NSW HEALTHY FLOODPLAINS

Building the river system model for the Macquarie Valley regulated river system

Conceptualisation, construction and calibration

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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 Planning, Industry and Environment – Water (the department) manages the river system models that have been developed for this purpose. A model exists for each of the regulated river valleys in NSW. These models are being extended (or rebuilt) to determine volumetric entitlements for floodplain harvesting consistent with the NSW Floodplain Harvesting Policy (the policy).

This report describes the rebuild of the Macquarie Valley river system model – its conceptualisation, construction and calibration. It includes sections that describe the Macquarie 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 9 appendices. Key findings and messages from the model build process are now reported.

Modelling approach

The Macquarie Valley river system model (Macquarie Valley model) is designed to support contemporary water management decisions in the Macquarie Valley regulated river system, 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: (i) to support traditional water policy, planning and compliance uses, such as implementing the (Murray-Darling) Basin Plan and estimating plan limits; and (ii) to determine volumetric entitlements for floodplain harvesting. Six design criteria were established to realise these objectives: 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 at sufficient spatial representation to allow for equitable sharing; and provide a pathway to update and improve accuracy (i.e. be update-able and extensible).

Building the model in the IQQM software provided sufficient functionality to simulate the process of water moving out onto floodplains and meet the design criteria. The model was built by connecting IQQM 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 Macquarie Valley, but 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 their estimated water requirements. This assessment focussed 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 are used to simulate the conversion of rainfall into streamflow. The Macquarie Valley has an extensive network of climate and river flow gauging stations to provide observed data. Using these data, separate models (one for every reach in the overall Macquarie Valley 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 two major **water storages** (Burrendong, and Windamere dams) simulate physical processes (such as the effect of evaporation on the storage volume) and operating rules.

Modelling water sources and licensing

The main licence categories of high security, general security, 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 groundwater. Modelling of these components is complex and involves 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 modelling. 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 Macquarie Valley model as no use was identified for any of the floodplain harvesting properties on the regulated river system.

Modelling water users

Water users include urban areas, irrigators, the environment, and water for stock and domestic supply. **Town water supply** volumes are represented using fixed monthly patterns.

The largest water users are (mainly cotton growing) **irrigation properties** in the floodplain areas between Narromine and the Macquarie Marshes. Those properties assessed as eligible for floodplain harvesting entitlements are represented as individual irrigation 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 irrigation 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 datasets were made available through the Floodplain Harvesting Property farm surveys and from the Natural Resource Access

Regulator (NRAR); 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 with the same irrigation demand as the aggregated water users in each river reach. **Stock and domestic** replenishment flows are represented as a demand at the various offtake points or flow gauging stations.

Modelling water management rules

IQQM has functionality to assign and track the ownership of water throughout the model network. The **carryover accounting system** used in the Macquarie Valley is modelled to represent operational practice as closely as possible.

The effects of **water trading** are explicitly represented in the model for permanent trade, and in some instances for temporary trade where it has been observed to occur consistently. Where water trading is not able to be represented in the model, it is taken into account when assessing model results. **Environmental flow** rules to represent releases of environmental water and protection of flows under the water sharing plan are configured in the model.

The operations of major storages, including harmony operation between Windamere and Burrendong dams, and Warren Weir and other regulators (e.g. Marebone Regulator) 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 reports on the ability of the model to replicate important parts of the flow regime. Overall performance is measured by comparing to recorded data such as flows, metered diversions and irrigated (planted) 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 data.

Farm water balance (i.e. total irrigation water use) was checked at 3 spatial scales. At valley scale, metered diversion results closely match observed information. 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 is 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 to water the planted areas agree well with observed data, with differences attributable to 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 Macquarie Valley 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 Macquarie Valley are general security, followed by on-farm rainfall–runoff harvesting, overbank flow harvesting, supplementary access, town water supply, high security and lastly stock and domestic.

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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 Macquarie Valley, referred to as the Macquarie Valley model. The model is a complete rebuild in IQQM of an earlier departmental IQQM model, and takes advantage of additional data and improved methods.

The department uses river system models for many policy, planning and compliance uses. One key use for the new model is to determine floodplain harvesting entitlements[1] consistent with the 2013 NSW Floodplain Harvesting Policy (the policy) as revised September 2018.

1.1 Report objectives

Macquarie Valley communities 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 the limits on diversions set by the Watering Sharing Plan for the Macquarie and Cudgegong Regulated Rivers Water Source (the Macquarie WSP). This report has been written to underpin that confidence.

The Macquarie Valley model provides support to more than floodplain harvesting. Floodplain harvesting takes place within the context of all other processes operating within the Macquarie Valley including climate conditions, streamflow generation, water storage, water sharing rules, diversions, and 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 Macquarie Valley, the information available to inform the model, the design approach used to build the river system model, and model results relevant to assessing model performance (Figure 1).

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[1] 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.

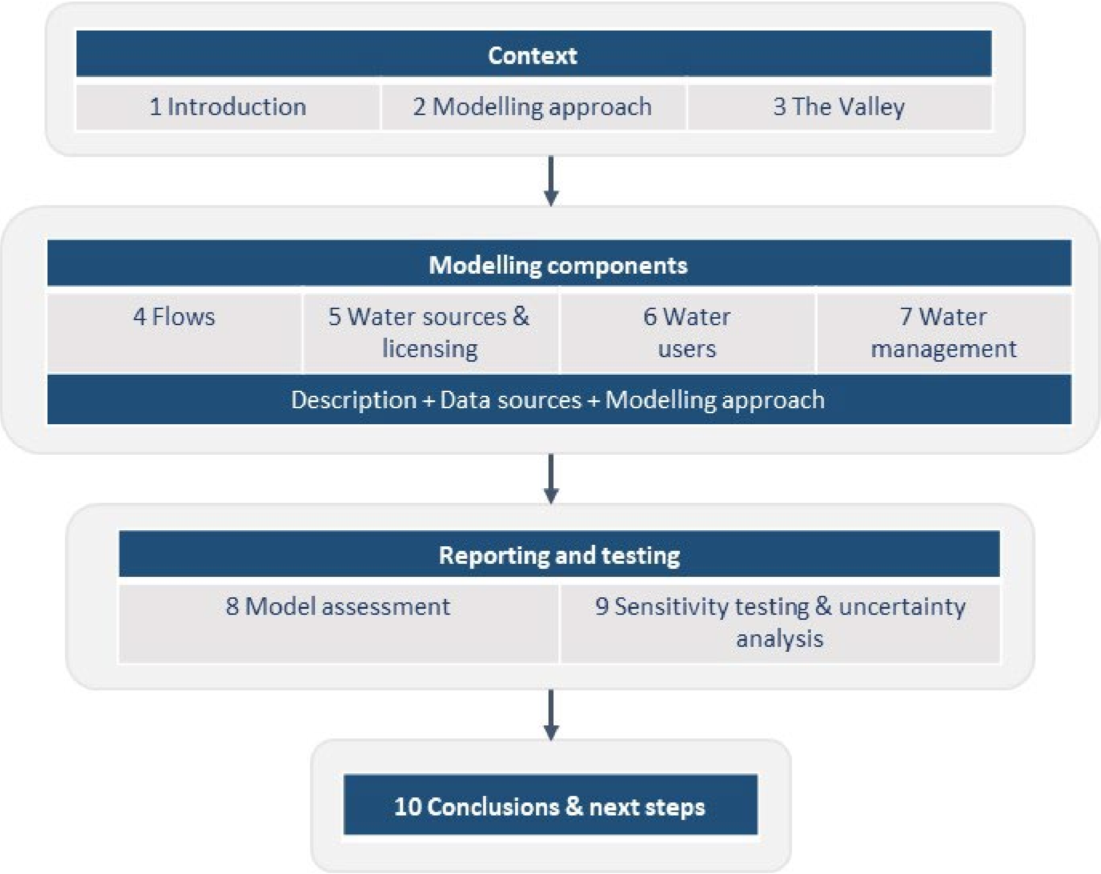

Figure 1 Report structure

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.

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 modelling of the water use limit permitted under the Macquarie WSP.

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 assessment of the model suitability 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 new baseline model for the Macquarie Valley regulated river system (the Macquarie Valley model).

How the model has been used to update the Macquarie WSP limit on diversions and calculate floodplain harvesting entitlements to bring total diversions back within that limit is described in companion report *Floodplain harvesting entitlements for the Macquarie Valley regulated river system: model scenarios* (DPIE Water 2021a).

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 Macquarie Valley* (DPIE Water 2021b).

The three reports together serve to describe how the modelling meets the objectives of the NSW Floodplain Harvesting Policy.

2 Modelling approach

This section describes the modelling approach used to construct a river system model for the regulated Macquarie River system (the Macquarie Valley 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 them to the best of our ability in this report.

The model has been developed using department standards and guidelines for good modelling practice. These are constantly refined over time and we also contribute to broader modelling guidelines[2]. Relevant guidelines, particularly in regard to assessing data quality, are 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 Macquarie Valley model is designed to support contemporary water management decisions in the regulated Macquarie river system, whether it is a rule change in the Macquarie Water Sharing Plan (WSP), 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 (Murray-Darling) Basin Plan and estimating water use limits set by the Macquarie WSP
- 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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[2] 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 Limits. • (NOTE: The Macquarie Valley 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 Macquarie Valley model, meeting these objectives and criteria required extensive redevelopment and enhancement of the earlier departmental model (DECCW 2009) which was built for a different purpose, primarily to model in-channel flows and 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 Macquarie Valley model has been built using updated versions of the IQQM software, continuing on from the model also previously built[3] using the IQQM software.

IQQM models are built from components which are linked, through adding nodes and links, to represent the system to be modelled (Simons et.al. 1996). There are many types of nodes to

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[3] As an example, the version of the Macquarie IQQM previously accredited under the Murray-Darling Basin Agreement for simulating 1993/94 Cap conditions is described in DECCW (2009).

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 river flow gauges and environmental assets.

Links connect, store and route water passing between nodes.

IQQM 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 convert 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 IQQM platform supports the coding of functions to dynamically calculate values based on other values during a model run. An example in the Macquarie Valley 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 IQQM 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 7.1.2
8	Storage operation	Subsection in Section 7.5.2

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 points 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.

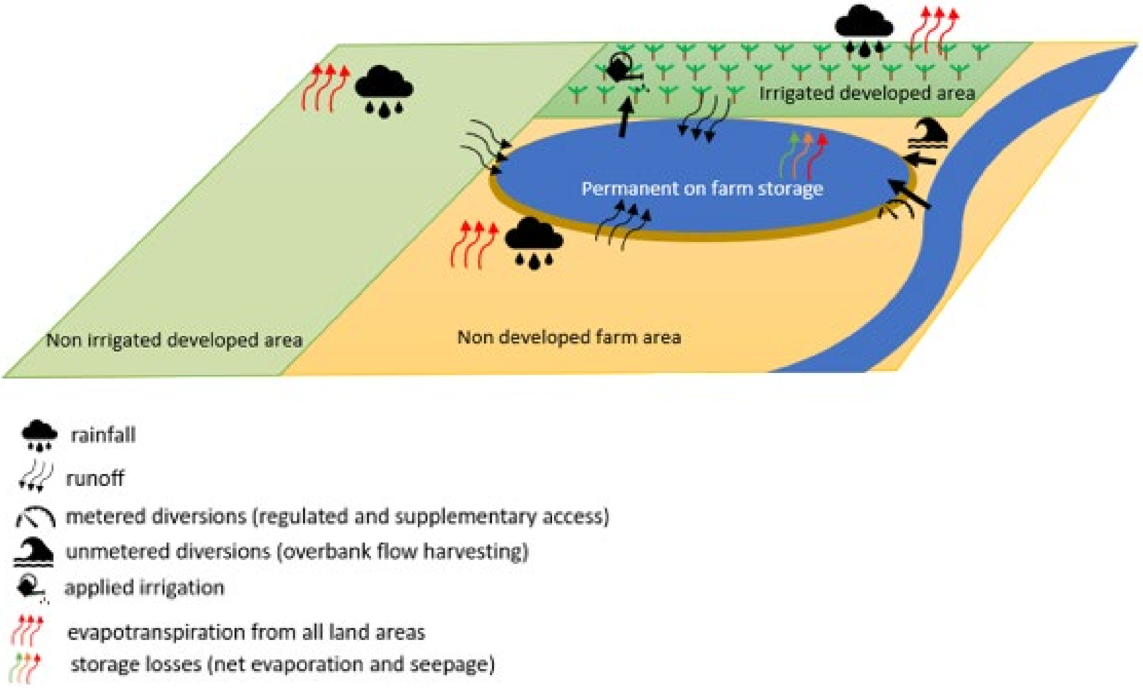

Figure 2 Schematic of farm-scale water balance components

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.

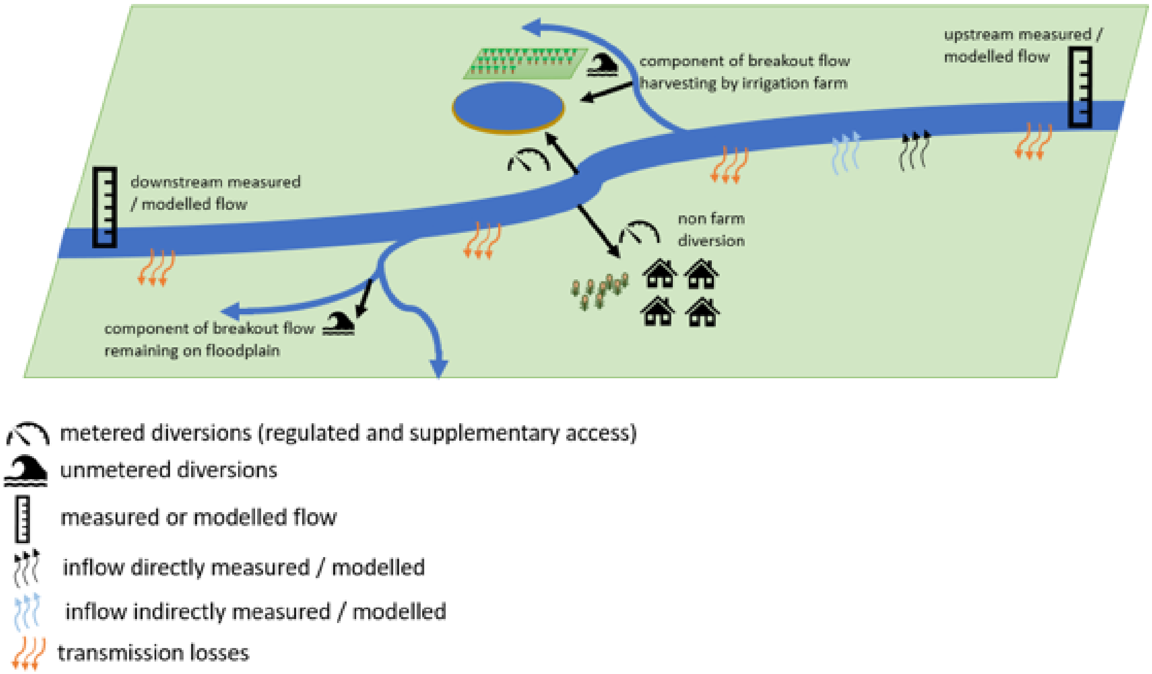

Figure 3 Schematic of reach-scale water balance components

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.

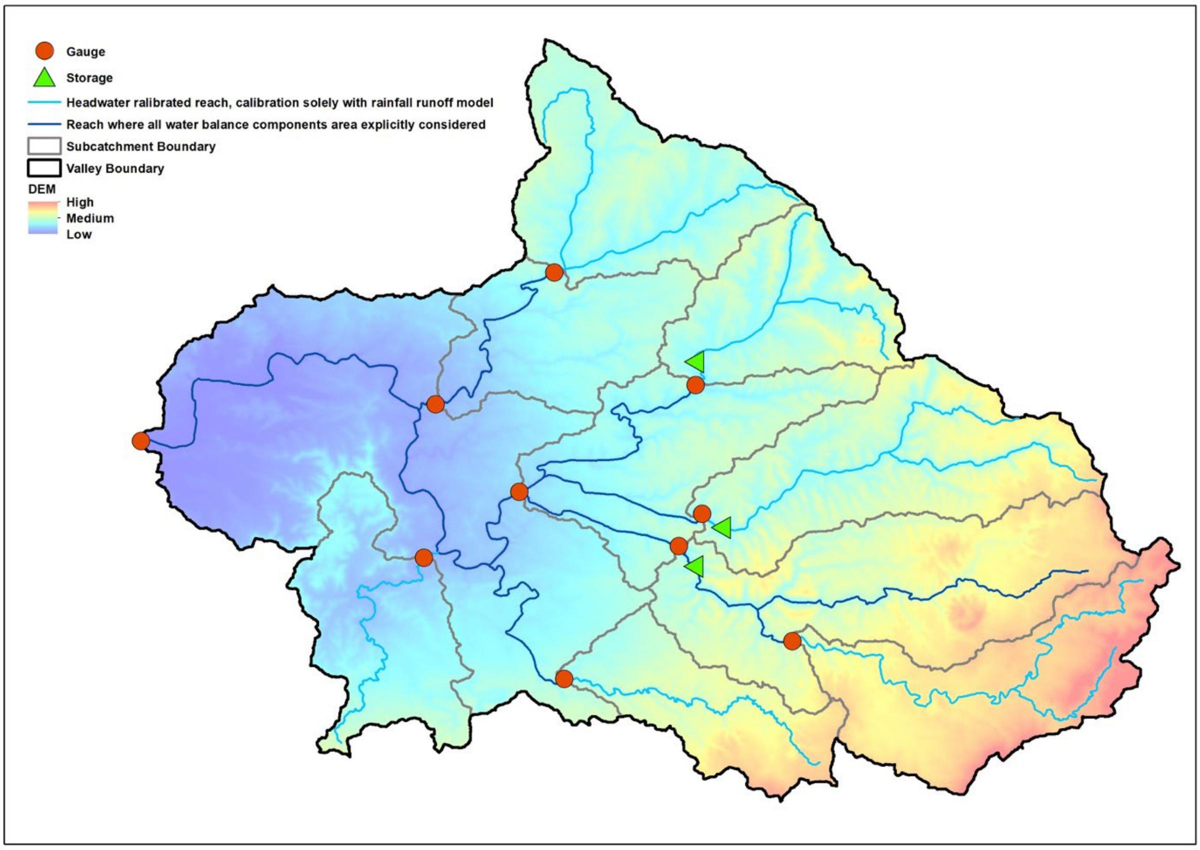

Figure 4 Schematic of valley-scale water balance components

2.3.4 The parameterisation process

Most river system model software (including IQQM) 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 the best available 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 (nodes and links) is shown in Figure 5.

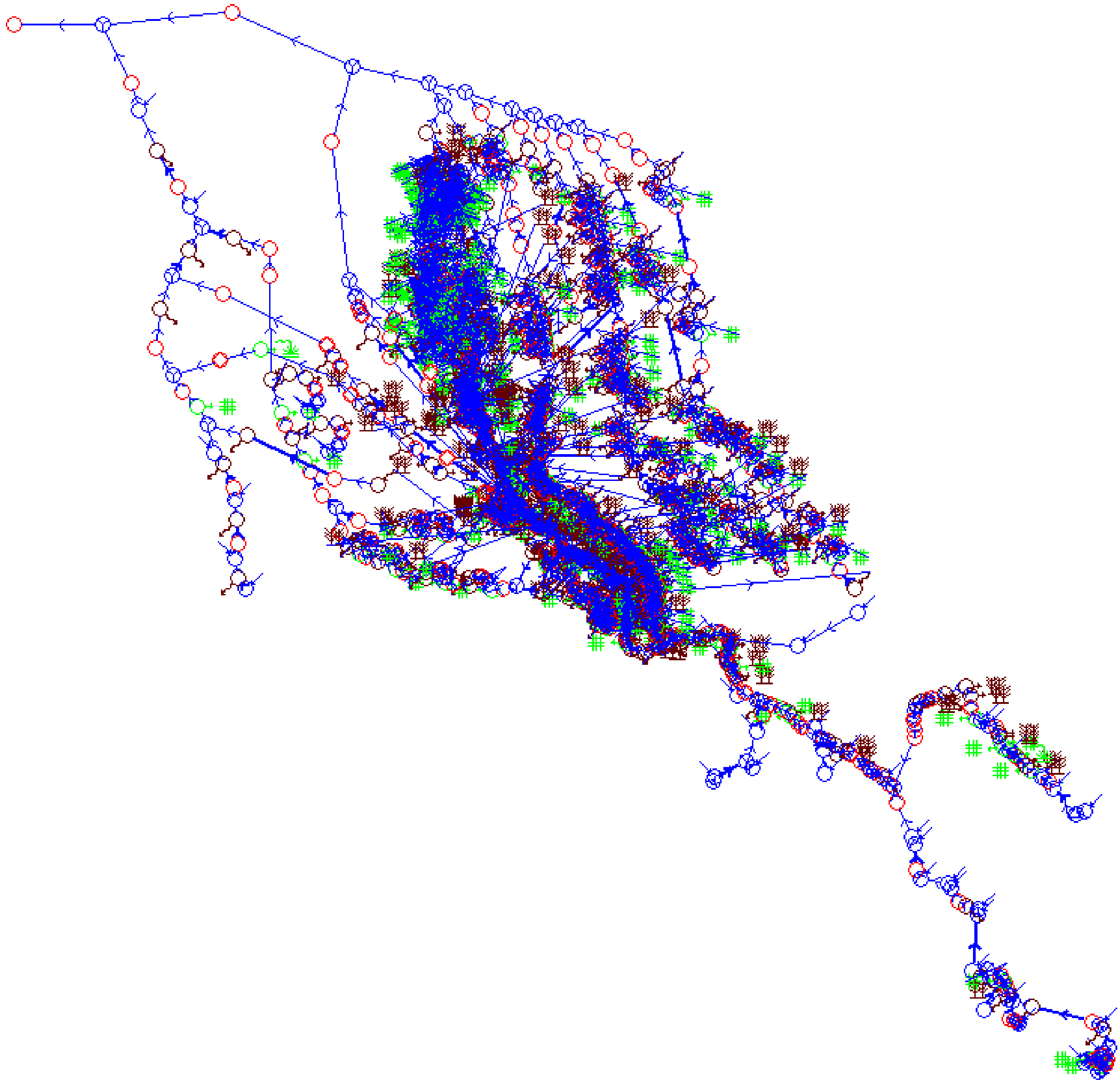

Figure 5 Assembled node-and-link model (as represented in IQQM). The model includes a node for every irrigation property assessed as eligible for a floodplain harvesting entitlement

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, the length of period dictated by data availability. The model 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. To extend the temporal scale of the model, the full climate period (to 30/6/2020) 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 Macquarie Valley modelling

Period term	Period	Note
Long term record	1/7/1889–30/6/2018	1889–1895 is the model warm-up[1] period; reporting commences from 1895
Reference climate period for reporting	1/7/1895–30/6/2009	Water years 1895/86 to 2008/09 (short form 1895–2009) Basin Plan reporting period. Period used for long-term averages
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 at flow gauging sites
Assessment period for diversions and water management using fully configured model	1/7/2004–30/6/2018	Water years 2004/05 to 2017/18[2] (short form 2004–2018) 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 at the start of the 2008/09 water year

[1] The first few years of long-term model scenarios are often excluded from reported results to avoid impacts from the choice of starting storage volumes and river flows.

[2] The model is run for the full period of available climate data 1890–2020, but results are assessed against observed data for the 2004–2018 period only.

2.3.7 Model validation

The assembled model is then tested to evaluate its performance by comparing model results with observed data over the period of calibration. For this model, the diversions and water management components were tested over the period 01/07/2004–30/06/2018, which includes key benchmark years for the policy and the Basin Plan.

To ensure that the assembled model can simulate the key processes of flows, diversions, and water management, a model scenario was configured to represent the 2008/09 level of development. The 2008/09 water year is in the middle of the calibration period for many of the model components; it represents the key date by which floodplain harvesting works must be constructed or approved to be eligible for estimating the floodplain harvesting licences.

We do note there have been some changes in development from 2004 to 2018. Consideration has been given to these and other factors in evaluating the results, as described in Section 8.

2.3.8 Scenario development

The fully assembled model with the full period of available climate data is now ready to simulate scenarios. A model 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 Macquarie 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 2021a). The scenarios developed for the Macquarie Valley and referenced in this report are listed in Table 4.

Table 4 Scenarios used in the Macquarie Valley model

Scenario ‘name’	Description
2008/09 Scenario	Represents the conditions in the valley, licences and diversions, as at 2008/09[4]
Cap Scenario	Uses the irrigation infrastructure, water licences, and management rules in place at 30 June 1994, to assess the diversions permissible under the Murray-Darling Basin Ministerial Council’s Cap on diversions
Water Sharing Plan (WSP) Scenario	Limit on long-term diversions set by the Macquarie WSP – uses irrigation infrastructure in place in the 1999/2000 water year, and the management arrangements and share components as at 1 July 2004
Baseline Diversion Limit (BDL) Scenario	Equivalent to the lesser of the Cap and WSP scenarios, also referred to as the 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 Macquarie Valley.

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

Table 5 Primary sources of data relevant to river system modelling and their uses (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[5], 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
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[6]	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

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[5] Farm surveys refer to the Irrigator Behaviour Questionnaire

[6] WaterNSW is a NSW state owned corporation that operates the state's rivers and water supply systems

Input / parameter	Primary data sources	Use – configure model	Use – direct input	Use – calibrate model	Use – validate model
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	Macquarie WSP, operational procedures	X	o	o	o

3 Overview of the Macquarie Valley

3.1 Physical description

The Macquarie River begins in the Blue Mountains of the Great Dividing Range, south of Bathurst, and flows in a north-westerly direction for 960 km where it joins the Barwon River near Brewarrina. 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 Macquarie Valley area. The Macquarie Valley covers more than 75,000 sq km and represents about 8% of the Murray-Darling Basin.

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 and wetlands at the lower end of the valley. The main tributaries entering the Macquarie River are:

- Cudgegong River which enters the Macquarie River above Burrendong Dam
- Bell and Talbragar Rivers which flow into the Macquarie River downstream of Burrendong Dam
- Castlereagh River which joins the Macquarie River below the regulated sections of the river, and just before the confluence of the Macquarie River with the Barwon River.

There are a number of effluent creeks that flow out of the Macquarie River in its lower reaches to the Bogan River or to the Barwon River. These include:

- Gunningbar Creek
- Mara Creek
- Duck Creek
- Crooked Creek.

The Ramsar-listed Macquarie Marshes at the end of the valley receive much of the river's flow, with only around 10% of the inflow to the Marshes passing through to the final unregulated sections of the Macquarie River. Figure 6 shows the main river network, together with the locations of major water storages and the Macquarie Marshes. Figure 7 shows the primary irrigation areas in the valley.

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.

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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.

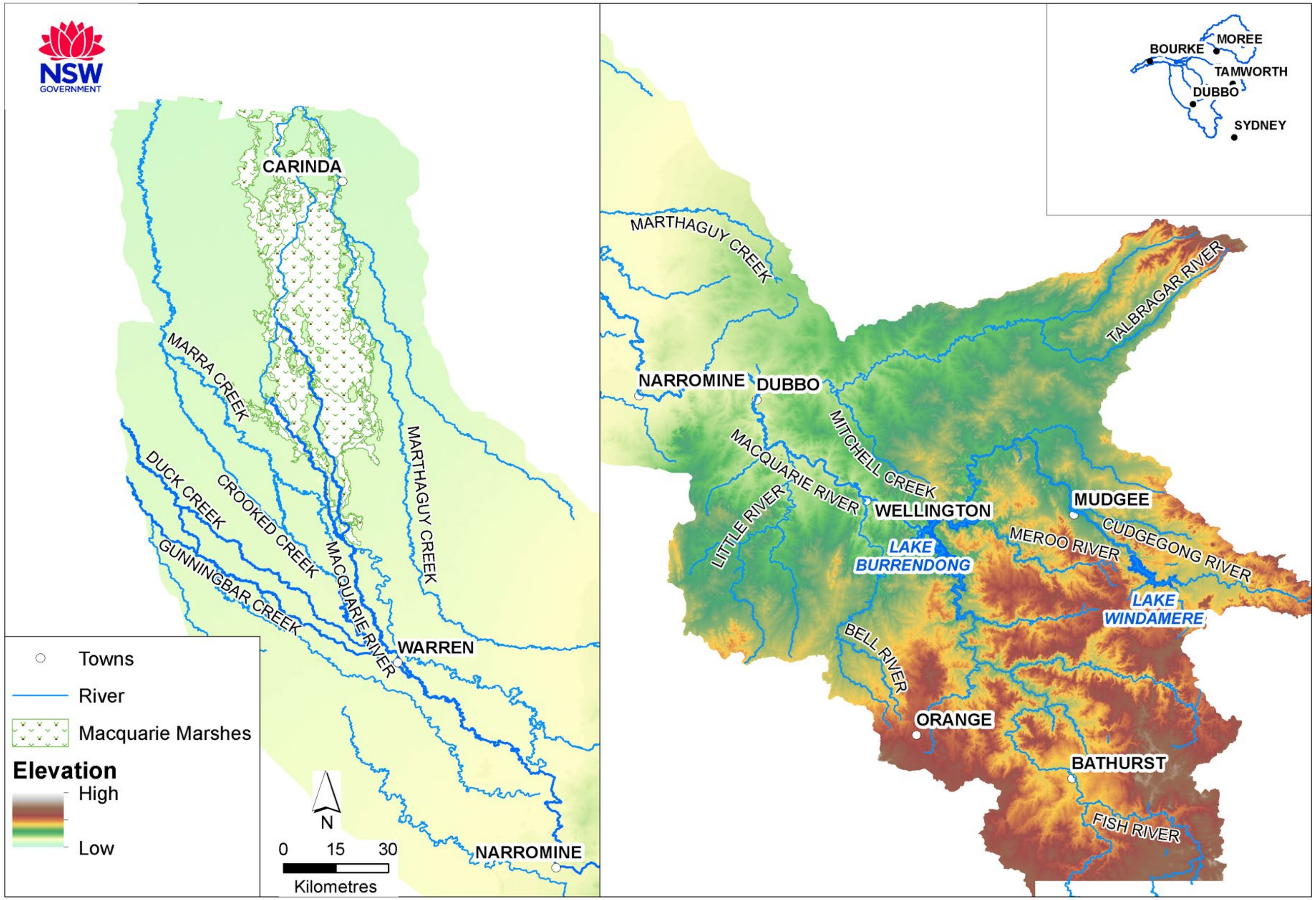

Figure 6 Map showing the river network (main channel and tributaries), locations of main towns and water storages, and the location of the Macquarie Marshes in the Macquarie Valley

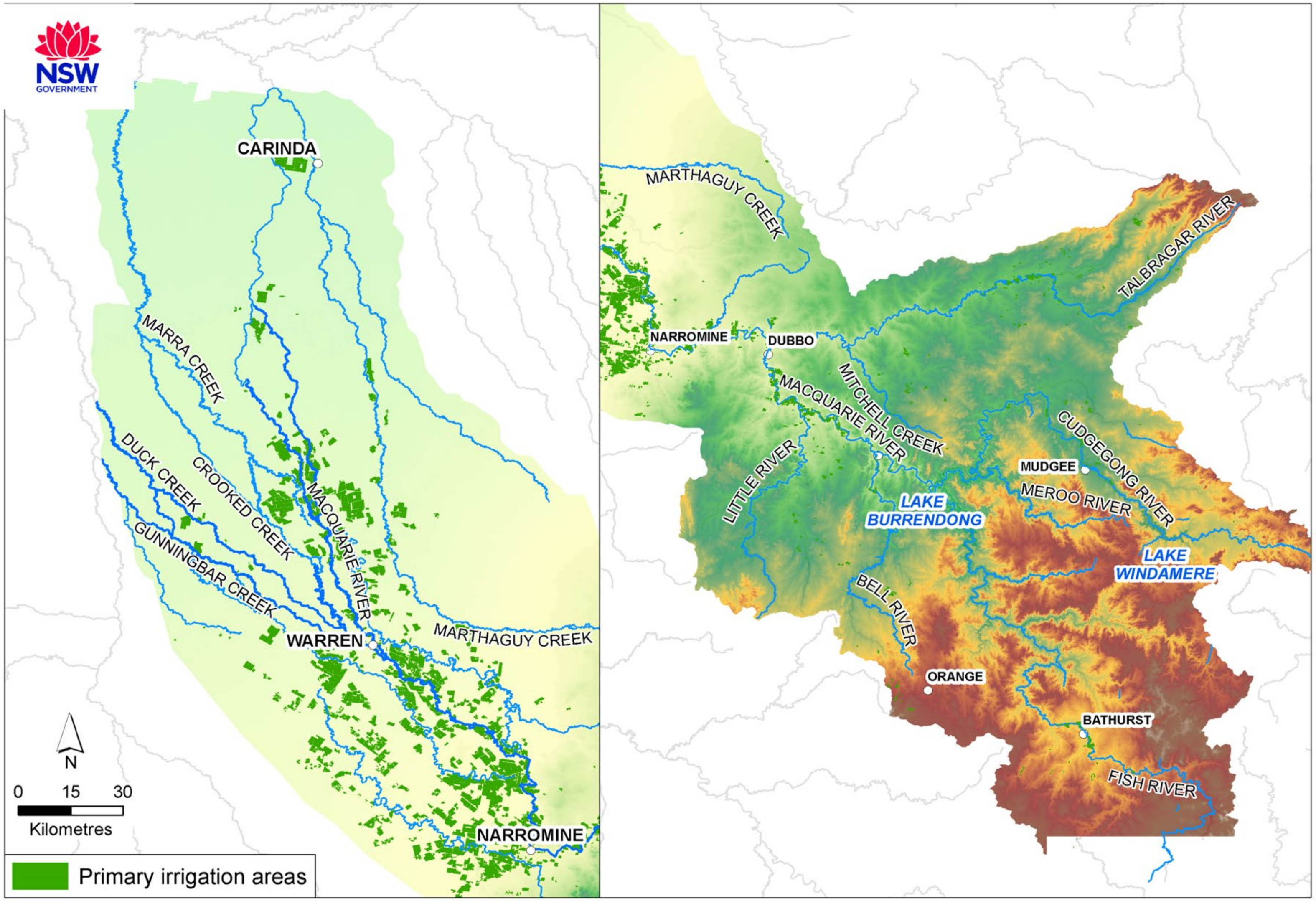

Figure 7 Map showing the primary irrigation areas in the Macquarie Valley (using the same map base and map legend as for Figure 6)

3.2 Regulation

Water in the valley is regulated through two major public water storages – Burrendong Dam on the Macquarie River, and Windamere Dam on the Cudgegong River – 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 the controlled or regulated delivery of water to water users, and issue of licences for the supply of water.

Access to regulated water is through licences and usage is metered. Unregulated water (such as in tributaries and headwater streams) can be accessed under licences when flows occur, subject to certain conditions. Groundwater and water that floods out onto the flat plain can also be accessed, subject to conditions. 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 in the valley are from the irrigation farm properties in the floodplain areas downstream of the major tributaries, between Narromine and the Macquarie Marshes. 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

Under the NSW *Water Management Act,* water sharing plans are made for major water sources such as the Macquarie and Cudgegong valleys. Water sharing plans set out the rules for sharing water between water users and the environment, and the allocation of water between different categories of water users.

The NSW policies and legislation that are referred to in this report are:

- *Water Management Act 2000 No 92*
- Water Sharing Plan for the Macquarie and Cudgegong Regulated Rivers Water Source 2020 (draft) (the Macquarie WSP)
- Water Sharing Plan for the Macquarie Bogan Unregulated and Alluvial Water Sources 2012
- (draft) Floodplain Management Plan for the Macquarie Valley Floodplain 2018
- NSW Floodplain Harvesting Policy 2013 (revised 2018) (the policy).

The Macquarie WSP applies to all regulated river sections of the Macquarie and Cudgegong Rivers. The management components described in this report closely reference key provisions of the Macquarie WSP and their practical implementation, as well as how water users in the valley 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 4–7) 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 33 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 Macquarie Valley (the previous IQQM Macquarie Valley model).

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

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 Macquarie Valley model 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 H.

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 regulated river system model.

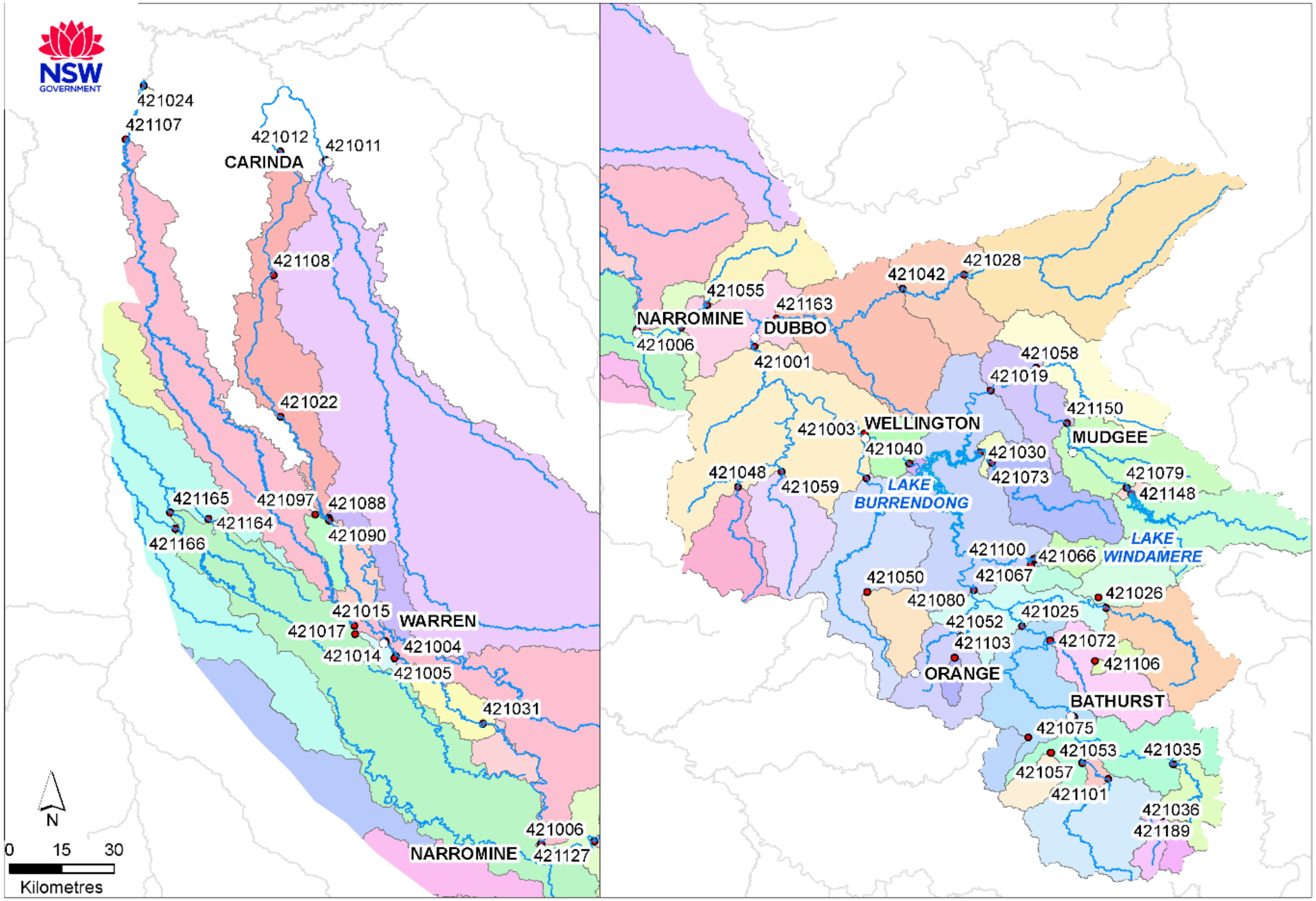

Figure 8 Map of the modelling units of the Macquarie Valley showing the gauging stations associated with each modelling unit

4.2 Rainfall

Average annual rainfall across the Macquarie Valley decreases from east to west, from over 1,200 mm in the eastern ranges around the Great Dividing Range to around 300 mm in the north-west area (Figure 9). Rainfall in the north of the region shows slight summer dominance with January and February being the months of highest rainfall at both Trangie and Coonamble, and the lowest months being August and September. At Mudgee in the upper catchment rainfall is significantly higher and more evenly distributed throughout the year. Summer months receive the highest rainfall while the autumn months are the driest.

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. Department guidelines recommend the use of the Queensland Government's Scientific Information for Land Owners (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 department guideline is to adopt the SILO infilling. 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 modelling period. Any significant periods of infilled data were checked for introduction of bias in the data.

The rainfall stations used within the Macquarie Valley 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.

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[9] https://www.longpaddock.qld.gov.au/silo/

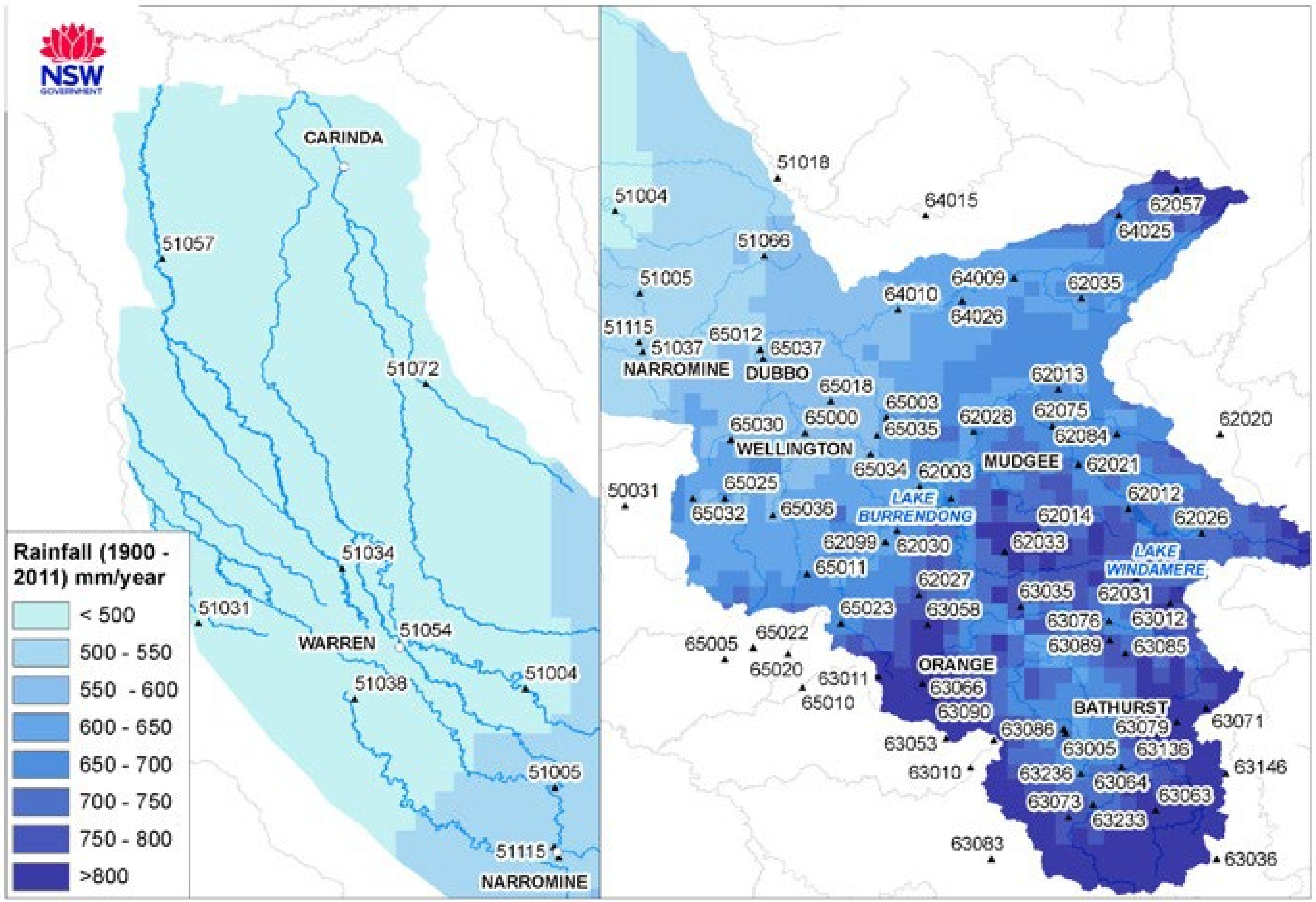

Figure 9 Map showing the rainfall gradient over the period 1900 to 2011 across the Macquarie Valley and location of rainfall stations used within the model

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 900 mm in the eastern ranges and over 2,200 mm in the north-west of the catchment.

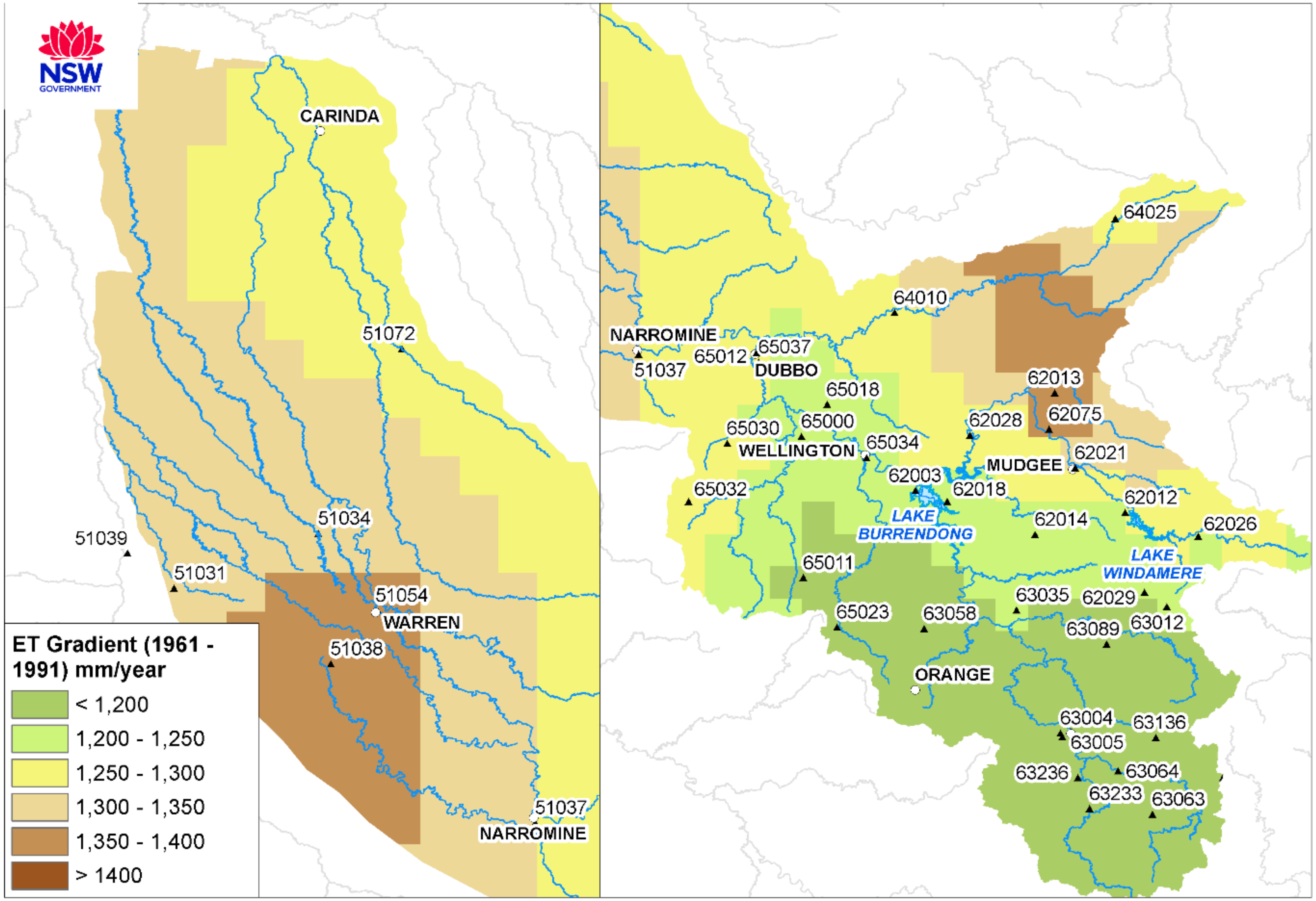

Figure 10 Map showing the evaporation gradient over the period 1961 to 1991 across the Macquarie Valley and the location of climate stations used for rainfall–runoff modelling

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 Macquarie Valley from the SILO database which provides Morton's estimated potential evapotranspiration data. We used three 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.
- Additional SILO evapotranspiration data calculated via the FAO56 method were used for crop modelling, using the SILO data for FAO56 method. These are the same as the climate stations shown in Figure 9.

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.

4.3.2 Modelling approach

When choosing evaporation stations for all purposes, the nearest stations were preferred, as local effects may be important.

4.4 Streamflow

As with many northern NSW inland rivers, the Macquarie River system experiences high flow variability in response to climate variability. A long term modelled flow is shown graphically for the Macquarie River at Dubbo (Station 421001, Figure 11) demonstrating this. This is a modelled (pre-development) flow, and is used here in preference to observed flow which, due to the regulation of flows by the major dams, does not give an indication of natural flow variability. This data shows that while the annual average is around 1,092 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.

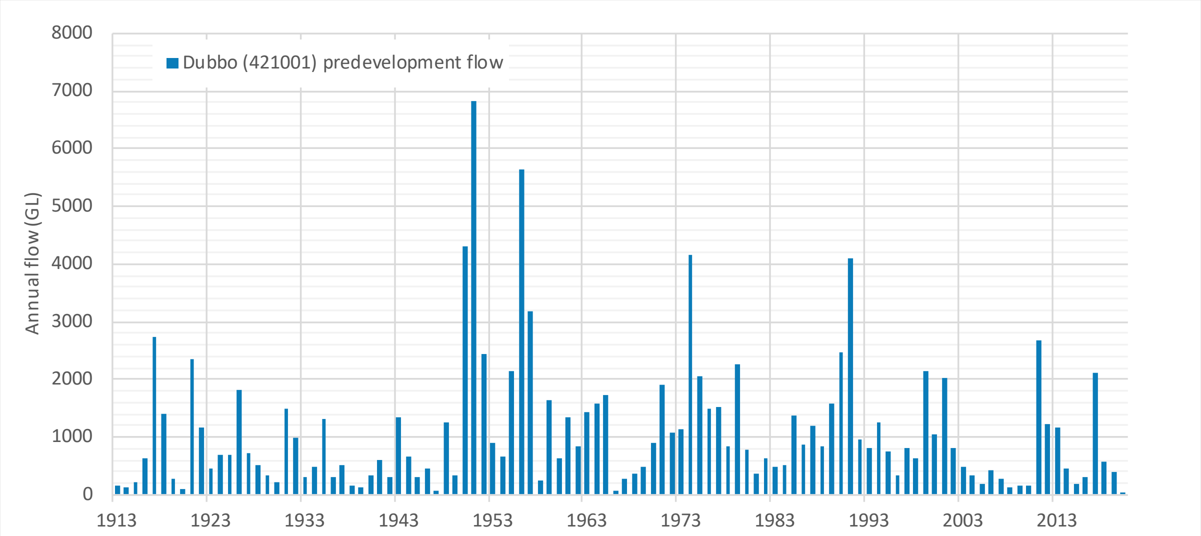

Figure 11 Modelled historical annual flow (GL) for the Macquarie River at Dubbo (421001) for the period 1913 to 2018

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 1955. The frequency and occurrence of such events plays a big part in floodplain harvesting behaviour.

4.4.1 Data sources

NSW maintains a network of river flow gauging stations across the Macquarie Valley catchment 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 for 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 94 flow gauging stations currently operating in the Macquarie, Bogan, and Castlereagh Valleys (including storage level gauges), with a further 87 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 19 stations were used to calibrate headwater inflows from 19 catchments that cover about 19,650 km^2 area, about 27% of the total Macquarie Valley. A further 14 stations were used to calibrate reach flow at 14 sites. Location of these stations is illustrated at Figure 12.

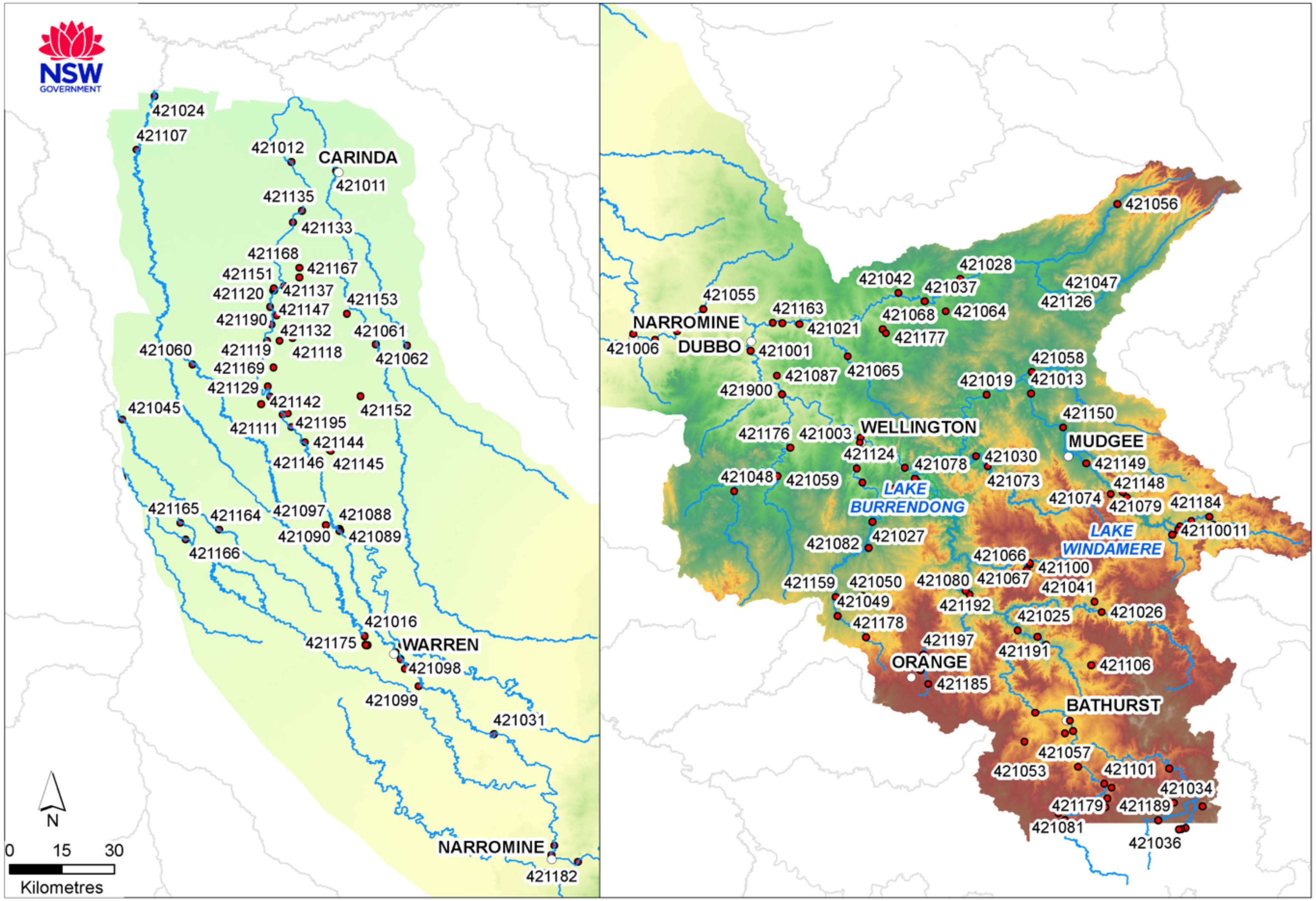

Figure 12 Map showing location of flow gauging stations in the Macquarie Valley

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
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 each headwater reach in the model (i.e. 18 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 Queensland 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 I.

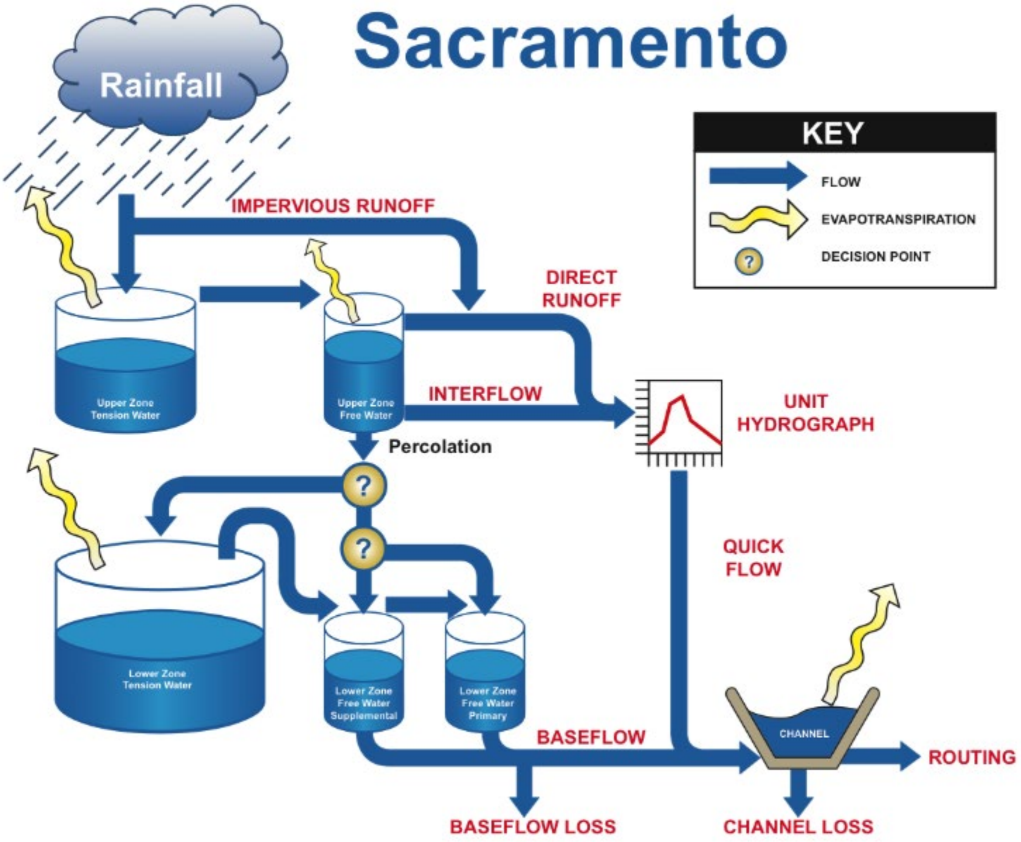

Figure 13 Conceptual diagram of the Sacramento rainfall–runoff model [Source: eWater 2016]

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 the 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

An effluent river is a river that flows out of another river and may also have a local catchment. Some effluent rivers only start flowing when the flows in the main river reach higher levels. Several effluent rivers/streams leave the main Macintyre River, sometimes with other smaller rivers and streams joining them at various points.

Gunningbar Creek effluent

Gunningbar Creek is a natural effluent stream from the Macquarie River just upstream of the township of Warren. With the exception of high flow events, flows into Gunningbar Creek are controlled by a regulator constructed across it adjacent to the Macintyre River.

Gunningbar Creek provides regulated flows along its length until it joins the Bogan River, and also provides regulated flows to two regulated effluents of its own; Crooked Creek (and its effluent, Duck Creek), and Bena Bila Creek. Gunningbar Creek also provides water to the Albert Priest channel that runs to the Bogan River to supply the township of Nyngan.

In addition to regulated licensed water users along these effluent creeks, regulated water is released by WaterNSW to replenish water for stock and domestic supply for landholders along Crooked Creek. These releases are known as replenishment flows.

Other effluent systems

There are several other effluent offtakes along the Macquarie River. These include:

- Marebone Break (Bulgeraga Creek)

- Mara Creek
- Gum Cowal (an ephemeral creek).

The Marebone Break offtake flows into the regulated Bulgeraga Creek, and provides water for licensed water users until it rejoins the Macquarie River (which is unregulated at this confluence) in the Macquarie Marshes.

The Mara Creek and Gum Cowal offtakes control water from entering these unregulated streams except for stock and domestic replenishment flows, environmental flows and high flow events. Mara Creek does not rejoin the regulated river system, and Gum Cowal flows into the eastern Macquarie Marshes and eventually into the unregulated Marthaguy Creek, which does rejoin the Macquarie River in the lower unregulated section below the Macquarie Marshes.

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 these areas.

There are numerous breakouts into floodway flow paths, and many of the flow paths have inter-connections. 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.

High flow breakouts are usually 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:

- floodplain harvesting properties boundaries and information from the farm surveys
- existing flooding information, including the floodway network from the 2008 *Macquarie River (Narromine to Oxley Station) Floodplain Management Plan* (DECC 2008), and flood aerial and satellite photography from historic flooding (1990, 2010 and 2016 floods)

- OEH flood modelling results for the 1955 flood (approximately 1 in 140 annual exceedance probability[10] (AEP), 1990 flood (approximately 1 in 40 AEP) and 2000 flood (approximately 1 in 10 AEP). The model has also been run using a slowly increasing hydrograph to help represent the time at which different key flow paths are activated.

Figure 14 shows the identified breakouts in the models overlaid on overland flow paths derived from results of the MIKE Flood[11] model which was developed for the *Macquarie River (Narromine to Oxley Station) Floodplain Management Plan 2008* (DECC 2008*)*. Further information on these breakouts is given in Appendix D.

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 Mike Flood 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.

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 DPIE Water (2021b).

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[10] Annual Exceedance Probability describes the probability of a flow of a certain size occurring in a river or stream

[11] MIKE Flood is a commercial software product, developed and maintained by the DHI Group. It is used around the world for hydraulic and hydrological modelling. MIKE FLOOD (mikepoweredbydhi.com)

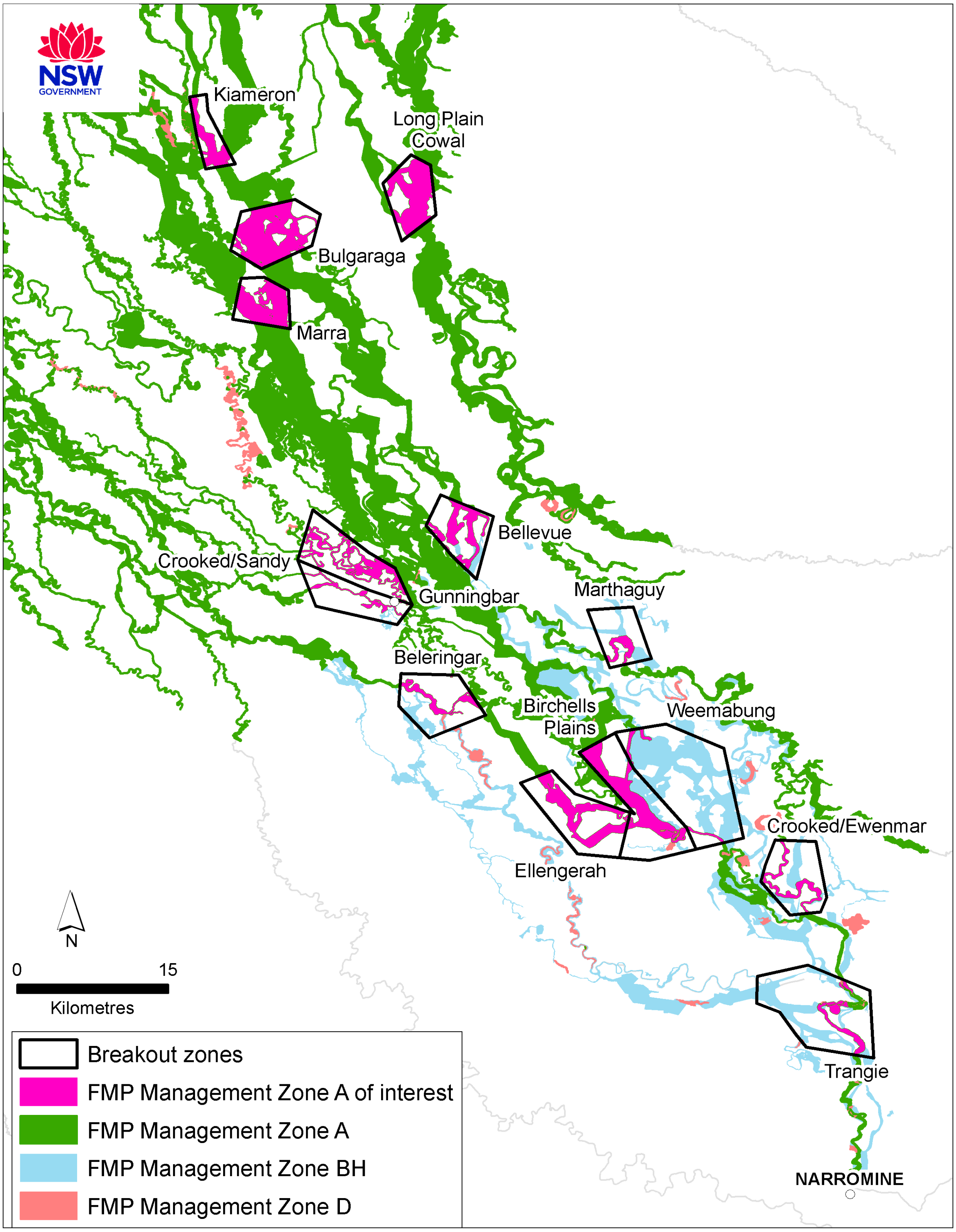

Figure 14 Map of the Macquarie Valley floodplain showing the Floodplain Management Plan (FMP) zones and the breakout zones

4.5.2 Modelling approach

Previous river system modelling included flows onto the floodplains as part of the flow-calibration for most river reaches and some tributary reaches (i.e. between headwater gauge and junction with the main river). This flow onto the floodplain was treated as a loss to the system. This Macquarie Valley model represents floodplain breakouts explicitly, i.e. as an effluent, and flow calibration results more closely represent instream losses.

The flow rates at which breakouts from the main channel were determined from a range of sources as described above.

The locations and flow conditions for breakouts in the model provide the water for properties to access floodplain harvesting (see Figure 14). The Macquarie Valley model now includes 15 high flow breakouts. The flow rates at which they breakout from the main channel were determined from a range of sources (as described in 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 IQQM 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[12].

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 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 effluent creeks to the main river where appropriate. 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 environmental assets. The impact of floodplain harvesting on these areas has been estimated using the nearest breakout flow relationship and the simulated floodplain harvesting in that part of the model. This is described further in in DPIE Water (2021b).

Macquarie Marshes

The Macquarie Valley model initially represented the Macquarie Marshes relatively simply. In 2010 a more detailed representation of the Macquarie Marshes was developed, based on a hydrodynamic MIKE Flood model developed by The NSW Department of Environment Climate Change and Water. The IQQM modelling for the Macquarie Marshes is described in *IQQM Wetland modelling for the Macquarie Valley* (DECCW 2010).

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[12] 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

4.6 Regulating infrastructure – dams and re-regulating storages

Flows in the Macquarie Valley are regulated by two major public storages – Burrendong Dam on the Macquarie River, and Windamere Dam on the Cudgegong River (see Figure 6 for locations). Basic details of these storages are summarised in Table 7.

Table 7 Major headwater storages in the Macquarie Valley

Storage	River	Commissioned	Capacity (GL)
Burrendong Dam	Macquarie River	1967	1,188
Windamere Dam	Cudgegong River	1984	368

These storages were constructed primarily to store and release water to downstream licensed water users (including for environmental flows). Burrendong Dam also has a flood mitigation zone that can store an additional 489 GL using the vertical gates across the main storage spillway. Windamere Dam has an ungated spillway that cannot actively manage spills during major floods. However, this storage still provides passive flood mitigation as it takes time to fill and discharge over the spillway.

Above Burrendong Dam, there are four smaller storages that provide water for nearby towns and industry. Basic details of these storages are summarised in Table 8.

Table 8 Town water supply storages in the upper Macquarie Valley

Storage	River	Commissioned	Capacity (GL)
Oberon Dam	Fish River	1959	45
Ben Chifley Dam	Campbells River	1956	30.8
Suma Park Dam	Summer Hill Creek	1962	18
Winburndale Dam	Winburndale Rivulet	1931	1.7

- Oberon Dam supplies water via the Fish River water supply scheme to Lithgow, Katoomba, and other smaller settlements
- Ben Chifley and Winburndale dams supply water to Bathurst
- Suma Park Dam supplies water to Orange.

These storages have ungated spillways, but also provide passive flood mitigation as they take time to fill and discharge over their spillways.

Within the regulated Macquarie River system below Burrendong Dam, there are two smaller weirs:

- Warren Weir
- Marebone Weir.

Warren Weir is a gated weir on the Macquarie River near the township of Warren. The weir has a storage capacity of 1,000 ML and its primary functions are to control the flow passing downstream in the Macquarie River, and to help conserve unregulated tributary inflows and operational surplus flows.

Marebone Weir is a gated weir on the Macquarie River downstream of the township of Warren. The weir has a very small storage capacity and its primary function is to control the flow passing downstream in the Macquarie River, and the flow into Bulgeraga Creek.

Other water management infrastructure in the regulated Macquarie Valley include:

- offtake regulators at Marebone Break and the Gum Cowal offtake
- a number of smaller structures on unregulated effluent creeks
- the Albert Priest channel from Gunningbar Creek to the Bogan River near Nyngan.

4.6.1 Data sources

Major water management infrastructure such as dams, weirs, and regulators are maintained and operated by WaterNSW. WaterNSW 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. Ben Chifley Dam and Winburndale Dam are operated and maintained by Bathurst Regional Council, and Suma Park Dam is operated and maintained by Orange Regional Council.

4.6.2 Modelling approach

Major dams

The two major water storages and Oberon Dam were configured based on the relevant engineering parameters provided by WaterNSW. Capacities are listed in Table 7 and Table 8 and storage curves are provided in Appendix E.

Ben Chifley Dam has been configured based on the relevant engineering parameters provided by Bathurst Regional Council. Suma Park and Winburndale Dams have not been represented in the Macquarie Valley model.

The IQQM 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

Warren Weir was configured as a re-regulatory weir that captures surplus flows and releases water to meet downstream demands. In the model, it is configured as an IQQM 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 Macquarie Valley model does not reproduce the historical operation of Marebone Weir. The model uses a fixed relationship of flow in the main river upstream of Marebone Weir versus release rate down Marebone Break. Historically, decisions to make releases down Marebone Break are made for a variety of reasons and are not governed by flows in the river.

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.

5 Modelling water access and licensing

Water can only be taken from rivers and streams in NSW under a licence or a right. The major categories of water access licences used in this report to describe water access are:

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

5.1 Water licences

The main licence categories for access to surface water sources are listed in Table 9. 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 Macquarie WSP.

Table 9 Surface water access licence types in the Macquarie Valley regulated river system

Licence type	Note
High security	Includes local water utilities, horticulture, permanent plantings, stock and domestic
General security	Water able to be ordered from storages
Supplementary water access	Water not reliant on infrastructure for storage or distribution
Unregulated river	Not included in the regulated system, but some properties with licences in the regulated river system may also have separate access to unregulated rivers or streams

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

Water access licences are issued 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 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 Water Licensing System. 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 10.

Table 10 Share components in the Macquarie and Cudgegong regulated river system (as at 30 June 2020)

Category	Consumptive	Environmental water	Total
Domestic and stock	5,953	0	5,953
Local water utility	[1]18,845	0	18,845
Regulated river (high security)	17,873	0	17,873
Regulated river (general security)	457,823	174,643	632,466
Supplementary water access	40,254	9,744	49,998
Total	540,778	184,387	725,135

[1]includes 40 ML of high security subcategory town water supply.

No information is available on water use under Basic Landholder Rights, other than the estimate in Part 4 of the Macquarie 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 and supplementary water access.

Irrigation enterprises based on high security and general security licences have been modelled as such. Small amounts of high security and stock and domestic entitlements belonging to enterprises based on general security have also been modelled as general security, but with a higher priority for allocations than general security licences. Where water users have significant groundwater or unregulated water access licences, these have also been configured.

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

5.2 Regulated water

Water controlled by the major dams is assessed each month, and the available water is shared to water access licences (except supplementary water access licences) via allocation announcements.

This water is known as regulated water, and licence holders may order delivery of this water from the river operator (WaterNSW) from time to time, 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 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.

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 maintains a database of water orders and use (the Water Accounting System – WAS) and arranges for meters to be read. Prior to 2004, water use records were maintained in a predecessor database system. Larger water users may have meter readings undertaken monthly or quarterly, whereas smaller water users have meter readings undertaken less frequently.

Water use records are available for the reaches below Cudgegong Dam and Burrendong Dam from the commencement of metering in the1980s to the present. 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. 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 2021.

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 to estimate water losses.

Records for the period prior to 2004, disaggregated from monthly or longer periods for previous Macquarie Valley models, have been re-used for the current work. Since 2004, metered data have been disaggregated to daily time steps, using water order data.

The total metered diversions over the period used to calibrate water use in the Macquarie Valley model are shown in Figure 15.

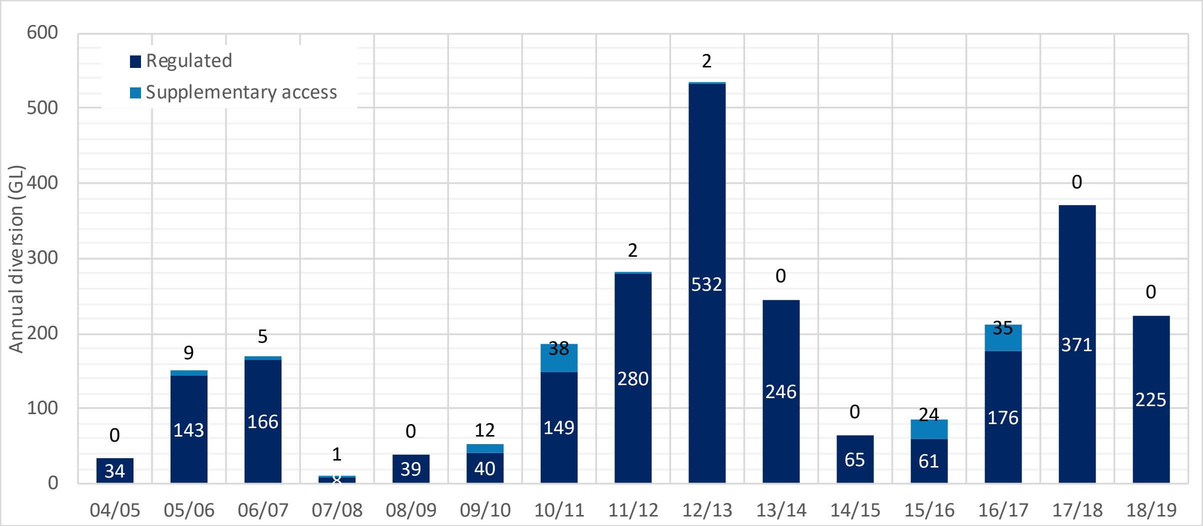

Figure 15 Total metered regulated and supplementary access diversions in the Macquarie Valley for the period 2004/05 to 2018/19

5.2.2 Modelling approach

The supply of regulated water involves the sharing of water between consumptive water use and environmental requirements as set out in the Macquarie WSP, the allocation of water to licences, together with the ordering and delivering of water in the regulated river system.

Water orders are generated by the model simulating 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, the river flows may exceed requirements for water orders or other flow requirements set out in the Macquarie WSP.

These excess flows are referred to as uncontrolled flows, which WaterNSW announces as available for supplementary water access.

Supplementary water access licences allow water to be taken during these flows up to the limit of the water in each licence’s account. Water meters measure the take of water by the majority of supplementary water access licences.

5.3.1 Data sources

Supplementary access periods announced by WaterNSW are recorded in the WAS. Diversions during these periods are measured from meter readings using the same meters as for regulated water use and are recorded in the 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 when flows are more than required for regulated water in the river and exceed the flow requirements set in the Macquarie WSP.

The model controls access via uncontrolled flow river reaches, with at least one uncontrolled flow river reach designated for each river reach in the model. Supplementary access is made available to each uncontrolled flow reach when the model meets conditions set out in the Macquarie WSP, and also when flows exceed user configurable thresholds that are used to reflect Water NSW's operational practices.

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.

The simulation of supplementary water access is summarised in Table 11 with licence flow thresholds listed in Table 12.

Table 11 Simulation of the components of supplementary water access

Component	Modelling method
Sharing between consumptive access and the environment	• Supplementary events in the system are not declared unless flows in excess of all other requirements under the Macquarie WSP will exceed 5,000 ML/day at Warren • Supplementary access from the Cudgegong River is only permitted when Burrendong Dam is spilling
Uncontrolled flow reach definition	• Uncontrolled flow reaches are aligned with operational river reaches, with some additional sub-divisions for model requirements to handle bifurcations and confluences in IQQM
Thresholds	• Event starts when flow > 'threshold volume' + orders • Event ends when flow < 'threshold volume' + orders • Threshold volumes are based on WSP rules and WaterNSW operational sharing practices as summarised below: ○ thresholds along the main Macquarie River vary between 933 ML/day and 8,233 ML/day ○ the threshold for Marebone Break and along Bulgeraga Creek is 933 ML/day ○ the threshold along Gunningbar Creek and along Duck Creek is 182 ML/day
Cap on usage	• The 1 ML/share usage limit is defined on a reach basis ('annual usage limit')

Table 12 Supplementary water access licence flow thresholds

Reach	Start flow trigger (ML/day)	End flow trigger (ML/day)
Macquarie River: d/s Burrendong to Gin Gin	8,233	8,233
Macquarie River: Gin Gin to Gunningbar O/T	2,260	2,260
Macquarie River: Gunningbar O/T to d/s Warren Weir	7,500	7,500
Macquarie River: d/s Warren Weir to d/s Marebone Weir	2,260	2,260
Macquarie River: d/s Marebone Weir to Oxley and d/s Macquarie-Bulgeraga confluence to Pillicawarrina	933	933
Marebone Break and Bulgeraga Creek	933	933
Gunningbar Creek and Duck Creek	182	182

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 areas (breakout zones) potentially covered by overland flow from breakout locations. Major irrigation areas are shown in Figure 7.

5.4.1 Data sources

Overbank flow

Water harvested from overbank flow is not currently officially recorded. A small number of farm survey respondents 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 assess floodplain harvesting volumes. 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 estimated their water requirements. This assessment focussed on the reach and valley scale to ensure that the total volume of water, including historical metered use and estimated floodplain harvesting, was 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 58% of the developed area. In some instances properties can directly intercept runoff from local areas outside of the farm; this is accounted for in the model in one of two ways: through adding to the harvesting of overbank flow, or included in the rainfall–runoff modelling by adding additional area to the undeveloped area component model.

Some properties provided estimates of runoff volumes harvested. These estimates were analysed to estimate the percentage 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 water users is simulated through the breakouts (as described in Section 4.5). The extraction of this water is simulated in IQQM 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. These data were 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.

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 component 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 component 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.

It is possible for irrigators that access regulated water to 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 along the Lower Macquarie and Bogan Rivers and the effluent streams flowing from the Macquarie River.

5.5.1 Data sources

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 under the NSW metering policy.

5.5.2 Modelling approach

No individually modelled water users have unregulated water access licences, and this type of water access has not been included in the Macquarie Valley model.

Unregulated flow access in the upper parts of the valley is not explicitly represented, other than for the towns of Bathurst, Orange, and Oberon. The effects of these diversions are recognised inherently in the gauged inflow data and hence the inflows (observed and modelled) are net of any such usage.

5.6 Groundwater

NSW has issued licences that allow taking of water from the alluvial aquifers that underlie the Macquarie River and other streams for irrigation and town water supply. NSW has issued approximately 35,000 ML/year of aquifer access licences in three zones that overlap with the main areas of the regulated river system where floodplain harvesting occurs. Water use is limited to an average of approximately 100% of the licensed entitlements each year under the Water Sharing Plan for the Macquarie Bogan Unregulated and Alluvial Water Sources 2012.

5.6.1 Data sources

Records of groundwater volumetric entitlements and historical usage (where metered) are maintained in the WLS.

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

The construction of major dams and the regulation of river flows have enabled the delivery of water to water users, and issuing of licences for the supply of water. 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 irrigation properties hold general security water access licences that have larger entitlements to water designed to support irrigation of annual crops. Many of these irrigation properties also have licences that allow them to take water when there are uncontrolled flows in the river. These are known as supplementary water access licences.

6.1 Urban water supply

Within the regulated Macquarie Valley river system, local water utility licences have been issued to Mudgee, Dubbo, and Warren, and also to Nyngan, Cobar and Hermidale (supplied by the Albert Priest channel from Gunningbar Creek). These licences represent a relatively small proportion of the total entitlements in the regulated river system when compared to the larger licences used for irrigation; however they have the highest priority of supply.

Above the regulated Macquarie Valley river system, there are smaller storages supplying the urban centres of Bathurst, Orange, Lithgow and Katoomba.

6.1.1 Data sources

A small number of urban water utilities take water from the Macquarie Valley regulated river system to supply domestic, commercial, and industrial users in the towns. 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.

Upstream of the regulated river system, the urban centres of Bathurst, and Orange keep records of their water storage levels and water use. The Fish River Scheme, which supplies Oberon, Lithgow, and Katoomba, also keeps records of water storage levels, water transfers, and water use.

6.1.2 Modelling approach

The volumes of town water supply in the Macquarie Valley regulated river system and for Bathurst are represented as fixed monthly patterns with an annual use that is close to the annual entitlement, as per previous modelling in IQQM. The results in this report do not include these diversions for towns upstream of the regulated river system, including via the Fish River Scheme.

6.2 Irrigators

Diversions in the Macquarie Valley regulated river system are predominantly due to irrigated agriculture, which accounts for, on average, more than 95% of the total water use. These water users have access to a range of water sources: high and general security, supplementary access and floodplain harvesting. 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 small amounts of permanent plantings such as vineyards.

Numbers and distribution

There were 1,143 individual licences as at July 2020, with most being general security licences (650) and supplementary access licences (493). 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 distributed throughout the valley. The majority of larger water users are located on the floodplains below Narromine. 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 Macquarie Valley 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 13.

Table 13 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 Licensing 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 the model scenario	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 2 mm/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	• Remote sensing for individually modelled water users. For other relatively small water users estimated based on earlier survey data as per the pre-existing IQQM water sharing plan model	Configuring upper limit to planted areas, and contributions to rainfall–runoff for relevant water user nodes
River pumping capacity	• WAS database	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	• This 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 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 20 • Total available water is defined based on soil moisture capacity (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 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 51% of the licensed entitlement to water and over 51% 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 data 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 are required to model likely water harvesting and usage volumes. 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 were provided, these were used instead. In both instances a 1 m freeboard was assumed for permanent storages. Either of these methods (i.e. LIDAR or survey) provide an objective basis to determine capacity. Remote sensing methods were also used to validate the 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 surveys; 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 Macquarie Valley regulated river system are set out in Table 14. 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 15.

Table 14 Regulated system below Narromine latest estimates for on-farm irrigation infrastructure[13]

Reaches	Developed area (ha)	Permanent on-farm storage capacity (ML)	River pump capacity (ML/day)	On-farm storage pump capacity (ML/day)
Narromine to Gin Gin	53,287	47,011	6,495	4,707
Gin Gin to Warren	27,701	36,460	5,020	3,469
Warren to Marebone	18,236	23,227	3,847	2,683
Marebone to end of system	19,165	35,876	2,385	3,675
Total	118,389	142,574	17,746	14,534

Table 15 Total regulated system on-farm irrigation infrastructure estimates at 2004, 2008 and most recent

	2004	2008	Latest estimate
On-farm storage capacity (GL)	135	144	174
On-farm storage pump capacity (ML/d)	14,185	14,534	15,437
Installed river pump capacity (ML/d)	16,134	19,028	19,102
Maximum irrigable area (ha)	134,523	131,350	131,350

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 20% of the surveyed irrigators provided complete or partial irrigated cropping records for the 11-year period covered in the farm surveys. Most of these data only had planted areas for part of the 11-year record. Remote sensing data from Landsat were available from 2010/11 to 2018/19, and is shown in Figure 16. However, insufficient data were available in 2011/12 and 2012/13 due to cloud cover. The remotely sensed dataset compares well to the survey data for summer crops in the short period of overlap between the two datasets.

Due to the uncertainty regarding remotely sensed winter areas, only farm survey estimates of winter crops were used to inform modelling in first instance. However, where there were

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[13] All individually modelled properties eligible for floodplain harvesting are below Narromine.

significant regulated diversions or evidence of other water usage during winter season, the area was estimated during model calibration.

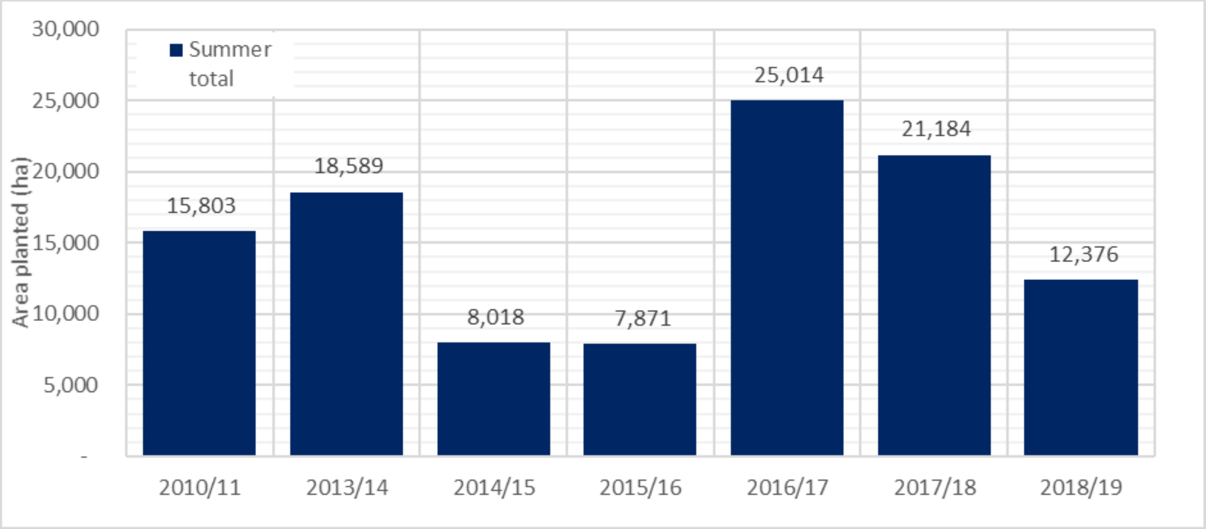

Figure 16 Reported summer planted crop areas from 2010/11 to 2018/19. Data for 2011/12 and 2012/13 are not included due to cloud cover [Source: Remote sensing data]

Analysis of crop types shows it is dominated by cotton with a small amount of cereal also grown in summer. Wheat is also grown in the winter growing season on an irregular basis. Small areas of a few other crop types are 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 1 ML/ha to 12 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 ML/ha to 11.5 ML/ha for cotton. Reasons for this wide range of water use were difficult to reconcile as there was no geographic basis for the range. Potential reasons include different calculation periods, whether pre-watering and efficiency were factored in, 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 in the Gwydir Model Build Report (DPIE Water 2020). 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 IQQM 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 16. In the model, all processes operate on a daily time step.

Table 16 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	• IQQM 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 use of 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 17.

Table 17 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) • On-farm storage operation (discussed further below)

Step	Fixed input data	Target to meet	Parameters
Crop areas	- Water available at planting decision date (simulated)	- Reported crop areas and checked against remotely sensed data	- Planting decision function

The Macquarie Valley model includes a number of scenarios representing development at different points in time. The primary model 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 in this report. While the period 2004/05 to 2017/18 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 2017/18 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 18). This is important to ensure that the model is robust during different periods of water availability
- includes key benchmark years for the NSW Floodplain Harvesting Policy (3 July 2008 for eligible floodplain harvesting works) and the Basin Plan (30 June 2009 baseline permitted diversions, which is the plan limit set by the Macquarie WSP).

Table 18 Comparison of rainfall statistics (average, minimum and maximum) over the assessment period (2003/04 to 2017/18) to the long-term record (1889/90 to 2017/18)

Metric	Long term (mm) (1889–2018)	Short term (mm) (2003–2018)
Average	618	610
Maximum	1138	867
Minimum	305	373

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 110 irrigator nodes, of which 73 represent individual eligible properties (or eligible enterprises consisting of several properties with one owner).

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 represents all on-farm storages for each irrigator node as one on-farm storage. 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 Macquarie Valley 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 from 1 ML/ha to 12.5 ML/ha between properties with the average being 7.3 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 and wheat. A default risk value was assumed for other crops and calibrated if required. These are summarised in Table 19.

Table 19 Adopted crop planting decision rates for winter wheat and cotton, i.e. the volume of water required to be available before an irrigator decides to plant one ha of the crop

Crop	Downstream of Narromine
Winter wheat	1.5 to 4 ML/ha (average of 1.5 ML/ha used if no information provided)
Cotton	3 to 10 ML/ha (average of 7.3 ML/ha used if no information provided)

As noted in the Data sources section, winter crops are planted irregularly and do not appear to be related to water availability. The model was configured to use the crop planting decision application rates reported in the farm surveys.

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

1. The model calculates 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 if for example the maximum area historically planted was less.

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.

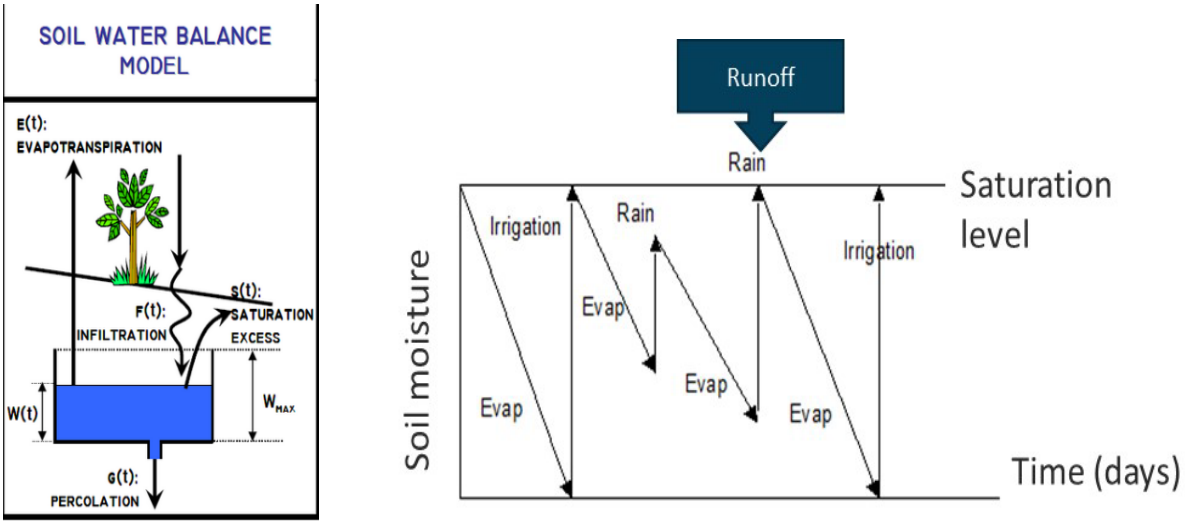

Figure 17 Schematic of the soil water balance model (left) with accounting for evapotranspiration, rain, and irrigation (right)

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 13. This was done to avoid inappropriate calibration of parameters in the model, and to ensure the overall calibration was 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 13. Surface water irrigation efficiency can vary widely. Gillies, 2012 application efficiency results (cited in Wigginton, 2012b, p26) were based on data collected from 2000/01 to 2011/12. The average was 76% with tailwater recycling with efficiencies up to 90% 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 be more representative of most irrigation enterprises over the recent period. Based on Gillies average result, with some allowance for channel losses, we have adopted an application loss of 30% for all scenarios[14].

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.

A single soil moisture capacity for crop types and fallow is defined directly in IQQM as referenced in Table 13. An upper and lower moisture store can also be specified to limit the effect of evaporation from the soil moisture store. Actual soil moisture capacity will vary depending on soil type and farm management practices. While this is an averaged approximation, it is used in combination with other parameters to ensure that the generated crop demand is reasonable. This reduces the sensitivity of the results to this one. Similarly, the soil moisture capacity 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).

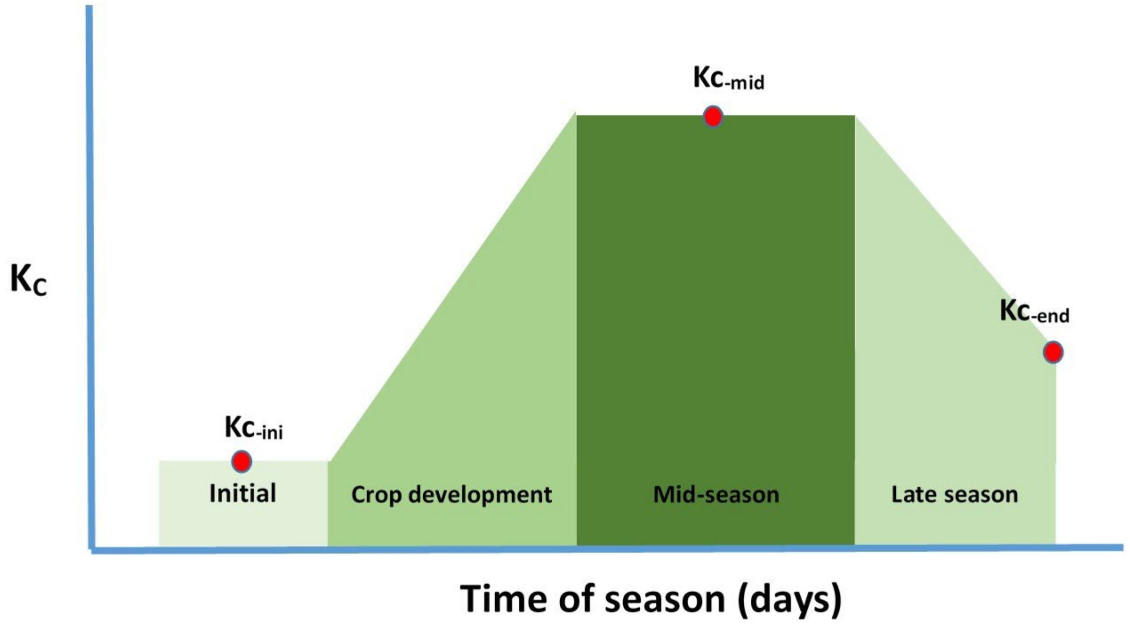

Figure 18 The relationship of Kc crop factors to time of season [adapted from Fig 34, Allen et al. 1998]

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[14] 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.

Derivation of crop factor values, soil parameters and crop planting dates for the individually modelled irrigators is provided in Table 13 and values summarised in Table 20. In Table 20, note that the late season cotton period is shorter than the likely actual period[15].

For the aggregated smaller irrigators, the crop factors from the pre-existing Macquarie Valley IQQM have continued to be used (DECCW 2009).

Table 20 Crop parameters used for individually modelled properties: crop factors (Kc), periods and planting date

Crop class	Winter cereal	Cotton
Kc-ini	0.30	0.35
Kc-mid	1.15	1.20
Kc-end	0.25	0.60
Initial	16	30
Development	31	50
Mid-season	67	60
Late season	41	20
	15 May	Late Sep to end Oct

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, a 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 21. 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.

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[15] This has been done to enable the simulation of depletion of soil moisture at the end of the season.

Table 21 Calibration of parameters which control rainfall–runoff harvesting

Parameter	Adopted value	Comment
Fallow area interception loss	4	Estimated and in conjunction with the other parameters produces the expected runoff response (Appendix F)
Rainfall–runoff return efficiency for developed areas	90%	Estimated and in conjunction with the other parameters produces the expected runoff response (Appendix F)
Rainfall–runoff return efficiency for undeveloped areas	20%	Estimated and in conjunction with the other parameters produces the expected runoff response (Appendix F)

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 volume of water above this threshold that leaves the river then flows along a conceptual floodplain flow path, and can then be harvested by one or more properties that are hydraulically connected to that storage as it flows past them, as illustrated in Figure 19.

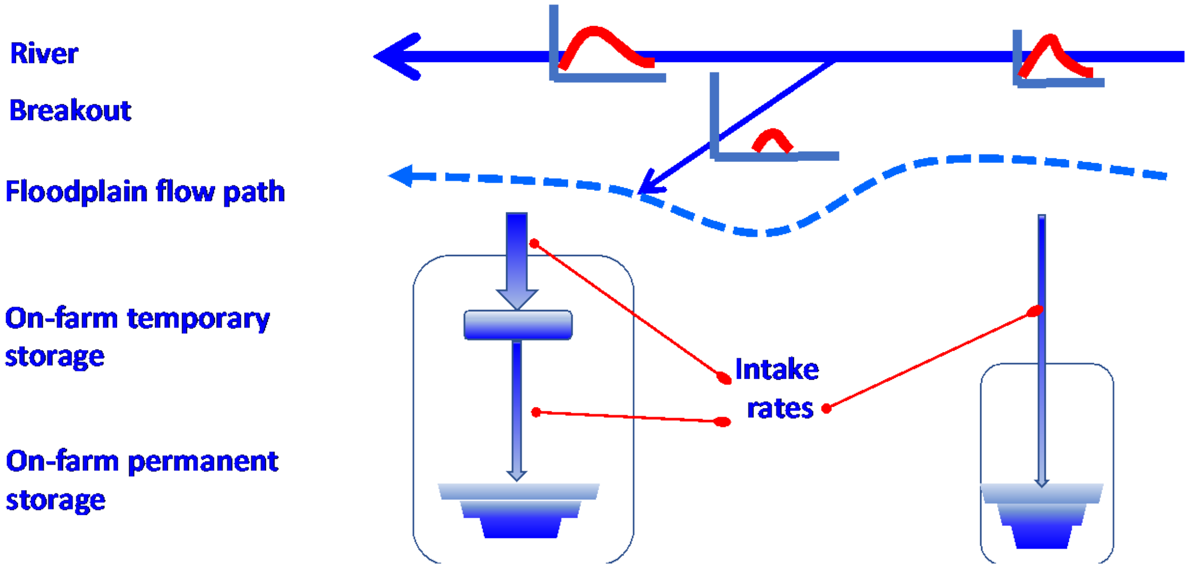

Figure 19 Relationship between breakouts, floodplain storages and overbank flow harvesting

Table 22 Setting of parameters which affect modelling of irrigator overbank harvesting

Parameter	Adopted value	Rationale
Days over which harvesting occurs	Variable	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 since most storages were able to be filled during overbank flow events without additional access to floodplain storage. Period of access is defined to be the period of time above the overbank threshold for the flood runner a given property is situated on. Could be an underestimate as floodplain storage is not represented.
Length of time water is able to be held in temporary storages	14 days	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, 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 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 23.

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 23 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. 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 24.

Table 24 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 Riverbank Program, which operated between 2005 and 2011, the NSW Government has purchased water licences with approximately 25,800 shares, across the general and supplementary licence categories to use for environmental outcomes. The management of these water licences is undertaken by the department (Energy Environment and Science).

The department (Energy Environment and Science) also hold another 24,000 shares across the general and supplementary licence categories for environmental purposes.

Under the Murray-Darling Basin Plan, the Commonwealth Government has purchased water licences with approximately 134,500 shares across the general and supplementary licence categories 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 HEW entitlements linked to the NSW WLS. Total holdings presently are 184,387 unit shares which comprise:

- 174,643 unit shares of general security licences
- 9,744 unit shares of supplementary licences.

This represents approximately 25% of the total entitlement in the regulated Macquarie River system.

6.3.2 Modelling approach

There were only a small number of water licences purchased for environmental purposes in 2008/09, and held environmental water is not represented in the validation scenario model described in this report. These licences continue to be modelled as if they remained with the original licence holders, i.e. modelled as a consumptive use. Representation of water use for environmental purposes will be addressed in separate reporting for other model scenarios where relevant.

6.4 Stock and domestic use

Landholders in the Macquarie River 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 Gunningbar Creek, Mara Creek, Gum Cowal, and the lower Macquarie River (see Section 7.5).

6.4.1 Data sources

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

Operational records of stock and domestic replenishment flows are maintained by WaterNSW. Flows diverted to the Bogan River (via Gunningbar Creek), Gum Cowal, and Mara Creek are measured at the offtake gauging stations at the Macquarie River and stored in WaterNSW Hydstra database.

No data is available on water use under Basic Landholder Rights. The Macquarie WSP estimates water requirements of holders of domestic and stock rights at 1.2 GL/year as at 1 July 2004.

6.4.2 Modelling approach

Stock and domestic replenishment flows are represented in the model, as a demand at the appropriate offtake. This is described as part of the overall operation of the effluent creek offtakes described in section 7.5.

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

7.1 Resource assessment

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 there is an improvement in water available, the department undertakes an available water determination (AWD), as set out in the Macquarie 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 Macquarie WSP.

7.1.1 Data sources

Announced AWDs 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 25 (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 25 Macquarie announced allocations (%) for general security licences

Year	General security
2004/05	9%
2005/06	44%
2006/07	0%
2007/08	10%
2008/09	10%
2009/10	0%
2010/11	100%
2011/12	49%
2012/13	64%
2013/14	6%
2014/15	2%
2015/16	7%
2016/17	100%
2017/18	38%
2018/19	0%
2019/20	0%

Source: NSW water register, as at 1 November 2020

7.1.2 Modelling approach

Resource assessments are simulated on a daily timestep in the model.

Additional unallocated water is assessed and credited to individual water accounts according to the volumes available via the water accounting parameters described in the next section.

7.2 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.

Water accounting rules are set out in the relevant Water Sharing Plan (WSP).

An **annual accounting system** is used in the Macquarie regulated river system to allocate the water available for diversion by the higher priority licence categories and transmission and operation losses.

- At the commencement of each water year[16], an assessment is made of the water available for allocation, taking into account any requirements for water set out in the Macquarie WSP, and requirements for transmission and operation losses.
- Water is then allocated to each category of licence in order of priority: local water utilities, domestic and stock, high security, and general security licences. Individual licences receive a share of the water in each category according to the proportion of the licence shares they have.
- The volume of water required to meet transmission and operation losses is dependent on the volume of water to be delivered. This means that water is allocated iteratively to licences and for the transmission and operation losses.

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.

Under the Macquarie WSP, a **carryover accounting system** operates for general security, with individual accounts for each licence receiving allocations into an AWD sub-account. At the end of each water year, general security licences are allowed to carryover up to 100% of their entitlement in a carryover sub-account from one water year to the next. The estimated increase in storage evaporation from carryover is subtracted from this sub-account each year, and any diversions are debited from the sub-account in priority to the AWD sub-account.

High security licences may not carryover water from one year to the next, but have a carryover sub-account that can only be credited with water traded from a general security licence.

To deliver water as efficiently as possible, general security 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.

7.2.1 Data sources

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

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[16] The water year runs from 1 July to 30 June.

occurred. Prior to 2004, an annual accounting database was used to record account balances, but only a limited set of data were maintained.

Information sources to inform the model include:

- Water Sharing Plan for the Macquarie Cudgegong Regulated Rivers Water Source 2020
- various resource assessment spreadsheets used by WaterNSW.

7.2.2 Modelling approach

Carryover accounting

The modelled carryover accounting system has been developed to represent operational practice as closely as possible.

Key parameters are summarised in Table 26.

Table 26 Key parameters for modelling of NSW carryover water accounting system

Component	Comment
Debiting type	Water orders for general security, water use for all other categories
Timestep	Daily
Assigned storages	Windamere Dam for licences in the Cudgegong regulated water source, and Burrendong Dam for the regulated Macquarie water source. Other weirs are not included in the resource assessment. However any increase in water use will be picked up in the apparent inflows as part of the monthly reconciliation
Transmission & Operational Loss	Transmission and operation losses set aside vary monthly, ranging from 17 GL to 110 GL (July–June) to commence general security allocations, up to 186 GL to 791 GL for full general security allocations
Carryover limit	General security licences – 1 ML/unit share (i.e. 100% of entitlement)
Storage reserve	Windamere – 90,000 ML Burrendong – 165,000 ML

7.3 Water trading

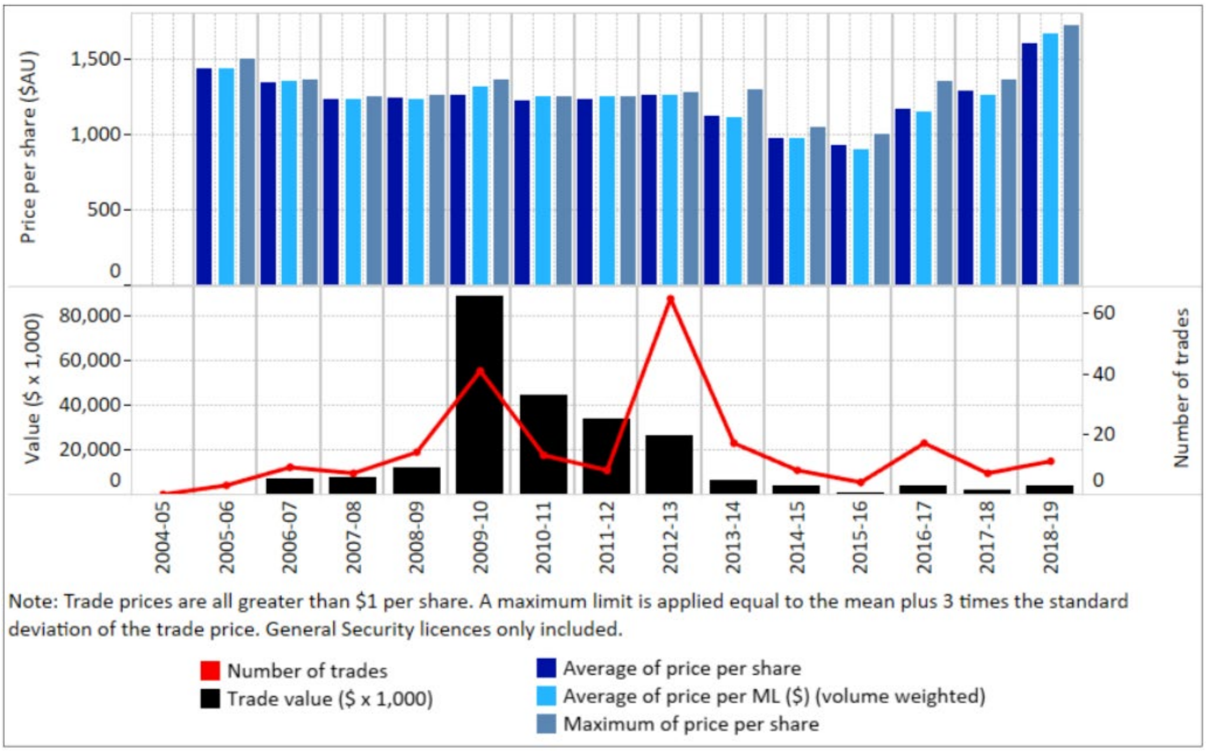
Trading of licence shares (known as permanent trade) and account water (known as temporary trade) has been permitted since the 1980s.

There is no direct hydrologic connectivity between the Macquarie and other regulated river systems, and there is no inter-valley or inter-state trade permitted.

7.3.1 Data sources

Records for all water trading are maintained by WaterNSW in the WAS database and, prior to 2004, in the predecessor departmental database.

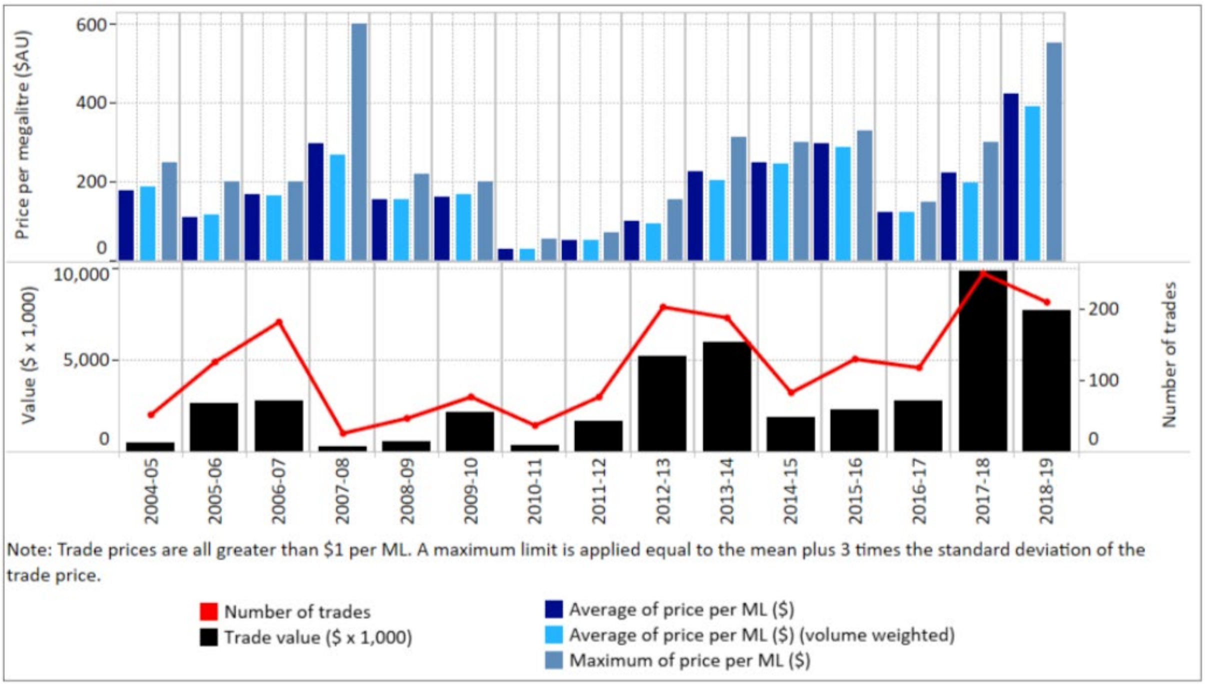
Figure 20 shows temporary trading within the regulated Macquarie River system. All entitlement categories (including supplementary) are included.



Note: Trade prices are all greater than $1 per share. A maximum limit is applied equal to the mean plus 3 times the standard deviation of the trade price. General Security licences only included.

Figure 20 Annual permanent trade of licence shares and prices from 2004/05 to 2018/19

Figure 21 shows temporary trading within the Macquarie Valley regulated river system. All licence categories (including supplementary) are included.



Note: Trade prices are all greater than $1 per ML. A maximum limit is applied equal to the mean plus 3 times the standard deviation of the trade price.

Figure 21 Annual temporary trade of allocations (volumes and prices) from 2004/05 to 2018/19

7.3.2 Modelling approach

Temporary water trading is not dynamically represented in the model due to software limitations. However, the entitlements configurations at irrigation nodes have been adjusted to incorporate the effect of permanent trade, and of temporary trade where this is observed consistently.

When assessing the results of the model (Section 8), significant water trading was considered. Permanent trades are considered in scenario development. While assessing the calibration of individual irrigation properties, the contribution of possible error in representation of temporary trade was taken into account.

7.4 Planned environmental water

Macquarie Valley Environmental Water Allowance (EWA)

The Macquarie WSP sets out an Environmental Water Allowance (EWA) which provides for up to 160,000 ML to be set aside for the environment. Water is allocated to the EWA on the same basis as allocations to general security licences, with three-fifths of the allocated water credited to a ‘translucent’ sub-allowance and two-fifths credited to an ’active’ sub-allowance.

- Releases must be made from the translucent subaccount from 15 March to 30 November each year when Burrendong storage and/or downstream tributary inflows exceed specified trigger levels.
- Releases may be made from the active sub-allowance for a wide range of purposes related to wetland or river health or for the direct benefit of water birds, fish or other fauna. An Environmental Flow Reference Group provides advice on releases of water from the active sub-allowance.

Figure 22 shows the usage of the Environmental Water Allowance in the Macquarie Valley. The releases of water from the EWA are made to the Macquarie Marshes.

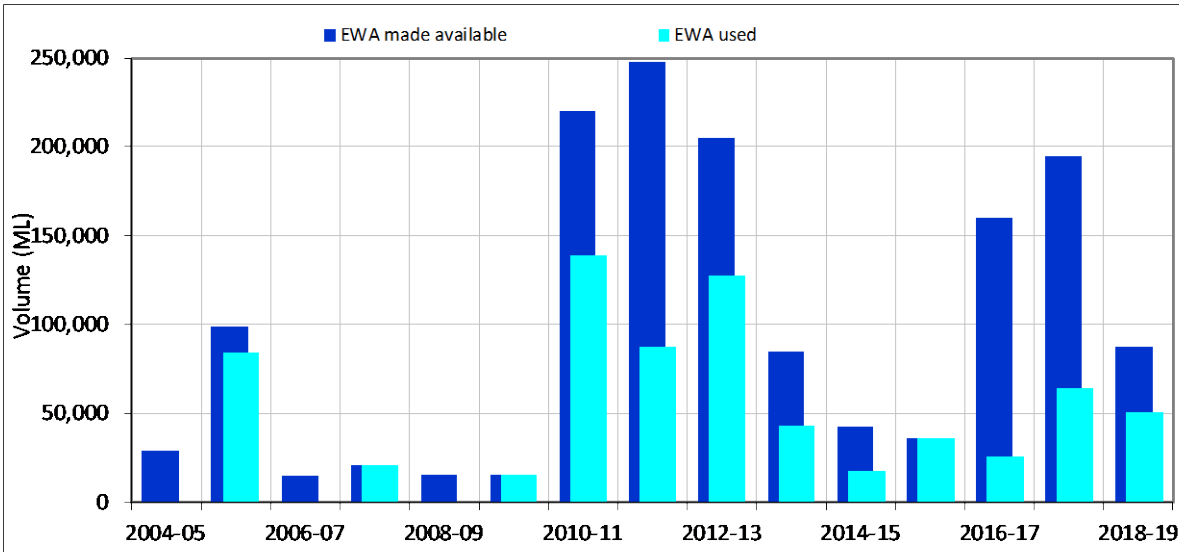


Figure 22 Annual Environmental Water Allowance availability and usage in the Macquarie Valley from 2004/05 to 2018/19

EWA active sub-allowance releases have been guided by an operating plan prepared by the department’s Environment Energy and Science division in conjunction with the Environmental Flow Reference Group. The operating plan has evolved over the years as experience has been gained through use of the active sub-allowance.

Different sets of EWA active sub-allowance release rules have been developed for the Macquarie Valley model in collaboration with environmental water managers from the department and its predecessors. An initial set of rules based on the original operating plan were developed as part of the modelling for the Macquarie WSP. In 2019, the rules in the Macquarie Valley model were revised to represent what is referred to as the Mark IV operating plan to support the Regional Water Strategy process.

Cudgegong planned environmental water releases

The Macquarie WSP sets out requirements to release water from Windamere Dam whenever the flows at Rocky Water Hole will exceed 150 ML/day for a two-day period. The rate of releases must not exceed the inflows to the storage or 1,500 ML/day, and may only be made:

- whenever Windamere storage exceeds 110,000 ML
- up to a limit of 10,000 ML each water year
- during any period specified by the relevant Minister.

These releases are protected from extraction from the Cudgegong River, but they are treated as normal tributary inflows to Burrendong Dam, and allocated according to the various rules in the Macquarie WSP.

7.4.1 Data sources

WaterNSW also prepares reports on compliance with the 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.

7.4.2 Modelling approach

The Macquarie Valley model represents delivery of water from the general security EWA to the Macquarie Marshes according to specified event-based triggering rules, and delivery is accounted as the flows delivered at Marebone Weir that are in excess of ordered water for other licences. How the model represents the trigger rules is provided in Table 27.

Table 27 Key environmental water provisions and how they are implemented

Environmental water provision	Description
Planned environmental water translucency (96,000ML)	• These releases are made without exceeding the storage inflow or 4,000 ML/day upstream of Marebone Weir when: o tributary inflows downstream of Burrendong plus Burrendong inflow are capable of providing 500 ML for 5 days or more upstream of Marebone Weir o Burrendong water level is below its flood mitigation zone o tributary inflows downstream of Burrendong are less than 1,000 ML/day
Planned environmental water active (64,000ML)	• Order between 300 and 3,000ML of water depending on the account balance and time of year to enhance bird and fish breeding.

7.5 Storage and weir operation

Releases from the major dams and access to water for licensed water users and other statutory purposes are managed by WaterNSW. Central to the operation of a regulated river system is a daily process to set a release rate from each major storage to meet downstream water requirements. River operators optimise the release of water to the river so that they can meet downstream demands for water without any unnecessary flows passing out the end of the regulated system (referred to as operational surplus).

The travel time flows to reach the lower end of the regulated river can take up to two weeks, and river operators must take many factors into account when setting daily releases, including water orders, other flow requirements, and short-term forecasts of weather and inflows. Required releases from storages are particularly sensitive to operational forecasts of inflows from downstream tributary streams.

The Cudgegong and Macquarie rivers are treated as a combined regulated system. However separate reserves are set aside in each of the dams to ensure that full available water determinations (100% of share components) for domestic and stock access licences, local water utilities and high security licences can be maintained through a repeat of the worst period of low inflows into each water source, based on historical flow information held by the department. For the Cudgegong river system, a 10-year drought sequence is used.

High volume transfers (known as bulk water transfers) of water from Windamere Dam to Burrendong Dam are made from time to time to pass on the minimum volume of water that is additional to the high priority Cudgegong requirements, at a timing to ensure that Burrendong storage can meet anticipated supply requirements in the coming water year.

Burrendong Dam can hold an additional 489,000 ML of storage for short periods through use of the large gates that control releases from the spillway. This storage capacity is known as the flood mitigation zone, and the Macquarie WSP sets out maximum release rates that can be made to release water from this zone. Cudgegong Dam does not have a gated spillway.

The small downstream weirs along the Macquarie River are primarily managed to provide the capability to meet targeted offtake requirements. The weirs are also managed to capture unregulated tributary inflows when possible, subject to maintaining the weir pool within a target operating range to ensure offtake requirements can be met. Unregulated tributary inflows are allowed to pass through the weir when through flows exceed the upper limit of the weir pool height.

7.5.1 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, including bulk water transfers. 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 each weir, the gate openings, upstream and downstream water levels are continuously logged. Storage levels are also stored in WaterNSW’s Hydstra database.

7.5.2 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 Windamere Dam or Burrendong Dam to meet orders, reflecting operator practice. This part of the model is 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 recession factor. Adopted values are summarised in Table 28. For headwater inflows, the forecast rate is generally 1, which means inflows are assumed to be 100% of yesterday's flow when determining how much regulated water should be released. Confluences with a forecast inflow of zero are not shown in Table 28.

Table 28 Adopted tributary recession factors to forecast rates of inflow from unregulated tributaries

Tributary	Tributary trend forecast rate
Bell River	1
Little River	1
Buckinbah Creek	1
Talbragar River	1
Coolbaggie Creek	0.05
Ewenmar Creek	0

Weirs and regulators operation

Marebone Weir is represented as a controlling structure with a single fixed relationship between river flow and outflow into Marebone Break. The effluent relationship represented in the model was derived using operational flow records. The relatively small volume of re-regulatory capacity was not significant compared to river flows and has been ignored.

Warren Weir is represented as a 1 GL storage in the model with a 400 ML/day valve capacity that allows the weir to empty within a day when it is below 400 ML of volume. The spillway relationship assumes that flow is not restricted by the weir when it is overtopped.

8 Model assessment

8.1 Overview

This section reports the results of:

- the calibration of the component models, e.g. how well the modelled flow matched observed flows
- the fully assembled Macquarie Valley model.

For flow calibration, it is important to replicate several 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 known differences in irrigation behaviour, potential inaccuracy of metered diversions and historically ineligible harvesting).

Appendix J details the version of the Macquarie Valley model 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, we 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 metrics 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 both 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 versus observed results as one or more of an exceedance graph, a time series at daily or longer time steps, 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 29.

Table 29 Overview of flow and water use simulation 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 30)
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 historical irrigation areas are reproduced	Observed vs modelled & measure of model bias (%) Sensitivity testing to variations in simulated crop water demand
Planted areas	How well historical irrigated areas are simulated	Annual total crop area compared to 2010–2018 remote sensing data
Metered diversions	How well general security and supplementary access metered diversions are simulated	Total, general security & supplementary access diversions over the full 2004/05 to 2017/18 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 Macquarie Valley model, the diversions and water management components have been assessed over the period 2004/05 to 2017/18, which is a period that also includes key benchmark years for the NSW Floodplain Harvesting 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 development17. We refer to this as the **2008/09 Validation 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 have been some changes in irrigation infrastructure development over the period 2004 to 2018. However, in the Macquarie Valley, there was very little change in irrigation development levels between 2008/09 and 2017/18. Whilst there was some irrigation infrastructure development between 2004/05 and 2008/09, mainly for floodplain harvesting activities, only small volumes of floodplain harvesting are 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[18].

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, in particular overall volumes, distribution across the full flow range from low to high, daily variability, and interannual variability. The methods to calibrate the models are intended to reproduce those characteristics.

The department has 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 30. A subset of results from the workflow reporting is described below for the Macquarie River at Dubbo and summarised in Appendix I for all flow calibrations.

These multiple lines of evidence are presented as a report card for each gauge (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 for a key location at Dubbo that demonstrates how well daily variability relevant to overbank flows has been reproduced is presented in Section 8.3.1.

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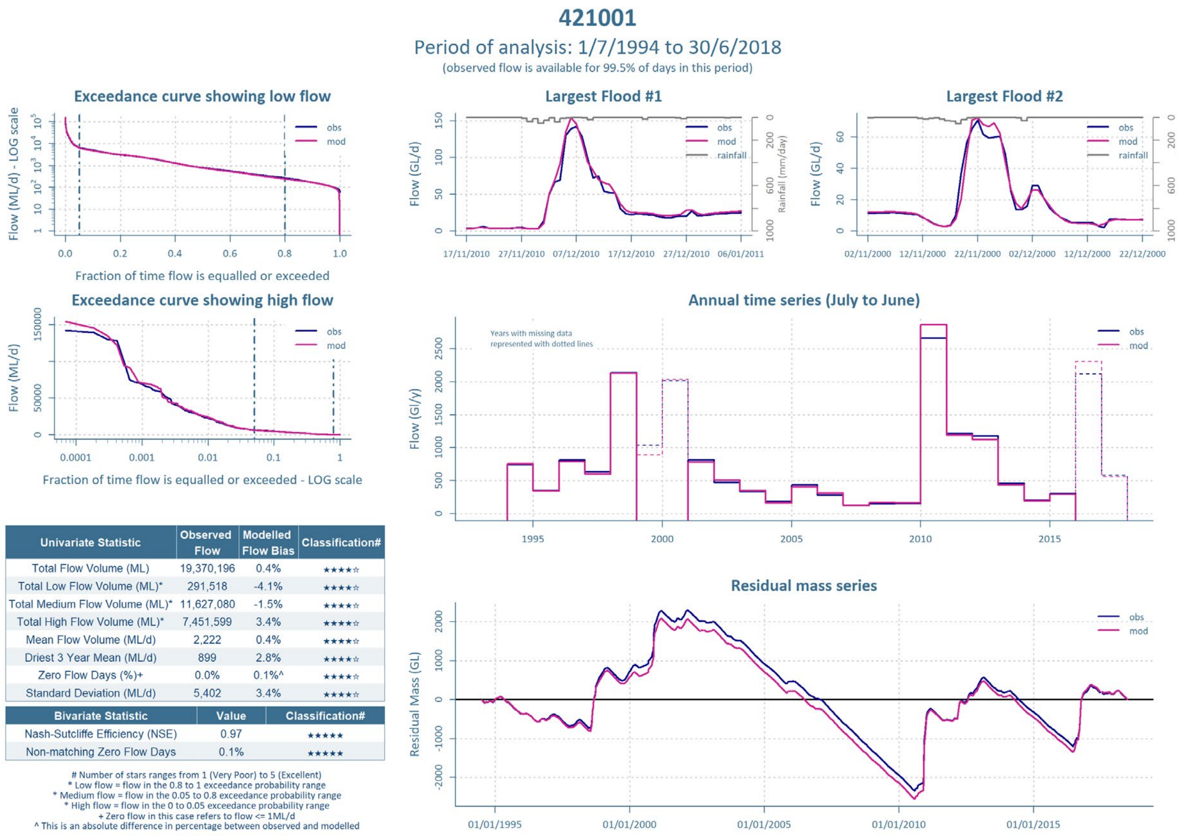
[17] This scenario is configured with all eligible storages, which includes one storage built post 2008.

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



Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	19,370,196	0.4%	★★★★☆
Total Low Flow Volume (ML)*	291,518	-4.1%	★★★★☆
Total Medium Flow Volume (ML)*	11,627,080	-1.5%	★★★★☆
Total High Flow Volume (ML)*	7,451,599	3.4%	★★★★☆
Mean Flow Volume (ML/d)	2,222	0.4%	★★★★☆
Driest 3 Year Mean (ML/d)	899	2.8%	★★★★☆
Zero Flow Days (%)+	0.0%	0.1%^	★★★★☆
Standard Deviation (ML/d)	5,402	3.4%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.97	★★★★★
Non-matching Zero Flow Days	0.1%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.05 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.05 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

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

Table 30 Flow metrics used to assess flow calibration

Metric	Importance
Tabular	
Station Number	Identifier and location
Mean annual flow	Relative importance to total flow. For comparative purpose, values in Appendix I are over the full simulated period and not the observed data period. Other comparisons are modelled versus observed
Runoff % of rainfall	Confidence in water balance if spatially coherent and within published ranges for rainfall versus 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 in high flow range (threshold defined in flow exceedance graphs)

Metric	Importance
Graphical	
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

There are 18 headwater catchments where Sacramento rainfall-runoff models have been calibrated. The flows simulated by these models are used to extend the observed flow records at the gauging stations for these catchments to allow the Macquarie Valley model to run over the full period of climate records. They are also used to fill any gaps in the observed flow records. These models were re-calibrated during 2018 and 2019 to take advantage of new automated calibration techniques and additional periods of flow and climate records since the models were previously calibrated.

These results refer to Appendix I with reference to the flow metrics listed in Table 30.

Mean annual flows for the 18 modelled headwater catchments range from 3 GL/year to 126 GL/year, and collectively account for 817 GL/year of inflow, with runoff coefficients in the range 2.6% to 34.0%. 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 range from 0.5 to 0.77, with the exception of four catchments (421053, 421055, 421058 and 421059) which have a result of 0.34 to 0.46. 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. Except for low flows, the distribution of flows in these 4 catchments is well represented. In the case of the gauges mentioned above, the inter-annual variability closely matches the gauged flow data with the exception of gauge 421053.

Flow biases across the full flow range are in most cases 0.0%, with 3 exceptions, the largest being −1.2% of observed. This close match is because flow bias has a high weighting in the automated calibration process. The distribution across the flow ranges has considerably more variation, with in most cases overestimates of 10% to 29% for the low flow range. The discrepancies are much less for the medium flow range (mostly less than ± 8%) 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 as this represents flows less than 5 ML/day to 10 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 low flows. 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

To validate the calibration of the simulated river flows in the model, a **Flow Validation Scenario** was created with each irrigator (water user node) in the model forced to divert the metered diversions, and flows from each dam forced to match the observed releases.

As with the headwater catchments, the modelling of flows along the Macquarie River down to Narromine was re-calibrated during 2018 and 2019 to take advantage of new automated calibration techniques and additional periods of flow and climate records since the model was previously calibrated. This includes some sections above Burrendong Dam and the regulated reaches of the Cudgegong River. Below Narromine, the pre-existing flow calibration continues to be used, with the river transmission losses subdivided into within-channel losses and the new flow breakouts described in Appendix D.

These results for the recently recalibrated sections to Narromine refer to Table 49and Figure 57 to Figure 65 in Appendix I with reference to the flow metrics described in Table 30.

The results for the remaining 3 flow gauging stations along the Macquarie River below Narromine to Marebone Weir are from a comparison of the observed flows with the fully simulating 2008/09 Validation Scenario. This means that the model is also simulating planted crop areas, diversions, and releases from the major storages. As can be expected, the flows for these sites are not as closely replicated, although the results are still reasonable, including for the high flow range.

Mean annual flows at these gauging locations vary in the range 27 GL/year to 1,409 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.

Daily Nash Sutcliffe values down to Narromine range from 0.8 to 1.0, with a mean value of 0.92. For the remaining sections the values range from 0.57 to 0.62, which are still reasonable for a fully simulating model. These high values are one line of evidence that provides us with confidence that mainstream flows are simulated well.

Overall **flow bias** ranges down to Narromine from 0% to +1% and reflect the bias in the low flow range at a limited number of gauges. For example, the positive (overestimated) low flow bias at Narromine can be attributed to a short period during the year with lowest mean rainfall. For the positive (overestimated) low flow bias at Burrendong Dam inflows, this can be attributed to limitations in, and much less confidence around, the low calculated inflows. Hence, the calibration did not focus on these low flows, and instead much more importance was placed on the overall calibration, monthly inflow comparison and the ability of Burrendong to meet downstream recorded releases with modelled inflows. For the stations below Narromine, the overall flow bias is within ±3.7%, with high flow bias within −8.2%, which is considered reasonable for a fully simulating model, and most important for floodplain harvesting.

The **medium range flow** results indicate a good match between observed and modelled flows, with flow bias ranging from −3% to +3%. Below Narromine, low and moderate flow ranges are dominated by the model's replication of diversions and operational management of flows, and would not be expected to match well.

The graphical comparisons in Figure 57 to Figure 68 provide a summary of model performance. **Interannual variability** is closely reproduced in all cases. There is also a 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 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.

For the floodplain harvesting models developed in the Border Rivers and Gwydir valleys, 4 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. These tests are described in more detail in the reports that describe those model builds (DPIE Water 2020, 2021c). Those tests found that each independent method has its own sources of uncertainty in its representation of crop water use for specific periods and long-term averages. Overall, the testing of the approach taken to model irrigation crop demands for the Border Rivers and Gwydir valleys indicated that modelled results compared reasonably well to the other methods and provide confidence that our modelling of crop water use is a robust estimate. Consequently, we have adopted the same approach for the Macquarie Valley model, using climate data for the Macquarie Valley.

Runoff harvesting

Runoff from developed and undeveloped areas on irrigation properties 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 component model 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)
- 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 after rainfall in areas with high water holding capacity (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 long-term averages to the best available data sources available.

Simulated **rainfall–runoff rates** are summarised in Table 31. 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 31, 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 31 Rainfall–runoff rates for Narromine 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
Developed	7.2%
Fallow	5.8%
Undeveloped	3.3%

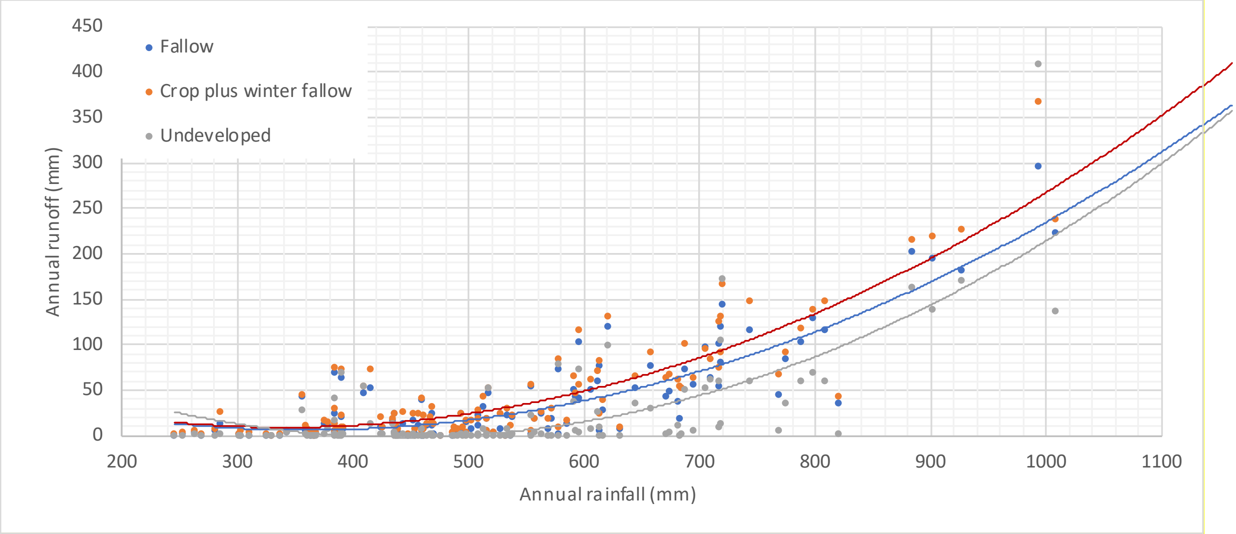


Figure 24 Annual runoff depth (mm) compared to annual rainfall (mm) for 3 on-farm land area types: fallow, developed (crop plus winter fallow), and undeveloped area

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 the true value.

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 to reproduce these is shown at Figure 25, with summary statistics reproduced at Table 32.

These show that the modelled **duration of overbank flow** closely matches the observed behaviour. The number of days above **minor flood threshold** since 1994 is close to observed (Table 32). Prior to this period the modelled data also matches observed reasonably well.

Volumes above the commence to breakout threshold reproduces inter-annual variability well, although it has a −19% bias overall. This bias is likely the result of the calibration period not coinciding with the observed data at Warren, and from variations in operational management of releases from Burrendong during high flow events. However, given the model is more sensitive to frequency and duration of overbank access for modelling overbank flow extractions, this bias was deemed to be acceptable.

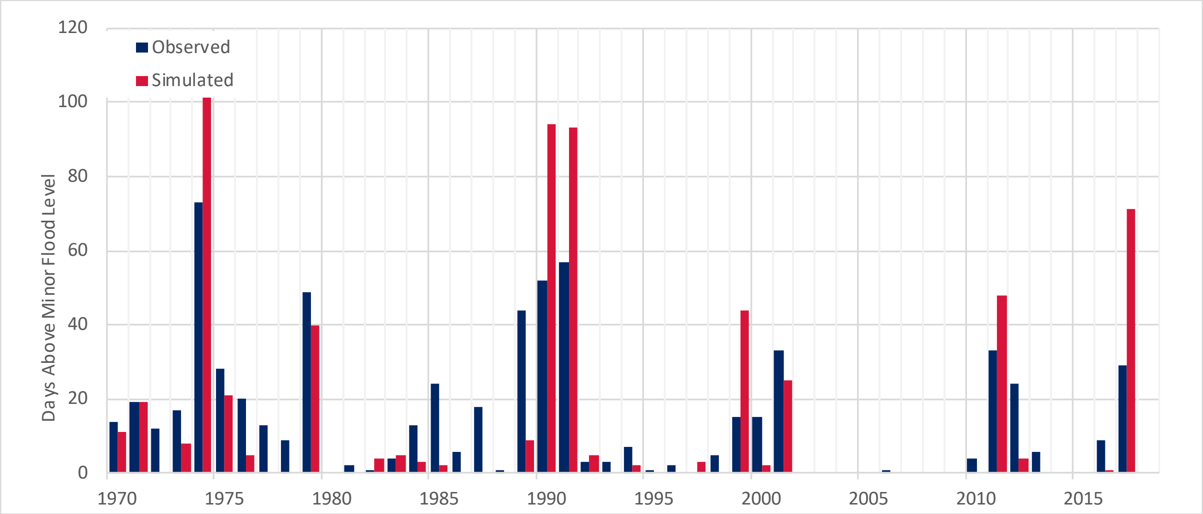


Figure 25 Annual modelled vs observed days above minor flood threshold @ Warren

Table 32 Total observed vs modelled days above minor flood threshold @ Warren

Periods	Observed (days)	Modelled (days)
Minor flood events (>9,700 ML/day)		
1970 to 1993	482	442
1994 to 2018	184	200

Apart from the data that were analysed to form the breakout relationships, there are no more data that can be used to validate the volume on the floodplain during an event[19]. We have investigated whether it will be possible to use remote sensing data to estimate change in on-farm storage volumes over an event. These 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[20]. Very high-resolution data are required to undertake this analysis and we found

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[19] 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.

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

insufficient historical data to undertake this assessment immediately prior and post a floodplain harvesting event.

Irrigation 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.

The model was checked to ensure that there was not extensive crop water stress from insufficient on-farm water availability. These checks were done at 3 scales:

- whole-of-valley
- reach
- property.

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 33 shows that valley total results are close to the observed data, with no overall bias in estimating diversions.

Further detail on metered diversion components is discussed in Section 8.3.3.

Table 33 Total metered diversions (GL) (1/7/2004 to 30/6/2018)

Sub-region	Simulated (GL)	Observed (GL)	Model bias (%)
upstream Narromine	169	252	+49%
Narromine to Gin Gin	1,079	1,072	+1%
Gin Gin to Warren	512	582	-12%
Warren to Marebone	363	424	-14%
Marebone to end of system	285	313	-9%
Total	2,484	2,559	-3%

Reach scale results should be reasonable to indicate that the distribution between reaches is consistent. Table 33 shows that the bias is only significant in the section of the model upstream of Narromine and that the total bias is small especially when considering the downstream of Narromine sections where floodplain harvesting occurs.

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:

- 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 were assessed for large anomalies, and if so whether there was a reasonable explanation. Other supporting information was also assessed using, for example, comparison to IBQ farm surveys, nearby properties, and remote sensing.

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 historical harvesting.

8.3.2 Planted areas

The Macquarie Valley 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 calibration model using 2008/09 conditions were compared to the observed data over the 2011 to 2018 period. There was very little reliable farm survey data for crop areas, and only one year of overlap with remote sensing data, so only remote sensing was used for comparison with modelled results. The remote sensed crop area data was not available in 2011/12 and 2012/13 due to cloud cover.

The modelled **planted areas for individual properties** are in reasonable agreement with those in the remote sensing data (Figure 26), with the exception of simulated crop areas for 2010/11 and 2016/17, which were considerably larger than observed. Both of these were drought-breaking years, and modelled water availability at the model’s planting date were higher than observed. The observed planting behaviour was also more conservative than that indicated in the farm surveys (and adopted in the model).

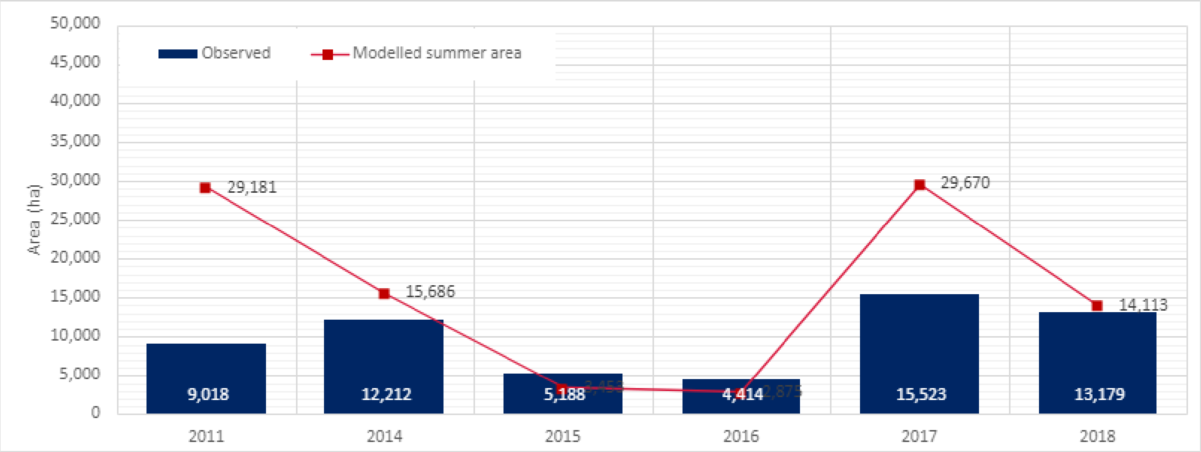

Figure 26 Observed (remote sensed) and modelled total summer crop areas for floodplain harvesting properties

8.3.3 Metered diversions

Results of simulated diversions from the fully assembled, calibrated model for the 2008/09 Validation Scenario 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 2004/05 to 2017/18 comparison period are illustrated in Figure 27 with summary results reported in Table 34.

Table 34 Total simulated and observed metered diversions from 2004/05 to 2017/18

Diversion type	Observed (GL)	Simulated (GL	Bias (%)
General security	2,437	2,323	-5%
Supplementary access	122	160	31%
Total	2,559	2,484	-3%

The model under-simulates **total diversions** from the river by 3% which is around 75 GL over the assessment period. The model slightly over-simulates **general security diversions** and more significantly over-simulates the much smaller **supplementary access diversions.**

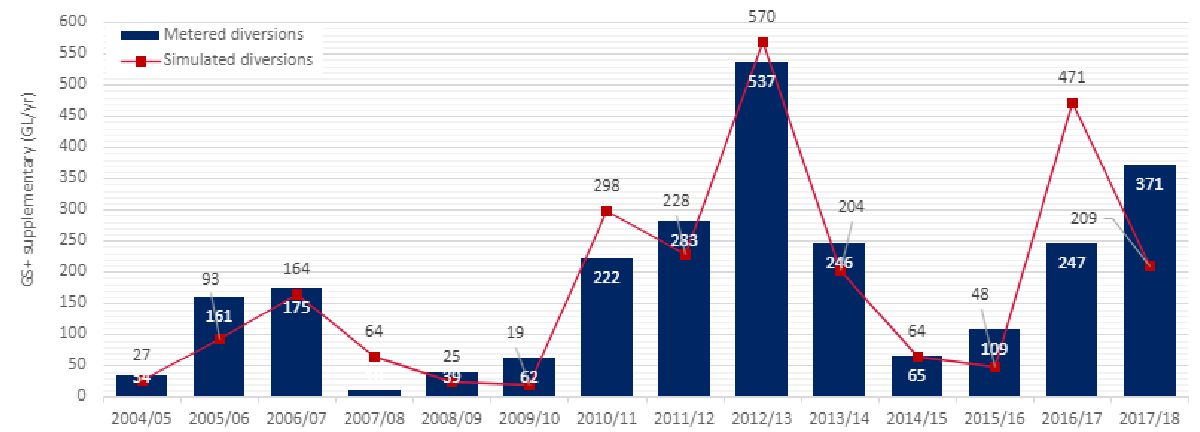

Figure 27 Annual simulated and observed (metered) diversions from 2004/05 to 2017/2018

General security diversions

We have examined how well the model performs during the first five years and the last nine years of this period, and the results of this are reported in Table 35. The model under-estimates general security diversions in the early period and a lower positive bias in the later period. The first five year period was dominated by the millennium drought, including the suspension of normal water access in 2007.

The later 9 years includes a much larger range of wet and dry climate. As noted in Section 8.3.2, the larger planted areas in 2010/11 and 2016/17 have resulted in higher diversions, although this tends to create a reverse effect in the following years. Overall, this result is considered acceptable given the year to year variability in irrigation behaviour shown in Figure 27.

Table 35 Split period simulated versus observed total diversion (GL) comparison

Type / period	Observed (GL)	Simulated (GL)	Bias (%)
General security			
01/07/2004–30/06/2009	405	337	-17%
01/07/2008–30/06/2018	2071	2011	-3%
Supplementary access			
01/07/2004–30/06/2009	14	36	160%

01/07/2008–30/06/2018	108	124	15%

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 31%, with a high bias for the earlier period during the millennium drought, indicating the difficulties simulating the very small volumes of supplementary water access during that time. This section examines more closely the annual supplementary access diversions in the model compared with those observed.

The **total** modelled compared with observed supplementary access diversions were over-estimated as reported in Table 34. The **annual** modelled compared to observed are shown in Figure 28. These results show that **inter-annual variability** is reproduced reasonably well with the over-estimation noted above during the millennium drought and during 2011/12.

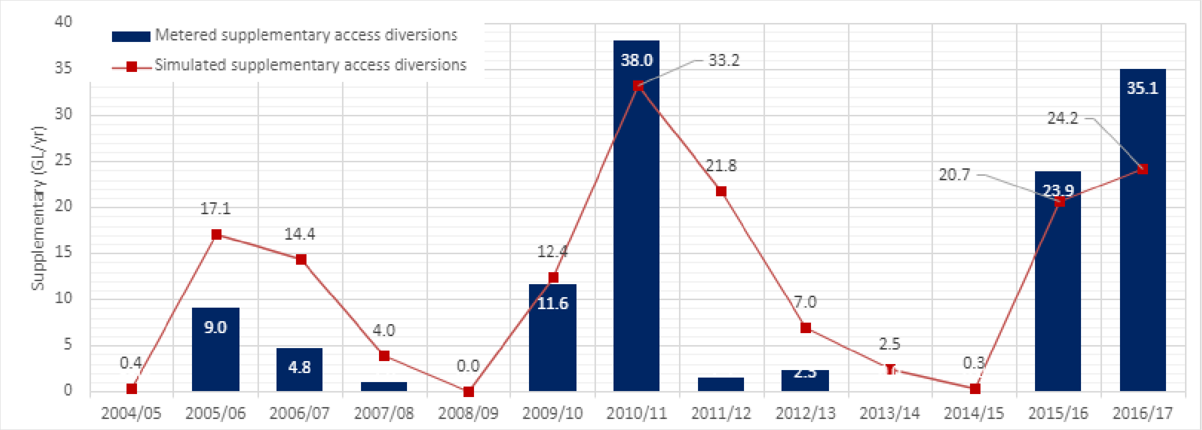

Figure 28 Annual simulated and observed (metered) supplementary access diversions from 2004/05 to 2016/17

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 Macquarie Valley model is compared to the observed storage volumes in Figure 29. There are some differences to observed data, however, this are considered within acceptable limits.

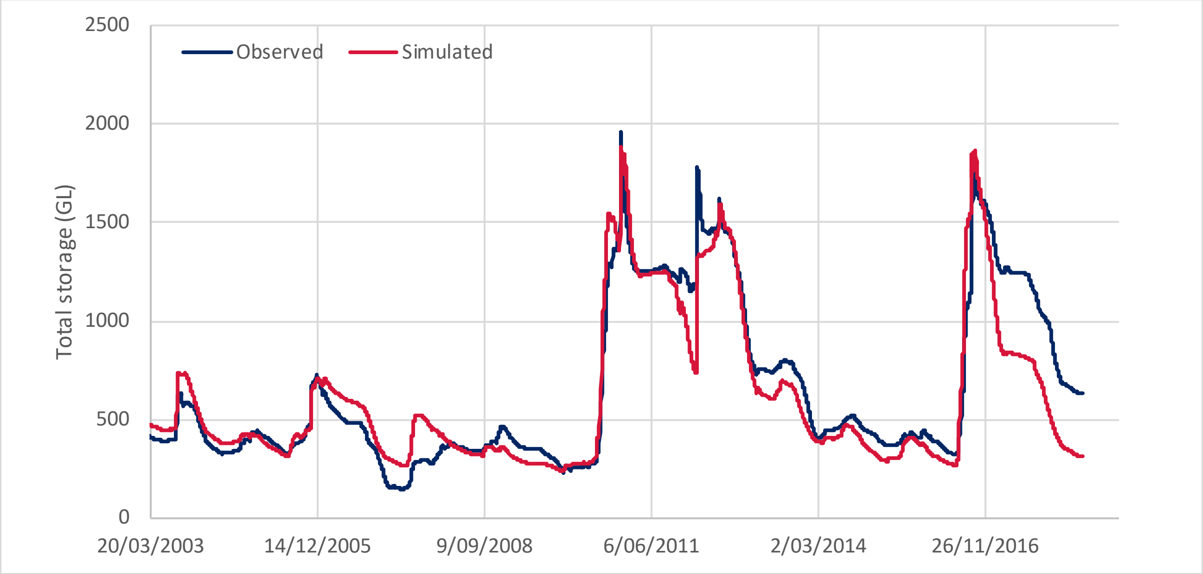

Figure 29 Time series of observed versus simulated total storage volume at Burrendong and Windamere dams from 2003/04 to 2016/17

There can be multiple causes for variations in headwater storage volumes, including variations in modelled 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 higher simulated drawdown of total storage in 2016/17 is consistent with the over-simulation of planted areas in that year, however, no systematic issues are evident.

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 Macquarie 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 2021a). 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 30) 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, which dominate water use in the Macquarie Valley regulated river system, followed by much smaller volumes of rainfall–runoff harvesting, then overbank flow harvesting, then supplementary access. **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 much reduced scale.

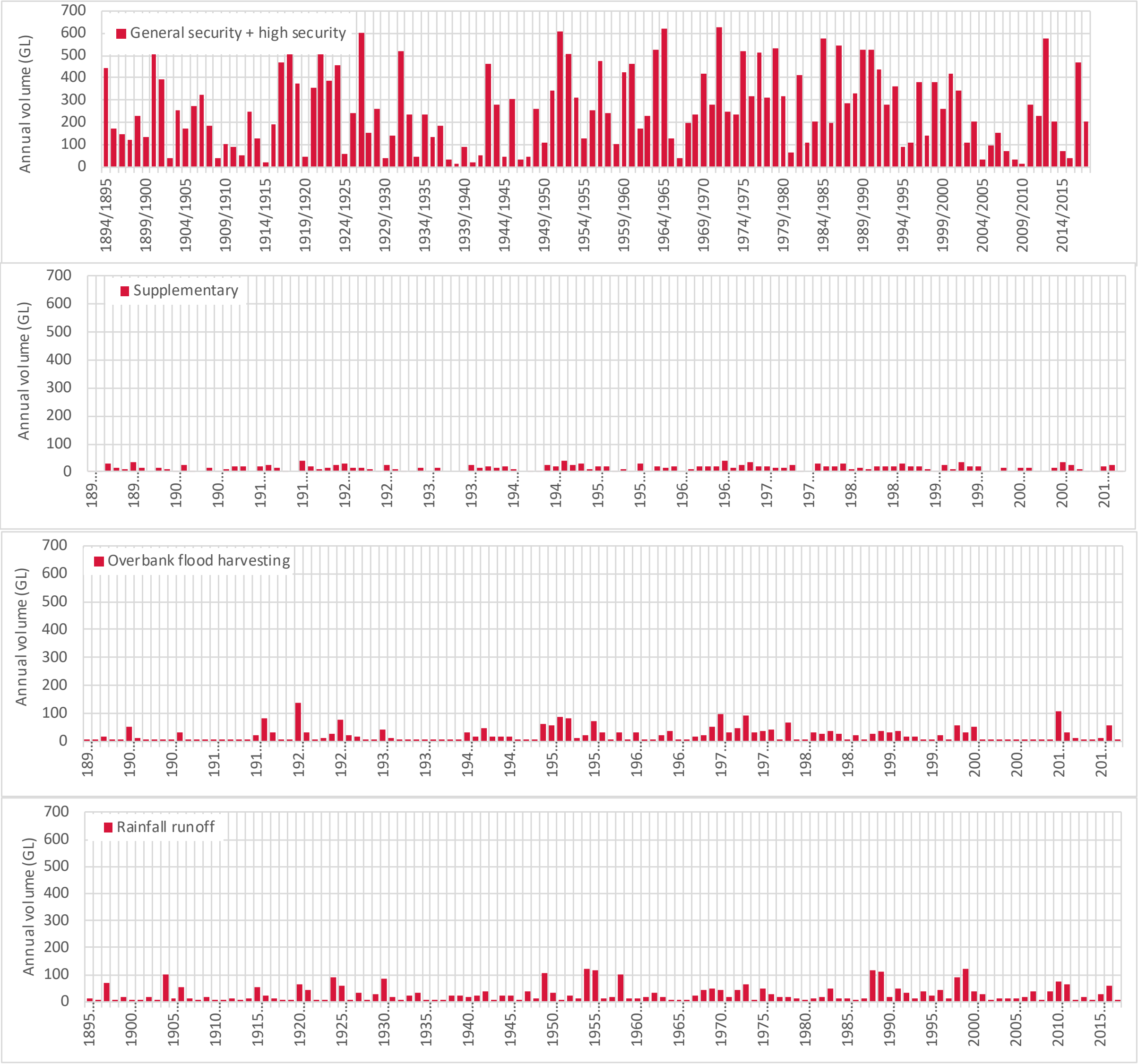

Figure 30 Simulated annual volumes of high and general security, supplementary access, floodplain and rainfall harvesting flow diversions from 1895 to 2009

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 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:

- 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 37 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 36 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	

Table 37 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.	Low
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

Source of uncertainty	Comment	Significance rating
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 IBQ farm surveys, 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
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

Source of uncertainty	Comment	Significance rating
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. 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. The sensitivity may be higher when considered in conjunction with other issues. 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 (1 m 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	Low

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. 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, these data are 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[21]. 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. 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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[21] The FMP models are described in technical appendices for each valley. https://www.industry.nsw.gov.au/water/plans-programs/healthy-floodplains-project/plans

For the first floodplain harvesting models developed in the Border Rivers and Gwydir valleys, the 6 sensitivity tests referred to throughout Table 37 were done (DPIE Water 2020, 2021c). These test have not been undertaken for the Macquarie model, because the sensitivity of models to certain parameters and changes is expected to be consistent between model builds of other river systems in northern NSW.

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 38. The appropriateness of the adopted methodology in addressing each criteria relies on the conclusions made in Table 38.

Table 38 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
Existing water access licences	Department database data as at 2008 has been used in determining individual shares

Capability assessment criteria	Confidence in modelled approach
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 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 Macquarie Valley model is the primary tool that will be used for the NSW Government to provide the technical information about the Macquarie 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 Macquarie Valley 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 (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.

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 access 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.

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 01/01/1889 to 30/06/2018 and includes this period.

The calibration period varies depending on the component. The flow calibration uses the period of flow record. Most of the calibration for diversions and on-farm harvesting is more recent, with floodplain harvesting based on a 10-year period with wet and dry periods, the adequacy of which was discussed in section 8.2.

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.

Criteria 3: spatial resolution sufficient for multi-scale analysis

The spatial detail in the Macquarie Valley 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.

Criteria 4: temporal resolution sufficient for multi-scale analysis

The standard time step for calculation in the IQQM 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.

Criteria 5: supports replication of historical usage

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 4%. Some potential reasons for the over-estimation 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.

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.

Criteria 6: pathway for upgrades

Water resource models in the department have been and will continue to be used as ongoing tools to inform water management in NSW. The existing IQQM model has been periodically updated for over two decades, and it is intended to update the Macquarie Valley model from IQQM to the Source modelling platform. 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 valuable 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 Macquarie Valley 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 floodplain harvesting monitoring policy. The additional data can be used within the existing model framework to better parameterise components of the farm models. Into the future, the Source software platform has sufficient onboard capability to customise components where needed.

In addition to the available data, another significant limitation of the Macquarie Valley 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.

10.3 Conclusion

The updated Macquarie Valley 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 to 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 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.

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 the recommendations section.

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 39 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 39 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: 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
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	Including stock and domestic entitlements and usage within the model (where significant)
7	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

These priorities recognise that there is already work underway to improve aspects of the Macquarie Valley model in other programs such as the Regional Water Strategies. This work includes improving the representation of environmental water use, and the development of enhanced climate datasets to better understand climate variability and climate change.

11 References

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*

Natural Resources Access Regulator Act 2017. https://legislation.nsw.gov.au/#/view/act/2017/64

Macquarie Valley specific

Water Sharing Plan for the Macquarie and Cudgegong River Regulated Rivers Water Source 2016. Last updated 2018. https://www.legislation.nsw.gov.au/view/html/inforce/current/sl-2015-0630. Referred to in this report as the Macquarie WSP.

Water Sharing Plan for the Macquarie Bogan Unregulated and Alluvial Water Sources 2012. https://www.legislation.nsw.gov.au/view/html/inforce/current/sl-2012-0490

Reports and journal articles

Allen RG, Pereira LS, Raes D, Martin M (1998) Crop evapotranspiration – Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. Food and Agriculture Organization of the United Nations, Rome. ISBN 92-5-104219-5. http://www.fao.org/docrep/X0490E/X0490E00.htm

Alluvium (2019) Independent review of NSW Floodplain Harvesting policy implementation. A report for the NSW Department of Planning, Industry and Environment Water, Sydney. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0004/272146/Final-floodplain-harvesting-independent-review.pdf

Alluvium (2020) Border Rivers Model Build Report – Independent Reviewer Comments. A memo for the NSW Department of Planning, Industry and Environment Water, Sydney.

Barma Water Resources (2019) Assessment of the additional cropped area rainfall–runoff occurring due to irrigation, Final Report October 2019, unpublished report prepared for the NSW Department of Planning, Industry and Environment.

Beven KJ, Binley AM (1992) The future of distributed models: Model calibration and uncertainty prediction, Hydrol. Processes 6, 279–298.

Connolly RD, Kennedy IR, Silburn DM, Simpson BW, Freebairn DM (2001) Simulating endosulfan transport in runoff from cotton fields in Australia using the GLEAMS model. Journal of Environmental Quality 30, 702–713.

DECC (2008) Macquarie River (Narromine to Oxley Station) Floodplain Management Plan. NSW Department of Environment and Climate Change. Macquarie River FMP - Main report (nsw.gov.au)

DECCW (2009) Macquarie River Valley: IQQM Cap Implementation Summary Report (Issue 2). NSW Department of Environment Climate Change and Water.

DECCW (2010) IQQM Wetland modelling for the Macquarie Valley. NSW Department of Environment, Climate Change and Water. Unpublished.

DLWC (2000) Regional crop factors derived in consultation with Department of Agriculture for the purposes of area based license conversion, unpublished data. NSW Department of Land and Water Conservation

DPIE Water (2020) Building the river system model for the NSW Border Rivers Valley regulated river system: report. NSW Department of Planning, Industry and Environment

DPIE Water (2021a) Floodplain Harvesting entitlements for the Macquarie Valley regulated river system: model scenarios. NSW Department of Planning, Industry and Environment

DPIE Water (2021b) Environmental outcomes of implementing the Floodplain Harvesting Policy in the Macquarie Valley. NSW Department of Planning, Industry and Environment.

DPIE Water (2021c) Building the river system model for the Gwydir Valley regulated river system: Conceptualisation, construction and calibration. NSW Department of Planning, Industry and Environment.

eWater Ltd (2016) Source Scientific Reference Guide (v4.1) [Online]. https://wiki.ewater.org.au/display/SD41

Freebairn DM, Wockner GH, Hamilton NA, Rowland P (2009) Impact of soil conditions on hydrology and water quality for a brown clay in the north-eastern cereal zone of Australia. Australian Journal of Soil Research 47, 389–402.

FSA Consulting and Aquatech Consulting (2011) Estimating Land Surface Diversions: Stage 2, Final Report (August 2011), Murray Darling Basin Authority, Canberra. https://www.researchgate.net/publication/277004542_Assessment_of_Land_Surface_Diversions_from_water_balance_and_remote_sensing_data

Haghnazari F (2015) Factors affecting the infiltration of agricultural soils: review, International Journal of Agronomy and Agricultural Research (IJAAR) 6 (5), 21–35.

Kavetski D, Kuczera G, Franks SW (2006) Bayesian analysis of input uncertainty in hydrological modeling: 1. Theory, Water Resources Research 42, W03407. https://doi.org/10.1029/2005WR004368

Kisters Pty Ltd (2010) Hydstra. http://kisters.com.au/hydstra.html

Larsen D, Weir D (2012) Managing soils for irrigation. In: Wiggington, David (2012b) 188–195.

McInerney D, Thyer M, Kavetski D, Bennett B, Lerat J, Gibbs M et al (2018) A simplified approach to produce probabilistic hydrological model predictions. Environmental Modelling & Software 109, 306–314. DOI: 10.1016/j.envsoft.2018.07.001

MDBA (2017–2019) Hydrologic modelling practice notes. https://www.mdba.gov.au/publications/mdba-reports/hydrologic-modelling-practice-notes

MDBA (2018) Irrigation demands on the Murray and Lower Darling rivers. Murray Darling Basin Authority. https://www.mdba.gov.au/sites/default/files/pubs/crop-water-model-murray-lower-darling-2018.pdf

Morrison Tim, Chu Cat-Tuong (2018) Storage Bathymetry Model Update and Application (Gwydir Valley), report prepared by Hydrospatial Pty Ltd for Department of Industry. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0010/271936/Storage-bathymetry-model-update-and-application-gwydir.pdf

Neumann L, Brown A, Zhang L, Zheng H, Davidson A, Egan C, Korn A (2017) Assessing residual inflow and loss estimates methods in river reach calibration using the Budyko Framework. In Syme G, Hatton MacDonald D, Fulton B, Piantadosi J (eds) MODSIM2017 International Congress. MSSANZ. 1649–1655.

NOW (2016a) Irrigator Behaviour Questionnaire, Irrigator survey as part of application for floodplain harvesting entitlement. NSW Office of Water

NOW (2016b) Source Transition Modelling Guidelines and Quality Assurance Processes. Unpublished.

NSW Agriculture (2003) Border Rivers (NSW) Catchment Irrigation Profile. https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0010/164368/irrigation-profile-border-rivers.pdf2

NSW Department of Industry (2019) Modelling and data collection for implementing floodplain harvesting, PUB18/640. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0003/179931/Floodplain-harvesting-water-modelling-overview.PDF

NSW DPIE (2019) Fact sheet: Estimating rainfall run-off and harvesting in the NSW Murray–Darling Basin, INT19/141340. NSW Department of Planning, Industry and Environment. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0008/272726/Estimating-rainfall-run-off-and-harvesting-in-the-NSW-Murray-Darling-Basin-Fact-Sheet.pdf

NSW DPIE (2020) Guideline for the implementation of the NSW Floodplain Harvesting Policy. March 2020. NSW Department of Planning, Industry and Environment. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0007/272338/floodplain-harvesting-implementation-guidelines.pdf

Prasad A (2010) Use of modern technologies in estimating unaccounted water uses in the Murray-Darling Basin, Australia. In: Hydrocomplexity: New Tools for Solving Wicked Water Problems. Kovacs Colloquium, July 2010 (IAHS Publ. 338, 2010). https://iahs.info/uploads/dms/15035.11-43-45-Prasad1.pdf

Silburn M, Montgomery J, McGarry D, Gunawardena T, Foley J, Ringrose-Voase A, Nadelko T (2012) Deep drainage under irrigated cotton in Australia: a review. In: Wiggington, David (ed) (2012b) 40–58.

Simons M, Podger G, Cooke R (1996) IQQM—A hydrologic modelling tool for water resource and salinity management, Environmental Software Volume 11, Issues 1–3, 1996, Pages 185-192. https://www.sciencedirect.com/science/article/pii/S0266983896000196

Tennakoon S, Richards D, Milroy S, Harris G (2012) Water use efficiency in the Australian cotton industry, In: Wiggington, David (ed) (201b). 22–27.

Vleeshouwer J, Car NJ, Hornbuckle J (2015) A Cotton Irrigator's Decision Support System and Benchmarking Tool Using National, Regional and Local Data. In: Denzer R, Argent RM, Schimak G, Hřebíček J. (eds) Environmental Software Systems. Infrastructures, Services and Applications. ISESS 2015. IFIP Advances in Information and Communication Technology, vol 448. Springer, Cham.

Wigginton D (2012a) Measuring to improve water storage efficiency, in Australian Cotton Research Institute & Cotton Catchment Communities Cooperative Research Centre (Australia) 2012, The Australian cotton water story : a decade of research & development 2002–2012, Cotton Catchment Communities CRC Limited : Australian Cotton Research Institute, Narrabri, NSW. http://www.crdc.com.au/publications/australian-cotton-water-story

Wigginton David (ed) (2012b) WATERpak — a guide for irrigation management in cotton and grain systems. Cotton Research and Development Corporation. Third edition. December 2012. http://www.cottoninfo.com.au/sites/default/files/documents/WATERpak.pdf

Appendix A Quality assurance

A.1 Quality assurance practices

The department has 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[22] 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 Floodplain Harvesting 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[23].

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

[23] 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 2021a).
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 Macquarie valley, 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 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 2021a).

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 40 Rainfall stations used in headwater inflow calibration, their station numbers, location (latitude/longitude) and mean annual rainfall

Station #	Station name	Lat (°S)	Long (°E)	Mean annual rainfall* (mm)
048143	Coolabah Post Office	31.03	146.71	406
050008	Peak Hill (Bruie Plains)	32.78	147.86	522
050011	Tottenham (Burdenda)	32.13	147.41	469
050031	Peak Hill Post Office	32.72	148.19	561
050034	Nevertire (Beverley)	32.02	147.43	460
050037	Tullamore (Old Post Office)	32.63	147.57	493
050108	Wilmatha (Wanganui)	32.57	147.22	496
051004	Trangie (Old Bundemar)	31.81	148.16	484
051005	Narromine (Mumble Peg)	32.06	148.24	533
051018	Gilgandra (Chelmsford Ave)	31.71	148.66	558
051031	Nyngan (Canonbar)	31.64	147.32	458
051034	Warren (Mumblebone)	31.50	147.69	441
051037	Narromine (Alagalah St)	32.24	148.24	527
051038	Nevertire (Clyde St)	31.84	147.72	460
051039	Nyngan Airport	31.55	147.20	446
051049	Trangie Research Station Aws	31.99	147.95	493
051054	Warren (Frawley St)	31.70	147.83	490
051057	Marra Creek (Womboin)	30.70	147.22	397
051066	Eumungerie Post Office	31.95	148.62	562
051072	Quambone (Carwell)	31.02	147.90	440
051115	Narromine Airport	32.22	148.23	605
062003	Mumbil (Burrendong Dam)	32.67	149.10	666
062012	Cudgegong (Kiora)	32.73	149.75	662
062013	Gulgong Post Office	32.36	149.53	648
062014	Hargraves (General Store)	32.80	149.47	630
062018	Katella	32.70	149.20	602
062020	Bylong (Montoro)	32.50	150.03	663
062021	Mudgee (George Street)	32.60	149.60	668
062023	Olinda (Springdale)	32.85	150.13	648
062026	Rylstone (Ilford Rd)	32.81	149.98	763

Station #	Station name	Lat (ºS)	Long (ºE)	Mean annual rainfall* (mm)
062027	Shepherds Creek	33.00	149.10	667
062028	Goolma (Brooklyn)	32.49	149.27	651
062029	Ilford (Tara)	32.98	149.81	727
062030	Wallaroi	32.80	149.03	662
062031	Ilford (Warrangunyah)	32.95	149.77	665
062033	Hargraves (Weeroona)	32.87	149.37	807
062035	Leadville (Moreton Bay)	32.08	149.61	635
062057	Coolah (Coolah Creek)	31.74	149.90	776
062075	Galambine (Gooree Park)	32.48	149.52	651
062084	Budgee Budgee (Botobolar Vineyard)	32.50	149.71	674
062099	Stuart Town (Canobla)	32.84	149.00	678
063004	Bathurst Gaol	33.42	149.55	622
063005	Bathurst Agricultural Station	33.43	149.56	635
063010	Blayney Post Office	33.54	149.26	766
063011	Borenore Store	33.25	148.98	811
063012	Running Stream (Brooklyn)	33.03	149.88	843
063033	Gurnang State Forest (Oberon (Young Adul	34.01	149.84	1009
063035	Hill End Post Office	33.04	149.41	783
063036	Oberon (Jenolan Caves)	33.82	150.02	966
063037	Oberon (Jenolan State Forest)	33.75	150.04	1158
063053	Millthorpe (Inala)	33.45	149.18	806
063058	Mullion Creek (Mullion Range Forest)	33.09	149.13	964
063063	Oberon (Springbank)	33.67	149.83	834
063064	O'Connell (Stratford)	33.53	149.73	638
063066	Orange (Mclaughlin St)	33.27	149.11	872
063071	Portland (Jamieson St)	33.35	149.99	701
063073	Rockley Post Office	33.69	149.56	697
063076	Sofala Old Post Office	33.08	149.69	632
063079	Sunny Corner (Snow Line)	33.39	149.90	932
063083	Trunkey Creek (Trunkey (Black Stump Hole	33.82	149.32	850
063085	Paling Yards (Ulabri)	33.18	149.74	756
063086	Blayney (Vittoria)	33.45	149.33	776
063087	Black Springs Forestry	33.85	149.74	903
063089	Wattle Flat General Store	33.14	149.69	759

Station #	Station name	Lat (ºS)	Long (ºE)	Mean annual rainfall* (mm)
063090	Wellwood	33.32	149.15	884
063136	Yetholme (Kurrawong)	33.43	149.85	969
063146	Cheetham Flats (Jundas)	33.55	150.05	840
063233	Rockley (Clevelands)	33.65	149.64	749
063236	The Lagoon (Springfield)	33.55	149.60	709
063254	Orange Agricultural Institute	33.32	149.08	910
063293	Oberon (Jenolan Caves Road)	33.74	149.88	729
064009	Dunedoo Post Office	32.02	149.40	609
064010	Elong Elong (Bendeela St)	32.11	149.04	610
064015	Mendooran Post Office	31.82	149.12	587
064025	Coolah (Binnia St)	31.82	149.72	654
064026	Cobbora (Kundiawa)	32.04	149.24	589
065000	Arthurville (Cramond)	32.50	148.75	579
065003	Bodangora Post Office	32.45	149.00	554
065005	Bumberry	33.20	148.50	644
065010	Cudal Post Office	33.29	148.74	531
065011	Cumnock (Willow Park)	32.94	148.75	649
065012	Dubbo (Darling Street)	32.24	148.61	588
065018	Geurie Post Office	32.40	148.83	568
065020	Manildra (George St)	33.18	148.69	593
065022	Manildra (Hazeldale)	33.16	148.59	520
065023	Molong (Hill St)	33.09	148.86	705
065025	Obley	32.70	148.50	574
065030	Dubbo (Mentone)	32.52	148.52	638
065032	Wandoo Wandong	32.70	148.40	602
065034	Wellington (Agrowplow)	32.56	148.95	613
065035	Wellington Research Centre	32.51	148.97	620
065036	Yeoval Post Office	32.75	148.65	582
065037	Dubbo State Forest	32.27	148.62	606

* Mean annual rainfalls are from the BOM website and are for the available period of record for each station.

Table 41 Evapotranspiration stations used in headwater inflow calibration, their station numbers, location (lat/long), mean potential evapotranspiration (PET) and mean lake evaporation (MLake)

Station #	Station name	Lat (°S)	Lon (°E)	Mean PET (Mwet) (mm/y)	Mean lake evap (MLake) (mm/y)
050011	Tottenham (Burdenda)	32.13	147.41	1464	1542
050031	Peak Hill Post Office	32.72	148.19	1472	1496
050034	Nevertire (Beverley)	32.02	147.43	1466	1551
051031	Nyngan (Canonbar)	31.64	147.32	1486	1579
051034	Warren (Mumblebone)	31.50	147.69	1480	1575
051037	Narromine (Alagalah St)	32.24	148.24	1473	1507
051038	Nevertire (Clyde St)	31.84	147.72	1472	1552
051039	Nyngan Airport	31.55	147.20	1474	1573
051049	Trangie Research Station Aws	31.99	147.95	1474	1534
051054	Warren (Frawley St)	31.70	147.83	1462	1556
051072	Quambone (Carwell)	31.02	147.90	1501	1602
062003	Mumbil (Burrendong Dam)	32.67	149.10	1397	1421
062012	Cudgegong (Kiora)	32.73	149.75	1310	1332
062013	Gulgong Post Office	32.36	149.53	1388	1411
062014	Hargraves (General Store)	32.80	149.47	1293	1316
062018	Katella	32.70	149.20	1367	1391
062021	Mudgee (George Street)	32.60	149.60	1356	1379
062026	Rylstone (Ilford Rd)	32.81	149.98	1300	1322
062028	Goolma (Brooklyn)	32.49	149.27	1388	1411
062029	Ilford (Tara)	32.98	149.81	1249	1271
062075	Galambine (Gooree Park)	32.48	149.52	1374	1397
063004	Bathurst Gaol	33.42	149.55	1273	1295
063005	Bathurst Agricultural Station	33.43	149.56	1262	1283
063010	Blayney Post Office	33.54	149.26	1236	1257
063012	Running Stream (Brooklyn)	33.03	149.88	1248	1270
063033	Gurnang State Forest (Oberon (Young Adul	34.01	149.84	1150	1168
063035	Hill End Post Office	33.04	149.41	1296	1319
063058	Mullion Creek (Mullion Range Forest)	33.09	149.13	1276	1299
063063	Oberon (Springbank)	33.67	149.83	1182	1202
063064	O'Connell (Stratford)	33.53	149.73	1241	1262
063087	Black Springs Forestry	33.85	149.74	1169	1188

Station #	Station name	Lat (°S)	Lon (°E)	Mean PET (Mwet) (mm/y)	Mean lake evap (MLake) (mm/y)
063089	Wattle Flat General Store	33.14	149.69	1245	1267
063236	The Lagoon (Springfield)	33.55	149.60	1253	1275
063254	Orange Agricultural Institute	33.32	149.08	1261	1283
064010	Elong Elong (Bendeela St)	32.11	149.04	1442	1467
064025	Coolah (Binnia St)	31.82	149.72	1373	1397
065000	Arthurville (Cramond)	32.50	148.75	1438	1462
065011	Cumnock (Willow Park)	32.94	148.75	1368	1392
065012	Dubbo (Darling Street)	32.24	148.61	1461	1486
065018	Geurie Post Office	32.40	148.83	1431	1455
065023	Molong (Hill St)	33.09	148.86	1342	1365
065030	Dubbo (Mentone)	32.52	148.52	1443	1467
065032	Wandoo Wandong	32.70	148.40	1422	1446
065034	Wellington (Agrowplow)	32.56	148.95	1422	1446
065035	Wellington Research Centre	32.51	148.97	1422	1446
065037	Dubbo State Forest	32.27	148.62	1462	1486

Appendix C Streamflow gauges

Table 42 Inflow headwater gauges used in Border Rivers Valley model, their station number and name, catchment area (CA), start and end dates of gauge, highest recorded and highest gauged flows

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m^3/s)	Highest gauged flow (m^3/s)
421018	Bell River at Newrea	1620	29/07/1939	-	1214	1238
421026	Turon River at Sofala	883	1/09/1949	-	1839	941
421034	Slippery Creek at Dam Site	15	27/11/1954	10/04/2002	20.2	3.3
421036	Duckmaloi River at Below Dam Site	112	26/10/1954	20/02/1981	90.0	4.6
421041	Crudine Creek U/S Turon River Junction	231	9/12/1963	26/06/1980	271	25.7
421042	Talbragar River at Elong Elong	3050	10/11/1964	-	755	164
421048	Little River at Obley No.2	612	9/07/1965	-	788	110
421052	Lewis Ponds Creek at Ophir	621	17/07/1965	9/03/1978	537	70.4
421053	Queen Charlottes Creek at Georges Plains	217	22/07/1965	19/01/1983	157	16.1
421055	Coolbaggie Creek at Rawsonville	626	10/12/1965	-	248	194
421058	Wyaldra Creek at Gulgong	855	24/08/1966	31/12/1982	-	27.3
421059	Buckinbah Creek at Yeoval	709	6/09/1966	-	14.9	7.2
421062	Marthaguy Creek at Quambone	3140	16/09/1966	1/01/1983	-	30.4
421066	Green Valley Creek at Hill End	119	19/08/1966	1/02/2002	311	131
421067	Pyramul Creek at Hill End	198	19/08/1966	5/06/1975	-	8.8
421072	Winburndale Rivulet at Howards Bridge	720	5/02/1968	31/10/1978	829	613
421073	Meroo Creek at Yarrabin No.2	1620	12/03/1968	31/12/1982	-	77.3
421075	Evans Plains Creek at Near Bathurst	170	24/05/1968	30/06/1982	-	2.3

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m^3/s)	Highest gauged flow (m^3/s)
421076	Bogan River at Peak Hill No.2	980.8	23/08/1967	-	342	75.4
421100	Pyramul Creek at U/S Hill End Road	193	14/02/1975	1/10/1986	227	104
421101	Campbells River at U/S Ben Chifley Dam	950	18/08/1978	31/01/2004	782	65.6

Table 43 Stream gauges used for reach calibration in Macquarie Valley model, their station number and name, catchment area (CA), start and end dates of gauge, and highest recorded and highest gauged flows

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m^3/s)	Highest gauged flow (m^3/s)
421001	Macquarie River at Dubbo	19,600	01/06/1885	-	2,343	3,424
421002	Macquarie River at Burrendong (Campbell S Dam)	13,880	01/01/1891	29/05/1961	-	4,494
421004	Macquarie River at Warren Weir	26,570	01/01/1898	-	232	228
421005	Gunningbar Creek at Below Regulator	-	01/12/1899	-	62.2	51.8
421006	Macquarie River at Narromine	25,950	1/06/1901	1/07/1982	7,077	2,552
421011	Marthaguy Creek at Carinda	6,475	16/04/1926	-	311	181
421012	Macquarie River at Carinda (Bells Bridge)	30,100	15/04/1926	-	134	134
421015	Duck Creek at Offtake	-	1/03/1936	-	28.3	10.6
421016	Crooked Creek at Profile	-	1/03/1936	-	14.0	10.6
421017	Gunningbar Creek at D/S Weir	-	1/03/1936	-	46.7	41.6
421019	Cudgegong River at Yamble Bridge	3,490	2/08/1939	-	2,277	1,481
421020	Nyngan Channel at Offtake	-	22/04/1942	27/10/2011	2.5	1.4

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m^3/s)	Highest gauged flow (m^3/s)
421022	Macquarie River at Oxley Station	3,565	1/01/1941	-	48.6	39.4
421023	Bogan River at Gongolgon	27,970	2/11/1945	-	1,329	815
421025	Macquarie River at Bruinbun	4,425	5/09/1947	2/04/2014	2,696	776
421031	Macquarie River at Gin Gin	26,936	29/07/1954	-	1,122	1,029
421035	Fish River at U/S Tarana Road Bridge	570	20/10/1954	1/01/1990	648	171
421039	Bogan River at Neurie Plains	14,760	21/05/1959	-	675	156
421040	Macquarie River at Downstream Burrendong Dam	13,980	9/03/1960	-	2,091	1,390
421045	Duck Creek at U/S Bogan River Junction	-	26/05/1965	1/04/1972	-	27.0
421057	Campbells River at Apsley	1,010	8/08/1966	30/09/1978	207	44.6
421078	Macquarie River at Burrendong Dam - Storage Gauge	13,880	1/06/1967	-	-	-
421079	Cudgegong River at D/S Windamere Dam	1,088	26/02/1970	-	297	157
421083	Bogan River at Dandaloo	5,440	1/12/1971	-	1,999	203
421088	Marebone Break at D/S Marebone Regulator	-	13/08/1975	-	35.8	34.2
421090	Macquarie River at D/S Marebone Weir	-	17/09/1976	-	50.5	41.7
421097	Marra Creek at Carinda Road	-	6/10/1975	-	83.7	38.4
421107	Marra Creek at Billybingbone Bridge	-	26/08/1980	-	79.1	77.8
421108	Northern Bypass Channel at Below Regulator	-	13/07/1971	20/07/2012	3.9	3.3
421109	Monkey Creek at Break	-	2/04/1979	14/04/2014	6.8	6.5

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m^3/s)	Highest gauged flow (m^3/s)
421111	Buckiinguy Creek at Break	-	1/01/1980	-	6.1	4.1
421116	Macquarie River at Gibson Way	-	7/09/1980	-	19.1	9.8
421118	Bulgeraga Creek at Gibson Way	-	1/01/1980	-	96.3	65.7
421127	Macquarie River at Baroona	25,700	17/05/1982	-	2,165	1,984
421129	Monkeygar Creek at U/S Western Arm Return	-	2/04/1979	-	20.2	16.8
421132	Monkeygar Creek at D/S Gibson Way	-	4/04/1979	-	15.1	7.0
421135	Macquarie River at Miltara	-	1/01/1982	-	121	113
421138	Bogan River at Nyngan	-	8/06/1993	-	150	1,126
421145	Bulgeraga Creek at Bifurcation	-	6/07/1979	-	10.7	5.9
421146	Gum Cowal at Bifurcation	-	1/09/1987	-	20.6	6.9
421147	Macquarie River at Pillicawarrina	-	23/06/1987	-	93.7	63.4
421148	Cudgegong River at Windamere Dam-Storage Gauge	-	25/02/1986	-	-	-
421149	Cudgegong River at Rocky Water Hole	1,208	24/07/1985	-	232	18.6
421150	Cudgegong River at Wilbertree Road	2,021	17/05/1985	-	432	120
421152	Gum Cowal at Oxley	-	3/09/1987	-	27.6	17.4
421153	Terrigal Creek at U/S Marthaguy Creek	-	9/09/1987	-	35.0	21.7
421158	Bogan River at Monkey Bridge	-	10/06/1993	-	310	406
421164	Duck Creek at Napali	-	22/09/1994	-	51.9	2.5
421165	Beni Billa Creek at Downstream Canonba Road	-	23/09/1994	-	143	15.0

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m^3/s)	Highest gauged flow (m^3/s)
421166	Gunningbar Creek at Fairview Dam	-	22/09/1994	-	24.0	8.7
421169	Breakaway at Offtake	-	3/06/1994	13/02/2012	9.4	7.8
421188	Duckmaloi River at Weir Spillway	-	28/09/2009	-	29.2	4.2
421189	Fish River at Oberon Dam - Storage Gauge	-	28/09/2009	-	-	-
421191	Macquarie River at Yarracoona	-	31/05/2011	-	1,000	344

Appendix D Sources of flow breakout information

Multiple sources of information have been considered when defining within channel breakouts to creeks and also overland flow breakouts. However, detailed information from the MIKE model, which was developed for the (draft) *Floodplain Management Plan for the Macquarie Valley Floodplain 2018* have been the primary source of information used to configure breakouts. Peak overland flow rates were obtained for a flood event approximating the 2010 flood. These data were used to cross check the modelled floodplain breakouts in the Macquarie Valley model, and make adjustments where appropriate. More details on the MIKE model are provided in the (draft) *Floodplain Management Plan for the Macquarie Valley Floodplain 2018*).

Table 52 Macquarie Valley effluents and breakouts: their name, location (reach) and downstream gauge

Reach No.	Downstream gauge	Effluent name in model	ID in Figure 14	Comments
27	421031	Trangie	1	Hydraulic modelling & calibrated
		Crooked/Ewenmar	2	Hydraulic modelling & calibrated
		Weemabung	3	Hydraulic modelling & calibrated
28	421004	Birchells Plains	4	Hydraulic modelling & calibrated
		Elengerah	5	Hydraulic modelling & calibrated
		Beleringar	6	Hydraulic modelling & calibrated
		Gunningbar	7	Hydraulic modelling & calibrated
29	421090	Sandy Creek	8	Hydraulic modelling
		Marra Break	9	Hydraulic modelling & calibrated
		Bulgeraga	12	Hydraulic modelling & calibrated
30	421063	Crooked/Ewenmar – Marthaguy Split	10	Hydraulic modelling & calibrated
		Crooked/Ewenmar – Bellevue FW split	11	Hydraulic modelling
32	Weemabung Floodway	Weemabung – Crooked/Ewenmar Connection	16	Hydraulic modelling
32	Birchells Plains Floodway	Birchells – Weemabung Connection	15	Hydraulic modelling
		Birchells – Bellevue Connection	19	Hydraulic modelling
		Birchells – Macquarie Connection	18	Hydraulic modelling

Reach No.	Downstream gauge	Effluent name in model	ID in Figure 14	Comments
32	421062	Marthaguy – Birchells Connection	20	Hydraulic modelling
		Marthaguy – Long plain cowal split	14	Hydraulic modelling & calibrated
		Marthaguy – Long plain connection	25	Hydraulic modelling
32	421145	Bulgeraga to Macquarie Connection	21	Hydraulic modelling & calibrated
		Bulgeraga – Kiameron Split	13	Hydraulic modelling
		Bulgeraga to Long Plain Cowal Connection	24	Hydraulic modelling
32	Kiameron Floodway	Kiameron to Macquarie Connection	23	Hydraulic modelling
	Elengerah Floodway	Elengerah to Trangie Connection	17	Hydraulic modelling
	Macquarie Overbank Flow	Macquarie – Marra Connection	22	Hydraulic modelling

Appendix E Major storage characteristics

Table 44 Windamere storage curves (level, volume, surface area relationships)

Level (m)	Volume (ML)	Surface area (ha)
0	0	0
2.43	1,130	27
8.455	3,932	93
13.304	11,471	218
18.264	26,301	380
23.175	50,709	614
30.534	112,224	994
38.005	204,712	1,437
45.46	331,711	1,962
47.243	368,120	2,030

Table 45 Burrendong storage curves (level, volume, surface area relationships)

Level (m)	Volume (ML)	Surface area (ha)
0	0	0
0.9	496	49.4
2.5	1,416	84.2
7.5	10,225	264.2
13.5	33,730	589.2
19.8	91,842	1,407
28.8	285,889	2,939
37.9	641,992	4,881
45.4	1,083,523	6,776
53.1	1,679,721	8,876

Appendix F Irrigation farm runoff: data review

F.1 Background

The irrigator nodes in the IQQM 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 to 16% for average annual rainfall from 800 to 1100 mm/year.

Two gauged catchments[24] in the Macquarie 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 31. 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 24% of annual rainfall volume with a long term average of about 4%.

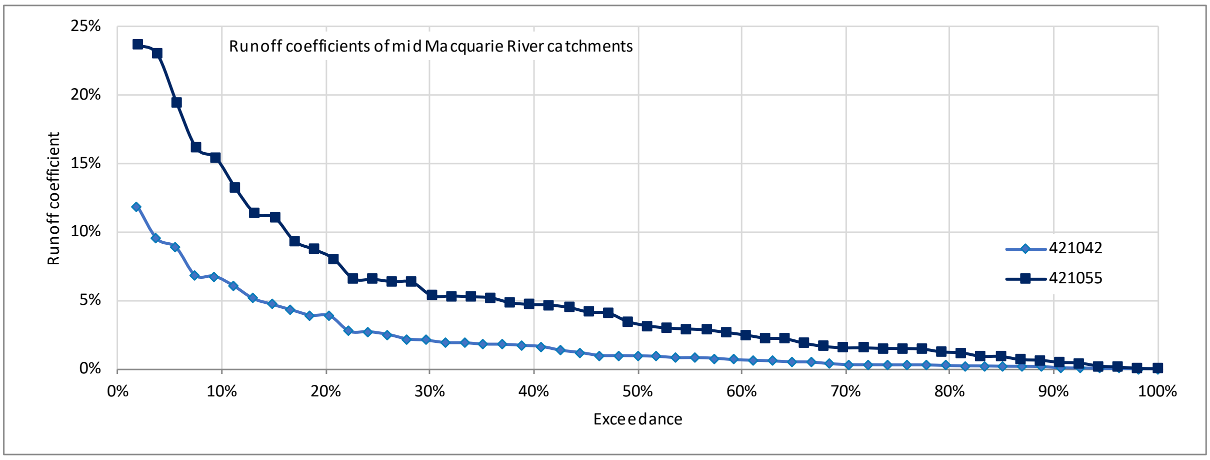

Figure 31 Comparison of annual runoff coefficients for two mid-system gauged inflows (gauges 421042 and 421055)

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 (MDBA 2017–2019) developed by modellers across the Murray-Darling Basin jurisdictions. Neumann et al. (2017) have demonstrated the approach using 213 catchments in

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[24] 421042 - Talbragar River at Elong Elong, and 421055 - Coolbaggie Creek at Rawsonville

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 are 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 (Alluvium 2019), we undertook 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 (e.g. 30 year simulation in Connolly et al. (2001). They measured 16 mm runoff for a dryland cotton site on black vertisols in Emerald, Queensland 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 were 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 Macquarie Valley model development

The parameters for the rainfall–runoff model in the Macquarie Valley model were calibrated to achieve the desired runoff rates for each rainfall station in the floodplain harvesting section of the model. The final fallow and undeveloped area runoff rates appear to be reasonable compared to the median values in the Budyko framework (Figure 32).

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 model has 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.

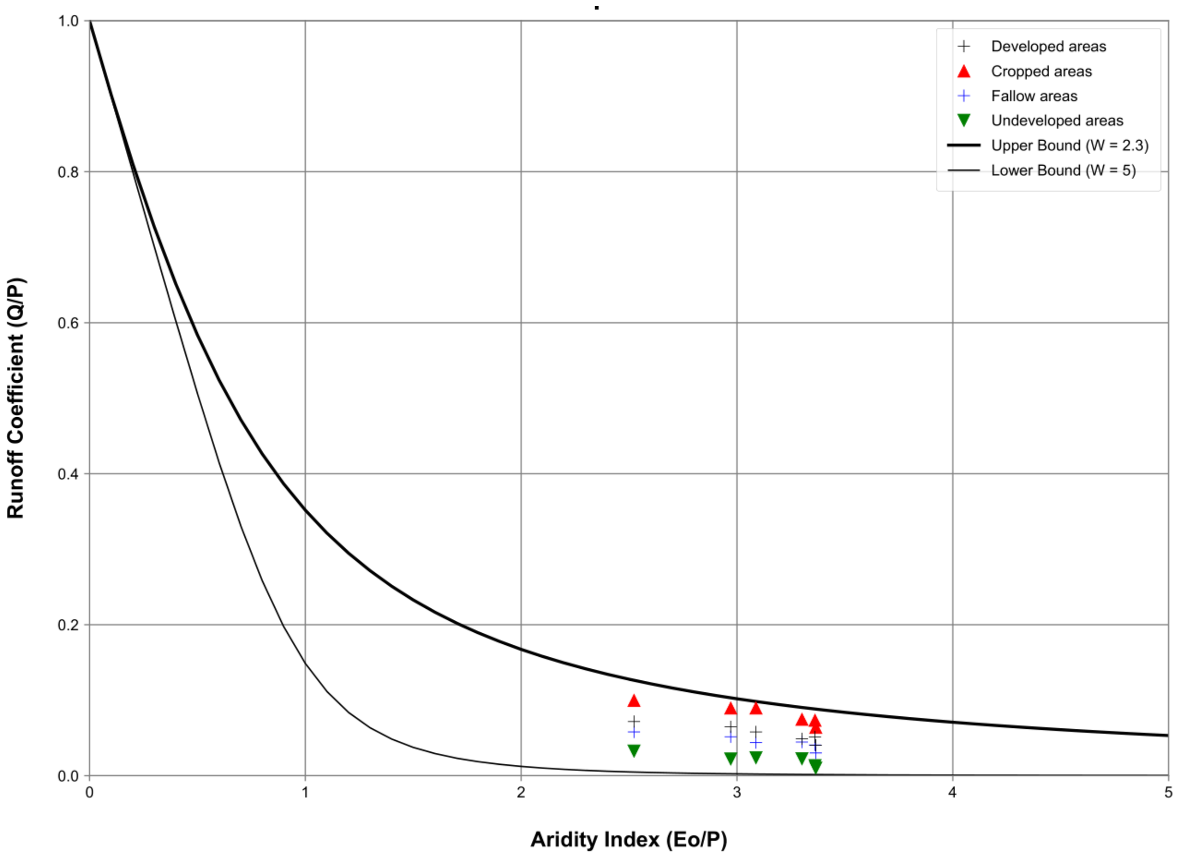

Figure 32 Runoff and aridity results for the Macquarie Valley (1965–2009 as per Neumann et al. 2017)

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 33).

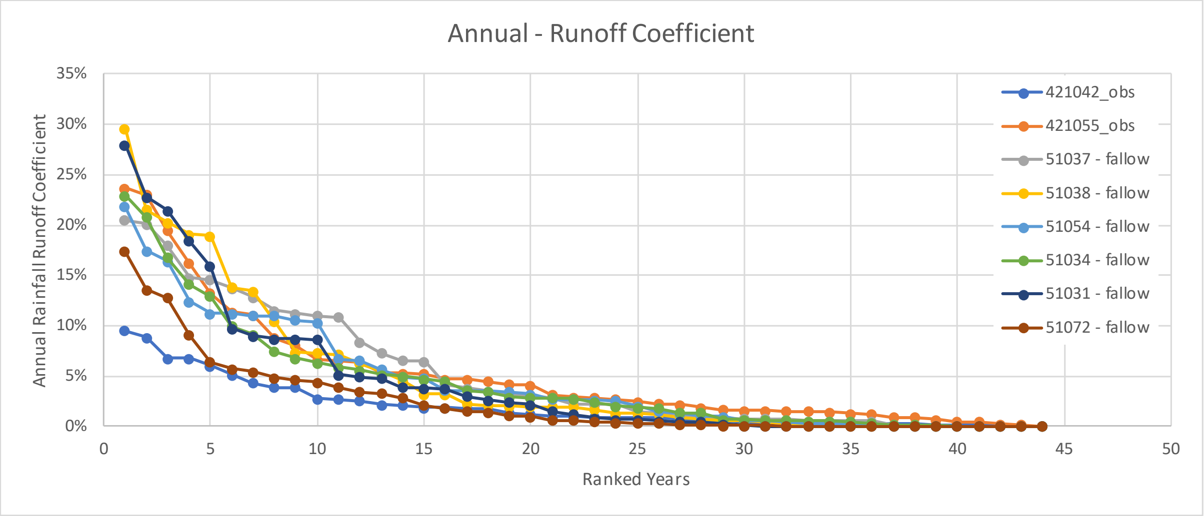

Figure 33 Range of annual runoff coefficients for 8 gauged inflows in the Macquarie Valley; data are ranked over the 44-year period from 1969 to 2015

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[25]. A 1 m freeboard has been assumed for all permanent storages.

The spatial maps of storages were combined with Landsat data to confirm the dates when the on-farm storages were built. These were then used to estimate levels of development for model 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 remote sensing data where available.

Temporary storages have only been accounted for in the model where NRAR have advised that they should be included. The policy position is that temporary storages are not to be included in

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[25] https://www.industry.nsw.gov.au/__data/assets/pdf_file/0010/271936/Storage-bathymetry-model-update-and-application-gwydir.pdf

the storage capacity assessment for the property. However, the buffering effect of temporary storages such as surge areas and sacrificial fields which allow for a fast intake of water and then transfer to permanent storages (within 14 days), can be accounted for. It is only the water transferred to permanent storage that 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 on-farm storage 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. Including 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 farm survey 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 been undertaken to assess the impact of variable pump rates on the floodplain harvesting estimate.

G.3.1 Pump rate analysis

The adopted flow rate and expected range are illustrated in Figure 34 and Figure 35. The adopted flow rates have also been compared to check for reasonably consistency (Figure 36).

The adopted flow rate has good consistency with average flow rate information obtained from a combination of farm survey data and industry advice.

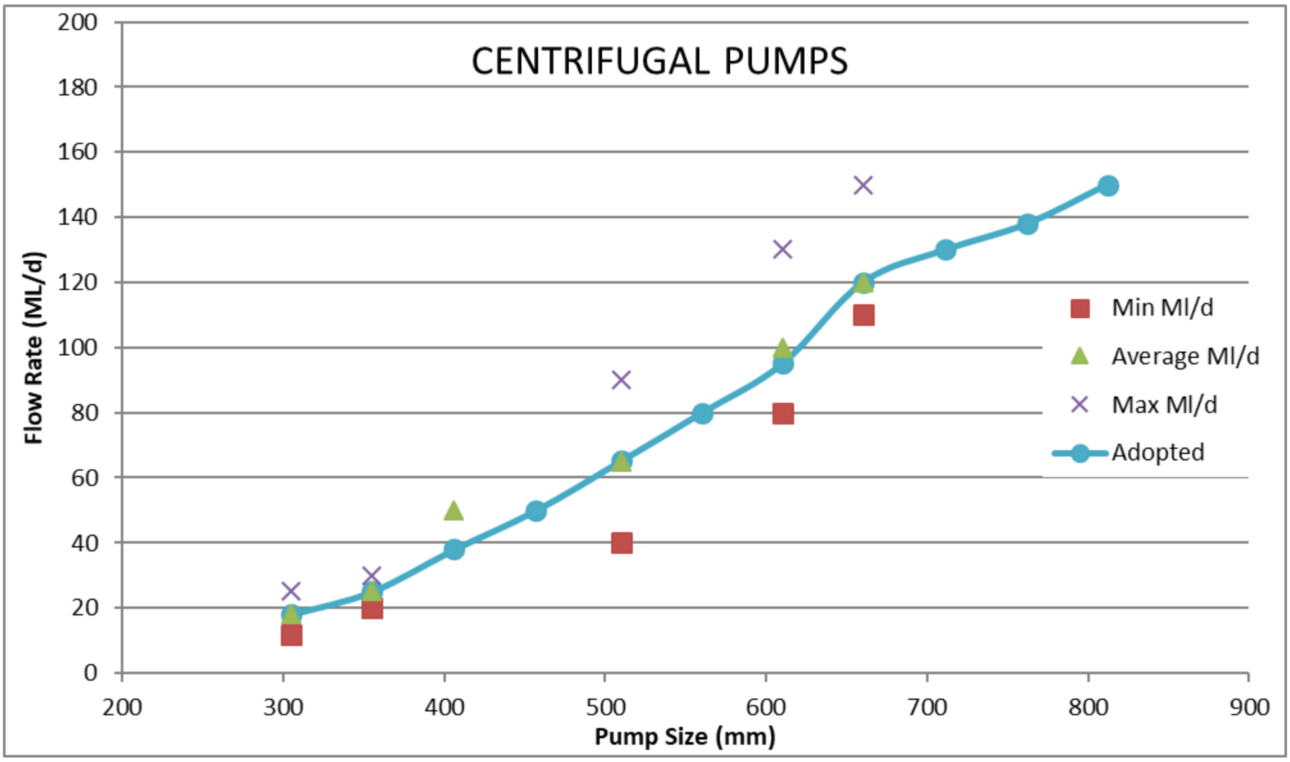


Figure 34 Centrifugal pumps flow rate analysis showing minimum, average, maximum and adopted flow rates (ML/day) for a range of pump sizes (mm)

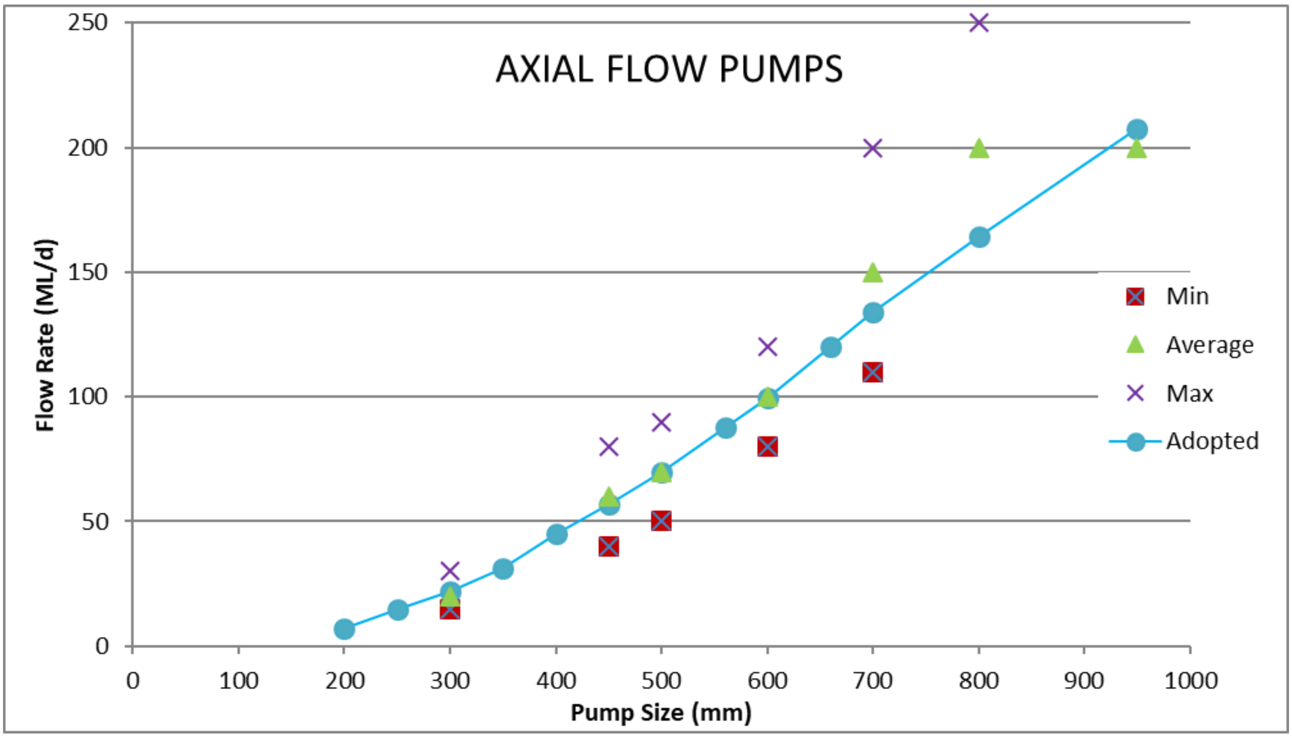


Figure 35 Axial flow pumps flow rate analysis showing minimum, average, maximum and adopted flow rates (ML/day) for a range of pump sizes (mm)

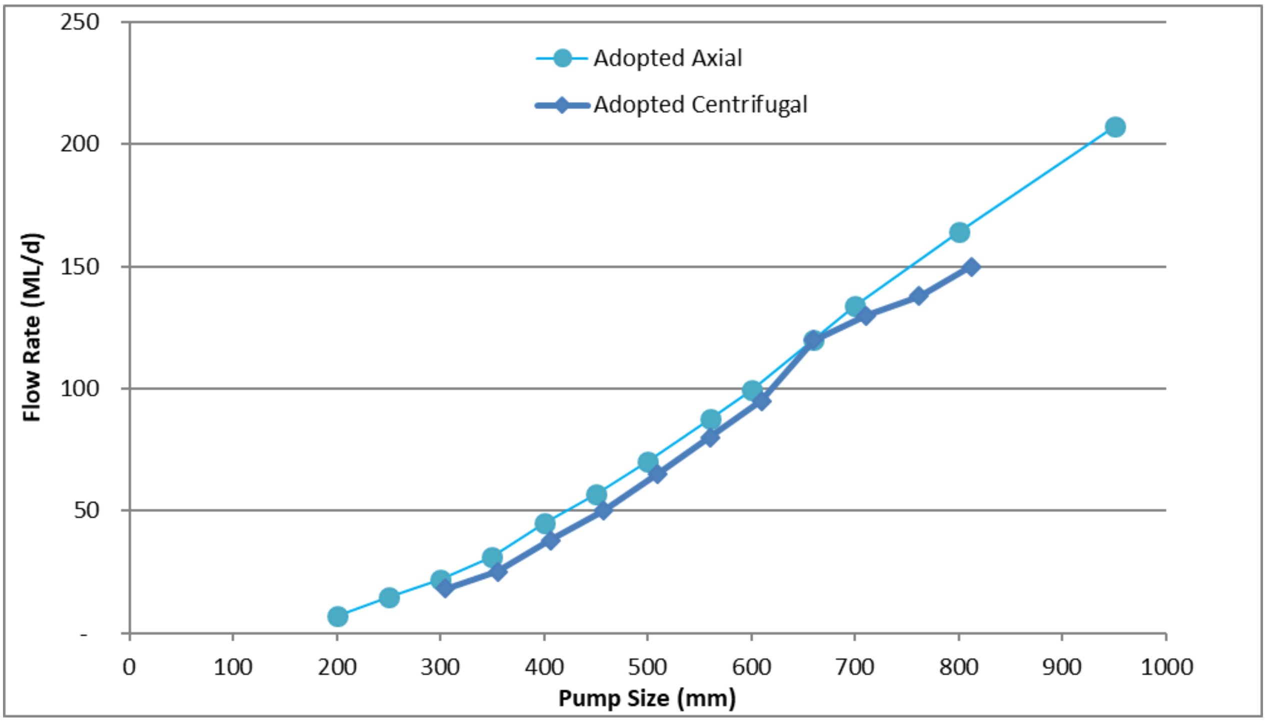


Figure 36 Comparison of adopted centrifugal and axial flow rates (ML/day) for a range of pump sizes (mm)

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 a few exceptions to this and these are discussed in Section 6.2.2.

The flow rates assumed in the review of pipes are set out in Table 46.

Table 46 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 with 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:

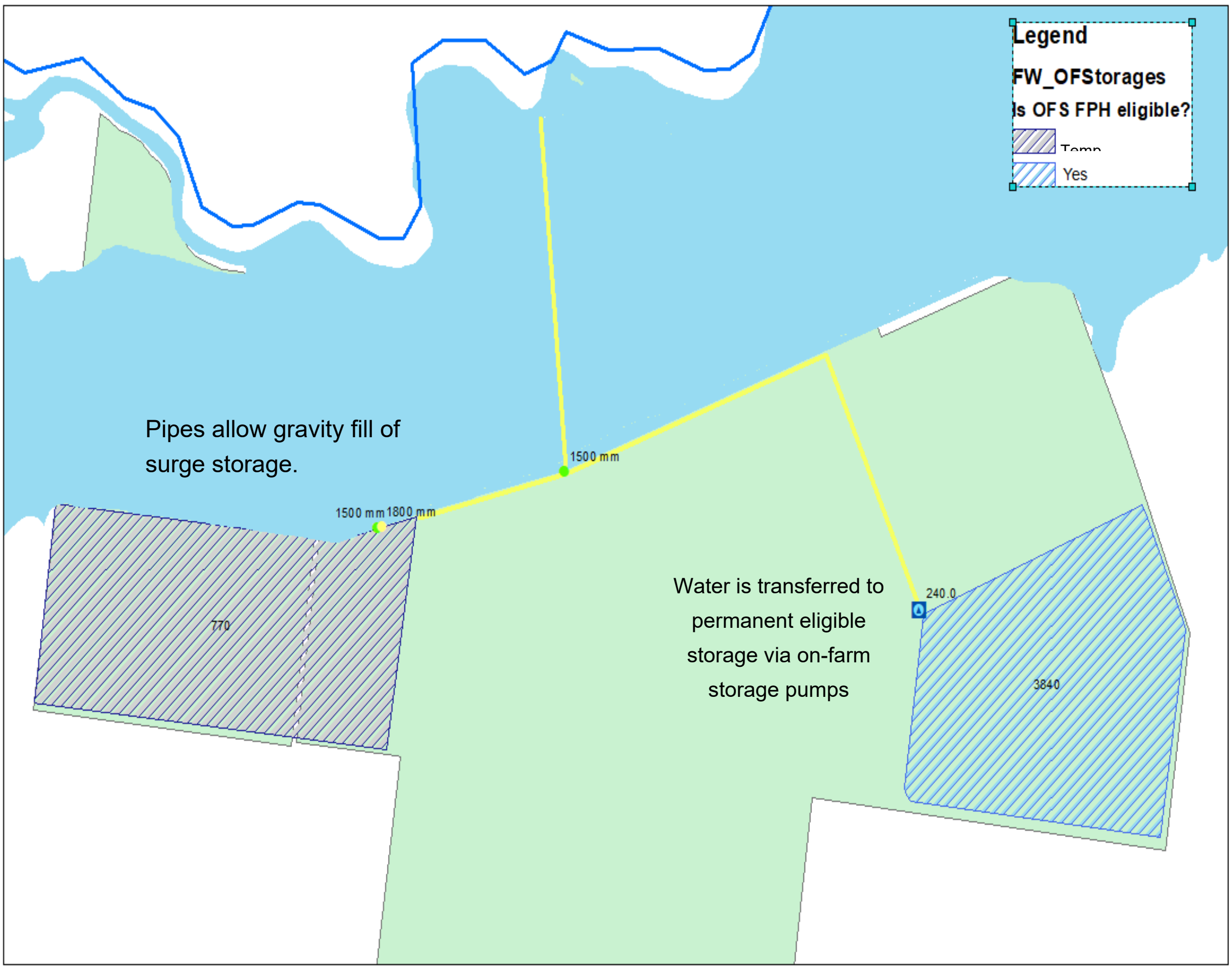
- one eligible storage with a relatively small total lift pump capacity estimated at 240 ML/day
- one surge area which is able to intake water at a much higher rate through three pipes. While the head will vary in practice, we adopt a simplified approach and assume a head of 0.2 m is representative. 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 0.2 m, 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 770 ML.

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 1500 mm 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 (770 ML), then the maximum rate of 813 ML/day (630 ML/day plus 183 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 37 demonstrates this example.



Pipes allow gravity fill of surge storage.

Water is transferred to permanent eligible storage via on-farm storage pumps

Figure 37 Schematic of the example property with temporary storage

G.6 Worked example for representing floodplain harvesting works with 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 river 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 a breakout zone on a creek . The channel crossing the creek requires modification and is not included in the water supply work approval. The within bank flow in the creek is not to be included in the floodplain harvesting entitlement; we have estimated overbank flow in this region and included access to it in the floodplain harvesting access.

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 however included in the Current Conditions Scenario.
- There are 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 the eligible rate is 720 ML/day for the licensing of floodplain harvesting.

Figure 38 demonstrates this example.

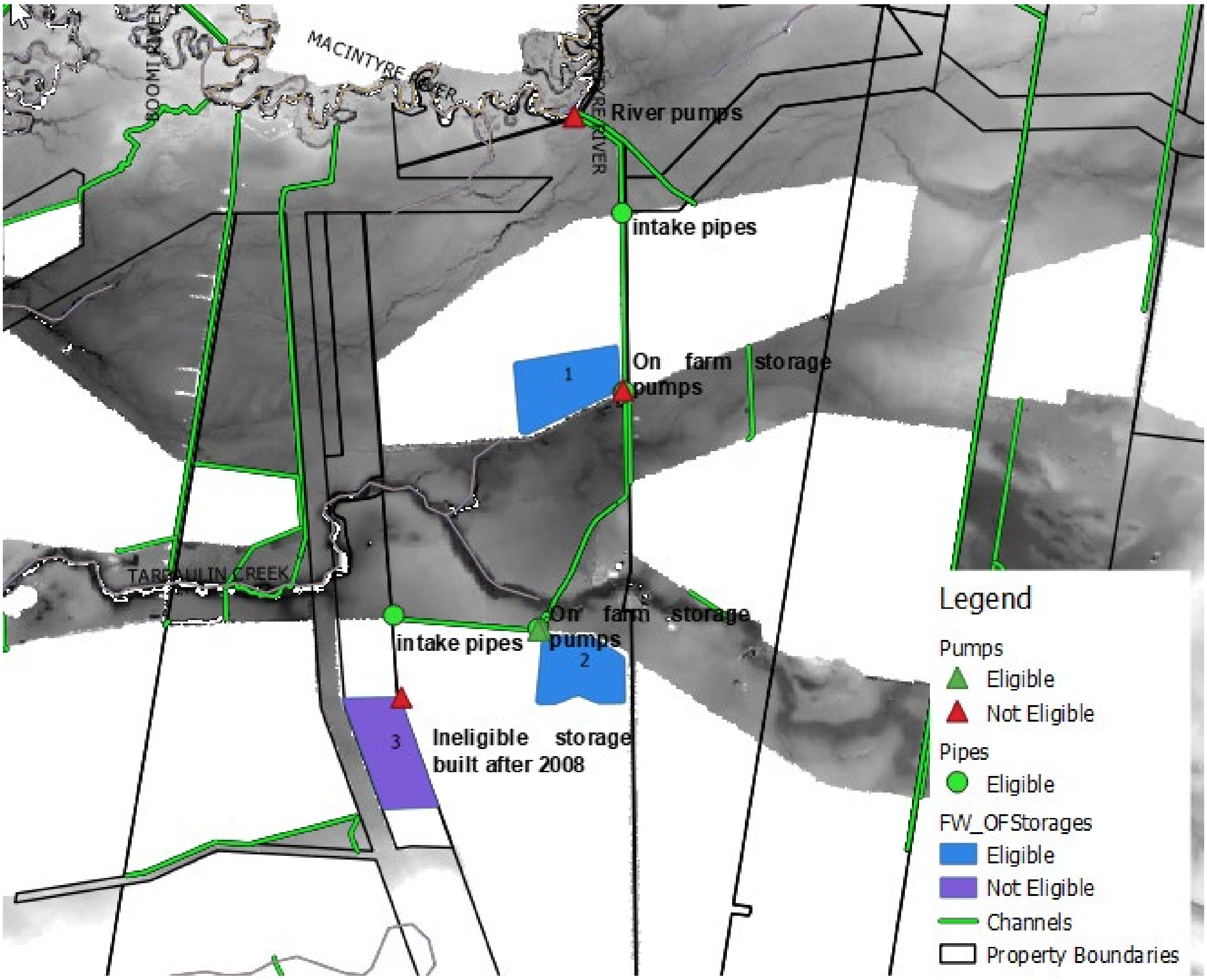


Figure 38 Schematic of the example property with multiple storages and intakes

Appendix H River reaches in the river system model

Table 47 Macquarie Valley reach division

Reach name	Upstream gauge	Downstream gauge
421079 Cudgegong DS Windamere	421148	421079
421149 Cudgegong at Rocky Water Hole	421079	421149
421150 Cudgegong at Wilbetree Road	421149	421150
421019 Cudgegong at Yamble Bridge	421058 421150	421019
421035 Fish River at Tarana	421187 421036	421035
421025 Macquarie at Bruinbun	421035 421053 421072 421160	421025
421080 Macquarie at Dixons Long Point	421025 421026 421041 421052	421080
421040 Macquarie DS Burrendong	421080 421019 421073 421067 421066	421040
421001 Dubbo	421040 421018 421059	421001
421127 Macquarie at Baroona	421001 421042 421055	421127
421006 Macquarie at Narromine	421127	421006
421031 Macquarie at Gin Gin	421006	421031
421004 Macquarie at Warren Weir	421031	421004
421090 Macquarie at DS Marebone Weir	421004	421090
421012 Macquarie at Carinda	416204A	416202A

Appendix I Flow calibration tables and graphs

For headwater gauges, the Sacramento rainfall–runoff model results are compared to recorded flows.

Calibrations for some of the headwater rainfall–runoff models show a reasonable deviation on the residual mass series (shown in each standard report card). There are a number of possible reasons for this including:

- limitations of the Sacramento model
- available rainfall stations not being representative of the catchment
- change of available rainfall stations over the calibration period
- errors in calibration data, e.g. rainfall and water level gauge errors
- errors in water level gauge rating curves
- poorer quality data for earlier parts of the record
- single large events not being adequately captured by the modelling.

These issues are often not possible to address without decreasing the overall quality of the Sacramento model calibration, and as such the calibrations reported in Table 48 represent the best possible balance of the Nash-Sutcliffe Efficiency metric, volume bias (full, low, medium, high) taking into account residual mass series deviation.

Table 48 Headwater inflow flow calibration statistics

Station no.	Mean annual flow (GL)	Runoff as % of rainfall	Daily Nash-Sutcliffe	Flow bias for full flow range	Flow bias for low flow range	Flow bias for medium flow range	Flow bias for high flow range	Figure reference
421018	125.6	12.1%	0.63	0%	1.3%	4.4%	-0.6%	Figure 39
421026	92.7	13.2%	0.76	0%	11.9%	2.4%	-0.4%	Figure 40
421034	2.9	23.8%	0.66	0%	-7.6%	2.1%	-0.5%	Figure 41
421036	33.2	34.0%	0.76	0%	1.4%	-0.5%	0.2%	Figure 42
421041	31.0	17.4%	0.7	0%	25%	1.1%	-0.3%	Figure 43
421042	49.3	2.6%	0.77	0%	0.4%	1.7%	-0.3%	Figure 44
421048	32.5	8.0%	0.64	0%	-7.5%	2.3%	-0.3%	Figure 45
421052	98.9	19.5%	0.67	0%	1.4%	0%	0%	Figure 46
421053	15.7	8.8%	0.36	0%	4.8%	7.9%	-0.8%	Figure 47
421055	28.5	7.5%	0.46	0%	18.7%	1.7%	-0.1%	Figure 48
421058	26.3	3.8%	0.34	0%	20.4%	-0.1%	-0.2%	Figure 49
421059	17.9	4.2%	0.36	-0.6%	14.7%	3.1%	-1.6%	Figure 50
421066	16.1	16.3%	0.57	0%	29.2%	3.6%	-0.4%	Figure 51
421067 + 21100	29.9	22.9%	0.52	-1.2%	12.1%	1.8%	-1.5%	Figure 52
421073	106.6	9.4%	0.6	0%	7.2%	-0.7%	0.1%	Figure 53
421075	13.5	10.0%	0.5	0%	18.1%	3.2%	-0.8%	Figure 54
421076	18.3	3.6%	0.67	0.1%	19.8%	-0.7%	0.1%	Figure 55

Station no.	Mean annual flow (GL)	Runoff as % of rainfall	Daily Nash-Sutcliffe	Flow bias for full flow range	Flow bias for low flow range	Flow bias for medium flow range	Flow bias for high flow range	Figure reference
421101	78.1	9.6%	0.64	0%	-8.8%	3.3%	-0.8%	Figure 56

For main river gauges, the Macquarie Valley model results are generally based on the Flow Validation Scenario 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 Flow Validation Scenario has only been completed down to Narromine, and calibration statistics were not available for the final three flow gauging stations in Table 49. The statistics for these three flow gauging stations are instead taken from the final fully simulating 2008/09 Validation Scenario. Unlike the Flow Validation Scenario, planted crop areas and diversions (including supplementary access) are being simulated.

Calibrations for some of the headwater rainfall runoff models show a reasonable deviation on the residual mass series (shown in each standard report card below). There are a number of possible reasons for this including:

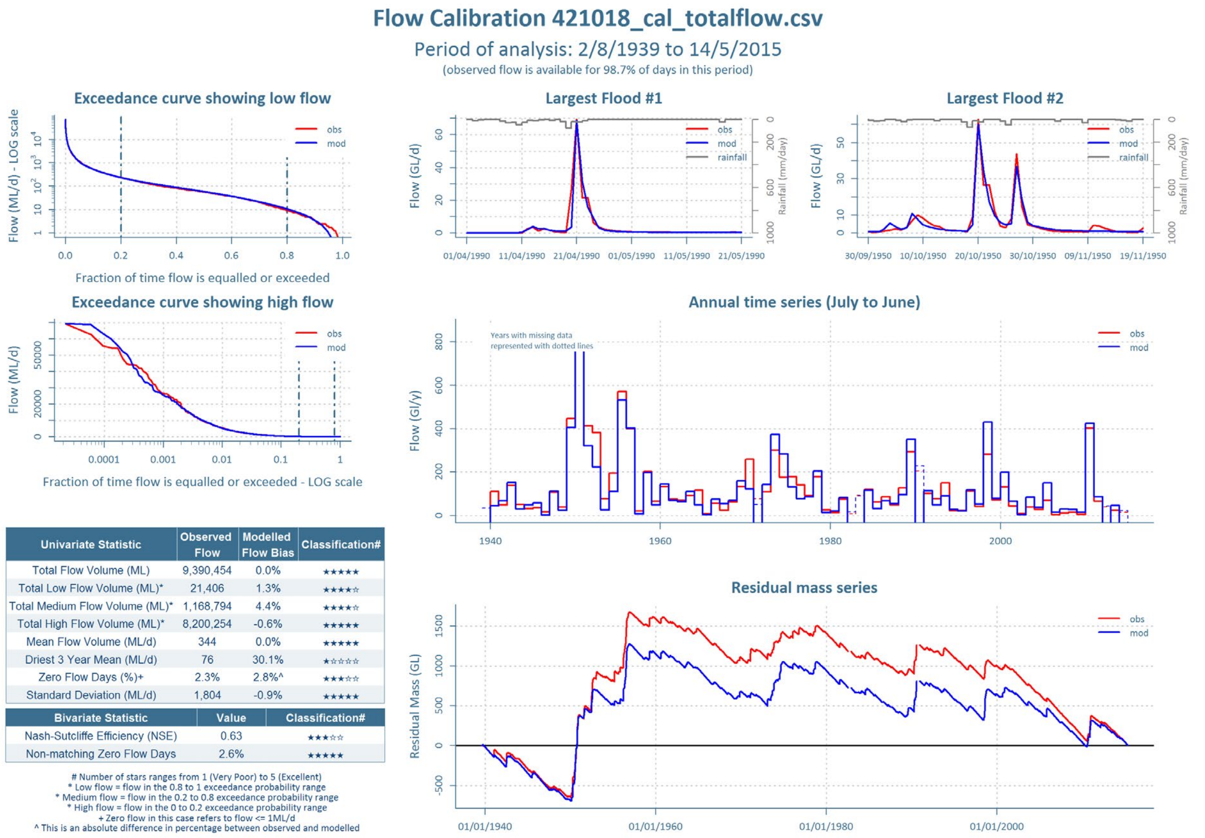
- Limitations of the Sacramento model
- Available rainfall stations not being representative of the catchment
- Change of available rainfall stations over the calibration period
- Errors in calibration data, e.g. rainfall and water level gauge errors
- Errors in water level gauge rating curves
- Poorer quality data for earlier parts of the record
- Single large events not being adequately captured by the modelling

These issues are often not possible to address without decreasing the overall quality of the Sacramento model calibration, and as such the below calibrations represent the best possible balance of NSE, volume bias (total, high and low) and residual mass series deviation.

Table 49 Reach flow calibration statistics[1]

Station no.	Daily Nash-Sutcliffe	Flow bias for full flow range	Flow bias for low flow range	Flow bias for medium flow range	Flow bias for high flow range	Figure reference
421001	0.97	0.4%	-4.1%	-1.5%	3.4%	Figure 57
421006	0.98	1.3%	18.2%	2.3%	-2.0%	Figure 65
421019	0.92	0.0%	4.7%	-3.3%	0.8%	Figure 59
421025	0.90	0.0%	2.4%	-0.1%	-1.0%	Figure 60
421035	0.91	0.3%	-0.2%	0.7%	0.2%	Figure 61
421079	0.95	0.2%	0.5%	1.3%	-0.6%	Figure 62
421149	0.89	0.0%	4.4%	1.2%	-1.1%	Figure 63
421150	0.84	0.0%	-5.9%	2.7%	-0.9%	Figure 64
Burrendong inflow	0.94	0.0%	48.5%	-0.6%	0.2%	Figure 65
421004[1]	0.58	-3.7%	121.6%	13.2%	-8.2%	Figure 66
421031[1]	0.62	-0.5%	60.4%	19.0%	-6.4%	Figure 67
421090[1]	0.57	3.4%	-50.2%	20.4%	-0.7%	Figure 68

[1] Results from final fully simulating validation scenario



Flow Calibration 421018_cal_totalflow.csv

Period of analysis: 2/8/1939 to 14/5/2015

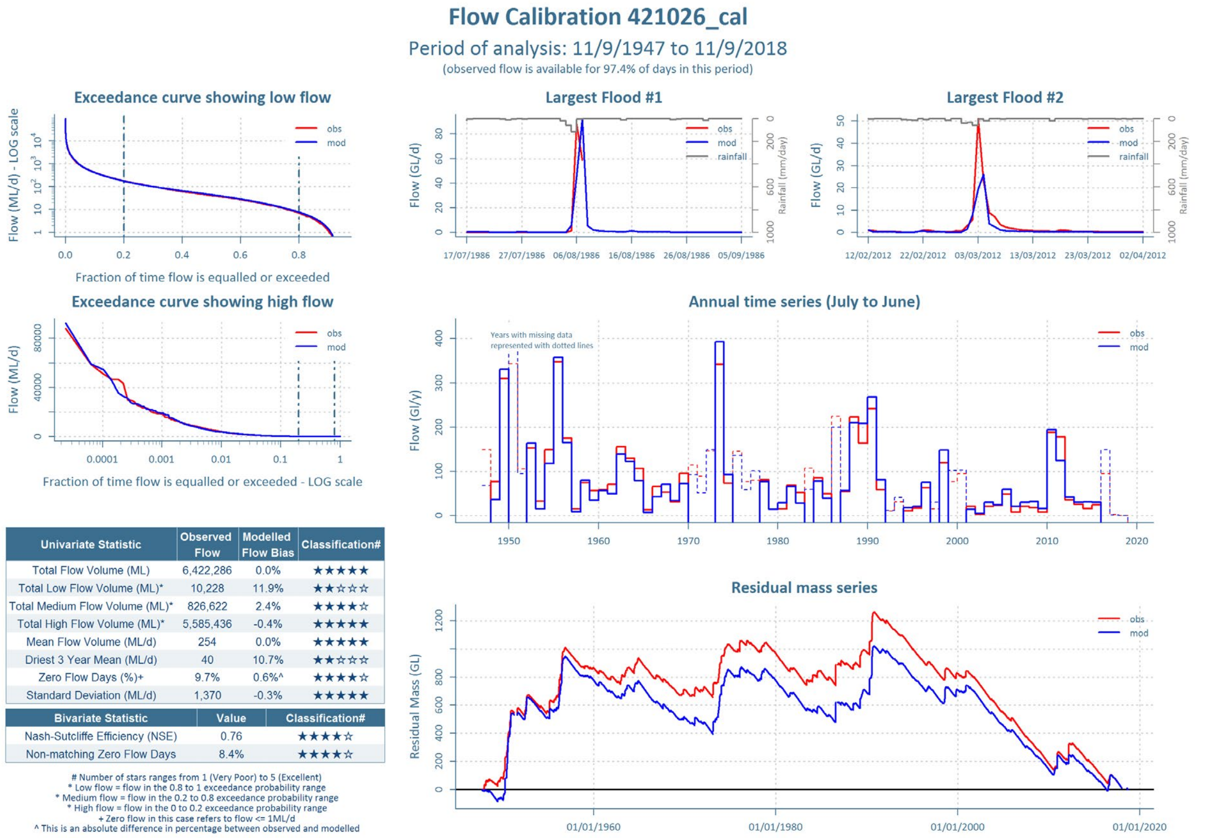
(observed flow is available for 98.7% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	9,390,454	0.0%	★★★★★
Total Low Flow Volume (ML)*	21,406	1.3%	★★★★☆
Total Medium Flow Volume (ML)*	1,168,794	4.4%	★★★★☆
Total High Flow Volume (ML)*	8,200,254	-0.6%	★★★★★
Mean Flow Volume (ML/d)	344	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	76	30.1%	★☆☆☆☆
Zero Flow Days (%)+	2.3%	2.8%^	★★★☆☆
Standard Deviation (ML/d)	1,804	-0.9%	★★★★★

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.63	★★★☆☆
Non-matching Zero Flow Days	2.6%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.2 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.2 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 39 Flow calibration graphs for gauging station 421018 Bell River @ Newrea



Flow Calibration 421026_cal

Period of analysis: 11/9/1947 to 11/9/2018

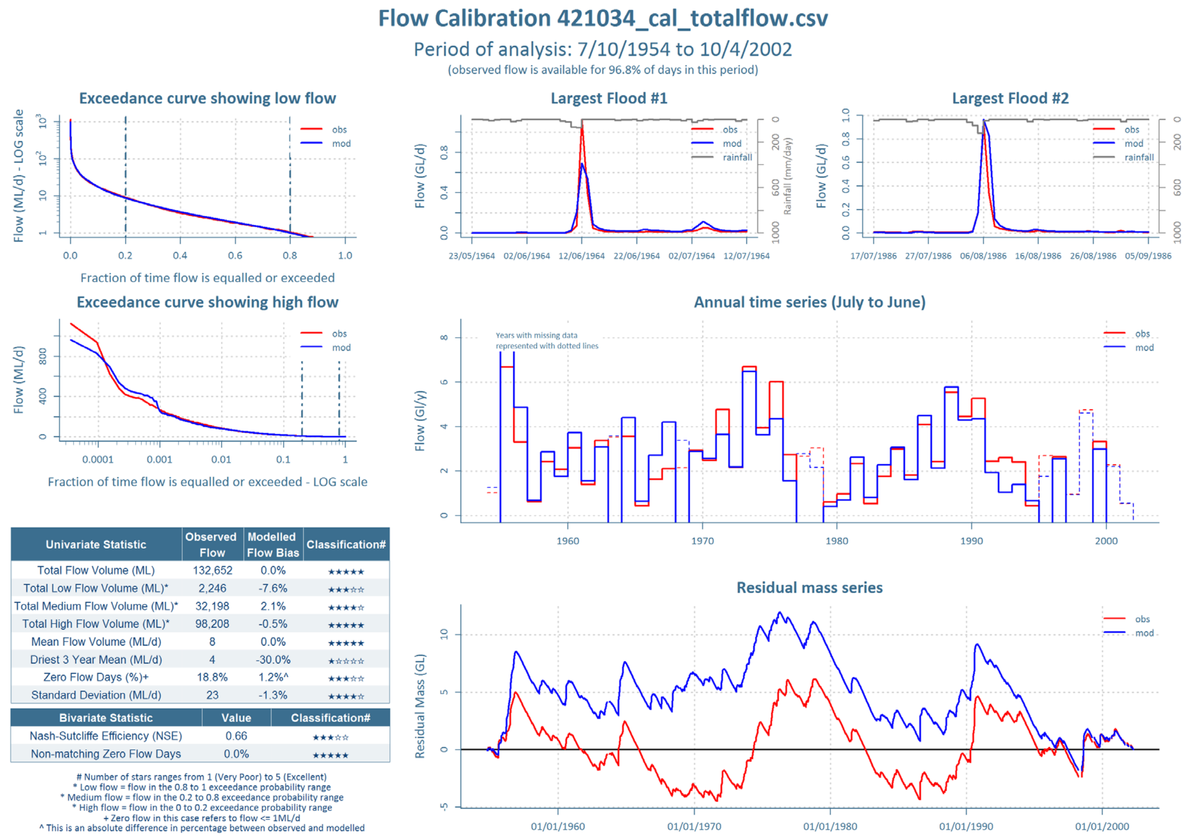
(observed flow is available for 97.4% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	6,422,286	0.0%	★★★★★
Total Low Flow Volume (ML)*	10,228	11.9%	★★☆☆☆
Total Medium Flow Volume (ML)*	826,622	2.4%	★★★★☆
Total High Flow Volume (ML)*	5,585,436	-0.4%	★★★★★
Mean Flow Volume (ML/d)	254	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	40	10.7%	★★☆☆☆
Zero Flow Days (%)+	9.7%	0.6%^	★★★★☆
Standard Deviation (ML/d)	1,370	-0.3%	★★★★★

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.76	★★★★☆
Non-matching Zero Flow Days	8.4%	★★★★☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.2 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.2 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 40 Flow calibration graphs for gauging station 421026 Turon River @ Sofala



Flow Calibration 421034_cal_totalflow.csv

Period of analysis: 7/10/1954 to 10/4/2002

(observed flow is available for 96.8% of days in this period)

Exceedance curve showing low flow

Largest Flood #1

Largest Flood #2

Exceedance curve showing high flow

Annual time series (July to June)

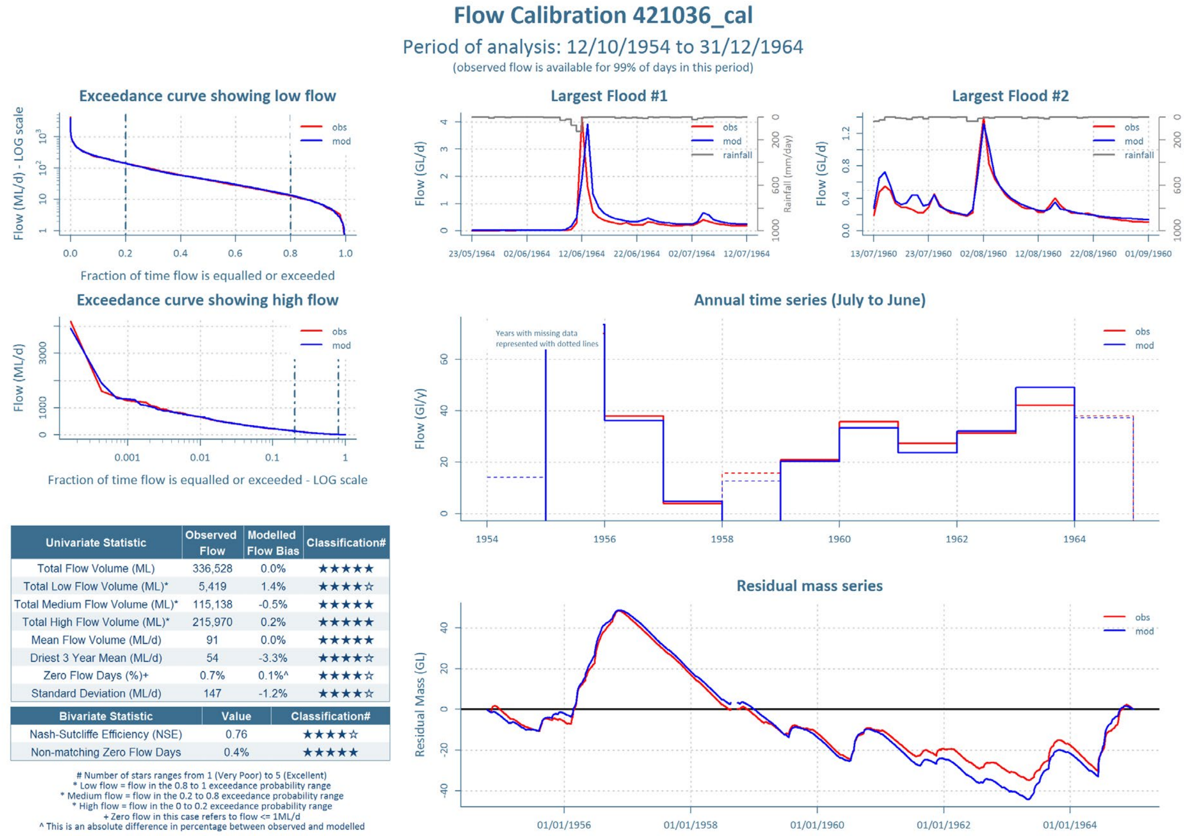
Residual mass series

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	132,652	0.0%	★★★★★
Total Low Flow Volume (ML)*	2,246	-7.6%	★★★☆☆
Total Medium Flow Volume (ML)*	32,198	2.1%	★★★★☆
Total High Flow Volume (ML)*	98,208	-0.5%	★★★★★
Mean Flow Volume (ML/d)	8	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	4	-30.0%	★☆☆☆☆
Zero Flow Days (%)+	18.8%	1.2%^	★★★☆☆
Standard Deviation (ML/d)	23	-1.3%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.66	★★★☆☆
Non-matching Zero Flow Days	0.0%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.2 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.2 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 41 Flow calibration graphs for gauging station 421034 Slippery Creek @ Dam Site



Flow Calibration 421036_cal

Period of analysis: 12/10/1954 to 31/12/1964

(observed flow is available for 99% of days in this period)

Exceedance curve showing low flow

Largest Flood #1

Largest Flood #2

Exceedance curve showing high flow

Annual time series (July to June)

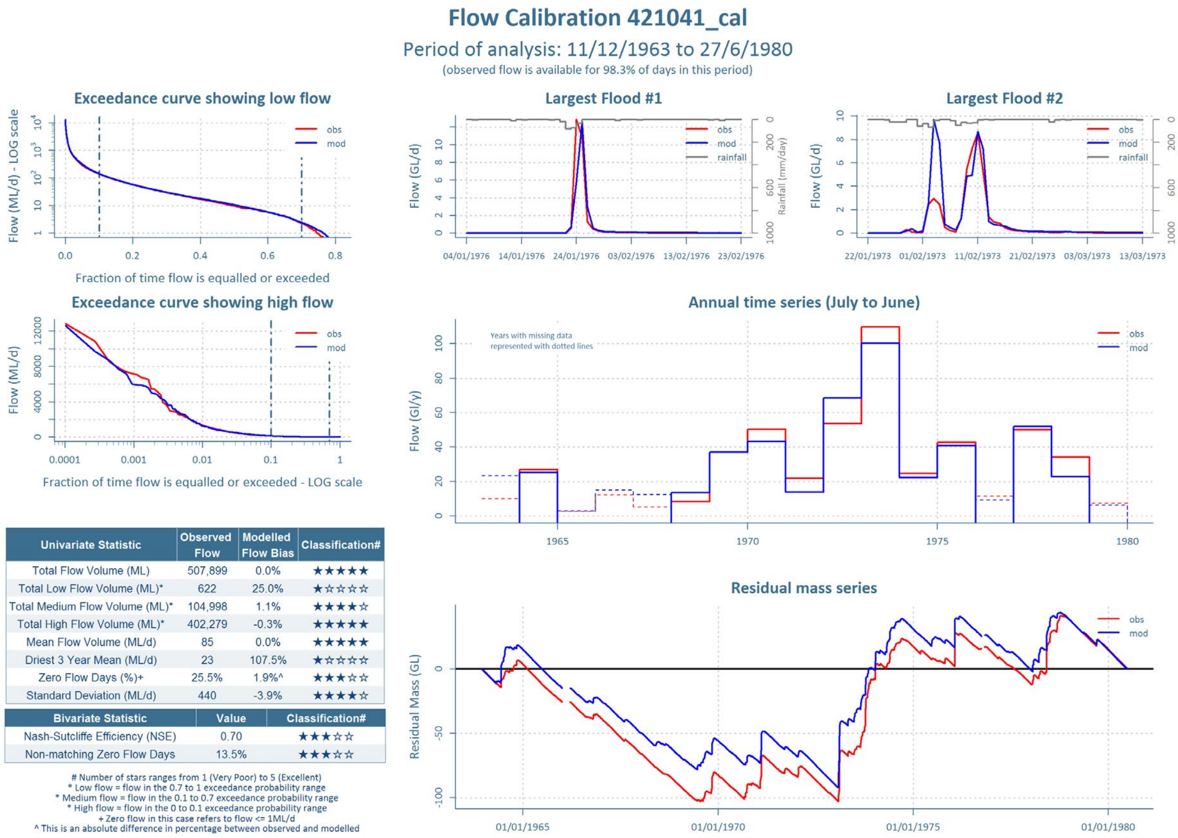
Residual mass series

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	336,528	0.0%	★★★★★
Total Low Flow Volume (ML)*	5,419	1.4%	★★★★☆
Total Medium Flow Volume (ML)*	115,138	-0.5%	★★★★★
Total High Flow Volume (ML)*	215,970	0.2%	★★★★★
Mean Flow Volume (ML/d)	91	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	54	-3.3%	★★★★☆
Zero Flow Days (%)+	0.7%	0.1%^	★★★★☆
Standard Deviation (ML/d)	147	-1.2%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.76	★★★★☆
Non-matching Zero Flow Days	0.4%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.2 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.2 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 42 Flow calibration graphs for gauging station 421036 Duckmaloi River @ Below Dam Site



Flow Calibration 421041_cal

Period of analysis: 11/12/1963 to 27/6/1980

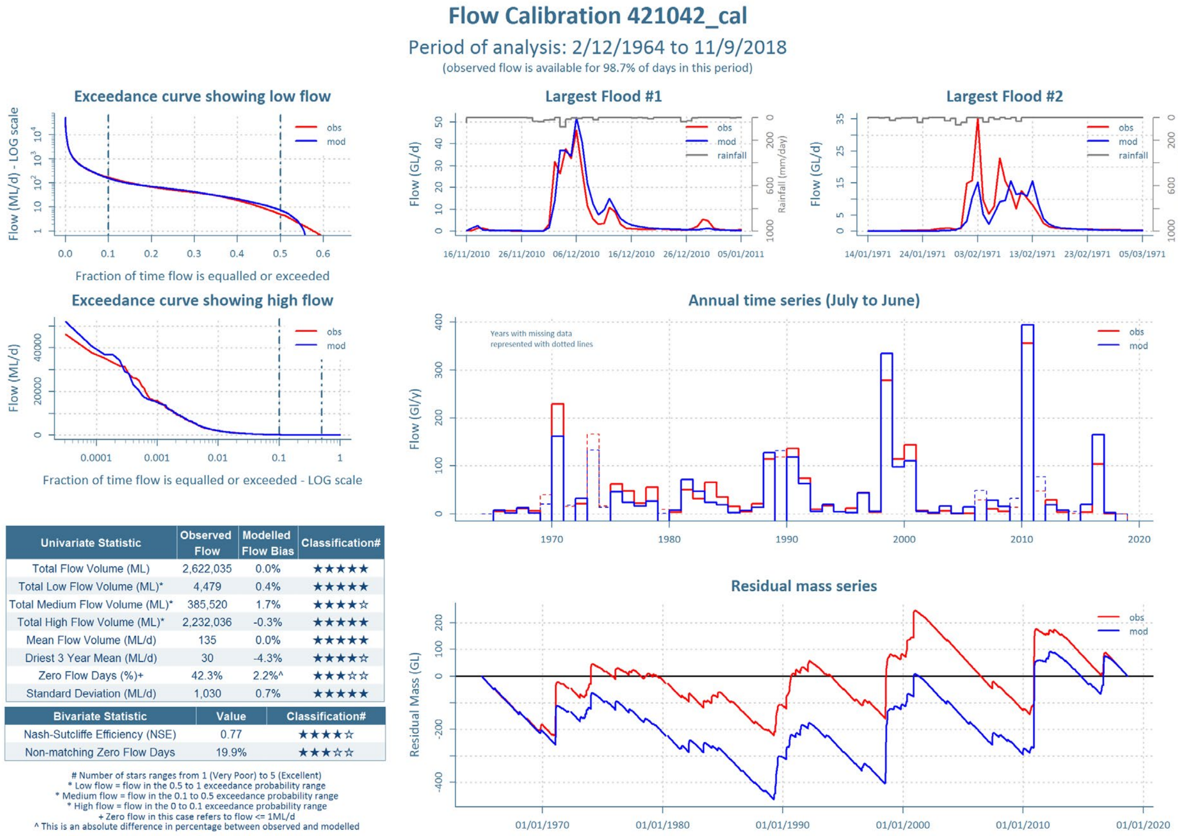
(observed flow is available for 98.3% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	507,899	0.0%	★★★★★
Total Low Flow Volume (ML)*	622	25.0%	★☆☆☆☆
Total Medium Flow Volume (ML)*	104,998	1.1%	★★★★☆
Total High Flow Volume (ML)*	402,279	-0.3%	★★★★★
Mean Flow Volume (ML/d)	85	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	23	107.5%	★☆☆☆☆
Zero Flow Days (%)+	25.5%	1.9%^	★★★☆☆
Standard Deviation (ML/d)	440	-3.9%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.70	★★★☆☆
Non-matching Zero Flow Days	13.5%	★★★☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.7 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.7 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 43 Flow calibration graphs for gauging station 421041 Crudine Creek @ u/s Turon



Flow Calibration 421042_cal

Period of analysis: 2/12/1964 to 11/9/2018

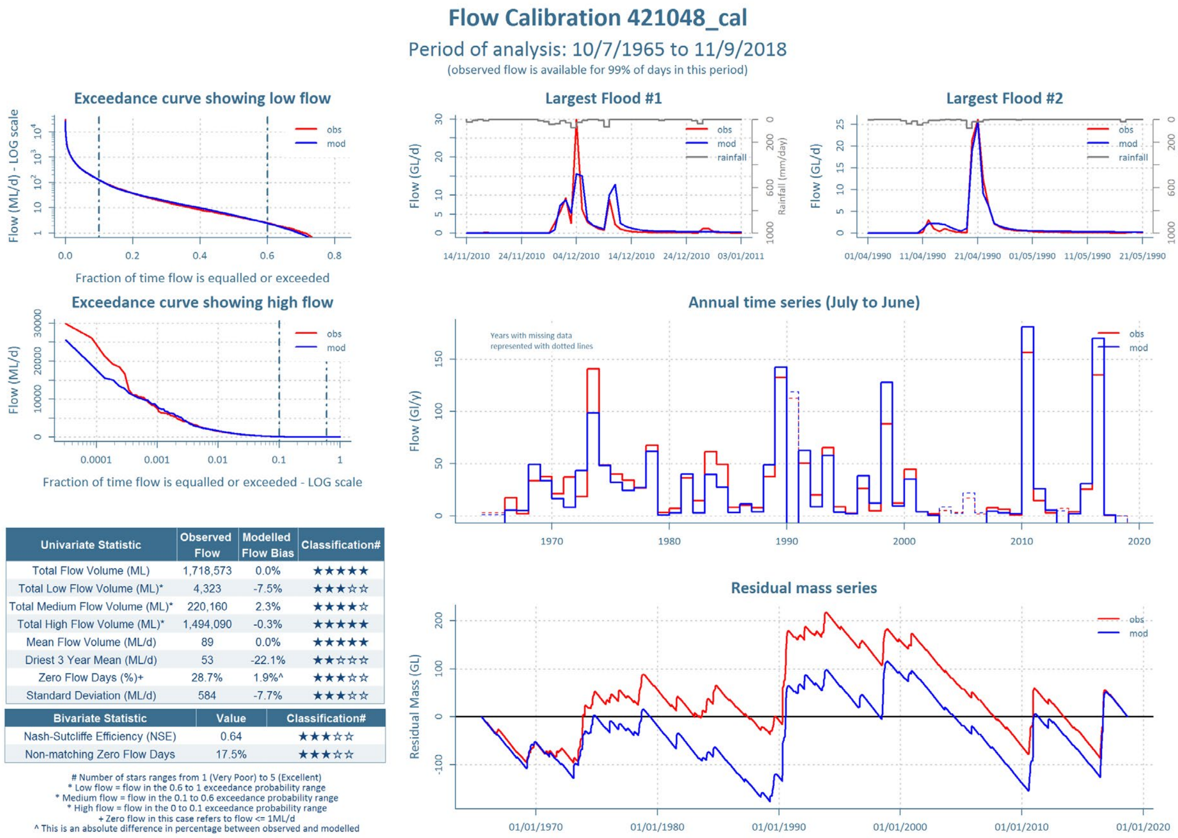
(observed flow is available for 98.7% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	2,622,035	0.0%	★★★★★
Total Low Flow Volume (ML)*	4,479	0.4%	★★★★★
Total Medium Flow Volume (ML)*	385,520	1.7%	★★★★☆
Total High Flow Volume (ML)*	2,232,036	-0.3%	★★★★★
Mean Flow Volume (ML/d)	135	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	30	-4.3%	★★★★☆
Zero Flow Days (%)+	42.3%	2.2%^	★★★☆☆
Standard Deviation (ML/d)	1,030	0.7%	★★★★★

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.77	★★★★☆
Non-matching Zero Flow Days	19.9%	★★★☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.5 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.5 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 44 Flow calibration graphs for gauging station 421042 Talbragar River @ Elong Elong

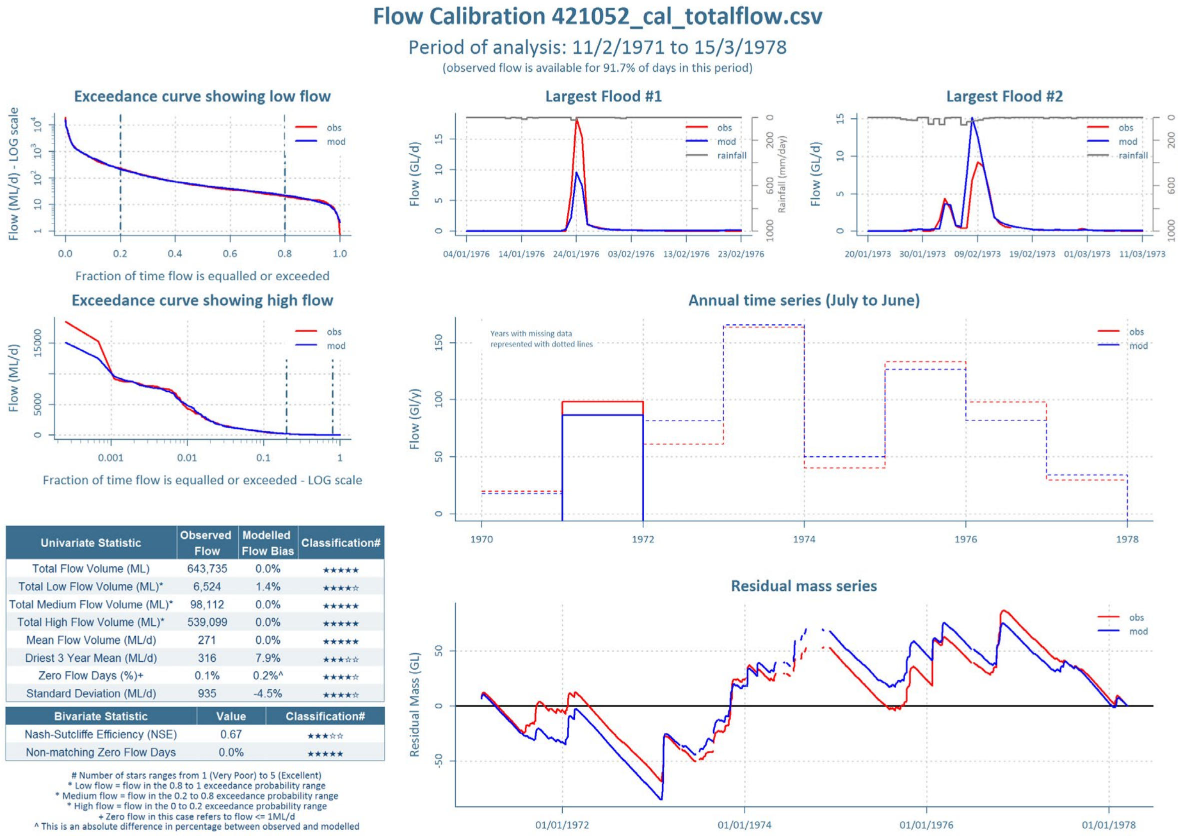


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	1,718,573	0.0%	★★★★★
Total Low Flow Volume (ML)*	4,323	-7.5%	★★★☆☆
Total Medium Flow Volume (ML)*	220,160	2.3%	★★★★☆
Total High Flow Volume (ML)*	1,494,090	-0.3%	★★★★★
Mean Flow Volume (ML/d)	89	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	53	-22.1%	★★☆☆☆
Zero Flow Days (%)+	28.7%	1.9%^	★★★☆☆
Standard Deviation (ML/d)	584	-7.7%	★★★☆☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.64	★★★☆☆
Non-matching Zero Flow Days	17.5%	★★★☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.6 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.6 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
\+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 45 Flow calibration graphs for gauging station 421048 Little River @ Obley

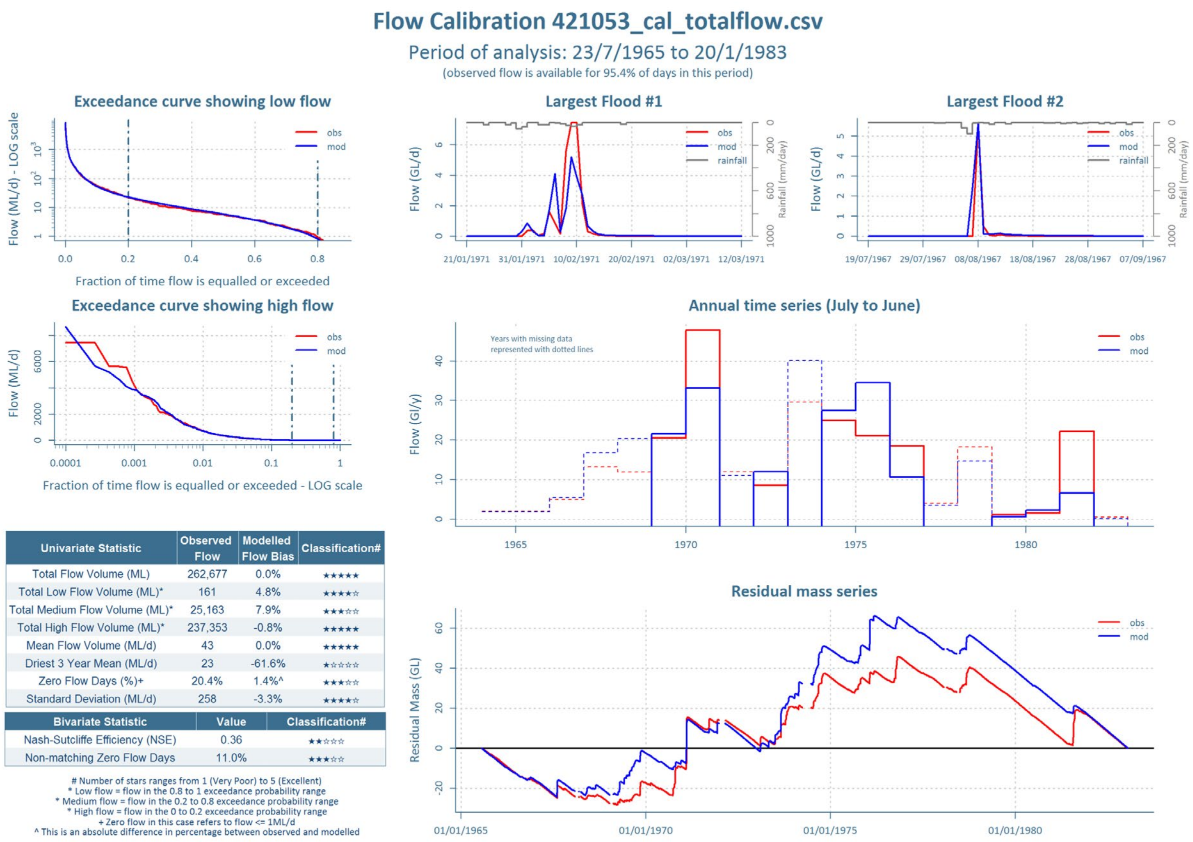


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	643,735	0.0%	★★★★★
Total Low Flow Volume (ML)*	6,524	1.4%	★★★★☆
Total Medium Flow Volume (ML)*	98,112	0.0%	★★★★★
Total High Flow Volume (ML)*	539,099	0.0%	★★★★★
Mean Flow Volume (ML/d)	271	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	316	7.9%	★★★☆☆
Zero Flow Days (%)+	0.1%	0.2%^	★★★★☆
Standard Deviation (ML/d)	935	-4.5%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.67	★★★☆☆
Non-matching Zero Flow Days	0.0%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.2 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.2 exceedance probability range
\+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 46 Flow calibration graphs for gauging station 421052 Lewis Ponds @ Ophir

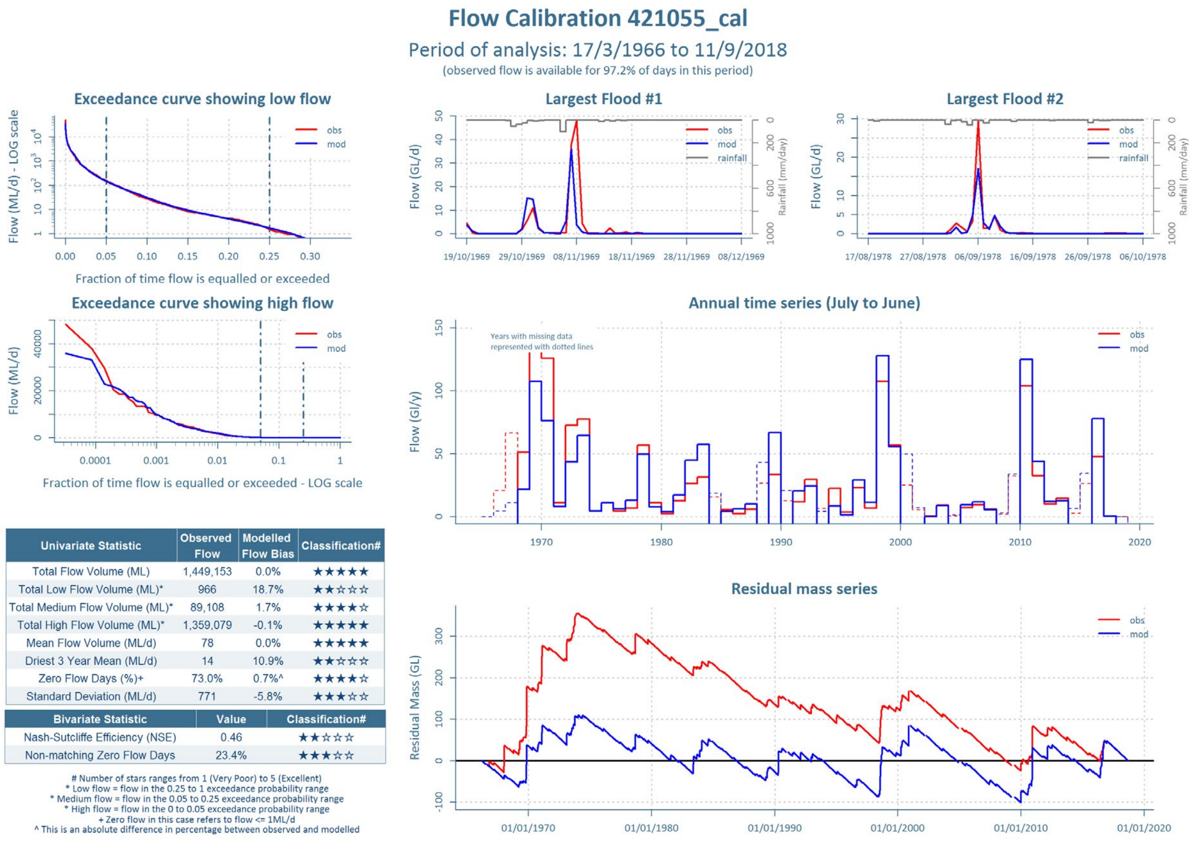


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	262,677	0.0%	★★★★★
Total Low Flow Volume (ML)*	161	4.8%	★★★★☆
Total Medium Flow Volume (ML)*	25,163	7.9%	★★★☆☆
Total High Flow Volume (ML)*	237,353	-0.8%	★★★★★
Mean Flow Volume (ML/d)	43	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	23	-61.6%	★☆☆☆☆
Zero Flow Days (%)+	20.4%	1.4%^	★★★☆☆
Standard Deviation (ML/d)	258	-3.3%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.36	★★☆☆☆
Non-matching Zero Flow Days	11.0%	★★★☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.2 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.2 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 47 Flow calibration graphs for gauging station 421053 Queen Charlottes @ Georges Plain

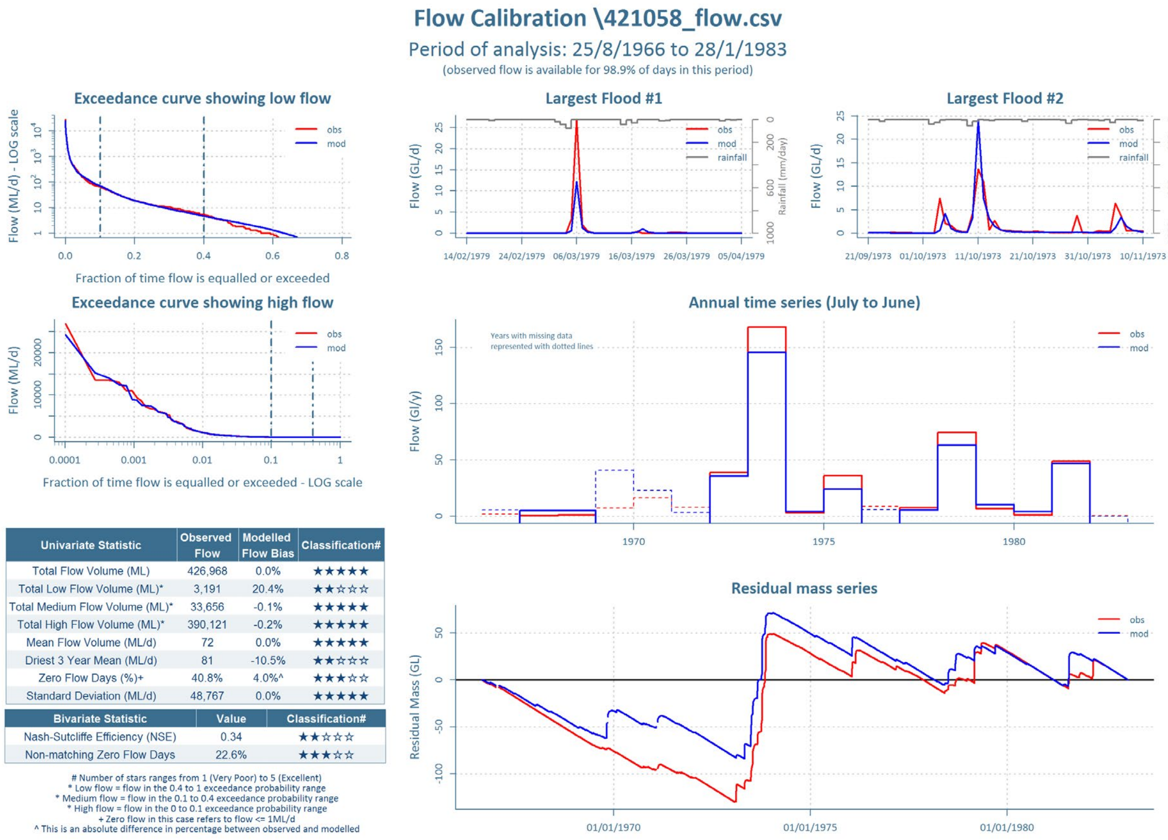


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	1,449,153	0.0%	★★★★★
Total Low Flow Volume (ML)*	966	18.7%	★★☆☆☆
Total Medium Flow Volume (ML)*	89,108	1.7%	★★★★☆
Total High Flow Volume (ML)*	1,359,079	-0.1%	★★★★★
Mean Flow Volume (ML/d)	78	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	14	10.9%	★★☆☆☆
Zero Flow Days (%)+	73.0%	0.7%^	★★★★☆
Standard Deviation (ML/d)	771	-5.8%	★★★☆☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.46	★★☆☆☆
Non-matching Zero Flow Days	23.4%	★★★☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.25 to 1 exceedance probability range
* Medium flow = flow in the 0.05 to 0.25 exceedance probability range
* High flow = flow in the 0 to 0.05 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 48 Flow calibration graphs for gauging station 421055 Coolbaggie Creek @ Rawsonville

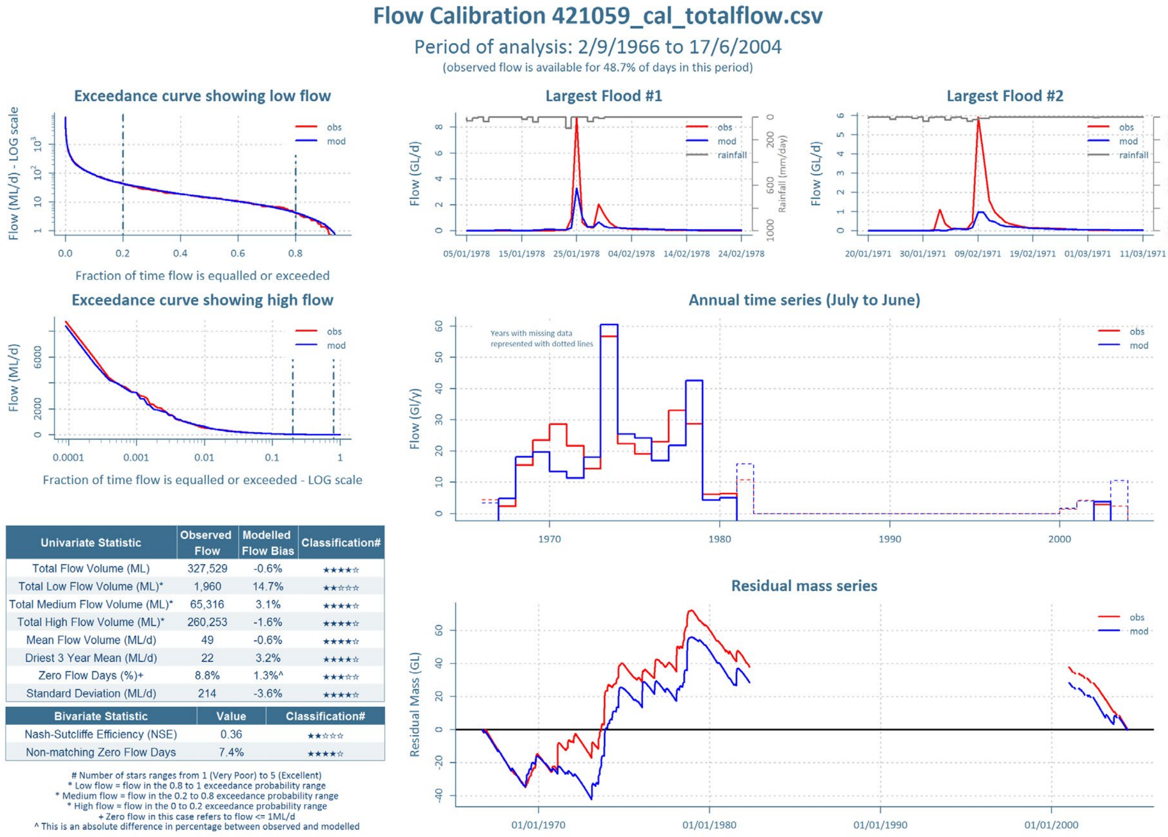


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	426,968	0.0%	★★★★★
Total Low Flow Volume (ML)*	3,191	20.4%	★★☆☆☆
Total Medium Flow Volume (ML)*	33,656	-0.1%	★★★★★
Total High Flow Volume (ML)*	390,121	-0.2%	★★★★★
Mean Flow Volume (ML/d)	72	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	81	-10.5%	★★☆☆☆
Zero Flow Days (%)+	40.8%	4.0%^	★★★☆☆
Standard Deviation (ML/d)	48,767	0.0%	★★★★★

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.34	★★☆☆☆
Non-matching Zero Flow Days	22.6%	★★★☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.4 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.4 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
\+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 49 Flow calibration graphs for gauging station 421058 Wyaldra Creek @ Gulgong

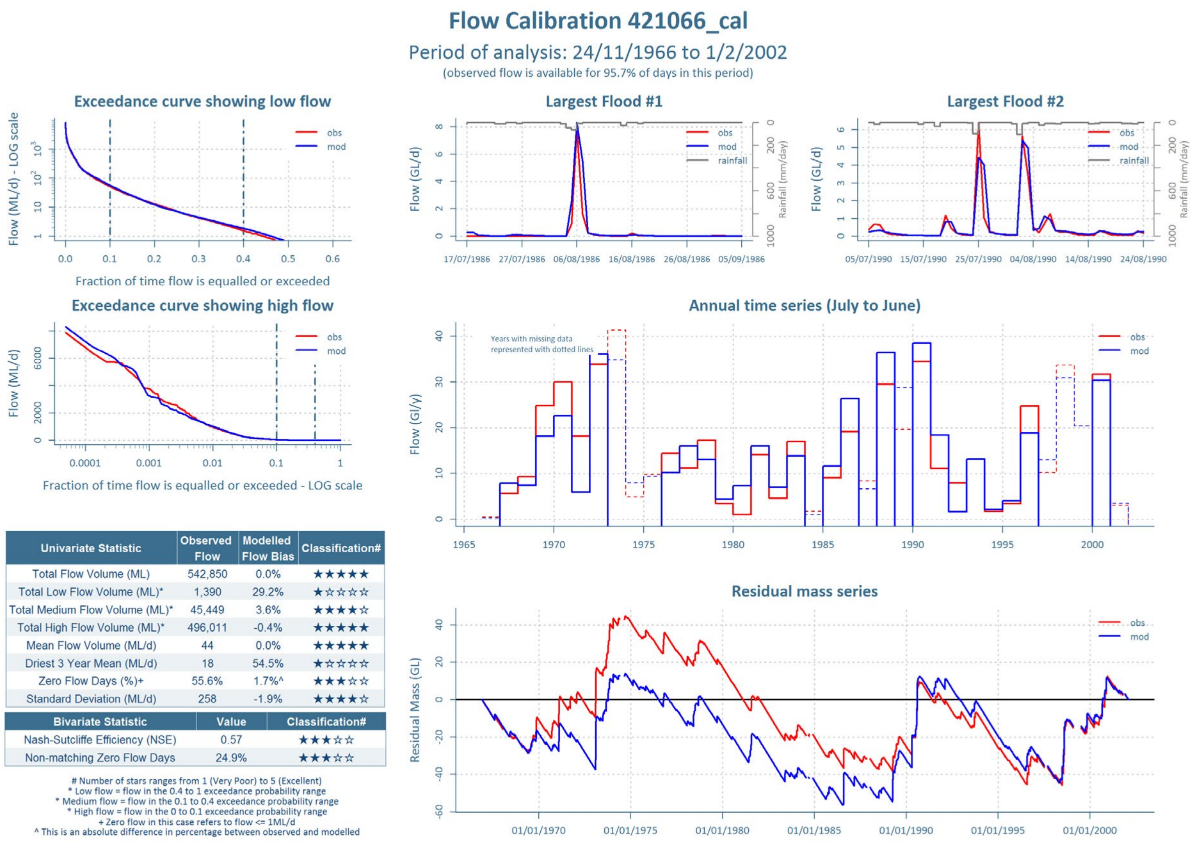


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	327,529	-0.6%	★★★★☆
Total Low Flow Volume (ML)*	1,960	14.7%	★★☆☆☆
Total Medium Flow Volume (ML)*	65,316	3.1%	★★★★☆
Total High Flow Volume (ML)*	260,253	-1.6%	★★★★☆
Mean Flow Volume (ML/d)	49	-0.6%	★★★★☆
Driest 3 Year Mean (ML/d)	22	3.2%	★★★★☆
Zero Flow Days (%)+	8.8%	1.3%^	★★★☆☆
Standard Deviation (ML/d)	214	-3.6%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.36	★★☆☆☆
Non-matching Zero Flow Days	7.4%	★★★★☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.2 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.2 exceedance probability range
\+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 50 Flow calibration graphs for gauging station 421059 Buckinbah Creek @ Yeoval



Flow Calibration 421066_cal

Period of analysis: 24/11/1966 to 1/2/2002

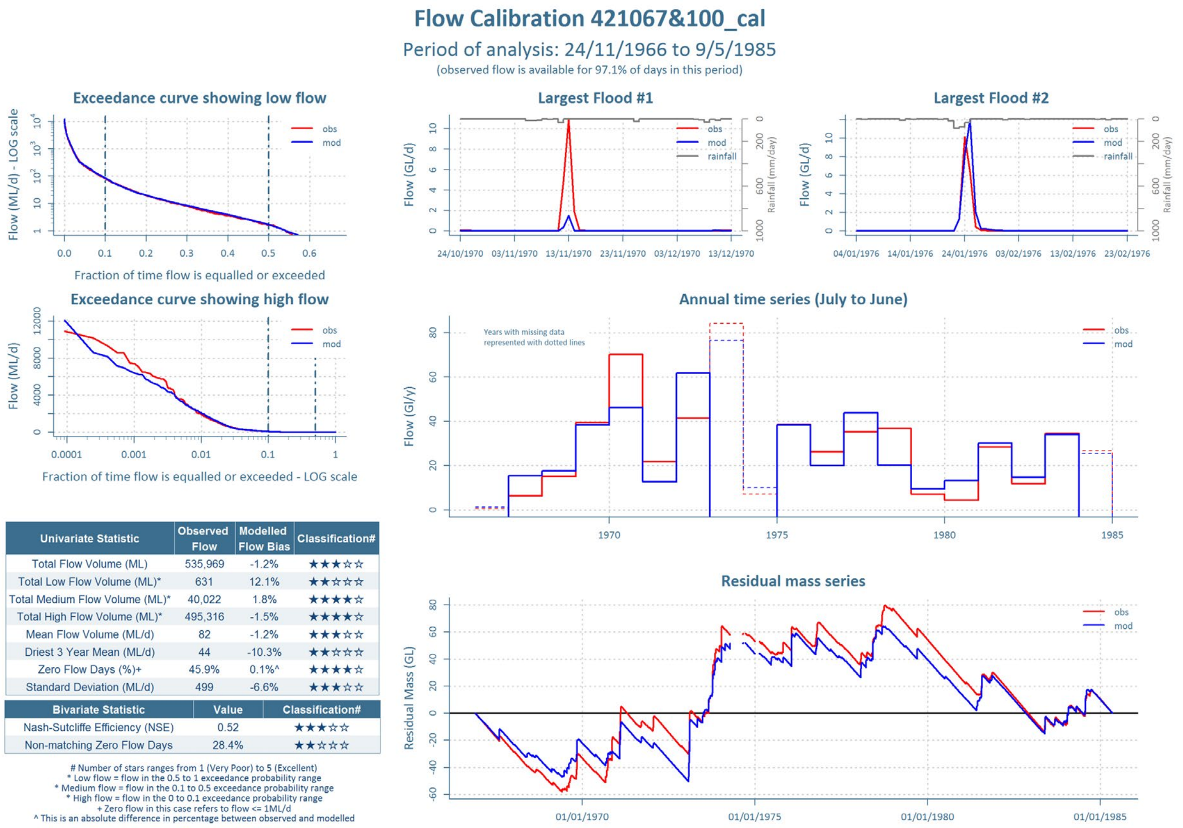
(observed flow is available for 95.7% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	542,850	0.0%	★★★★★
Total Low Flow Volume (ML)*	1,390	29.2%	★☆☆☆☆
Total Medium Flow Volume (ML)*	45,449	3.6%	★★★★☆
Total High Flow Volume (ML)*	496,011	-0.4%	★★★★★
Mean Flow Volume (ML/d)	44	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	18	54.5%	★☆☆☆☆
Zero Flow Days (%)+	55.6%	1.7%^	★★★☆☆
Standard Deviation (ML/d)	258	-1.9%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.57	★★★☆☆
Non-matching Zero Flow Days	24.9%	★★★☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.4 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.4 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
\+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 51 Flow calibration graphs for gauging station 421066 Green Valley Creek @ Hill End



Flow Calibration 421067&100_cal

Period of analysis: 24/11/1966 to 9/5/1985

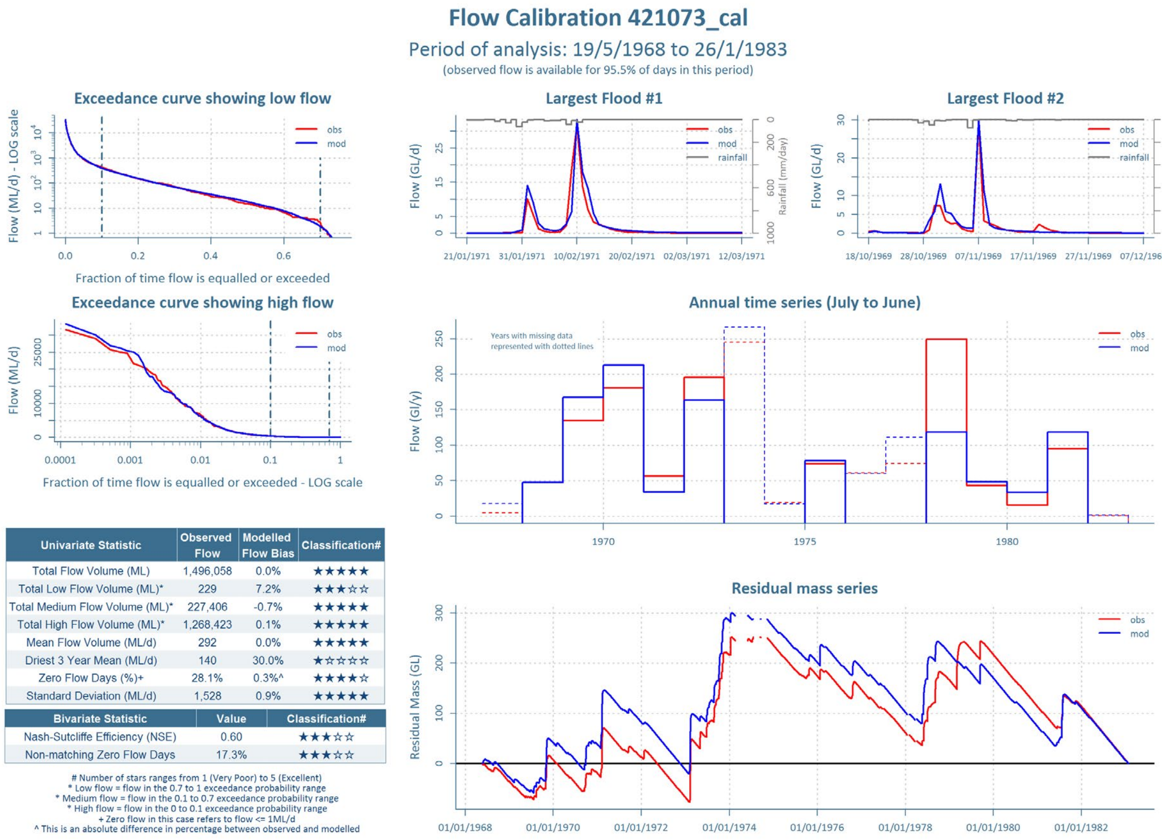
(observed flow is available for 97.1% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	535,969	-1.2%	★★★☆☆
Total Low Flow Volume (ML)*	631	12.1%	★★☆☆☆
Total Medium Flow Volume (ML)*	40,022	1.8%	★★★★☆
Total High Flow Volume (ML)*	495,316	-1.5%	★★★★☆
Mean Flow Volume (ML/d)	82	-1.2%	★★★☆☆
Driest 3 Year Mean (ML/d)	44	-10.3%	★★☆☆☆
Zero Flow Days (%)+	45.9%	0.1%^	★★★★☆
Standard Deviation (ML/d)	499	-6.6%	★★★☆☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.52	★★★☆☆
Non-matching Zero Flow Days	28.4%	★★☆☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.5 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.5 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
\+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 52 Flow calibration graphs for gauging station 421067 & 421100 Pyramul Creek @ Hill End & U/S Hill End Road

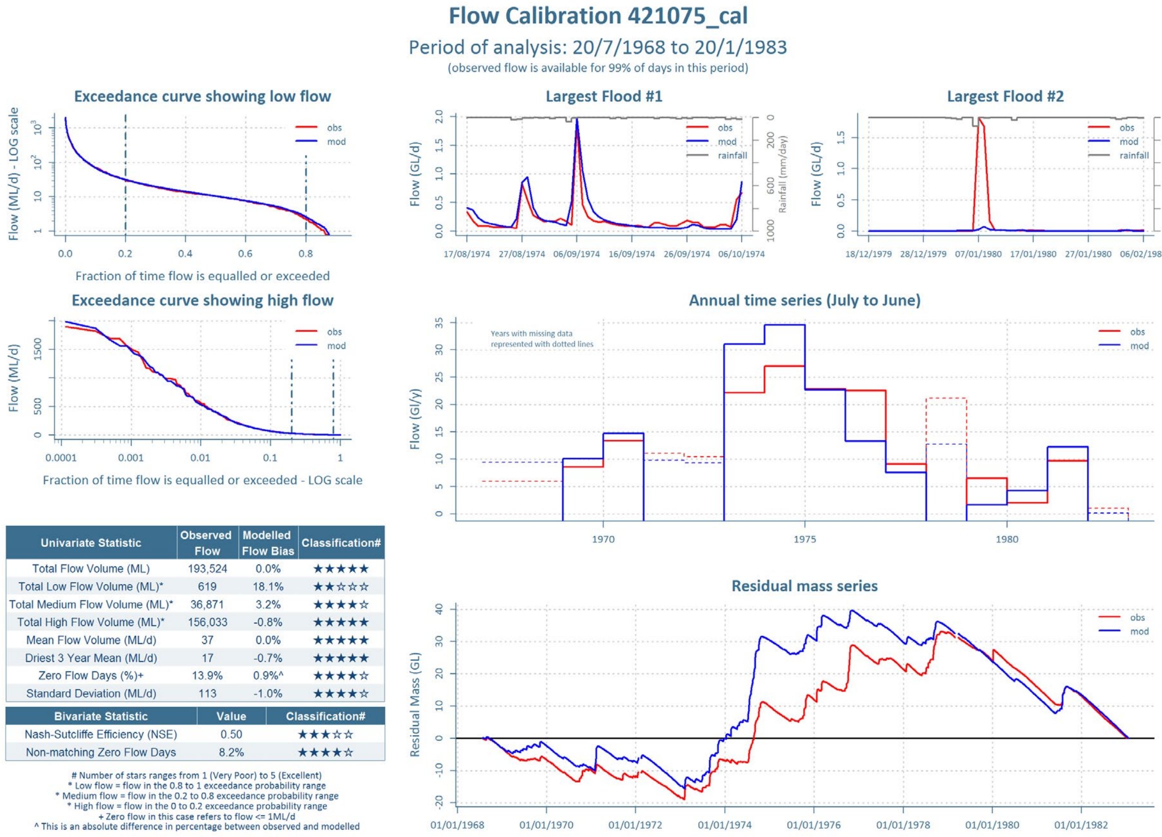


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	1,496,058	0.0%	★★★★★
Total Low Flow Volume (ML)*	229	7.2%	★★★☆☆
Total Medium Flow Volume (ML)*	227,406	-0.7%	★★★★★
Total High Flow Volume (ML)*	1,268,423	0.1%	★★★★★
Mean Flow Volume (ML/d)	292	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	140	30.0%	★☆☆☆☆
Zero Flow Days (%)+	28.1%	0.3%^	★★★★☆
Standard Deviation (ML/d)	1,528	0.9%	★★★★★

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.60	★★★☆☆
Non-matching Zero Flow Days	17.3%	★★★☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.7 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.7 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 53 Flow calibration graphs for gauging station 421073 Meroo Creek @ Yarrabin

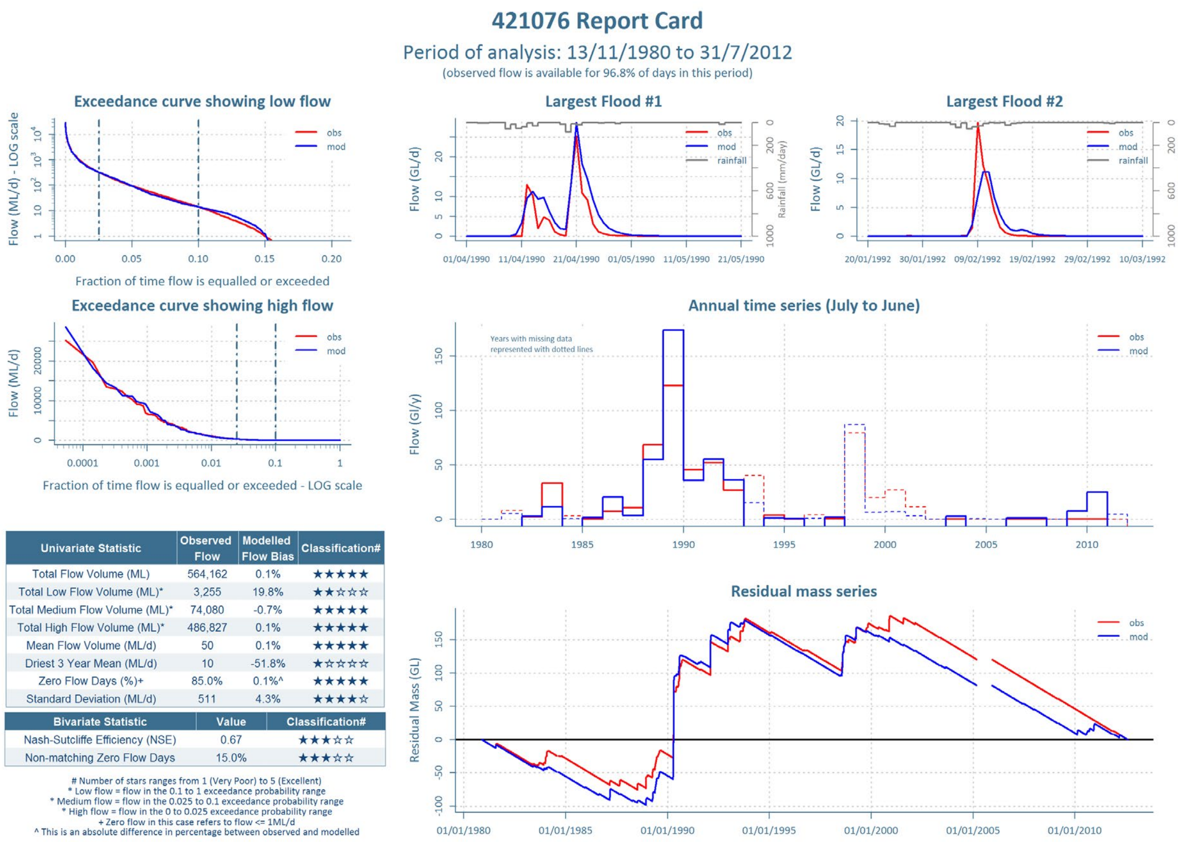


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	193,524	0.0%	★★★★★
Total Low Flow Volume (ML)*	619	18.1%	★★☆☆☆
Total Medium Flow Volume (ML)*	36,871	3.2%	★★★★☆
Total High Flow Volume (ML)*	156,033	-0.8%	★★★★★
Mean Flow Volume (ML/d)	37	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	17	-0.7%	★★★★★
Zero Flow Days (%)+	13.9%	0.9%^	★★★★☆
Standard Deviation (ML/d)	113	-1.0%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.50	★★★☆☆
Non-matching Zero Flow Days	8.2%	★★★★☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.2 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.2 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 54 Flow calibration graphs for gauging station 421075 Evans Plains Creek @ Bathurst

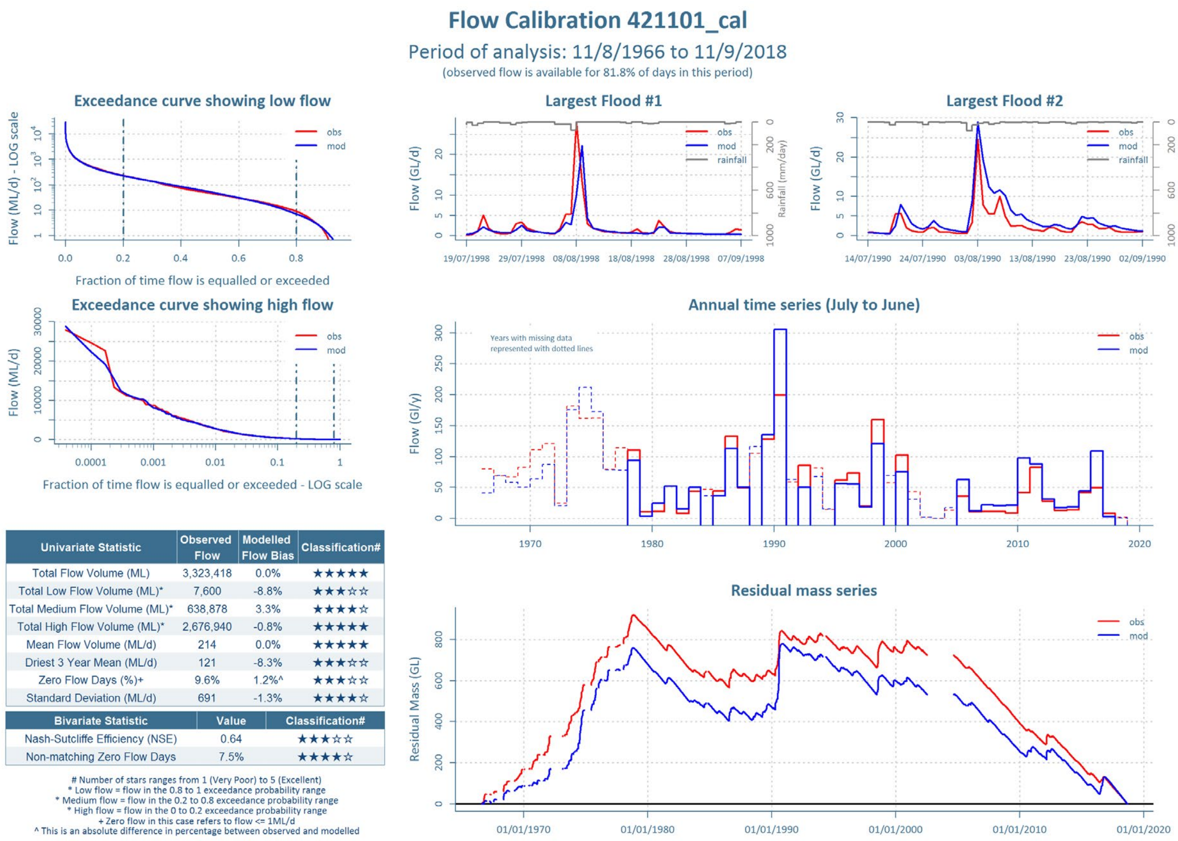


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	564,162	0.1%	★★★★★
Total Low Flow Volume (ML)*	3,255	19.8%	★★☆☆☆
Total Medium Flow Volume (ML)*	74,080	-0.7%	★★★★★
Total High Flow Volume (ML)*	486,827	0.1%	★★★★★
Mean Flow Volume (ML/d)	50	0.1%	★★★★★
Driest 3 Year Mean (ML/d)	10	-51.8%	★☆☆☆☆
Zero Flow Days (%)+	85.0%	0.1%^	★★★★★
Standard Deviation (ML/d)	511	4.3%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.67	★★★☆☆
Non-matching Zero Flow Days	15.0%	★★★☆☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.1 to 1 exceedance probability range
* Medium flow = flow in the 0.025 to 0.1 exceedance probability range
* High flow = flow in the 0 to 0.025 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 55 Flow calibration graphs for gauging station 421076 Bogan River @ Peak Hill No.2

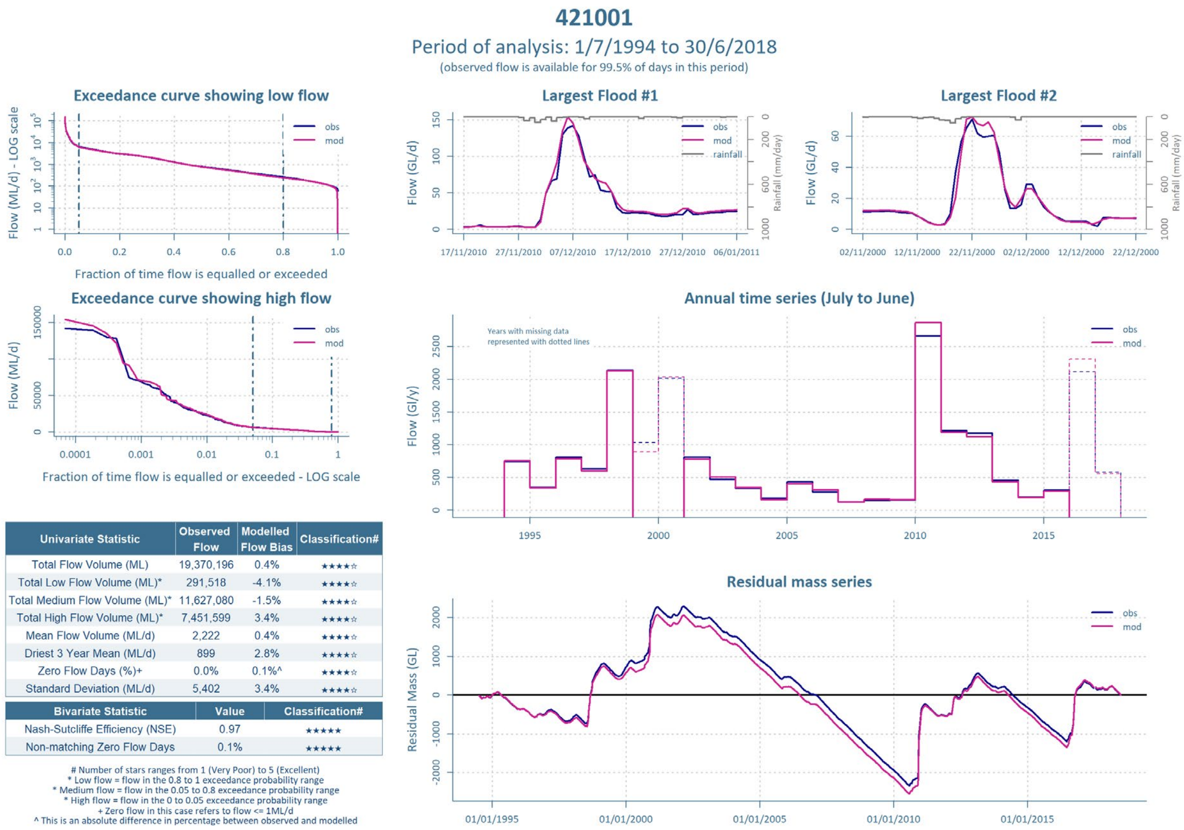


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	3,323,418	0.0%	★★★★★
Total Low Flow Volume (ML)*	7,600	-8.8%	★★★☆☆
Total Medium Flow Volume (ML)*	638,878	3.3%	★★★★☆
Total High Flow Volume (ML)*	2,676,940	-0.8%	★★★★★
Mean Flow Volume (ML/d)	214	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	121	-8.3%	★★★☆☆
Zero Flow Days (%)+	9.6%	1.2%^	★★★☆☆
Standard Deviation (ML/d)	691	-1.3%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.64	★★★☆☆
Non-matching Zero Flow Days	7.5%	★★★★☆

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.2 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.2 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 56 Flow calibration graphs for gauging station 421101 Campbells River @ U/S Ben Chiefly Dam



Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	19,370,196	0.4%	★★★★☆
Total Low Flow Volume (ML)*	291,518	-4.1%	★★★★☆
Total Medium Flow Volume (ML)*	11,627,080	-1.5%	★★★★☆
Total High Flow Volume (ML)*	7,451,599	3.4%	★★★★☆
Mean Flow Volume (ML/d)	2,222	0.4%	★★★★☆
Driest 3 Year Mean (ML/d)	899	2.8%	★★★★☆
Zero Flow Days (%)+	0.0%	0.1%^	★★★★☆
Standard Deviation (ML/d)	5,402	3.4%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.97	★★★★★
Non-matching Zero Flow Days	0.1%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.05 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.05 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

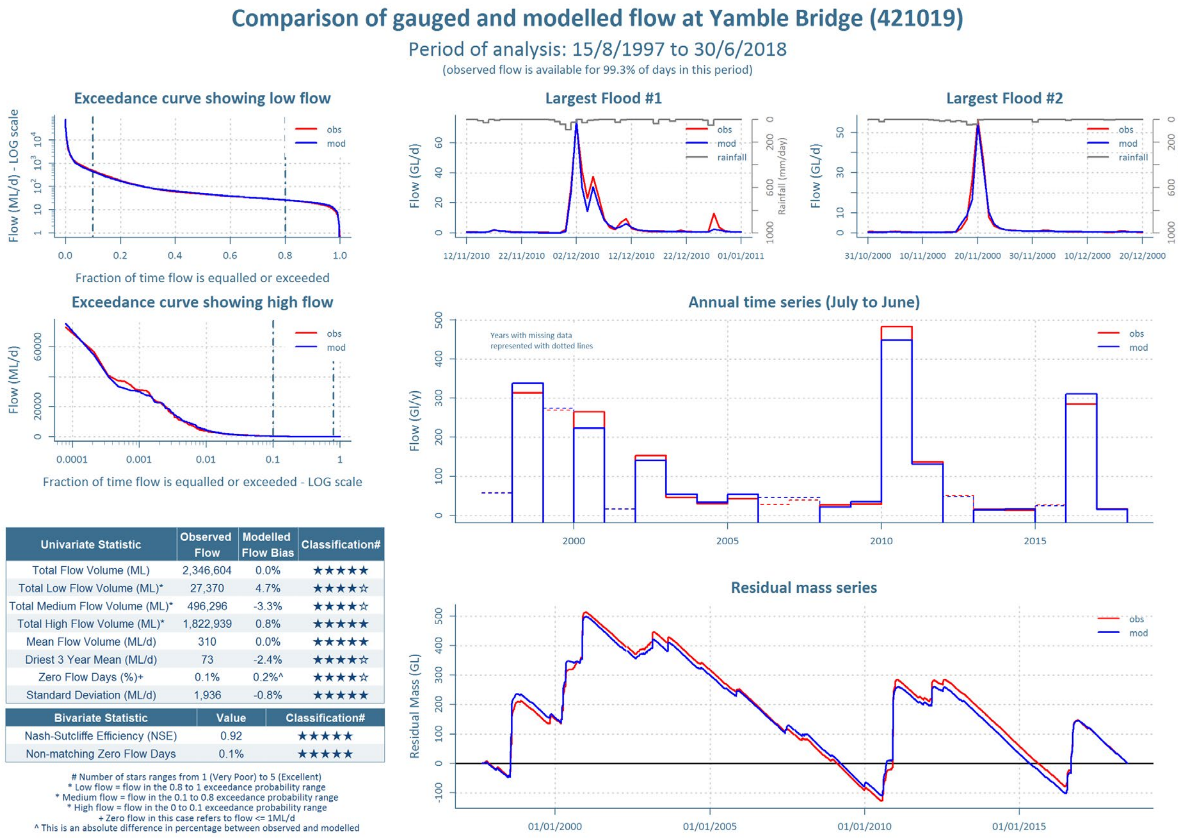
Figure 57 Flow calibration graphs for reach to Gauge 421001 Macquarie River @ Dubbo

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	8,460,540	1.3%	★★★☆☆
Total Low Flow Volume (ML)*	306,950	18.2%	★★☆☆☆
Total Medium Flow Volume (ML)*	4,986,675	2.3%	★★★★☆
Total High Flow Volume (ML)*	3,166,915	-2.0%	★★★★☆
Mean Flow Volume (ML/d)	3,860	1.3%	★★★☆☆
Driest 3 Year Mean (ML/d)	3,531	-3.1%	★★★★☆
Zero Flow Days (%)+	0.0%	0.0%^	★★★★★
Standard Deviation (ML/d)	6,412	-2.9%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.98	★★★★★
Non-matching Zero Flow Days	0.0%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.05 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.05 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 58 Flow calibration graphs for reach to Gauge 421006 Macquarie River @ Narromine



Comparison of gauged and modelled flow at Yamble Bridge (421019)

Period of analysis: 15/8/1997 to 30/6/2018

(observed flow is available for 99.3% of days in this period)

Exceedance curve showing low flow

Exceedance curve showing high flow

Largest Flood #1

Largest Flood #2

Annual time series (July to June)

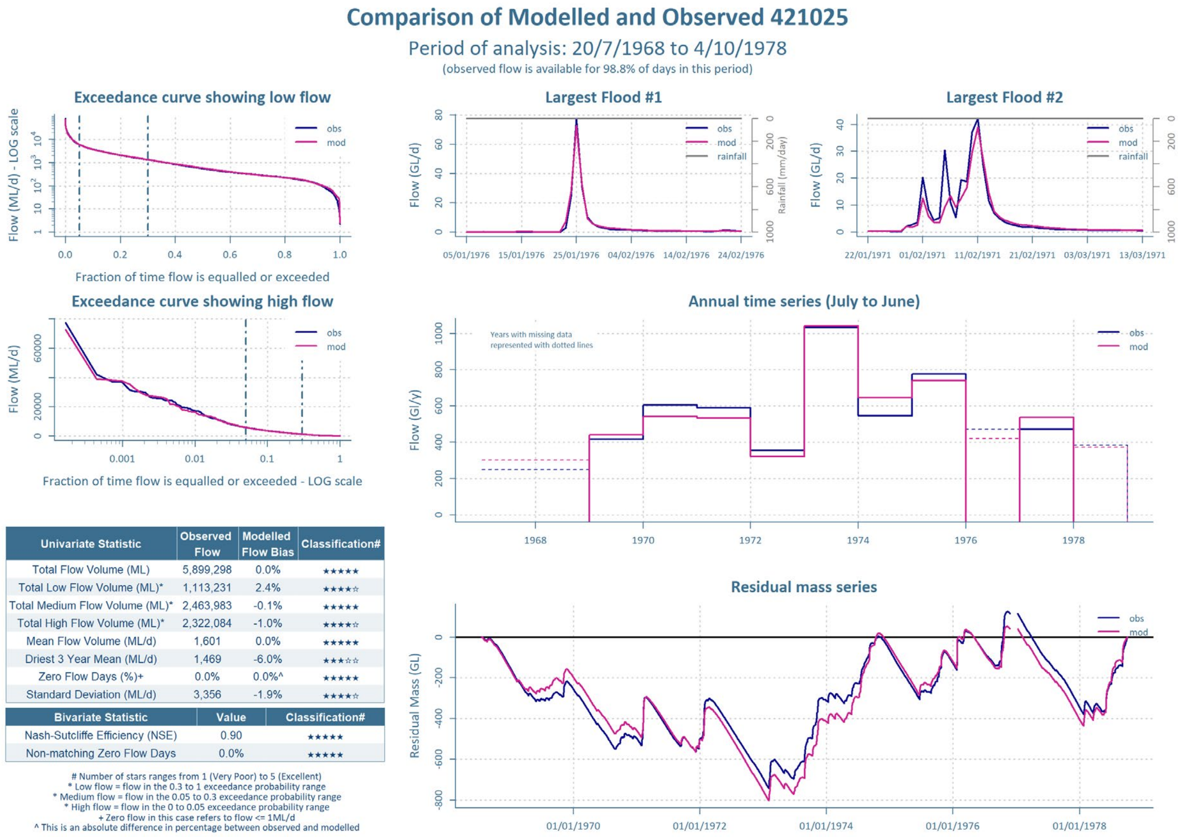
Residual mass series

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	2,346,604	0.0%	★★★★★
Total Low Flow Volume (ML)*	27,370	4.7%	★★★★☆
Total Medium Flow Volume (ML)*	496,296	-3.3%	★★★★☆
Total High Flow Volume (ML)*	1,822,939	0.8%	★★★★★
Mean Flow Volume (ML/d)	310	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	73	-2.4%	★★★★☆
Zero Flow Days (%)+	0.1%	0.2%^	★★★★☆
Standard Deviation (ML/d)	1,936	-0.8%	★★★★★

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.92	★★★★★
Non-matching Zero Flow Days	0.1%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 59 Flow calibration graphs for reach to Gauge 421019 Cudgegong River @ Yamble Bridge



Comparison of Modelled and Observed 421025

Period of analysis: 20/7/1968 to 4/10/1978

(observed flow is available for 98.8% of days in this period)

Exceedance curve showing low flow

Exceedance curve showing high flow

Largest Flood #1

Largest Flood #2

Annual time series (July to June)

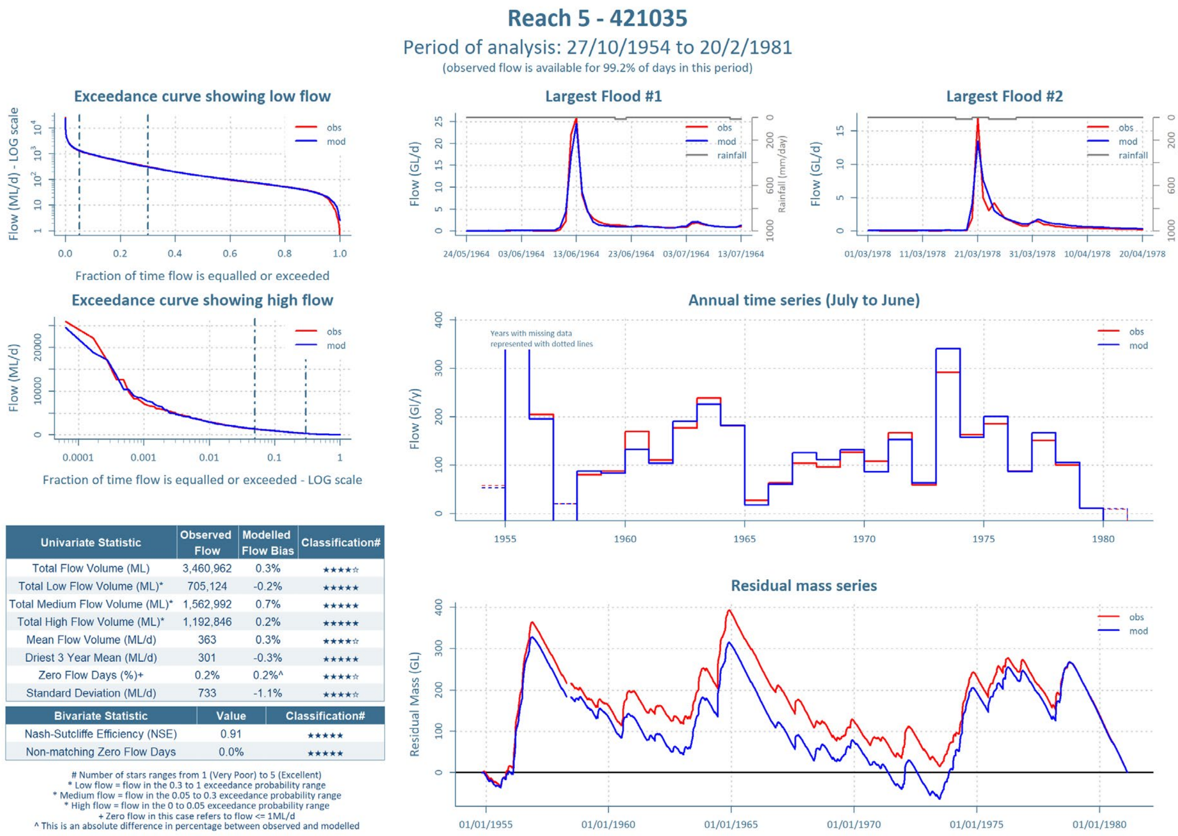
Residual mass series

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	5,899,298	0.0%	★★★★★
Total Low Flow Volume (ML)*	1,113,231	2.4%	★★★★☆
Total Medium Flow Volume (ML)*	2,463,983	-0.1%	★★★★★
Total High Flow Volume (ML)*	2,322,084	-1.0%	★★★★☆
Mean Flow Volume (ML/d)	1,601	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	1,469	-6.0%	★★★☆☆
Zero Flow Days (%)+	0.0%	0.0%^	★★★★★
Standard Deviation (ML/d)	3,356	-1.9%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.90	★★★★★
Non-matching Zero Flow Days	0.0%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.3 to 1 exceedance probability range
* Medium flow = flow in the 0.05 to 0.3 exceedance probability range
* High flow = flow in the 0 to 0.05 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 60 Flow calibration graphs for reach to Gauge 421025 Macquarie River @ Bruinbun

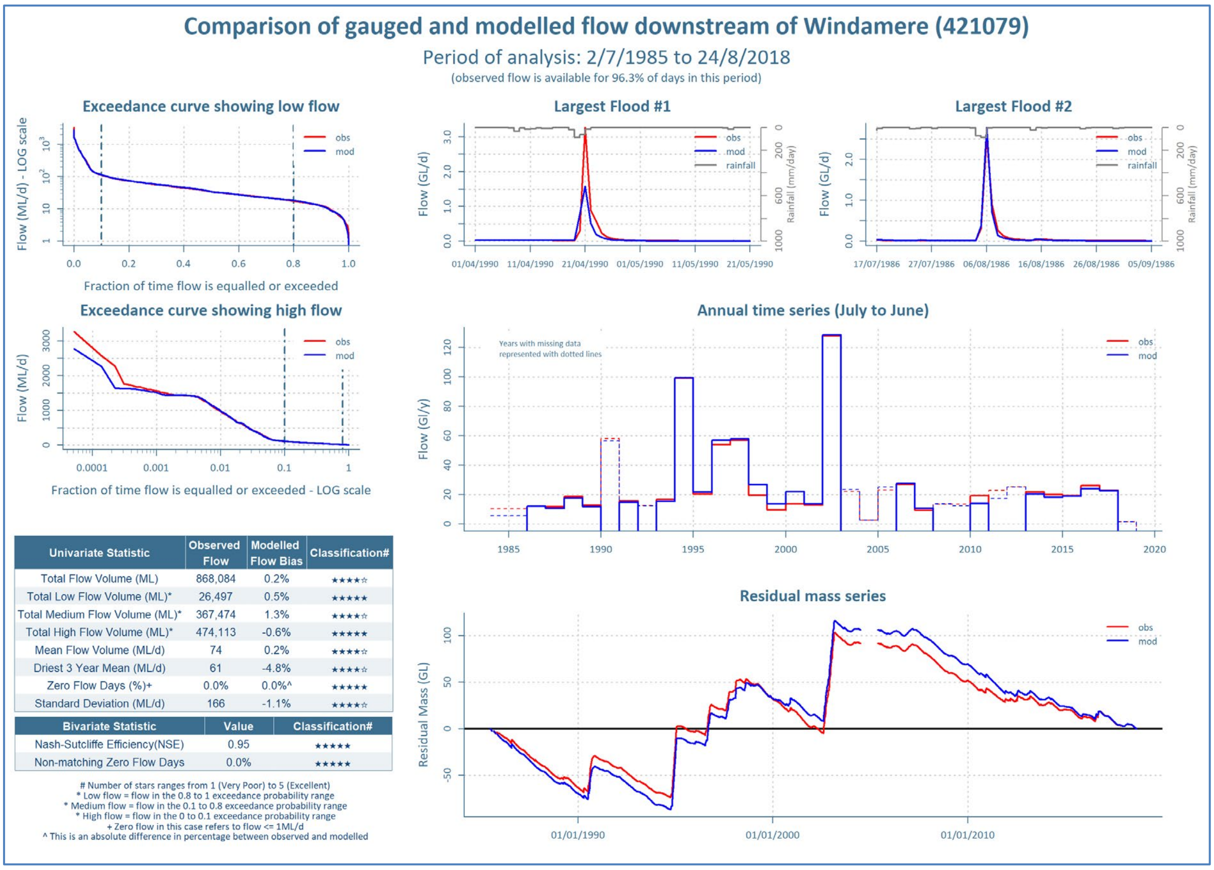


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	3,460,962	0.3%	★★★★☆
Total Low Flow Volume (ML)*	705,124	-0.2%	★★★★★
Total Medium Flow Volume (ML)*	1,562,992	0.7%	★★★★★
Total High Flow Volume (ML)*	1,192,846	0.2%	★★★★★
Mean Flow Volume (ML/d)	363	0.3%	★★★★☆
Driest 3 Year Mean (ML/d)	301	-0.3%	★★★★★
Zero Flow Days (%)+	0.2%	0.2%^	★★★★☆
Standard Deviation (ML/d)	733	-1.1%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency (NSE)	0.91	★★★★★
Non-matching Zero Flow Days	0.0%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.3 to 1 exceedance probability range
* Medium flow = flow in the 0.05 to 0.3 exceedance probability range
* High flow = flow in the 0 to 0.05 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 61 Flow calibration graphs for reach to Gauge 421035 Fish River @ Tarana

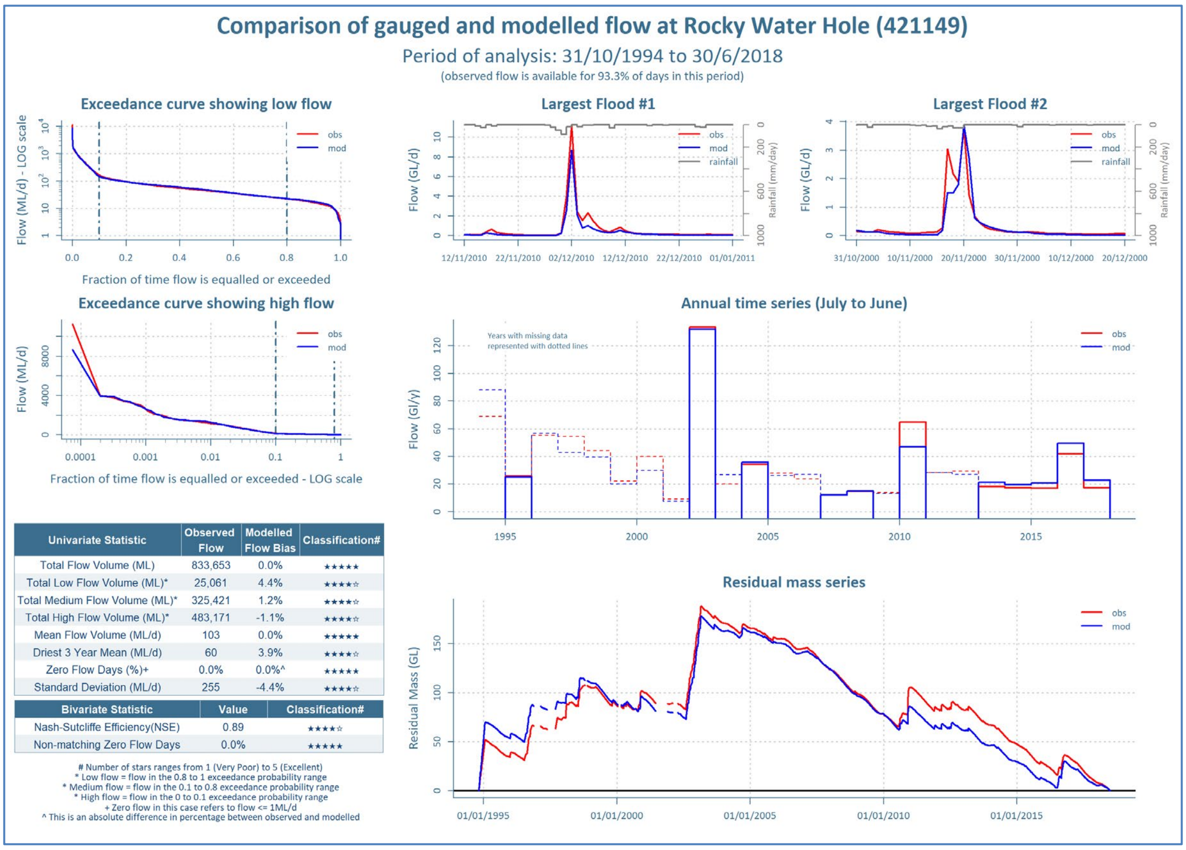


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	868,084	0.2%	★★★★☆
Total Low Flow Volume (ML)*	26,497	0.5%	★★★★★
Total Medium Flow Volume (ML)*	367,474	1.3%	★★★★☆
Total High Flow Volume (ML)*	474,113	-0.6%	★★★★★
Mean Flow Volume (ML/d)	74	0.2%	★★★★☆
Driest 3 Year Mean (ML/d)	61	-4.8%	★★★★☆
Zero Flow Days (%)+	0.0%	0.0%^	★★★★★
Standard Deviation (ML/d)	166	-1.1%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency(NSE)	0.95	★★★★★
Non-matching Zero Flow Days	0.0%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 62 Flow calibration graphs for reach to Gauge 421079 (Windamere inflows)



Comparison of gauged and modelled flow at Rocky Water Hole (421149)

Period of analysis: 31/10/1994 to 30/6/2018

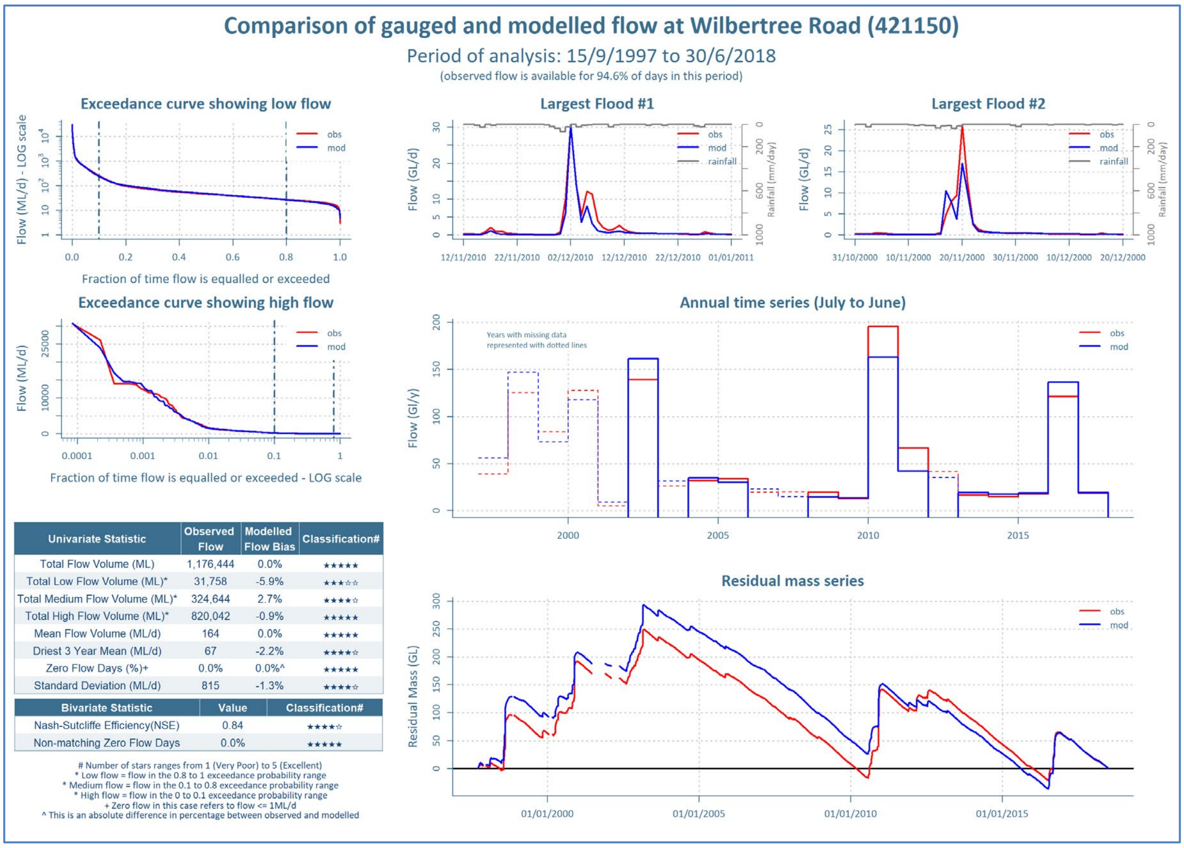
(observed flow is available for 93.3% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	833,653	0.0%	★★★★★
Total Low Flow Volume (ML)*	25,061	4.4%	★★★★☆
Total Medium Flow Volume (ML)*	325,421	1.2%	★★★★☆
Total High Flow Volume (ML)*	483,171	-1.1%	★★★★☆
Mean Flow Volume (ML/d)	103	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	60	3.9%	★★★★☆
Zero Flow Days (%)+	0.0%	0.0%^	★★★★★
Standard Deviation (ML/d)	255	-4.4%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency(NSE)	0.89	★★★★☆
Non-matching Zero Flow Days	0.0%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 63 Flow calibration graphs for reach to Gauge 421149 Cudgegong River @ Rocky Water Hole



Comparison of gauged and modelled flow at Wilbertree Road (421150)

Period of analysis: 15/9/1997 to 30/6/2018

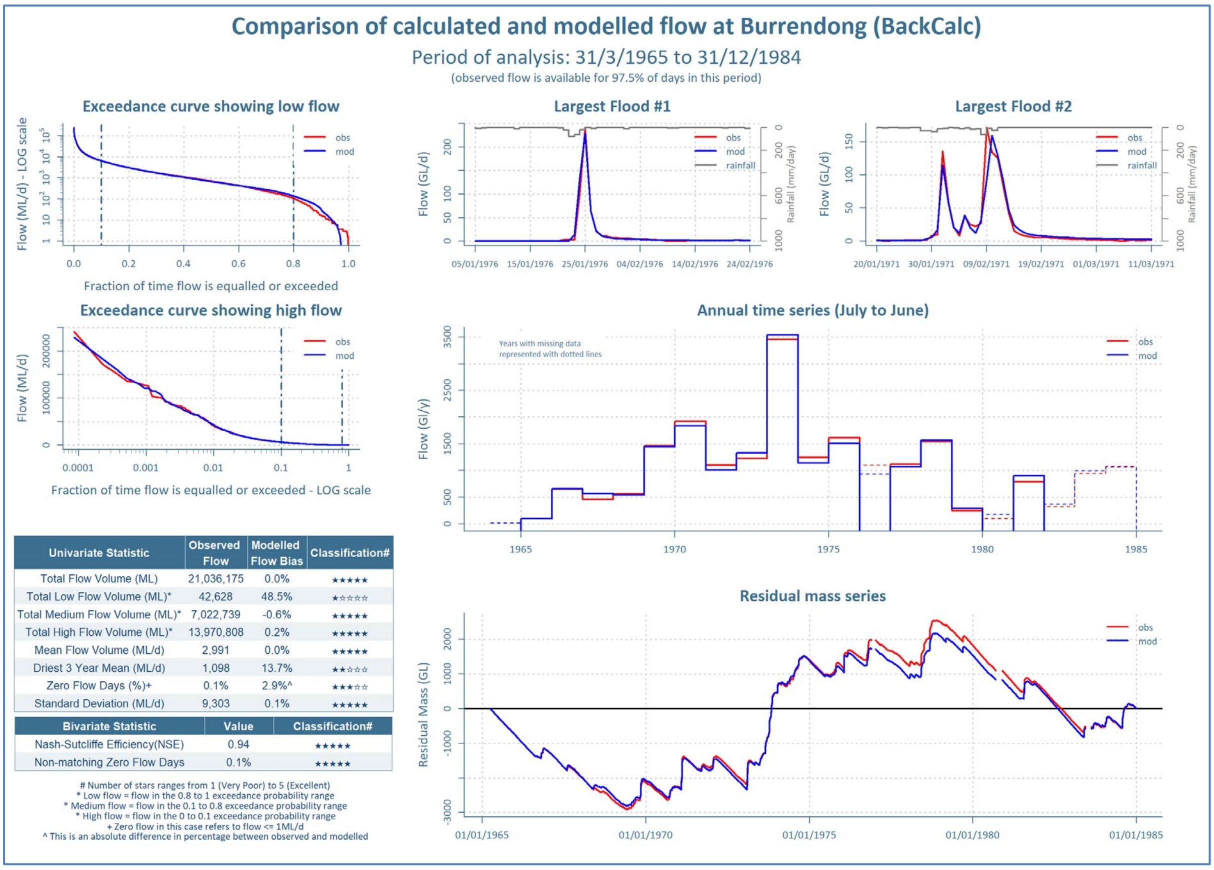
(observed flow is available for 94.6% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	1,176,444	0.0%	★★★★★
Total Low Flow Volume (ML)*	31,758	-5.9%	★★★☆☆
Total Medium Flow Volume (ML)*	324,644	2.7%	★★★★☆
Total High Flow Volume (ML)*	820,042	-0.9%	★★★★★
Mean Flow Volume (ML/d)	164	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	67	-2.2%	★★★★☆
Zero Flow Days (%)+	0.0%	0.0%^	★★★★★
Standard Deviation (ML/d)	815	-1.3%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency(NSE)	0.84	★★★★☆
Non-matching Zero Flow Days	0.0%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 64 Flow calibration graphs for reach to Gauge 421150 Cudgegong River @ Wilbertree

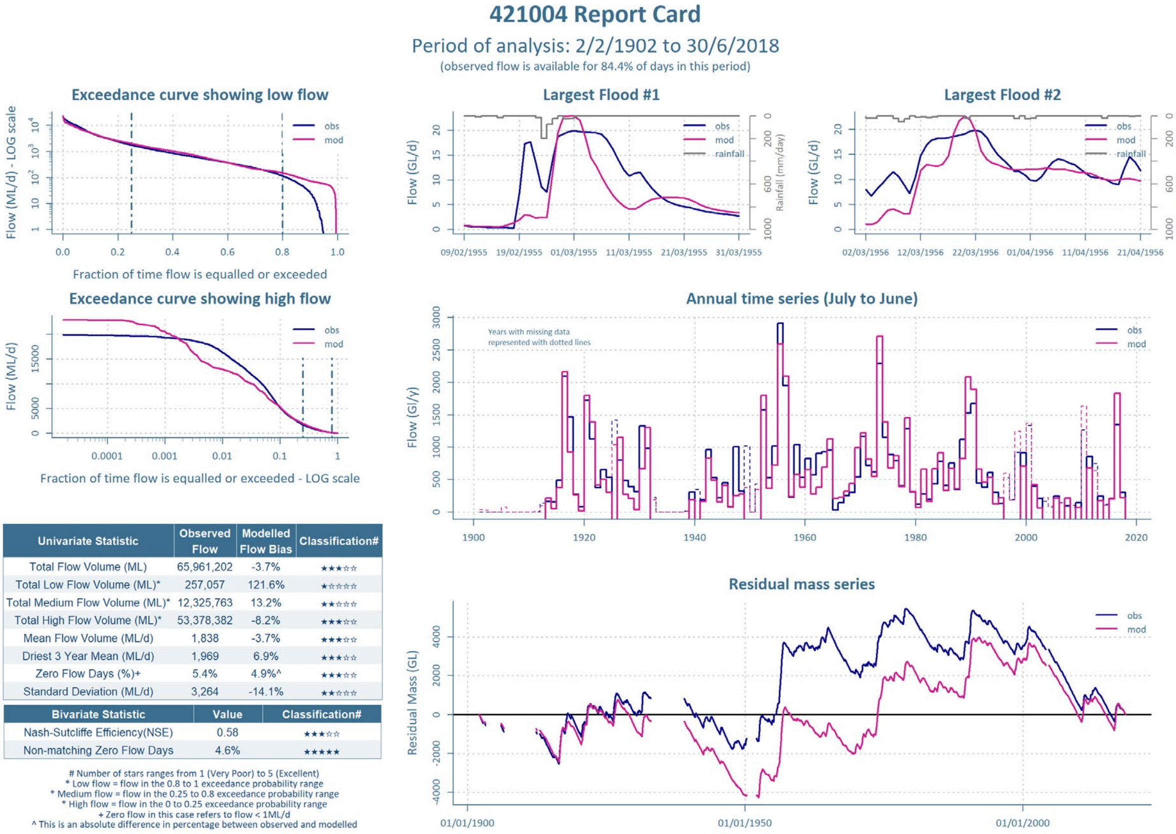


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	21,036,175	0.0%	★★★★★
Total Low Flow Volume (ML)*	42,628	48.5%	★☆☆☆☆
Total Medium Flow Volume (ML)*	7,022,739	-0.6%	★★★★★
Total High Flow Volume (ML)*	13,970,808	0.2%	★★★★★
Mean Flow Volume (ML/d)	2,991	0.0%	★★★★★
Driest 3 Year Mean (ML/d)	1,098	13.7%	★★☆☆☆
Zero Flow Days (%)+	0.1%	2.9%^	★★★☆☆
Standard Deviation (ML/d)	9,303	0.1%	★★★★★

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency(NSE)	0.94	★★★★★
Non-matching Zero Flow Days	0.1%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.1 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.1 exceedance probability range
+ Zero flow in this case refers to flow <= 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 65 Flow calibration graphs for Burrendong Dam inflows

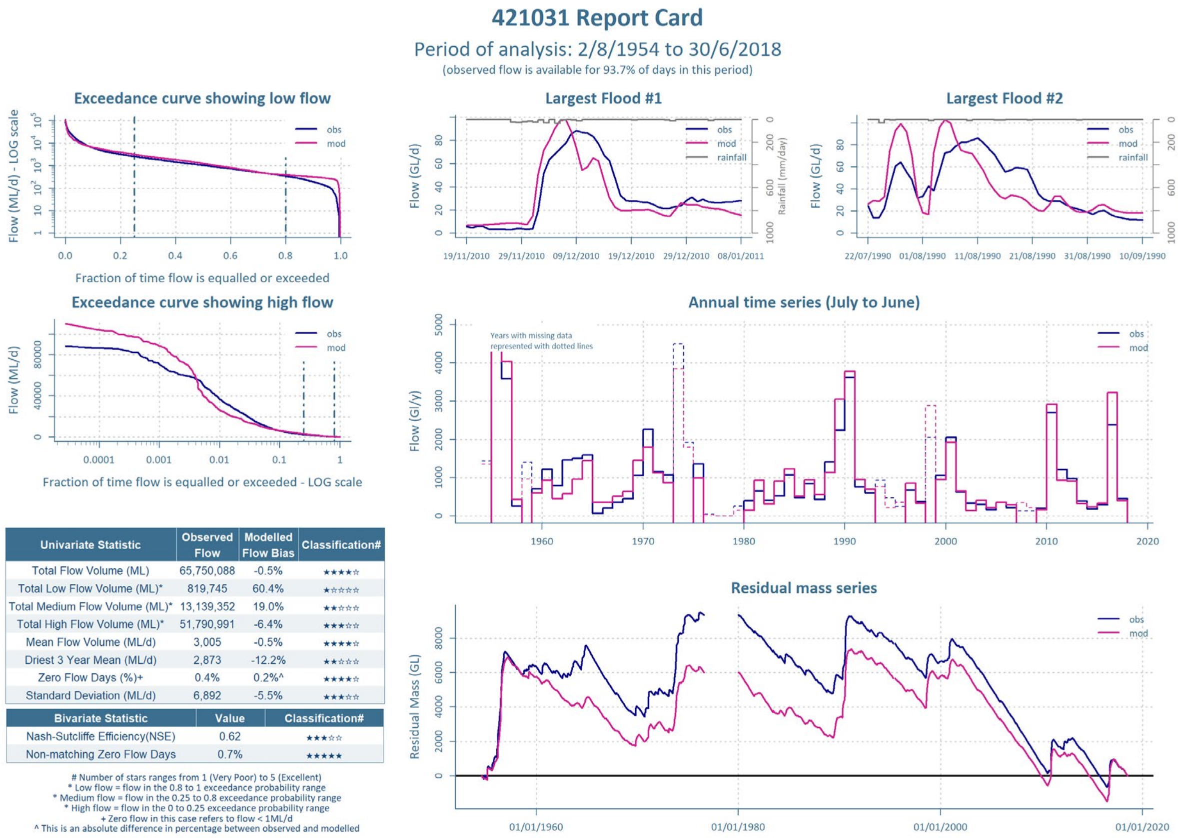


Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	65,961,202	-3.7%	★★★☆☆
Total Low Flow Volume (ML)*	257,057	121.6%	★☆☆☆☆
Total Medium Flow Volume (ML)*	12,325,763	13.2%	★★☆☆☆
Total High Flow Volume (ML)*	53,378,382	-8.2%	★★★☆☆
Mean Flow Volume (ML/d)	1,838	-3.7%	★★★☆☆
Driest 3 Year Mean (ML/d)	1,969	6.9%	★★★☆☆
Zero Flow Days (%)+	5.4%	4.9%^	★★★☆☆
Standard Deviation (ML/d)	3,264	-14.1%	★★☆☆☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency(NSE)	0.58	★★★☆☆
Non-matching Zero Flow Days	4.6%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.25 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.25 exceedance probability range
+ Zero flow in this case refers to flow < 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 66 Flow calibration graphs for reach to Gauge 421150 Macquarie River @ Warren Weir



421031 Report Card

Period of analysis: 2/8/1954 to 30/6/2018

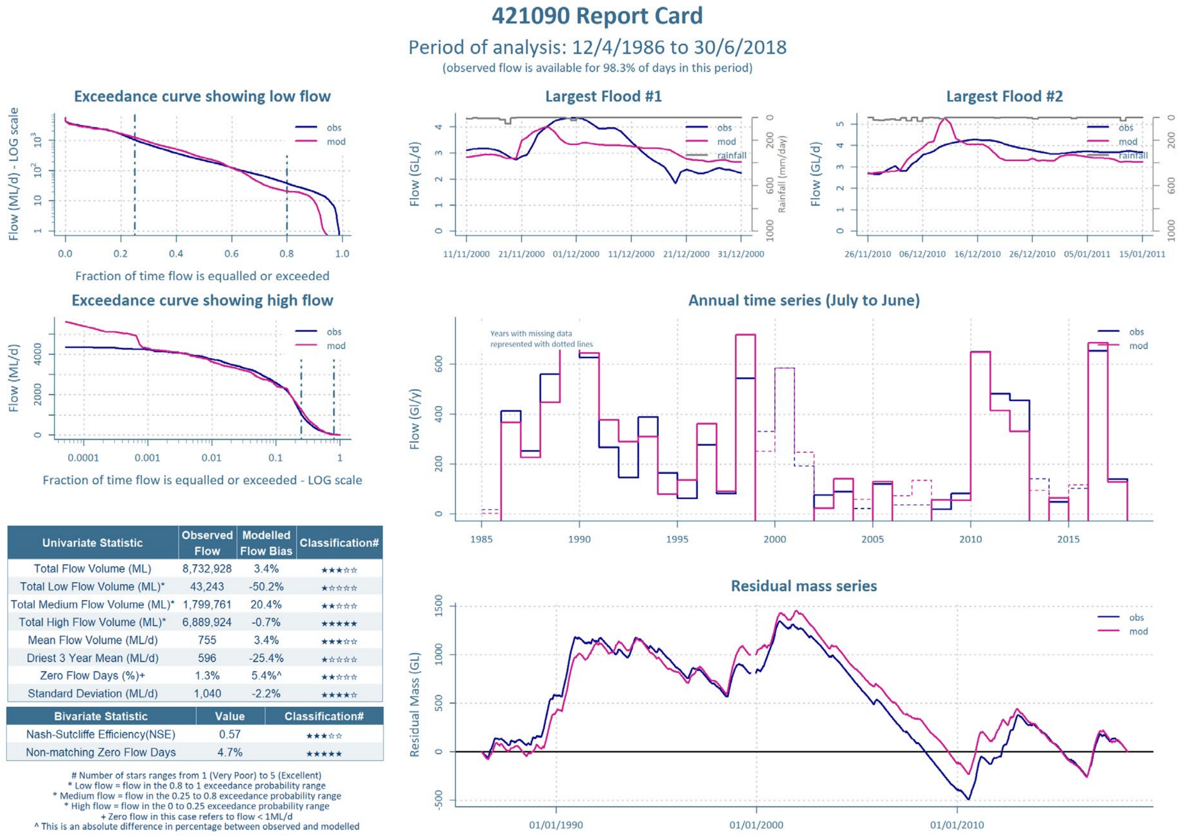
(observed flow is available for 93.7% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	65,750,088	-0.5%	★★★★☆
Total Low Flow Volume (ML)*	819,745	60.4%	★☆☆☆☆
Total Medium Flow Volume (ML)*	13,139,352	19.0%	★★☆☆☆
Total High Flow Volume (ML)*	51,790,991	-6.4%	★★★☆☆
Mean Flow Volume (ML/d)	3,005	-0.5%	★★★★☆
Driest 3 Year Mean (ML/d)	2,873	-12.2%	★★☆☆☆
Zero Flow Days (%)+	0.4%	0.2%^	★★★★☆
Standard Deviation (ML/d)	6,892	-5.5%	★★★☆☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency(NSE)	0.62	★★★☆☆
Non-matching Zero Flow Days	0.7%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.25 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.25 exceedance probability range
+ Zero flow in this case refers to flow < 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 67 Flow calibration graphs for reach to Gauge 421031 Macquarie River @ Gin Gin



421090 Report Card

Period of analysis: 12/4/1986 to 30/6/2018

(observed flow is available for 98.3% of days in this period)

Univariate Statistic	Observed Flow	Modelled Flow Bias	Classification#
Total Flow Volume (ML)	8,732,928	3.4%	★★★☆☆
Total Low Flow Volume (ML)*	43,243	-50.2%	★☆☆☆☆
Total Medium Flow Volume (ML)*	1,799,761	20.4%	★★☆☆☆
Total High Flow Volume (ML)*	6,889,924	-0.7%	★★★★★
Mean Flow Volume (ML/d)	755	3.4%	★★★☆☆
Driest 3 Year Mean (ML/d)	596	-25.4%	★☆☆☆☆
Zero Flow Days (%)+	1.3%	5.4%^	★★☆☆☆
Standard Deviation (ML/d)	1,040	-2.2%	★★★★☆

Bivariate Statistic	Value	Classification#
Nash-Sutcliffe Efficiency(NSE)	0.57	★★★☆☆
Non-matching Zero Flow Days	4.7%	★★★★★

Number of stars ranges from 1 (Very Poor) to 5 (Excellent)
* Low flow = flow in the 0.8 to 1 exceedance probability range
* Medium flow = flow in the 0.25 to 0.8 exceedance probability range
* High flow = flow in the 0 to 0.25 exceedance probability range
+ Zero flow in this case refers to flow < 1ML/d
^ This is an absolute difference in percentage between observed and modelled

Figure 68 Flow calibration graphs for reach to Gauge 421090 Macquarie River @ d/s Marebone Weir

Appendix J Model version

The final version of the model and software used for reporting results are:

- File Name MACQ_IEW_20220908.sqq
- IQQM Version iqmgui_v7_101_0_rc1

Appendix K 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[26].

Table 50 Abbreviations used in the report

Abbreviation	Description
ABARE	Australian Bureau of Agricultural Research
ABS	Australian Bureau of Statistics
AEP	Annual Exceedance Probability (the probability of a flow of a certain size occurring
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
DS	downstream
ESID	Extraction Site IDentification number
HEW	Held Environmental Water
Hydstra	Product brand name for database that stores water data
IBQ	Irrigator Behaviour Questionnaire (used interchangeably with ‘farm survey’)
IGA	Inter-Governmental Agreement
IQQM	Integrated Quantity-Quality Model
LANDSAT	A series of Satellites that monitor the Earth’s surface
LIDAR	LIght Detecting And Ranging
MIKE	MIKE Flood Model, developed by Danish Hydraulic Institute. Globally widely used
MODIS	Moderate Resolution Imaging Spectroradiometer
NRAR	Natural Resources Access Regulator
NSE	Nash-Sutcliffe Efficiency
OEH	Office of Environment and Heritage
OFS	On-Farm Storage
SBM	Storage bathymetry model
SDL	Sustainable Diversion Limit

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[26] 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

Abbreviation	Description
SILO	Scientific Information for Land Owners
TOL	Transmission and Operational Loss
WAS	Water Accounting System (database)
WLS	Water Licensing System
WSP	Water Sharing Plan

Table 51 Terms used in the report

Term	Description
2008/2009 Scenario	Uses the levels of irrigation infrastructure, water licences, and management rules in the Macquarie regulated river system in place at the start of 2008/09
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 the lesser of the Cap and WSP scenarios, also referred to as the Plan Limit Scenario
Cap Scenario	Uses the irrigation infrastructure, water licences, and management rules in place at 30 June 1994, to assess the diversions permissible under the Murray-Darling Basin Ministerial Council's Cap on diversions
Current Conditions Scenario	Uses the best available (more contemporary than 2008) information on current levels of irrigation infrastructure, water licences, and current water management arrangements, in the Macquarie regulated river system
Eligible Development Scenario	Uses the levels of irrigation infrastructure determined to be eligible for floodplain harvesting entitlement, water licences, and management rules in the Macquarie regulated river system as at the start of 2008/09
Macquarie Valley model	Shortened term for the Macquarie Valley regulated river system model
Macquarie WSP	Shortened term for the Water Sharing Plan for the Macquarie Regulated River Water Sources 2020
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 Compliance Scenario	See BDL Scenario
Scenario Input Set	Each scenario has its unique set of input parameters. The model provides functionality to store these as a set of parameters. The model can then be run with a unique input set that represents that scenario. Within the modelling platform, sets can be named. These are listed in the companion Scenarios report (DPIE Water 2021a)
Source	Australian National Hydrological Modelling platform, managed by eWater and adopted by the department as its default modelling platform (to replace IQQM)

Term	Description
the policy	Shortened term for the *NSW Floodplain Harvesting Policy*
WSP Scenario	Uses the irrigation infrastructure in place in the 1999/00 water year, and the management arrangements and water licences set out in the water sharing plan