered to be the limiting factor and the capacity of the pipes was generally not used in the modelling. There were only a few exceptions to this as discussed in section 6.2.2.

The flow rates assumed in the review of pipes are set out in Table 55.

Table 55 Pipe diameter and estimated flow rate at 0.2m head

Diameter (m)	Flow rate (ML/d)
1.8	264
1.5	183
1.2	117
1.05	92
0.9	66
0.75	48
0.6	29
0.5	20

G.5 Worked example for representing floodplain harvesting works including temporary storage

This section describes an example property where allowance for temporary storage has been included in the modelling. All data in this example are draft, for the purposes of illustrating the modelling methodology.

The property can access overbank flow in the following way:

- one eligible storage with a relatively small total lift pump capacity estimated at 240 ML/d
- one surge area which is able to intake water at a much higher rate through three pipes. While the head will vary in practice, we adopt a simplified approach and assume a head of 0.2m is representative. In larger floods, the head may be higher, however this is not really relevant where the model is filling storages regardless. Assuming a head of 0.2m, we estimated a representative rate of around 813 ML/day through the pipes to both the temporary storage and direct to the permanent storage.

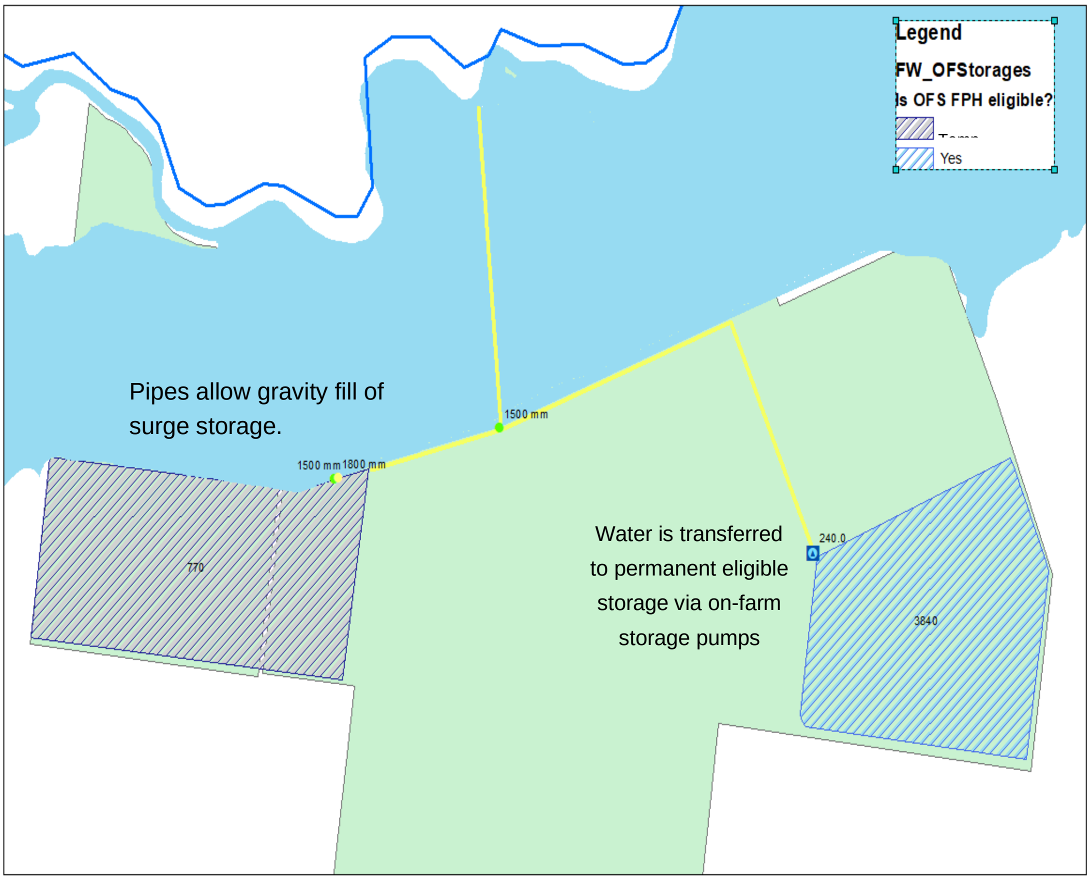
Using LIDAR, we estimated the surge capacity at 770ML.

If we were to represent the temporary storage and transfer to permanent storage, this would require a complex model arrangement with several additional nodes. A much simpler approach is to account for the temporary storage by adjusting the pump rate on the permanent eligible storage. This approach assumes that the water in surge is immediately put into the permanent storage.

The model initially assumes that water is put into the on-farm storage at the maximum rate of total harvesting. This is estimated as 630 ML/day into the surge plus 183 ML/day direct to the on-farm storage via one 1500mm pipe. However this high rate cannot continue if the surge is filled. To represent this, the model uses a function on the on-farm storage pump as follows:

- If the total volume pumped in the last 10 days is less than the capacity of the surge (770ML), then the maximum rate of 813 ML/day is assumed to be the permanent on-farm storage pump capacity
- Otherwise, the surge is assumed to be filled and the on-farm storage pump rate drops to 240 ML/day.

Figure 41 demonstrates this example.



Pipes allow gravity fill of surge storage.

Water is transferred to permanent eligible storage via on-farm storage pumps

Figure 41 Example property with temporary storage

G.6 Worked example for representing floodplain harvesting works where multiple storages and intakes

This section describes an example property where there are multiple storages and floodplain harvesting intake points. All data in this example are draft, for the purposes of illustrating the modelling methodology.

The property can access overland flow in the following way:

- overbank flow from the Macintyre intercepted by below ground channels. The upstream properties have first access to overbank flow from this region and the model represents this order of access
- overbank flow from Tarpaulin Creek. The channel crossing the creek requires modification and is not included in the water supply work approval. The within bank flow in Tarpaulin Creek is not to be included in the floodplain harvesting entitlement; we have estimated overbank flow in this region and included.

The property has multiple works:

- two eligible storages with a total estimated pump capacity of 720 ML/day
- one ineligible storage. This storage is not included in the assessment of eligible floodplain harvesting. The storage is included in the Current Conditions Scenario, however.
- multiple pipes which bring water in from the channels into the developed part of the farm and allow delivery to the storages. The total capacity of these pipes was estimated to be greater than 720 ML/day. Hence the on-farm storage pumps were considered the

limiting factor. The rate of floodplain harvesting is therefore set to the same as the total on-farm storage pumps rate; this means for the eligible scenario the rate is 720ML/day.

Figure 42 demonstrates this example.

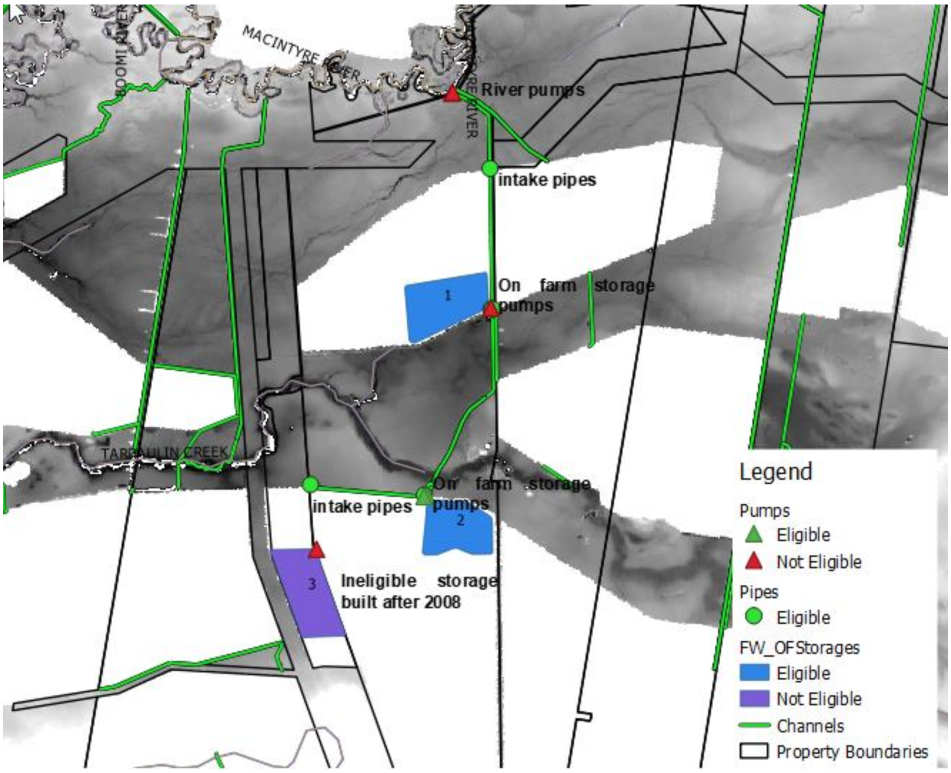


Figure 42 Example property with multiple storages and intakes

Appendix H Crop area verification

The IBQ farm survey reported summer crop areas were compared against two remotely sensed datasets, MODIS and Landsat. Winter crop areas have not been analysed as remote sensing data are less reliable during these periods. The Border Rivers is also dominated by summer irrigation.

The remote sensing data were obtained from 2009/10 to 2013/14 for one tile in the Border Rivers. This covers approximately 55% of the total developed area for floodplain harvesting properties and approximately 65% of the floodplain harvesting entitlement.

- MODIS analysis uses a time series analysis to look for spectral response which approximates the expected crop behaviour.
- Landsat offers higher spatial resolution; however, the time series analysis is more difficult as LANDSAT has a slower orbit with resulting lower temporal resolution.

Both datasets compared well to the reported survey data. MODIS was 5% higher than survey and LANDSAT was 2% less than survey data. Annual totals for the Landsat data compare very well to the survey data (Figure 43).

Additional MODIS data are available for all floodplain harvesting properties and for additional years. These data are presented in the companion report (DPIE Water 2020b).

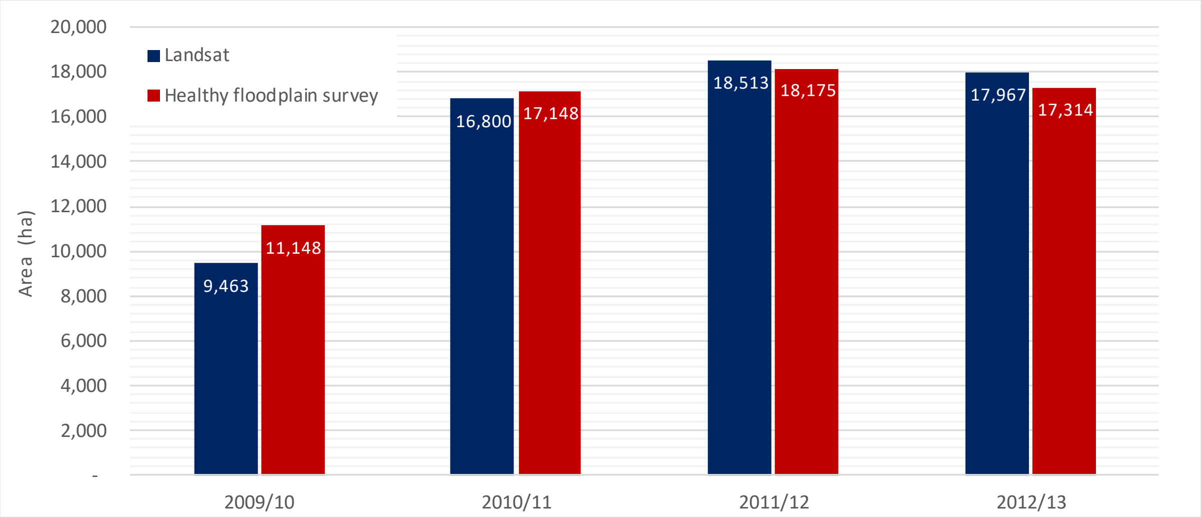


Figure 43 Summer crop area comparison. Only properties completely within the Landsat tile are included and only if survey data was also provided in these years. The 2013/14 year is excluded as not many surveys included data for this year

H.1 Completeness of survey crop area data

Survey data on crop area and crop type were supplied by most floodplain harvesting properties. The properties which supplied no data represent 6% of the total developed area.

Not all properties filled in crop areas starting from 2003/04. In some cases, this may be due to no crops being planted; however, there will be cases where crops were planted but no records were available. An analysis of the completeness of the planted areas was undertaken as follows:

- properties were classified based on year in which crop areas were originally reported
- the sum of the developed area was determined for all properties with records (i.e. they started recording in that year or in an earlier year)
- this area was divided by the total developed area for all floodplain harvesting properties.

Results are presented in Figure 44.

The farm water balance test was completed using the 2007/08 to 2012/13 water years. Earlier years and the 2013/14 year were not included due to gaps.

Bar chart with years on x-axis and % crop history completeness on y-axis

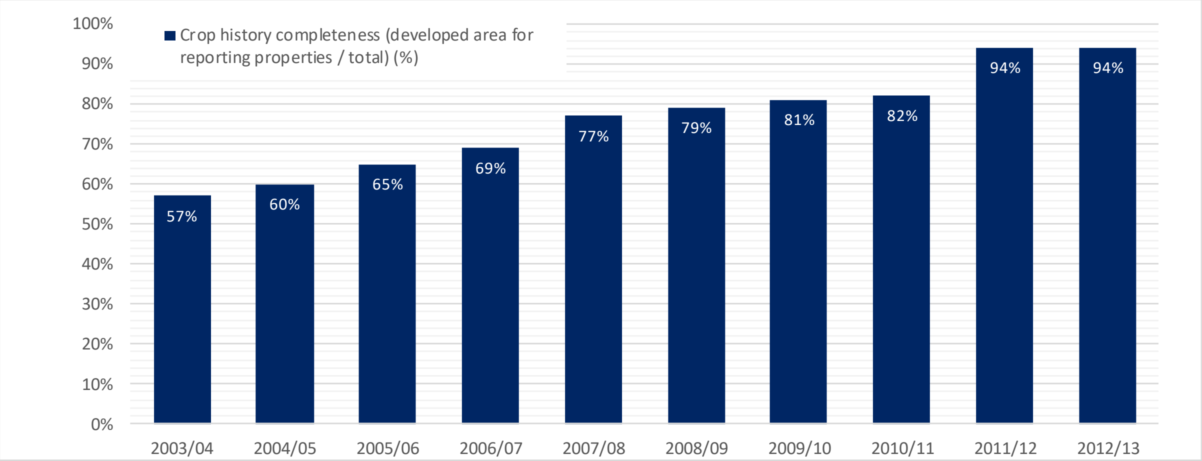


Figure 44 Completeness of reported crop area records

Appendix I Irrigation demands

To provide confidence in the water demands generated by the crop modelling, the modelled application rates were compared to published data. The following review focuses on cotton as this represents the majority of irrigation water use. This analysis used two types of modelled results:

- full irrigation application rates (no water availability restrictions)[38]
- modelled irrigation application rates as used in the Border Rivers model.

The first test allows for comparison of the theoretical irrigation water use to other estimates such as WaterSched Pro. In practice, full irrigation may not be occurring during dry years. Hence the second test is designed so that comparisons can be made to published data on actual application rates (e.g. ABS and IrriSAT).

In both cases, the modelled results are assessed in terms of water applied to the field (ML/ha). The application rates are defined as follows:

- includes application losses
- excludes rainfall, on-farm storage losses and tailwater returns.

Available literature on average irrigation requirements is not consistent or clear on whether the requirements include some or all losses, making comparison difficult. It is also difficult to compare published data for large areas and/or for short periods as different climatic conditions in each season need to be taken into account.

I.1 Farm surveys

The farm surveys we undertook to collect information for assessing floodplain harvesting included questions on water application rates, pre-watering rates, and tailwater returns. After adjusting for tailwater returns, analysis of the survey results showed a range of application rates from 3.6–11.5 ML/ha, with an average of 7.9 ML/ha. There is no geographical relationship or other physical factor that explains this range. It is likely the variability can be attributed in part to averaging over different periods. Given the range, this information was referred to when assessing results, but not otherwise used directly in the model parameterisations.

I.2 IrriSAT

The IrriSAT methodology uses satellite images to determine the Normalized Difference Vegetation Index (NDVI) for each field, from which the plant canopy size can be determined and a specific crop coefficient (Kc) can be estimated. By combining Kc with daily reference Evapotranspiration (ET_o) observations from a nearby weather station, the crop water usage can be determined.

The method to estimate Kc and crop water use has been published internationally (Vleeshouwer et al, 2015), however verification for the IrriSAT method has not been published for Australian cotton. We note that the IrriSAT method uses a different reference evapotranspiration dataset, hence new verification is required. Until the uncertainty in evapotranspiration estimates is established, the IrriSAT dataset will only be used by the department as a secondary information source.

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[38] A simple test model was used with a notional unit crop area over a long term period with an unrestricted water supply. This model has been used to calculate the simulated water use per hectare for cotton.

The IrriSAT website[39] publishes estimates of crop factors and actual evapotranspiration. These data can be assessed at paddock scale and compared to modelled data. The IrriSAT website contains downloadable data for one year only near Goondiwindi, hence we only compared for the 2017–18 year. Kc values estimated by IrriSAT, near Goondiwindi, have been compared to parameters assumed in Source[40] as show graphically in Figure 45.

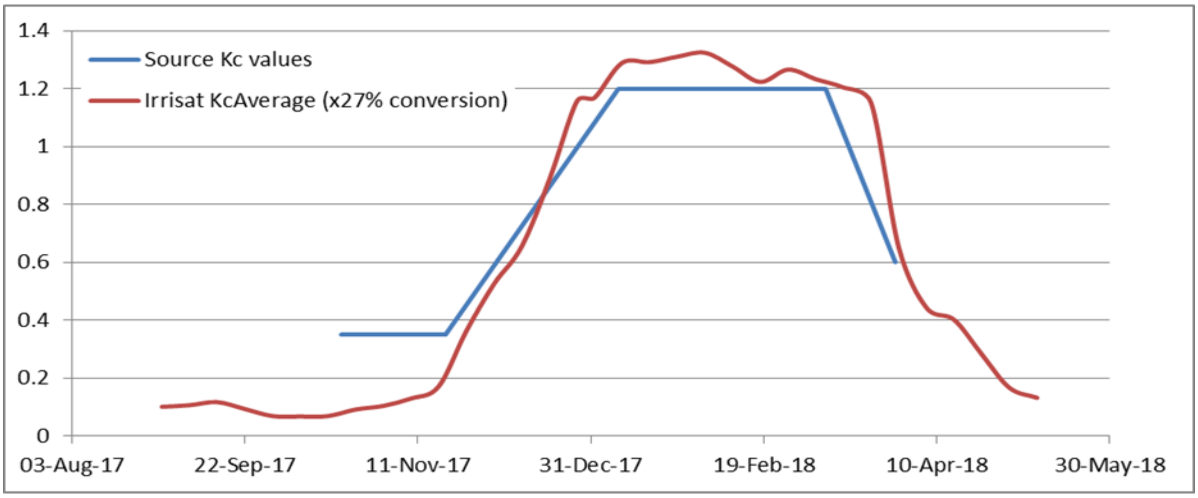

Figure 45 Comparison of Border Rivers river system model Kc values to IrriSAT estimate for 2017/18

This analysis indicates that the Border Rivers Source Model K_c values are consistent for the growing season with those from IrriSAT. The Border Rivers Source Model K_c values are higher at the start of the season, which is consistent with FAO56 for simulating bare soil. The crop model parameterisation in Border Rivers Source model assumes that the crop finishes earlier than IrriSAT indicates. This was a deliberate consideration, to allow the soil moisture to deplete, and not schedule further irrigation.

Sample estimates at three locations of actual evapotranspiration were also obtained from IrriSAT and compared to the unrestricted water availability modelled results (Table 56) for the 2017/18 year. The NVDI values at Goondiwindi looked to be fairly even and compare well to our modelled results, whereas a range of values was observed at both Boomi and Mungindi. This indicates that the modelled ET estimates are close to IrriSAT values around Goondiwindi and Mungindi, and possibly underestimating by about 12% near Boomi.

Future work to more systematically compare and analyse IrriSAT and modelled results is needed to assess uncertainty in this method to develop confidence as to the best available estimate of actual crop water use.

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[39] https://IrriSAT-cloud.appspot.com/

[40] IrriSAT uses a different reference ET which needs to be taken into account when comparing Kc values. We use FAO56 ET from SILO. The IrriSAT uses the ASCE method which can also be obtained from SILO, and was 27% greater during the summer season. The IrriSAT Kc values were scaled accordingly for comparison purposes.

Table 56 Evapotranspiration estimate (mm) for the period 15 Oct 2017–23 Mar 2018 at 3 IrriSAT sample locations – Boggabilla, Boomi and Mungindi

ET estimate	Boggabilla	Boomi	Mungindi
Source	870	900	930
IrriSAT sample 1	890	1,070	1,060
IrriSAT sample 2	–	1,020	940

I.3 WaterSched Pro

WaterSched Pro is an irrigation management tool that informs irrigation scheduling and crop water use[41] developed in Qld, with comparable conditions to northern Murray Darling Basin. WaterSched Pro provides an estimate of long-term average crop water use using FAO56 crop coefficients assuming an unrestricted water supply. This utility does not account for any pre-watering, whereas the Source model parameterisation includes this[42].

The WaterSched Pro results are compared to the unrestricted water availability modelled results in Table 57. The following assumptions were used in WaterSched Pro for cotton:

- 70% efficiency[43]
- 70 mm soil water deficit at15 October plant date, 180-day, typical water use
- averaged using climate data for 1900–present.

WaterSched Pro does not account for any pre-watering, whereas the Border Rivers Source model includes this. This largely accounts for differences in modelled values being 1.1 ML/ha higher, which is about the averaged modelled fallow soil depletion of 0.92 ML/ha at the beginning of the modelled irrigation season of 15 October.

Pre-watering requirements would be larger in the northern valleys where there is less spring rainfall preceding the irrigation season.

Table 57 Long-term annual average irrigation (mm) for cotton at Boomi: WaterSched Pro versus modelled

Site	WaterSched Pro (mm)	Border Rivers Source model (mm)
Boomi	793	907

I.4 Australian Bureau of Statistics data

The Australian Bureau of Statistics (ABS) collects data on irrigation application rates for various crop types and regions. These data appear to represent water applied to field, including application loss, and is assumed to include data from unregulated cropping areas.

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[41] https://waterschedpro.net.au/

[42] WaterSched Pro assumes a full soil moisture profile at planting whereas Source modelling assumes soil moisture based on simulation of water balance in a fallowed area. The extent to which pre-watering is required will vary depending on fallow and soil management practises (e.g. Harris, 2012).

[43] Gillies (2012) analysed 542 surface irrigation performance evaluations from the past decade. The average application efficiency with tail water recycling was 76.3% (cited in Tennakoon *et al*. 2012). The assumption of 30% loss allows for channel losses not modelled explicitly. On-farm storage losses are modelled separately.

The ABS reports application rates over a large region covering both the Gwydir and Border Rivers. The ABS data has been compared to WaterSched Pro results in Figure 46. The data are reasonably close during the wetter years, but ABS data are significantly lower during dry years, and may indicate under-irrigation during dry years in this area.

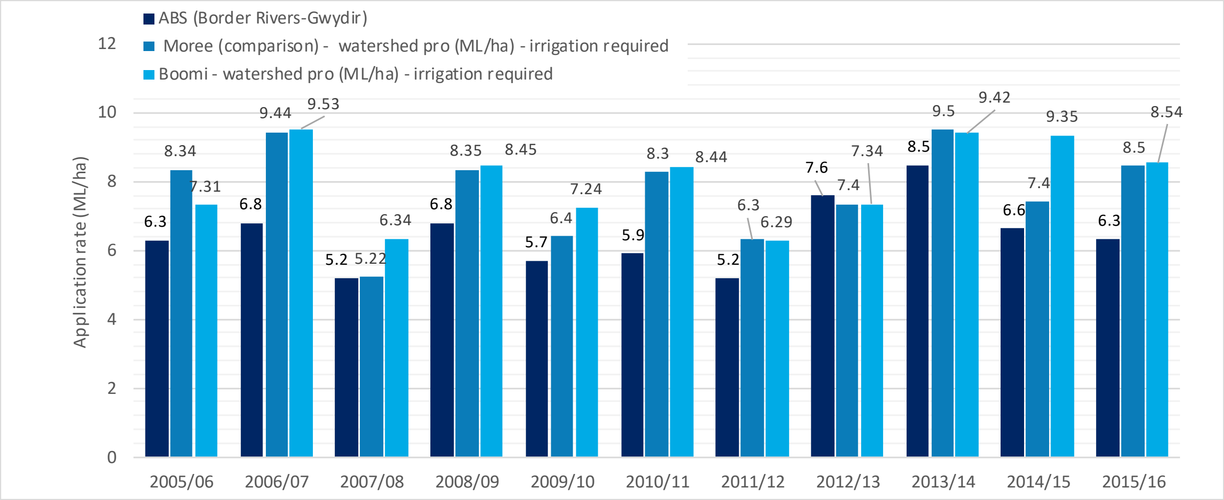

Figure 46 ABS data versus WaterSched Pro estimates for Border Rivers and Gwydir

The Border Rivers Source model under-irrigates to some extent during dry years because of limits to availability. In particular, if a high-risk crop area planting decision (for example, 4 ML/ha) was defined for a water user based on farm survey, then water stress is likely to occur in the model during dry years.

Unrestricted and actual water availability modelled application rates from the Border Rivers Source model are is illustrated in Figure 47 which show some years where the actual modelled values are less than unrestricted supply. The Border Rivers actual modelled results are slightly higher than ABS during this period; the overall average is 7.4 ML/ha (modelled) versus 6.4 ML/ha (ABS). This is considered acceptable, particularly when the size of the ABS region is considered which makes comparison in individual years difficult.

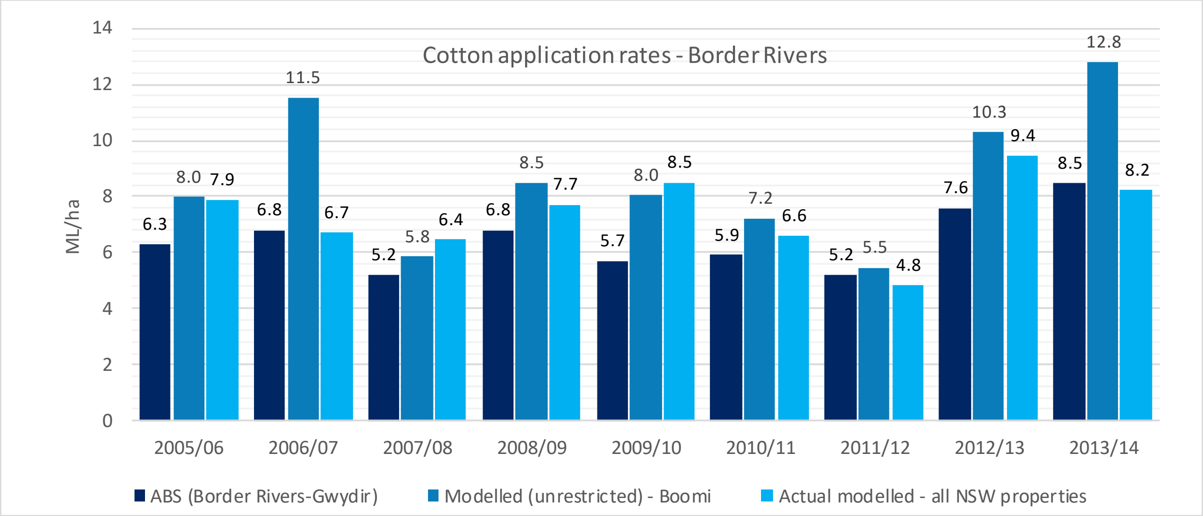

Figure 47 Border Rivers: theoretical and actual modelled v ABS

Appendix J River reaches in the river system model

Table 58 Border Rivers Valley reach division

Reach Name	Upstream gauge	Downstream gauge
416032 Mole R. at Donaldson	416023	416032
416007 Dumaresq R. at Bonshaw	416008 416011	416007
416011 Dumaresq R. at Roseneath	416309A/B 416310A 416003 416032	416011
416409A/B Coolmunda Dam Headwater	416410A 416404B/C	416409A/B
416402B/C Macintyre Brook at Inglewood	416409A	416402B/C
416415A Macintyre Brk. at Booba Sands	416402B/C	416415A
416040 Dumaresq River at Glenarbon	416007 416312A 416305A/B	416040
416039 Severn River at Strathbogie	416022	416039
416030 Pindari Dam Headwater Gauge	416039	416030
416006 Severn R. at Ashford	416030 416021	416006
416010 Macintyre R. at Wallangra	416016	416010
416012 Macintyre R. at Holdfast	416006 416010	416012
416201A Macintyre River at Goondiwindi	416020 416012 416036 416040 416415A	416201A
416046 Macintyre at Boonanga Bridge	416201A/B	416046
416202A Weir River at Talwood	416204A	416202A
416001 Barwon River at Mungindi and 416028 Boomi River at Neeworra	416046 416037 416202A 416034	416001 416028

Appendix K Flow calibration tables and graphs

For headwater gauges, the Sacramento model results are compared to recorded flows.

For main river gauges, the results are generally based on using the final flow data inputs, which are a combination of gauged flows and Sacramento flows to extend (to meet the modelling period) and fill gaps. The figures also include another validation test for main river gauges, where inputs are based on Sacramento model results only. The two versions of the validation test are noted in the figures as 'Sac' for Sacramento inputs only and 'final' for inputs based on final flow data inputs.

Table 59 Headwater inflow flow calibration statistics. For each station, mean annual flow, runoff as % of rainfall, daily Nash Sutcliffe, flow bias for full, low, medium and high flow range (%) and reference to graph in this report (Figure number) are reported

Station No	Mean annual flow (GL)	Runoff as % of rainfall	Daily Nash Sutcliffe	Full flow bias (%)	Low flow bias (%)	Medium flow bias (%)	High flow bias (%)	Graph reference
416003	51.1	9.5	0.53	0.0	24.7	0.4	-0.3	Figure 48
416008	67.2	8.2	0.53	0.0	42.1	3.5	-0.6	Figure 49
416016	55.7	6.2	0.61	0.0	15.4	2.3	-0.5	Figure 50
416020	10.9	4.1	0.73	0.0	-4.4	6.6	-0.6	Figure 51
416021	59.0	8.1	0.75	0.0	-0.4	-0.5	0.3	Figure 52
416022	90.6	8.7	0.74	0.0	12.9	0.2	-0.2	Figure 53
416023	44.0	8.6	0.69	0.0	11.9	0.1	-0.2	Figure 54
416034	26.2	3.2	0.71	0.0	18.1	11.5	-0.3	Figure 55
416036	6.6	3.4	0.68	0.0	38.6	3.7	-0.2	Figure 56
416204a	137.1	3.6	0.85	-0.7	211.2	12.1	-2.1	Figure 57
416305b	9.7	5.3	0.56	0.0	39.5	-0.5	-0.1	Figure 58
416309A/B& 416315A	78.5	6.4	0.71	-2.5	-28.2	-7.2	-1.3	Figure 59
416310A	95.6	7.5	0.81	0.0	24.7	1.0	-0.4	Figure 60
416312A	16.8	5.2	0.39	0.0	-0.7	-5.7	1.5	Figure 61
416404B/C	26.3	5.0	0.69	0.0	18.0	13.9	-0.2	Figure 62
416410A/B	26.3	6.8	0.72	0.0	35.7	2.1	-0.2	Figure 63

Table 60 Reach flow calibration statistics. For each station, mean annual flow, runoff as % of rainfall, daily Nash Sutcliffe, flow bias for full, low, medium and high flow range (%) are reported. Final flow bias is from the fully assembled flow calibration model (validation model)

Station No	Mean annual flow (GL)	Runoff as % of rainfall	Daily Nash Sutcliffe	Full flow bias (%)	Low flow bias (%)	Medium flow bias (%)	High flow bias (%)
416001	550	0.70	-7.0	87.3	-1.0	-12.1	Figure 64
416006	241	0.77	-8.9	14.1	-0.5	-11.5	Figure 65
416007	398	0.89	-1.2	-18.8	-2.1	-0.6	Figure 66
416010	123	1.00	0.0	0.0	0.0	0.0	Figure 67
416011	340	0.84	0.4	-41.4	-1.0	1.3	Figure 68
416012	403	0.87	2.1	17.0	2.6	1.8	Figure 69
416028	233	0.77	-3.0	31.9	1.5	-4.7	Figure 70
416032	110	1.00	0.1	10.7	0.2	0.0	Figure 71
416040 /416049	410	0.98	-0.4	7.1	0.0	-0.6	Figure 72
416046	546	0.90	6.7	-39.8	40.1	-9.0	Figure 73
416201A	865	0.82	-7.2	-27.8	-16.3	-3.0	Figure 74
416202A	121	0.87	-9.7	182.7	-5.5	-10.3	Figure 75
416402B/ C	103	0.70	16.1	116.3	41.1	12.3	Figure 76
416415A	112	0.91	12.1	-50.1	4.2	13.4	Figure 77

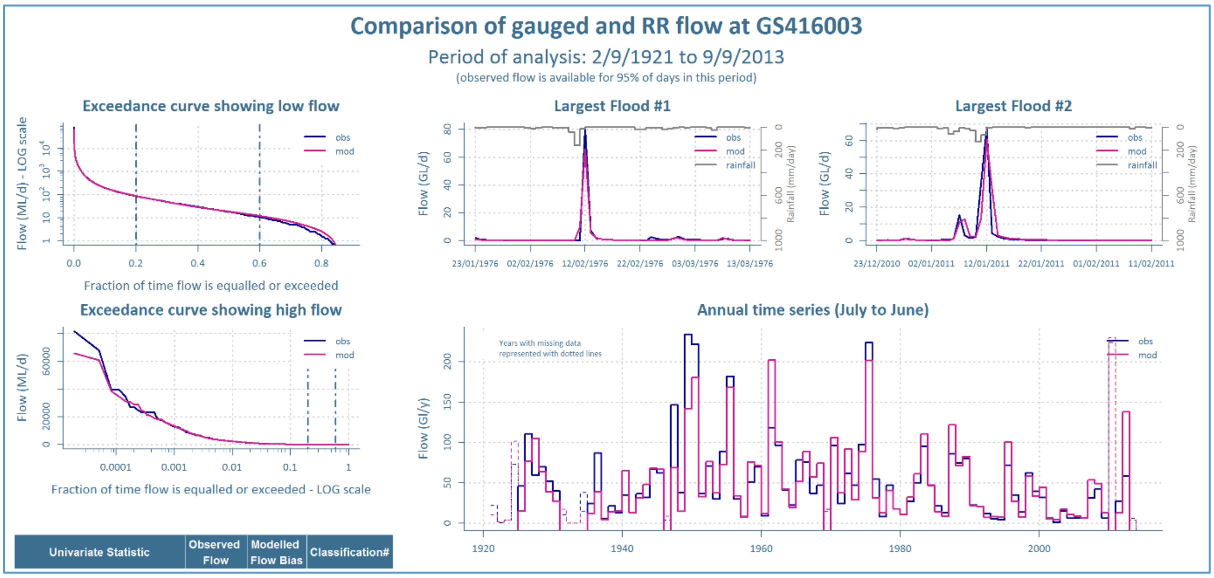

Figure 48 Flow calibration graphs for gauging station 416003 Tenterfield Creek @ Clifton

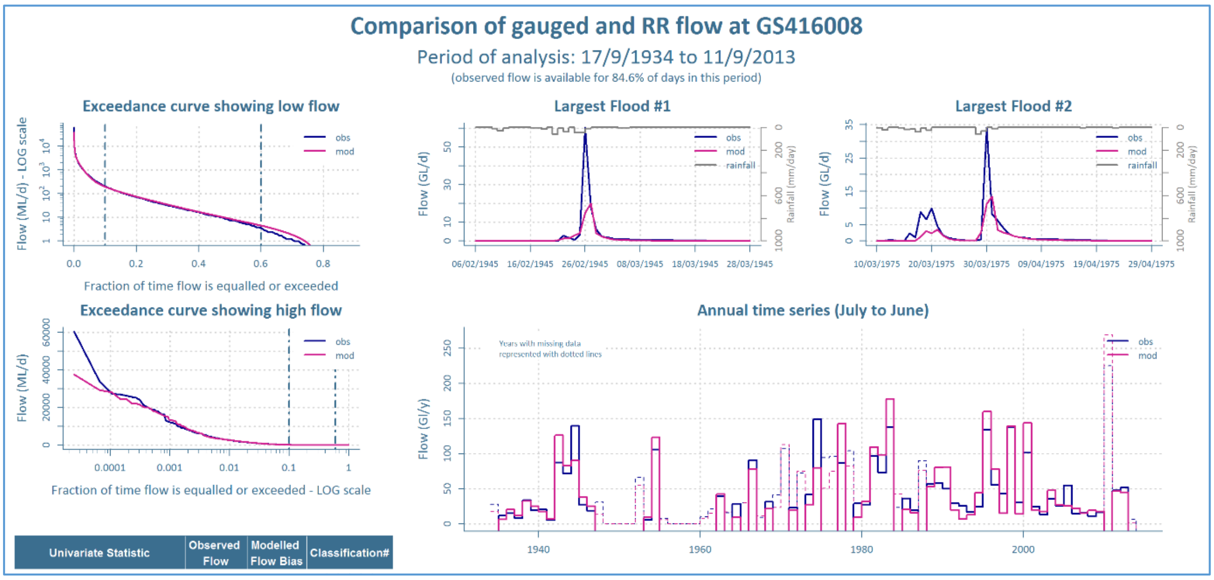

Figure 49 Flow calibration graphs for gauging station416008 Beardy River @ Haystack

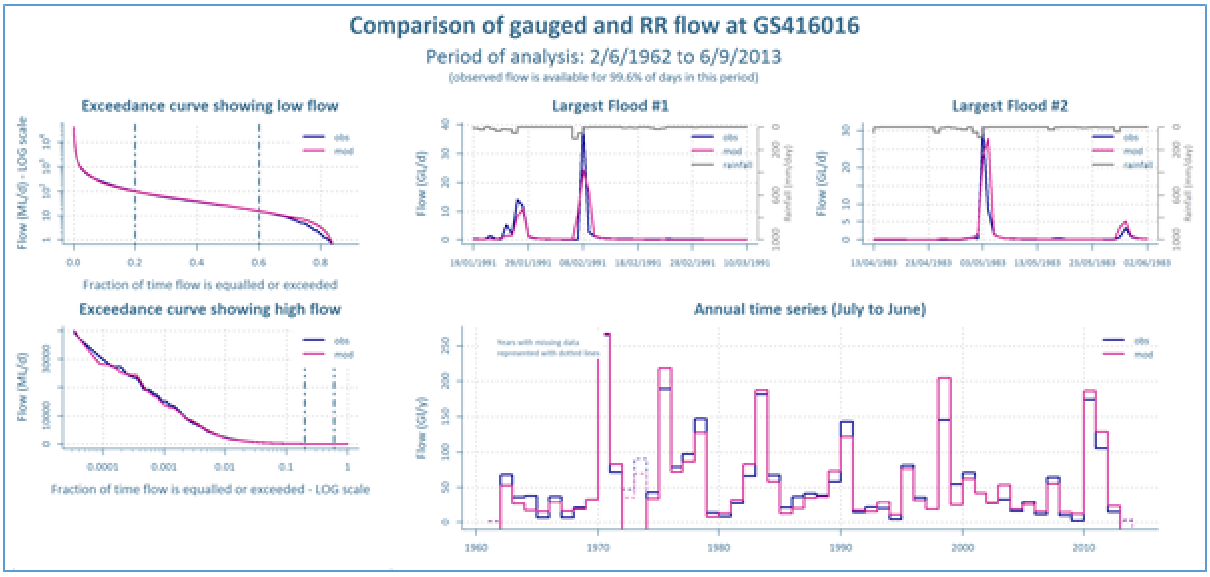

Figure 50 Flow calibration graphs for gauging station 416016 Macintyre River @ Inverell

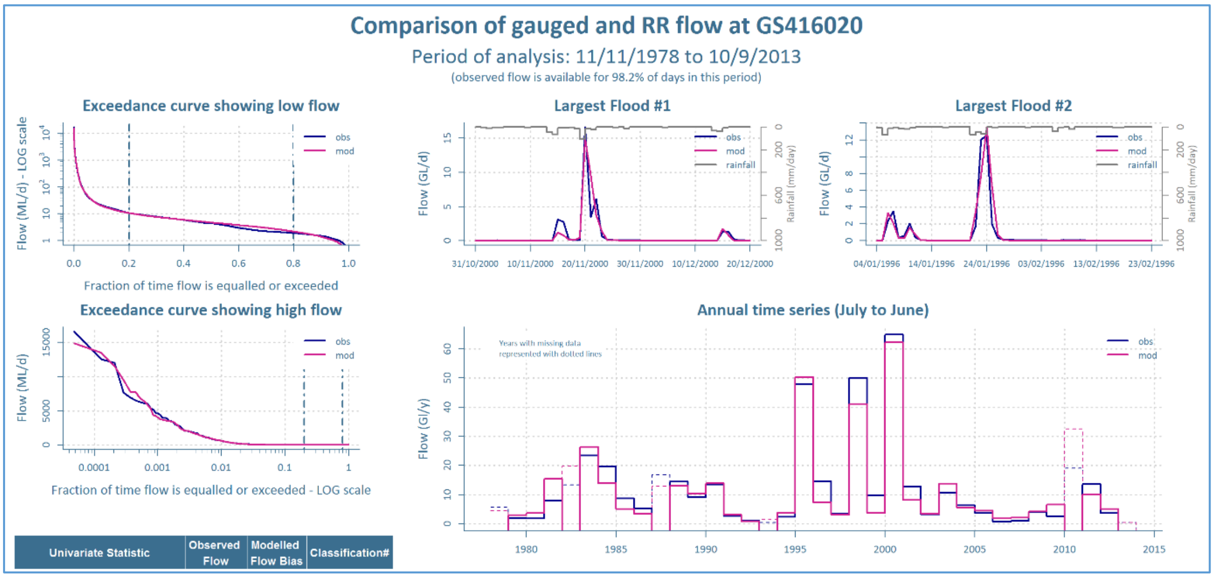

Figure 51 Flow calibration graphs for gauging station 416020 Ottleys Creek at Coolatai

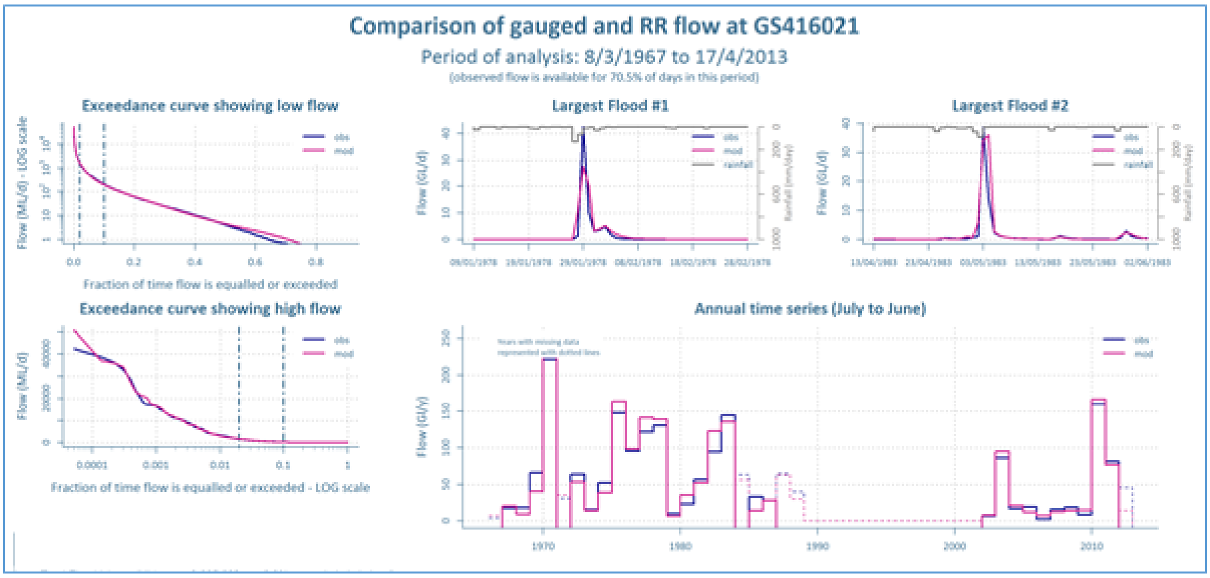

Figure 52 Flow calibration graphs for gauging station 416021 Frazers Ck @ Westholme

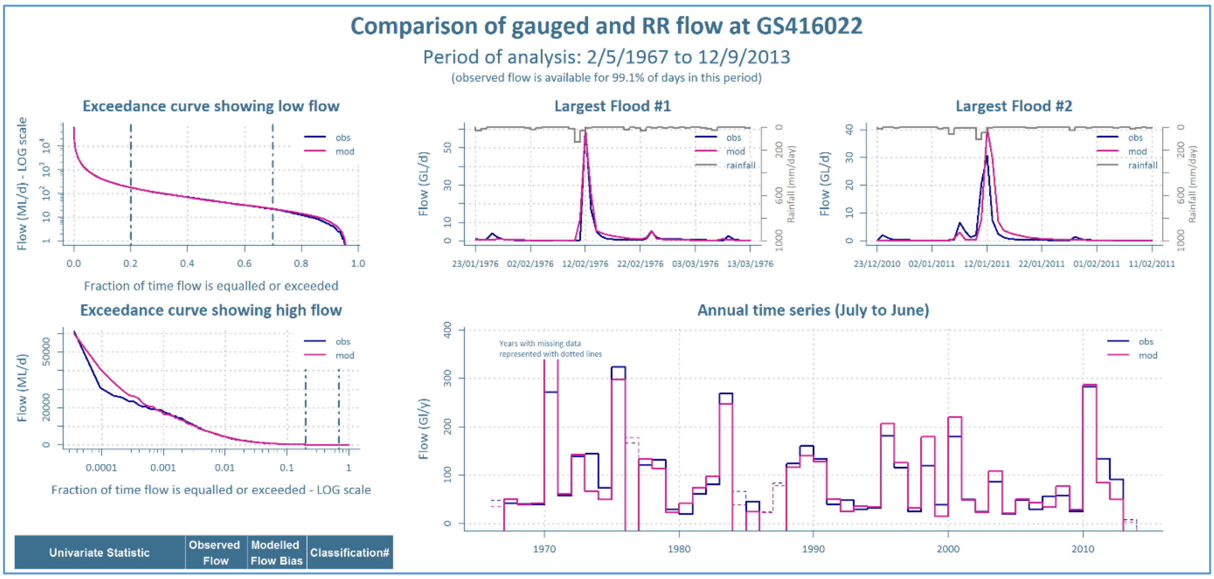

Figure 53 Flow calibration graphs for gauging station 416022 Severn River @ Fladbury

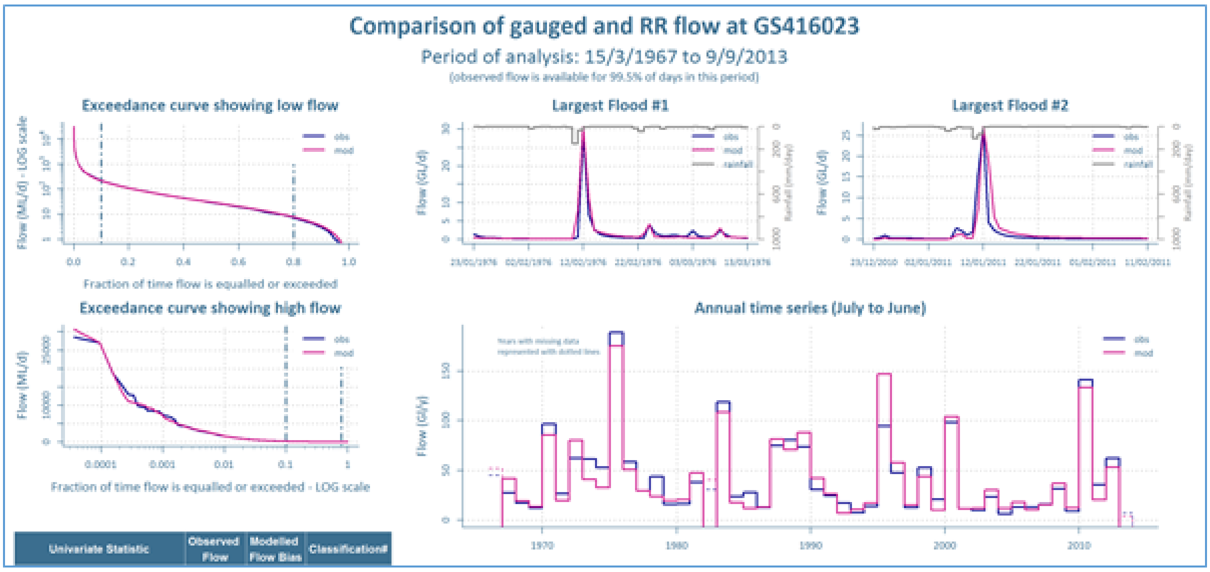

Figure 54 Flow calibration graphs for gauging station 416023 Deepwater River @ Bolivia

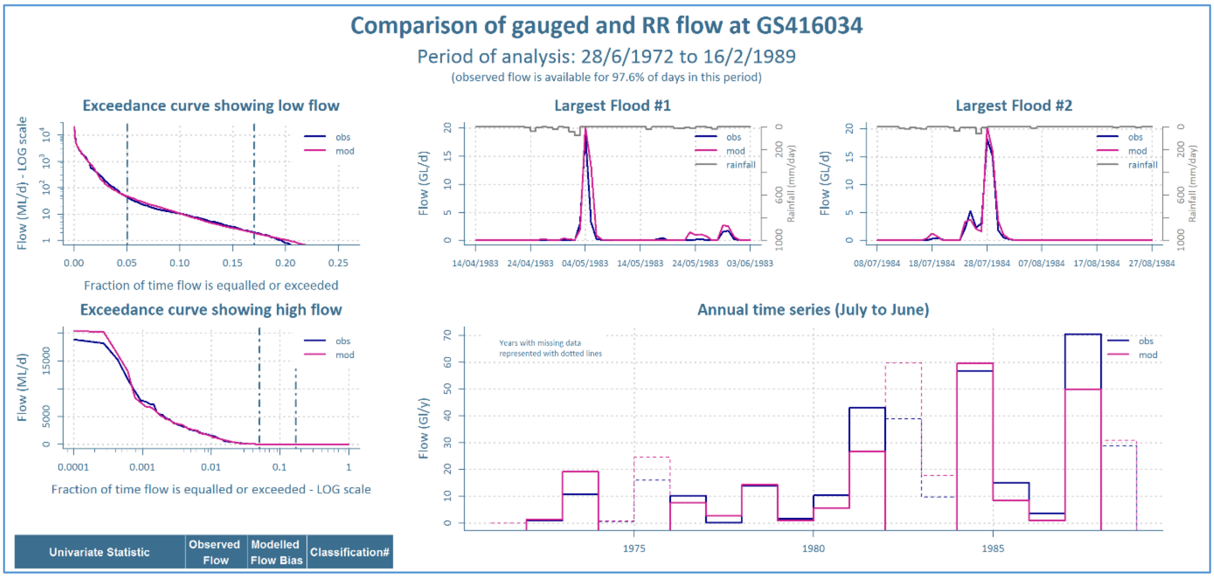

Figure 55 Flow calibration graphs for gauging station 416034 Croppa Creek @ Tulloona Bore

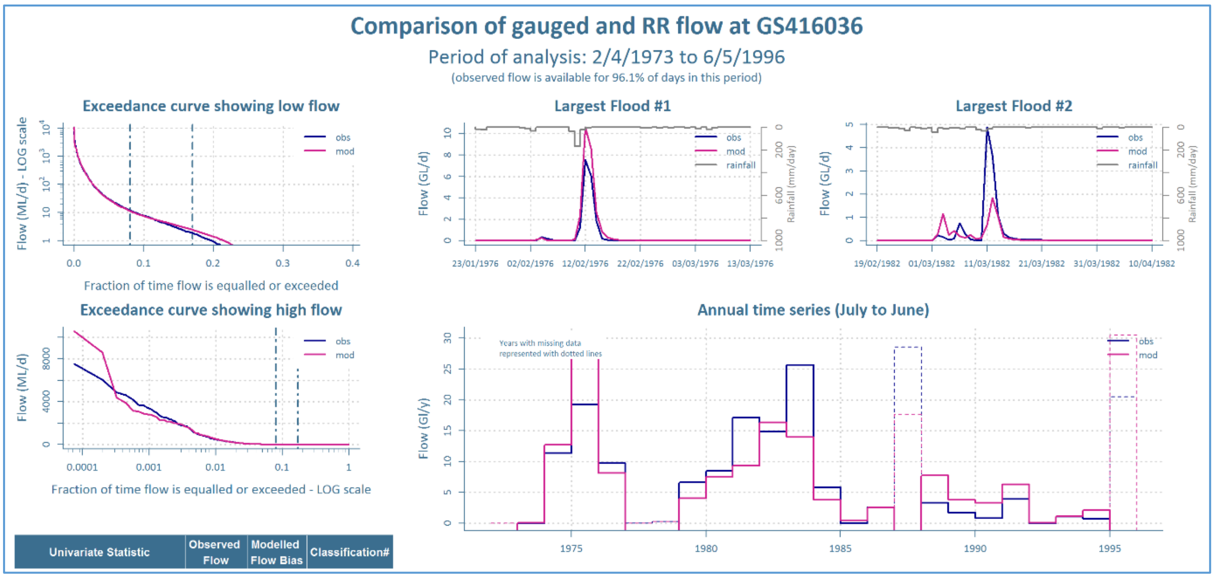

Figure 56 Flow calibration graphs for gauging station 416036 Campbells Creek near Beebo

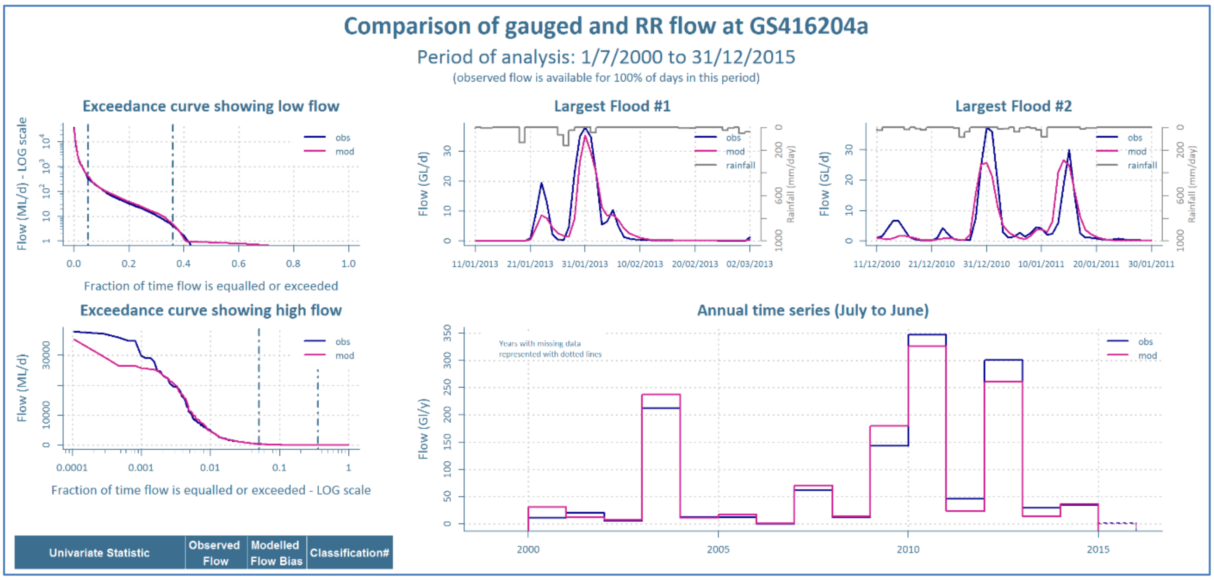

Figure 57 Flow calibration graphs for gauging station 416204A Weir River @ Gunn Bridge

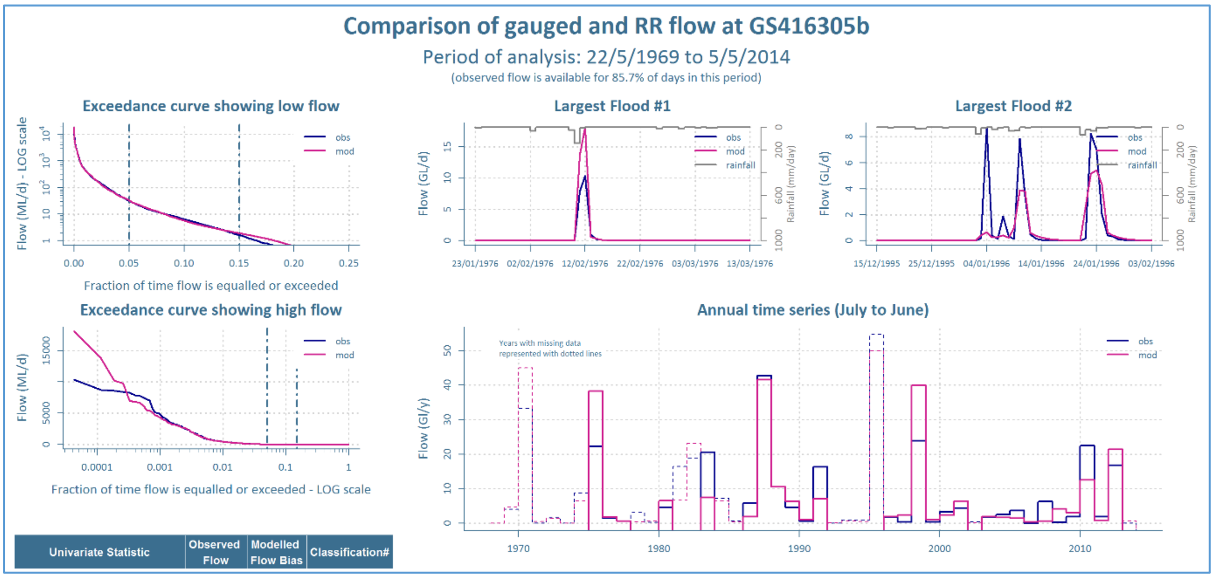

Figure 58 Flow calibration graphs for gauging station 416305B Brush Creek @ Breebo

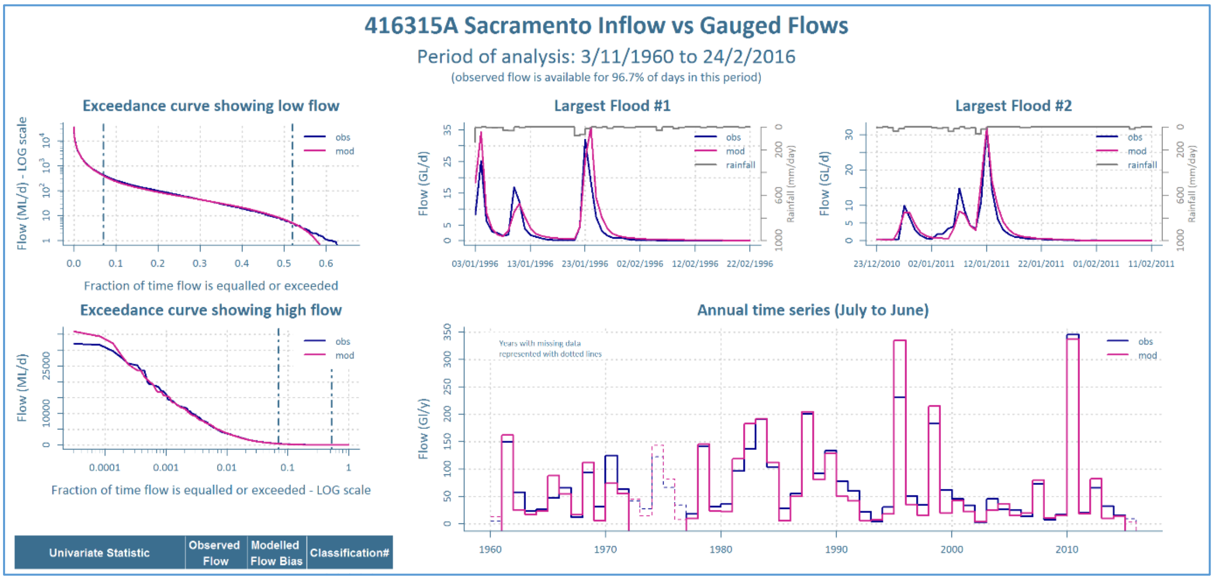

Figure 59 Flow calibration graphs for gauging station 416315A Pike Creek @ Glenlyon Dam headwater

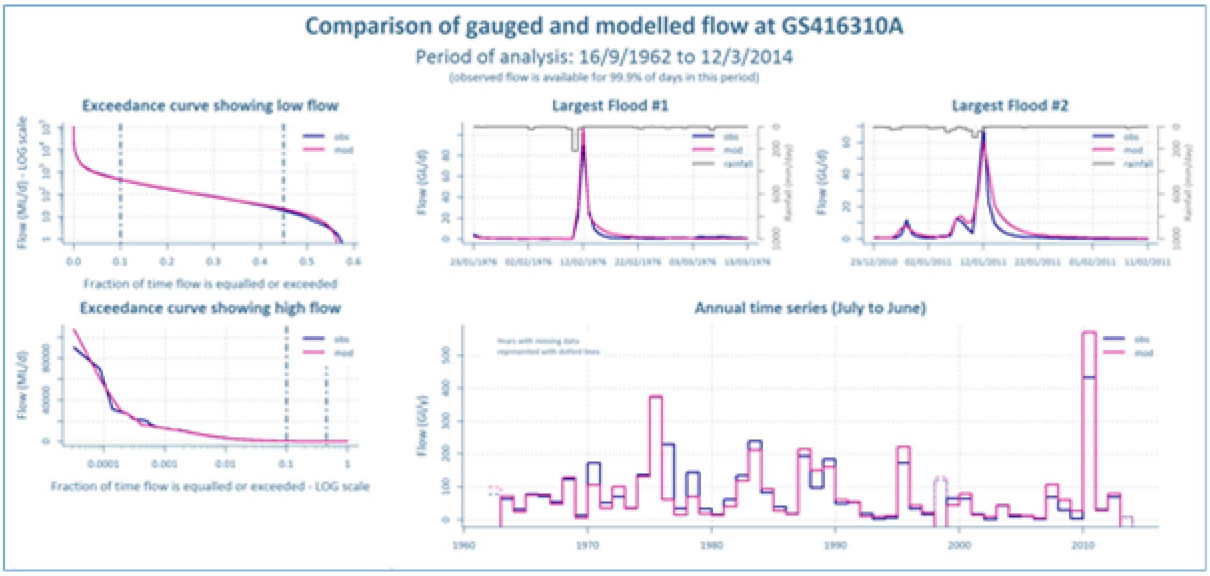

Figure 60 Flow calibration graphs for gauging station 416310A Dumaresq River @ FArnbor

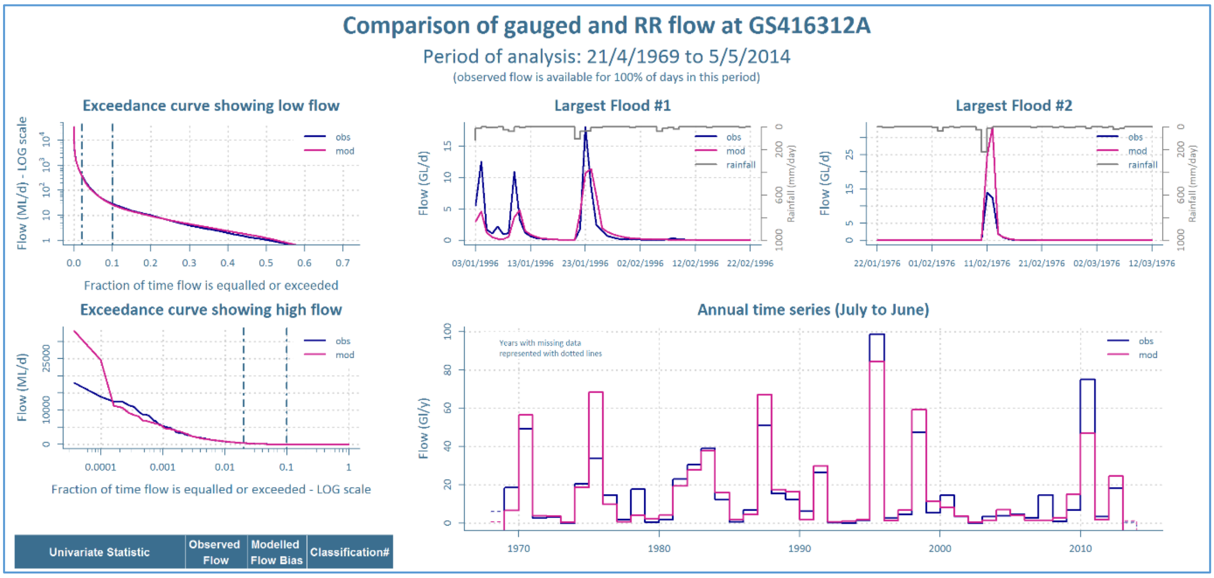

Figure 61 Flow calibration graphs for gauging station 416312A Oaky Creek @ Texas

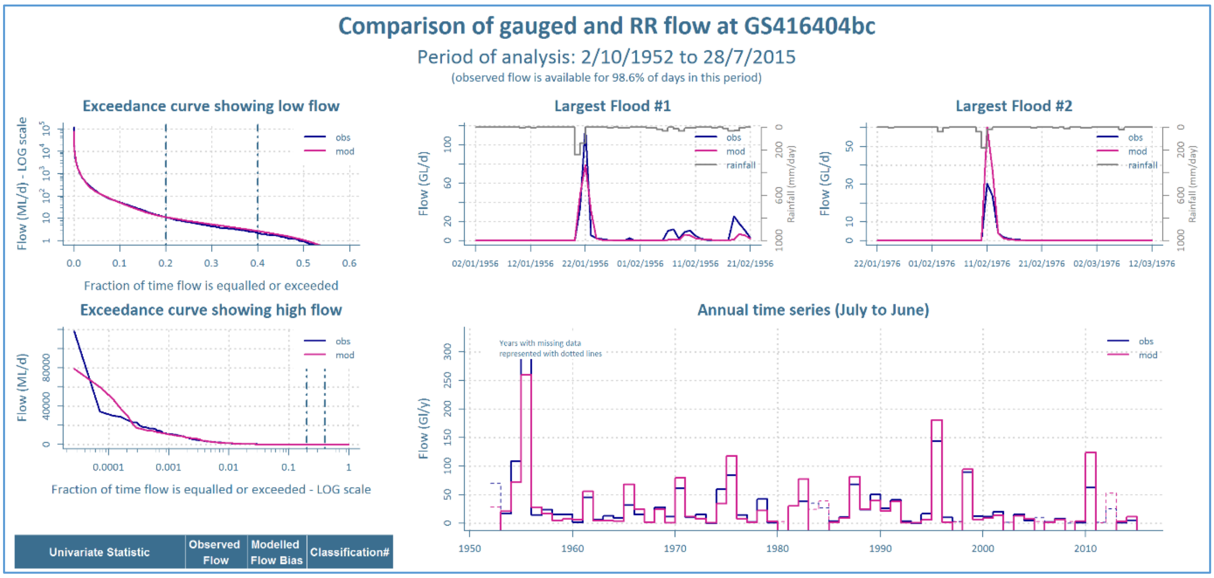

Figure 62 Flow calibration graphs for gauging station 416404B/C Bracker Creek @ Terraine

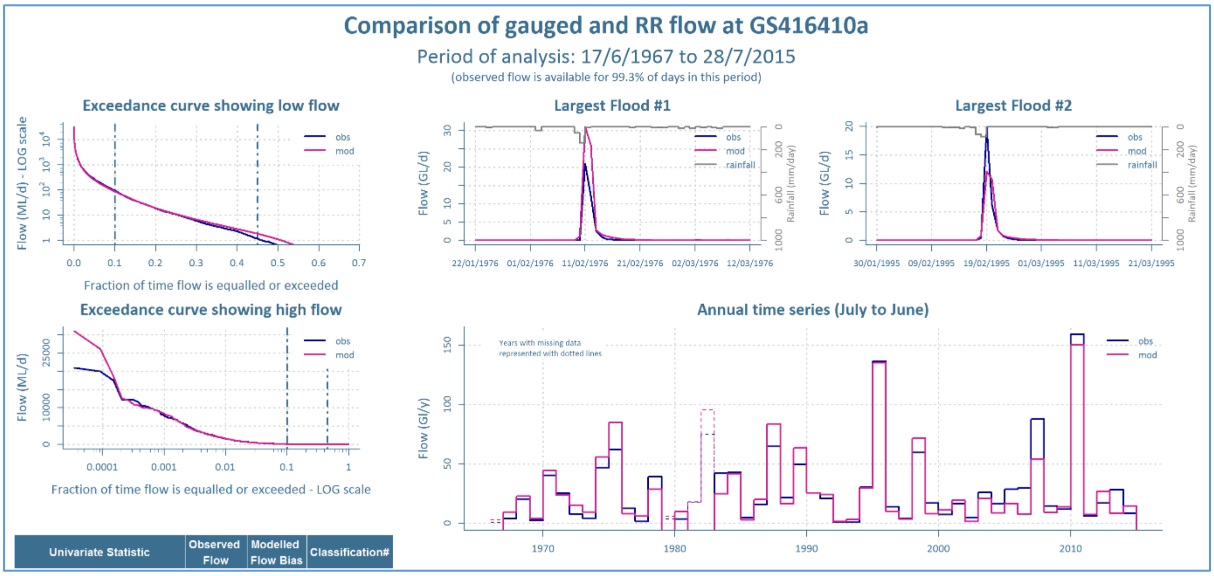

Figure 63 Flow calibration graphs for gauging station 416410A Macintyre Brook @ Barongarook

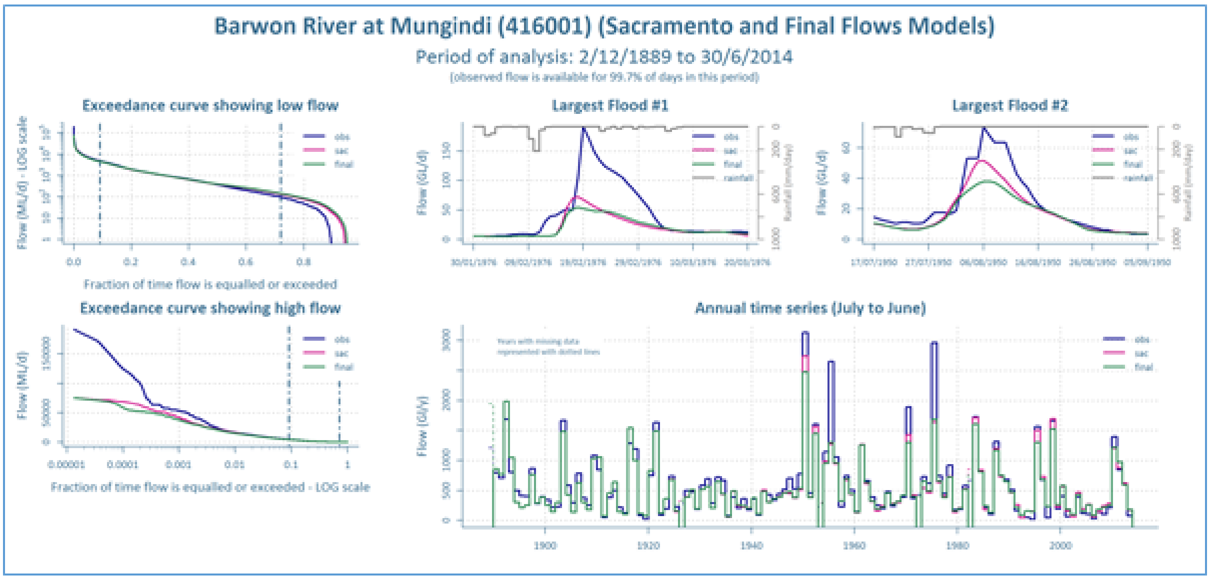

Figure 64 Flow calibration graphs for gauging station 416001 Barwon River @ Mungindi

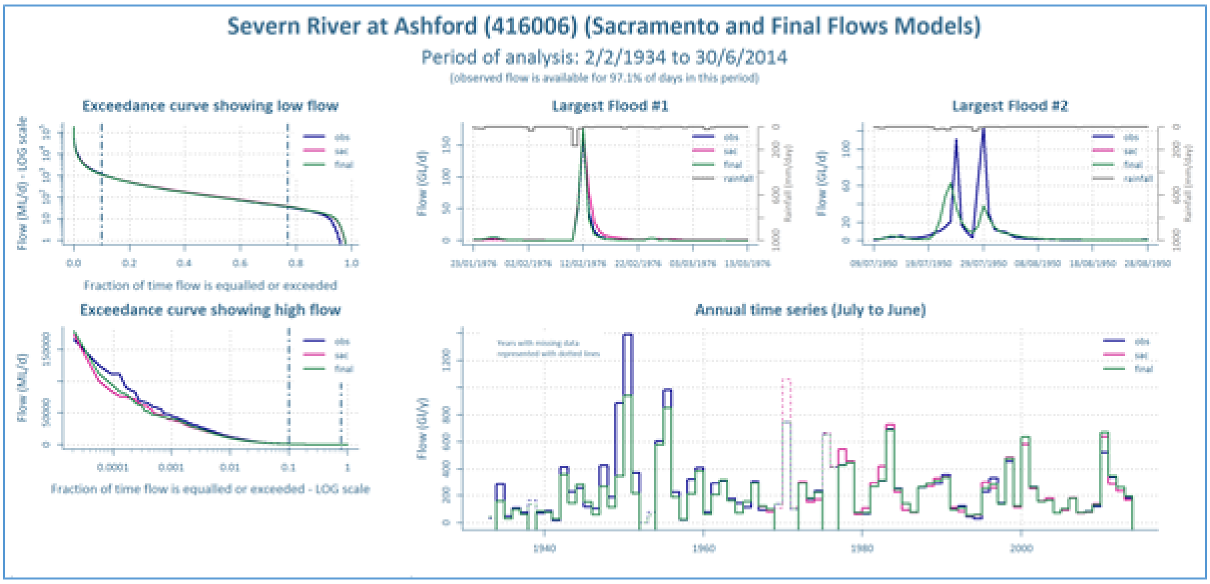

Figure 65 Flow calibration graphs for gauging station 416006 Severn River @ Ashford

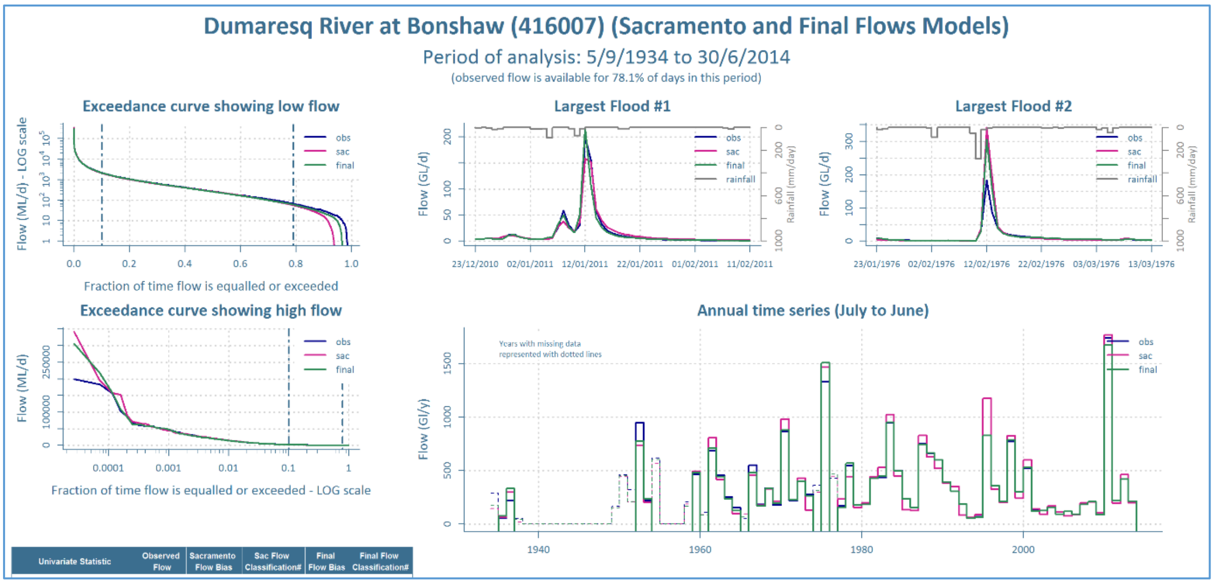

Figure 66 Flow calibration graphs for gauging station 416007 Dumaresq River A Bonshaw

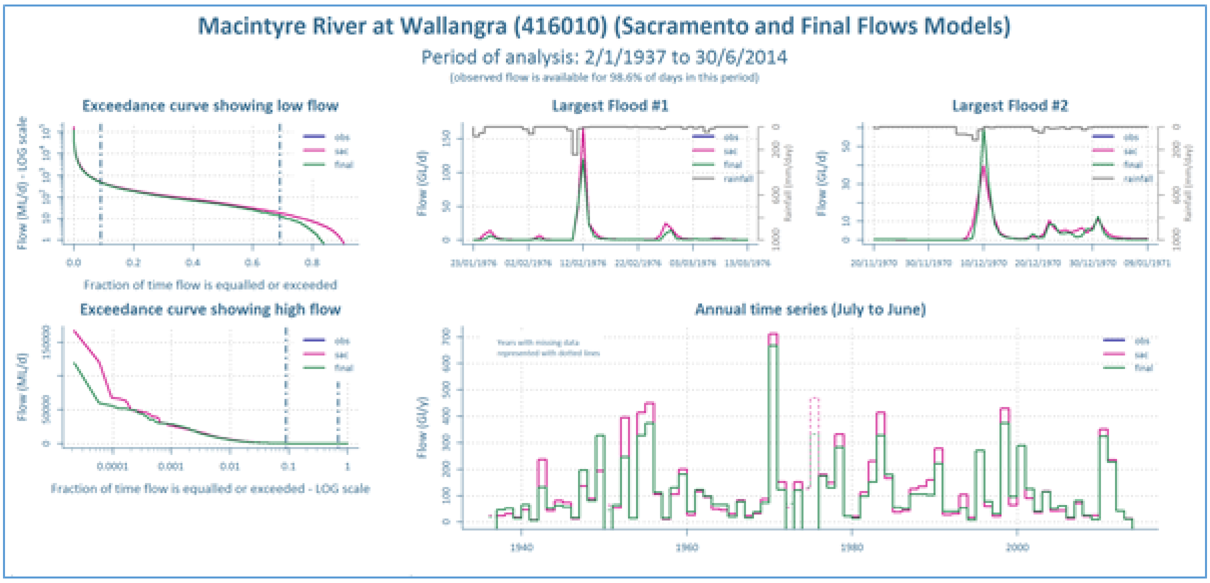

Figure 67 Flow calibration graphs for gauging station 416010 Macintyre River @ Wallangarra

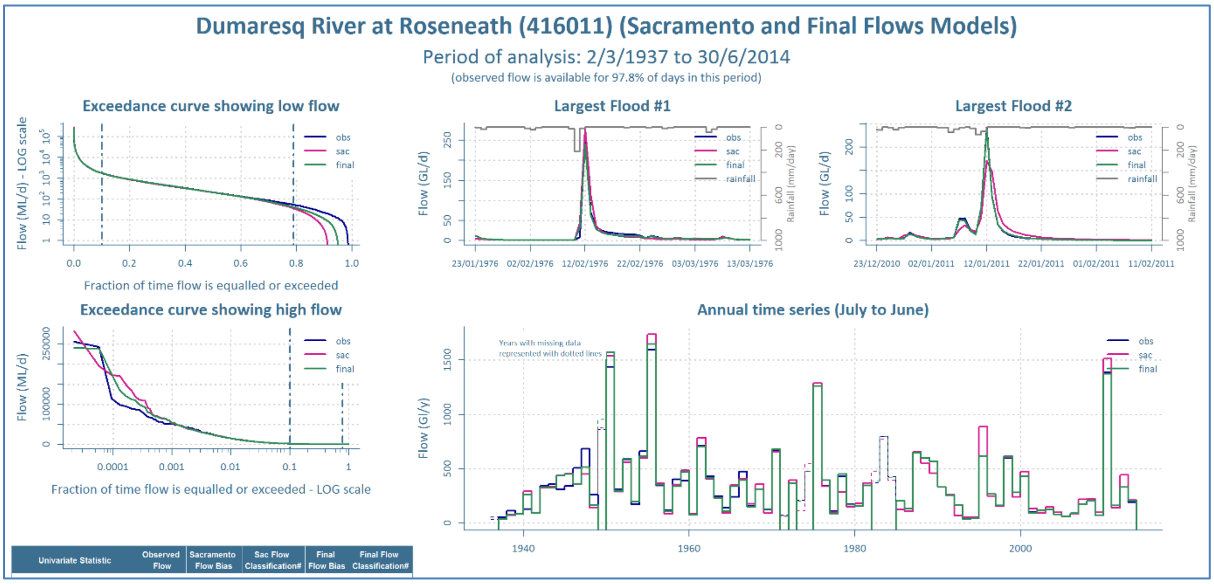

Figure 68 Flow calibration graphs for gauging station 416011 Dumaresq River @ Roseneath

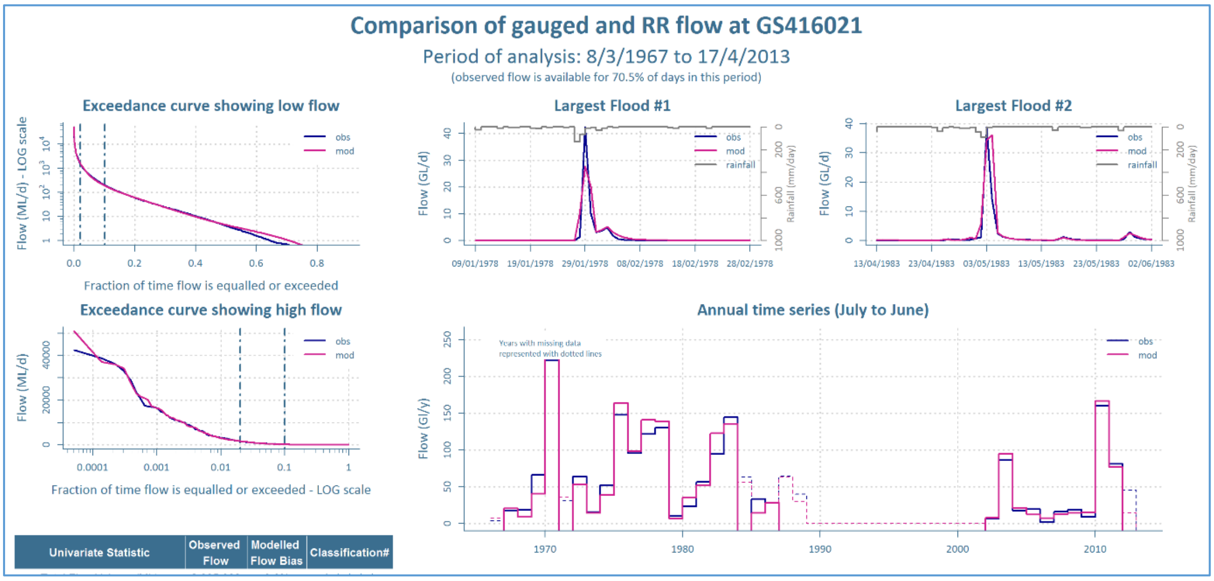

Figure 69 Flow calibration graphs for gauging station 416021 Macintyre River @ Holdfast

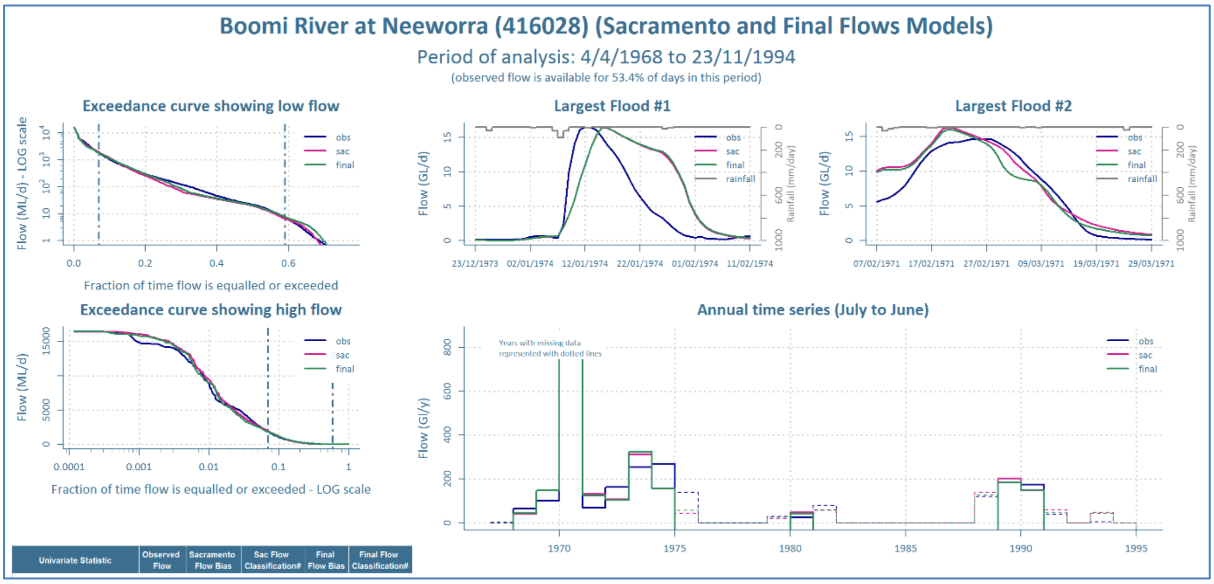

Figure 70 Flow calibration graphs for gauging station 416028 Boomi River @ Neeworra

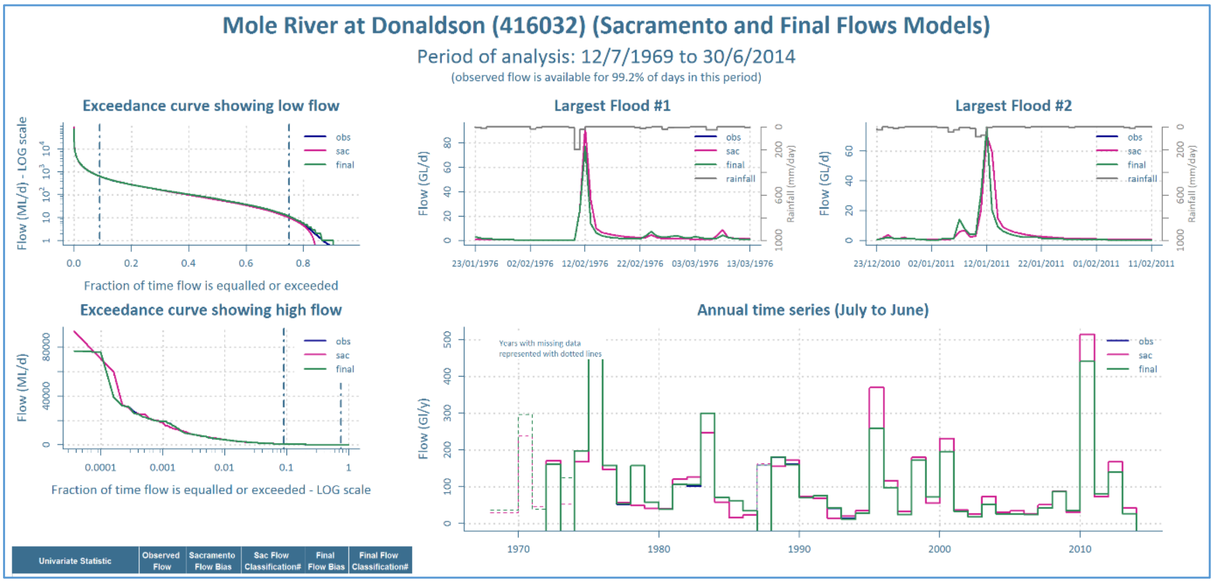

Figure 71 Flow calibration graphs for gauging station 416032 Mole River @ Holdfast

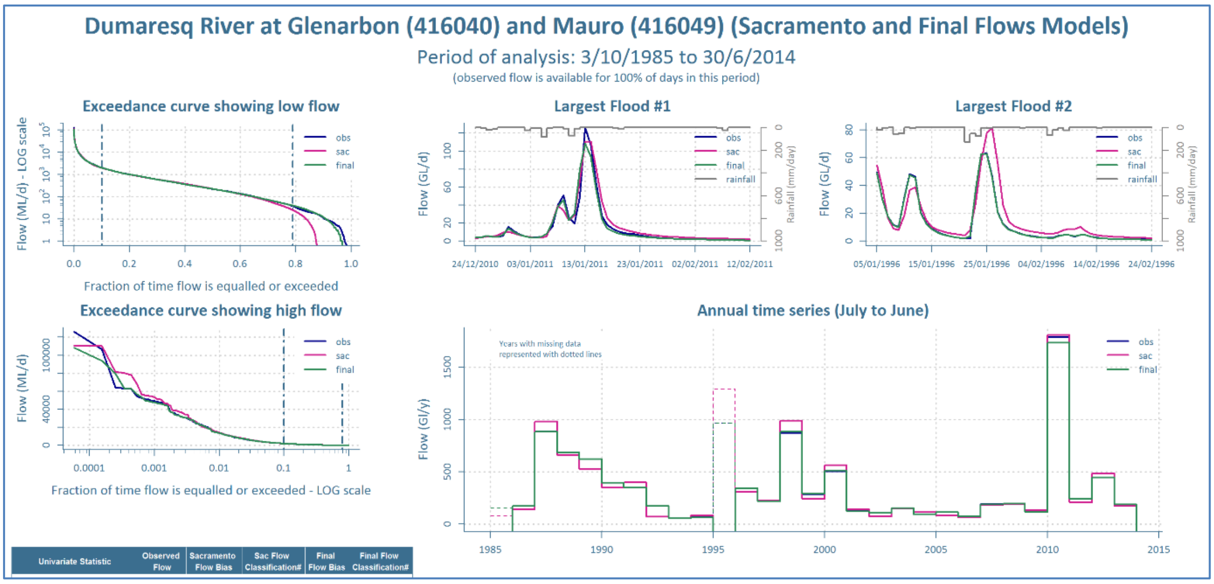

Figure 72 Flow calibration graphs for gauging station 416040 Dumaresq River @ Glenarbon

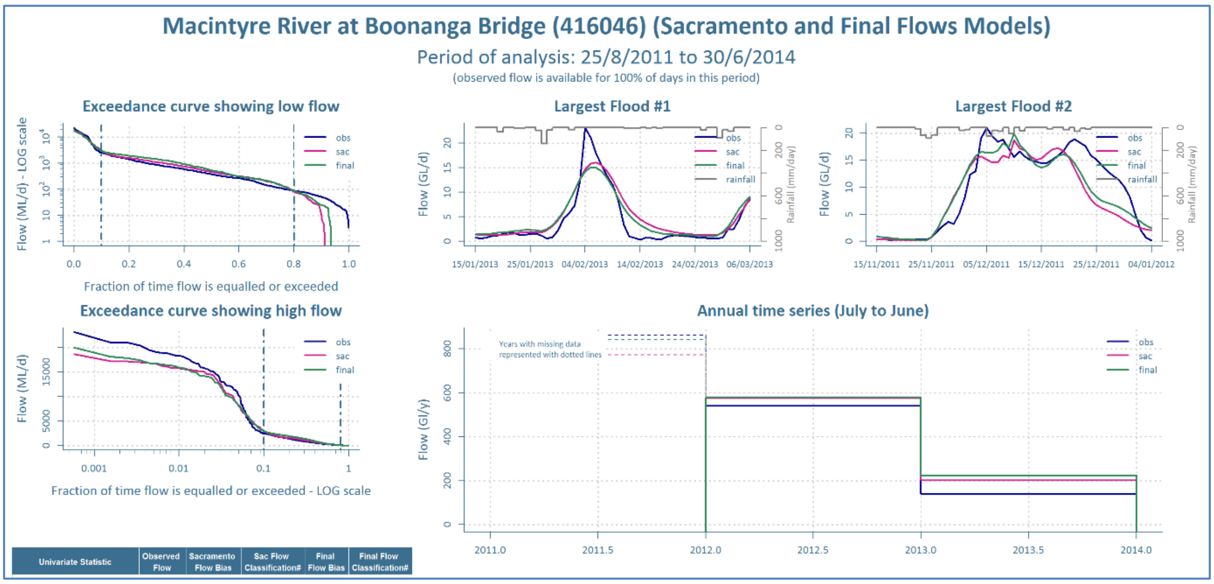

Figure 73 Flow calibration graphs for gauging station 416046 Macintyre River @ Boonanga Bridge

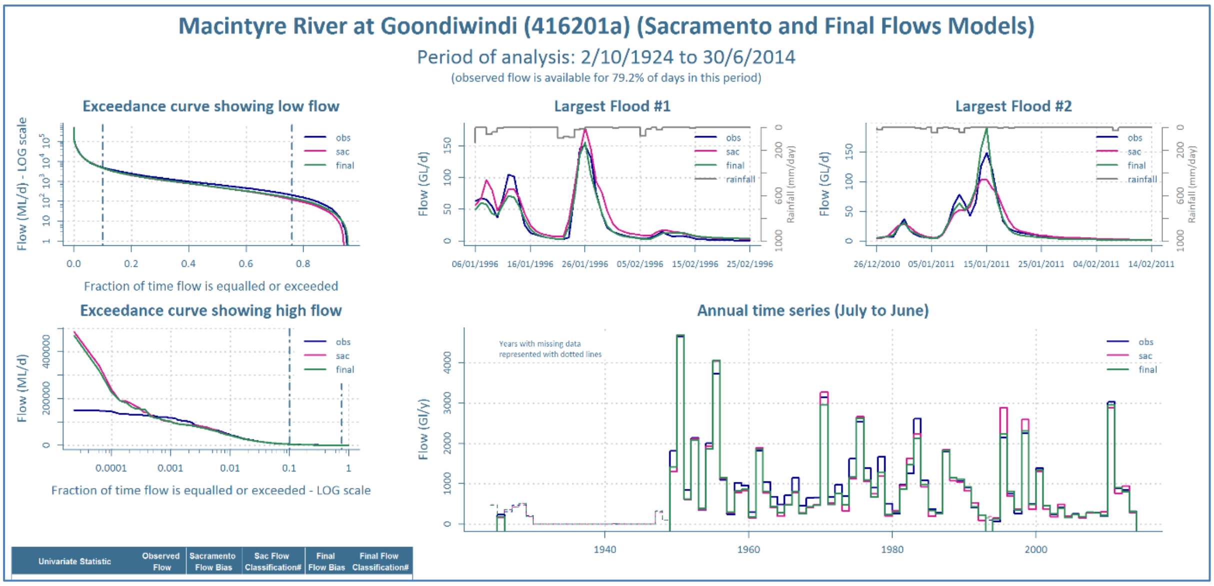

Figure 74 Flow calibration graphs for gauging station 416201A Macintyre River @ Goondiwindi

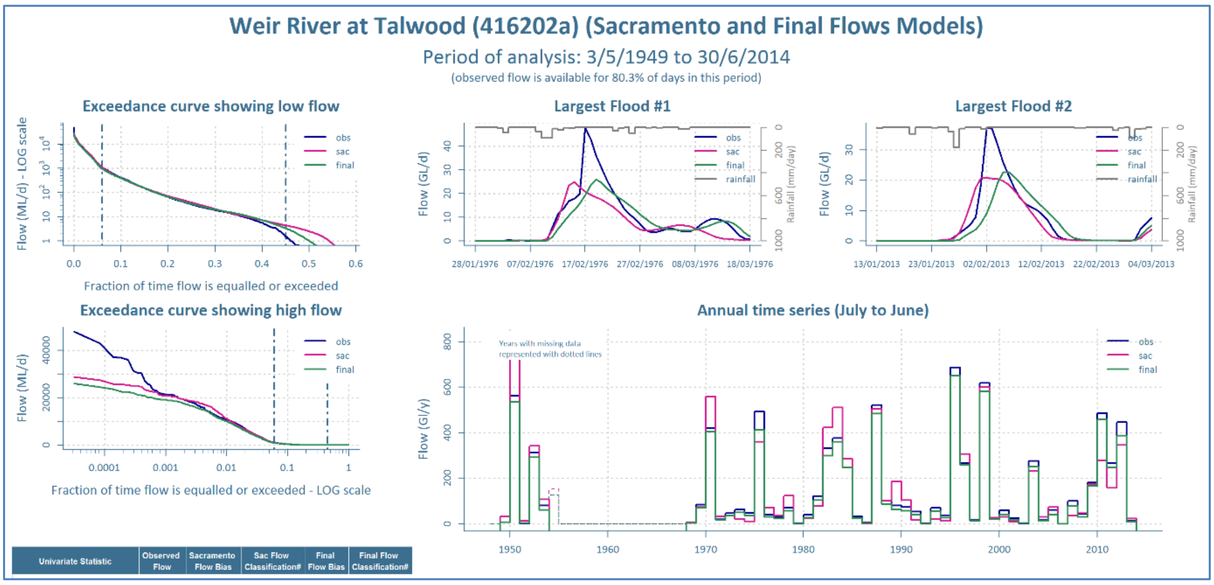

Figure 75 Flow calibration graphs for gauging station 416202A Weir River @ Talwood

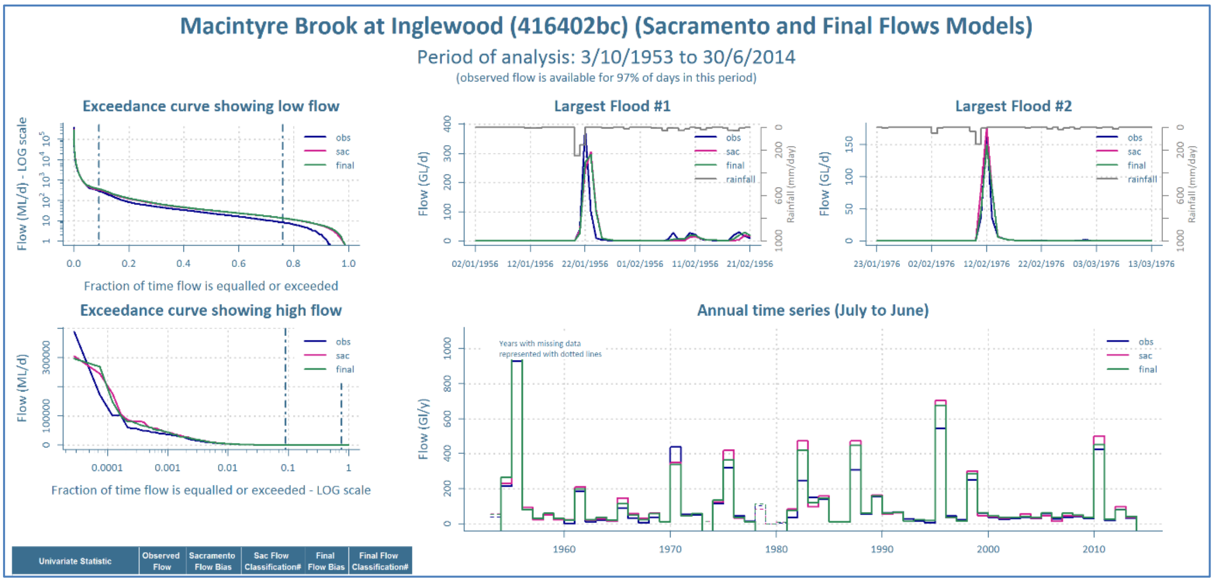

Figure 76 Flow calibration graphs for gauging station 416402B/C Macintyre Brook @ Inglewood

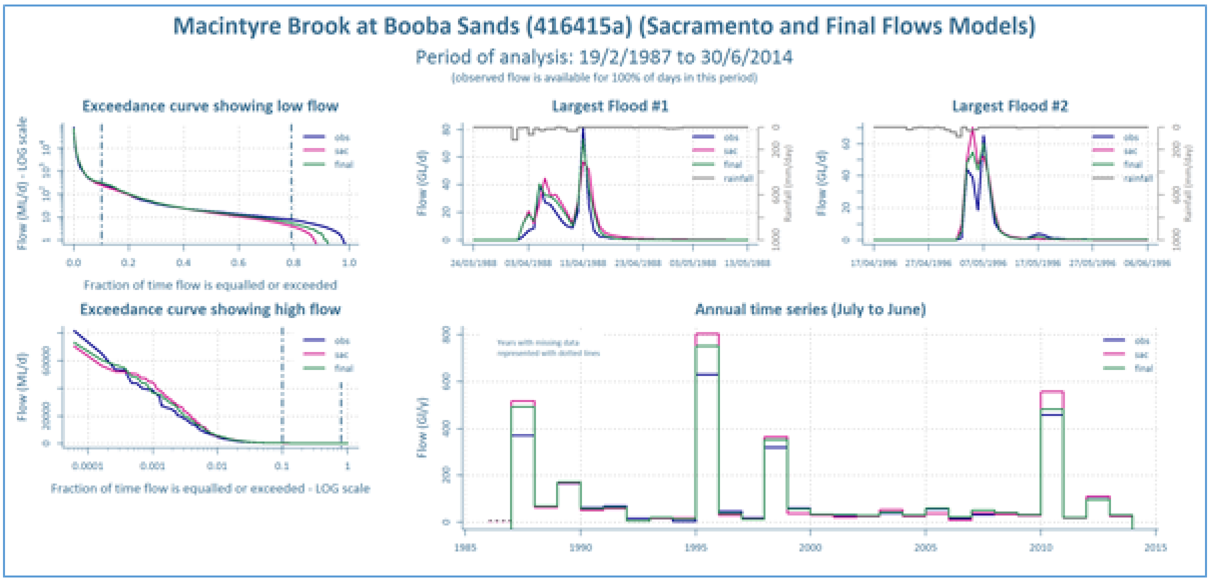

Figure 77 Flow calibration graphs for gauging station 416415A Macintyre Brook @ Booba Sands

Appendix L Supplementary access periods

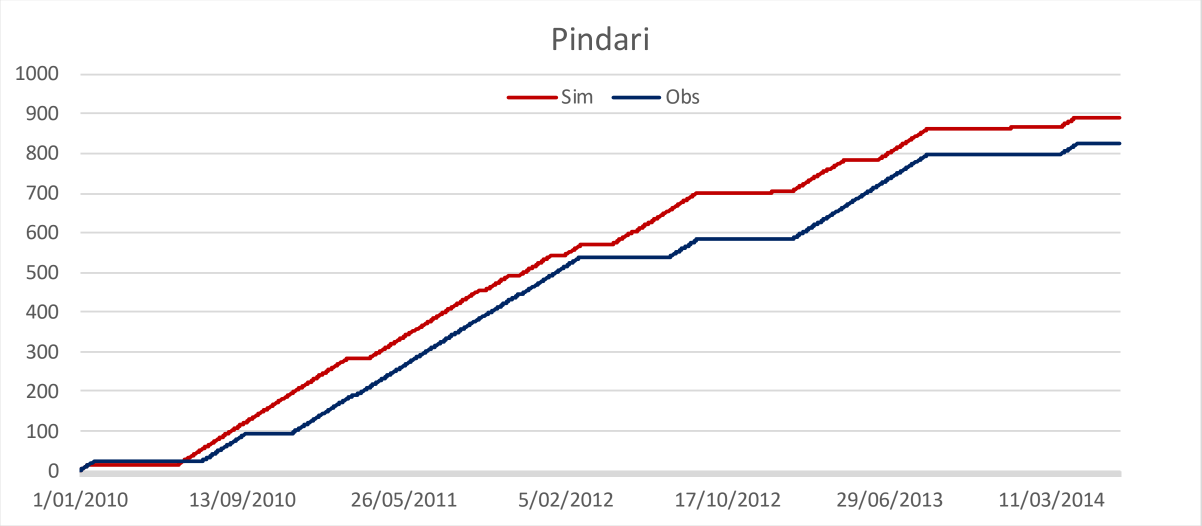

Figure 78 Observed and simulated cumulative supplementary access from Pindari to Dumaresq River junction

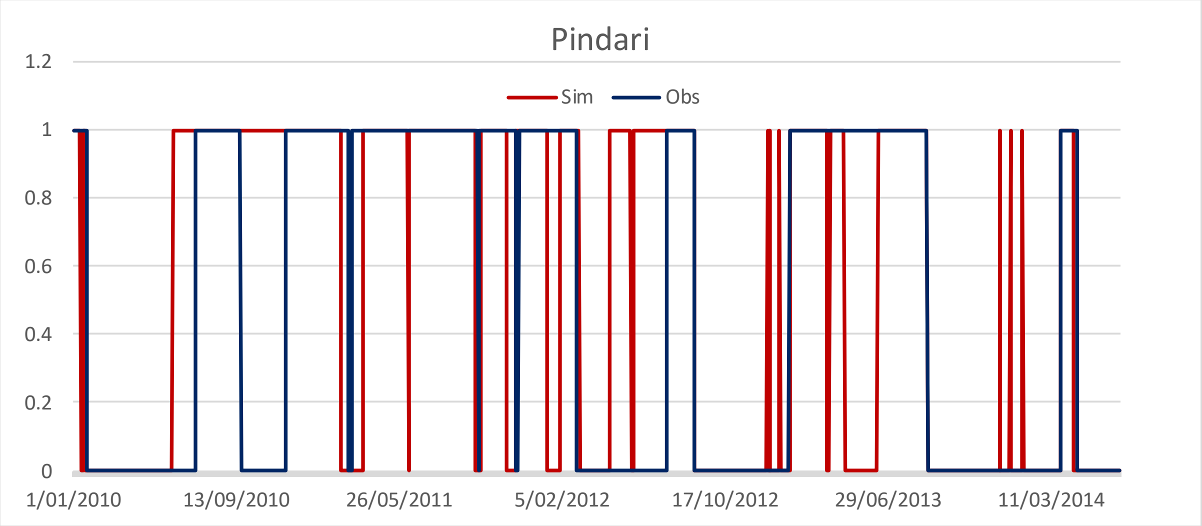

Figure 79 Observed and simulated supplementary access periods from Pindari to confluence

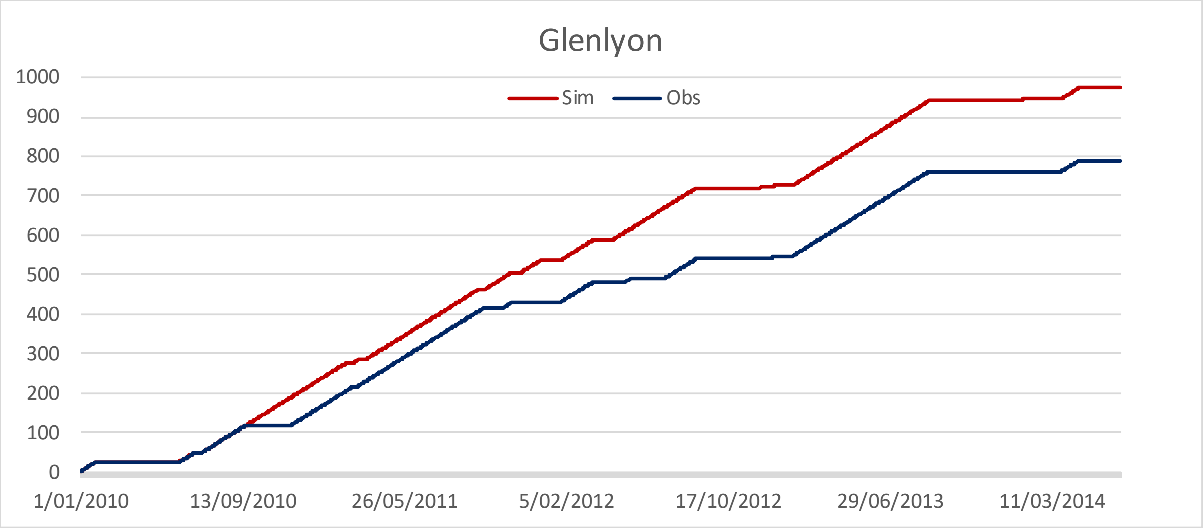

Figure 80 Observed and simulated cumulative supplementary access from Glenlyon Dam to confluence

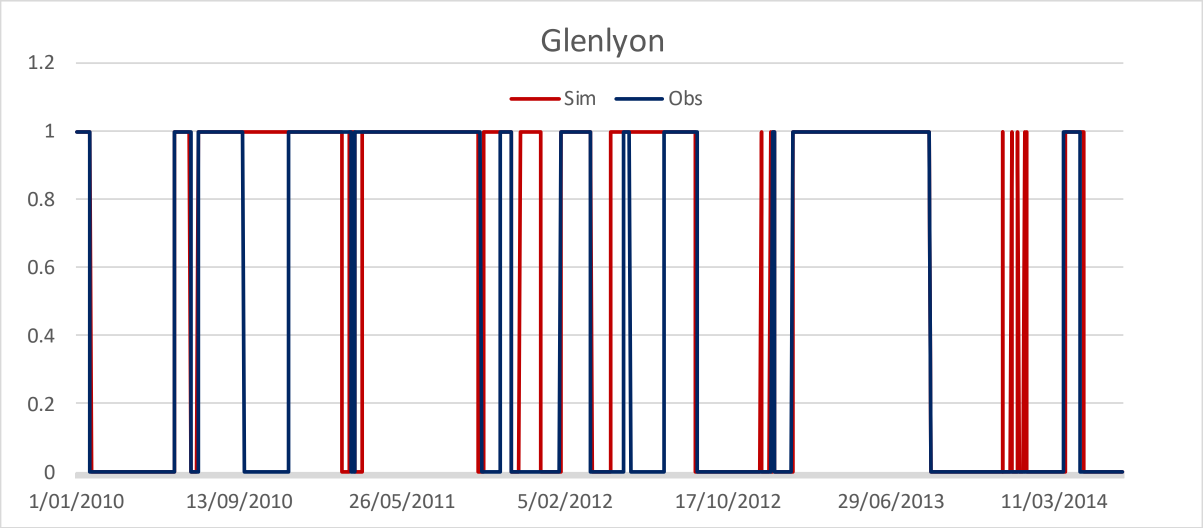

Figure 81 Observed and simulated supplementary access periods from Glenlyon Dam to confluence

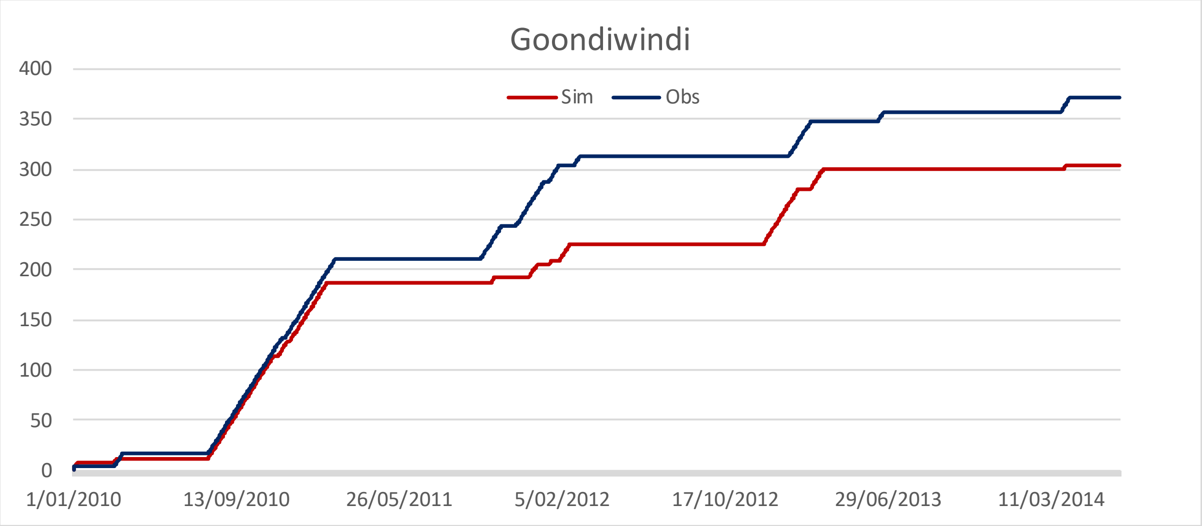

Figure 82 Observed and simulated cumulative supplementary access from Goondiwindi to Kanowna

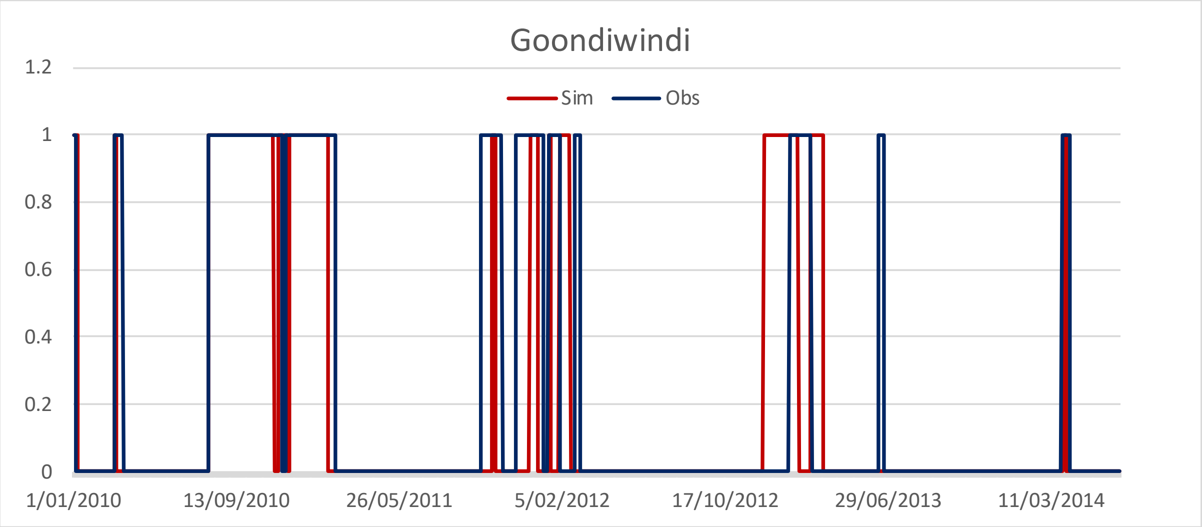

Figure 83 Observed and simulated supplementary access periods from Goondiwindi to Kanowna

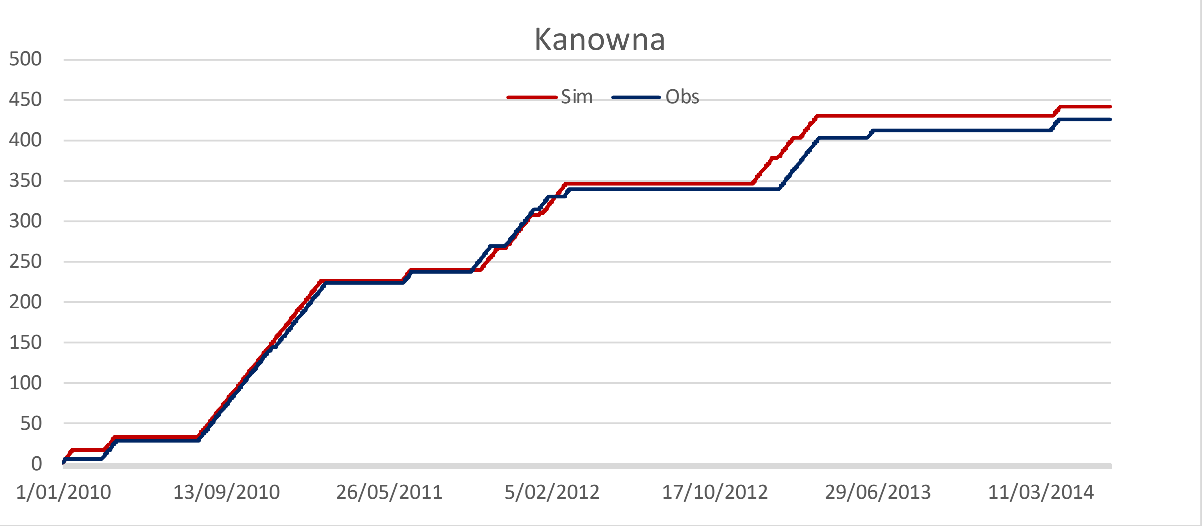

Figure 84 Observed and simulated cumulative supplementary access downstream of Kanowna

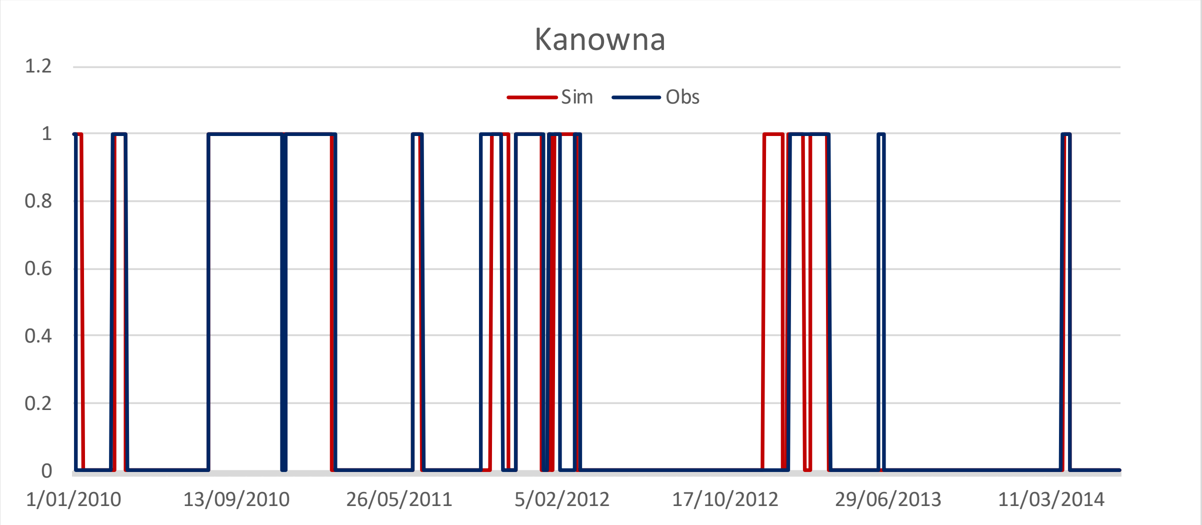

Figure 85 Observed and simulated supplementary access periods downstream of Kanowna

Appendix M Model versions

Over the period of development several upgrades of Source were adopted. The final versions of the model and software used for reporting results are listed in Table 61.

Table 61 Model version details: Source rsproj file name, relevant scenario input set and Source version

Source file name	Scenario input set	Source version
Used in section 8.2 in this report: BorderRivers_2017_07_31_ValidationModel.rsproj	Sacramento input set for headwater gauges. Two tests are used for main river gauges; Sacramento input set for testing all inflows based on Sacramento modelling and default input set for final model which uses observed data where available	4.2.5.5727 Beta
Used in sections 8.3 and 8.4 in this report: BorderRivers_2020_09_02.rsproj	Default input set with the exception that NSWForcedAreas was used to replicate historical areas in the farm water balance test	4.11.0.10112 Beta

Sensitivity tests were completed sensitivity tests in a slightly earlier version of the software/model, but this is not expected to make an appreciable difference to the outcomes presented in the report.

Appendix N Glossary

In addition to the information provided in this appendix, the reader is directed to excellent online resources, such as that provided by Water NSW[44].

Table 62 Abbreviations/acronyms

Abbreviation	Description
ABARE	Australian Bureau of Agricultural Research
ABS	Australian Bureau of Statistics
AWD	Available Water Determination
BDL	Baseline Diversion Limit
BRC	(Dumaresq-Barwon) Border Rivers Commission
CEWH	Commonwealth Environmental Water Holder
DES	(Qld) Department of Environment and Science
ESID	Extraction Site IDentification number
HEW	Held Environmental Water
Hydstra	Product brand name
IBQ	Irrigator Behaviour Questionnaire (used interchangeably with ‘farm survey’)
IGA	Inter-Governmental Agreement
IQQM	Integrated Quantity-Quality Model (the department’s in-house river system model)
LANDSAT	A series of Satellites that monitor the Earth’s surface
LIDAR	LIght Detecting And Ranging (a remote sensing method)
MODIS	Moderate Resolution Imaging Spectroradiometer (a remote sensing instrument)
NRAR	Natural Resources Access Regulator
NSE	Nash-Sutcliffe Efficiency (a goodness-of-fit calibration measure)
OFS	Off-Farm Storage
SBM	Storage bathymetry model
SDL	Sustainable Diversion Limit
SILO	Scientific Information for Land Owners (always called SILO)
TOL	Transmission and Operational Loss
WAS	Water Accounting System (database)
WLS	Water Licensing System
WSP	Water Sharing Plan

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[44] https://www.waternsw.com.au/customer-service/service-and-help/tips/glossary#:~:text=Glossary%20of%20water%20terms%201%20Basic%20landholder%20rights.,7%20Carryover%20Spill%20Reduction.%20...%20More%20items...%20

Table 63 Terms

Term	Description
2008/2009 Scenario	Model baseline scenario representing floodplain harvesting works in place in 2008/09. The derivation of this baseline scenario is described in companion Model Build report
2020/21 water year	A water year runs from 1 July to 30 June, in this example from 1 July 2020 to 30 June 2021. A slash is used to identify this and to be consistent with Basin legislation. (2020-2021 would refer to the range of years, 2020 and 2021)
Baseline Diversion Limit (BDL) Scenario	Equivalent to Plan Limit Scenario
Cap Scenario	Generally based on 1993/94 conditions however an allowance was made for enlargement of Pindari Dam which means some development levels are based on November 1999
Current Conditions Scenario	Model scenario that uses the best available information on most recent known levels of irrigation infrastructure and entitlements
NSW Border Rivers WSP	Shortened term for the Water Sharing Plan for the NSW Border Rivers Regulated River Water Source 2009
Plan limit	The authorised long-term average annual extraction limit as defined in the Water Sharing Plan
Plan limit compliance	Compliance with the Plan limit, which is assessed using long-term modelling.
Plan Limit Scenario	Model scenario that includes cap on diversions – uses development levels as at 2001/02 and management arrangements and share components as at 1 July 2009
Source	Australian National Hydrological Modelling platform, managed by eWater and adopted by the department as its default modelling platform (to replace IQQM)
the policy	Shortened term for the *NSW Floodplain Harvesting Policy*