Department of Planning and Environment

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Building the river system model for the Barwon-Darling Valley unregulated river system

Conceptualisation, construction and calibration

May 2022

Acknowledgement of Country

The Department of Planning and Environment acknowledges that it stands on Aboriginal land. We acknowledge the Traditional Custodians of the land and we show our respect for Elders past, present and emerging through thoughtful and collaborative approaches to our work, seeking to demonstrate our ongoing commitment to providing places in which Aboriginal people are included socially, culturally and economically.

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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 Murray-Darling 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 update of the river system model for the Barwon-Darling Valley unregulated river system. It includes sections that describe the Valley (section 3), and how it has been represented in the model. This extends beyond the physical components of the river system (section 4) to water licensing (section 5), water users (section 6) and water management (section 7). The model developers describe their approach to the updated 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, reference is made to the results of broader sensitivity tests that 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 updated river system model; and (b) recommendations for further data collection to reduce residual uncertainty in the model. Extensive supporting material is provided in 6 appendices. Key findings and messages from the model build process are now reported.

Modelling approach

The existing Barwon-Darling Valley river system model has been used to support contemporary water management decisions in the Barwon-Darling Valley, 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. The existing Barwon-Darling Valley river system model already represents individual water users and floodplain harvesting. The objective of this model update is to update farm infrastructure and key floodplain harvesting processes in the model using best available information to determine volumetric entitlements for floodplain harvesting. Six design criteria were established to realise these objectives across all of the northern NSW valleys where floodplain harvesting licensing is being implemented (Section 1): represent key processes affecting water availability and sharing; use a sufficiently long period of climate data to capture the climate variability; have detailed spatial resolution to allow system analysis and reporting at multiple spatial scales; use a daily time step to enable flow variability assessment and reporting at multiple time scales; represent historical usage on a seasonal basis at a sufficient spatial representation to allow for equitable sharing; provide robust estimates of annual water use; and provide a pathway to update and improve accuracy (i.e. be update-able and extensible).

Updating 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. These components were then populated (parameterised) with data, in most cases specific to the Barwon-Darling 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, and how these might change in response to licensing of harvesting of floodplain water. These data are not yet available – to address this, we undertook a multiple-lines-of-evidence approach to assessing floodplain harvesting. We used a **capability assessment** to consider the physical infrastructure used for floodplain harvesting and also the opportunity irrigators may have to access floodplain flows based on their location and climatic variability. We also used a water balance assessment given historical crops grown and the estimated water requirements. This assessment focuses on the reach and valley scale to ensure that the total volume of water including historical metered use and estimated floodplain harvesting is representative of the estimated historical water use.

Modelling flows

Most inflow to the Barwon-Darling Valley river system is from major tributaries that have valley-scale models developed for them. Output from these models forms the majority of inflows to the Barwon-Darling Valley river system model and is used for long-term simulations. In addition, four rainfall–runoff models have been used to simulate the conversion of rainfall into streamflow for tributaries where no upstream model has been developed. The Barwon-Darling Valley has an extensive network of climate and river gauge stations and 9 models (one for every reach in the model) were built and calibrated to reproduce historical flows. **Effluents** (i.e. rivers/streams that flow out of a river, often only at high flows) and **breakouts** (i.e. the points where the river spills over onto its floodplains) provide the water for properties to access floodplain harvesting. Breakouts and effluents are modelled using flow thresholds estimated from multiples lines of evidence including surveys, hydraulic modelling, remote sensing and gauged flows.

Modelling water sources and licensing

The main licence categories of unregulated A, B and C class licences are configured for relevant water users and regulate access to the water sources in the Valley. The water available for **floodplain harvesting** for water users is simulated through the flow thresholds at access points and rainfall–runoff. Harvesting of **rainfall–runoff** water is embedded in the crop water model included for each property which calculates runoff based on soil moisture and rainfall. **Groundwater** is not included in the Barwon-Darling Valley river system model as use of significant groundwater has not been identified for any of the floodplain harvesting properties on the river system.

Modelling water users

Water users include urban areas, irrigators, and water for stock and domestic supply. **Town water supply,** and stock and domestic water use is very small in relation to other water users and has not been explicitly modelled. However, these types of water use are effectively included in the river transmission losses that have been calibrated in the model.

The largest water users are (mainly cotton growing) **irrigation properties** in the floodplain areas along the Barwon River and Darling River. 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 (irrigator node) These included information on farm infrastructure such as historical and current river pump capacities, areas developed for irrigation, area planning decisions and irrigated crops for the period 2003/04 to 2013/14 made available through the Floodplain Harvesting Property farm surveys and from property inspections by the Natural Resource Access Regulator (NRAR); 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 access to river flows and on irrigation 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 use 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 an unused entitlement – this reflects the current practice to not extract water against these licences.

Modelling water management rules

The rules of the Water Sharing Plan for the Barwon-Darling Unregulated and Alluvial Water Sources 2012 are incorporated into the model, including the **continuous carryover system** and licences as shares of the 1993/94 Cap on diversions in the Barwon-Darling Valley river system.

The effects of **water trading** are explicitly represented in the model for permanent trade, and for some instances of 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.

There are no major public in-river storages in the Barwon-Darling Valley water source. The weirs along the Barwon-Darling Valley river system are not modelled explicitly, but some of their effect is recognised during the calibration of river flows in the model.

Model performance

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

Statistics and plots for key model components under conditions as at 2008/09 and as configured to meet the plan limit (i.e. extraction limits set in the water sharing plan) 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 **main river flows**.

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-breakout flows match observed sufficiently well for this purpose.

Summer Planted areas agreed reasonably with those derived from remote sensing, taking into account changes in water management and water recovery under the Murray-Darling Basin Plan 2012 (Basin Plan). Seasonal variability in summer area planted in response to water availability was also reasonably captured. Winter planted areas are significantly under-simulated at times, but do not appear to be regularly irrigated.

The model under-simulated **metered diversions** from the river by 7% over the model validation period, and reasonably captures inter-annual variability.

Summary

This report captures the considerable body of intellectual effort and modelling expertise that sits behind the update of the Barwon-Darling Valley river system model. It reports on the modelling approach adopted, how the component parts were modified or updated, 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 Barwon-Darling Valley river system are the currently licensed and metered B Class and C class diversions, then overbank flow harvesting and on-farm rainfall–runoff harvesting followed by A class and small B class diversions.

1. Introduction

The Department of Planning Industry and Environment – Water (the department) has updated and extended the existing river system model of the Barwon-Darling Valley (the Barwon-Darling model). The model is an update of the department's IQQM model for the Barwon-Darling Valley and takes advantage of additional data and improved methods for modelling floodplain harvesting.

The department uses river system models for many policy, planning and compliance uses. One key use for the updated 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

Barwon-Darling 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. This report has been written to help underpin that confidence.

The Barwon-Darling model provides support to more than floodplain harvesting. Floodplain harvesting takes place within the context of all other processes operating within the Barwon-Darling 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.

The following sections of the report describe relevant physical water-related processes and their management in the valley, the information available and its use, modelling approach, and how well the various components, as well as the complete model, perform.

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 Barwon-Darling Valley, the information available to inform the model, our design approach to building these river system models, and model results relevant to assessing model performance (Figure 1).

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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.

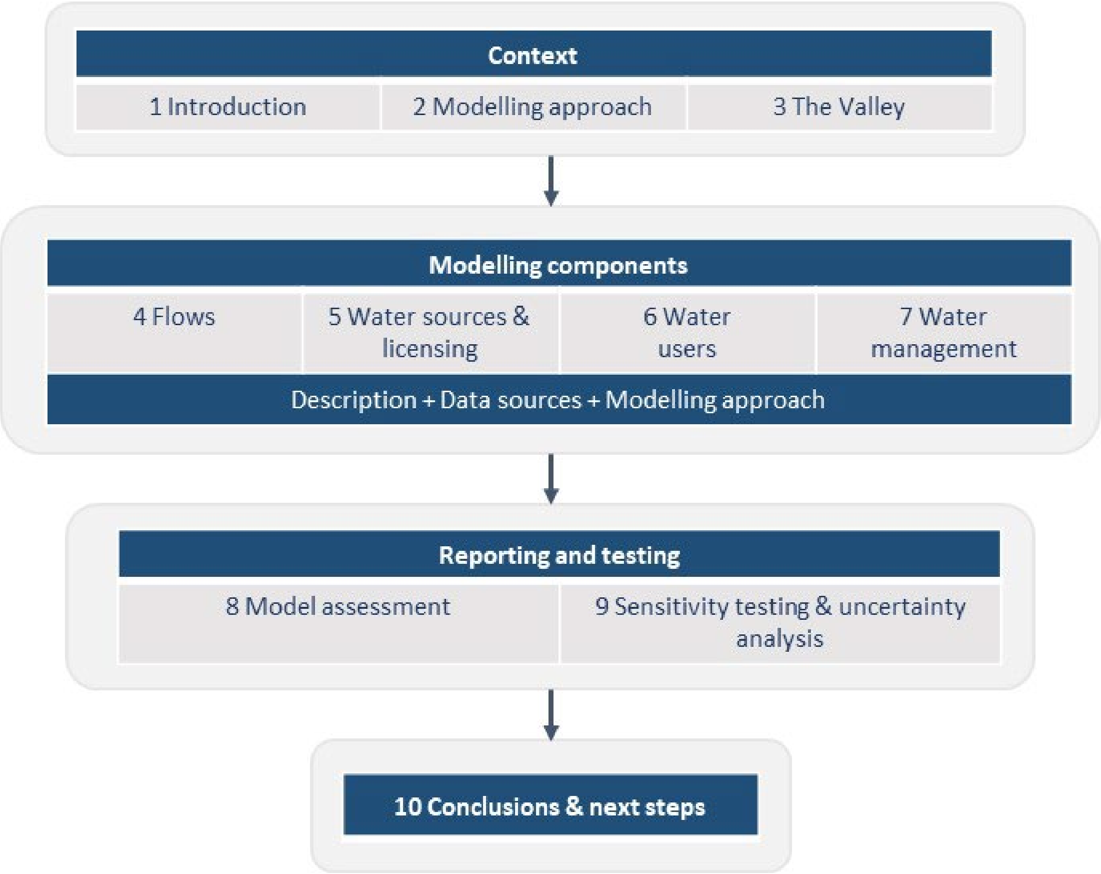

Figure 1 Report structure

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 through 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 inflow and main river flow, and water use.

Uncertainty analysis and sensitivity testing of key parameters, input data and modelling assumptions are important steps in modelling practice. These are discussed in Section 9.

Section 10 concludes 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 report

This report describes the updating of the existing Barwon-Darling model that simulates the rules of the *Water Sharing Plan for the Barwon-Darling Unregulated and Alluvial Water Sources 2012* (as amended 2020) (the Barwon-Darling WSP) to better represent floodplain harvesting in the Barwon-Darling Valley.

How the model has been used to update the estimate of the long-term average annual extraction limit (Long Term Average Annual Extraction Limit, or plan limit) set by the Barwon-Darling WSP, and calculate floodplain harvesting entitlements to bring total diversions back within that limit definition is described in companion report *Floodplain Harvesting entitlements for the Barwon-Darling Valley unregulated river system: Model scenarios* (DPE Water 2022).

2. Modelling approach

This section describes the modelling approach used to update and extend the Barwon-Darling Valley river system model to be fit for purpose to determine floodplain harvesting entitlements. The existing Barwon-Darling model was originally developed with many of the key enhancements required to model floodplain harvesting, such as modelling of individual properties and floodplain harvesting access. However, for consistency with other model build reports, this model update is described in the context of the steps normally undertaken to build a 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 departmental standards and guidelines for good modelling practice. 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 Barwon-Darling model is designed to support contemporary water management decisions in the Barwon-Darling, whether it is a rule change in the Barwon-Darling WSP, or estimating long term average water balances for components such as diversions for compliance purposes. It has 2 overarching objectives, being to:

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

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

Table 1 Model design criteria to meet modelling objectives

	The model must:
1	**Represent the key physical and management processes that affect water availability and sharing within the river system, at a sufficient spatial scale to estimate floodplain harvesting volumes and entitlements at irrigation property level** Essential to enable the conceptualisation and model execution to meet the other design criteria
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 capture 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 over the period 1895–2009 for calculating SDLs and Baseline Diversion Limits (BDLs). (NOTE: The Barwon-Darling 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 (farm 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 Barwon-Darling model, meeting these objectives and criteria required enhancement of the earlier departmental model (IQQM) which was built for a different purpose, primarily to model in-channel diversions.

2.2 Type of model and modelling platform used

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

The Barwon-Darling model has been built using updated versions of the IQQM software, continuing on from the model also previously built using earlier versions of the IQQM software.

2.3 Modelling steps

After we understand key aspects of the river system through model conceptualisation and assess the available information, the existing model of the system can be updated. 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 original model build and model update processes require the model inflows and outflows to be accounted for at all scales. The model was originally built systematically using a number of stages; this model update has subsequently improved the model at key stages for floodplain harvesting. 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 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 4 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	Not required for the Barwon-Darling[1]
7	Water management	Not required for the Barwon-Darling[1]
8	Storage operation	Not required for the Barwon-Darling[1]

[1] Inflows to the Barwon-Darling from most major tributaries are affected by major water storages. However flows in the Barwon-Darling River system itself are not directly managed by major water storages, meaning that the processes at stage 6 to 8 are not relevant. There are also no supplementary access licences, and all irrigation diversions occur under unregulated river access licences, which are addressed in stage 4 and 5.

For this model update, we have improved the model at stages 4 and 5 to better represent floodplain harvesting.

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 focal point for most of these farms is the permanent on-farm storage(s) 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.

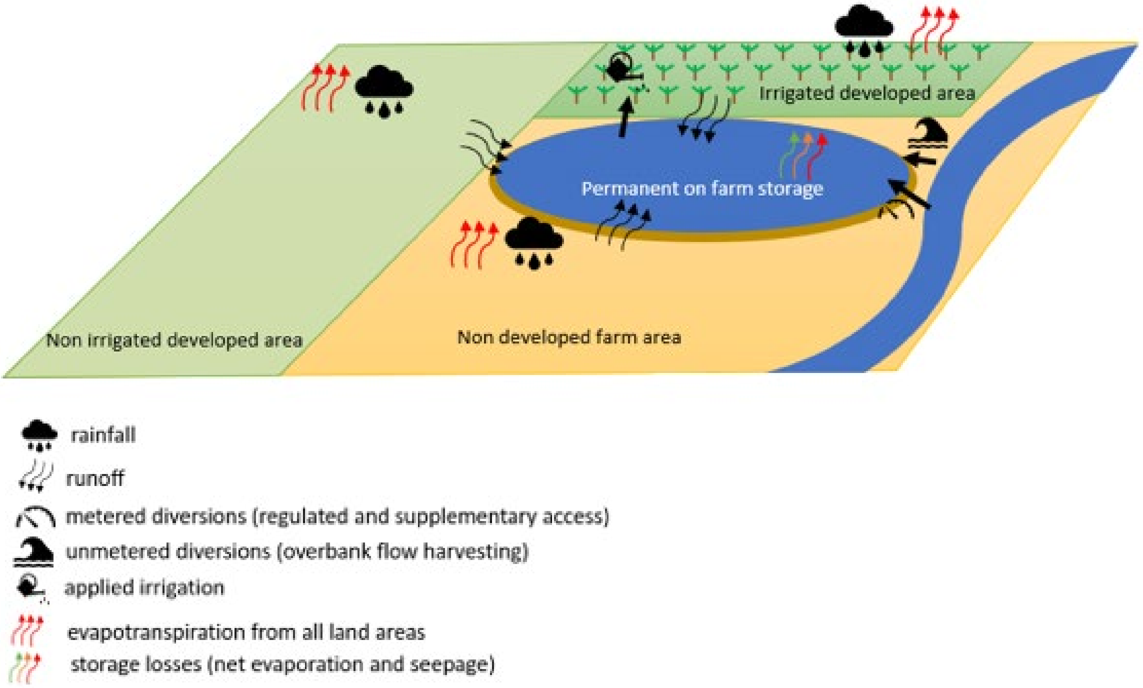

Figure 2 Schematic of farm-scale water balance components
In the Barwon-Darling Valley river system, metered diversions are from unregulated river access licences

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.

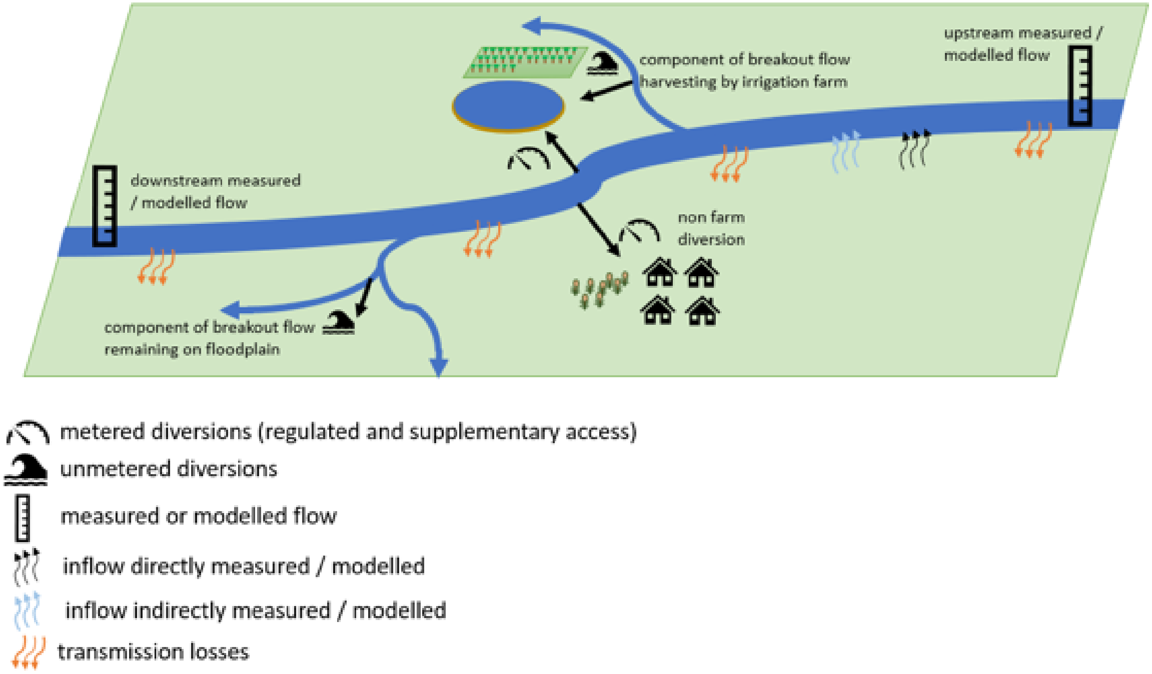

Figure 3 Schematic of reach-scale water balance components
In the Barwon-Darling Valley river system, metered diversions are from unregulated river access licences

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. Whilst the Barwon-Darling Valley river system does not have large headwater storages or dams, for river systems where flows are directly regulated by large storages, 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.

Map that shows the water balance components as described in the text. Legend: gauge, storage, subcatchment boundary, valley boundary. Map also shows elevation bands (high, medium, low)

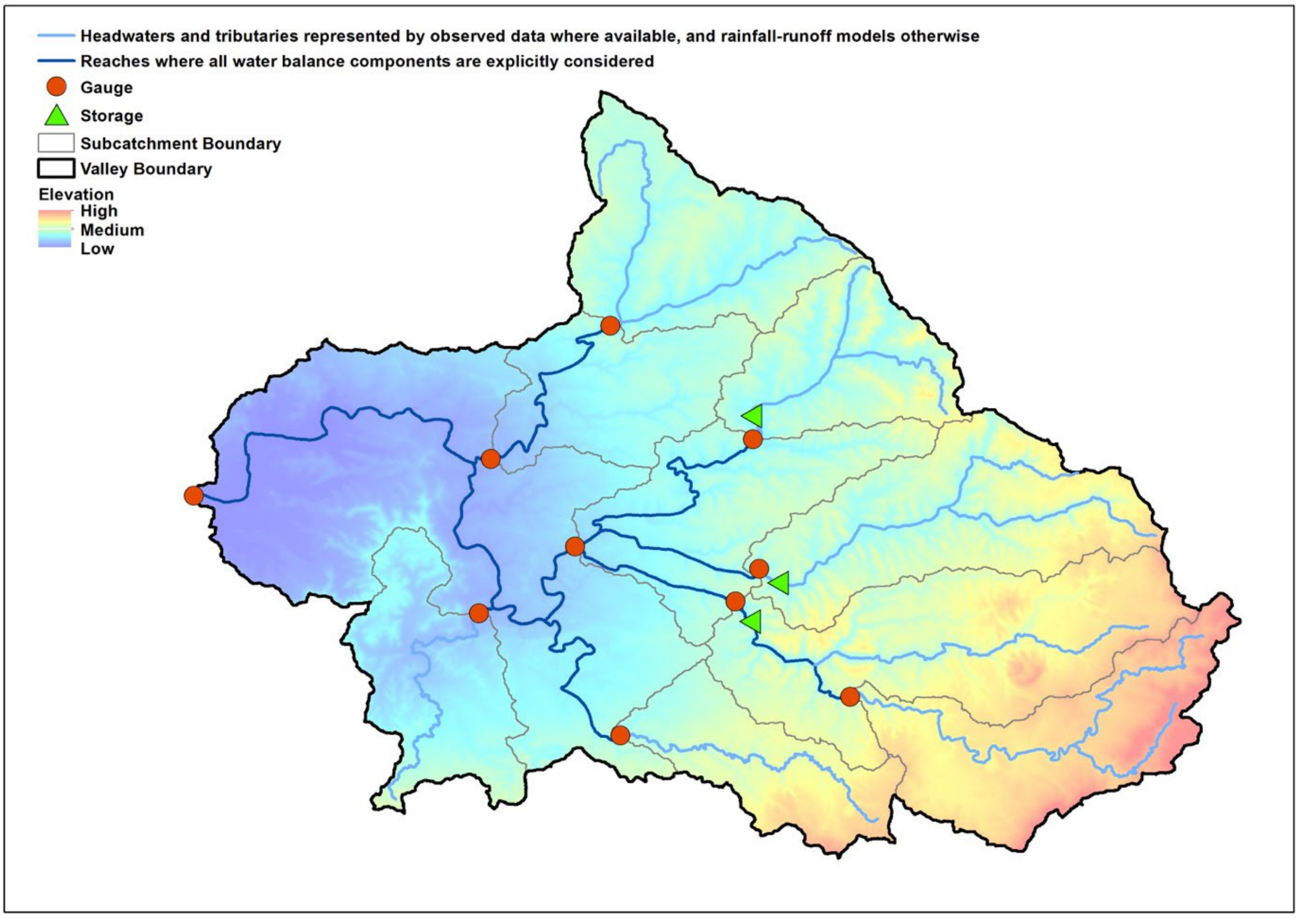

Figure 4 Example of valley-scale water balance components

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 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 Murray-Darling Basin 1993/4 Cap modelling, data are needed 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 reduces the risk of unrealistic parameters that may not result in the model being robust when simulating outside the calibration period. For this update to the Barwon-Darling model, we have used the existing model parameters (NOW 2011) unless better information was available.

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 2 stages of model calibration listed in Table 2, water management and storage operation, are parameterised only when the model is assembled (although this was not required for the Barwon-Darling model).

2.3.6 Data periods

The last step is required to enable use of the model for scenario analysis and to extend all the input data to its fullest temporal extent. During earlier build stages, the component models and the fully assembled models were simulated for shorter climate periods depending on data availability. The scenarios need to be simulated for at least the climate period 1895–2009 for Basin Plan Sustainable Diversion Limit compliance purposes, and for longer to account for more recent data. The full climate period for all rainfall and evaporation stations was input directly to the model, as well as used to generate inflows at some points for input to the model. The same process is followed for upstream models to generate other inflows to this Barwon-Darling model. Table 3 lists the periods and their durations used in the modelling.

Table 3 Time periods used in the Barwon-Darling Valley modelling

Period term	Period	Note
Long term record	1/7/1895–30/6/2020	Reporting commences from 1895
Reference climate period for reporting	1/7/1895–30/6/2009	Basin Plan reporting period. Period used for long-term averages. Water years 1895/96–2008/09; short form 1895–2009
Available climate data period	1/1/1895–30/6/2020	SDL compliance process requires extension of climate period each year

Period term	Period	Note
Period for calibration and validation of flow modelling	various	Based on data availability at flow gauging sites
Assessment period for diversions using fully configured model	1/7/2003–30/6/2014	Water years 2003/04 to 2013/14; short form 2003–2014 Covers key benchmark years for the NSW Floodplain Harvesting Policy and the Basin Plan and was based on data availability at time of model development
Base model conditions	2008/09	Represents development conditions at the start of the 2008/09 (i.e. 1 July 2008) water year

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 updated model, the diversions and water management components have been tested over the period 01/07/2003 – 30/06/2014, which 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 was configured to represent the 2008/09 level of development. The 2008/09 water year is in the middle of the period for much of the new information that has been collected about floodplain harvesting, and it represents a key date for estimating extraction volumes for floodplain harvesting licences.

However, we note there have been some changes in development from 2004 to 2013, and consideration was given to these and other factors in evaluating the results, as described in Section 8.

2.3.8 Scenario development

The updated model with the full period of available climate data is now used to simulate scenarios. A scenario for managed river systems includes the following characteristics:

- fixed development conditions: including catchment and land use, headwater and re-regulating storages, areas developed for irrigation, on-farm storage volumetric capacity, and pump capacity.
- fixed management arrangements, including all rules, resource assessment and allocation processes, and accounting as set out in the water sharing plan (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 (DPE Water

2022). The scenarios developed for the Barwon-Darling and referenced in this report are listed in Table 4.

Table 4 Scenarios referenced in the Barwon-Darling Valley model

Scenario 'name'	Description
2008/09 Scenario	Uses the levels of irrigation infrastructure, water licences, and management rules in the Barwon-Darling Valley river system as at 2008/09
Validation Scenario	The 2008/09 Scenario
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 Barwon-Darling Valley river system*
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.
Plan Limit Scenario	This is the Cap Scenario, as set out in the Barwon-Darling WSP.
Baseline Diversion Limit (BDL) Scenario	Equivalent to Plan Limit Scenario, equivalent to the Cap Scenario

*We have based this scenario on the pre-existing scenario that represented the rules of the Barwon-Darling WSP as at 2020, and included the most recent infrastructure levels (2020 for on-farm storages and licence volumes, and 2014 for other irrigation infrastructure).

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 Barwon-Darling Valley.

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[2], State Emergency Service (SES), flow gauges, hydraulic modelling, remote sensing imagery of flood events	X	o	o	o
Component: climate					

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[2] Farm surveys refer to the Irrigator Behaviour Questionnaire

Input / parameter	Primary data sources	Use – configure model	Use – direct input	Use – calibrate model	Use – validate model
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: water users					
Licences, water sources, metered water use	NSW government (WaterNSW) Water Accounting System (WAS) and Water Licensing System (WLS)	X	o	X	X
Component: farm infrastructure					
Pump capacities, crop areas, developed areas, on-farm storage capacities	Farm surveys, remote sensing (LIDAR), site inspections	X	o	o	X
Component: crop areas					
Crop type and area planted each year	Farm surveys, remote sensing, survey records (WaterNSW, ABARE, ABS, industry groups)	X	o	X	X
Component: water management					
Water sharing, announcing allocations and supplementary access, planned environmental water requirements	Barwon-Darling WSP, operational procedures	X	o	o	o

3. Overview of the Valley

3.1 Physical description

The Barwon-Darling Valley (Surface) Water Resource Plan area (WRPA) (Crown Lands & Water Division 2017) is located in the area surrounding the Barwon and Darling Rivers. The Barwon-Darling Valley starts with the Barwon River from Mungindi at the confluence of the Macintyre River. The Barwon River flows for 700 km until the confluence of the Culgoa River below which it becomes the Darling River. The Barwon-Darling Valley extends to the upper limit of Lake Wetherell (Menindee Lakes) in the south.

The catchment area for the Darling River is 700,000 km^2 although most of this is comprised of tributary valleys, such as the Border Rivers, Gwydir, Namoi, Macquarie and others. The Barwon-Darling Valley covers more than 2,400 km^2 or about 0.1% of the Murray-Darling Basin. The river network is made up of the main river and its tributaries, effluents[3] and breakouts[4], with a complex series of small anabranches, billabongs and flood runners along the length of the river.

The Floodplain Management Plan for the Barwon-Darling Valley Floodplain 2017 applies to the area defined as the Barwon-Darling Valley Floodplain, an area of 11,000 km^2 from Mungindi in the north to the township of Louth in the south (coloured background in Figure 5). This covers the majority of the Barwon-Darling Valley, and all major water users and floodplain harvesting.

Within the Barwon-Darling Valley, elevations range from 500 m around Cobar and Broken Hill to between 50 and 100 m on the floodplain between Wilcannia and Menindee. The Barwon River starts at an elevation of 200 m at the confluence of the Macintyre and Weir rivers, and flows for approximately 700 km over a low gradient to an elevation of 110 m at its confluence with the Culgoa River, north-east of Bourke. Below the Culgoa confluence, the Barwon River becomes the Darling River which flows for another 900 km to the Menindee Lakes, situated at less than 100 m elevation.

Grazing and dryland cropping are the major agricultural land uses in the Valley, with irrigated agriculture, mainly cotton, covering around 2% of the NSW Barwon-Darling Valley.

The valley sits in a sub-tropical climate zone, transitioning to a semi-arid climate zone. Average annual rainfall across the valley decreases from east to west, from over 582 mm in the north-east at Mungindi to less than 260 mm at Wilcannia in the south-west. The rainfall is strongly seasonal with the highest volumes during the summer months occurring through

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[3] 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

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

summer storm activity. Annual evaporation is very high, with an east-west decreasing gradient across the valley, and average Class A pan evaporation exceeding the average rainfall across the entire valley. Annual evaporation is over 1,250 mm across the valley, varying from 1,260 mm to almost 1,400 mm.

The flooding regime in the valley floodplain is complex, as flood flows can arise from a number of sources. Flooding can originate from inland southern and central Queensland via the Culgoa, Birrie, Bokhara and Warrego rivers and from the Macintyre and Dumaresq rivers along the border between Qld and NSW. Floodwaters can also originate from the north-western and central river valleys of NSW including the Gwydir, Namoi, Castlereagh, Macquarie and Bogan rivers. Floods can also arise from a combination of all the above sources.

Occasional relatively short periods of high flow result in the river overtopping its banks and inundating part or all the floodplain. Flood duration can range from a few hours to months with some areas of the floodplain, such as deep billabongs adjacent to the main channel, remaining inundated for several years.

The Barwon-Darling Valley has a number of ecological and waterway assets. These are outlined in Appendix 13 of the *Floodplain Management Plan for the Barwon-Darling Valley Floodplain 2017.*

3.2 River regulation

The tributaries to the Barwon-Darling are for the most part regulated and water is supplied for use within the tributaries' valley. The water that is received by the Barwon-Darling is typically unregulated flows, sourced either downstream of regulating structures in tributary valleys or during uncontrolled events where the natural flows exceed the regulating capacity of the tributary valley. In addition, the Barwon-Darling receives periodic inflows from the unregulated tributaries, for example the Castlereagh and Bogan rivers.

For the purposes of managing water users, the Barwon-Darling Valley river system is split into 4 sections and 14 management zones:

- Mungindi-Walgett section
    - Mungindi to Boomi River Confluence
    - Boomi River Confluence to Mogil Mogil
    - Mogil Mogil Weir Pool
    - Mogil Mogil to Collarenebri
    - Collarenebri to Walgett
- Walgett-Brewarrina section
    - Walgett Weir Pool
    - Walgett to Boorooma
    - Boorooma to Brewarrina
- Brewarrina to Bourke section

    - Brewarrina to Culgoa River Junction
    - Culgoa River Junction to Bourke
- Bourke-Menindee section
    - Bourke to Louth
    - Louth to Tilpa
    - Tilpa to Wilcannia
    - Wilcannia to upstream Lake Wetherell.

There are 17 weirs along the Barwon-Darling Valley river system between Mungindi and Wilcannia, 2 of which have been decommissioned. The primary purpose of the weirs is to provide town and stock and domestic water. All weirs are fixed crest weirs with no ability to operate gates or valves to manage river flow rates. Given the long travel time from any upstream dam to the Barwon-Darling, and the intermediate water users, the Barwon-Darling is operated as an unregulated water source. Users have the ability to extract water at given flow rates depending on their licence type and entitlement volumes. The main points of usage (water taken) from the river itself within the valley are metered, whereas floodplain harvesting diversions are currently unmetered.

3.3 Water users

Water users in the Barwon-Darling Valley include urban areas, irrigators, the environment, stock and domestic supply, and Indigenous environmental and cultural uses.

The largest consumptive water demands in the Barwon-Darling Valley are from the irrigation farms in the floodplain areas between Mungindi and Bourke. These areas are principally cotton growing, although comparatively small areas of other summer and winter crops are irrigated. A map of the primary irrigation areas is provided at Figure 5.

Dryland grazing predominates in the northern regions of the Barwon-Darling Valley Water Resource Plan area, whereas native vegetation is more prominent in the central and southern regions of the Plan area.

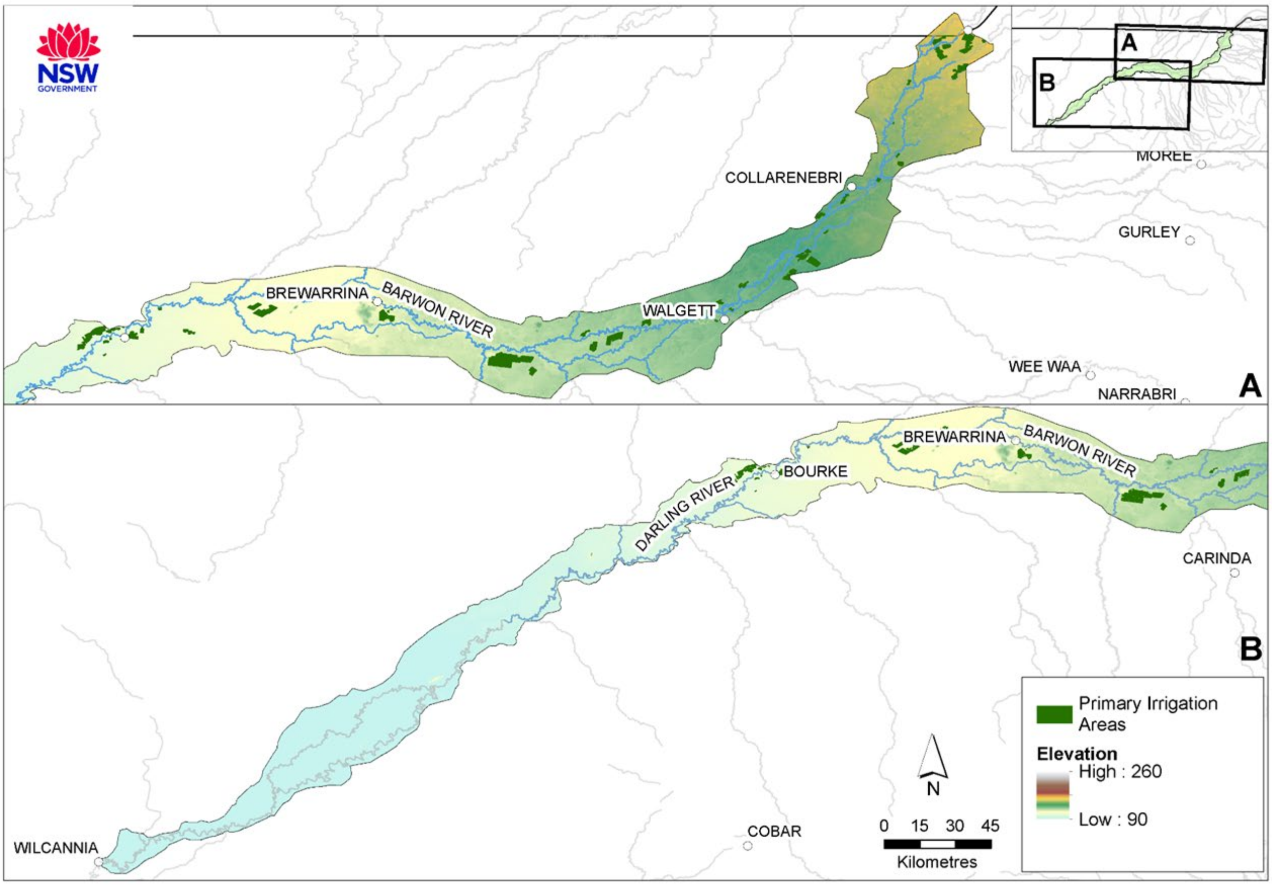

Figure 5 Map showing the river network (main channel and tributaries), the designated floodplain area, areas of primary irrigation and main towns in the Barwon-Darling Valley

3.4 Legislation, policies and operating procedures

NSW policies/legislation that are referred to in this report are:

- (NSW) *Water Management Act 2000 No 92*
- Water Sharing Plan for the Barwon-Darling Unregulated and Alluvial Water Sources 2012 (the Barwon-Darling WSP)
- Floodplain Management Plan for the Barwon-Darling Valley Floodplain 2017
- NSW Floodplain Harvesting Policy 2013 (revised 2018) (the policy).

The Barwon-Darling WSP applies to all unregulated river sections in the Barwon and Darling rivers but does not cover the regulated portion of the Darling River from Menindee Lakes to the River Murray. The management components described in this report closely reference key provisions of the Barwon-Darling WSP and their practical implementation, as well as how water users in the Valley choose to use their water based on water availability.

The Barwon-Darling WSP sets a long-term average annual extraction limit (the plan Limit) that is equal to the 1993/94 Cap on diversions. New water access licences were issued at the commencement of the Barwon-Darling WSP with access share components (shares) that summed to the long-term average diversions permitted under the plan limit. This arrangement was agreed in 2006 as part of a memorandum of understanding between the NSW government and Barwon-Darling water users, and commenced administratively in 2007.

3.5 Summary

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

- flows (Section 4)
- water sources and licensing (Section 5)
- water users (Section 6)
- water management (Section 6.3).

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 shown in Figure 5.

The river network is used to define the spatial relationship of components that cause changes in the 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 (disaggregated) into 12 modelling units (catchments, sub-catchments and reaches) (Figure 6).

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 Barwon-Darling (e.g. the earlier version of this IQQM Barwon-Darling 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 Barwon-Darling model are shown in Figure 6[5]. 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 G.

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

The configuration of river reaches is typically the same as those in the previous Barwon-Darling model, except for some cases where a river reach has been sub-divided into two smaller reaches to improve the representation of access to overbank flows.

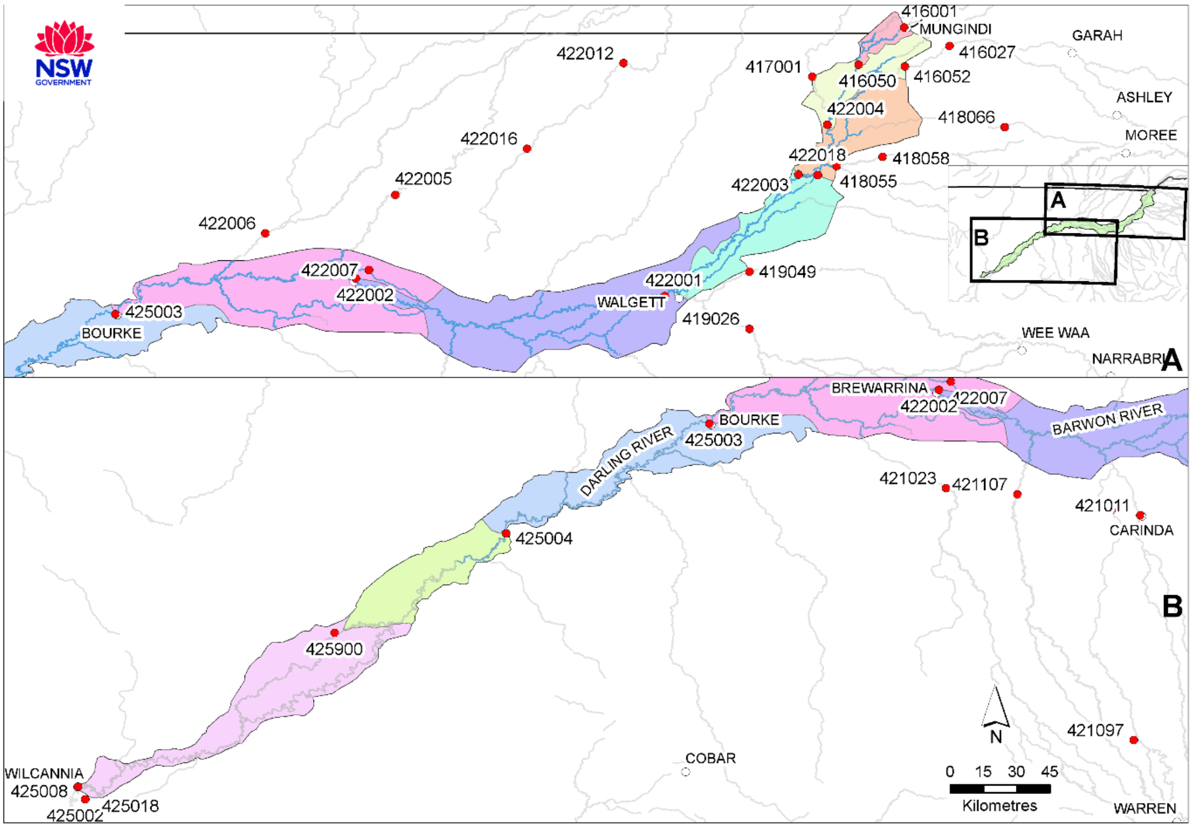

Figure 6 Map of river reaches and location of flow gauging stations in the Barwon-Darling Valley unregulated river system

4.2 Rainfall

Average annual rainfall in the Barwon-Darling Valley varies from 582 mm per year in the northern part of the catchment to less than 260 mm in the south-western areas. In the more moderate middle parts of the catchment, average annual rainfall is 350 mm per year. The rainfall is strongly seasonal with the highest volumes during the summer months occurring through summer storm activity.

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[5] The modelled flows at Wilcannia are used by the Source Murray Model to calculate inflows to Menindee Lakes.

4.2.1 Data sources

Rainfall data are used extensively through the model, as input for rainfall–runoff modelled inflows, storage water balance, and crop water demands. Departmental guidelines recommend the use of the Queensland Government's Scientific Information for Land Owners (SILO) patch point data[6]. 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 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. Significant periods of infilled data were checked to assess whether they introduced bias in the data.

The rainfall stations used within the model are shown at Figure 7. 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 model. This modelling occurs separately to the river system model. A full list of rainfall stations including spatial coordinates and long-term annual average is included in Appendix B.

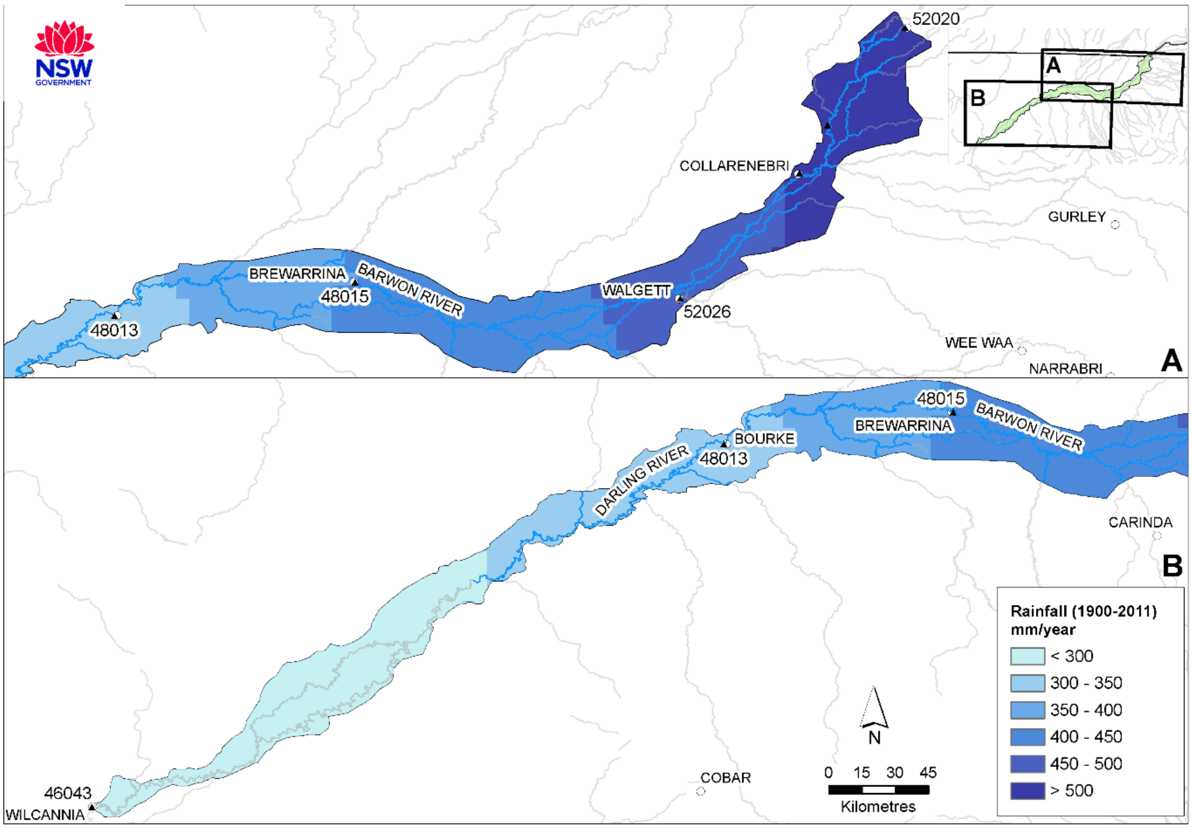

Figure 7 Map showing the rainfall gradient (1900 to 2011) across the Barwon-Darling Valley and location of rainfall stations used within the model

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

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 adopted the nearest suitable climate station in each part of the model.

4.3 Evaporation

Annual evaporation is very high – over 1,250 mm across the valley, varying from 1,260 mm to almost 1,400 mm with an east-west decreasing gradient across the valley. Average Class A pan evaporation exceeds the average rainfall across the entire valley. The average evaporation rate at Bourke in December is 282 mm, more than 8 times the average rainfall for that month. Evaporation in winter is around 58 mm per month, compared to mean monthly rainfall of 27 mm.

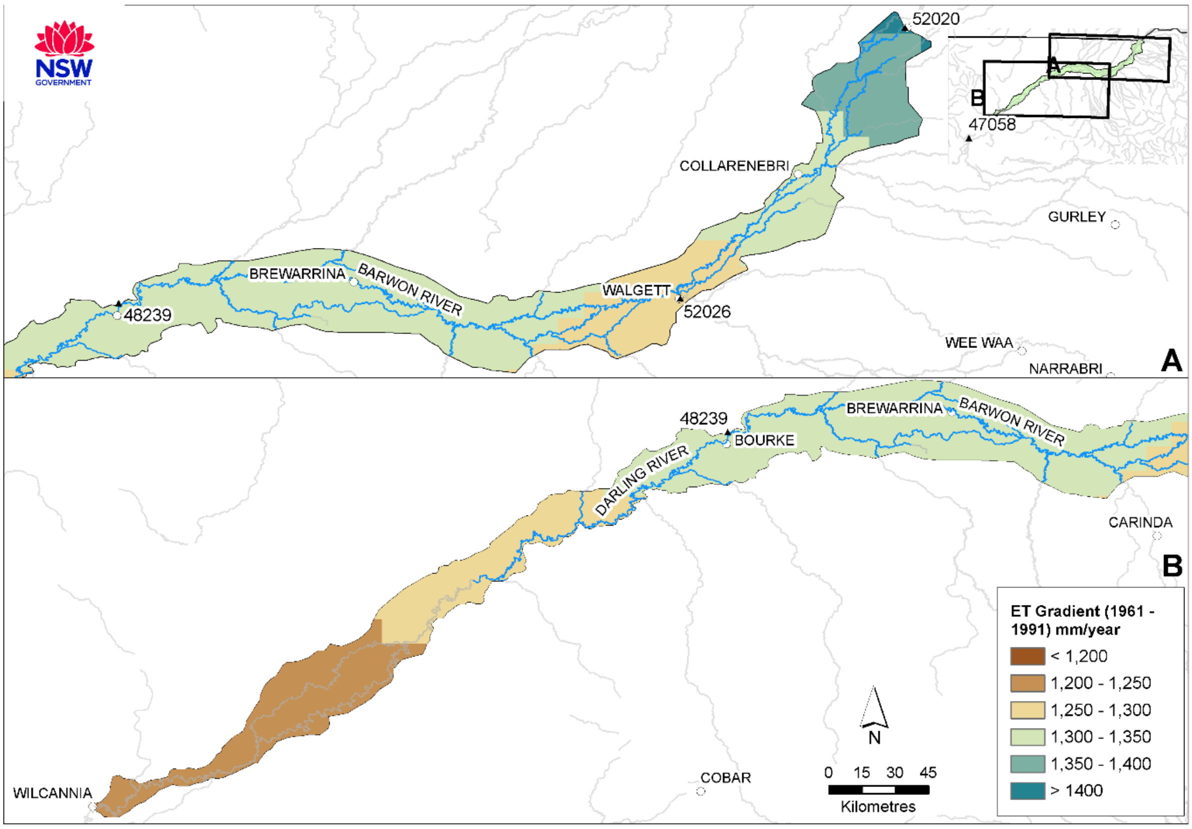

Figure 8 Map showing the evaporation gradient (1961 to 1991) across the Barwon-Darling Valley and the location of climate stations used for rainfall–runoff modelling

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 Barwon-Darling Valley from the SILO database which provides synthetic Class A pan records. The evaporation station locations used for the flow calibration components of the river system modelling are shown in Figure 8 and listed in Appendix B. Additional evaporation data were used for crop modelling, using the SILO evaporation data. These are the same as the climate stations shown in Figure 7.

4.3.2 Modelling approach

Of the available evaporation stations (Class A Pan) in the valley, the following criteria were used to select an appropriate subset for use in the Barwon-Darling model:

- adequate representation of spatial variability of the evaporation
- availability of long-term records (unlike rainfall data, evaporation data have only been regularly recorded for the last 30 years or so)
- continuity and quality of data
- availability of a nearby rainfall site that could be used to generate long-term evaporation data.

4.4 Streamflow

As with many northern NSW inland rivers, the Barwon-Darling Valley river system experiences high flow variability in response to climate variability. The Barwon-Darling is a semi-arid river characterised by extreme climatic variability with large areas of the valley often subject to prolonged drought periods. Rainfall is low and highly variable and, as a result, discharge along the river is highly variable. Large proportions of average flows occur in wet years and major flood events, with high flows more frequent in late summer and early autumn.

The long-term modelled pre-development flow (with no water use occurring) at Walgett flow gauging station (422001) (Figure 9) demonstrates this.

These data show that while the annual average is around 2,900 GL/year, it is highly variable with extended low flow periods from 1920 to 1948, 2002 to 2010 and 2013 onwards, and wet periods in the 1950s and the 1970s.

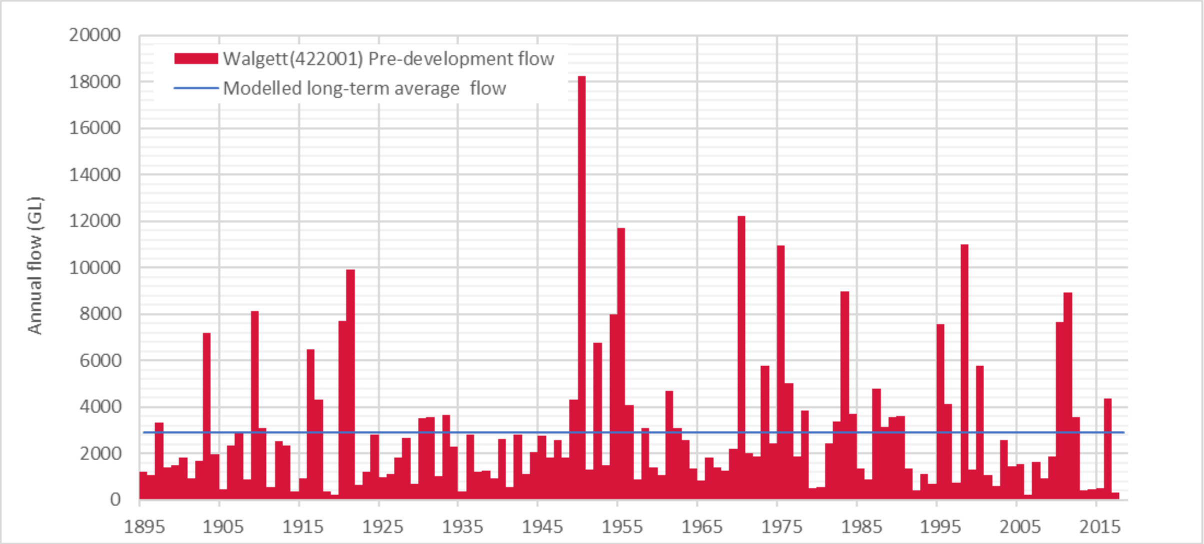

Figure 9 Modelled pre-development annual flow (GL) at Walgett (422001) for the period 1895 to 2018

As well as the annual flow variability, monthly and daily flow variability also matters. A large rainfall event in an otherwise low volume year can still provide significant local runoff and tributary inflows. For the Barwon-Darling Valley river system, daily flow variability is often lower than for other valleys.

4.4.1 Data sources

NSW maintains a network of river flow gauging stations across the Barwon-Darling Valley to support water management activities. Data for each station are archived in the Department's Hydstra hydrometric database (Kisters Pty Ltd 2010). These continuous flow records are the foundation of the river system modelling.

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

There are 13 flow gauging stations currently operating along the Barwon-Darling Valley river system, and a further 22 flow gauging stations on tributaries are used.

Flood flows are difficult to measure where flows breakout across wide floodplains, and it has been found that this is a significant issue for many flow gauging stations along the Barwon-Darling system, and for flow gauges in the lower reaches of tributary rivers. This results in significant under-estimates of the actual flows during flooding. However, there are 4 key flow gauging stations along the Barwon-Darling system that do not have this issue, and are located at Walgett, Bourke, Wilcannia, and Menindee. These stations form 4 primary river sections that were used for flow calibration over the entire flow range.

The stations used to calibrate flow in the model are listed in Appendix C. Data from 22 stations were used to calibrate headwater inflows from catchments that cover the northern

Basin. A further 13 stations were used for 9 river reaches. The locations of these stations are shown in Figure 6.

4.4.2 Modelling approach

As previously noted, this updated Barwon-Darling model is based on the existing Barwon-Darling model, and the approach to modelling of flows remains unchanged in the updated model. This section describes how we have modelled flows in the existing model. A summary of the parameters used for the tributary inflows and main river reaches flow calibration is provided 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 downstream 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 • Indirectly gauged catchment inflows	• 3 Sacramento models with 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 10 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 the department has considerable experience and skills in obtaining good calibrations with this rainfall–runoff model.

For the Barwon-Darling model, calibration of rainfall–runoff models for directly gauged tributary inflows as described at Table 6 has only been undertaken where a separate valley model has not been developed. Three Sacramento models, together with calibrated flow routing and losses, were developed for:

- Bogan River (also including modelled inflows coming across from the Macquarie River model)
- Castlereagh River
- Thalaba Creek.

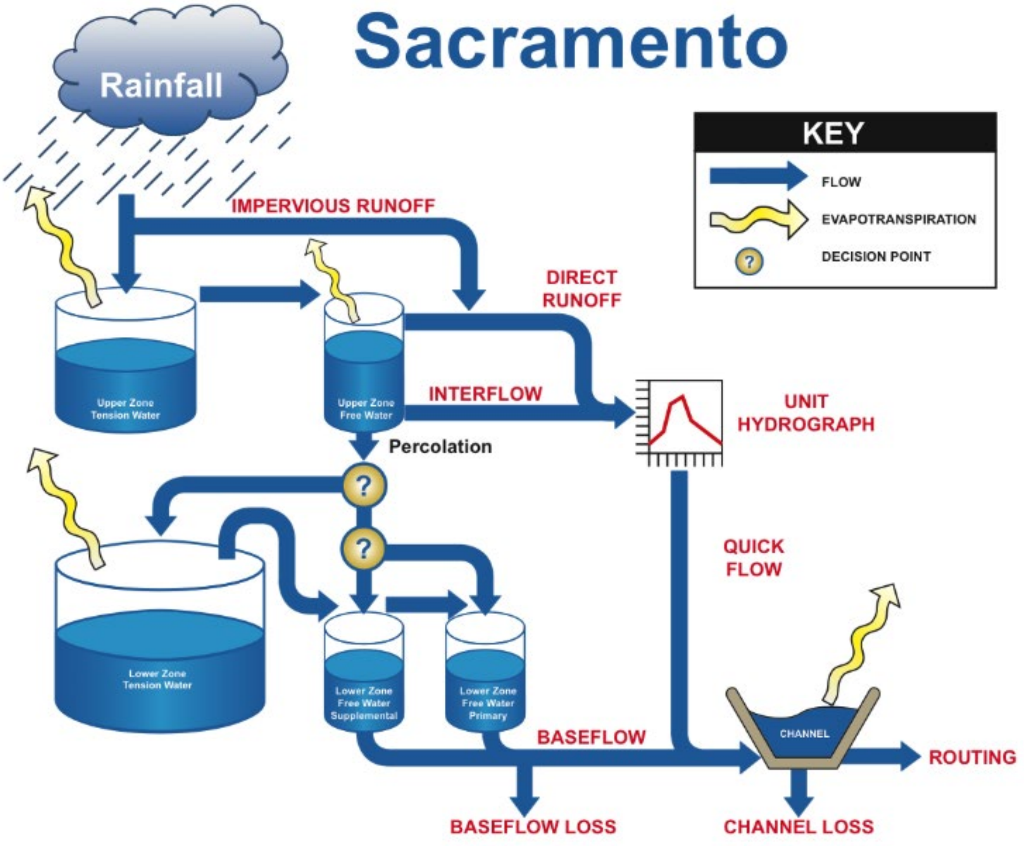

Figure 10 Conceptual diagram of the Sacramento rainfall–runoff model [Source: eWater Scientific Reference Guide]

Upstream valley modelled flows

Most inflow to the Barwon-Darling Valley river system is from major tributaries that have valley-scale models developed for them. Output from these models forms the majority of inflows to the Barwon-Darling model and is used for long-term simulations. For calibration of river flows in the Barwon-Darling Valley river system, observed inflows from flow gauging stations in the lower reaches of tributary rivers are used rather than the inflows produced by the tributary models.

To represent the additional floodplain inflows from tributaries during flood periods that are not measured at tributary flow gauging stations, a set of factors have been applied to the observed flows from 10 of the 16 gauged inflows upstream of Bourke. This has been done to achieve a satisfactory water balance at the 4 gauging stations on the Barwon-Darling that measure the full floodplain flows. Development of these factors is described further in the *Barwon-Darling Valley – IQQM Cap Implementation Report* (NOW 2011).

Calibration

The 3 Sacramento tributary models were calibrated firstly by setting them up with the local climate station data and catchment areas as input, and then applying an automated calibration process using automated software.

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.

The automated 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.

The 3 Sacramento models used for Barwon-Darling modelling have been developed for areas where there is limited flow, water use, and rainfall data available, and have extended periods of little or no flow in their lower reaches. These types of catchments are generally difficult to model. These flows represent 10% of the total valley inflows.

Indirectly gauged inflows and main 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 river network from tributaries, 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 along the river. These processes are configured in the model using a structured series of steps at a reach scale, considering the components shown in Figure 3.

To address issues associated with significant flows by-passing many flow gauging stations during floods, the flow calibration for the Barwon-Darling Valley river system has used the 4 flow gauging stations that measure flows across the full floodplain to calibrate across the full flow range. Other flow gauging stations have only been used to calibrate within channel flows.

Flows contributing from local, indirectly gauged catchments are normally estimated in the river reaches where they were considered significant using rainfall–runoff models matched to either another gauged catchment or a water balance calculation within each reach along the river. For the Barwon-Darling model, local, indirectly gauged inflows do not generally contribute significant inflows to the Barwon-Darling Valley river system, and only one such inflow has been configured in the model, representing inflows from the floodplain in the river reach above Walgett.

Flow was calibrated at the downstream gauge in each river reach 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.

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. Talyawalka Creek is the only major effluent stream along the Barwon-Darling Valley river system above Menindee, leaving the Darling River above Wilcannia and rejoining below Menindee if there are sufficient flows.

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 flow paths.

A map of key breakout locations and breakout paths is presented in Figure 11, noting that ‘break out’ depends on river levels.

4.5.1 Data sources

The major effluent offtake for Talyawalka Creek has a flow gauge and initially follows a well-defined channel that is easily identifiable on mapping and digital terrain models.

High flow breakouts are often well-known locally by river operators, State Emergency Service personnel, and landholders. However, they may be difficult to identify from maps and there are no direct measurements of flow rates. We used a combination of local knowledge (e.g. 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. Local hydraulic modelling was also undertaken to estimate overbank flows in some areas.

In reality, overland flow paths can be very complex. Where appropriate, simplifications were made by amalgamating some flow paths and connections. Generally, 2 or more flow paths were amalgamated where they:

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

The flow paths for these breakouts, and the properties that have access to them, have been identified using multiple sources, including satellite imagery, modelling of floodplain flows, and information from the farm surveys. Figure 11 shows the identified breakouts in the models overlaid on overland flow paths derived from results of the MIKE 21 model (see point 5 below).

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 (DPI Water 2017)*
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 also 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.

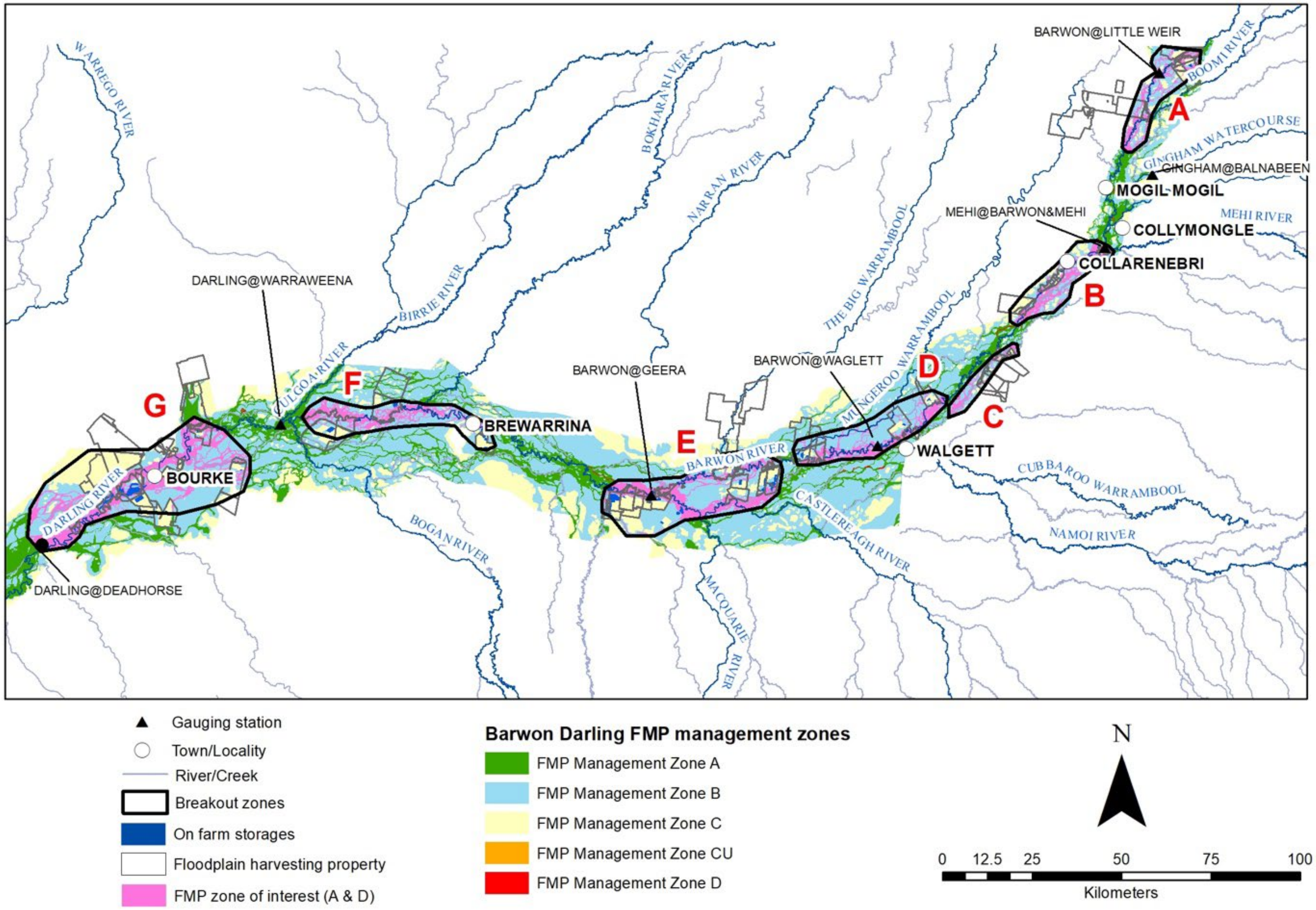

Figure 11 Floodplain Management Plan (FMP) zones and key breakout locations in the Barwon-Darling Valley [adapted from Appendix 2 of Floodplain Management Plan for the Barwon-Darling Valley Floodplain 2017]

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 net flow onto the floodplain was treated as a loss to the system. Where significant, the Barwon-Darling model represents effluent streams, but no additional effluents have been configured to represent floodplain breakouts explicitly, i.e. as an effluent. This is because many of the overbank flow breakouts in the Barwon-Darling remain close to the river itself and usually rejoin the main river system. Where this occurs, the flow breakout is not separately simulated. As the model simulates the total flow, including at flow rates that are above the channel capacity, floodplain harvesting access by water users is simulated via use of higher flow thresholds.

The flow rates at which breakouts occur from the main channel were determined from a range of sources as described in the preceding paragraph.

4.6 Regulating infrastructure

The Barwon-Darling Valley does not contain any controllable flow regulating structures. A number of tributaries that flow into the system are regulated but the water received to the Barwon-Darling Valley is downstream from the regulated river reaches and is managed as an unregulated river system. The Barwon-Darling Valley primarily receives water from uncontrolled events (flooding) and unregulated tributaries, for example the Castlereagh and Bogan rivers.

There are a number of weirs along the Barwon-Darling that capture flow as it moves downstream; however these are all fixed crest and WaterNSW does not have the ability to release water from or otherwise operate the structures.

5. Modelling water access and licensing

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

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

5.1 Water licences

The main licence types to access surface water sources are listed in Table 7. 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 Barwon-Darling WSP.

Table 7 Surface water access licence types in the Barwon-Darling Valley unregulated river system

Licence type (NSW)	Note
Basis Land Holder Rights (BLR)	BLR includes water for Domestic and Stock extracted from a water source fronting a landholder's property, or from any aquifer underlying the land, and for native title rights. A licence is not required for this water extraction
Unregulated river access licences	Unregulated river access licences in the Barwon-Darling Valley river system are divided into 3 priority classes: A, B and C class licences
Local Water Utility	6 town water supplies along the length of the Barwon-Darling Valley river system

There are a small number (6) of high priority licences issued to towns (local water utility licences) that may take water at very low or no flows from weir pools.

The majority of licences are unregulated river access licences and are used for irrigation. As flows in the Barwon-Darling Valley river system are not regulated, water access for each class is based on flow thresholds (known as **commence-to-pump thresholds**) that are specified in the Barwon-Darling WSP. A class licences may take water at lower flow thresholds than B class licences that, in turn, may take water at lower flow thresholds than C class licences. Water taken by the larger licences is usually held in privately owned on-farm storages and used for irrigation as needed.

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

In the early 1990s the water access licences along the Barwon-Darling Valley river system were converted from area-based to volumetric licences, resulting in a total of 521 GL of Annual Volumetric Limit (NOW 2011). In 2006 the NSW Government and licensed water users agreed to restructure the licences to have shares in the long-term average diversions under the 1993/94 Cap (modelled to be 173 GL/year for A, B, and C class licences at that time). These arrangements commenced administratively in 2007/08 and were formalised in the Barwon-Darling WSP in 2012. In 2013/14, the recalibrated Barwon-Darling model estimated diversions under the 1993/94 Cap to be 189 GL/year, and the A, B, and C class licence shares were subsequently revised to reflect this.

5.1.1 Data sources

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

All information used in our models regarding the category and number of water access licences, the shares they hold, the works (pumps, etc) they are attached to, and the location of those works are taken from the WLS. For some scenarios that are historical (e.g. cap on diversions which requires some 1993/94 data), prior records within the department are used. The total number of share components issued for each licence category is shown in Table 8.

Table 8 Total entitlement components in the Barwon-Darling unregulated river system (as at 1 March 2021)

Category	Consumptive	Environmental water	Total
Unregulated river	0	1,488	1,488
Unregulated river A Class	9,594	262	9,856
Unregulated river B Class	116,958	16,111	133,069
Unregulated river C Class	33,248	12,498	45,746
Local Water Utility	5,373	0	5,373
Domestic and Stock	968	0	968
Total	**166,141**	**30,359**	**196,500**

No information is available on water use under Basic Landholder Rights, other than the estimated total non-licensed water requirement for domestic and stock rights of 1.047 ML/day in Part 4 of the Barwon-Darling WSP.

5.1.2 Modelling approach

Licences are configured for all of the individual irrigation 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 category of unregulated river access licence and the classes within that category.

Local water utilities have not been represented in the Barwon-Darling model, and the primary focus of the model has been on the much larger irrigation water use.

Small amounts of stock, or domestic entitlements belonging to enterprises based on larger unregulated river irrigation licences have also not been modelled. Smaller A and B class unregulated river licences have been represented as a single combined irrigation water user (irrigator node) in each river reach.

Water use under Basic Landholder Rights is not explicitly included in the model but are implicitly accounted for in the calibration of flow-loss relationships.

5.2 Unregulated water

The Barwon-Darling is an unregulated river system that receives flows from both regulated and unregulated river tributaries.

River flows along the Barwon-Darling may exceed licence commence-to-pump thresholds when there are significant inflows from rainfall in tributaries, including regulated tributaries when they receive significant inflows downstream of headwater storages or spills from major storages. 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 larger B class and C class licences, which accounts for the majority of water use.

A number of irrigation properties on the Barwon-Darling system also access water from both the Barwon-Darling main river system and unregulated tributary streams. This access has been configured in the model for each irrigation property as follows:

- For 2 properties, the licensed diversions from the tributary streams and the floodplain harvesting have been reported as Barwon-Darling diversions, consistent with previous reporting for the 1993/94 Cap.
- For 3 properties, the floodplain harvesting and the diversions from the tributary streams have not been reported as Barwon-Darling diversions, consistent with previous reporting for the 1993/94 Cap. These have been reported elsewhere as diversions from the relevant tributaries.

5.2.1 Data sources

Larger water users with unregulated river access licences measure water use via flow meters installed and maintained at pump sites, with the exception of floodplain harvesting. Small A class and small B class licence holders do not have meters installed to measure their diversions. WaterNSW maintains a database of water use (the Water Accounting System (WAS)) and arranges for meters to be read at varying intervals. Water use records are downloaded from individual data loggers at each meter into a predecessor database system and processed to provide annual water use totals that are then transferred to WAS.

These records are available for the reaches along the Barwon-Darling Valley river system from the commencement of metering in the mid-1990s to the present.

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. The time-event meters originally installed in the 1990s recorded when pumps operated, and diversions were calculated from this data by using pump rates that were determined from initial field tests and manufacturer's specifications. Periodic review of meter accuracy has shown that this metering process under-estimates water take by up to 20% across the valley. A subsequent process to install in-line impellor meters also experienced accuracy issues arising from incorrect meter installation and inadequate maintenance.

The national standard for non-urban water measurement is intended to ensure measurement errors are within 5% of the volume diverted. The *NSW non-urban water metering policy* (DPIE Water 2018) now requires meters and installations to meet these standards, with a phase-in period up to December 2021 for inland northern NSW.

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

Daily water use records for the period prior to 2012 were calculated from the database holding information downloaded from the individual meter loggers for the previous Barwon-Darling model builds and have been re-used for the current work.

The total metered diversions over the period used to calibrate water use in the model are shown in Figure 12.

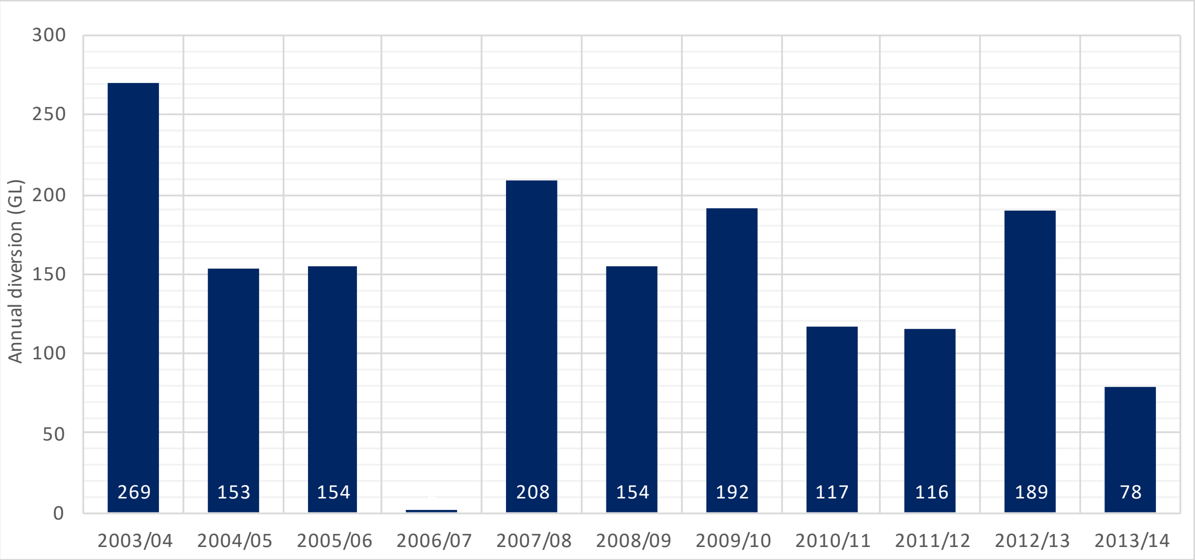

Figure 12 Total Barwon-Darling Valley river system metered diversions from 2003/04 to 2013/14 [Data sourced from DPIE Water databases]

5.2.2 Modelling approach

Access to water from the river is permitted for unregulated river water access licences when flows exceed the commence-to-pump requirements set in the Barwon-Darling WSP for each river reach.

5.3 Floodplain harvesting water

In addition to access under the unregulated river licences 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 harvesting of overland flows will be managed through the determination 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 11 shows the area potentially inundated by overland flow from breakout locations. Major irrigation areas are shown in Figure 5.

5.3.1 Data sources

Overbank flow harvesting

Harvesting occurs from areas developed for irrigation as well as other undeveloped areas within the property. Water harvested from overbank flow has not been recorded. Only one respondent for the IBQ farm survey (NOW 2016) included estimated overland flow information for their property across most years of the survey period, with 5 others providing information for a limited number of years. These estimated volumes provide information on water that was collected from the overbank flows during the summer period, with 2 respondents providing estimates for during the winter period for a limited number of years. This part of the farm survey data was used as a guide when assessing model performance.

Due to the absence of recorded data, we undertook a multiple lines of evidence approach to assessing floodplain harvesting. We used a capability assessment to consider the physical infrastructure used for floodplain harvesting and also the opportunity irrigators may have to access floodplain flows based on their location and climatic variability. Where appropriate, additional checks using satellite imagery and aerial photography were undertaken. Following the initial reconfiguration of irrigator properties to better represent floodplain harvesting, we undertook an early model run that forced crop areas to observed values to check that metered water use was being simulated well, and then assessed the water balance for each property. This assessment focussed on the reach and valley scale to ensure that the total volume of water use represented in the model was consistent with the areas of crops being irrigated.

Rainfall–runoff harvesting

The IBQ farm survey (NOW 2016) requested information on rainfall–runoff harvested from within properties. No respondents included estimated rainfall–runoff information for their property. In some instances, it was recognised that some properties can directly intercept runoff from local areas outside of the irrigation property: this is accounted for either in the estimation of overbank flow harvesting or in rainfall harvesting by adding additional undeveloped area to the model when simulating runoff. The undeveloped areas reported as contributing to rainfall–runoff harvesting were smaller than the developed areas; around 55% of the developed area reported.

To improve our confidence in runoff rates, alternate lines of evidence were considered as detailed in Appendix D. Further data collection is required to confirm the runoff patterns and volumes under different cropping conditions.

5.3.2 Modelling approach

Overbank flow harvesting

The water available for floodplain harvesting through the breakouts (as described in Section 4.5.2) is represented through the use of a higher river flow threshold, above which the overbank pump capacity, or intake rate, was generally set to the total capacity of on-farm storage pumps for the property, but also took into account the pipes and open channel capacity. This data were obtained by NRAR through field inspections. 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.

Rainfall–runoff harvesting

The upgraded models for floodplain harvesting use the best available information on rainfall–runoff, and account for differences in runoff rates between undeveloped, developed and irrigated areas. A separate rainfall–runoff model embedded in the crop water model is included for each property, continuously tracking the soil moisture of undeveloped, developed and irrigated areas. Irrigation return water recycling efficiency was also considered in these parameters. This enables the calculation of different rates of runoff from these areas based on soil moisture and rainfall. We calibrated these property area models to produce a long-term average rate consistent with available data as outlined in Section 6.2.2.

Rainfall–runoff harvesting generally refers to harvesting within the property; in 3 cases eligible access to local regional runoff from outside of the property has been incorporated into the property area model via a separate rainfall-runoff (AWBM[7]) model and included as part of the rainfall–runoff harvesting result. As there were little available data on rainfall runoff for these areas, an AWBM rainfall-runoff model was calibrated for 9 catchments with similar aridity and topography in other parts of the Basin where gauged flows were available. These 9 AWBMs were used as reference models, and the averaged parameters from these were applied to the local regional catchment areas for these 3 properties. The approach taken for these is detailed in Appendix D.

5.4 Groundwater

NSW has issued licences that allow taking of water from the alluvial aquifers that underlie the Barwon-Darling Valley river system and other streams for irrigation and town water supply. In the Barwon-Darling, only local water utilities have a licence to extract from the Upper Darling Alluvial groundwater source. This has not been represented in the model as use of significant groundwater has not been identified for any of the floodplain harvesting properties on the river system.

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[7] The Australian Water Balance Model (AWBM) is a catchment water balance model that relates daily rainfall and evapotranspiration to runoff (Boughton 2004).

6. Modelling water users

Water users along the Barwon-Darling can only take water when it is available during flow events and cannot order water for release from an upstream storage. Water taken during the flow events are stored in on-farm storages by the more significant irrigators for later use on crops.

6.1 Urban water supply

There are 6 town water supplies located along the length of the Barwon-Darling Valley river system that have local water utility licences: Collarenebri, Walgett, Brewarrina, Bourke, Louth and Wilcannia.

Local water utility licences are very small licences compared to the larger licences used for irrigation. However they have the highest priority of supply in that they are able to pump during very low flow conditions, and generally have access to water in a weir pool.

6.1.1 Data sources

A small number of urban water utilities take water from the Barwon-Darling Valley river system to supply domestic, commercial, and industrial users in the town, as shown in Table 9. Water use information is available from individual local councils.

Table 9 Barwon-Darling local water utility licence volumes

Water utility	Management Zone / water source	Licence volume (ML/yr)
Collarenebri town water supply	Mogil Mogil to Collarenebri	416
Walgett town water supply	Mogil Mogil to Collarenebri	63
Brewarrina town water supply	Boorooma to Brewarrina	1,000
North Bourke town water supply	Culgoa River Confluence to Bourke	300
Bourke town water supply	Culgoa River Confluence to Bourke	3,200
Louth town water supply	Bourke to Louth	25
Wilcannia town water supply	Tilpa to Wilcannia	400
Wilcannia town water supply	Upper Darling Alluvial	220
Total		5,624

6.1.2 Modelling approach

These very small volumes of town water supply are not represented in the model. The usage of these water utilities has effectively been included within the simulated stream losses.

6.2 Irrigators

Irrigation water users in the Barwon-Darling IQQM may have any of A, B or C class unregulated river licences, as well as access to rainfall–runoff harvesting and harvesting from overbank flows on the floodplain.

It has been assumed that floodplain harvesting water is generally taken in preference to licensed (A, B or C class) water by irrigators as advised by landholders via the farm surveys and during interviews.

Numbers and distribution

There are 36 irrigation properties each with an installed pump (at some point since 1993/94) and each growing in excess of 100 hectares that are individually represented in the Barwon-Darling model. These have been termed 'major' irrigators. This includes 1 additional smaller irrigator that has been identified as having eligible works for floodplain harvesting and has been modelled individually in this model update.

There are over 100 B and A class irrigation licences which have very small entitlements and with little, or more usually no, irrigated areas distributed along the Barwon-Darling system, with the majority of water use occurring above or near Bourke. These have been aggregated into 17 reach irrigation water user nodes.

6.2.1 Data sources

Diversion of water by irrigation enterprises is a major component of the water balance in a river system. Information on metered diversions, private irrigation infrastructure and the areas of crops irrigated in the Barwon-Darling Valley river system each year is essential for configuring the model and for calibrating the modelled demand and water use patterns by irrigators. A summary of data sources is presented in Table 10.

Table 10 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) and predecessor databases. The final model uses licences fixed to a point in time depending on which scenario is being run	Configuring Resource Assessment which links the licence to an individual water user node
Farm infrastructure (storages, developed area, additional rainfall–runoff harvesting areas, pumps)	Permanent on-farm storage capacity initially based on farm survey and updated based on NRAR advice (a combination of LIDAR and physical survey data). On-farm storage losses modelled through Morton's Lake evaporation data and seepage based on existing model's	Configuring permanent on-farm storage geometry for relevant water user nodes

Data type	Data source	Model use
	individually calibrated parameters (NOW 2011)	
Area on farms developed for cropping, and undeveloped area contributing to rainfall–runoff	Existing area parameters were considered for change when the farm survey indicated a difference of more than 10% and a history of plantings supported the change. For other relatively small water users, estimated based on earlier survey data (see Development History Project described in Appendix F) as per the existing model parameters	Configuring upper limit to planted areas, and contributions to rainfall–runoff for relevant water user nodes
River pumping capacity	Intake capacity defined by river pumps based on installed pump capacity, with information provided by IBQ farm survey responses verified against the WLS data. Smaller users are based on earlier survey data (see Development History Project described in Appendix F) as per the existing model parameters (NOW 2011)	Configuring rate of water diversions from the river for all water user nodes
Floodplain harvesting rate	FPH rate was generally set to the combined on-farm storage lift rate. This was initially based on farm survey data but the final model was based on NRAR advice. In a couple of instances, the FPH rate was set higher or lower than the on-farm storage pump rate as outlined below: • 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 the property before transfer to permanent storage NRAR supplied pump rates, using standard conversions for pump type and size (Appendix E). They also supplied estimated rates for pipes; generally 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 based on existing model's individually calibrated parameters (NOW 2011) Note that tailwater returns are not explicitly modelled – efficiency and hence application rates are net of returns	Configuring rate of on-farm losses during irrigation watering for relevant water user nodes. Some allowance for channel losses was included in this parameter
Crop factors and soil parameters	Crop factors and root depth based on existing model's individually calibrated	Configuring crop models for relevant water user nodes to

Data type	Data source	Model use
	parameters (NOW 2011), which were based on FAO56	simulate total crop water requirements
Crop planting dates each year	Planting date based on farm survey data where available (preferred date) and existing model parameters otherwise	Configuring crop models for relevant water user nodes
Climate data	SILO p synthetic Class A pan records	Input to crop models that drives simulation of crop water requirements for relevant water user nodes

Metered diversion data are described in Section 5.2. Information on entitlement distribution is maintained in the Water Licensing System (WLS). Information on some on-farm infrastructure has been collected in the past by WaterNSW. However, the farm survey and NRAR field verification of farm infrastructure represents a significantly expanded and updated dataset and has undergone various verification checks.

These structured farm surveys are undertaken for the Floodplain Harvesting Project for every property that registered interest and provide information on farm infrastructure, area planting decisions, irrigated crops for the period 2003/04 to 2013/14. The participants in the farm survey represented all but 5 of the currently active individually modelled water users, covering approximately 60% of the long-term annual water use in the Barwon-Darling Valley. Infrastructure information in these surveys was verified 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, and areas of crop irrigated. The various lines of evidence used to supplement the farm survey are discussed in the following sub-sections on irrigator infrastructure, crop areas, and floodplain harvesting.

For all major water users and A class and small B class water users, information on cropped areas and infrastructure was collected as part of an earlier Development History Project[8] undertaken for the 1987–2000 period. Information for the A and small B class users was collected by survey and interviews, indicating that they irrigated about 1,700 ha of a range of crops, but no cotton was irrigated.

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

Infrastructure

Knowing details of on-farm infrastructure such as areas developed for irrigation, storages and pump capacities allows us to model likely water harvesting and usage volumes. Some

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[8] The Development History Project is described further at Appendix F. While these data were collected over 20 years ago, these users are very small and more recent data are not available. In future, their water use will be metered under the 2018 NSW metering framework.

information on current levels of infrastructure were 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.

Contemporary on-farm storage volumes and surface areas were derived using remote sensing (LIDAR) data and supplemented by photogrammetry. Where good quality physical survey data were provided during the farm scale validation process described in Appendix A.3, this has been used instead. In both instances a 1 m freeboard was assumed for permanent storages unless other verifiable evidence was provided such as the existence of a constructed spillway. Either of these methods provide an objective basis to determine capacity. Remote sensing methods were also used to validate history of development of storages. This is explained further in Appendix section E.1.

Pump flow rates for 'major' irrigators measured during tests undertaken by WaterNSW have been used to configure pump capacities. Pump capacities for earlier scenarios have been taken from the Development History Project (Appendix F).

Where the model has been configured to represent more recent conditions, NRAR data for on-farm storage pump size and type, and NRAR advice on associated capacity and intake restrictions if any (Appendix G) have been used. 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 intake rates.

Historical on-farm storage pump capacity was determined at key dates based on what storages were constructed at that date. 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. We also reviewed farm survey data and NRAR data for any advice about pump upgrades that occurred over time.

Areas developed for irrigation were primarily based on remote sensing, or information from the prior development history project for 1993/94 conditions. We also compared the developed area to maximum historical cropping, which was also verified using remote sensing.

Comparative levels at other dates used in scenario development are summarised in Table 12, which shows a no increase in developed area, and a 4% increase in on-farm storage capacity from 2008/09 to now (after allowing for properties subject to water recovery that no longer undertake irrigation).

Table 11 On-farm irrigation infrastructure estimates as at 2008

River sections (reaches)	Developed area (ha)	Permanent on-farm storage capacity (ML)	Temporary on-farm storage capacity (ML)	FPH rate of take capacity (ML/day)	River pump capacity (ML/day)
Mungindi to Walgett	12,878	80,963	0	4,387	2,270

River sections (reaches)	Developed area (ha)	Permanent on-farm storage capacity (ML)	Temporary on-farm storage capacity (ML)	FPH rate of take capacity (ML/day)	River pump capacity (ML/day)
Walgett to Brewarrina	7,996	81,230	4,850	2,524	1,885
Brewarrina to Bourke	12,553	70,488	0	2,835	3,171
Bourke to Menindee Lakes	5,923	47,286	0	2,362	2,520
Total	**39,350**	**279,967**	**4,850**	**12,108**	**9,816**

Table 12 On-farm irrigation infrastructure estimates at prior dates

Dates of development	Developed area (ha)	Permanent on-farm storage capacity (ML)	Temporary on-farm storage capacity (ML)	FPH rate of take capacity (ML/day)	River pump capacity (ML/day)
1993/94	28,371	209,887	550	9,153	6,485
2008/09	39,350	276,235	4,850	12,108	9,816
Latest estimate	[1]30,315	[2]224,741	4,850	[4]11,643	[5]8,686
Small A and Bs 1993/94	1,430	549	NA	NA	382
Small A and Bs 2008/09[3]	1,240	723	NA	NA	340

[1] The reduction in developed areas is primarily due to the purchase of a major property (Toorale, 2,085ha) by the NSW and Commonwealth governments, and the purchase of all Barwon-Darling licences from another major property (Colly Farms, 7,190ha).

[2] Current Condition scenario modelling does not include the 65,256ML combined storage capacity of Colly Farms and Toorale.

[3] Small A and B class water users have only been updated for licence shares since 2008/09.

[4] 990 ML/day capacity pumps for Colly and Toorale are not included. There were increases in pump capacity for two other properties.

[5] 1,130 ML/day reduction in pump capacity compared to 2008/2009 was due to the sale of Toorale and Colly Farms unregulated river access licences to the Commonwealth.

Irrigated crops, crop areas 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.

Only 6 of the surveyed irrigators provided irrigated cropping records for at least 8 of the 11 year period covered in the farm surveys. Another 6 irrigators provided limited crop areas for up to 4 of the 11 years surveyed. Overall, across the period covered by the survey, farms did not report irrigated crop areas in approximately 70% of years. The coverage of information arising from the farm surveys is described further in Appendix F.

To address this, remote sensing of crop areas was undertaken over the period 2003/04–2013/14. This is explained further in Appendix F.2. The derived irrigated crop areas were used in preference to the farm surveys, with survey data used only where remote sensed crop areas were not available.

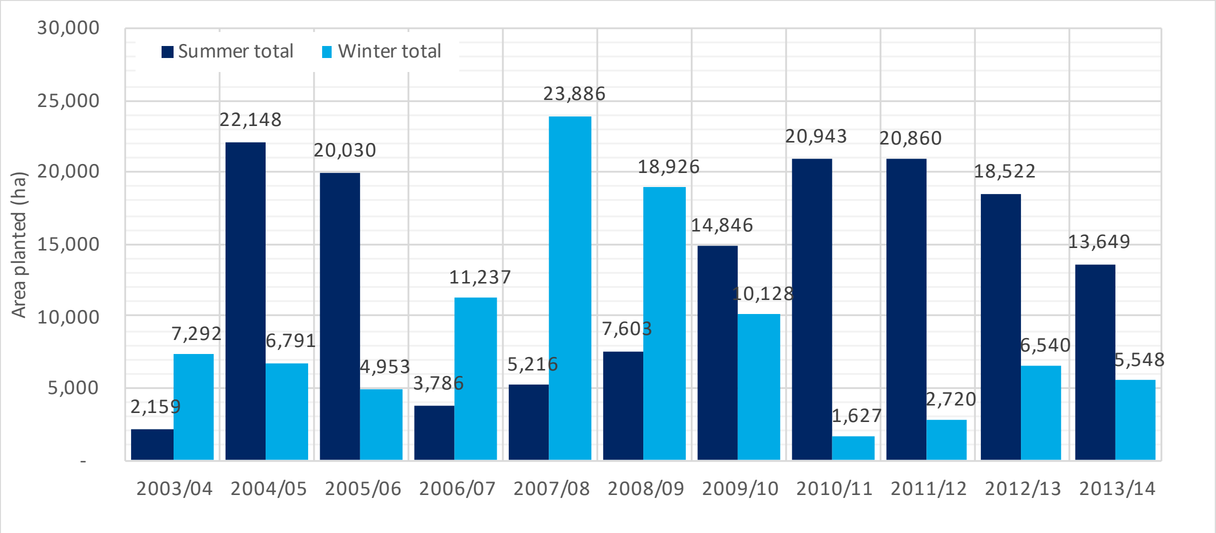

Figure 13 Reported summer and winter planted crop areas for eligible properties over the period 2003/04 to 2013/14 [Source: IBQ farm surveys infilled with remote sensing]

Note: Remote sensing data were not available for a significant number of properties during 2013/14

Analysis of reported crop types shows it is dominated by cotton grown during the summer growing season in many years, typically when more water is available. However, in the drier years of the millennium drought, there are large areas of wheat and other crops also grown in the winter growing season.

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 5 to 13 ML/ha for cotton and other summer crops, and in the range of 1 to 4 ML/ha for winter wheat.

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 6 to 12 ML/ha for watering of cotton. There was no geographic basis for this wide range; potential reasons could be different periods over which rates were calculated, whether the rates factored in pre-watering and efficiency, and different approaches to recordkeeping and management practices.

In other valleys, further lines of evidence were used to develop a common set of parameters (apart from climate station and planting decision and date) that were adopted for all properties. However, for the Barwon-Darling model update we have retained the individually calibrated parameters for each property from the existing model to simulate crop water use, which were based on FAO56 methods as noted in Table 10.

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, and 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 CROPMOD2 model within the Type 8.3 Unregulated irrigator node in IQQM for this purpose. We refer to this 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 13. In the model, all processes operate on a daily time step.

Table 13 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 water usage under licences 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 (RS). However, in long term simulation modelling, the crop areas were 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 of use climate data (rainfall, and evapotranspiration) to estimate the water use by each crop type. When the soil moisture falls below configured trigger levels the crop model orders water
Rainfall–runoff harvesting	Simulates rainfall–runoff from within the property boundaries from fallow, irrigated crop and undeveloped areas In a few instances is also used to simulate localised rainfall–runoff harvesting from outside of the farm
Overbank flow harvesting	Simulates the diversion into storage of water on the floodplain outside of the property and can include localised rainfall–runoff

The parameter summary for the simulation of water demands is given in Table 14.

Table 14 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 model parameters, either calibrated or pre-set to defined values, are derived to achieve crop requirements) On-farm storage operation (discussed further below)
Crop areas	Water available at planting decision date (simulated)	Reported crop areas and checked against remotely sensed data	Planting decision function

Each irrigation farm or group represented in the model was initially parameterised as described in previous model reports (NOW 2011). Further assessment and refinement occurred in subsequent stages of this model update process. Adjustments made during these later stages are noted in relevant sections. While the period 2003/04 to 2013/14 was used as a validation 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 configured to match expected long-term average results from research using a longer period of time to match published data. We therefore refer to the period 2003/04 to 2013/14 as an assessment period for the final model performance. This period was chosen for the following reasons:

- best available relevant data at the time of model development
- sufficiently long enough period to represent climatic range in the region (Table 15). This is important to ensure that the model is robust during different periods of water availability
- includes key benchmark years for the policy and the Basin Plan.

Table 15 Comparison of rainfall statistics at Bourke over assessment period to long term record

Metric	Long term (mm) (1890/91–2013/14)	Short term (mm) (2003/04–2013/14)
Average	344	389
Maximum	777	647
Minimum	95	154

Numbers and distribution

All 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 36 major irrigators being represented in the model, of which 27 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 associated with unregulated river access licences, 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 an irrigation property) as one 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. This assumption was tested in other valleys (Section 9) which showed that the floodplain harvesting model 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 other river system modelling, planting decisions were estimated using independent data analysis relating crop areas to water availability at the time of planting. This approach has not been suitable for the Barwon-Darling model as we do not have records of the volume of water in on-farm storages which is the primary component of water availability. This means that water availability needed to be simulated.

The planting decision application rate for cotton was based on risk values reported in the farm surveys and varied between 4–12 ML/ha between properties with the average being 8 ML/ha. In some cases, the reported value was adjusted slightly to achieve a better match between simulated and historical planted areas. The survey data did not include risk values for crops other than cotton. A default risk value was assumed for winter wheat crops and calibrated if required. These are summarised in Table 16.

Table 16 Adopted crop planting decision rates, i.e. the volume of water required to be available before an irrigator decides to plant 1 ha of a given crop

River section	Summer decision rate (ML/ha)	Winter decision rate (ML/ha)
Mungindi – Walgett	8	0.5
Walgett – Brewarrina	7.33	1
Brewarrina – Bourke	8	1

As noted in the Data sources section, winter crops are planted irregularly. The existing model crop planting decision rates for winter crop areas have been retained (NOW 2011).

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

1. A function was defined to calculate water availability as the sum of the volume currently stored in on-farm storages and licence account balances
2. This is then divided by the ‘risk factor’ which defines how many hectares to plant per ML of water available, constrained by a maximum area
3. The total area planted cannot be larger than the developed area. Where required, a smaller maximum area was specified, e.g. if the maximum area historically planted was less. For winter crops, the maximum area was calibrated to match historical winter diversions over the 2003/04 to 2013/14 period.

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 take water from the river where licence conditions allow. 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 use water (Figure 14). In the right-hand figure in Figure 14, 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.

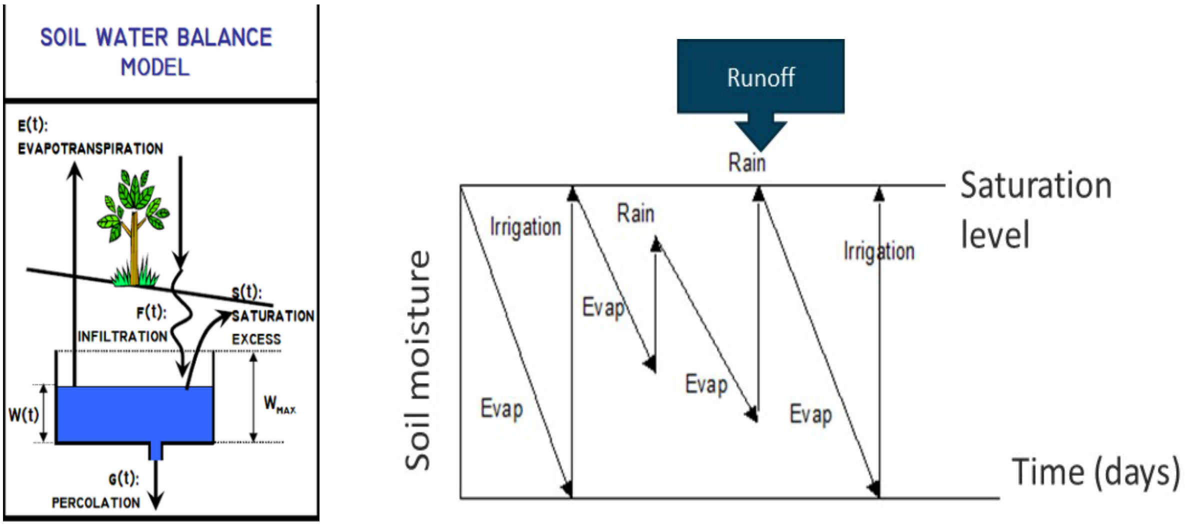

Figure 14 Schematic of the soil water balance model (left) with accounting for evapotranspiration, rain, and irrigation (right)

The delivery of water to the crops is subject to an 'efficiency factor' that represents delivery and application loss. 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 – however efficiencies up to 90% were recorded. As the industry improves efficiency over time, this dataset may under-estimate efficiency for the more recent period. Gillies highlighted that an optimised irrigation approach results in average application efficiency of around 85% with tailwater recycling and would be more representative of most irrigation enterprises over the recent period.

The application losses in the existing Barwon-Darling model were set during calibration for each individual irrigator, varying between 25% and 30% (NOW 2011), and have been retained for this updated model.

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 store for crop types and fallow is defined directly in IQQM. The previous IQQM Barwon-Darling model's calibrated soil moisture store parameters of 150 mm store with 50 mm store for fallow were retained for all crops except for all cotton and cotton fallow where 300 mm and 80 mm were used, respectively. These adjustments were made to ensure simulated rainfall–runoff rates were consistent with expected long-term averages from literature reviews (Appendix D). 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 approximation. 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 15).

Derivation of crop factor values, soil parameters and crop planting dates are provided in Table 10 and values summarised in Table 17.

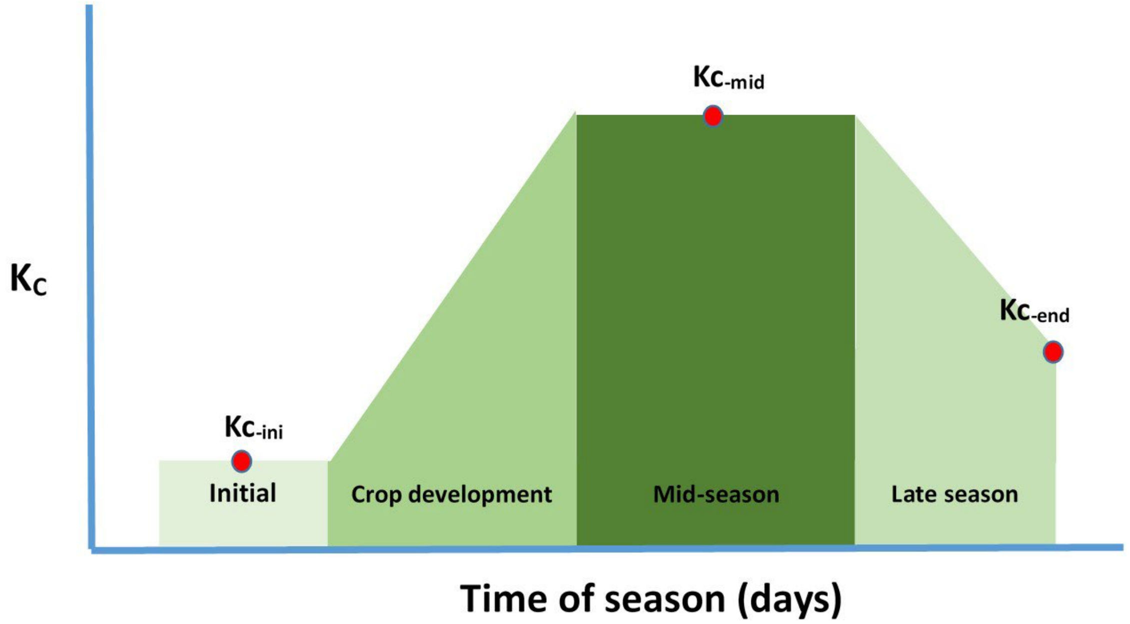

Figure 15 The relationship of Kc crop factors to time of season [adapted from figure 34 in Allen et al. 1998]

Table 17 Crop parameters used in the model: crop factors (Kc), periods and planting date for cotton

Crop class	Cotton
Kc-ini	0.29
Kc-mid	0.95
Kc-end	0.83
Length of season (days)	
Initial	30
Development	60
Mid-season	60
Late season	30
Planting decision date	Late Sep to end Oct

Note: There is some variation on Kc values for a small number of properties.

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 14). 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 undeveloped areas separately, enabling calculation of runoff following a rainfall event with consideration of antecedent conditions.

Under the model conceptualisation used, 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 18. The supporting literature is further described in Appendix D.

Table 18 Calibration of parameters which control rainfall–runoff harvesting

Parameter	Adopted value
Fallow crop factor (developed areas)	0.4
Fallow crop factor (undeveloped areas)	0.6
Rainfall–runoff return efficiency for fallow and winter irrigated areas	45%
Rainfall–runoff return efficiency for summer irrigated areas	45%
Rainfall–runoff return efficiency for undeveloped areas	45%

Note: These parameters have been estimated in conjunction with the other parameters to produce the expected runoff response (Appendix D).

Rainfall–runoff harvesting has previously 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, with less than 800 ML in total (NOW 2011), and hence their rainfall–runoff harvesting is expected to be relatively small.

Overbank flow harvesting

The flow breakout access described in Section 5.3.2 and verified through flow calibration, allows water to be taken directly by the irrigator node.

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 river when flows exceed the flow breakout threshold. 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. Temporary storages have been identified at 2 properties; for these, a larger intake rate to the temporary storage and later slower transfer to permanent storage have been configured.

Seepage from storages was not captured in the farm surveys, and the calibrated values in the existing Barwon-Darling model (0–2 mm/day) have been used.

The model software includes the ability to define a target reserve volume to hold in the storage during the cropping period. However, this is not relevant for the unregulated Barwon-Darling Valley river system, where water cannot be ordered in advance of the intended water use. Capacity of the on-farm storages has been defined such that it excludes a 1 m freeboard (airspace at the top of a storage) unless there was evidence of other practices such as constructed spillways that allowed use of the full capacity. This information is summarised in Table 19.

Table 19 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	0-2 mm/day	Based on existing model calibration

Non harvesting properties

Each river reach has an irrigator node to represent smaller farms that did not participate in the farm survey. The irrigated crop areas outside of the individually represented irrigation properties are relatively small. These small water users have not been required to have water meters prior to the updated NSW metering framework announced in 2018, and the only information available is cropped areas and infrastructure for these smaller users (generally holders of A class and small B class licences) collected as part of an earlier History of Development Project undertaken for the 1987–2000 period (Appendix F, DLWC 2000). Information for these small users was collected by survey and interviews[8]. These irrigator nodes have been configured as set out in Table 20.

Table 20 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 2000/01 survey data	Used in previous IQQM modelling, based on the Development History Project
Developed area	Based on 2000/01 survey data	Used in previous IQQM modelling, based on the Development History Project
Rate of river extractions	Based on prior 2000/01 survey data	Used in previous IQQM modelling, based on the Development History Project

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 Pipeline NSW Program, which operated between 2009 and 2013, the NSW and Commonwealth governments replaced inefficient stock and domestic water distribution systems with more efficient piped water supply systems. Following the upgrading of the Barwon Channel Association Stock & Domestic Pipeline upstream of Brewarrina, an unregulated river licence for 1,488 shares was issued for the water savings. This licence has no class, and effectively has no commence-to-pump threshold condition, recognising the stock and domestic priority of the original licence. The management of this water licence is undertaken by the department (Energy, Environment and Science).

The large irrigation property at the confluence of the Darling and Warrego Rivers known as Toorale was purchased by the NSW and Commonwealth governments in September 2008. This included 67 A class licence shares, 2,527 B class licence shares, and 5,078 C class licence shares, and additional licences on the lower Warrego River that are now held by the Commonwealth Environmental Water Holder.

In addition to Toorale, the Commonwealth Government has purchased water licences with approximately 21,000 shares across the unregulated river A class, B class, and C class licence categories to use for environmental outcomes. The management of these water licences is undertaken by the Commonwealth Environmental Water Office.

In total, 30,359 shares have been purchased or created from water savings in the Barwon-Darling Valley to use for environmental outcomes as at 1 July 2020.

6.3.1 Data sources

The department maintains a register of held environmental water entitlements linked to the NSW Water Licensing System. Total holdings presently are 30,359 unit shares which comprise:

- 1,488 shares of unregulated river (no class) licence
- 262 shares of unregulated A class river licence
- 16,111 shares of unregulated B class river licence
- 12,498 shares of unregulated C class river licence.

This represents approximately 15% of the total entitlement in the Barwon-Darling Valley.

6.3.2 Modelling approach

No water licences were 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.

For the modelling of later conditions described in the companion Scenarios report (DPE Water 2022), entitlements owned by the Commonwealth are treated as inactive water users for modelling purposes. This is a reflection of the current approach taken by environmental water managers to ‘use’ the entitlements by not extracting water and thereby increasing in-river flows. In the Barwon-Darling Valley river system, underuse by one set of entitlements does not allow growth in usage by remaining entitlements due to the unique characteristics of the new entitlements issued under the 2012 Barwon-Darling WSP.

New WSP provisions for the use of Held Environmental Water via Active Management came into force in 2020. Active Management and other new environmental flow rules are described further in Section 7.5. It is expected that the use of Held Environmental Water within the Barwon-Darling Valley will evolve over time, and representation of this in the model will be included as part of ongoing improvements to the Barwon-Darling model.

7. Modelling water management rules

Water sharing rules included in the Barwon-Darling WSP are:

- access rules – which determine at what flows or river heights extraction is allowed
- extraction limits – which set the total volume of water that can be extracted on a long-term average annual basis from the water source.

Notes in the WSP also foreshadow the use of 'temporary water restrictions' afforded by section 324 of the *Water Management Act 2000* in order to enact the provisions of the Interim Flow Management Plan for the North West (Barwon-Darling WSP, section 6.1.1) and/or to maintain 2 years security of supply in Menindee Lakes for Broken Hill's town water supply. Note also that the Minister's powers under section 324 of the *Water Management Act 2000* cannot be limited by a water sharing plan.

7.1 Resource assessment

The Barwon-Darling Valley river system receives inflows from 4 NSW regulated river valleys; Border Rivers, Gwydir, Namoi and Macquarie. In a regulated river, WaterNSW undertakes a resource assessment every month, or when any significant inflow event occurs to calculate how much water is available. There is no resource assessment process for the Barwon-Darling as it is an unregulated valley, and water users may only take water opportunistically as river flows and licence conditions permit.

7.2 Water accounting and access

All Barwon-Darling unregulated water licences have an associated water account, and receive an annual allocation at the start of each water year. The Cap management arrangements agreed in 2007 resulted in A, B, and C class licences receiving an annual allocation equal to the long-term average diversion under the 1993/94 Cap, and were able to carryover that allocation from one year to the next without limit.

These arrangements were formalised at the commencement of the Barwon-Darling WSP in 2012, with licences being issued with share components that summed to the WSP plan Limit (1993/94 Cap)[9]. and the annual allocation was 100%. This was increased to 109% in 2013/14

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[9] Modelling in 2007 indicated that the long-term average level of diversions by A, B, and C class licences was 173 GL/year under the 1993/94 Cap conditions, which was the basis for the issuing of individual licences at the commencement of the Barwon-Darling WSP in 2012.

following a model recalibration that indicated the plan limit had been under-estimated[10]. These accounts are managed differently between access licence categories.

Water accounting rules are set out in the Barwon-Darling WSP. Under these rules unregulated river water access licences:

- may accrue water allocated to their accounts across water years without limit
- must not take more than 300% of their share component in any single water year.

An extraction share component has been issued for all unregulated river access licences in the Barwon-Darling water source at the commencement of the 2020/21 water year (known as an individual daily extraction component, or IDEC) and sets the maximum volume of water that can be taken in each 24-hour period.

During drought periods, restrictions on water access have been announced along the Barwon-Darling when the storage levels at Menindee Lakes have fallen to critically low levels. These restrictions are sometimes referred to as embargos and have occurred on a number of occasions during the millennium drought and more recently. The intention of the restrictions has been to ensure sufficient water in Menindee Lakes to meet critical needs for water supply to Menindee, Broken Hill, and Pooncarie township, although there are no specific rules regarding these restrictions. The approach to restrictions is currently under review following the construction of a new pipeline from the Murray River to Broken Hill in 2019, and the critically low water levels experienced at Menindee Lakes in 2019/20.

7.2.1 Data sources

Daily access conditions for each class of licence, and the rules for managing individual water access accounts, are set out in the Barwon-Darling WSP.

Individual water accounts are maintained within the WAS, including all account transactions and balances. Individual account holders can view accounts online, and the WAS provides a variety of reports that describe water in accounts and the various types of transactions that have occurred. Prior to 2012, the previous water licensing database was used to record licensed entitlements and water use.

Information sources to inform the model include:

- Water Sharing Plan for the Barwon-Darling Unregulated Water Source
- The WLS, WAS, and the prior water licensing database.

7.2.2 Modelling approach

Continuous accounting

The modelled continuous accounting system has been developed to represent operational practice as closely as possible. Key parameters are summarised in Table 21.

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[10] Revised modelling indicated that the long-term average level of diversions by A, B, and C class licences was 189 GL/year under the 1993/94 Cap conditions. Individual licence shares were subsequently adjusted in 2015/16 to reflect the revised modelling and allocations returned to 100%.

Table 21 Key parameters for modelling of NSW continuous water accounting system

Component	Comment
Debiting type	Debiting based on water use
Timestep	Daily
Usage limits	3 ML/share in any water year
Account limits	No upper limit
Allocation limit	1 ML/year

Drought restrictions

The model simulates drought restrictions based on a trigger storage volume at Menindee Lakes. As part of the earlier development and accreditation of a 1993/94 Cap model for the Barwon-Darling, a volume of 150 GL has been adopted as the trigger storage volume based on an assessment of the critical needs for Broken Hill and Menindee township.

7.3 Water trading

Trading of licence shares (known as permanent trade) and account water (known as temporary trade) has been permitted since the commencement of the Barwon-Darling WSP in 2012. However, both permanent and temporary trade are subject to restrictions to limit the potential for impacts to other licence holders and the environment:

- Permanent trade is only permitted if it does not increase the total shares in that class of licence beyond the limits set for each of the 4 main river sections defined in the Barwon-Darling WSP.
- Temporary trade is only permitted if it is traded to another access licence with the same or higher commence to pump conditions.
- The introduction of individual daily extraction components (IDECs) for the 2020/21 water year provides a mechanism to limit impacts of trade by placing an upper limit on the number of IDECs permitted in each of the 4 main river sections defined in the Barwon-Darling WSP.

7.3.1 Data sources

Records for all water trading are maintained by WaterNSW in the WAS database. Figure 16 shows permanent trading within the Barwon-Darling Valley river system. All entitlement categories are included.

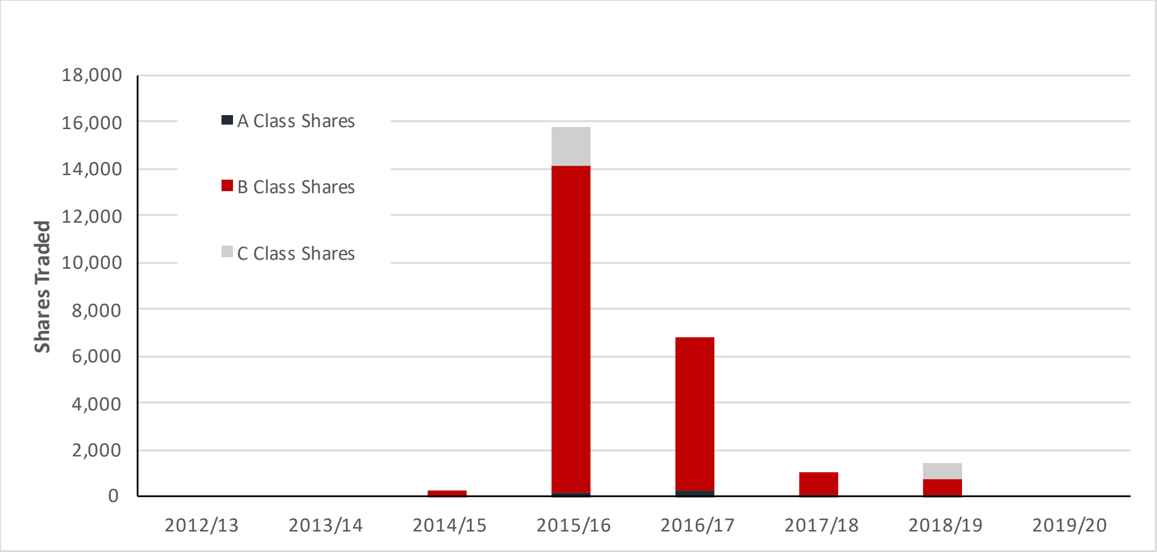

Figure 16 Annual permanent trade of shares over the period 2012/13 to 2019/20

Figure 17 shows temporary trading within the Barwon-Darling Valley river system. All licence classes are included. In some years there is a significant volume of trade between properties that have the same owner.

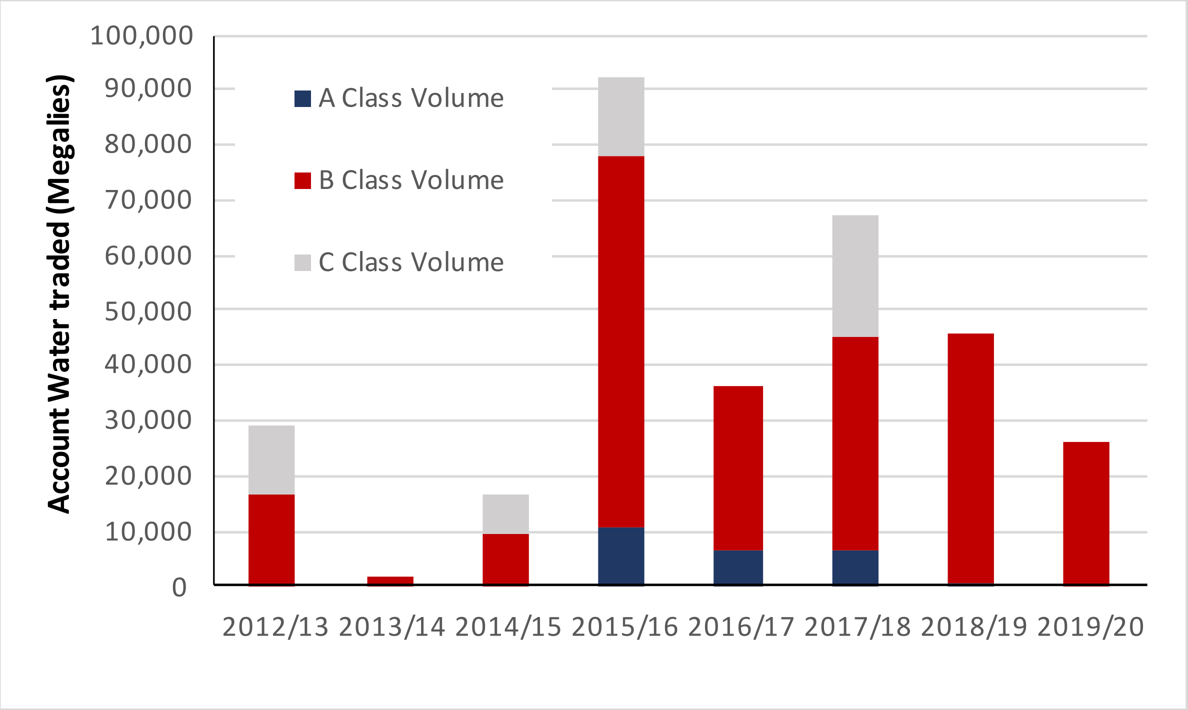

Figure 17 Annual temporary trade of allocations (volumes, ML)) over the period 2012/13 to 2019/20

7.3.2 Modelling approach

Temporary water trading is not represented in the model due to software limitations.

7.4 Weir operation

The weirs along the Barwon-Darling Valley river system facilitate storage of water for town water supplies, and act as a pumping pool for other water users. These on-river weirs have not been represented in the Barwon-Darling model, as they are fixed crest weirs that are not operable in the sense of having gates or valves to manage river flows and have a minor effect on streamflows that is included when calibrating river flow routing and evaporation.

7.5 Environmental flow rules

In 2020 four new environmental flow rules commenced in the Barwon-Darling Water Source, and are set out in the Barwon-Darling WSP.

Increase in A Class commence-to-pump thresholds

The A Class commence-to-pump flow thresholds have been varied in response to the NSW Natural Resource Commission recommendations, based on the environmental water requirements (EWRs) from the Long-Term Environmental Watering Plan for the Barwon-Darling Valley prepared by Department of Planning, Industry and Environment - Biodiversity and Conservation. The new thresholds protect the low flow range and 10 percent of the baseflow range. The commence-to-pump thresholds for other licence classes remain unchanged.

Raising the A class flow thresholds will help protect the flow classes identified as key to maintaining riverine habitat. Protection of these flows supports social outcomes and ensures water security for basic rights and critical town water supplies.

The A Class commence-to-pump thresholds across 4 management zones near the top of the Barwon-Darling system have been decreased slightly, and the thresholds for 8 management zones in the middle and lower sections of the system have been increased significantly. There are two management zones where the thresholds will remain unchanged.

Individual Daily Extraction Components (IDECs)

Existing Barwon-Darling water access licences have been amended to include an individual daily extraction component, in addition to the existing share component. This limits the daily volume of water that licence holders can access under an individual water access licence once commence-to-pump (CtP) thresholds have been reached. IDECs limit the effect of pumping during peak irrigation periods to achieve both local and downstream benefits, including environmental benefits. Permanent trade of IDECs is limited to within river sections.

Resumption of flows

To maintain and connect vital refuge pools for water-dependent biota, improve water quality and replenish town water supplies, the first flow of water after a dry period is protected. The rule comes into effect when a flow event occurs after a continuous period of dry or low flow conditions and prevents water users from accessing the first flow until target flows set out in the Barwon-Darling WSP are met.

The resumption of flow rule applies in four river system sections measured at Walgett, Brewarrina, Bourke and Wilcannia. This plan allows for the first flow after an extended period of no flow or low flows to be protected from extraction. The rule is applied by sections and is triggered according to the criteria in Table 22.

Table 22 Criteria for the first flush flow protection to commence

	Criteria set at Section 1 (Walgett)	Criteria set at Section 2 (Brewarrina)	Criteria set at Section 3 (Bourke)	Criteria set at Section 4 (Wilcannia)
Section 1 restriction is activated if:	If Section 1 flow has been below 326 ML/d for 150 days OR	If Section 2 flow has been below 468 ML/d for 150 days OR	If Section 3 flow has been below 450 ML/d for 120 days OR	If Section 4 flow has been below 200 ML/d for 90 days
Section 2 restriction is activated if:		If Section 2 flow has been below 468 ML/d for 150 days OR	If Section 3 flow has been below 450 ML/d for 120 days OR	If Section 4 flow has been below 200 ML/d for 90 days
Section 3 restriction is activated if:			If Section 3 flow has been below 450 ML/d for 120 days OR	If Section 4 flow has been below 200 ML/d for 90 days
Section 4 restriction is activated if:				If Section 4 flow has been below 200 ML/d for 90 days

Normal access conditions then apply once the flow reaches the required target flows. The length of the river must reach target flows before access resumes, as described in Table 23.

Table 23 Criteria for the first flush flow protection to cease

	Criteria set at Section 1 (Walgett)	Criteria set at Section 2 (Brewarrina)	Criteria set at Section 3 (Bourke)	Criteria set at Section 4 (Wilcannia)
Section 1 restriction is relaxed	If Section 1 is forecasted to have a flow of greater than 706 ML/d for 10 days at Walgett OR The cumulative flow past Walgett is forecast to cause a cumulative flow past Bourke greater than 30 GL AND	If Section 2 is forecasted to have a flow of 1008 ML/d for 10 days at Brewarrina OR The cumulative flow past Brewarrina is forecast to cause a cumulative flow past Bourke greater than 30 GL AND	If Section 3 is forecasted to have a flow of 972 ML/d for 10 days at Bourke OR The cumulative flow past Bourke is forecast to be greater than 30 GL AND	If Section 4 is forecasted to have a flow of 400 ML/d at Wilcannia for 10 days OR a cumulative flow past Bourke (since start of restriction) greater than 30 GL
Section 2 restriction is relaxed		If Section 2 is forecasted to have a flow of 1008 ML/d for 10 days at Brewarrina OR The cumulative flow past Brewarrina is forecast to cause a cumulative flow past Bourke greater than 30 GL AND	If Section 3 is forecasted to have a flow of 972 ML/d for 10 days at Bourke OR The cumulative flow past Bourke is forecast to be greater than 30 GL AND	If Section 4 is forecasted to have a flow of 400 ML/d at Wilcannia for 10 days OR a cumulative flow past Bourke (since start of restriction) greater than 30 GL
Section 3 restriction is relaxed			If Section 3 is forecasted to have a flow of 972 ML/d for 10 days at Bourke OR The cumulative flow past Bourke is forecast to be greater than 30 GL AND	If Section 4 is forecasted to have a flow of 400 ML/d at Wilcannia for 10 days OR a cumulative flow past Bourke (since start of restriction) greater than 30 GL

	Criteria set at Section 1 (Walgett)	Criteria set at Section 2 (Brewarrina)	Criteria set at Section 3 (Bourke)	Criteria set at Section 4 (Wilcannia)
Section 4 restriction is relaxed				If Section 4 is forecasted to have a flow of 400 ML/d at Wilcannia for 10 days OR a cumulative flow past Bourke (since start of restriction) greater than 30 GL

Active management

In the Barwon-Darling Valley, unregulated Lower Macquarie Valley, and some unregulated streams in the Gwydir Valley, licensed, or Held Environmental Water (see also Section 6.3) will be protected by managing access to water by unregulated river water access licences. In the Barwon-Darling, the commence-to-pump thresholds for each flow class are adjusted by the amount necessary to protect Active Environmental Water and the adjusted flow classes announced (either permitting or prohibiting access). If access is permitted and the available volume is less than the sum of the individual daily extraction limits in the management zone, the volume will be distributed among licence holders by announcing the volume they can take per daily flow share.

Any unregulated river access licence holder in an actively managed water source may request the water otherwise permitted to be taken to remain in the water source and be protected from extraction. Water otherwise permitted to be taken by an unregulated river access licence holder that is to remain in the river is debited from the water allocation account and is then protected from extraction as it flows along the Barwon-Darling Valley river system.

7.5.1 Modelling approach

The environmental flow rules that commenced in 2020 are represented in the Current Conditions Scenario, except for Active Management, which will be dependent on the use of Held Environmental Water. It is expected that the use of Held Environmental Water within the Barwon-Darling Valley will evolve over time, and representation of this in the model will be included as part of ongoing improvements to the Barwon-Darling model.

The model parameters have been updated to represent the IDECs, and the new A Class commence-to-pump thresholds for the Current Conditions Scenario.

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 Barwon-Darling model, 2008/09 Validation Scenario.

It describes the criteria that has been used to evaluate the ability of the model to address key objectives.

The results in Section 8.3.1 graphically show climate used in the model to demonstrate that a range of climate variability is included in the full simulation, and those periods used to calibrate the sub-models sample this range.

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

The volumes of water diverted for floodplain harvesting are reported. A key component for estimating total floodplain harvesting is the estimation of total irrigation water use based on historical crop areas and a crop model which is in line with published information. The important results here are whether there is sufficient water from all sources, including floodplain harvesting, to irrigate the historical crops. These checks are primarily at the valley and reach scales. While checks are completed at individual properties, some variation is allowed for given known differences in irrigation behaviour and potential inaccuracy of metered diversions at individual farms.

We used the fully assembled model for the validation of metered diversions and report average annual volumes and annual time series of planted crop areas, and unregulated river water access licence diversions. In the following sections, the key simulated results from the model (flows, diversions, and crop areas) are compared with recorded information to assess model performance. All results in this report reflect the final fully simulating 2008/09 model unless otherwise noted.

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 wet and dry periods. It is not possible to replicate every historical flow event; however, the overall characteristics such as frequency of low, medium and high flows as well as replicating wet and dry periods are important.

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

The assessment criteria/methods are summarised in Table 24.

Table 24 Overview of assessment criteria

Component	Performance test	Metrics and/or visuals
Flow simulation for the 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 25
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 compared to industry research estimates and, for the 3 properties with significant local runoff beyond the property boundary, other catchments with similar characteristics
Overbank flow harvesting	How well frequency and volume of overbank flows are simulated	Modelled flow events exceeding overbank flow thresholds compared to observed
Crop water use rates	How well crop water use rates (ML/ha) are reproduced	Based on existing individual property calibrations (NOW 2011)

Component	Performance test	Metrics and/or visuals
Planted areas	How well historical irrigated areas are simulated	Modelled crop area compared to combination of farm survey and remote sensing crop areas
Metered diversions	How well A, B & C class metered diversions are simulated	Total A, B and C class diversions over full 2003/04 to 2013/14 period compared to observed, model bias (%) metric

8.1.2 Model validation – 2008/09 Validation Scenario

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 Barwon-Darling model, the diversions and water management components have been assessed over the period 2003/04 to 2013/14, 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 development[11]. We refer to this as the **2008/09 Validation Scenario**.

The 2008/09 water year was selected for this 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 2003 to 2014. However, in the Barwon-Darling Valley, there was very little change in irrigation development levels between 2008/09 and 2013/14. 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 changes in irrigation infrastructure and water management rules that actually occurred over the comparison period when reviewing results.

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 particularly important – 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.

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[11] This scenario is configured with all eligible storages, which includes one storage approved on 3 July 2008 but built post 2008, and is eligible under NSW floodplain harvesting policy.

The flow calibration of the existing Barwon-Darling model was retained for this updated version, as the existing model already represented floodplain harvesting by individual irrigation properties, and calibrated flows and losses have already taken into account the volume of water estimated to be taken by floodplain harvesting.

This previous flow calibration has been found to reproduce low flows poorly, due to the extreme variation in flows along the Barwon-Darling, and the extended periods of very low or no flows that occur periodically. However, representation of low flows in the model has very little effect on the simulation of metered diversions and no effect on floodplain harvesting. DPIE Water is preparing a new Source model for the Barwon-Darling Valley river system, and this will recalibrate flows to address these issues with low flows.

Consequently, this flow simulation assessment focusses on the higher flows that result in overbank flow access. The simulation of overbank flow events seeks to replicate the observed frequency and volume of these events. This ability of the model to reproduce these is shown in Section 8.2.2.

These show that the modelled **frequency and number of overbank flow events** reasonably matches the observed behaviour.

Table 25 Flow metrics used to assess flow calibration

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

Only 3 Sacramento models were needed to extend and gap-fill flows from smaller tributaries not included in the major upstream valley models. The 3 Sacramento models simulate inflows from the

Bogan River, the Castlereagh River, and Thalaba Creek. These inflows represent approximately 10% of the total inflows on average to the Barwon-Darling Valley river system. All other inflows are directly gauged flows, or from upstream valley models.

The calibration of these 3 Sacramento models was undertaken as part of the initial development of the Barwon-Darling model (NOW 2011) to infill and extend observed flow records, or to provide an estimate of inflows to the Barwon River where no observed flows are available (e.g. Thalaba Creek). These are largely ephemeral streams and the initial modelling was based on limited climate, flow and water use data in these catchments.

The 2008/09 Validation Scenario uses the observed inflow from the Border Rivers at Mungindi rather than the modelled outflow from the Border Rivers Source model. This change is in response to some under-simulation of Mungindi flows, and small to moderate flow events in particular, due to the full development approach (also known as entitlement modelling) taken for Queensland water users in the Border Rivers Source model[12]. This underestimation of modelled Mungindi flows has led to a reduction of the time that floodplain harvesting is available in the upper sections of the Barwon-Darling Valley river system. Use of these observed flows will improve the assessment of floodplain harvesting capability between individual properties under historical climate. A review of other modelled inflows did not indicate any systematic issues.

The effects of using the observed inflows at Mungindi diminishes along the Barwon-Darling Valley river system and only has a discernible impact for properties in the upper reaches.

For other scenarios described in the companion Scenarios report (DPE Water 2022) such as the 1993/94 Cap and Plan Limit Scenarios, modelled outflows from the Border Rivers Source model have been used.

8.2.2 Main river flow simulation

The calibration of flows for the previous Barwon-Darling IQQM has been used for this Barwon-Darling model. Flows for the previous Barwon-Darling IQQM were initially calibrated over the much earlier period from 1970 to 1984, when diversions from the river were significantly lower. In 2010, the previous IQQM model was recalibrated to take into account flows between 1995 and 2005, when metered diversions became available. Results of this flow calibration for each river section are described in NOW (2011).

It has also been recognised that the Barwon-Darling model does not reproduce low flow behaviour well, and the department has committed to upgrading the model to address this. However, the new Source model for the Barwon-Darling is still under development and was not available to use for the implementation of the NSW Floodplain Harvesting policy.

To assess the current Barwon-Darling model's suitability for simulating floodplain harvesting access, we have reviewed the reproduction of higher flow events that are more relevant to floodplain harvesting. The number of days where flows exceeded the moderate flood level has been examined, with observed and modelled flows compared for key flow gauges along the system where the majority of floodplain harvesting occurs. The comparison of the number of days each year

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[12] Entitlement modelling assumes that all licences take as much water as they are permitted under their licence conditions whenever water is available to be taken. This modelling approach is used to determine water use limits in the Queensland portion of the Murray-Darling Basin.

that observed and modelled flows exceeded the moderate flood level at Walgett is shown in Figure 18. This shows that the inter-annual pattern of high flow days is reproduced well, and the total number of modelled days above this threshold across the period 1970–2014 is very close to the observed number of days (+1.4%).

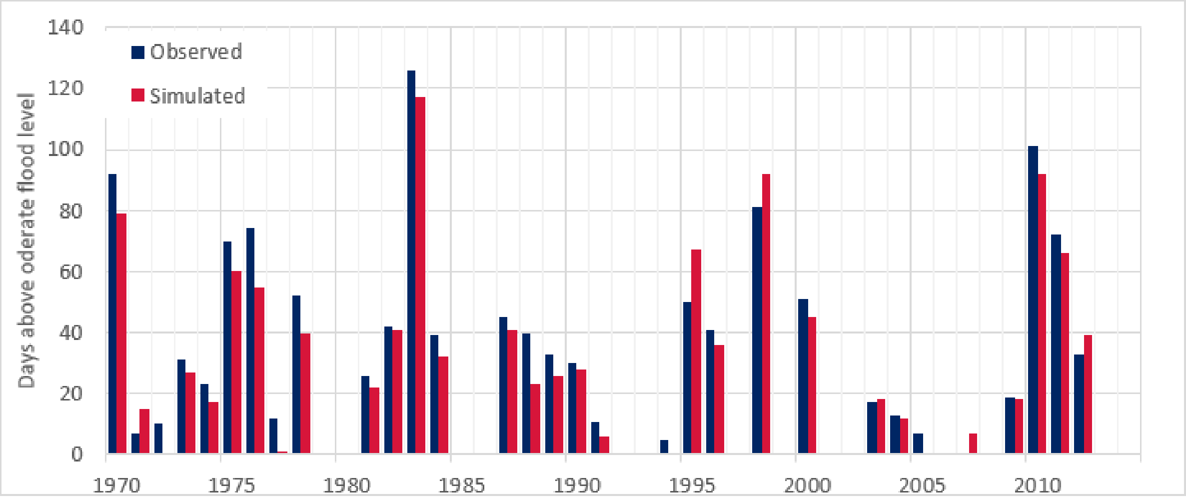

Figure 18 Annual modelled vs observed days at Walgett above moderate flood threshold over the period 1970 to 2014

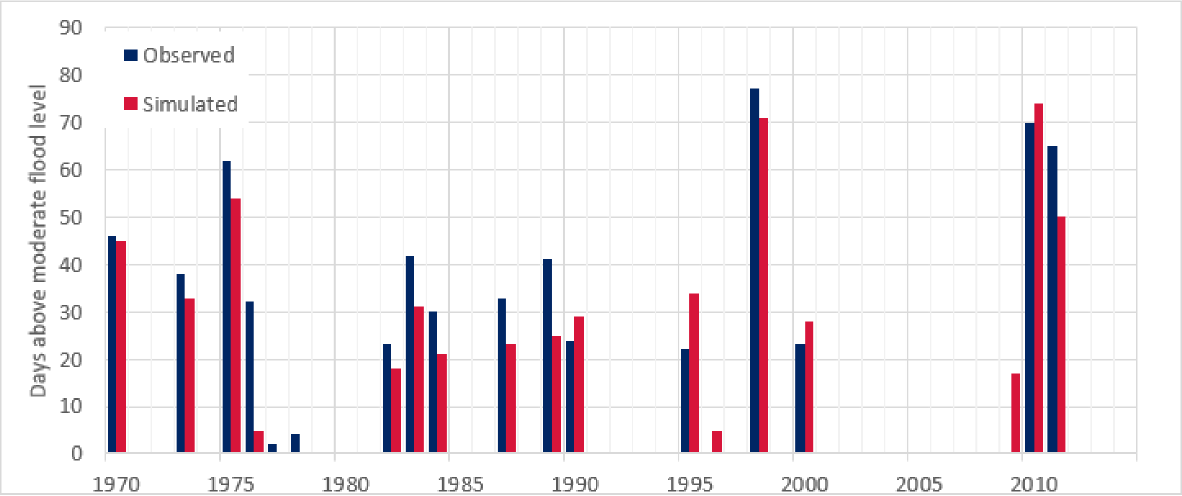

Figure 19 Annual modelled vs observed days at Bourke above moderate flood threshold over the period 1970 to 2014

The comparison of days above moderate flow threshold is shown for key flow gauging stations along the river system in Table 26. For Walgett and Bourke, where the flow gauging station represents the full range of flows, there is a relatively good overall match between simulated and observed days during the validation period. The under-simulation of days where flow at Bourke exceeds the moderate flood threshold largely occurs in the very wet periods during the 1950s, 1970s, and 1980s. More generally, we expect to see some under-simulation of flows in the earlier periods, as the contemporary irrigation development in the model was much higher than actually in place. This can be seen more so at Bourke which is downstream of most of the irrigation in the Barwon-Darling Valley.

The comparison of modelled and observed flows in Table 26 commences from 1950 at Bourke reflecting the availability of digitised daily flow data.

Table 26 Number of days when flows exceeded the moderate flood threshold at key (Walgett and Bourke) flow gauging stations

	Observed	Simulated	Bias*
Walgett			
1895 to 2014	2,420	2,455	+1.4%
2003 to 2014	262	252	-3.8%
Bourke			
1950 to 2014	1,075	885	-17.7%
2003 to 2014	135	141	+4.4%

* A positive bias means that simulated was higher than observed

8.3 Water use simulation assessment

8.3.1 Irrigation

This section describes the results of updating the parameters for the major water balance components affecting water use by irrigation farms. The modelling methods adopted for these are described in Section 6.2.2.

This section reports on crop areas, metered water use, runoff harvesting and overbank flow harvesting. Crop areas were held to observed for the initial re-calibration. However, the results presented in this section have been taken from the fully assembled Validation Scenario. Simulation of planting areas is reported in Section 8.3.2. The metered diversion results after using simulated planting areas are in Section 8.3.3. Sources of uncertainty in the simulation of irrigation diversions and use are described in Table 30.

Modelled crop water use

Our approach to estimating irrigation water use is described in Section 6.2.2, including where we have continued to use the existing model parameters that were calibrated as described in the calibration report for the Cap model (NOW 2011). Whilst this is not the same approach as other valleys, the existing Barwon-Darling model crop water use is based on the same approach (Allen et.al. 1998) that has been used in other valleys.

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, 2021). 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.

Rainfall–runoff harvesting

Runoff from developed and undeveloped areas on farm were simulated with climate variability and irrigation as inputs to a soil moisture accounting component model of the same simple crop water model used to model the crop water use above.

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 et al. 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 to rainfall in areas with high water-holding capacity (e.g. Freebairn et al. 2009), which is the case for most of the valley. 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 do 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.

Simulated **rainfall–runoff rates** are summarised in Table 27. The runoff rates from both fallow and irrigated areas are in line with the results from the literature review described in Appendix D.

The **interannual variability in modelled runoff depths** from climate variability is well represented (Figure 20). As well as reinforcing the relative rates of runoff response summarised in Table 27, this also shows a clear relationship of higher annual runoff depths with more annual rainfall for each land use type.

Table 27 Rainfall–runoff rates for Bourke Airport (rainfall station 48245), calculated as total runoff over the period (1890 to 2015), divided by total rainfall

Area	1890–2015
Summer irrigated + winter fallow	7.1%
Continuous fallow	1.9%
Undeveloped	2.0%

Note: The same parameters are applied for other climate stations however a small amount of variation occurs due to differences in rainfall characteristics

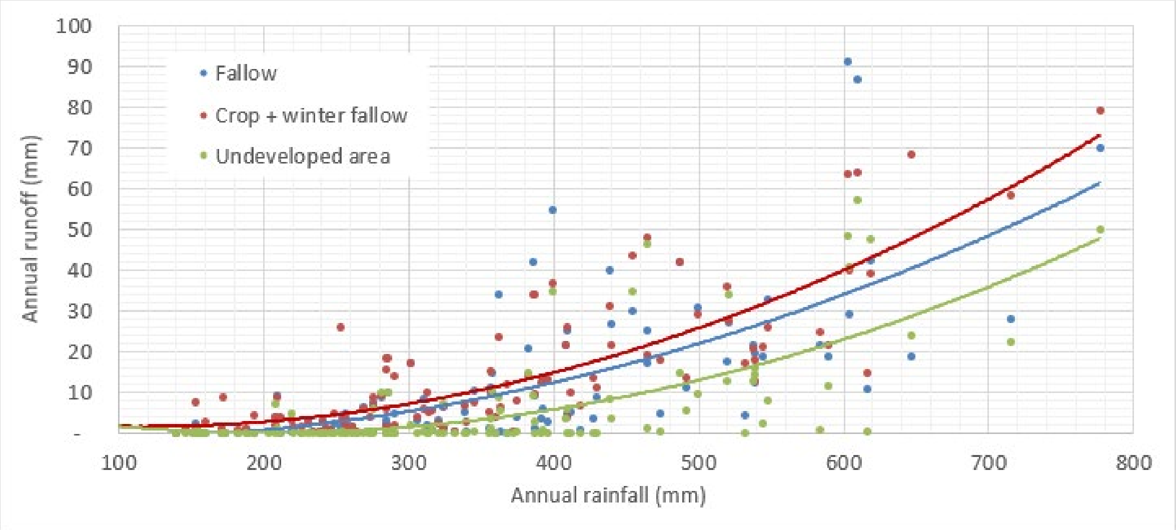

Figure 20 Modelled annual runoff depth compared to rainfall for different on-farm land area types from an irrigator near Bourke

While the runoff depths are the best available, considerable uncertainty remains, largely due to 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 20). An average obtained over a short-term period is likely to have a different average runoff coefficient compared to the long term.
- An overall farm water balance check is undertaken (described in a following section) where the combined metered use, rainfall runoff, and overbank flow harvesting is compared to the simulated total crop water requirements for each individually simulated irrigation enterprise. To achieve an overall balance, the bias in rainfall–runoff rates is likely to be offset by a bias in overbank harvesting estimates. The access to overbank flow has been estimated through the use of a farm water balance approach as described in Section 2.3.1. This means that when the assumed rainfall–runoff rates are lower than actual, then the model is likely to have been calibrated to assume higher access to overbank flow compared to actual.

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 flow characteristics is shown at Figure 18 and Figure 19 and shows that the modelled **frequency and number of overbank flow days** closely match observed behaviour.

Apart from the data that were analysed to form the breakout relationships, there is no further data that can be used to validate the volume on the floodplain during an event[13]. We have investigated whether it will be possible to use remote sensing data to estimate change in on-farm storage volumes during an event. These type of data could provide more confidence than looking at volumes on the floodplain, as not all water can be and is diverted. Very high-resolution data are required to undertake this analysis and we found insufficient historical data to undertake this assessment immediately prior and post a floodplain harvesting event. In some cases. we were able to use remote sensing of on-farm storage filling events to independently verify harvesting periods nominated by landholders. Data capture and modelling approaches will continue to improve as advances are made in remote sensing capability.

8.3.2 Planted areas

The Barwon-Darling model estimates the area planted on the basis of water availability using a constant planting decision (i.e. a fixed volume required to be available per hectare planted) that was taken from the farm surveys. Other factors such as markets also affect planting decisions, hence some variability between years is expected.

The modelled planted summer crop areas have been compared with the remote sensing areas at a valley scale in Figure 21, for all individually modelled properties. Remote sensing data were not available for many properties during 2012/13, and for 3 of the eligible properties across all of the years, and this has affected the observed areas.

Figure 21 shows that while the model simulates approximately 14% more area than observed over the validation period, it follows annual variability reasonably well. There can be changes in other socio-economic variables that influence crop areas for individual years, and some variability between modelled and observed areas at the annual level can be expected.

In particular, differences between simulated and observed irrigated crop areas can be seen in 2008/09. This corresponds to the significant increase in observed winter crop areas shown in Figure 21. This suggests that the model has over-simulated summer crop areas and under-simulated winter crop areas

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[13] 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.

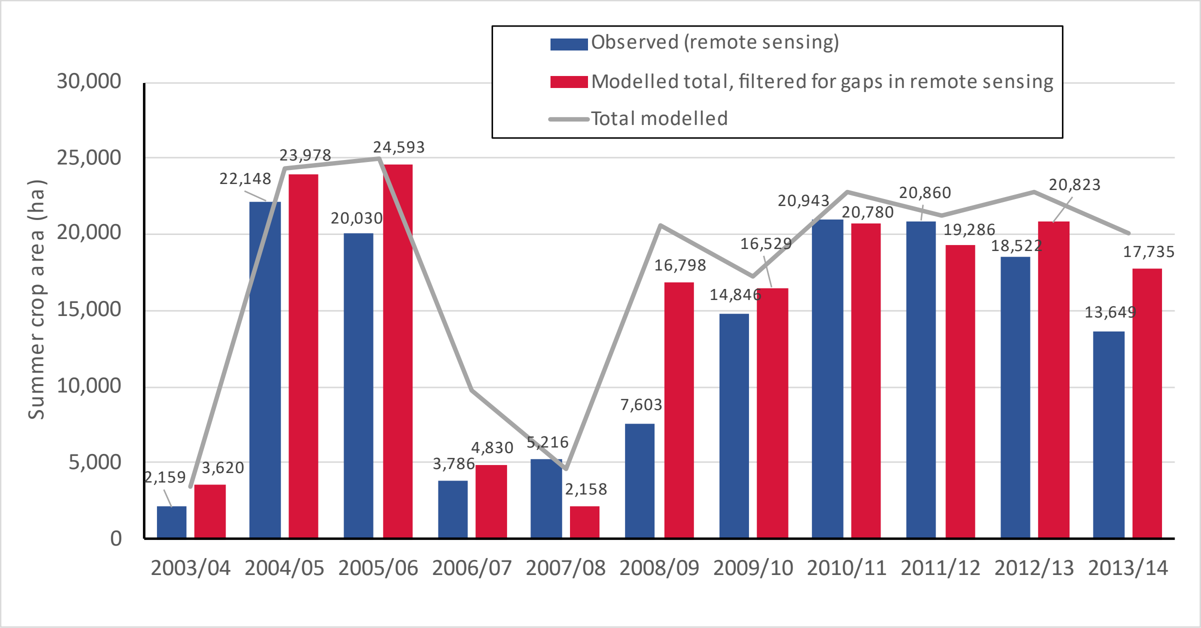

Figure 21 Observed (remote sensing) and modelled summer crop areas for all individually modelled properties over the period 2003/04 to 2013/14

The modelled winter crop areas have been compared with the remote sensing areas at a valley scale in Figure 22. The modelled winter crop areas are much lower than observed, and were based on surveyed crop area data from 1989/90 to 1999/00. As noted in Section 6.2.1, farm surveys indicated that areas of summer crops planted were strongly related to water availability, whereas for winter crops this was not as significant a factor. Surveys also indicated that planting decisions for winter crops were often based on very low water availability (1-4 ML/ha), which suggests that winter crops are not intensively irrigated.

The large under-simulation of winter crop areas in 2007–10 has likely led to some over-simulation of summer crop areas in the model.

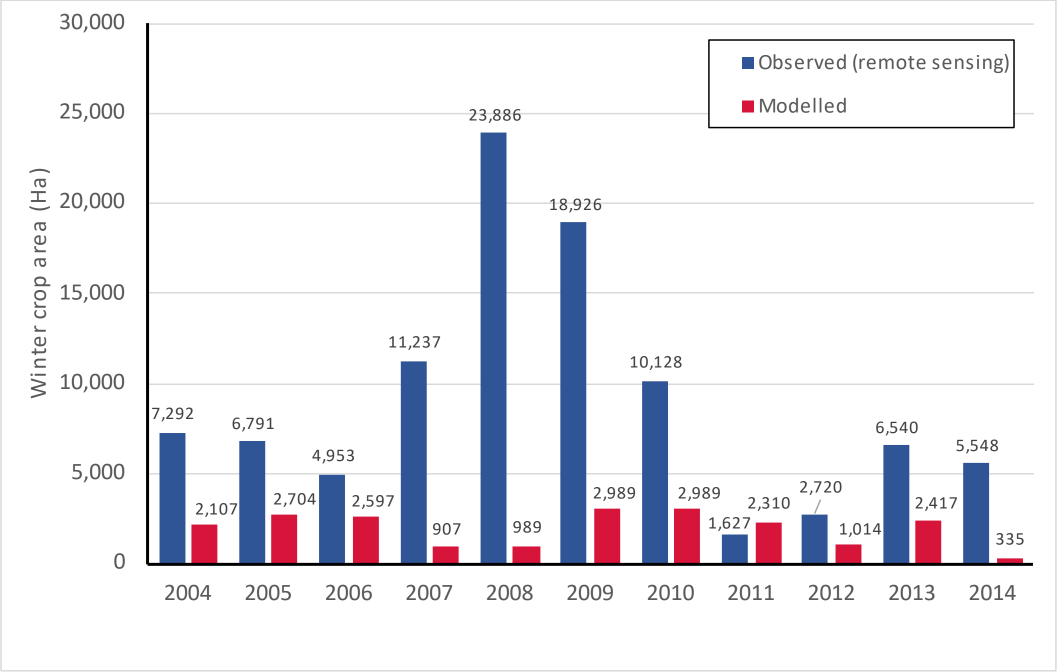

Figure 22 Observed (remote sensing) and modelled winter crop areas for all individually modelled properties over the period 2003/04 to 2013/14

8.3.3 Metered diversions

Results of simulated diversions from the fully assembled, calibrated model for the 2008/09 Validation Scenarios were compared with recorded diversions. Totals for the 2003/04 to 2013/14 comparison period are illustrated in Figure 23 with summary results reported in Table 28.

Table 28 Comparison of total simulated and observed metered diversions (GL) over the period 2003/04 to 2013/14

Period	Metered diversions[1] (GL)	Modelled diversions[2] (GL)	Bias
2003/04–2013/14	1,633	1,520	-6.8%
2003/04–2008/09	942	878	-7.0%
2009/10–2013/14	692	643	-6.9%

[1]This includes metered B and C class licences and excludes A class and small B class licences that are not metered.

[2]Modelled diversion by A class and small B class licences is approximately 5 GL/year on average, but is excluded from these results as there are no metered diversions for these licences.

Table 28 shows that the model simulates **metered diversions** reasonably well across the whole period, but under-simulates diversions across the assessment period. The **inter-annual pattern of diversions** is also well reproduced, as shown in Figure 23. To reflect the water recovery under the Basin Plan and the purchase of all licences from 2 major irrigation enterprises (Toorale in 2008, and Colly farms in 2009)[14] the modelled diversions reported do not include these two properties after they ceased irrigation.

During the millennium drought (2003–08), there were a series of restrictions placed on access to water along the Barwon-Darling to help improve the critically low water levels at Menindee Lakes. These restrictions were not consistently applied, and evolved over that period, whereas the model has a fixed representation of these restrictions.

In addition to the millennium drought restrictions, interim Cap management measures were put in place during 2010/11 - 2011/12. During these two years, access to water in accounts that was carried over from previous water years was suspended, and water users were limited to the 173 GL annual allocation for 2010/11, and 198 GL in 2011/12. This short-term measure is not included in the model and may have contributed to the difference between observed and modelled diversions in these years that is evident in Figure 23.

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[14] Following the purchases, all diversions from the Barwon-Darling Valley river system ceased at these two properties

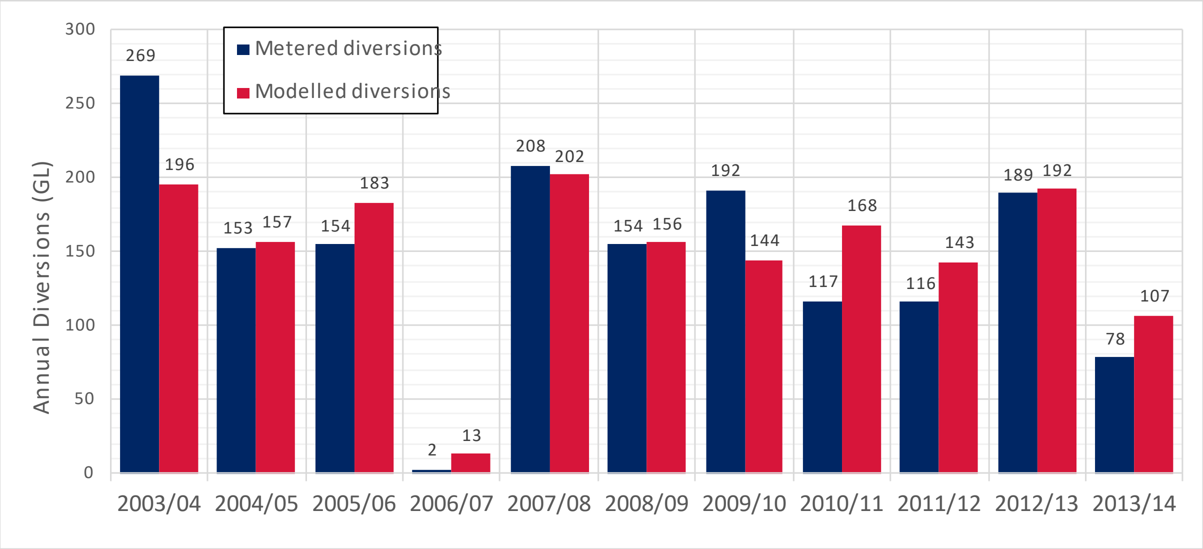

Figure 23 Total simulated vs observed annual metered diversions 2003/04 to 2013/2014

8.4 Long-term annual diversions

An indication of how these different diversion components vary based on long-term climate conditions is illustrated using the model set up to run a long-term simulation. The results shown at Figure 24 illustrate 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 metered diversions, followed by overbank flow access, and lastly on-farm rainfall –runoff harvesting. The metered water use inter-annual variability reflects the impacts of climate and the management of the upstream valleys. Overbank flow harvesting has the greatest inter-annual variability and corresponds with the occurrence of flow breakout events as shown in Figure 18 and Figure 19. Rainfall–runoff harvesting has a similar pattern, albeit at a reduced scale.

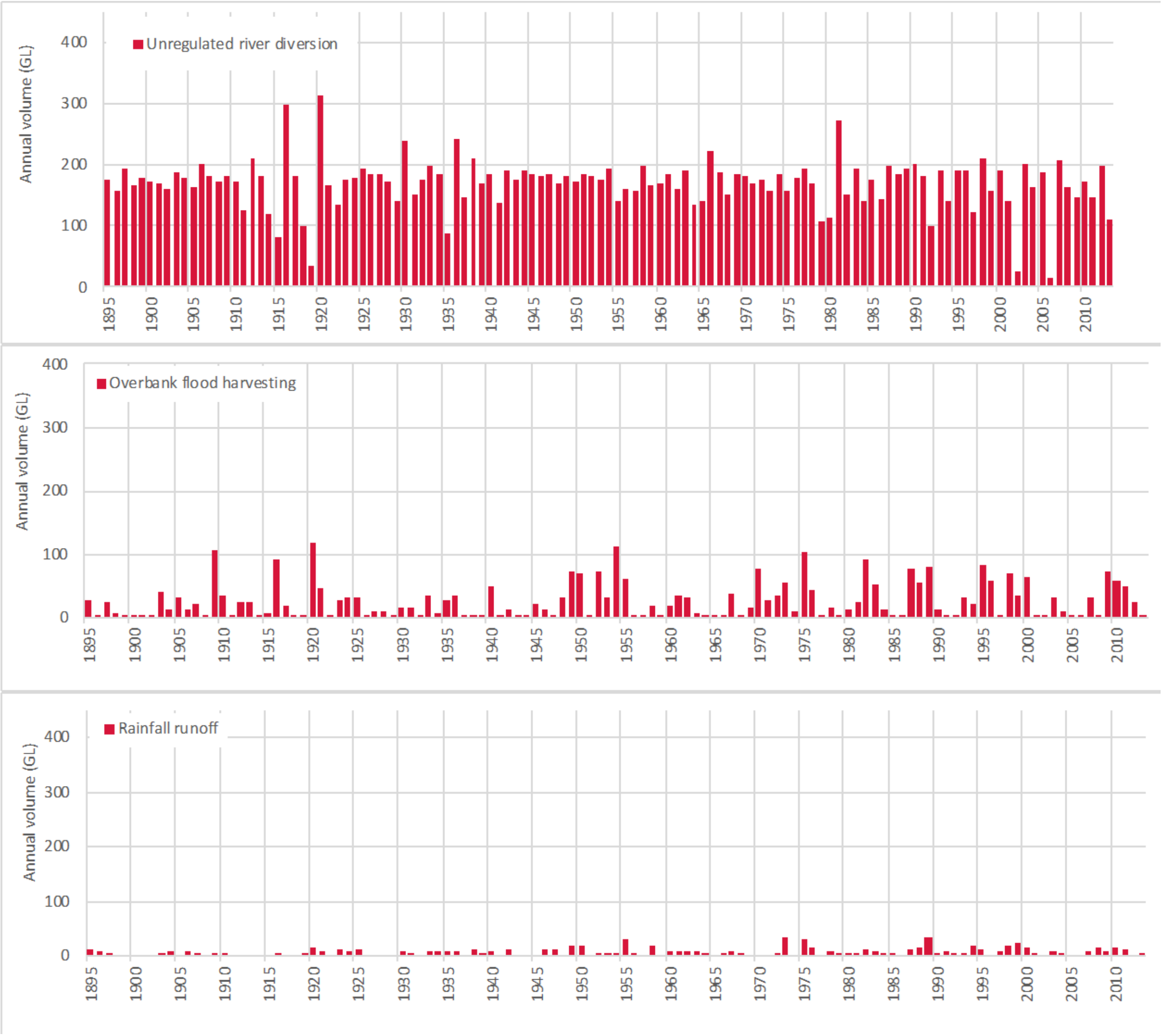

Figure 24 Simulated annual volumes of unregulated river diversions (top), overbank flood harvesting (middle) and rainfall–runoff harvesting (bottom) over the period 1895 to 2014

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.'*

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 plan limit
- the **distribution** of floodplain harvesting entitlements **between individual properties.**

These 2 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.

9.1 Sources of uncertainty

During model development, these issues are considered, and a number of actions taken to minimise uncertainty, as described below. It is not possible to define total uncertainty in quantitative terms. Table 29 and Table 30 summarise the significance of a range of sources of uncertainty on the modelling of floodplain harvesting and the Plan Limit based on work undertaken in the NSW Border Rivers Valley and the Gwydir Valley. Whilst the Barwon-Darling model is an update of the existing Barwon-Darling IQQM, the summary below draws on the sensitivity testing undertaken for these other valleys.

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

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

We considered these issues during model development and took a number of actions to minimise uncertainty as described in Table 30 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, where practical, we tested 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 29 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 30 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
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 diversions have known uncertainties of up to ±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 the installation of new meters that are compliant with the Metering Framework and on-farm storage monitoring data through the Floodplain Harvesting measurement requirements.	High

Source of uncertainty	Comment	Significance rating
Sparsity of records on harvested volumes	There is a lack of reliable records on actual volumes harvested from overbank flow events or rainfall–runoff. Whilst other lines of evidence have been used, such as information gathered through farm surveys (Irrigator Behaviour Questionnaires), the lack of data makes it difficult to validate both the valley total and individual variability in floodplain harvesting. **This is the principal cause of uncertainty in modelling floodplain harvesting.** However, the data provided through the measurement requirements for floodplain harvesting properties will reduce this uncertainty over time	High
Model assumptions / simplifications		
Property scale rainfall–runoff model operating on a daily timestep does not account for rainfall intensity	Research indicates that the primary predictors of rainfall–runoff in areas with high water holding capacity are rainfall and soil moisture content. Our model continuously tracks soil moisture content. Therefore, in most areas, any limitations in accounting for rainfall intensity would not be a significant issue for a long-term simulation period	Low
Evaporation and seepage loss from storages is based on assumed sequential filling rather than simultaneous filling of storages	This assumption relies on this being the most efficient mode of operation to minimise losses. Long term results have low sensitivity to changes in this assumption. 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	Medium

Source of uncertainty	Comment	Significance rating
	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)	
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
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. In other regulated river systems, 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, this data is limited, and it is not possible to verify and account for individual variation in irrigation practice and runoff generation. In response to recommendations of the Independent Review (Alluvium 2019), we have also undertaken another independent review of the assumptions for runoff from irrigation areas (Barma Water Resources 2019). This found that: • the estimates were uncertain due to limited available data • the adopted approach represents a step forward compared to other approaches reviewed • harvesting of rainfall–runoff is likely to be a fairly small component of total valley diversions.	generally Medium may be High for some properties where rainfall–runoff is the dominant form of take

Source of uncertainty	Comment	Significance rating
	In the future, data from the floodplain harvesting measurement requirements will be used to review and verify our assumptions.	
Relationships between river flow and overbank flow and access to that flow	We have generally based overbank flow relationships where possible on hydraulic models of floodplain flow developed for Floodplain Management Plans[15]. In a number of cases these relationships were based on other evidence. 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 in the Border Rivers shows that valley wide totals are not sensitive to these assumptions. The majority of individual results also have low sensitivity (see Table 45 in the Border Rivers report, test 3). Adopting a standard set of rates is considered to be the most equitable approach that also enables a robust review of eligible and historical works.	Low

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[15] 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 30 were done (DPIE Water 2020, 2021). These tests have not been repeated for the Barwon-Darling model because the sensitivity of the models to certain parameters and changes is expected to be consistent between model builds of other river systems in northern NSW.

9.2 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.

9.3 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 31. The appropriateness of the adopted methodology in addressing each criterion relies on the conclusions made in Table 31.

Table 31 Capability assessment criteria and confidence to inform the distribution of individual entitlements

Capability assessment criteria	Confidence in modelled approach
Know with some confidence	

Capability assessment criteria	Confidence in modelled approach
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
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 in the Border Rivers 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 in the Border Rivers 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 in the Border Rivers has been undertaken which shows the model formulation 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).

9.4 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 ongoing 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.

9.5 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 have 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 in other valleys 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 river diversions.

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

In other valleys, we have assessed 5 cases where standardised parameter 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 we have 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. The proposed rainfall–runoff harvesting partial exemption[16] should reduce the significance of uncertainty in these parameter 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.

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[16] Information on the partial exemption is provided in the companion Scenarios report (DPE Water, 2022a)

10. Conclusions

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

The updated Barwon-Darling model is the primary tool that will be used for the NSW Government to determine floodplain harvesting licences. This update will subsequently be brought together with other model versions being used for the NSW Regional Water Strategy program to continue to provide technical information about the Barwon-Darling Valley. This model has known uncertainties that inform how fit it is for current purposes. Recommendations for addressing these are set out in Section 10.4.

10.1 Meeting objectives

The Barwon-Darling model represents the key physical and management processes that affect water availability and access within this river system. This model is proposed as the best available model to simulate water use for estimating floodplain harvesting entitlements. The 2 objectives were that it would:

- support traditional water policy, planning and compliance uses, such as implementing the Basin Plan and estimating water sharing 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 2 caveats:

- 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
- that the lack of actual harvested volumes data reduced our ability to minimise uncertainty in the model and thus our ability to verify the accuracy of the modelling.

10.2 Meeting design criteria

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

1. represent key processes affecting water availability and sharing

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

A qualitative assessment of how well these modelling objectives and criteria have been met is provided 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 5.4 *Modelling water users* and Section 6.3 *Held environmental water*.

Criteria 2: period of data sufficient to capture climate variability

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

The calibration period varies depending on the component. The flow calibration uses the period of flow record. 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. The Barwon-Darling model has been designed to enable use of different climate data. A climate risk dataset has been developed for that purpose which includes a stochastic element derived from historical climate observations and a paleo-logical climate signal; and combines these with future climate projections from dynamically downscaled climate models.

Criteria 3: spatial resolution sufficient for multi-scale analysis

The model was developed with high spatial detail. Where possible a physical representation of processes was implemented (rather than a statistical approach), allowing for better managing uncertainties by revealing the link between cause and effect which allows for diagnostics of behaviour.

The spatial detail in the Barwon-Darling model has 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 use of all available gauged flow data of reasonable quality. This combined with the large number of rainfall stations allows for coverage of the spatio-temporal variability of water availability from climate. The resultant flow variability enables representation of currently licensed water access, as well as for floodplain harvesting. The checking of flow variability as both inflows and mainstream flow was covered in detail in Section 8.2.

The detailed reporting and assessment of diversions was with reference to available data. This model provides results at a farm scale, including a separate calculation point for each and every property that was assessed as eligible for a floodplain harvesting entitlement. The detailed data collected from farm surveys and other sources for each property were used to undertake a capability assessment of each property.

The model configuration of river network, breakout relationships, and individual property detailed representation allow for the type of calculations that enable individual farm water balance to be estimated under different scenarios, and from that, entitlements that fairly reflect their share of the total permitted water use based on policy detail.

The model includes all significant breakouts based on local knowledge supplemented by farm surveys, flow change analysis and hydraulic modelling, as well as a high level of physical detail for each farm.

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 help parameterise 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: report at multiple time scales (daily to annual)

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.

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 simulation results in Section 8.4. This capability will be further tested in the annual diversion compliance for the Basin Plan.

Criteria 5: supports replication of historical usage

The replication of historic usage has been undertaken using simulation of crop areas (Section 8.3.2). This test shows that historical metered usage is reasonably represented. Total simulated metered diversions had a 7% bias when using the planting decision. The model replicated inter-annual variability well.

The fully assembled model with simulated crop areas generates metered diversions which are close to observed metered diversions as discussed in Section 8.3.3. Overall bias was 7%, which was consistent across the validation period. Some potential reasons for the under-estimation include variations in restrictions to access when the water in storage at Menindee Lakes fell to critically low levels, as well as variations in planted area, efficiency and application rates and limitations in rainfall data.

The balance of diversions from unmetered sources, i.e. **floodplain harvesting**, was inferred from farm infrastructure and management combined with overbank flow and rainfall–runoff access opportunities, and known crop areas and previously calibrated crop application rates. Given there was a severe paucity of data to validate these results directly, they could only be assessed on water balance considerations as discussed in Section 8.3.1.

It is recognised that the installation of new meters under the NSW metering policy framework will provide better information for the currently licensed diversion of water under unregulated river licences. Together with measured floodplain harvesting volumes, this will enable a more robust modelling of the water balance at each farm property in the future.

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 previous models are about 2 decades old, and it is foreseeable that the planned Barwon-Darling Source model will likewise be around for at least a generation.

The department will transition to the new Source modelling platform over the next few years, including for the Barwon-Darling Valley. This will be a significant step as it will use new metered water use data to better estimate metered diversions from the river.

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 Barwon-Darling model, 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.

The other significant limitation of the Barwon-Darling 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 Barwon-Darling model represents floodplain harvesting with more confidence than previous models. 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 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, 2, 3 and 4. Meeting these is important for the model to meet the remaining design criteria and objectives.

With respect to criteria 5, we can 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 total metered diversions.

There are some significant differences in simulated 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 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 Section 10.4 Recommendations.

We conclude that through the model we have made the best available estimate based on the available data. Data on actual harvested volumes is needed to confirm accuracy.

The model has sufficiently demonstrated its ability to estimate annual water use over the long-term.

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 update, we have gone to great lengths to develop methods and datasets, for example, the hydraulic models and satellite data. Additional analysis of these data, as well as the consideration of data from the floodplain harvesting monitoring program and the installation of new meters for the currently licensed diversion of water, 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 8 recommendations listed in Table 32 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 32 Recommendations for future work to improve model results

	Recommendation
1	Comparison to data that will be obtained through the floodplain harvesting monitoring program and the rollout of new meters for water taken directly from the Barwon-Darling Valley river system. 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 reference number, rather than sharing the same reference number 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	Determine the impacts of future climate on diversion and flows for consideration during 5-yearly reviews of Water Sharing Plans and the development of the department’s Regional Water Strategies

	Recommendation
5	Including local water utility, stock and domestic entitlements and usage within the model (where significant)
6	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[17]

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[17] A version of the model configured with the latest available irrigation development and management rules, as described in Table 4.

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Appendix A Quality assurance

A.1 Quality assurance practices

The department maintains a set of in-house modelling practice guidelines for the development of river system models. These are based on the collective application of modelling over many decades and the broader modelling community of practice across the Murray-Darling Basin and internationally. These guidelines cover recommended data sources, extraction, validation and preparation techniques. They are regularly reviewed to capture new learnings including those circumstances which deviate from the expected, and to improve the department's modelling practice. As they are a 'living' document, i.e. they continue to evolve, they are not published in report form. However, many of the principles and practices are published through contributions to other initiatives, most recently with eWater[18] and MDBA (MDBA 2017–19).

The department's approach to selection and review of data is further detailed in Section A.2.

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 was 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. Further information on this review and our action plan to respond to the recommendations is available from the department's website[19].

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*". This review has been conducted and is described in Section A.3.

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.

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

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

Available data are first reviewed and checked for completeness, and to ensure that the quality of the data is 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 is 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.

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 departmental 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 will be contained in the companion Scenarios report.
3. Prioritise verifiable data sources, e.g. 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 (NOW 2016) 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 valley, outlining some key information that we would use to determine floodplain harvesting entitlements for their property. This included a letter from NRAR with details on their works that were 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 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* (DPIE 2020).

A.4 Report review process

This report has gone through an extensive review and editorial process. A key finding of the Independent Review of the NSW Floodplain Harvesting Implementation (Alluvium 2019) was the lack of documentation of the model development process, in particular in 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 2021). Overall, the review team congratulated the report authors for how well they had documented the modelling calibration results and assessment of suitability, while drawing attention to areas where more detail was required. In all they listed multiple 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 includes responses to those review comments, either through adding more explanatory material to this report, or through adding material to the companion Scenarios report (DPE Water 2022).

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 33 Rainfall stations used in flow calibration and irrigation demand, their station numbers, location (latitude/longitude) and mean annual rainfall

Station #	Station name	Lat (ºS)	Long (ºE)	Mean annual rainfall (mm)
52020	Mungindi Post Office	28.98	148.99	502
52019	Mogil Mogil (Benimore)	29.35	148.69	492
48031	Collarenebri Post Office	29.54	148.58	500
52026	Walgett Post Office	30.02	148.12	473
48015	Brewarrina Post Office	29.96	146.87	407
48013	Bourke Post Office	30.09	145.94	355
48245	Bourke Airport	30.04	145.95	344
46043	Wilcannia Post Office	31.56	143.37	264
46004	Wilcannia (Culpaulin)	31.73	143.22	232
47043	Menindee (Weinteriga)	32.10	142.92	239
47019	Menindee Post Office	32.39	142.42	242
47000	Gum Lake	32.53	143.37	237

Table 34 Evapotranspiration stations used in flow calibration and irrigation demand, their station numbers, location (lat/long) and mean potential evapotranspiration (PET)

Station #	Station name	Lat (ºS)	Lon (ºE)	Mean PET (mm/y)
52020*	Mungindi	28.98	148.99	1,900
53048	Moree	29.48	149.84	2,159
52026	Walgett	30.02	148.12	1,765
48239	Bourke	30.04	145.95	1,825
48027	Cobar	31.48	145.83	2,411
47058	Menindee	32.39	142.42	2,140

* weighted mean of Boggabilla (53004), Moree (53048) and St George (43053)

Appendix C Streamflow gauges

Table 35 Inflow headwater gauges used in the Barwon-Darling model, their station number and name, catchment area (CA), start and end dates of gauge, highest recorded and highest gauged levels. N.A = not available

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded level (m)	Highest gauged level (m)
416001	Barwon River @ Mungindi	44,070	1889	Current	7.99	7.85
416027	Gil Gil Creek @Weemelah No. 2	N.A	1968	Current	4.04	3.94
416028	Boomi River @ Neewoora	N.A	1968	1994	6.61	6.02
416052	Gil Gil Creek @ Galloway	N.A	1987	Current	4.24	3.88
417001	Moonie River @Gundabluie	15,810	1945	Current	6.38	6.14
418031	Gwydir River @ Collymongle	N.A	1970	1999	3.16	1.73
418055	Mehi River @ Collarenebri	N.A	1980	Current	7.17	6.23
419026	Namoi River @Goangra	36,290	1954	Current	8.94	7.97
419049	Pian Creek @ Waminda	36,290	1972	Current	3.40	3.29
420005	Castlereagh River @ Coonamble	8,400	1960	Current	6.23	6.22
421011	Marthaguy Creek @ Carinda	6,475	1944	Current	4.49	4.28
421012	Macquarie River@ Carinda	30,100	1960	Current	3.75	3.73
421023	Bogan River @ Gongolgon	27,970	1942	Current	1.52	1.48
421024	Marra Creek @ Yarrawin	N.A	1945	1977	N.A	1.36
421097	Marra Creek @ Carinda Road	N.A	1980	Current	3.03	2.59
421107	Marra Creek @ Billybingbone Bdge	N.A	1980	1997	4.26	4.25
422001	Narran Lake @ Storage Gauge	132,200	1982	1990	13.77	13.77
422005	Bokhara River @ Bokhara (Goodwins)	N.A	1944	Current	3.72	3.38
422006	Culgoa River @ D/S Collerina	N.A	1944	Current	7.00	6.66
422012	Narran River @ New Angledoon	N.A	1959	Current	2.87	2.72
423001	Warrego River @ Ford's Bridge	60,500	1921	Current	2.74	2.72
423002	Warrego River @ Ford's Bridge byewash	60,500	1921	Current	3.21	3.20

Table 36 Stream gauges used for reach calibration in the Barwon-Darling model, their station number and name, catchment area (CA), start and end dates of gauge, highest recorded and highest gauged flows. N.A = not available

Station #	Station name	CA (km^2)	Start date	End date	Highest recorded flow (m^3/s)	Highest gauged flow (m^3/s)
416050	Barwon River @ U/S Pressbury Weir	44,100	1987	Current	6.45	5.16
422004	Barwon River @ Mogil Mogil	64,800	1944	Current	9.26	9.06
422003	Barwon River @ Collarenebri	85,500	1944	Current	8.34	7.74
422018	Grawan Creek @ Old Pockataroo	N.A	1965	Current	7.218	6.505
422001	Barwon River @ Walgett	132,200	1886	Current	13.77	13.77
422002	Barwon River @ Brewarrina	297,850	1892	Current	12.14	10.62
422007	Cato Creek @ Brewarrina	N.A	1947	Current	9.19	9.19
425003	Darling River @ Bourke	385,000	1880	Current	14.18	14.09
425004	Darling River @ Louth	489,300	1954	Current	13.77	13.29
425900	Darling River @ Tilpa	502,500	1995	Current	12.99	12.96
425008	Darling River @ Wilcannia (main channel)	569,800	1913	Current	11.592	11.535
425018	Talyawalka Creek @ Barrier Highway (Wilcannia)	N.A	1971	Current	4.740	4.685
425002	Darling River @ Wilcannia (total flow)	569,800	1886	Current	11.58	N.A

Appendix D Irrigation farm runoff: data review

D.1 Background

The irrigator nodes in the IQQM 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 were collected and reviewed as part of our modelling.

There is little long term monitoring data available for natural catchments in the region, and there is also 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% to 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 1,100 mm/year.

As part of the broader floodplain harvesting modelling, 2 gauged catchments in the Border Rivers Valley were evaluated to understand how much the rainfall–runoff coefficient might vary from year to year; this is shown as an exceedance graph in Figure 25. While runoff from individual rainfall events may be very high, especially for high rainfall events on a wet soil, the long-term average will be much lower. For example, annual runoff from these gauged inflows can be up to 18% of annual rainfall volume with a long-term average of about 4%.

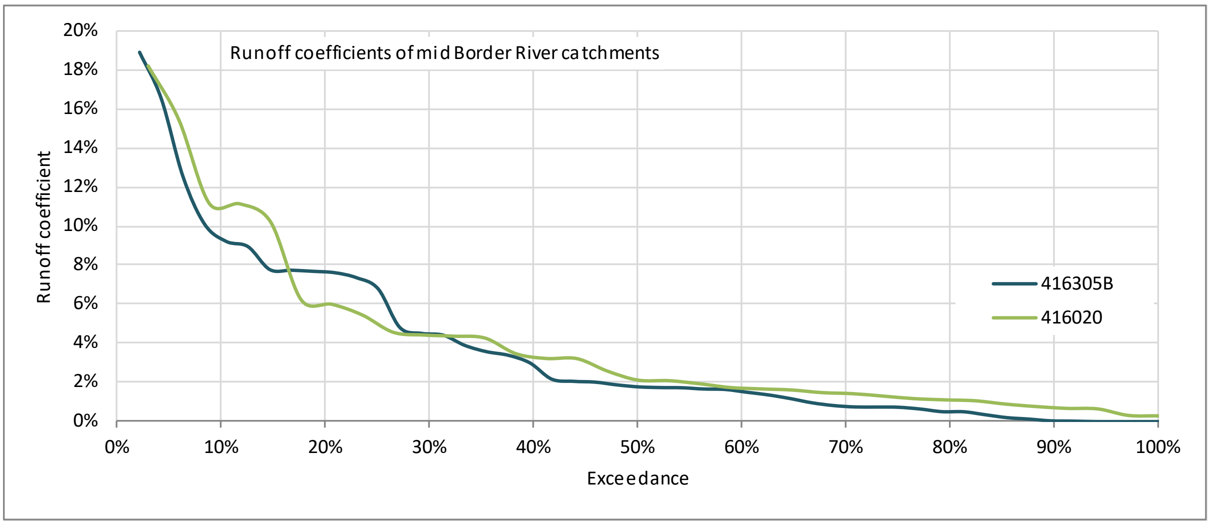

Figure 25 Comparison of mid-system gauged inflow annual runoff coefficients

Two catchments were considered to provide an estimate for regional runoff in the Barwon-Darling system: 421062 (Marthaguy Creek at Quambone) and 418032 (Tycannah Creek). The estimated average annual runoff coefficient (volume of flow as a percentage of rainfall over the catchment) is around 1.9% for 421062 and 4.4% for 418032. The rainfall for 418032 is in the order of 750 mm whereas for 421062 it is around 500 mm. The runoff from 421062 is considered more typical for farms in the Barwon-Darling Valley given the lower rainfall (average annual rainfall at Walgett is around 500 mm and 350 mm at Bourke).

Long-term mean annual rainfall–runoff rates are useful to develop trends for different climate zones. The Budyko framework is one such assessment method that can be used to estimate lower and upper bounds for runoff coefficients. These bounds can be used to test that inflow estimates are within the expected range at the mean annual timescale given the climate characteristics for the site. This is the recommended approach adopted by the good modelling practice guideline[1] developed by modellers across the MDB jurisdictions. Neumann et al. (2017) have demonstrated the approach using 213 catchments in the Basin over the 1965 to 2009 period. Their results have been used to characterise the expected and range of runoff rates 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 modelling results for individual properties conducted in the NSW Border Rivers and Gwydir Valleys. This gives us some confidence that the farm-scale runoff results for fallow and undeveloped land should be within the bounds suggested by Neumann et al. (2017).

Runoff rates for irrigated land are expected to be higher than the fallow and undeveloped rates due to elevated soil moisture. In response to recommendations of the Independent Review, we have undertaken another independent review of the assumptions for runoff from irrigation areas (Barma Water Resources 2019). This found that:

- the estimates were uncertain due to limited available data
- the adopted approach represents a step forward compared to other approaches reviewed
- harvesting of rainfall–runoff is likely to be a fairly small component of total valley diversions.

A small amount of relevant farm scale data was available and is summarised below.

- In field data for furrow-irrigated cotton fields was collected by Connolly et al. (2001) to calibrate a daily water balance model (GLEAMS). This has been used to assess runoff rates 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.
- No rainfall–runoff rates were reported in the farm survey data for the Barwon-Darling Valley.
- MDBA commissioned a study (FSA Consulting and Aquatech Consulting 2011) which included field data collection over a 3-year period from 2008 to 2011 from 6 representative sites in the northern Basin (3 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.

D.2 AWBM to estimate regional rainfall–runoff for Barwon-Darling irrigation properties

The licensing of floodplain harvesting diversions in the Barwon-Darling Valley river system through the Healthy Floodplains Program is based on modelled estimates of farm scale water balances.

Most modelled farms estimate collection of local runoff by using a simple area relationship with rainfall, as the local runoff contribution is a small component of the water balance at that farm. A few farms are located on natural drainage lines that concentrate relatively large local catchment areas and during wet periods or after local storm events, significant volumes of runoff have historically occurred and have been harvested.

In other valleys, the modelling approach adopted uses relationships with nearby or otherwise representative gauged tributary catchments, however in the Barwon-Darling this methodology is unavailable as there are no gauged minor catchments available.

An alternative modelling technique is the use of a rainfall-runoff model that calculates the expected runoff taking into consideration rainfall, evaporation, and a set of calibrated parameters to describe the catchment characteristics. With no local Barwon-Darling gauged small catchments available, the method adopted is to select a range of gauged catchments further afield that we would expect to have similar geographic, vegetation and soil characteristics.

Past studies on this approach have found that rainfall runoff model parameters calibrated in one catchment do not transfer well to other catchments when the models have complex parameters or the catchments are not physically similar.

The Australian Water Balance Model (AWBM) is a daily catchment water balance model used for estimating runoff from catchments. AWBM has extensive Australian application as the model has been calibrated against runoff data from 19 gauged Australian catchments. AWBM was adopted as a method to estimate rainfall runoff from ungauged catchments in the Barwon-Darling as it requires only 3 parameters to be specified for:

- runoff characteristics RC
- base flow index BFI
- baseflow recession constant Kb.

Using a simple model such as AWBM instead of the normally accepted Sacramento model was a trade-off between the reduced capability of a simpler model and the difficulties with transferring parameters from complex models to ungauged catchments.

The approach used results from 9 representative NSW and Qld gauged catchments (to the Barwon-Darling) which had been calibrated using AWBM to obtain an average of parameters. These parameters were then used to calibrate the 3 ungauged catchments for the 3 floodplain harvesting properties that were found to have access to runoff from a significant local regional catchment. The 3-step process approach involved is detailed below.

Step 1. Obtain average of AWBM parameters from calibrations

AWBM (in Source) was used to calibrate the following 9 gauged catchments in NSW and Qld:

1. 417205A Moonie River @ Flinton
2. 422210A Bungil Creek @ Tabers
3. 422401A Maranoa River @ Mitchel
4. 424201A Paroo River @ Caiwarro
5. 421055 Coolbaggie Creek
6. 421076 Bogan River @ Peak Hill No2
7. 421039 Bogan River @ Neurie Plain
8. 420015 Warrena Creek
9. 419072 Baradine Creek.

Step 2. Re-apply the averaged parameters back to the calibrated models to determine their impact

To understand the possible representativeness of the averaged rainfall-runoff model parameters, the mean model parameters were re- applied to each of the model calibration catchments and modelled flows with mean parameters were compared to the gauged flow and the calibrated modelled flow.

The overall result of the assessment showed that the average cumulative difference was positive (27%) noting that removing 419072 (Baradine Creek) gave an average cumulative positive difference of 8% suggesting that the approach was not overly biasing one way or another. However the absolute cumulative difference was 63%, which suggests a large variance and uncertainty.

The overall modelled runoff proportion was on average 4.7%, and the average runoff proportions using the gauge data around 4.69%.

These results were sufficient to conclude that the method could be reasonably expected to represent periods when significant volumes of harvestable water were likely to be available; but could not be relied on to make accurate estimates of volumes in individual events. This limitation meant that secondary evidence should be used to confirm important storage filling events wherever possible.

Step 3 Model rainfall–runoff using the averaged parameters with storage depth adjusted to catchment area and matched to available anecdotal evidence from landholders and spatial analysis (e.g. Landsat, Digital Earth Australia waterbodies) for verification.

AWBM was used to estimate the regional rainfall-runoff for three properties that had significant contribution from surrounding catchments. The average parameters from Step 2 were applied to the AWBM for the properties:

Table 37 lists the parameter values adopted for calibration for:

- surface storage capacity (C1) and its area (A1)
- surface storage capacity (C2) and its area (A2)
- surface storage capacity (C3) and its area (C3)
- baseflow recession constant (Kbase)
- daily surface runoff recession constant (Ksurf)
- base flow index (BFI).

Example of using AWBM to estimate Regional Rainfall Runoff for a property

For this sample property (which has a catchment area of 3,786 ha) the calibration attempted to match the following criteria obtained from stakeholder engagement:

- produce runoff for rainfall events > 30mm
- have cumulative volume of ~1,100 ML in the 2011/12 water year
- have cumulative volume of ~1,300 ML in the 2016 water year
- have a runoff yield of approximately 3-5%.

AWBM parameters obtained from the calibration for the sample model irrigator are given in Table 37. Plots of how well the calibration met the calibration criteria are provided in Figure 26 and Figure 27, with result of the calibration provided in Figure 28.

Table 37 Example of AWBM parameters adopted for calibration for a sample property

A1	A2	Kbase	Ksurf	BFI	C1	C2	C3	A3	Cumulative storage (mm)
0.125	0.41	0	0.69	0	33	90	200.51	0.465	135.139

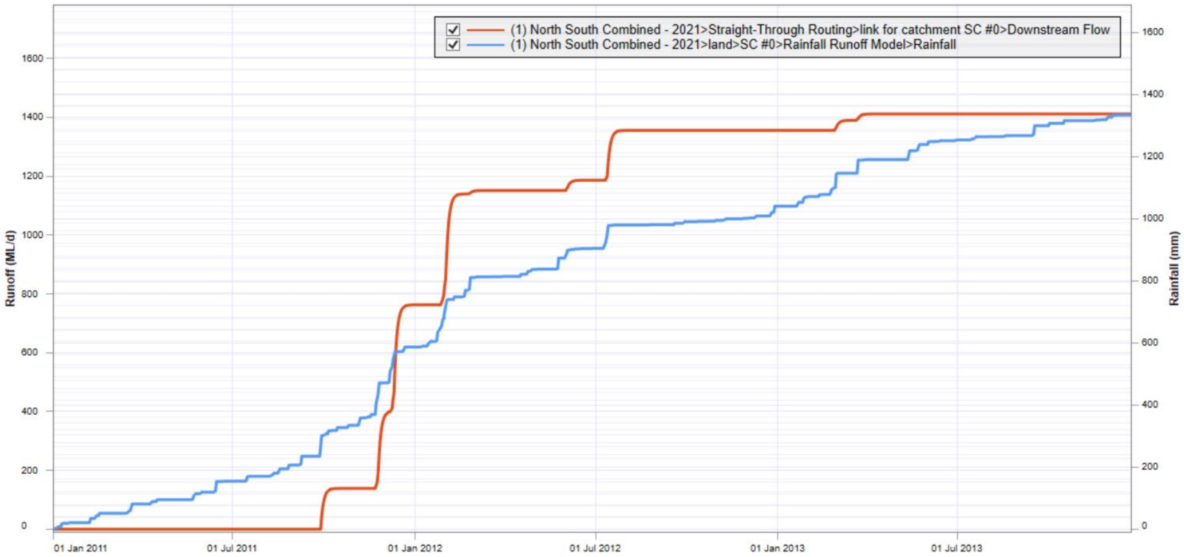

Figure 26 Cumulative rainfall (blue line) and generated runoff (red line) for the period 1 January 2011 to 1 January 2014. The cumulative 2011/12 runoff is approximately 1,100 ML, meeting the model calibration criterion of ~1,000 ML in 2011/12

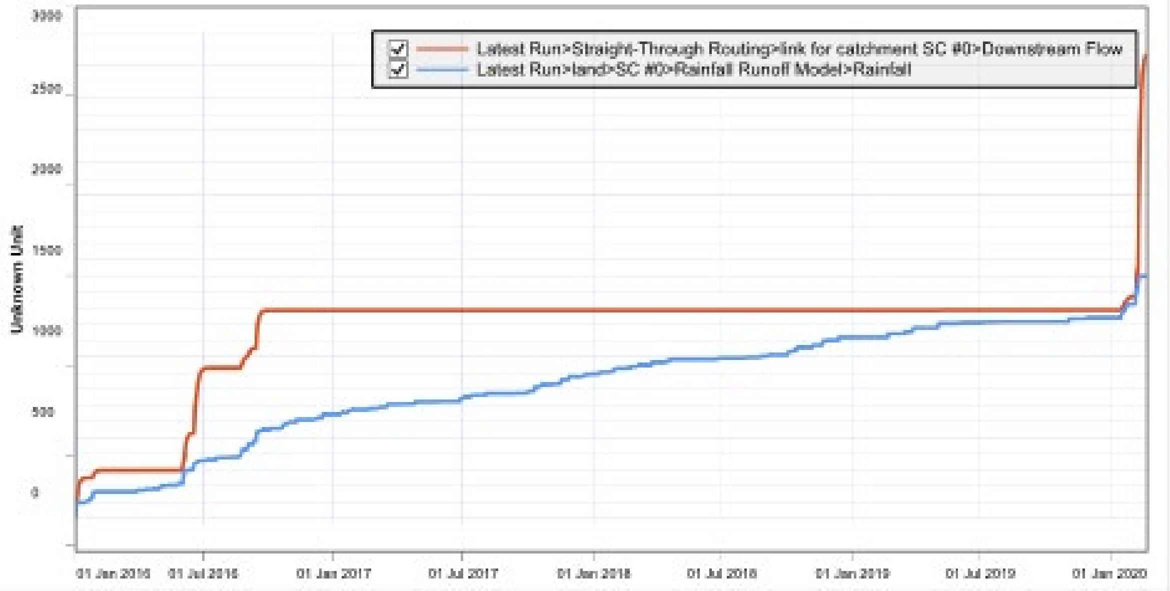

Figure 27 Cumulative rainfall (blue line) and generated runoff (red line) for the period 1 January 2015 to 1 July 2017. The cumulative 2016 calendar year runoff is 1,300 ML, meeting the model calibration criterion of ~1,300 ML in 2016/17

Using the AWBM parameters given in Table 37, the 2011 to 2020 calibration period yield is 3.2% and the 1895 to 2014 long-term yield is 5.7%.

Figure 28 shows the timeseries of runoff for the sample model irrigator. This runoff timeseries was used as an input to the model.

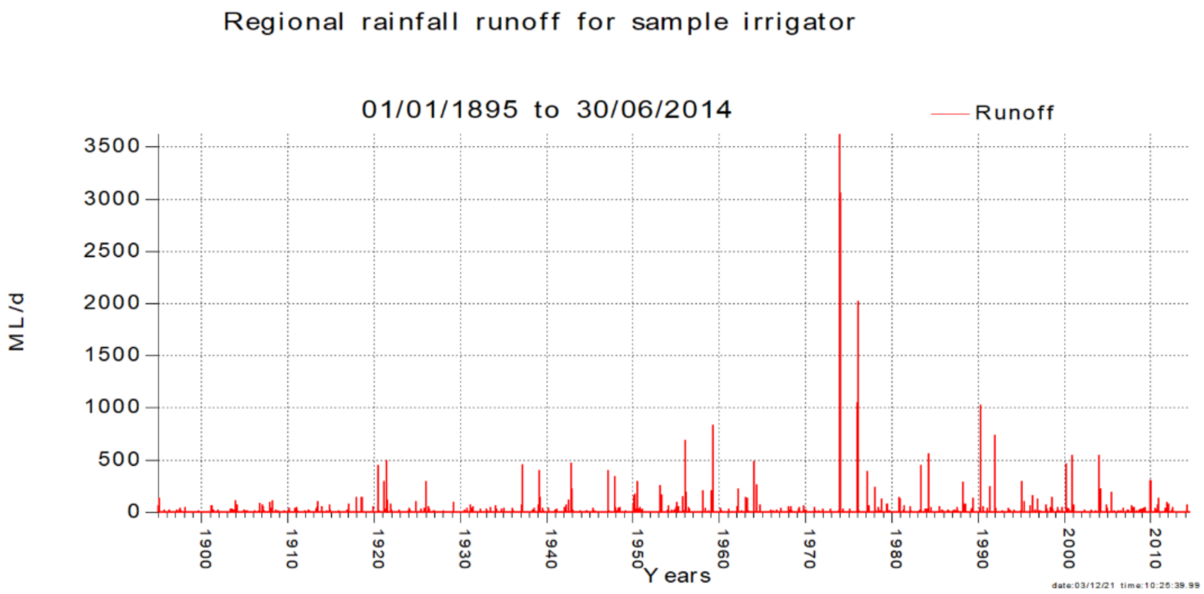

Figure 28 Calibrated runoff (ML/day) for the sample property over the period 1895 to 2014

Appendix E On-farm storage and pump rate verification and worked examples

As part of implementing the policy, there has been increased 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.

E.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. On the Barwon-Darling many properties were able to supply independently and professionally surveyed storage geometry data from a qualified surveyor. These high resolution surveys have generally been adopted after verification with LIDAR and storage bathymetry model (SBM) measurement methods.

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 5 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 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 in Morrison and Chu (2018). A 1 m freeboard has been assumed for all permanent storages unless verifiable evidence was available such as a formally constructed spillway structure that supports a smaller freeboard.

For some storages with complex bathymetry, such as billabongs and lagoons that have been augmented with levees, additional photogrammetry analysis was undertaken to provide a better estimate of the storage capacity.

The spatial maps of storages were combined with Landsat data to confirm the date on-farm storages were built, which was used to estimate levels of development for scenarios.

The Development History Project undertaken in 2002 (Brill 2002) to establish infrastructure and crop areas from 1987 to 2000 (described further in Appendix F.3) also used remote sensing of storage surface area and farmer surveys of average depth to estimate on-farm storage capacities. The 1993/94 on-farm storage capacity estimated by the Development History Project was 181 GL, compared with the 210 GL reported in Table 12 using the combination of the SBM technique described above, photogrammetry, and professional surveys. The Development History Project is slightly lower, as it did not include some storages that were under construction in 1993/94 but were subsequently included in the 1993/94 Cap modelling (and this modelling).

E.2 Verification and representation of temporary storages

As part of the detailed survey data collected from all farms, a few landholders indicated significant historical use of irrigation fields, surge areas, and supply channels, as temporary water storages. The extent of this was verified using the past 30+ years of Landsat data to assess instances of temporary water storage within property boundaries after a number of flood events using the following process:

- the archive of Landsat data was downloaded as Natural Colour images[20]
- flood events during this period were identified based on gauged flow data and breakout relationships
- the first usable Landsat image after the flood event was selected
- farm boundaries and permanent on-farm storage areas were overlayed over the Landsat data
- areas of temporary storage of water were manually detected and polygons drawn to estimate area.

Temporary storages have only been accounted for in the model where NRAR advise that they should be included. The policy position is that temporary storages are not to be included in the storage capacity assessment for the farm. However, where temporary storages such as surge areas and sacrificial fields allow for a fast intake of water and then transfer to permanent storages (within 14 days), this buffering effect can be accounted for. It is only the water transferred to permanent storage which counts as eligible floodplain harvesting. We include these in the model where:

- the storage is (i) a property constructed buffer storage mapped by NRAR or (ii) 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.

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[20] https://earthexplorer.usgs.gov/

Small surges, or surges that do not allow a much faster intake rate compared to the on-farm storage pumps, will have little impact on modelling results. Adding the temporary storages adds significant complexity to the modelling (particularly in IQQM) and hence we developed this approach to avoid unnecessarily complicating the modelling.

E.3 On-farm storage pump rate

NRAR has 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 also been undertaken to assess the impact of variable pump rates on the floodplain harvesting estimate.

Pump rate analysis

The adopted flow rate and expected range are illustrated in Figure 29 and Figure 30. The adopted flow rates have also been compared to check for reasonably consistency (Figure 31).

The adopted flow rate has good consistency with average flow rate information obtained from a combination of IBQ and other industry advice.

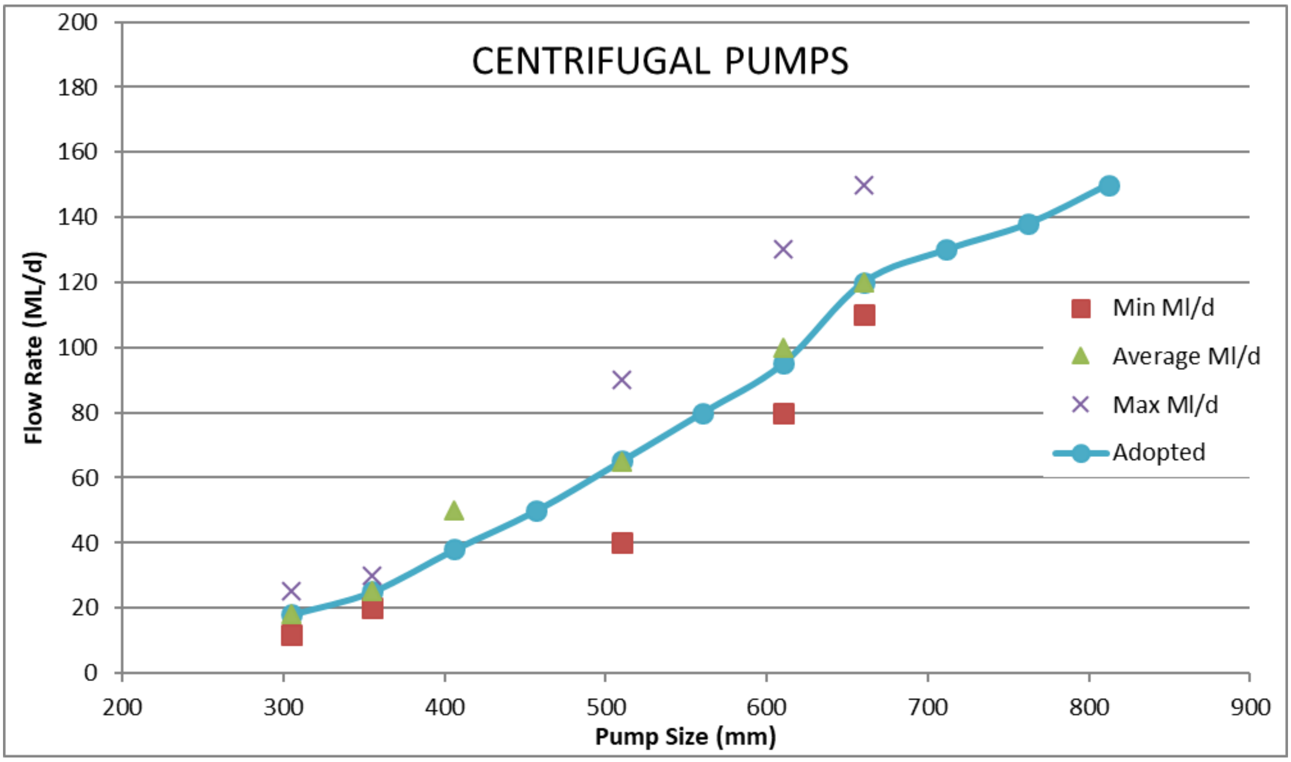

Figure 29 Centrifugal pumps flow rate analysis (ML/day) for a range of pump sizes (mm)

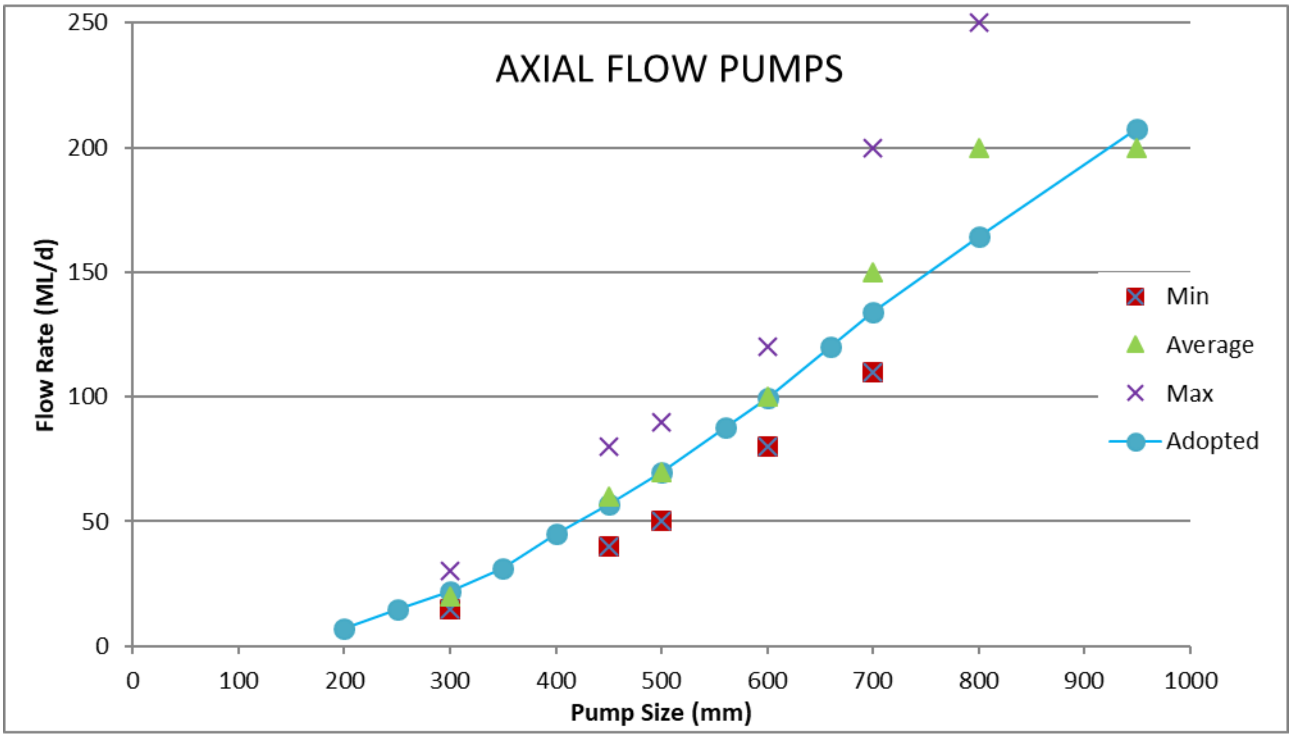

Figure 30 Axial flow pumps flow rate analysis (ML/day) for a range of pump sizes (mm)

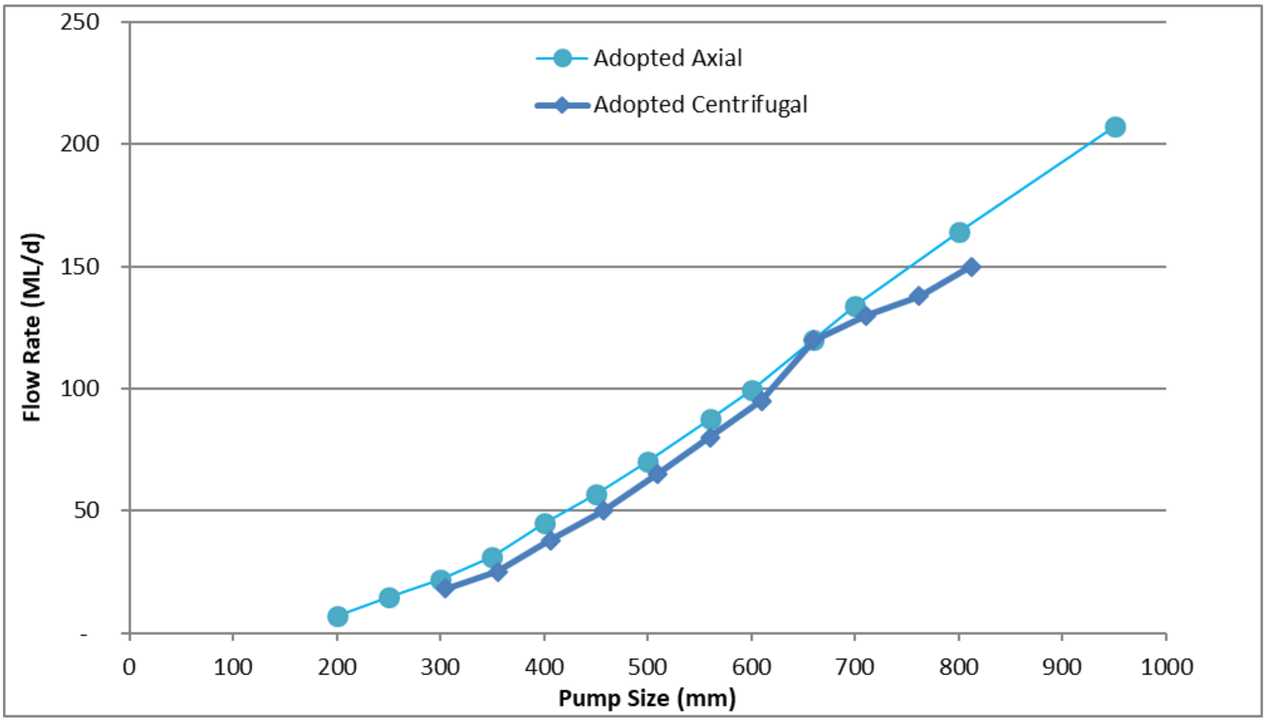

Figure 31 Comparison of adopted centrifugal and axial flow rates for a range of pump sizes (mm)

E.4 Intake infrastructure

There are typically a number of pipes which bring water in from the floodplain to the area developed for irrigation. In some cases, regulators and pumps also serve this function. These were all assessed to estimate the capacity of 'intake' into the property. In general, the total 'intake capacity' was more than the total on-farm storage pump capacity. This means that the on-farm storage pumps were considered to be the limiting factor and the capacity of the pipes was generally not used in the modelling. There were only a few exceptions to this as discussed in Section 6.2.2.

The flow rates assumed in the review of pipes are set out in Table 38.

Table 38 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

E.5 Worked example for representing floodplain harvesting works including temporary storage

This section describes an example property where allowance for temporary storage has been included in the modelling. All data in this example are draft, for the purposes of illustrating the modelling methodology.

The property can access overbank flow in the following way:

- one eligible storage with a relatively small total lift pump capacity estimated at 240 ML/day
- one surge area which is able to intake water at a much higher rate through 3 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 1,500 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 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 32 demonstrates this example.

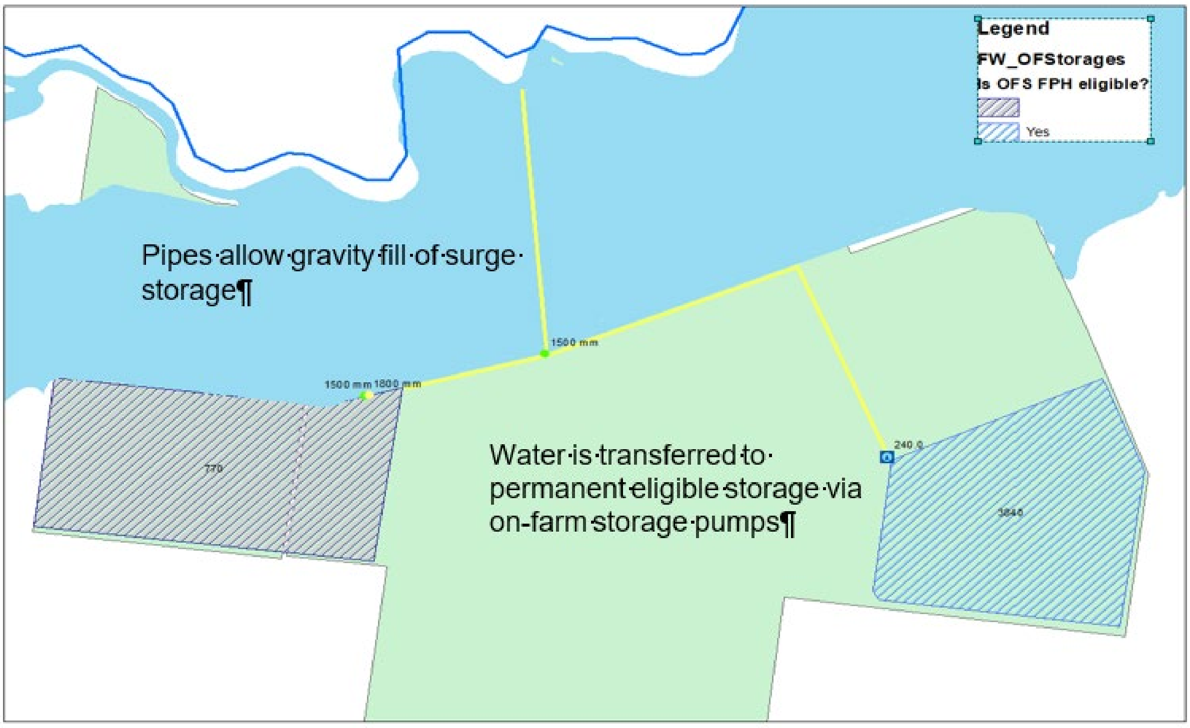

Figure 32 Schematic of example property with temporary storage

E.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 Tarpaulin Creek is not to be included in the floodplain harvesting entitlement; we have estimated overbank flow in this region.

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 for the eligible scenario the rate is 720ML/day.

Figure 33 demonstrates this example.

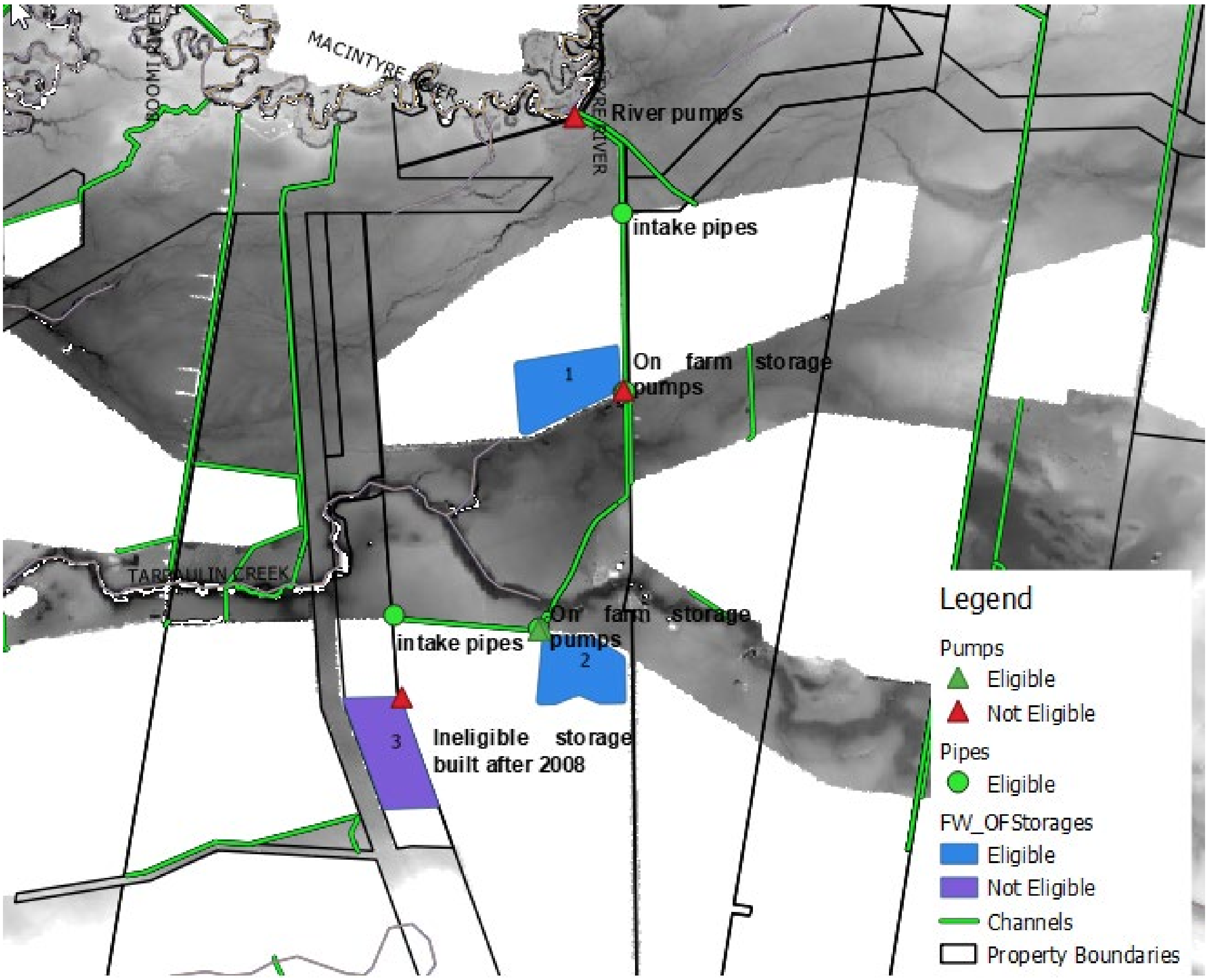

Figure 33 Schematic of example property with multiple storages and intakes

Appendix F Infrastructure and crop areas

F.1 Completeness of farm survey information

Farm survey data on crop area and crop type were only supplied by some floodplain harvesting properties, as shown in Figure 34. However, some properties supplied no data, and others did not provide crop areas starting from 2003/04. In some cases, this may be due to no crops being planted; however, there will be cases where crops were planted but no records were available. As there was a substantial proportion of properties and years with missing crop area information, the remote sensing described in Appendix F.2 was used as the primary data source, and farm surveys were used to fill gaps. A limited amount of checking of farm survey data against the remote sensing was also undertaken during gap filling. The results of the gap-filling and checking indicated that remote sensing and farm surveys generally aligned reasonably well, although there were a small number of properties where there were significant differences. There were also some years where remote sensing data were not available for all properties (particularly 2012/13) (Figure 34).

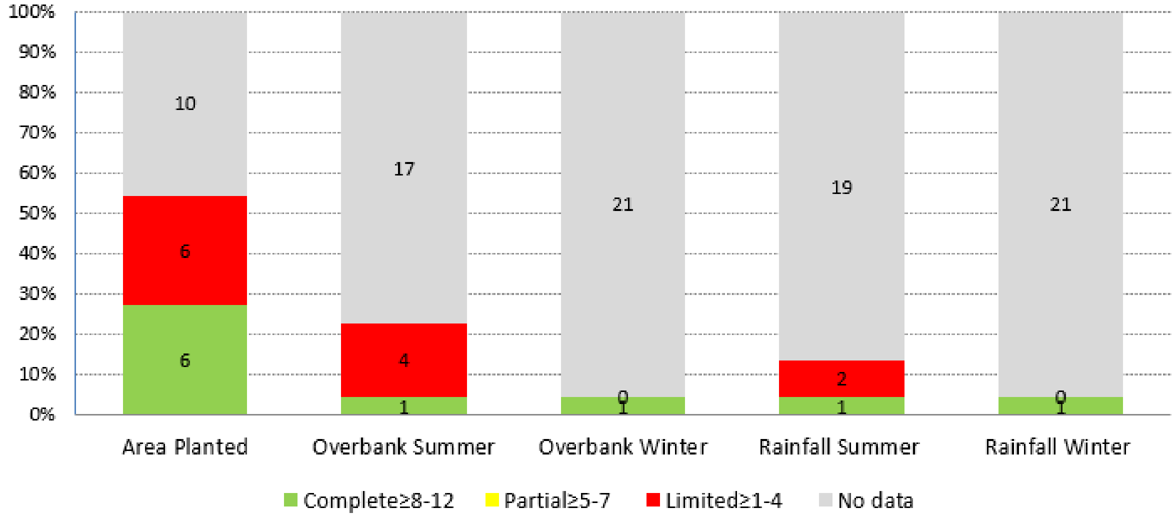

Figure 34 Farm survey data availability 2003/04–2014/15

F.2 Remote sensing of crop areas

Remote sensing of irrigated crop areas using MODIS and Landsat satellite imagery was undertaken for the Barwon-Darling Valley as an alternate line of evidence to the information provided in the farm surveys.

The farm survey reported **summer crop areas** were compared against both Landsat and MODIS data. Winter crop areas have not been analysed as remote sensing data are less reliable during these periods. Irrigation in the Barwon-Darling Valley is also dominated by summer irrigation.

The Landsat and MODIS remote sensing data were obtained for the model validation period from 2003/04 to 2013/14.

- MODIS analysis uses a time series analysis to look for spectral response which approximates the expected crop behaviour. It has lower resolution, but more frequent imagery.
- Landsat analysis also uses a time series analysis to look for spectral response, but offers higher spatial resolution. However, the imagery is less frequent.

However, the remote sensing data was still relatively incomplete:

- data was not obtained for some properties that were initially considered ineligible for floodplain harvesting licences, but were later found to be eligible
- there were still significant missing periods where imagery was unavailable, or cloud cover obscured crop areas, and
- remote sensing results for some properties were inconsistent with developed areas or diversion data.

To address these issues, Landsat remote sensing imagery was re-analysed manually, rather than with the auto-classification techniques used previously. This provided greater coverage of properties, and addressed the anomalies identified in the previous remote sensing.

F.3 Barwon-Darling Development History Project

The 1993/94 Cap on diversions is the limit on diversions set by the Barwon-Darling WSP, and the department previously undertook an extensive investigation to establish irrigation infrastructure and irrigation behaviour over the period 1987 to 2000 to inform modelling of the Cap on diversions, and the subsequent management rules associated with implementation of the Cap (now included within the Barwon-Darling WSP). This investigation, known as the Development History Project (Brill 2002), used remote sensing analysis with individual farm interviews to establish infrastructure and irrigation behaviour (including crop areas, on-farm storage and surface water areas) (Figure 35, Figure 36). This information was used to develop the Barwon-Darling IQQM Cap model that was accredited by the MDBA and has subsequently been used to develop the Cap Scenario described in the companion Scenarios report (DPE Water 2022).

For this project, high resolution colour images were derived by merging SPOT (Le Systeme Pour l’Observation de la Terre) high resolution (10 m pixel cellsize) black and white imagery with colour Thematic Mapper imagery (30 m pixel cellsize). This gave an image with 10 m colour pixels to use as a base image for the majority of digitising. The increased resolution gave greater accuracy for digitising.

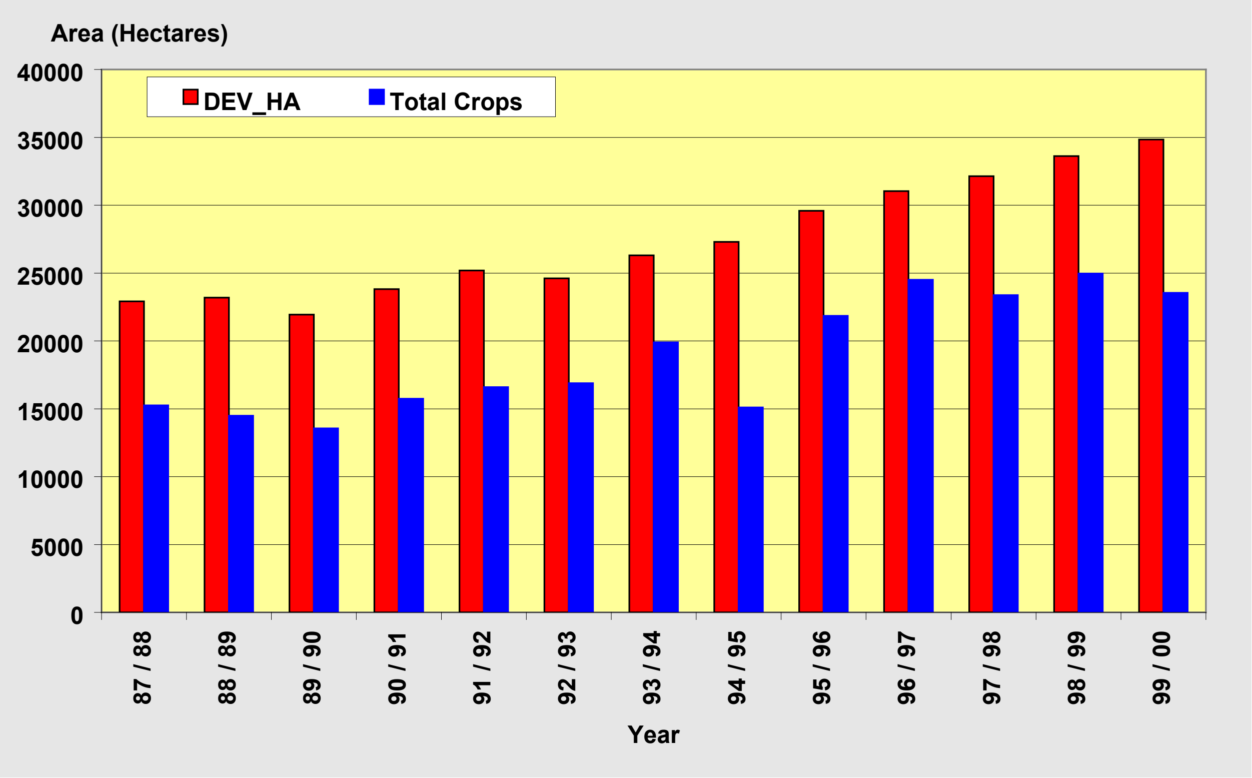

Figure 35 Developed and irrigated areas from the Development History Project (Brill 2002)

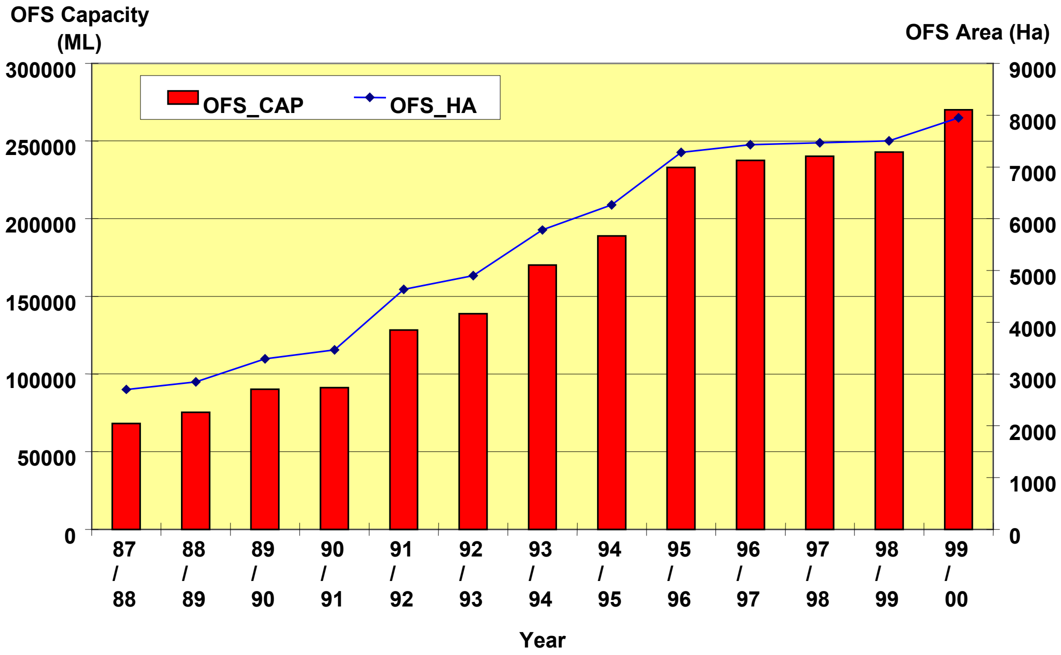

Figure 36 On-farm storage capacity and surface areas from the Development History Project (Brill 2002)

Appendix G River reaches in the river system model

Table 39 Barwon-Darling Valley reach division

Reach name	Upstream gauge	Downstream gauge
1a	Mungindi (416001)	Pressbury (416050)
1b	Pressbury (416050)	Mogil Mogil(422004)
1c	Mogil Mogil (422004)	Collarenebri (422003)
1d	Collarenebri (422003)	Walgett (422001)
2a	Walgett (422001)	Brewarrina (422002)
2b	Brewarrina (422002)	Bourke (425003)
3a	Bourke (425003)	Louth (425004)
3b	Louth (425004)	Tilpa (425900)
3c	Tilpa (425900)	Wilcannia (425002)

Appendix H Glossary

In addition to the information provided in this appendix, the reader is directed to excellent online resources, such as that provided by WaterNSW[21].

Table 40 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
AWBM	Australian Water Balance Model (Boughton 2004)
AWD	Available Water Determination
BDL	Baseline Diversion Limit
BRC	(Dumaresq-Barwon) Border Rivers Commission
DES	(Qld) Department of Environment and Science
DS	downstream
ESID	Extraction Site IDentification number
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems – a field-scale model of hydrology (Leonard et al 1987 referenced in Connolly et al. 2001)
HEW	Held Environmental Water
Hydstra	Product brand name for database that stores water data
IBQ	Irrigator Behaviour Questionnaire (used interchangeably with ‘farm survey’)
IDEC	Individual daily extraction component
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
MAF	Mean annual flow
MDBA	Murray–Darling Basin Authority
MIKE	MIKE Flood Model, developed by Danish Hydraulic Institute. Globally widely used
MODIS	Moderate Resolution Imaging Spectroradiometer
NOW	NSW Office of Water
NRAR	Natural Resources Access Regulator
NSE	Nash-Sutcliffe Efficiency

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[21] 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
OEH	Office of Environment and Heritage
OFS	On-Farm Storage
SBM	Storage bathymetry model
SDL	Sustainable Diversion Limit
SILO	Scientific Information for Land Owners
TOL	Transmission and Operational Loss
WALS	Water Access Licensing System
WAS	Water Accounting System (WaterNSW database)
WLS	Water Licensing System
WRPA	Water Resource Plan Area (used with reference to the Barwon-Darling Surface WRPA
WSP	Water Sharing Plan

Table 41 Terms used in the report

Term	Description
2008/2009 Scenario	Uses the levels of irrigation infrastructure, water licences, and management rules in the Barwon-Darling Valley 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)
Active Environmental Water	Environmental water from licences recovered under the Basin Plan that is used in-stream for environmental purposes, and protected from extraction.
Barwon-Darling model	Shortened term for the Barwon-Darling Valley river system model
Barwon-Darling WSP	Shortened term for the Water Sharing Plan for the Barwon-Darling River Unregulated and Alluvial Water Sources 2018 (amended July 2020)
Baseline Diversion Limit (BDL) Scenario	Equivalent to the lesser of the Cap and WSP scenarios, also referred to as the Plan Limit Scenario
Basin Plan	The Murray-Darling Basin Plan 2012
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 Barwon-Darling Valley river system
Irrigator node	Shortened term for the Type 8.3 Unregulated irrigator node in IQQM
plan limit	The authorised long-term average annual extraction limit as defined in the Water Sharing Plan, equal to the 1993/94 Cap on diversions
Pre-Basin Plan scenario	The pre-existing (prior to redevelopment of the Barwon-Darling Valley river system model) scenario that represented conditions in 2012/13, including the rules of the Barwon-Darling WSP
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 (DPE Water 2022a)

Term	Description
Source	Australian National Hydrological Modelling platform, managed by eWater and adopted by the department as its default modelling platform (to replace IQQM)
the plan	Shortened term for the *Water Sharing Plan*
the policy	Shortened term for the *NSW Floodplain Harvesting Policy*
Unregulated river access licences	Licences issued under the NSW Water Management Act that authorise the take of water from rivers and streams where flows are not regulated by major storages, and water cannot be ordered for delivery from major storages.
WSP Scenario	Uses the irrigation infrastructure and the management arrangements and water licences in place in the 1993/94 water year (also the Cap Scenario)