NSW HEALTHY FLOODPLAINS

Modelling and data collection for implementing floodplain harvesting

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The Floodplain Harvesting Policy

The NSW Floodplain Harvesting Policy 2013 brings floodplain harvesting into the water licensing framework. Floodplain harvesting includes rainfall runoff harvesting and overland flow harvesting that is not already authorised under another licence category, a basic landholder right or a licence exemption.

The purpose of the policy is to:

- manage floodplain water diversions more effectively to protect the environment and the reliability of water supply for downstream water users;
- ensure compliance with the requirements of the *Water Management Act 2000: and*
- meet the objectives of the National Water Initiative.

The policy outlines the methodology for determining eligibility for floodplain harvesting entitlements. The work approval process ensures only eligible floodplain harvesting works are considered. All regulated river floodplain harvesting entitlements will be determined by modelling, and unregulated floodplain harvesting licenses are determined using an update of the volumetric conversion process.

Limits to long-term diversions

The NSW Floodplain Harvesting Policy 2013 sets out upper limits to long-term average floodplain harvesting diversions based on statutory limits in state and Commonwealth legislation. Where these limits are being exceeded because of growth in use, the policy also sets out an accounting framework to bring the long-term average diversions to under these limits. These limits are estimated using the NSW Department of Industry’s modelling framework, and the accounting framework is then implemented to meet these limits.

The Murray–Darling Basin Plan (Basin Plan) requires that long-term average diversions do not exceed sustainable diversion limits (SDLs), which equal the baseline diversion limits (BDLs) less the water recovered for the environment. The BDL is essentially that allowed for under state legislation at a certain point in time, defined in Schedule 3 of the Basin Plan, which also includes an estimate of the BDL. In most cases, the BDL is equivalent to the plan limit defined in the state water sharing plan.

Each valley has a different definition of the plan limit. For most valleys, the plan limit is based on diversions that would occur with the infrastructure and management arrangements in place at 2000, combined with the water sharing plan rules. A key requirement of the plan limit is that total diversions cannot exceed those that would have occurred under the Murray–Darling Basin Cap on diversion (Cap) conditions. In most cases, this is infrastructure levels of development and management arrangements in place at 1993–94, except for the NSW Border River, which is at 1999–2000.

The Basin Plan allows for BDL estimates to be revised whenever a demonstrably better estimate is available. The hydrological models used for the original BDL estimates represent river diversions and flows accurately; however, the floodplain harvesting diversions were not well represented.

The Floodplain Harvesting Project remedies this with an unprecedented investment in data and modelling to quantify these floodplain processes more accurately. This allows limits to be correctly estimated, and accounting arrangements to be put in place to meet these limits.

Enhancements

Conceptual models

The NSW Department of Industry has had a river system modelling framework in place for the last twenty years that has been used for water management purposes, mainly testing the impact of water sharing plan rules and changes in development on flows and diversions, and for assessing annual diversion limit compliance. The models represent all key natural and management processes that influence water availability and water demand, and simulate these processes daily using long-term climate records. This is more fully described in the *Surface water modelling* section.

These models are improved incrementally as more information and better methods are included. The enhancements needed to adequately represent floodplain harvesting processes are the largest single change made to these models since they were originally developed.

The improvements were in these main areas:

- **Level of detail**: Whereas previously multiple irrigation farms were grouped along reaches of the river between two measurement points, now these farms are represented individually.
- **Representation of overland flow processes**: Whereas previously water leaving the rivers after they broke out of the channel was treated as a loss to the river system, these overland flow processes are now re-directed to the individual farms.
- **Representation of farm processes**: On-farm processes were modelled in more detail, including the storage of overland flow in temporary storages (where appropriate) before transfer to permanent storages. The capture of farm runoff was represented, and the operation of multiple storages.
- **Management arrangements**: New accounting capabilities were introduced to estimate entitlements in a way to bring current long-term average diversions to below plan limits.

These enhancements required much more data than previously used, as well as developments in modelling methods and procedures for model calibration and configuring of scenarios to better treat this information. The additional data and information is described below. Enhancements to the model and the methods are described in the *Floodplain Harvesting Modelling* section.

Data and information

The model development required a lot of new and updated data. While traditional corporate data sets such as climate, streamflow, diversions, and entitlements were all updated, new data on farm infrastructure, crop types and areas, and river breakouts were also collected. Much of the data pertaining to a property were collected using a structured survey completed by landholder representatives, with assistance from NSW Department of Industry staff.

The inclusion of this information within the modelling was subjected to multiple lines of evidence before and during modelling. Modellers are responsible for what is used in the models, so reviewing and checking of data is a standard process. Reviews factored information from gauged streamflow, hydraulic models, remote sensing, flood behaviour, licensing records, surveys, and on-ground inspections.

The data collected for use in models, and its treatment, are summarised below, and described in more detail in the *Floodplain Harvesting Modelling* section of this document.

Detailed farm descriptions

A structured survey (known as the irrigator behaviour questionnaire or IBQ) identified individual on-farm storage (OFS) capacity, areas developed for irrigation, pump capacities and other forms of floodplain harvesting infrastructure.

These were cross-checked by NSW Department of Industry licensing staff during the initial application and farm inspections. Light detection and ranging (LIDAR) data was used to confirm the capacity of on-farm storages and to derive a stage-volume relationship for use in monitoring.

The date of OFS construction was confirmed by remote sensing and applied to OFS pumps. The verification of OFS details is described in more detail in *On-farm storage remote sensing verification* section of this document.

Industry average data has been used to estimate OFS losses to seepage.

Overland flow processes hydraulic models

The Office of Environment and Heritage (OEH) developed hydrodynamic models for each valley for the floodplain management plans. Where possible, this information has been used to inform location of river breakouts, the relationship between river flow and breakout flow, and the order of access to floodplain harvesting

Irrigation water requirements:

The IBQs included information on the crop types and areas planted in some years for some farms. This information has been used in model development as is further outlined in the next section.

Remote sensing has been used to review these areas.

Industry average data has been used to estimate irrigation efficiency and irrigation application rates.

Surface water modelling

Water resource plans (WRPs) are a key requirement of the Commonwealth *Basin Plan 2012*. WRPs will set out arrangements to share water for consumptive use. They will also establish rules to meet environmental and water quality objectives and will take into account potential and emerging risks to water resources.

Modelling of surface water and groundwater sources is required to inform development of the water resource plans (WRPs). This section addresses the surface water models used to inform surface water WRPs.

Surface water models used for water resource planning

The NSW Department of Industry uses surface water models that are conceptual representations of the river systems and that allow for simulation and prediction of all key processes and interactions within the river valley. The department uses these models for all regulated and selected major unregulated systems. All models use either the Integrated Quantity and Quality Model (IQQM) software, or eWater's Source software.

The key processes modelled include **natural** processes, and **management** processes relating to water use and management.

The **natural** processes modelled include basic components of the hydrologic cycle, that is, rainfall and evapotranspiration changes to water balance, flow generation, flow routing and transmission losses. These essentially provide basic inputs to the model important for determining long-term water availability and its variation over time and space.

The **management** processes modelled are important for determining how this available water is shared between competing users. The processes include the storage of water in both public and private dams, water entitlements and accounting, resource assessment and allocation, crop planting decision-making, irrigated crop and other consumptive demands, diversions across different licence categories, environmental water demands, access rules, and storage operation.

Table 1 and Table 2 present these parameters and modelled processes.

Background to Department of Industry modelling

The water management arrangements that the NSW Government developed over the last two to three decades (entitlements, allocations, accounting, environmental flows) are specialised such that comparatively few software platforms were available globally that can capture the detail. For this reason, NSW decided in the early 1990s to develop the IQQM software. All NSW models were subsequently developed using IQQM, and used to inform development of environmental flow rules in the 1990s and water sharing plans from the early 2000s.

The models are periodically updated as more data becomes available to better calibrate certain water balance components and development conditions. Inputs are updated with the most recent climate and streamflow data. Comparison of outputs to recorded flows, diversions, crop areas, and storage operation are carried out to audit the model performance.

Periodically, models are redeveloped. Recently, the NSW Department of Industry has committed to updating some of the models using eWater's Source software platform. This is a medium- to long-term project and will not affect the development of WRPs for most valleys. Source models will have improved functionality, whilst retaining all functionality of the existing IQQM models.

How the models work

River system models

The IQQM and Source software is a modelling framework that contains the river system model along with a suite of utilities to prepare and analyse input data, and to analyse and report output data. From here on, the use of ‘IQQM’ or ‘Source’ will implicitly refer to the river system model components of the software.

IQQM and Source are daily water balance models that account for all water that enters the system as either outflows or a change in the amount of water stored in the system. A river system is represented using a combination of nodes and links, as shown in Figure 1.

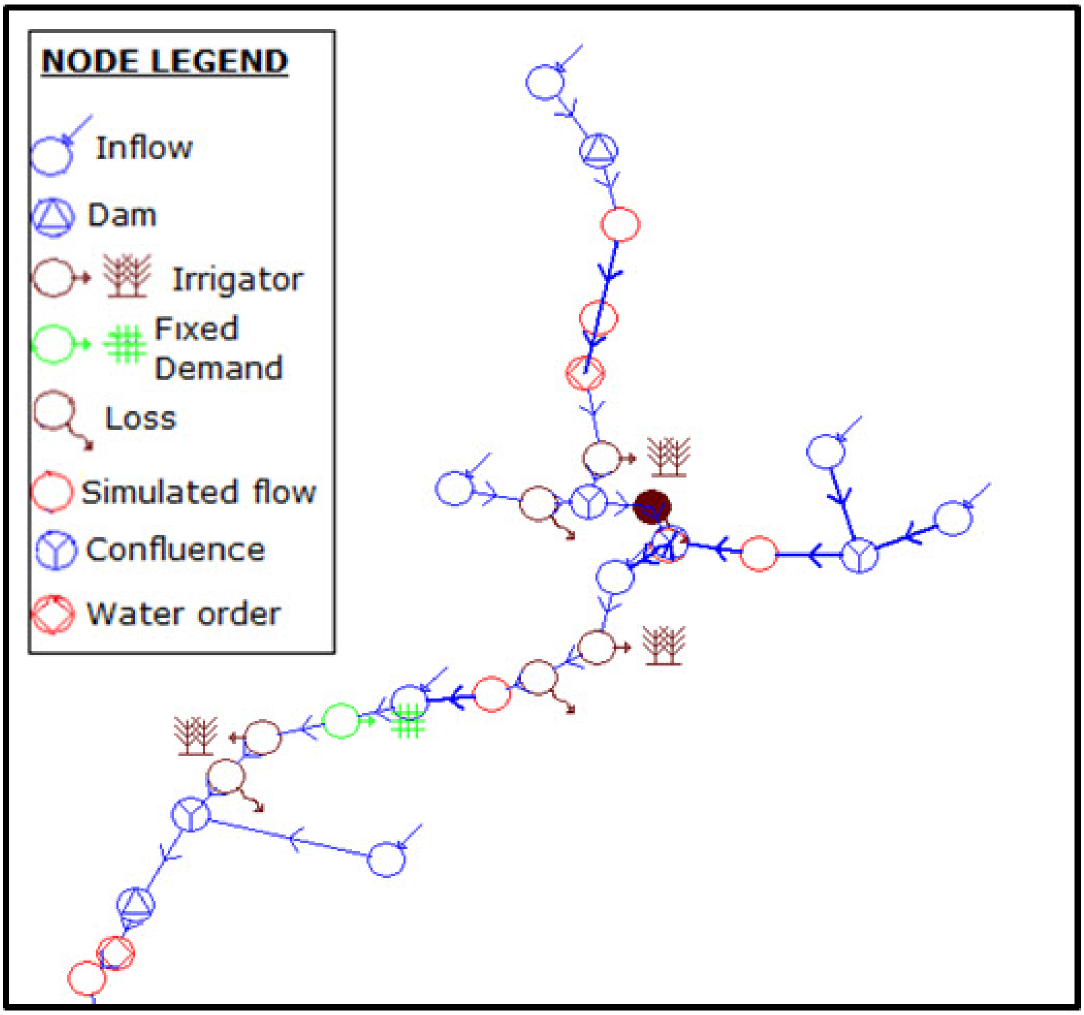
IQQM and Source both use similar concepts to build models. IQQM uses nodes to represent processes where water:

- enters the river system (inflows and confluences)
- is stored in the river system (dams and weirs)
- is ordered from storage (irrigation, other consumptive, and environmental demands)
- leaves the river (diversions and losses)
- is measured (gauges).

There are thirteen main types of node, each with several subtypes. IQQM uses links to move water from an upstream node to a downstream node, and to pass water orders from demand nodes to storages. As well as these building blocks, the resource assessment and accounting arrangements are set up, and work in conjunction with the information at the nodes.

A simple example of a node-link setup in IQQM is shown in Figure 1. A typical IQQM of a regulated river system would include approximately 400 nodes across most of the 13 main types.

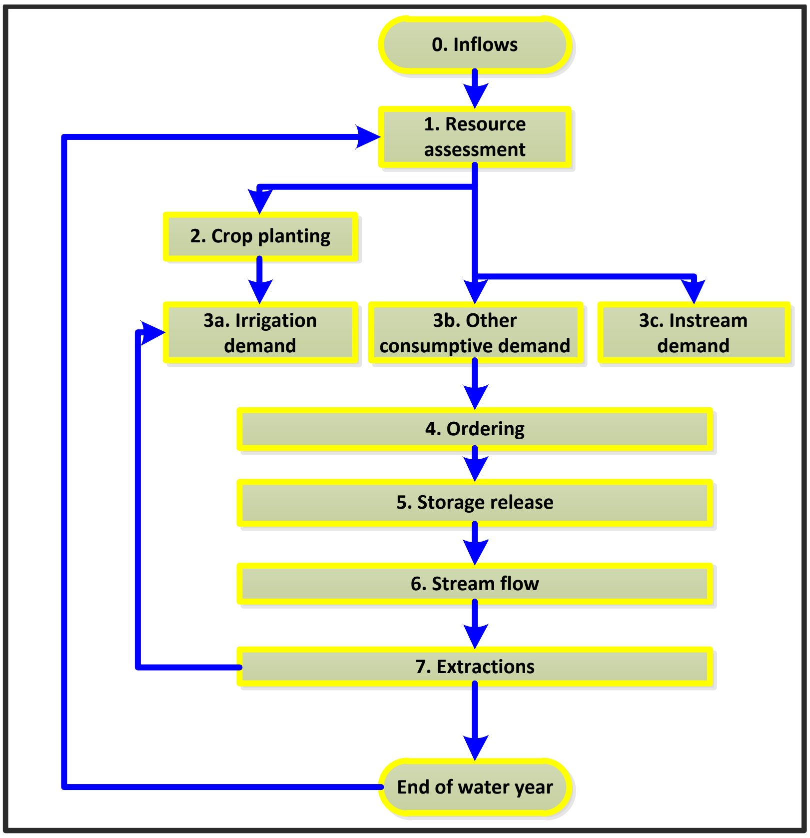
Figure 1. Simple node link setup as used in IQQM



A full IQQM model as used for water planning is then run, and will simulate water balance changes throughout the river system on a daily time step, except for crop information, which may be estimated one to two times per year. A simplified representation of the simulation processes is illustrated in Figure 2.

The simulation starts with (0) inputting the daily value of climate and inflow data; followed by (1) determining the water availability and allocations to different user groups: then (2) irrigators deciding how much crop to plant; (3) estimating the different demands; (4) sending an order to the storage, adjusting for processes along the river; (5) releasing water from storage; (6) routing the regulated and non-regulated flows along the river, and (7) diverting water and adjusting balance in accounts.

Figure 2. IQQM Simulation overview



Inflow models

Another important hydrologic modelling software routinely used by the NSW Department of Industry is the Sacramento rainfall runoff model. This was developed externally in the 1970s, and has been used by the NSW Department of Industry to estimate inflows to our river system models from the various tributaries. The model is calibrated to observed streamflow data using climate data, and the model parameters systematically adjusted so that the observed streamflow characteristics are matched.

The Sacramento model is run independently of IQQM or Source. However, when inflows need to be extended, adjusted, or altered based on different climate data, inflows are re-estimated using the calibrated Sacramento model.

Development of surface water models

The NSW Department of Industry's existing models have been in use for well over a decade and for a range of purposes, principally for planning and policy assessment and diversion limit compliance. They were built using guidelines developed internally, similar to those described in Black et al. (2011).

The following key steps represent the stages of model development:

- problem definition—objectives are defined, including technical requirements, budget and time
- data and tools availability—data, tools and skills assessed
- conceptualisation—the levels of process and spatial detail are defined
- design and construction— involves building the model framework (including the nodes and links) and the input of known spatial and temporally varying data

- Calibration and validation—model parameters including physical and management components and processes are modified within plausible ranges to match results from the model to observed data. Care is taken preparing the observed data to ensure that the data is representative of the component being modelled, that biases are understood, and errors are removed. The calibration process is described in more detail in the following section.
- Testing —a series of tests are undertaken to confirm that modelled outputs agree with expected outputs. Sensitivity of the model to input data and variation in management decisions (for example, reducing inflows by 10% should decrease diversions) is also tested.
- Scenario analysis—combinations of different rules and development levels representing potential policy and planning options are simulated
- Model outputs and reporting—NSW Department of Industry produces multiple model reports for the WRP in each valley, including a model description report; a baseline diversion limit technical note report and a technical note report presenting the current conditions. During the progress of the WRP development, a number of scenario assessment reports will be produced, describing the context and outcomes of agreed scenarios modelled.

Calibration

The NSW Department of Industry adopts a multi-stage process to calibrate a surface water model, starting with gauged inflows, followed by mainstream flows, crop demands, crop areas, supplementary access, and storage operation. This approach starts off with observed data for most parts, and progressively replaces them with modelled data. This ensures that the unknown component of the water balance is not affected by uncertainties from modelled estimates. For example, when calibrating mainstream flows, observed diversions would be used so that we can properly estimate how much additional inflow is needed or what transmissions losses are. The next stage would be to model diversions using observed crop types and areas and so on.

In all calibration stages, using all relevant observed data as inputs, a restricted set of model parameters are systematically adjusted so that model output matches observed data as closely as possible. The calibration, while attempting a best overall match, is also focused on important characteristics. For example, inflows may focus on medium to high flows, whereas the focus on calibrating mainstream flows may be in the operational flow range during the irrigation season. Diversions may focus on matching inter-annual variability of annual totals. Storage behaviour may focus on the slope of the drawdown in volume stored and spill frequency. The calibrated results progressively replace observed data, and adjustments made if necessary to maintain system calibration quality.

Calibration is assessed qualitatively and quantitatively. Visual assessment of match between observed and simulated outputs are followed by statistical assessment. The calibration statistics and the qualitative assessment are documented in calibration reports submitted to the Murray–Darling Basin Authority (MDBA) for model accreditation, which is required to use the model for compliance of annual diversions.

Using surface water models to support water resource planning

To support any decisions to be made, the NSW Department of Industry uses these surface water models to provide information on the impacts of proposed rule changes. Surface water models provide a robust and reliable way to understand the distribution of water in time and space in a river system, and to assess how the changes in climate and water management arrangements affect different users.

Providing equitable access to water for different purposes is important in any water source, especially those that have significant proportions of consumptive usage. Changes to the arrangements that determine when and how much water can be used for particular purposes will incidentally affect the availability of water for other purposes. Some of these changes will be predictable based on expert knowledge; however, there is potential for unintended consequences that the model will help identify.

What can be changed in a scenario

A scenario analysis can be thought of as determining the answer to a 'what-if' question. In this regard, nearly any component or input to a model can be changed. The natural processes in a model are either inputs such as climate and inflows, or spatial data (Table 1).

It is readily demonstrated that model outputs are sensitive to climate-based inputs. Hence the calibrated models can be used to simulate river system response under different climate conditions. Changing flow routing is probably not physically realistic; however, transmission losses may change with changing groundwater management. For the purposes of developing WRPs, these types of changes are outside scope.

Table 1. Natural parameters and modelled processes

Natural processes	Source of information	Use in model
Rain	Observations, statistical or climate models	Input use to estimate inflows in Sacramento model as well as directly acting on water surfaces, farm runoff, and reducing irrigation demand for crops
Potential evapotranspiration	Observations, statistical or climate models	Input use to estimate inflows in Sacramento model as well as directly acting on water surfaces, and determining crop water use for estimating irrigation demands
Inflows	Observations, rainfall runoff models	Provides water into storage, directly into river below storage to reduce size of orders and allow for supplementary access and environmental flows
Flow routing	Calibration, channel geometry	Moves flow from upstream to downstream, allowing for channel storage, flow attenuation, and travel times
Transmission losses	Calibration, groundwater levels	Causes losses to flow related to flow rate, and assumed loss to groundwater or surface retention
Effluence	Channel geometry, regulation	Causes water to leave mainstream and flow down an effluent channel, which may re-enter mainstream further downstream

Management processes (Table 2), however, are fully within scope of WRP development. All processes can be changed. Examples of management processes are:

- changing airspace in headwater storages for flood mitigation;
- operational release in response to orders and flood operations to manage spills;
- the spatial distribution and activity of entitlements;
- the decisions relating to resource assessment, including storage reserve management and minimum inflow design;
- access to unregulated flows for supplementary diversions;
- different accounting arrangements, including annual or multi-year use limits;

- irrigation decision-making and operational practices; and
- environmental flow decision-making.

Table 2. Management parameters and modelled processes

Management process	Source of information	Use in model
Water storage	Surveys	Captures inflows and re-regulates releases in case of public headwater storages, and stores entitlement and runoff water for private storage for on-farm usage
Storage release and spill	Operational records	Water releases to supply downstream demands, as rules based environmental flows, and as flood operation. Spills if storage capacity exceeded.
Entitlements	Records	Statutory basis for prioritising access to water, and allocating available water to individual entitlement holders.
Resource assessment	Operational procedures	Determines how much of water stored is available to distribute, after setting aside water for future use for high-priority users.
Supplementary access	Sharing plans rules, operational procedures	Assesses whether tributary inflows below dams are large enough to divert, allocates shares between reaches, and diverts
Water accounting	WSP rules	Keeps track of how much water is available to water users, based on entitlement, allocation, and usage.
Floodplain and runoff harvesting	Surveys, infrastructure, calibration	Diverts floodplain water into storages based on flow rates in rivers and on-farm infrastructure and accounting rules; and store water generated from rain falling on farm area.
Crop planting	Historical decision making, calibration	Decide how much crop to plant based on water availability, and economic risk taking behaviour.
Irrigation demands and ordering	Planted crop areas, crop types, calibration	Determine irrigation demand based on area and type of crop planted, crop transpiration, seepage, and irrigation efficiency. Places orders where these cannot be met by on-farm resources. Diverts water.
Other consumptive demands	Observed data	Determine demands for town water, mining, power generation etc., using a variety of estimating techniques. Diverts water.
Environmental demands	Operational behaviour, WSP rules	Determine demands for environment using a variety of estimating techniques. Does not divert water.

Other uses of the models

In addition to scenario testing for WRPs, the models are used for the following purposes:

- They are used routinely to assess annual compliance against diversion limits. This is currently the Murray–Darling Basin Cap on diversions, where the diversions are modelled using the water year's climate and inflows, and compared to the actual diversions. From 2019 onwards, this same process will be undertaken against sustainable diversion limit (SDL).
- The models are also used for estimating daily salinity at all points where water balance is estimated. This will be used for developing the Salinity Management Plan component of the Basin Plan, as well as to undertake accountability as part of the Basin Salinity Management Strategy.

Other uses over the years include entitlement equivalence of water savings, SDL offsets, urban water security assessment, strategic assessments, climate change assessment, bioregional assessment, and operational reviews, etc.

Performance of the models

Initially, the models were developed to aid in management, as part of the water reforms of the mid-1990s. The models were successfully used to inform the cap on diversions, and the development of water sharing plans. The models and calibration documentation were independently reviewed by MDBA-appointed technical experts in the field to assess suitability for estimating annual diversions. These were formally accredited as fit-for-purpose for all Murray–Darling Basin river systems.

The models were also positively assessed as to their suitability for large-scale, strategic planning projects including the CSIRO's 2007 Sustainable Yields Project and the development of the Basin Plan. Since then, the models have evolved, with additional levels of detail to address known limitations or opportunities for improvement, including recalibrating as more or better data becomes available.

Their performance needs to be understood for the purpose for which they are being used, and the accuracy of the model components being used. In most cases, a model is used to compare two different scenarios, say A and B. The differences between average diversions (Scenario A) or 90th percentile flow (Scenario B) at a key environmental reference site is of interest to stakeholders. The key results to get correct in decreasing order of importance are:

- direction of change, whether these increase or decrease;
- order of magnitude of change, that is, is it a large difference or small difference?
- actual magnitude, that is, is it 2% of 3%?

Models' performance for particular questions depends on what was foreseen when the model was last re-built and particular model components calibrated and tested. For that reason, the models are good at estimating annual total diversions, and flow variability for environmental purposes. Some results like end-of system flows, pre-development flows, and unregulated events in lower parts of the river system, low-flow characteristics of effluents, floodplain area inundated, etc., may be less reliable.

The NSW Department of Industry models for water resource planning tend to be highly reliable in the direction of change. For the other results, the accuracy for the order of magnitude of change may be uncertain, in which case the actual magnitude of the result would be highly uncertain.

Scenarios assessed to support surface water resource Planning

Two baseline scenarios are important as a starting point for the water resource plans, the baseline diversion limit scenario and the pre-Basin Plan (PBP) scenario. During the process of the WRP development, a range of other scenarios will be developed and tested against the PBP scenario. One of these scenarios will form the SDL scenario.

Baseline diversion limit (BDL)

The BDL scenario estimates the long-term average amount of water that would have been taken during the historical climate condition under state water management law as at 30 June 2009 (or 30 June 2010 in the Namoi). The BDL is typically the plan limit for the water resource.

Pre-Basin Plan (PBP)

The PBP scenario is similar to the BDL scenario, however with updated information on development levels and changes in entitlement distribution and on-farm management. This scenario is more reflective of actual conditions in the river system, and is the appropriate starting scenario for rule changes being proposed for the WRP.

Stakeholder advisory panel (SAP)

A range of model scenarios will be tested during the SAP process to understand the potential implications of policies and rules on diversions and environmental outcomes. Results from these scenarios may alter management rules such as translucency, carry-over rules, environmental watering regimes and other parameters.

A plausible set of scenarios will be modelled, and the results will be compared to the PBP scenario. The impacts of proposed long-term environmental watering plan will also be modelled and outputs presented and discussed with the SAP.

SDL scenario

The Basin Plan sets new limits on the amount of water that can be taken for consumptive use, that is, industry, agriculture and other human use. These new limits are called long-term average sustainable diversion limit (SDLs) and are set to commence in 2019. The SDL refers to the BDL less a fixed ‘reduction in consumptive use’.

Model outputs

The IQQM models produce a multitude of outputs, all at daily time steps for a minimum of 116 years of data to correspond with the climate data. Key modelled results include the following:

- inflows at multiple points or in aggregate
- volume in storage
- streamflow at gauge nodes
- transmission 'losses' by river reach
- diversions, for different entitlement categories
- crop areas planted
- crop water requirements
- irrigation orders
- soil moisture deficit
- order shortfall
- other consumptive demands and orders
- account balance
- storage releases and spills
- diversions for different entitlement category
- net evaporation from open water surfaces.

This list is not exhaustive, as there are many other results recorded which are usually used for diagnostic purposes by the modeller.

The results are often post-processed to facilitate interpretation, comparison, and trade-off analysis, reported graphically or in tables. Examples of model results are shown in Figures 3 to 8, showing major water balance components from various scenarios and river systems.

Figure 3. Long-term variability of storage inflows presented as annual total

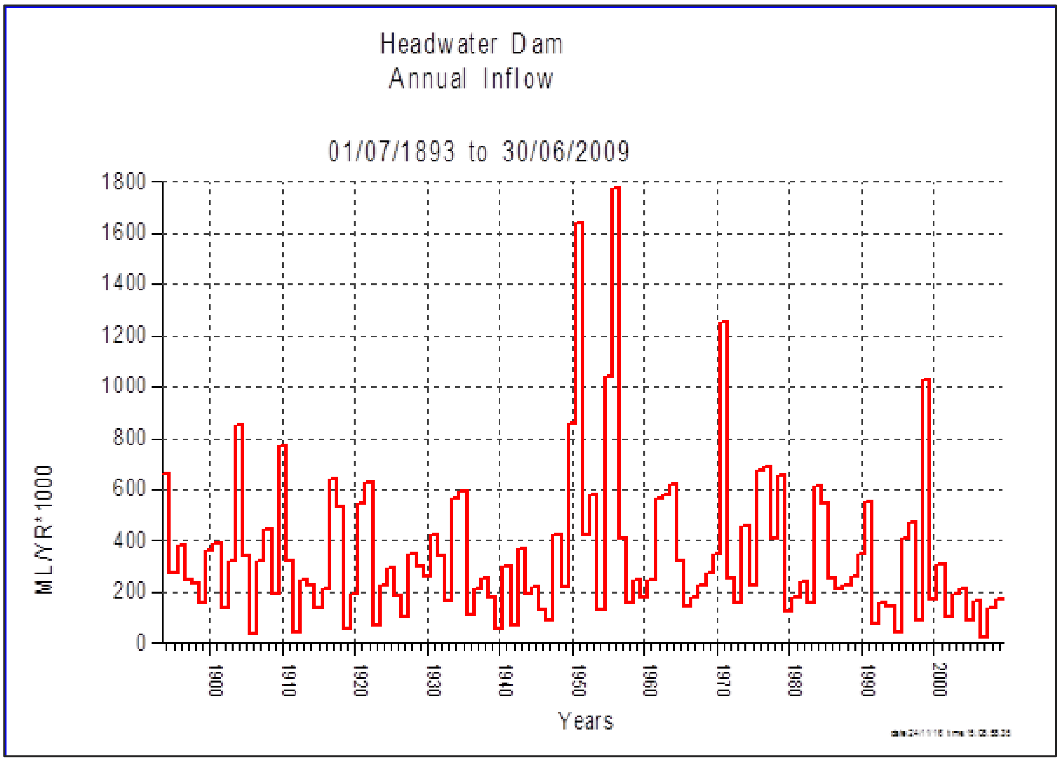


Figure 4. A cumulative departure from mean presentation of this data highlighting wet and dry periods in the twentieth century

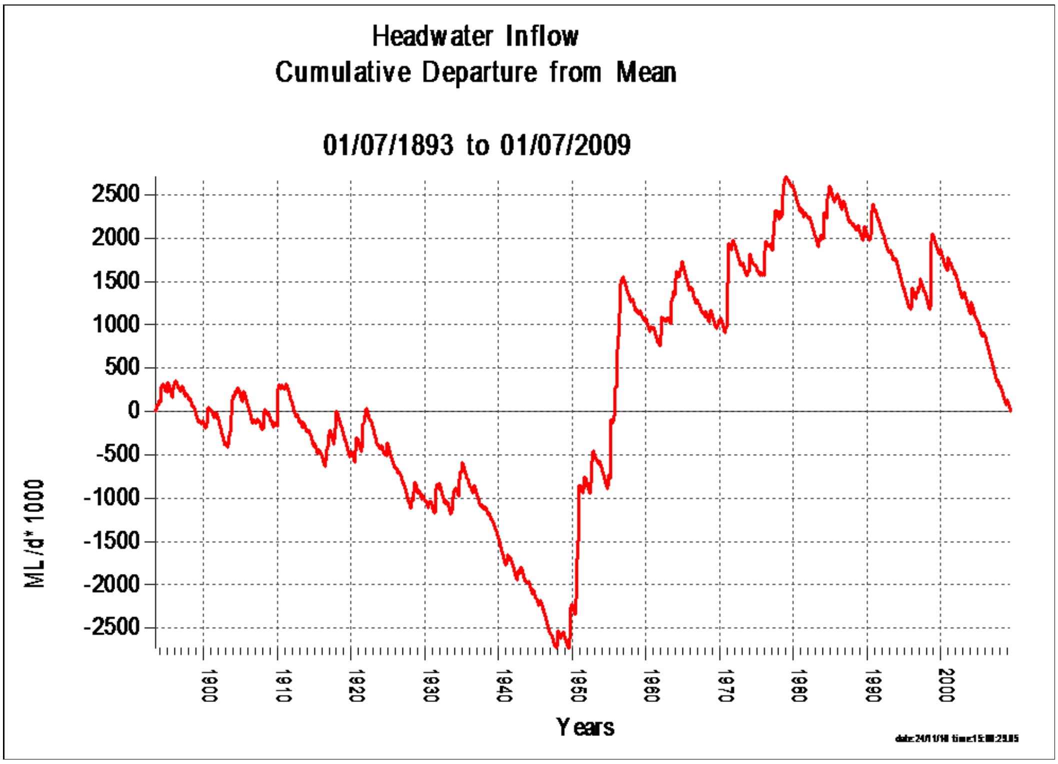


Figure 5. The volume that would have been stored in a headwater dam if it had been there for the full period, and with the modelled demands and releases

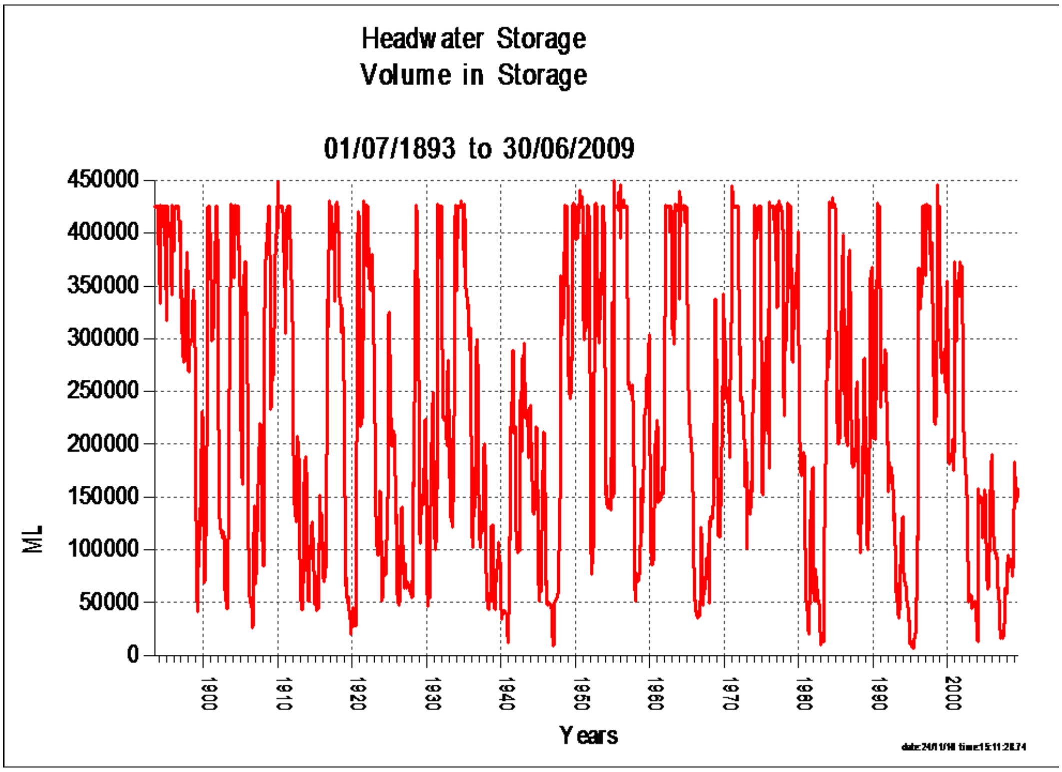


Figure 6. The allocation probability over the period, often referred to as a reliability graph

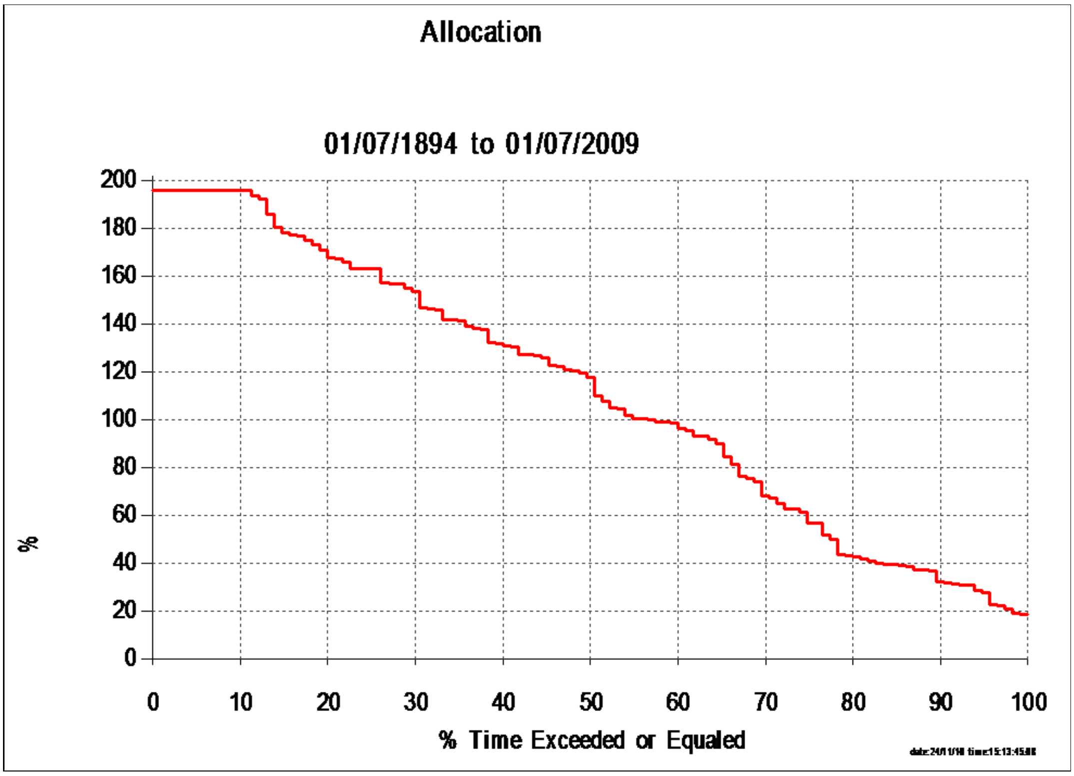


Figure 7. The resulting total regulated and corresponding supplementary diversions resulting from the allocation

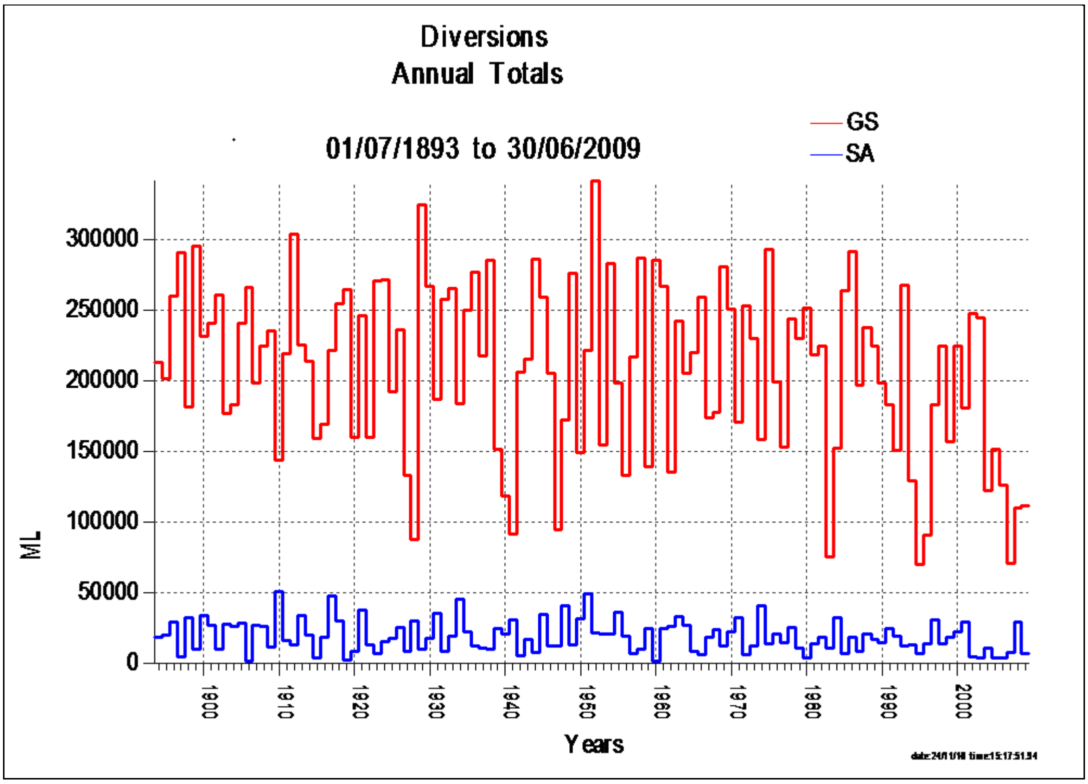
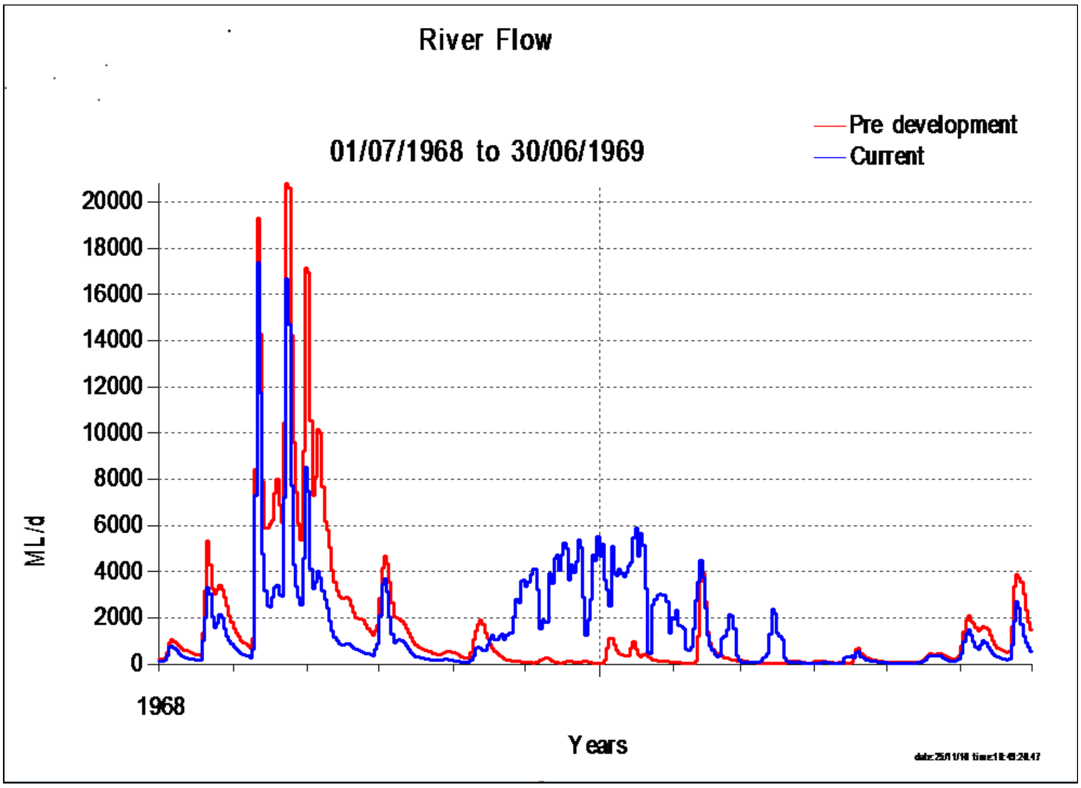


Figure 8. Changes in flow as a result of regulation compared to pre-development conditions at a location upstream of major diversions



Floodplain harvesting modelling

All regulated river floodplain harvesting entitlements will be determined by river system modelling. River system models are required to ensure that long-term average diversions not grow beyond limits allowed for under the existing statutory limits in water sharing plans (plan limits).

This section provides some background on river system models and the enhancements needed to determine floodplain harvesting entitlements. It includes details of the conceptual model of an individual farm with access to floodplain harvesting, and describes how important farm management aspects are configured. It also discusses what and how information provided by the landholders through floodplain harvesting entitlement application process has been used in modelling.

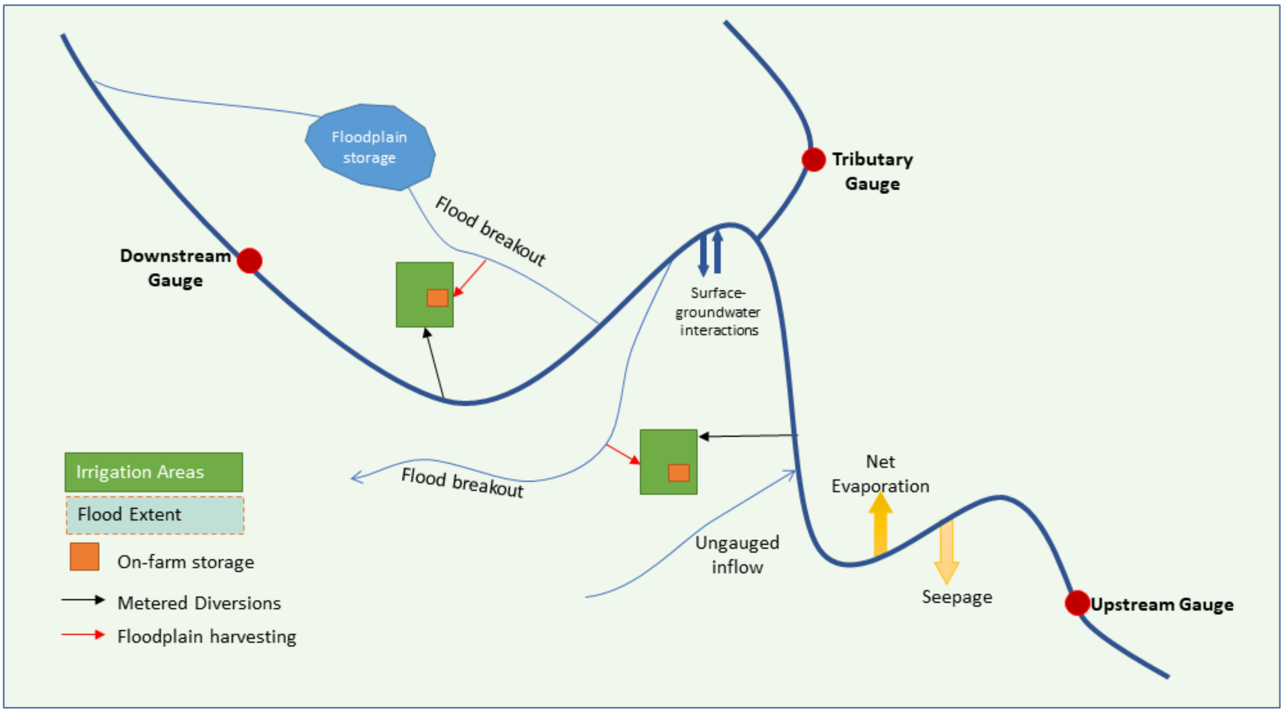
River system models

River systems models are water balance models designed to evaluate alternative water management strategies or policies for water sharing. The key processes modelled include natural processes, and management processes relating to water use and management. Figure 9 shows a range of river system processes that may occur.

The natural processes modelled include basic components of the hydrologic cycle that determine long-term water availability, that is, rainfall, evapotranspiration, and flow generation. These provide basic inputs to the model at the full geographic range of the river system.

The management processes modelled determine how this available water is shared between users. The processes include: the storage of water in both public and private dams, resource assessment and allocation, accounting, crop planting decision making, irrigated crop and other consumptive demand estimations, environmental demands, orders and storage releases.

Figure 9. Example of river system processes



The water management arrangements in NSW river systems are specialised to the extent that a customised platform is needed to correctly represent these. Thus far, this has been the IQQM software developed by the NSW Department of Industry, and will be the eWater Source software in the future. These models have been used for a range of policy and planning assessments, as well as setting of and compliance with diversion limits. For further general information on how river system models are developed and used, refer to the *Surface Water Modelling* section.

The pre-existing models reflect river diversions and flows accurately, but do not accurately represent floodplain harvesting processes. The enhancements to the modelling needed to implement the NSW Floodplain Harvesting Policy 2013 are described in the next section, along with a description of the data and information collected for and used in the models.

Process for determining entitlements

The floodplain harvesting entitlements were estimated using a four-stage process:

1. **Model enhancements and configuration:** Individual properties with their infrastructure and access to overland flow are represented.
2. **Calibration and validation:** River flow and a range of farm management parameters are derived using verified available data and then validated against complementary recorded data within a full model simulation model.
3. **Long-term scenario simulations**: Reference scenarios are configured and run in the models, and valley plan limits are determined.
4. **Volumetric assessment:** Floodplain harvesting entitlements are estimated based on long-term simulated floodplain harvesting diversions for the 2008–09 level of development[1], and assessed against the Valley Plan Limit in conjunction with floodplain harvesting accounting framework. In the case of floodplain harvesting growth, entitlements are derived so that the impact of the floodplain harvesting accounting framework on the unrestricted 2008–09 take is equalised between all individuals.

Model enhancements and configuration

The enhancements to the existing water management models involved both more detail as farms were modelled individually compared to being grouped; and the explicit modelling of processes that determine floodplain harvesting.

Floodplain harvesting includes rainfall runoff harvesting and overland flow harvesting. These components were modelled for each property that registered an interest and were determined to be eligible under the NSW Floodplain Harvesting Policy 2013. The amount any single property harvests is dependent on:

- water becoming available to harvest either as a consequence of water flowing breaking out of the main river channels and flowing across the land, or runoff from rain on the property, and
- the capability of the property to divert and store that water, and subsequently irrigate with it.

The first factor is influenced by the location of the property relative to breakouts from the river system as well as local topography, the size of the property, and the area used for irrigation. The second factor is affected by intake and storage capacity, as well as irrigation management practices.

Several enhancements were needed to the existing river system models. These are summarised in Table 3 and described in the sections following.

[1] This include eligible on the ground and yet to be constructed floodplain harvesting works

Table 3. Summary of key model changes for Healthy Floodplains project

Area	Existing model	Updated model
Individual farm modelling instead of groups	Historically, hydrological models were developed based on river reaches, which are defined based on the availability of flow gauges along the main streamflow. All water users within a defined river reach are combined into a single group with shared infrastructure and farm management practice averaged for the group.	All properties considered for floodplain harvesting entitlement are modelled individually, and other non-floodplain harvesting properties aggregated as before.
Rainfall harvesting within the property from both developed and undeveloped areas represented	Runoff from property's area is a single model output and was estimated as part of overall demand calibration.	Runoff generated from the developed and non-developed area is calculated and reported separately and the rate of runoff assessed against published data sources.
Overbank flow represented separately	The river system models estimated losses to floodplains using a simple flow-loss relationship. This overbank flow loss, in reality partially harvested, was represented as completely lost to system	Updated models represent floodplain breakouts explicitly, i.e. as an effluent. Calibrated river reach loss represents instream transmission loss only.
Representation of overbank flow harvesting	Floodplain harvesting was implemented in various NSW river models, but was limited in accuracy due to limited availability of data on floodplain harvesting infrastructure. It did not include floodplain harvesting from flood breakouts from the unregulated tributaries.	The models represent the infrastructure details for each eligible property, and their access to relevant flood breakout. Wherever appropriate floodplain harvesting from unregulated streams (gauge bypassing flow) is modelled.
More accurate infrastructure data	On-farm storage capacities were estimated based on NSW Department of Industry regional records. River pump capacities were estimated based on work approvals. Details on other infrastructure such as pipes and on farm storage pumps were generally not known. The relationship between volume and surface area did not account for the sequential filling and emptying of multiple storages or cells.	On-farm storage capacity (OFS), areas developed for irrigation, pump capacities and other forms of floodplain harvesting infrastructure have been assessed through a combination of irrigation surveys, field inspections and remote sensing data including LIDAR and Landsat. The volume to area relationship reflects the sequential filling and emptying of storages which allows for more accurate representation of losses.

Area	Existing model	Updated model
More accurate representation of other components of the farm water balance	Irrigation demands are represented through crop models, which were calibrated to match metered diversions. In some instances these may result in crop water use which is lower than actual, as ungauged water use such as floodplain harvesting was not properly accounted for.	Crop models have been configured in line with best available information on irrigation requirements and valley average application rates. Where possible, other water sources have also been represented, such as groundwater and unregulated diversions. However, due to lack of gauged data, simulated flow in the unregulated streams is not accurate.

Farm detail

A single irrigation node capable of modelling all key on farm processes is used to represent each floodplain harvesting property. This includes storage of water on farm, overland flow harvesting, rainfall runoff harvesting, regulated water diversion, supplementary access diversions, crop planting and watering.

Water is managed on-farm through the operation of their on-farm storages. The model allows for only one on-farm storage at each irrigation node, while in reality each farm may have multiple storages, with different geometry and function for on-farm water management. All eligible on farm storages at each farm are combined into a single storage with multiple cells, with each cell representing an individual on-farm storage.

The combined on-farm storage is configured to allow for sequential filling or emptying of the cells. The order of filling was based on information provided by landholders, or otherwise assumed to be most efficient filled first, or those closest to water extraction point. This representation allows for smaller surface area exposed to evaporation when held volumes are low, and not all storages would be use.

The IBQ included information on storage operation such as reserves maintained during the growing season and airspace retained. This information has been used in the models. The on-farm storage reserve is modelled in the cell which is filled first and emptied last. The OFS airspace applies to the top of the combined OFS.

The combined OFS is filled by all categories of water diversions[2] each farm has access to. Generally, the total rate of filling the storage is based on the combined rate of filling each individual storage. However, in some instances, concurrent take of different categories of diversions may lead to total filling rate in excess of the total of the second lift pump rates. The information on take rates is generally sourced from IBQ, but in some cases has been revised based on advice from licensing regarding the maximum rate for a given pump size, or farm water balance.

Rainfall runoff harvesting

Rainfall runoff harvesting is calculated for each property based on the property area, how much is irrigated, and available storage capacity. Runoff generated from different areas of a farm is modelled separately by differentiating between areas developed for irrigation and other farm areas.

The runoff rates from different areas vary significantly, based on developed or not developed, antecedent moisture conditions, and rainfall rates. The model continuously tracks the soil moisture

[2] Categories of diversions in addition to floodplain harvesting diversions may include on-allocation and supplementary diversions, licenced unregulated diversions and groundwater diversions.

of cropped, fallow and non-irrigable areas, enabling calculation of runoff following a rainfall event with consideration of antecedent conditions. The average rainfall-runoff coefficient is either derived through calibration (Gwydir) or adopted (Border Rivers, Macquarie and Barwon-Darling)[3] so that long-term average runoff is consistent with results from studies of this process[4]. The adoption of reference long-term averages compared to calibration addresses the uncertainty in separating rainfall runoff harvesting and overland flow harvesting components.

Overland flow harvesting

Access to over land flow varies between properties based on their geographical characteristics such as height of river banks, whether flood paths cross the property, topography within the property boundaries and neighbouring areas. Although these are largely natural, these may also have been altered works to enhance access. The ability to divert any overland flow that has accessed the property then depends on infrastructure developed to capture and store flood water, such as its intake capacity, and its on-farm storage capacity.

Main flood flow paths along river reaches were identified by overlaying a range of spatial data sets, which included:

- floodplain harvesting properties boundaries
- flood behaviour information, including the floodway network from floodplain management plans, aerial photography aerial and satellite imagery of historic floods
- results from flood models developed by Office of Environment and Heritage (OEH).

Thresholds of when flow breaks out of the main channel were determined using information from IBQ data, hydraulic model data, gauged flows, Landsat data and other flood records. Breakout relationships based on the hydraulic models were adjusted based on flow calibration at the downstream gauge to ensure that the model represents long-term average conditions. These flow paths were then simplified where possible, such as when they combine, or have low capacity, or are not accessed for overland flow harvesting at properties that registered interest.

It should be noted that the outflow is a permanent loss to the river system. In many instances, the breakouts are flood runners that either don't return to the river or the extent of return is unknown. Where the overland flow is localised to the river and some returns are expected, the flow calibration ensures that the overbank flow relationship excludes returns.

Some properties may have access to more than one overland flow source. All properties with access to the same overland flow source are given an order of access to this, in most cases from upstream to downstream, although variations may be informed by hydraulic model results.

While the representation of flood breakouts as effluents is the same for all models, what happens with that flow and how it is accessed varies between valleys. This is described briefly below, and will be discussed in more detail in valley reports.

While each of the identified flood breakouts is modelled as an effluent in all valley models, what happens with that flow next and how it is accessed by the floodplain harvesters varies between different valley models.

Border Rivers and Gwydir

When an overbank flow threshold is exceeded, a portion of the water from the river enters a virtual overland flow storage, which acts as a source of overland flow harvesting diversions for a group of farms. The volume in the virtual storage represents the volume notionally sitting on the floodplain that could be accessed by these farms.

[3] Runoff coefficients for non-floodplain harvesting nodes are left unchanged from previous model calibration

[4] This is discussed in separate paper on Crop Modelling Assumptions and Literature Review

This virtual storage is sized based on the estimated number of days after an overland flow event that water can be harvested, which was informed as part of the IBQ. This number of days, which varies from one week to one month, is multiplied by the total of all the overland flow harvesting intake rates for the group of farms accessing this water.

An access period of 10 days was set for the Border Rivers. This is likely to be an overestimate in the upper reaches; however, sensitivity testing indicated this was not a source of significant uncertainty. An access period of 14 days was used from Gwydir based on advice from IBQs. The intake rate is based on IBQ data in cases where these were assessed as reliable, and in a few instances the intake rates were estimated based on pipes or pump capacities advice from licencing. Any volume of an overland flow event volume in excess of the virtual storage becomes system loss.

Flood water is ‘released’ from the virtual storage for diversion at a rate equal to the sum of the daily intake rates for all properties accessing this storage. This means that in a small event, the water may be released quickly. If there is no available airspace in the on-farm storages to store released water, it becomes a system loss.

Macquarie

As the Macquarie has some unique flood characteristics, the hydraulic models are used to develop some conceptual differences in representing overland flow harvesting processes. This includes order of access, which could not be determined solely by the properties geographic location.

Individual temporary storage nodes are used rather than one virtual storage for each overland flow source to more accurately represent use of temporary storages within farm. This approach adds significant complexity to the modelling however, and is likely to only be of benefit in instances where temporary storages are a relatively large component of farm infrastructure. Remote sensing data is being used to review the extent to which temporary storages have been used.

The Macquarie set-up allows for significant return flows from these breakouts, and these have been reflected in the model. The OEH hydraulic model has been used to inform this. The returning portion excludes floodplain harvesting diversions.

Flood water is taken from the flood runner at a rate equal to the sum of rates at all floodplain harvesting intake points of the farm, and placed in the temporary storage if storage space is available. It is then transferred into combined permanent storage at a rate equal to the combined second lift capacity as long as there is space available there. Any excess water is made available for other floodplain harvesters by returning it into the flood runner.

Information on floodplain harvesting intake rates, temporary and permanent storages and second lift capacity is based on documentation provided by each landholder through the application process.

Barwon–Darling

The representation of access to overland flow harvesting in the Barwon–Darling is similar to that used for the Macquarie. However, because properties are generally geographically distant, individual flood runners were modelled for each property to minimise potential errors related to assumed order of access.

For properties located close to the flow gauges it was possible to relate individual breakout thresholds to the gauged flow. For other properties, floodplain harvesting thresholds were derived using a series of nested hydraulic models developed for this purpose.

Other water sources

Regulated and supplementary diversions are modelled as they have been in existing models. Additional water sources were also considered, as well as floodplain harvesting to get a complete estimate of a farm water balance. These were groundwater and unregulated use.

Groundwater use

Groundwater use has been modelled only in the Gwydir and Namoi where it is most prevalent. Groundwater access for each user with groundwater licences is configured in a simple way, allowing it to be considered in the farm's water balance model. Generally, groundwater is used subject to entitlement and pump capacity when volume in the on-farm storage during the cropping season drops below a certain level determined for each user. The groundwater entitlement is also considered in the planting decision.

Interaction between surface and groundwater use and groundwater level and surface water losses or gains is not modelled.

Unregulated licensed take

This refers to licensed diversions from unregulated streams by eligible floodplain harvesters in the regulated river systems. It has only been configured in the Gwydir for the same purpose and in the same manner as groundwater use.

For each such water user, the licence conditions are configured as defined in the NSW Department of Industry's Water Licensing System (WLS). However, absence of recorded data in many unregulated streams means there are uncertainties in the modelled unregulated estimate. While in some cases it is a part of the ungauged flow contribution, in other cases it may be an effluent with unknown relationship or even a stream which is not explicitly modelled.

Floodplain harvesting data and verification

Data sources

Various sources of data have been used and cross-validated throughout the development, configuration, and calibration of the models as well as validation model results. They are:

- conventional data sources such as our climatic, hydrometric, water use, and water licensing data bases;
- an intensive and detailed data collection program in the form of a survey known as the irrigator behaviour questionnaire (IBQ), undertaken for every property that registered interest;
- information from flood models and remote sensing to provide consistent information on breakouts, crop areas and farm development.

Climate data and flow data are used to estimate inflows to the system, and the proportion of flow breaking banks to source the overland flow component of floodplain harvesting. Further information on flow breakout relationships was derived from flood models developed for the floodplain management plans by OEH.

Data for property scale infrastructure such as on-farm storage capacity and pump capacity was collected as part of the IBQ, with cross-checking as part of inspections by departmental staff assisting with the survey, as well as other lines of evidence. The validation by LIDAR and Landsat data interpretation of on-farm storage capacity and history of use are detailed in a separate document.

Information on history of crop planted area and type was collected as part of the IBQ, and some of these were reviewed by Landsat data interpretation. Standard methods and industry average data has been used to estimate crop water use. This is discussed in more detail in a separate document.

Irrigator behaviour questionnaire (IBQ)

The IBQ was developed to obtain any available data to use in different aspects of modelling, including but not limited to model calibration, scenario set up and regional parameterisation. These include data on farm infrastructure and management, crop area planting decision, and water use.

The IBQ was designed to cater for all farms, and therefore not all IBQ questions are applicable to every floodplain harvesting property. More than 90% of all properties eligible for floodplain harvesting entitlements across the five northern valleys were surveyed using the IBQ and through farm visits by the NSW Department of Industry staff. However, as anticipated, for a number of reasons not all the information that was sought was provided. This presented difficulties in relying solely on the IBQ for the models. A fundamental task in modelling is taking responsibility for information used in the model, and this means reviewing the information used in modelling. Multiple lines of evidence were used to validate and fill gaps in IBQ data.

While data on recent farm infrastructure was, overall, readily available for most farms, information on historic development for a significant proportion of surveyed farms was either incomplete or uncertain because of change in ownership or incomplete record-keeping. Consequently, remote sensing methods were used to validate capacity and establish history of use of storages.

The history of crop areas and types planted is important. About 70% of all the surveyed water users provided either complete or partial record over the last 10–15 years. Remote sensing was used to check and complete reported planted areas.

Information on actual historical floodplain harvesting provided in the IBQs is limited. Overall, about 10% of water users indicated timing of the overland flow harvesting events, while less than 5% provided estimates of volumes. A review of the overland flow harvesting data revealed large inconsistencies between neighbouring sites with similar access to overland harvesting events of volumes and frequency of these events. Consequently, IBQ data was treated only as indicative, and modelling relied more heavily on flood models and satellite imagery to determine overland flow access at each farm. When supported by flood models and historical extent of floods IBQ data is used in model calibration.

Model calibration

The purpose of model calibration is to ensure that the model results in reliable estimate of the various components of the water balance with a known level of confidence, and that the river system behaviour is replicated during wet and dry periods.

Calibration involves systematically adjusting model parameters to match observed data where this is available, or comparable data from similar environments. A reliable estimate is one that is plausible and credible, and can be compared using rational criteria to be assessed as good as or better than other estimates. The various components of the water balance include principally river flow, diversions, water in storage, and irrigation application rates. If these estimates are reliable in wet and dry periods, then the estimates are likely to be reliable when averaged over wet and dry periods.

Model calibration with climate as the primary input 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 calibration steps are summarised in **Table 4**.

Table 4. Floodplain harvesting model calibration approach

Step	Fixed input data	Target	Parameters
Flow	• Climatic data • Gauged flow (mainstream reach u/s gauge and tributary inflow) • Dam releases • Metered diversions?	Reach d/s gauged flow	• Ungauged tributary contribution • Residual inflow • Effluent relationships (including flood outbreaks) • In-stream losses
Demand	• Climatic data • PET • Cropped area • Historical infrastructure	Metered diversions	• Crop requirements (a set of a number of model parameters either calibrated or pre-set to defined values are derived to achieve crop requirements in line with literature and reported application rates, i.e. ABS, Irrisat)
System	• Climatic data • Historical infrastructure	Headwater Dam volume	• Tributary utilisation • Over order factors • Supplementary access thresholds • Resource Assessment

The use of multiple sources of data improves the robustness of the calibration, that is, that we can match changes in flow along a reach with diversions, and application rates, increases the confidence that the apportionment into the different water balance components is sensible.

A range of other parameters that had sparse data to calibrate against were adjusted or set to values that produced results comparable to information from a range of sources, including research and industry literature. These mostly relate to farm management such as on-farm storage seepage rate, on-farm application loss from irrigation efficiency, crop area planting decision making, and long-term average runoff from undeveloped and irrigated areas This approach was adopted to streamline the calibration process, and circumvent ‘over calibration’ to data, which runs the risk of significant uncertainty as a result of unrealistic parameters.

Calibration of the model is done in stages through adjustment of a number of calibration parameters relevant to each calibration stage. Water balance is a fundamental principle of the river system model calibration overall, and of each of the calibration steps in particular.

Main calibration steps involved in calibrating floodplain harvesting model, and input and calibration parameters are summarised in Table 4.

Scenario development

Scenario modelling refers to long-term model simulation when the model configured with a pre-defined set of development and management conditions is run over a long sequence of climatic and flow conditions.

The NSW Floodplain Harvesting Policy 2013 requires that the long-term average diversions do not exceed statutory limits as specified in the water sharing plans, and must also be lower than the long-term cap. To meet the requirements of the policy, up to four scenarios need to be considered, with relevant development and management settings, in chronological order:

1. MDBMC Cap on diversions (the Cap);
2. water sharing plan;
3. 2008–09; and
4. current conditions.

The Cap and water sharing plan scenarios are developed to establish the plan limit; the current conditions scenario is used to assess whether any ‘growth in use’ has taken place for total and floodplain harvesting diversions.

The scenarios share the same calibration characteristic with development and management conditions adjusted to reflect those in place at the time each scenario is meant to represent. While system management rules can be readily adjusted, accurately representing development conditions is more difficult because there is incomplete historical information related to development such as on-farm storage capacities, surge areas, diversion structures, channels, in-take capacity and pumps. All these are summarised in the model to total storage capacity and take rate. While the presence of an on-farm storage on these dates can be determined from remote sensing, changes in capacity are problematic. The presence of these storages can inform adjustment of other infrastructure related to intake capacity.

Scenario validation is completed to assess its representativeness of the bench-mark development. The model performance is assessed over a short period around (that is, before and after with benchmark year in between) for river flow, regulated river diversions and headwater storage behaviour.

On-farm storage remote sensing verification

As part of implementing the NSW Floodplain Harvesting Policy, there has been unprecedented investment in data and modelling to improve modelled estimates of floodplain harvesting. The irrigator behaviour questionnaire (IBQ) has been used to collect a range of data, including information on permanent and temporary on-farm storages. Initial modelling was largely based on IBQ data; however, the OFS assumptions will be revised after a number of verification checks are complete. A range of checks are being undertaken using remote sensing as outlined in this report:

- LIDAR data is used to confirm the capacity of on-farm storages and to derive a water level–volume relationship for use in modelling and monitoring.
- Landsat data confirms the date of permanent on-farm storage construction, which will be used to create an updated plan limit scenario.
- Landsat data has also been used to assess history of temporary storage use.

Permanent storage capacity

The volumetric capacity of on-farm storages is an essential piece of information to determine floodplain harvesting entitlements. This information was provided in IBQs; however, the quality of this information is variable, with only a few properties providing surveyed data.

LIDAR data has been used to review the capacity of on-farm storages and to derive a water level–volume relationship for use in monitoring. This relationship also produces a surface area, which is important for evaporation calculations.

LIDAR methodology

As part of the development of the valley floodplain management plans for the Healthy Floodplains Project, significant areas within the five northern valleys had LIDAR survey undertaken to develop detailed land survey data. The LIDAR survey provides elevation data in the form of a high-resolution digital elevation model. This data can be used to develop water level versus volume curves for on-farm storages that were empty during the time of survey. However the LIDAR survey cannot penetrate stored water in partially full storages, and therefore processed LIDAR usually represents the water level as the ground surface.

This limitation can be overcome by modifying the ground surface using a storage bathymetry model (SBM) to estimate the storage curve below the water level. An initial SBM was based on five empty on-farm storages that ranged in shape, volume and surface area. The SBM was validated using on an additional six 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 the 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 has since been further refined using information from an additional 27 empty storages. The SBM model results are still being finalised. The final SBM model estimates will be adopted before entitlements are finalised. If survey data has been provided, this will be used instead of the LIDAR estimate, however any significant differences to LIDAR will be investigated. A full report detailing the methodology and validation results is being prepared.

All storages will have an assumed freeboard of 1 m as an accepted industry standard recommended by the Soil Conservation Service.

Permanent storages at cap and plan limit dates

The NSW Floodplain Harvesting Policy 2013 and the Murray–Darling Basin Plan requires that long-term average diversions do not grow beyond existing statutory limits. The floodplain harvesting program assesses growth in floodplain harvesting and implements measures to return long-term average diversions to that allowed for.

The Basin Plan includes an estimate of this limit. However, it allows for this to be revised whenever a demonstrably better estimate is available. The hydrological models that determined the existing plan limit estimates reflect river diversions and flows accurately, but do not accurately represent floodplain harvesting. The focus of these models when they were developed was on quantifying and managing within channel diversions and flows, not floodplain harvesting and flood flows. For this reason, the updated models are also being used to create an updated estimate of floodplain harvesting under the plan limit. In order to create this update, Landsat has been used to confirm which storages were constructed at plan limit dates.

Plan limit methodology

In order to update the plan limit modelling, a review has been undertaken to determine which storages were constructed at the relevant dates referred to in the plan. These dates are summarised in Table 5. Landsat data was used to detect which storages were present at these dates. This work also identified instances where storages were expanded.

The analysis was undertaken as a two-step process:

1. An initial automated process using a number of Landsat images close to the reference dates. If water was detected at the location of a current on-farm storage, then it was assumed that the on-farm storage had been developed by this date.
2. A manual process was adopted for the remaining current on-farm storages to check Landsat images for evidence of construction, to allow for the possibility that the storage had been constructed, but may not have had water in storage at the time.

The Landsat checks resulted in a number of differences compared with IBQ data as to when a storage was built. A final set of on-farm storage estimates at scenario reference dates will be compiled once the LIDAR capacity data is finalised.

Table 5. Plan limit reference dates

River system	Cap	WSP
Border Rivers	30/11/1999	30/06/2002
Gwydir	30/06/1994	30/06/2000
Namoi	30/06/1994	30/06/2000
Macquarie	30/06/1994	30/06/2000

Review of temporary storage use

Temporary storages within irrigation farms fall into one of the following categories: surge areas, supply channels and irrigation fields. As part of the detailed survey data collected from all farms, many users indicated significant historical use of irrigation fields as temporary water storages. Landsat data has been used to assess instances of temporary water storage within property boundaries after a number of flood events.

Temporary storage review methodology

Landsat imagery is the longest earth-monitoring satellite data, with more than 30 years of image archives. It is a powerful dataset able to map historical flooding events. Normally, Landsat imagery can be downloaded from USGS (US Geological Survey) and be processed one-by-one locally. This involves large amounts of work for imagery pre-processing, calibration, analysis, interpretation, post-classification and decision-making.

The project of mapping temporary storage takes advantages of Australia Geoscience Data Cube (AGDC) and significantly reduces the processing time and improves the mapping efficiency.

AGDC is a common analytical framework for large volumes of regularly gridded geoscientific data such as Landsat series, developed by Geoscience Australia (GA). Running AGDC on a supercomputing facility at the National Computational Infrastructure (NCI) is an innovative approach and makes it possible to store and generate useful information on regional and national scales without downloading and pre-processing. The images in the AGDC have been calibrated to internationally recognized standards. The data cube is organized into stacks of consistent, time series geographic tiles with 25-metre resolution and 100 km by 100 km coverage, so that it enables rapid manipulation and multi-decadal analysis of the entire Landsat archive from 1985-2018 (Geoscience Australia, 2015).

Water Observation from Space (WOfS) is a gridded product from AGDC and indicates areas where surface water has been observed for every Landsat 5, 7 and 8 image in AGDC. The water detection algorithm used to detect water from each observed pixel is based on a statistical regression tree analysis of a set of normalised difference indices and corrected band values. The dataset contains the water classification results for each individual pixel. Pixel values show the pixel status such as water present, water absent and water undetectable because of cloud, cloud shadow or no data. Quality checks ensure that the successfully classified water pixels can be physically verified as present on the Earth’s surface (Geoscience Australia, 2015).

Due to standardized processing, the WOfS product provides consistent water classification over a 30-year period, which is an important foundation for accurately mapping and monitoring water bodies across Australia.

The WOfS water pixel data is extracted for a number of dates following flood events. For each date, the data is further processed by combining with ancillary GIS layers, to estimate the area of temporary storage for each property:

- A developed area data layer has been developed for each property. Any water pixels outside of these areas are removed. This eliminates the water bodies in wetlands, lagoons, swamps and river reaches.
- An on-farm storage layer has been developed for each property. The final temporary water extents are created by removing the permanent on-farm storage area from masked WOfS surface water areas.
- Spatial statistical analysis is implemented in ArcGIS to calculate the temporary water storage areas in each FPH property. This includes both surge areas and unmapped areas such as fields.
- The raw Landsat data is also manually inspected to check for potential issues. This identified one small area which appears to be a constructed temporary storage which was outside of the developed area layer. This area was then added to the total area estimate.

The following process has been used to choose Landsat images to assess:

- Flood events have been identified using gauged flow data
- The first useable (that is, limited cloud cover) Landsat image after the event has been selected.

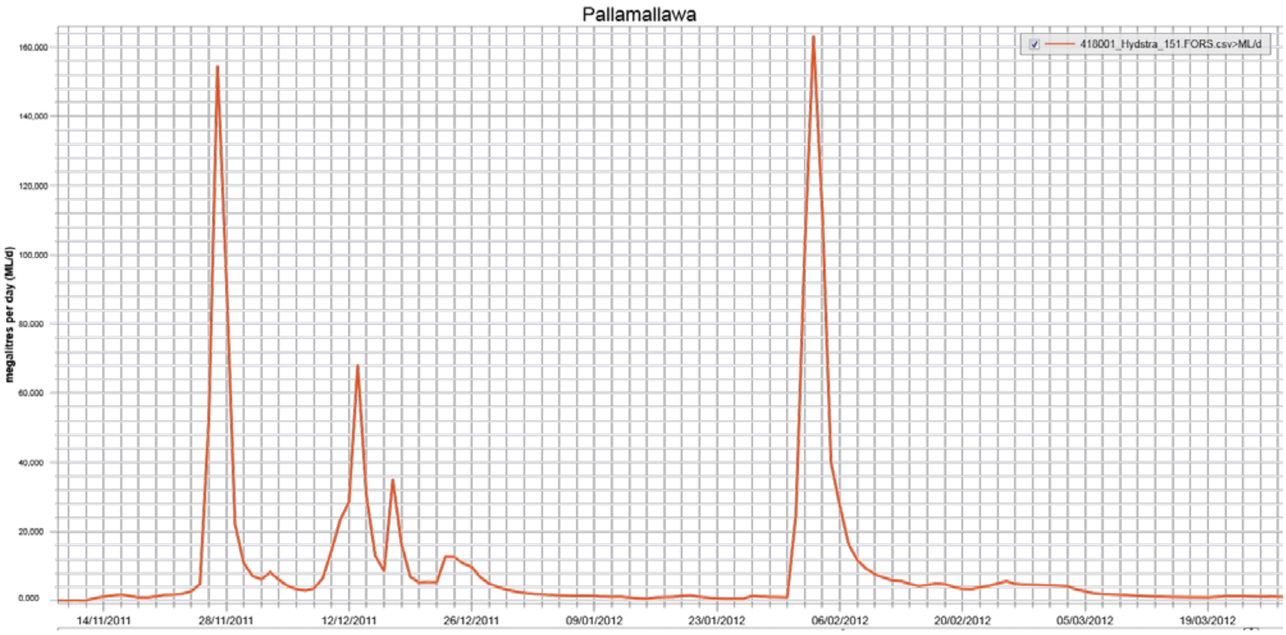
- Another image several weeks later is also analysed to assess how much temporary storages are used over a longer period (that is, more than 30 days).

Gwydir results

2011–12 events:

A number of flood flows occurred in late 2011 and early 2012, as illustrated in Figure 10. The two largest peaks occurred at Pallamallawa on 27 November 2011 and 3 February2012, with a third smaller event peaking on13 December 2011.

Figure 10. Pallamallawa flow 2011–12 events



The following images have been analysed for this period:

- Landsat data is available for 24 December 2011; however there is still significant localised flooding within property boundaries on that date. This makes it difficult to determine whether the detected water is actually held in storage or whether it is water in floodway.
- The next available image is 9 January 2012. This has been analysed as described above.
- The 29 March 2012 image has also been analysed to assess longer-term storage.

The analysis indicates around 2,700 ha of water was held in temporary storage on 9 January 2012 and less than 1,000 ha on the 29 March/ 2012 (Table 6).

The depth of temporary storages is not known. An assumed depth of 1.0 m has been adopted for the purposes of an initial review of the extent to which temporary storages have been used.

The depth in surge areas may be more than 1.0 m; however surge areas represent only a small percentage of the temporary storage area inundated. They represent 9.5% and 2% of total area on the 9 January 2012 and 29 March 2012 images respectively.

The majority of the temporary storage areas appear to be fields. In particular, a group of three properties which hold water in fields account for around 60% of the total area in temporary storage on 9 January 2012. It appears likely that an assumed depth of 1.0 m is generous for these areas:

- the bank heights and need for a freeboard indicate that less than 1.0 m could be stored
- the Landsat image shows that some of the fields are only partially holding water, which means that the actual depth is likely to be small.

If temporary storages are to be considered eligible for assessment, further review would be required to determine their capability to store water and the method and infrastructure used to fill them.

The estimated temporary storage volumes are very small in comparison to the permanent storage capacity; around 4% and 1% in January and March respectively.

Table 6. Area of within farm temporary storage—2012

Parameter	09/01/2012	29/03/2012
Area (ha)*	2,699	898
Volume assuming 1m deep (ML)**	26,989	8,980

*Area may be underestimated by around 10% due to gaps in data, cloud and cloud shadow

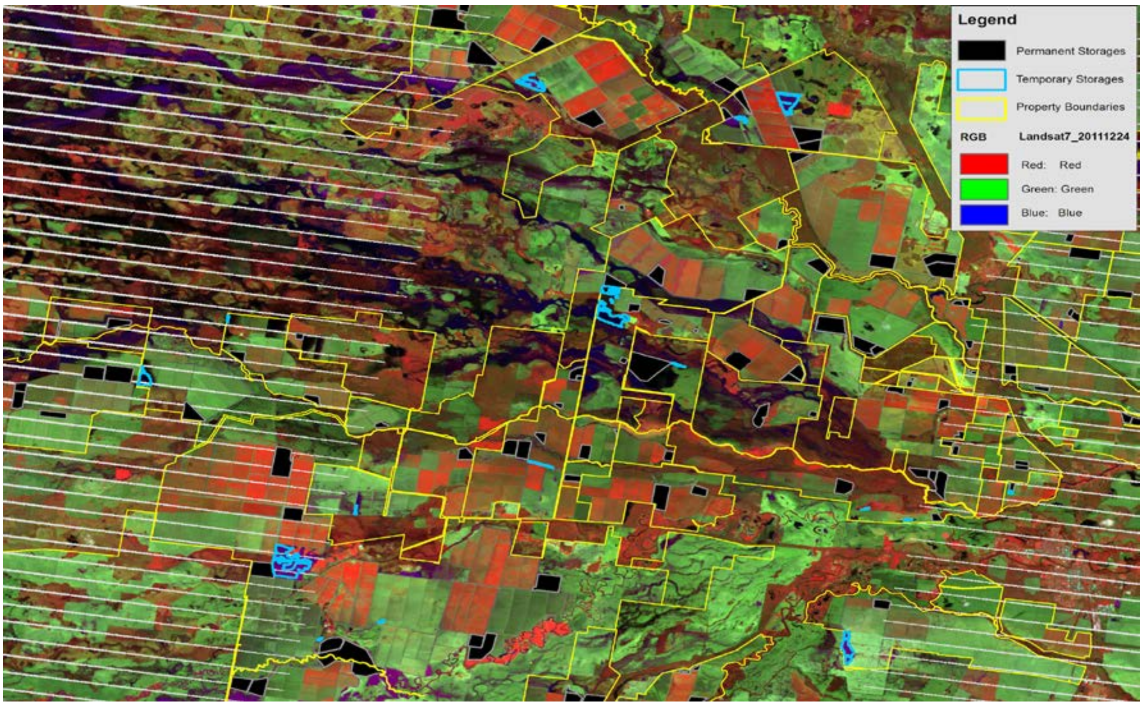
**The depth of temporary storages is not known. An assumed depth of 1m has been adopted for the purposes of an initial review of the extent to which temporary storages have been used.

A comparison has been made between the 24 December 2011 image and 9 January 2012 image to assess whether there were additional areas of temporary storage in the former. This was completed by creating a map which overlays the temporary storage areas detected on the 9 January 2012 on the 24 December 2011 image, an example of which can be found in Figure 11.

The maps have been manually inspected to determine whether flood-free areas have evidence of additional temporary storage. Inundated properties are ignored in this assessment, as it is not possible to determine whether the detected water is stored water or floodplain. This comparison indicates only a few small additional areas of water held in temporary storages on the 24 December 2011.

Around 60% of the temporary storage area is associated with a group of three properties in the lower floodplain. These properties have very similar area in temporary storage on the 24 December 2011 and 9 January 2012.

Figure 11. Landsat data for 24 December 2011 including layer depicting temporary storages detected on 9 January 2012



Earlier events

The methodology has been repeated for a range of earlier events as summarised in Table 7. The area in 2001 is larger than found for the 2012 event. However, it would still represent a relatively small volume compared to permanent storages.

Table 7. Area of water held within farm temporary storages

Event Details; Peak Pallamallawa flow (ML/d)	Image dates	A. Area soon after event (ha)	B. Area after several weeks (ha)
25 Jan 1996: 85,500 ML/d	A—6 Feb 1996	1,768	N/A
	B—9 Mar 1996	N/A	417
21 Nov 2000: 106,689 ML/d	A—9 Dec 2000	2,835	N/A
	B—26 Jan 2001	N/A	100
2 Feb 2001: 122,820 ML/d	A—11 Feb 2001	3,917	N/A
	B—15 Mar 2001	N/A	641

Border Rivers Results

The WOfS methodology has not been completed for the Border Rivers; however some initial manual analysis of Landsat data has been undertaken using data downloaded as Natural Colour images[5]. The farm boundaries and permanent on-farm storage areas were overlayed over the Landsat data. Other areas of temporary storage of water were manually detected and polygons drawn to estimate area.

This analysis was completed using Landsat data from 20 January 2011. A very large event had occurred prior, peaking at Goondiwindi on the 15 January 2011. Assuming a depth of 1 m, it is estimated that less than 1.5 GL was held in temporary storages on 30 January 2011.

Crop modelling assumptions and literature review

The volumes of water to irrigate crops are a key component of the water balance, along with climatically determined water availability. Getting this volume correct is important to get realistic, long-term average estimates of floodplain harvesting.

This section describes the methods adopted to model crop water use in the river system models, and compares results from this modelling with those produced by other methods. This will demonstrate how well the NSW Department of Industry crop modelling conforms to standard methods of estimating crop water demands, and how well the results compare with other estimates.

Crop modelling forms part of the overall river system modelling that is being used to determine floodplain harvesting entitlements. River system models are used to simulate the outcomes of given management rules and infrastructure over a long climatic period (>100 year simulation).

Crop models in the NSW Department of Industry river system modelling software estimates demands on a daily basis, and diverts water to meet these demands. The irrigation water use in any one year can be influenced by a large range of factors apart from climate. Some of these factors can be simulated and others are outside the feasibility of long term simulation modelling:

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

- The models have been developed to represent historic cropping behaviour, including how much is planted in response to conditions of water availability. Future changes in cropping behaviour such as changes in area planted, crop type or more wide-spread under-irrigation can be examined in future modelling. However, they are not relevant to the current implementation of the healthy floodplains program.
- The models are able to represent inter-annual variability in crop water use due to the use of long-term SILO (Scientific Information for Land Owners) climate data. Limitations in water availability are also simulated, and this can account for some of the historic under-irrigation of crops.
- The models are not able to explicitly predict the influence of hail, crop disease or market variation however. It may be possible to undertake some refinement of the methodology (for example, to account for heat stress); however this can only be included if there is long-term data available to support the simulation. These types of refinements are likely to have negligible impact on the long term modelling of floodplain harvesting.

The crop models implemented in the NSW Department of Industry river system models have been developed based on the best available data and methods for long-term simulation modelling. The adopted methodology is outlined below, along with comparisons to other data sources.

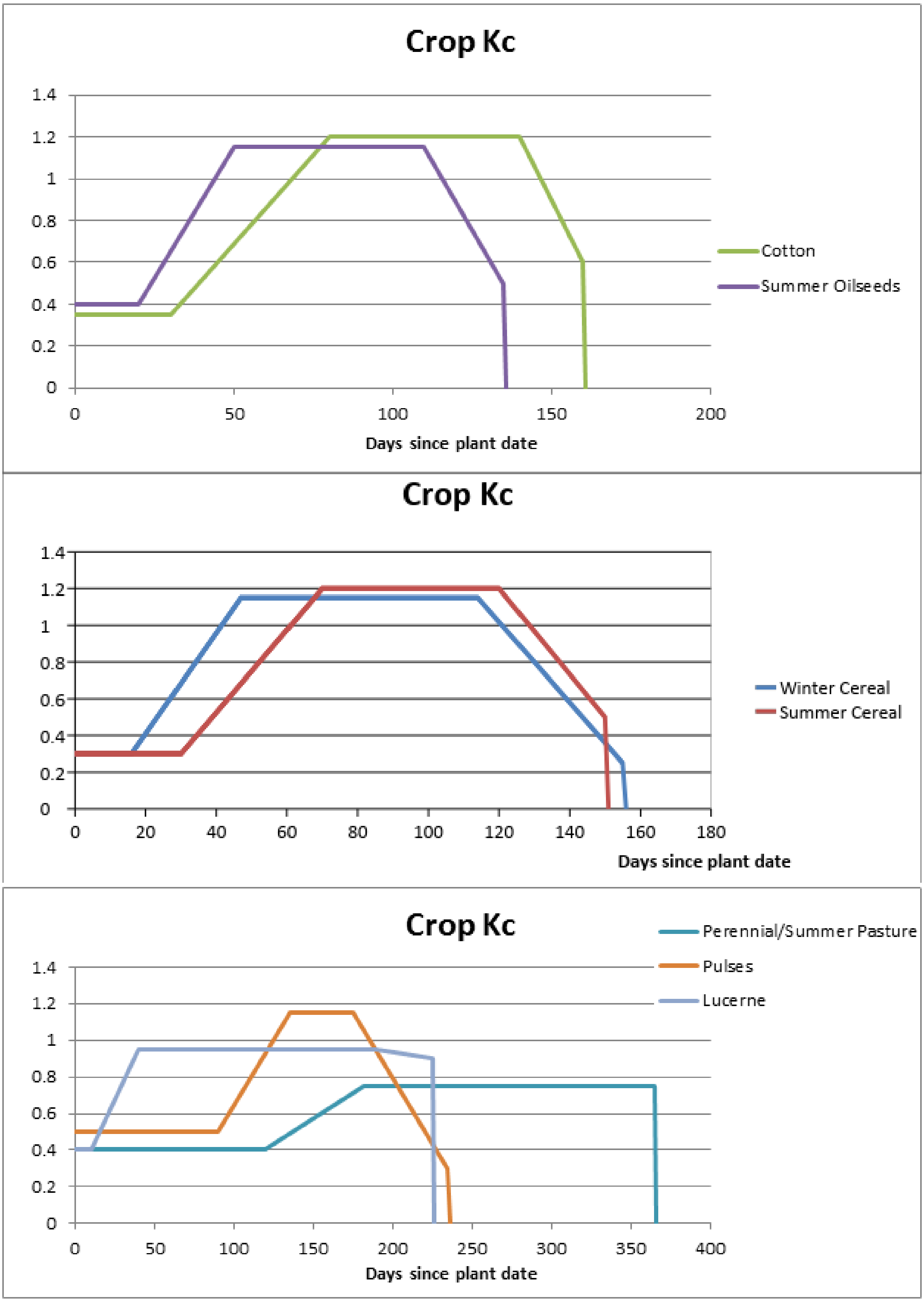
Crop assumptions used in Water River System Models

The crop water balance for each crop is represented using the method outlined in *FAO Irrigation and Drainage Paper 56, Crop Evapotranspiration—Guidelines for computing crop water requirements* (Allen et al, 1998).

This method uses crop factors (K_c) to convert potential evapotranspiration to crop evapotranspiration. These factors change as the crop develops over time from planting to harvest or between seasons for perennial crops. There are many different ways of estimating this factor: energy balance, soil water balance studies, lysimeters or remote sensing. However, in many cases the factors are taken from published data such as FAO56 (Allen et al, 1998). The FAO56 method divides the crop growth into four distinct stages: (i) initial, (ii) crop development, (iii) mid-season, and (iv) late season.

The FAO56 method provides a range of values. Specific values were derived in consultation with agronomists from Department of Agriculture for different climatic zones in NSW (DLWC, 2000). Cotton crop factors are based on more recent advice from DPI Agriculture. This data set has been used for Border Rivers, Macquarie and Namoi (Figure 12). Modelling for Gwydir and Barwon Darling are based more on model calibration processes, where crop factors were estimated within a known range to calibrate irrigation demand to regulated diversions. The planting dates used in the crop models are informed by the irrigator behaviour questionnaires.

Figure 12. Crop coefficients used in Border Rivers and Namoi river system models



Cotton irrigation application rates—comparison to other sources

The available literature on average irrigation requirements uses variable definitions, such as whether some or all water losses are included, and whether pre-watering is included. This difference in definitions makes comparison difficult. Publications that include data from large areas and over short periods of time also make it difficult to compare as different climatic conditions in each season need to be considered. The following review focuses on cotton as this represents the majority of irrigation water use.

Irrigation behaviour questionnaire data

The irrigator behaviour questionnaires included questions about water use rates, including pre-watering and tail-water returns. A large range in values was reported. For example, responses in the Border Rivers range from 3.6 ML/ha to 11.5 ML/ha after subtracting for tail-water returns. There is no geographical relationship to the responses and the accuracy and comparability of the data is not known, especially whether a similar period was used when responding to what is 'average'. This information was referred to when assessing results, but was not used directly in the model.

WaterSched Pro

WaterSched Pro[6] provides an estimate of long-term average crop water use, assuming an unrestricted water supply. It also uses crop coefficients based on FAO56. The results for cotton have been compared to the IQQM/Source model values in Table 8. The following assumptions were used in WaterSched Pro for cotton:

- 70% efficiency[7]
- 70mm deficit, 15 October plant date, 180 day, typical water use
- Average using climate data for 1900-present.

Table 8. Long-term annual average mm irrigation for cotton: WaterSched Pro versus modelled

Valley (site)	WaterSched Pro: Cotton water use*	WaterSched Pro: Irrigation Demand**	WaterSched Pro: Irrigation Required***	Department of Industry: Irrigation Applied****
Macquarie (Narromine)	762	554	792	793
Namoi (Wee Waa)	787	552	789	820 (draft)
Gwydir (Moree)	789	549	784	747
Border (Boomi)	794	555	793	907

*Water use includes rainfall

[6] https://waterschedpro.net.au/

[7] 'Gillies (2012) has summarised the analysis of 542 surface irrigation performance evaluations conducted in the past decade and the average application efficiency with tail water recycling was 76.3% (cited in Tennakoon *et al.* 2012). The assumption of 30% loss allows for some channel losses as these are not modelled explicitly. Losses from on farm storages are modelled separately however.

**Irrigation demand is irrigation water used by crop, excluding application losses

***Including 30% application/channel loss

****Equivalent to above. Values assume no water supply shortage.

This utility does not account for any pre-watering, whereas the river system modelled includes this[8] and would largely account for the differences in values. Pre-watering requirements would be larger in the northern valleys where there is less spring rainfall preceding the irrigation season.

The modelled results for the Border Rivers are approximately 1.1 ML/ha higher, a rate that lies between averaged modelled[9] fallow soil depletion at 15 October (0.92 ML/ha).

For Gwydir, the modelled average of application rate is about 4% lower than WaterSched Pro.

The draft modelled values for Namoi are slightly higher than WaterSched Pro, which is assumed to be due to pre-watering. Note however the Australian Bureau of Statistics (ABS) data indicates that there may be significant under-irrigation in dry years (see next section), hence the initial modelled values may be an overestimate. This will be further investigated during analysis of initial model results and addressed if required.

The modelled average for Macquarie is equivalent to WaterSched Pro. It is assumed that there is little pre-watering in Macquarie due to the wetter spring climate. The Macquarie modelled values compare very well to the ABS data as described in the next section.

ABS data

The ABS collects data on irrigation application rates for various crop types and regions. This data appears to represent water applied to field, including application loss.

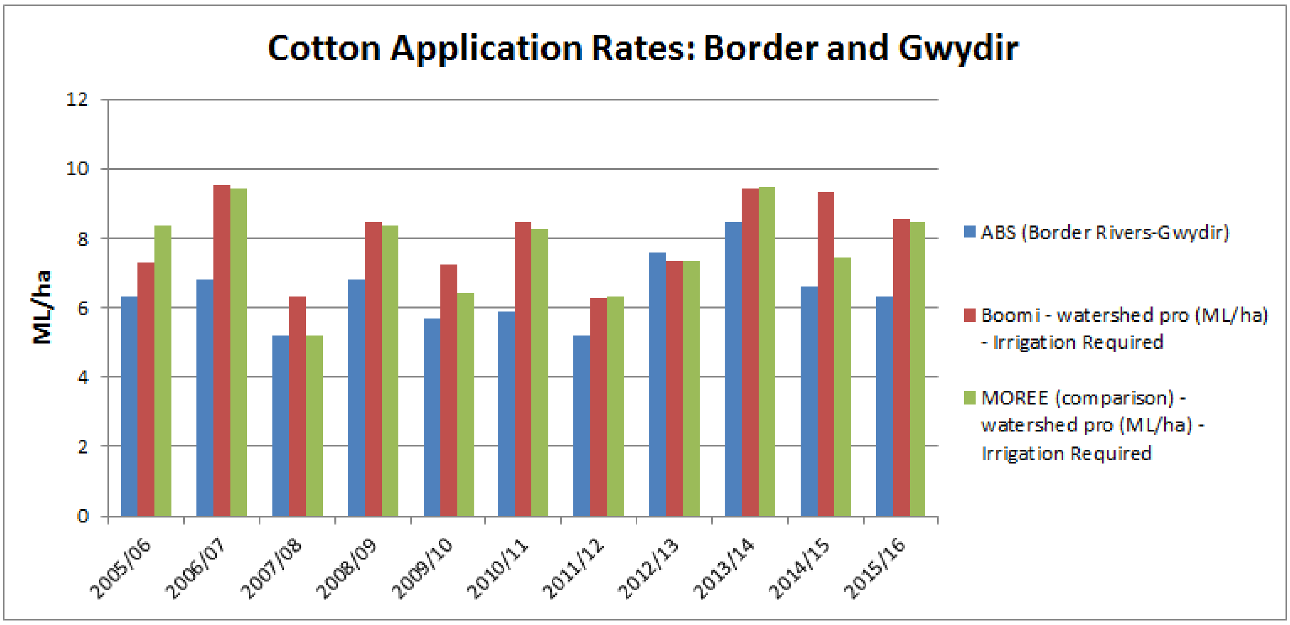
Gwydir and Border Rivers

The ABS reports application rates over a large region covering both the Gwydir and Border Rivers. It is assumed that this includes data from unregulated cropping areas. The ABS data has been compared to WaterSched Pro results in Figure 13. The data is reasonably close during the wetter years, but ABS data is significantly lower during dry years. This indicates that cotton is under-irrigated during dry years in this area.

[8] WaterSched Pro assumes a full soil moisture profile at planting whereas IQQM/Source modelling will assume soil moisture based on simulation of a fallow area. The extent to which pre-watering is required will vary depending on fallow and soil management practises (e.g. Harris, 2012).

[9] Boomi climate. A single crop factor for fallow of 0.6 is used in the Border model. Sensitivity testing using Kc of 0.4 gives a very similar outcome of 0.9 ML/ha.

Figure 13. ABS versus WaterSched Pro for Border Rivers and Gwydir



The NSW Department of Industry river system models under-irrigate to some extent during dry years because of limits to availability. In particular, if a high-risk crop area planting decision (for example, 4 ML/ha) has been defined for a water user based on IBQ, then water stress is likely to occur in the model during dry years. The average application rate modelled for all floodplain harvesting eligible properties is illustrated in Figure 14 and Figure 15 below. This illustrates some years where the actual modelled values are less than the theoretical full supply; hence under-irrigation is being simulated in those years.

Differences with ABS are further described below; however the comparison is complicated by the following issues:

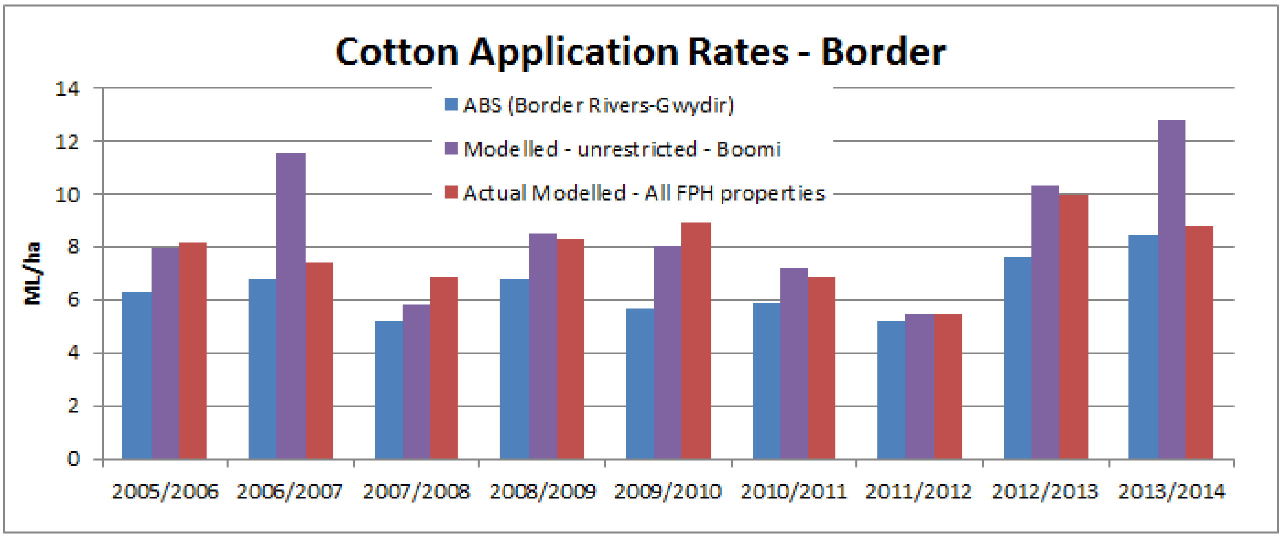
- The representativeness of the ABS data during dry years for either Border or Gwydir is not clear. It is assumed that the ABS includes data for unregulated areas where under-irrigation may be more severe.
- The region is very large, hence climatic differences makes it difficult to compare individual years.

Border Rivers

The Border Rivers actual modelled is higher than ABS in some years (Figure 14); the overall average is 7.9 ML/ha (modelled) versus 6.4 ML/ha (ABS). This indicates that the Border Rivers model may be overestimating application rates in dry years; however the current modelling is considered representative of best available information for the following reasons:

- The 2015–16 ABS includes more detailed reporting for a region around Goondiwindi—this has a 85% larger application rate than the whole region, which gives an indication that ABS data for the Border Rivers—Gwydir region may not be reliable for the MacIntyre area.
- The average application rate defined in IBQs, after subtracting for tail-water returns, was 7.9 ML/ha.
- If the model was over-estimating water use in dry years, this should translate as higher simulated diversions. The general security and supplementary diversion results have been evaluated over the period 2003–04 to 2013–14. This does not indicate a consistent bias in dry years. The only exception is the 2012–13 year, where supplementary diversions are over-estimated.

Figure 14. Border Rivers: theoretical and actual modelled versus ABS

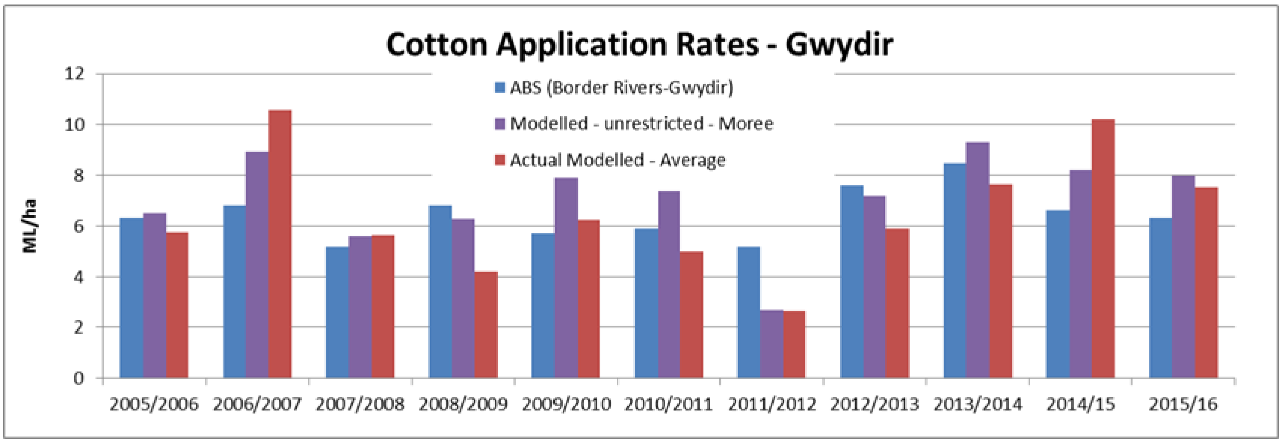


It may be possible in future work to obtain more reliable and detailed water use data for the region using remote sensing estimates of actual evapotranspiration (see next section). However, the accuracy of this method is still being established.

Gwydir

The Gwydir actual modelled application rates are overall very similar to ABS over the 2005–16 period. The ABS average over the 2005–2016 period is 6.45 ML/ha; the Gwydir modelled average[10] over the same period is 6.49 ML/ha. There is some variation between years however (Figure 15).

Figure 15. Gwydir: theoretical and actual modelled versus ABS



Namoi

ABS data for irrigated cotton application rates in the Namoi have been compared from 2010–11 to 2015–16 to the modelled irrigation application rate (Figure 16). The modelled values are for theoretical unrestricted supply based on Narrabri data. Actual modelled rates are not yet available.

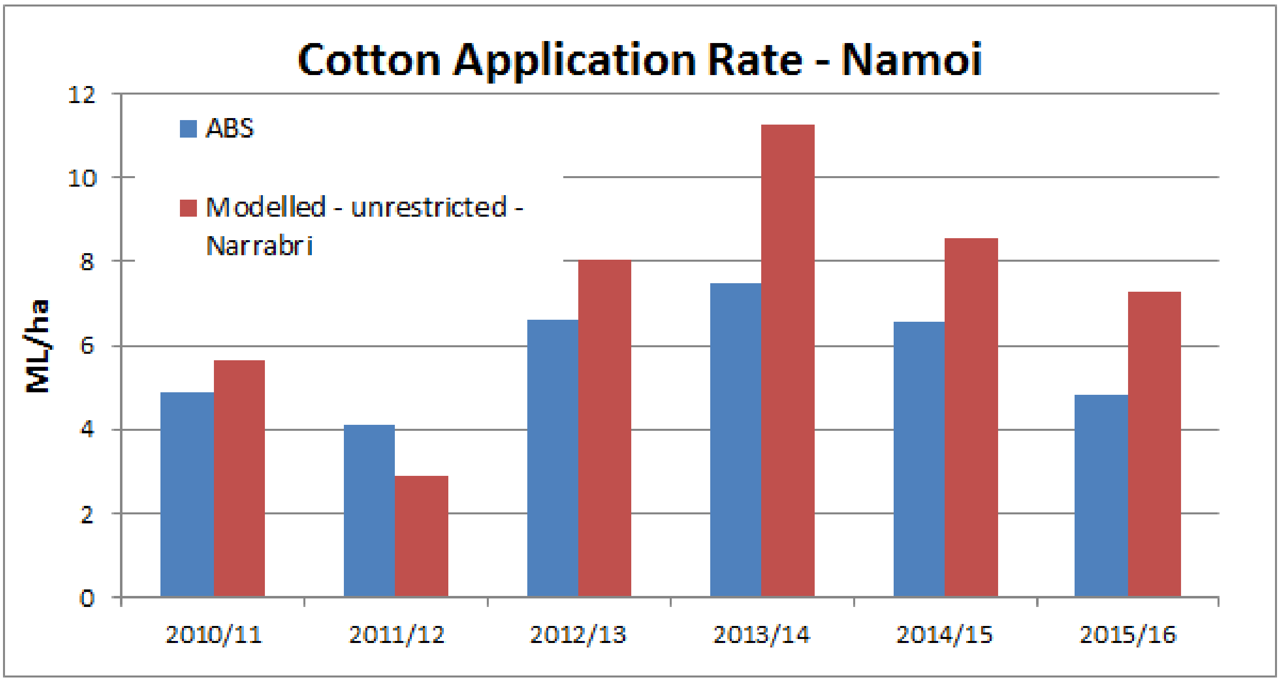
The data compares well in relatively wet years. In dry years, the modelled application rate is much higher than the ABS data. The ABS data indicates that in dry years, there is significant under-

[10] This is average between four medium to large farms each representative of the river reaches in Lower Gwydir, Carole, Mehi and Moomin.

irrigation of cotton. The Irrisat data, described below, also indicates that under-irrigation has occurred in the relevant areas in the Namoi.

The initial model results will be compared on an annual basis to recorded general security and supplementary diversions; if the model over-simulates diversions primarily in the dry years, it will be assumed that this is due to under-irrigation of cotton. In this case, a method to represent the under-irrigation will be established.

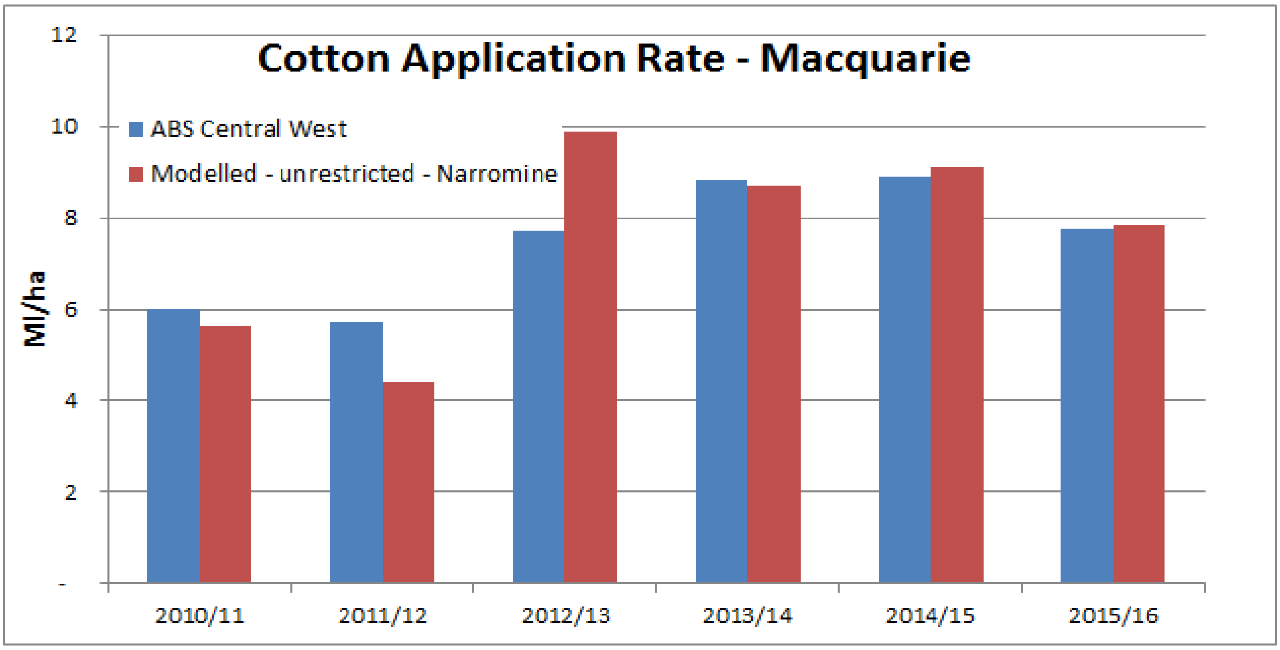
Figure 16. Namoi Irrigation application rates: Modelled versus ABS data



Macquarie

The ABS data for Central West cotton application rate has been compared to that modelled over the 2010–16 period (Figure 17). The modelled irrigation requirement compares well to ABS data; the averages over the period are 7.5 ML/ha (ABS) and 7.6 ML/ha (modelled).

Figure 17. Macquarie application rates



Irrisat

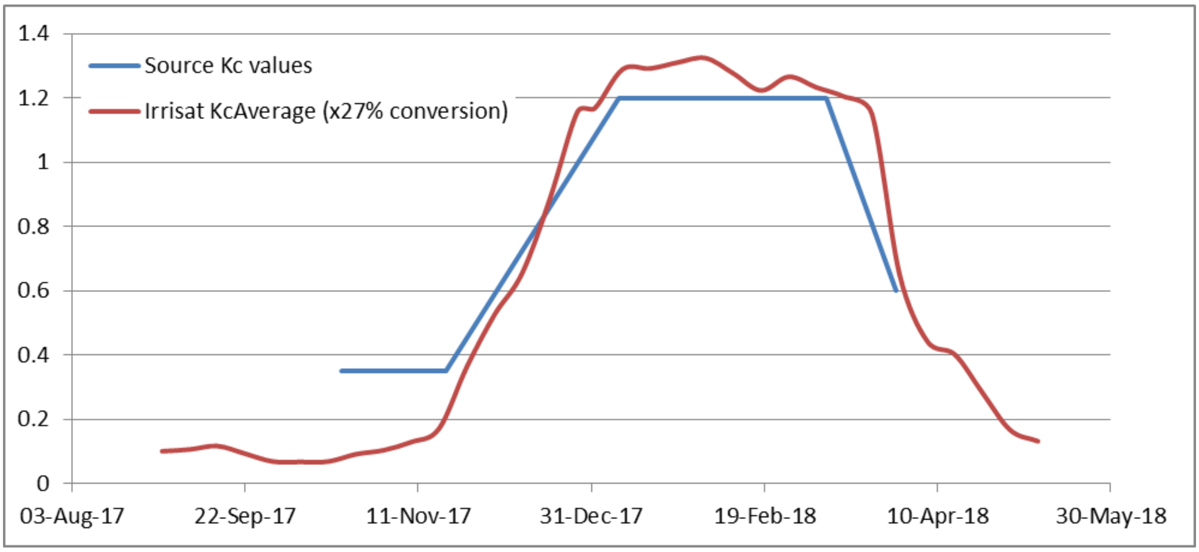
The IrriSAT methodology uses satellite images to determine the Normalized Difference Vegetation Index (NDVI) for each field, from which the plant canopy size can be determined and a specific crop coefficient (K_c) can be estimated. By combining K_c with daily reference Evapotranspiration (ET_0) observations from a nearby weather station, the crop water usage can be determined.

The general method to estimate Kc and crop water use has been published internationally, however verification for the Irrisat method[11] has not been published for Australian cotton. Until the uncertainty in evapotranspiration estimates is established, the Irrisat dataset is only being used by the NSW Department of Industry as a secondary information source.

The Irrisat website[12] publishes estimates of crop factors and actual evapotranspiration. The data can be assessed at paddock scale. Some sample areas have been assessed and compared to modelled data. The Irrisat website only contains downloadable data for one year hence the comparison has only been completed for the 2017–18 year. Kc values estimated by Irrisat, near Goondiwindi, have been compared to parameters assumed in Source[13] (Figure 18).

This analysis indicates that the Kc values used in Source are reasonable. The Kc values used in Source are higher at the start of the season, which is consistent with FAO56 for simulating bare soil. The crop simulation in Source assumes that the crop finishes earlier than Irrisat indicates. This is done in Source to enable the simulation of depletion of soil moisture at the end of the season.

Figure 18. Comparison of Source Crop Coefficients to Irrisat estimate for 2017–18 year (Goondiwindi)



The Irrisat data can be used to determine the variability in NDVI and hence provides an indication of variation in crop water use. For example, in the 2013–14 season, variation in NDVI was examined to determine whether there is significant variation in NDVI values, which would indicate that the cropped areas are not all fully irrigated[14]. For example, NDVI values for Namoi (Figure 19) indicate a large range in NDVI values, which may be indicative of areas of under-irrigation.

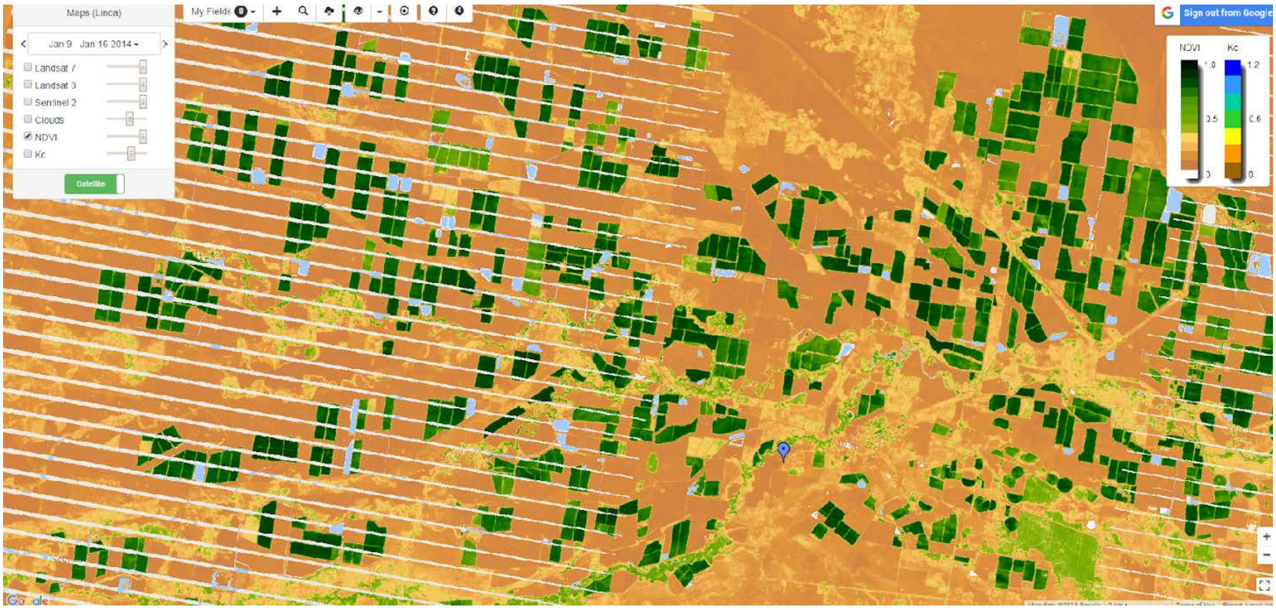
[11] The equation to convert NDVI to Kc is a published method. The method was derived using short crop Penman Monteith however Irrisat uses tall crop Penman Monteith. This change in method may result in an over-estimation of crop evapotranspiration hence further verification of the method is required.

[12] https://irrisat-cloud.appspot.com/#

[13] Irrisat uses a different reference ET hence this needs to be taken into account when comparing crop factors. We use FAO56 ET from SILO. The Irrisat method = ASCE which can also be obtained from SILO. The latter was 27% greater during the summer season. That is, the Kc values from Irrisat need to be scaled up by approximately 27% to be suitable to use in Source for this location.

[14] Assuming that the cropped areas are largely cotton, which is supported by IBQ data.

Figure 19. NDVI values in Namoi mid-January 2014



Rainfall Runoff

The irrigation nodes in the model are also used to model runoff from rain falling on fallow and irrigated areas. Rainfall runoff rates will vary depending on site specific, land and irrigation management practises (e.g. Haghnazari, 2015). While runoff from individual rainfall events may be very high, the long-term average will be much lower.

The river system models were developed to ensure that long-term average runoff was reasonably represented, as defined by the runoff coefficient, which is the proportion of rainfall that is converted to runoff. Studies from the cotton farms in the region were used to inform this, and runoff coefficients from nearby gauged inflows are used to give an indication of the variability in runoff from fallow and undeveloped areas.

For example, Connolly et al. (1998, 1999) (as quoted in Silburn *et al*., 2012) measured 16 mm run-off was for a dryland cotton site on black vertisols in Emerald, Queensland with 600 mm rainfall (2.6% of rainfall), whereas an irrigated field with the same rainfall generated 42 mm of runoff.

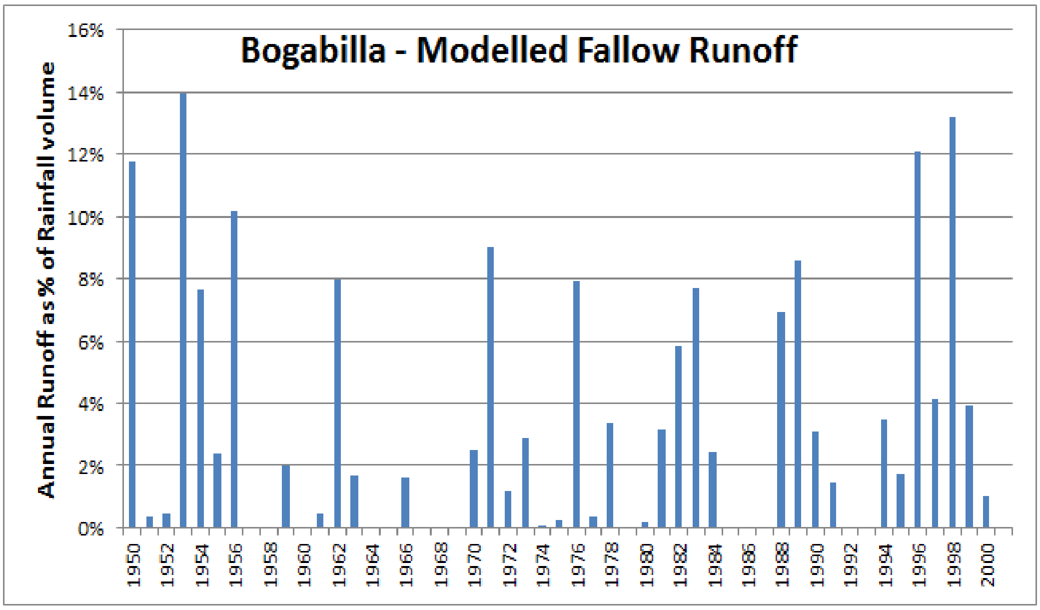
Connolly et al. (2001) found that total runoff under conventional irrigation practice is more than 700% of that under dryland conditions. However, most this is from irrigation excess, and not only runoff from rainfall. Their results indicate for a site near Warren in NSW with 625 mm of rainfall, that rainfall runoff under conventional irrigation is around 8.5% of rainfall, or approximately twice the rainfall runoff from under dryland conditions.

The runoff coefficients for the Gwydir were calculated as a part of the overall demand calibration for individual farms. Consequently, there is significant variability in runoff coefficients between individual properties. The average runoff values from non-developed areas are around 5% of rainfall, similar to that of nearby gauged inflows. The average runoff values from irrigated areas are around 10% of rainfall.

Other papers were also reviewed. However, they either referred to rainfall runoff from upland gauged areas, or use theoretical calculations rather than being informed by field data. Further data collection would be desirable to confirm the assumptions used. It will be important to ensure that any data is based on representative practices.

The coefficient can be very high in individual years. This can be seen in gauged inflow data as well as modelled results (Figure 20). This means that the average obtained over a short-term period, for example through field data collection, is likely to have a different average runoff coefficient compared to a long term average.

Figure 20. Annual variability in fallow rainfall runoff using Boggabilla climate data



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