Review of Harvestable Rights for Coastal Catchments, Modelling Component

Final v11

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Produced by Hydrology and Risk Consulting for New South Wales Department of Planning, Industry and Environment

Contents

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Final v11	27/11/2020	NSW Department of Planning, Industry and Environment	Phillip Jordan	Phillip Jordan	Minor typo fixed on page 34

Executive Summary

Background

Under Section 54 of the *Water Management Act 2000,* the Minister can establish harvestable rights orders to specify conditions around the capture and storage of harvestable rights water such as where dams can be constructed and the maximum harvestable right volume. The harvestable rights order for the Eastern and Central Division of NSW specifies that landholders can build dams that have a volume no greater than a defined estimate of 10% of the average regional runoff, provided that the dams are located only on minor streams, i.e. streams defined as having a Strahler order of 1st or 2nd.

The Farm Dam Policy was formulated to provide a balance between a landholder's reasonable requirement to use water on their property, and limiting impacts on downstream water users and the environment. Under the National Water Initiative farms dams are considered a land use that have the potential to intercept significant volumes, and need to be managed based on their risk to the integrity of water access entitlements and the achievement of environmental objectives.

Purpose of this investigation

The purpose of this project was to investigate how potential changes in harvestable rights policy would modify end of catchment flows for ten case study catchments in the coastal region of New South Wales. The case study catchments are shown in Figure ES- 1.

Spatial Tool for Estimating Dam Impacts (STEDI) Models were established in each of the case study catchments, first to derive the unimpacted streamflow time series, after removing the impact of existing dams on streamflow at the catchment outlet. The models were then run for 40 scenarios in each catchment, by including potential new farm dams that could be constructed under the existing harvestable rights policy and with the harvestable rights policy modified to permit larger dam volumes and/or dams located on up to either 2nd or 3rd order streams.

This report represents the modelling component of the current Department of Planning, Industry and Environment (DPIE) review into its Harvestable Rights policy for coastal catchments. The outcomes of the scenario modelling (of which only some are presented in this report) will be used by DPIE to develop recommendations regarding its Harvestable Rights policy.

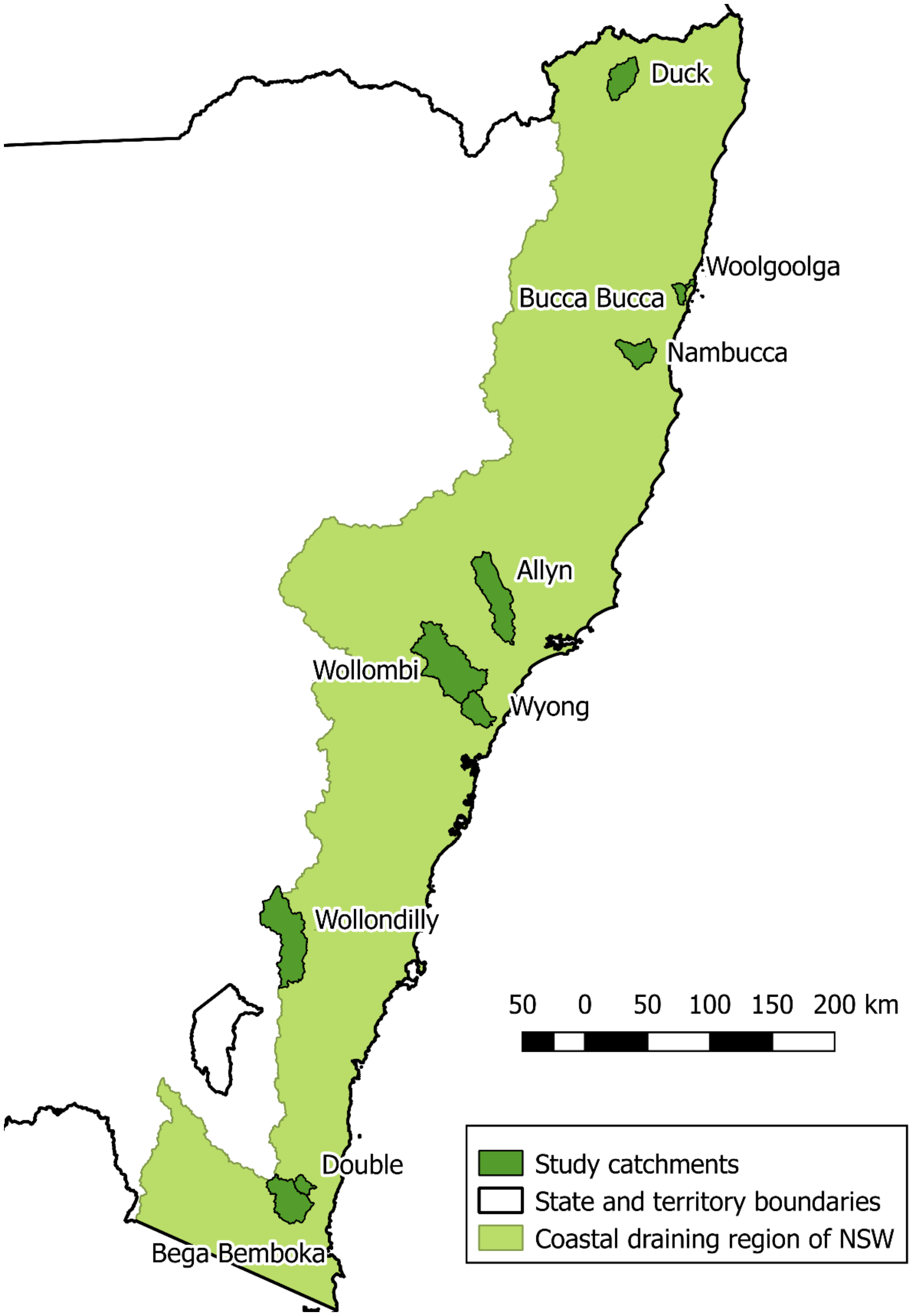


Figure ES- 1 Map of catchments modelled in this study

Method

Modelling of farm dam impacts, under both existing conditions and for the harvestable rights (HR) scenarios, was conducted in the Spatial Tool for Estimation of Dam Impacts (STEDI) model. STEDI is a water balance model. It uses information regarding catchment outflows, dam sizes, demands and climate to simulate individual dams within a catchment. STEDI was used to model:

- The impact of existing levels of dam development on the natural flow regime, and
- The impact of potential future dam development on the current flow regime.

STEDI was run on a daily time step for the 42 year period between 1975 and 2016 inclusive. Gauged flows at a representative streamflow gauge near the most downstream point of the each of the Water Sharing Plan areas were used, when available. The streamflow record was extended to cover the 1975-2016 period, including infilling of missing data, using rainfall runoff modelling and/or regressions with other nearby streamflow gauges.

Existing farm dams within each gauged catchment were identified using the polygon and point layers of water bodies provided by the former NSW Department of Primary Industries (now DPIE). The storage volume of each existing farm dam in the polygon spatial layer was estimated using the equation from Fowler et al. (2016):

$$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.321}}{9600}$$

Equation 1

The surface area of point dams was randomly sampled from a probability distribution, where the distribution was determined by digitising the surface area of 100 randomly selected dams in the point layer of the study area. Volumes of the point dams were then calculated from the randomly assigned surface area, using Equation 1.

A digitial terrain model was derived for defining catchment areas of each dam using the 3 arc-second Shuttle Radar Terrain Mission (SRTM) digital elevation model, with stream enforcement using the Strahler stream layer provided by the former NSW Department of Primary Industries (now DPIE). The Terrain Analysis Using Digital Elevation Models (TauDEM) toolbox from the Hydrologic Research Group of Utah State University (http://hydrology.usu.edu/taudem/taudem5/) was used to define the farm dam catchment areas and connectivity.

Scenarios were considered in this study that would consider relaxation of the HR policy: by increasing the Maximum Harvestable Right Dam Capacity (MHRDC) for each property and/or by permitting dams to be located on 3rd order as well as 1st and 2nd order streams. Scenarios also considered variations in the proportion of land holders that were assumed to utilise their maximum allowable HR. There were 40 scenarios that were modelled in each catchment, as shown in Table ES- 1.

Table ES- 1 Scenarios modelled in each catchment

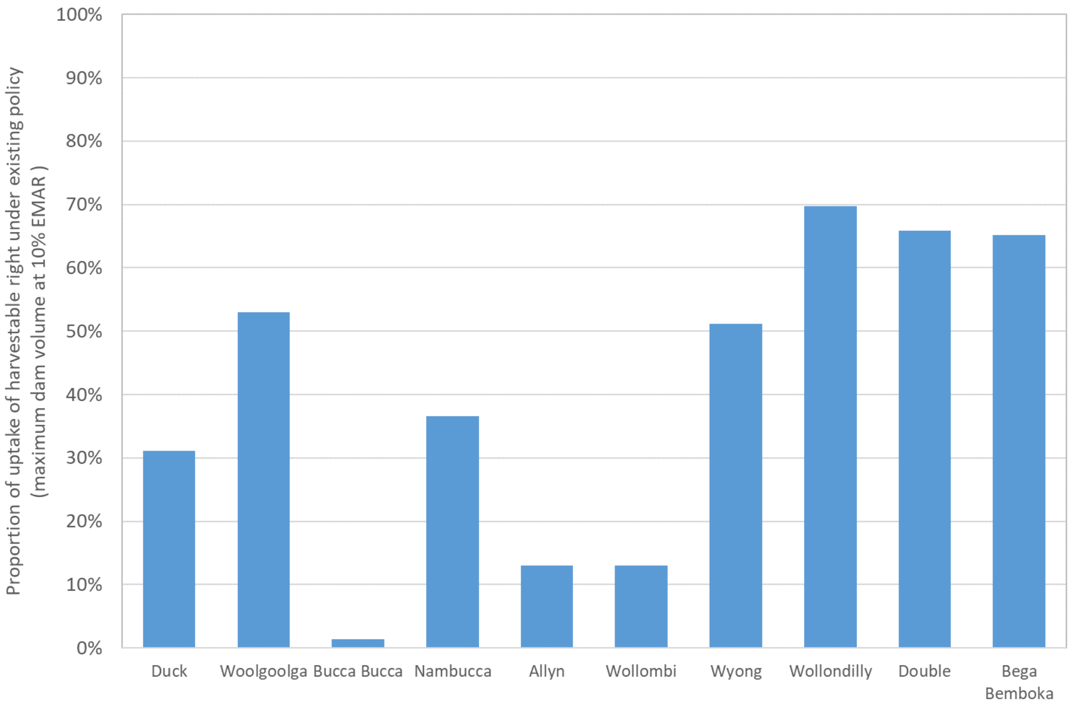
Dams permitted on 2nd and lower order streams (existing policy)				
	Volume of dams as a proportion of estimated mean annual runoff			
Proportion of uptake of allowable harvestable right	10% (Existing policy)	20%	30%	50%
Current (varies between catchments)	✓	✓	✓	✓
25%	✓	✓	✓	✓
50%	✓	✓	✓	✓
75%	✓	✓	✓	✓
100%	✓	✓	✓	✓
Dams permitted on 3rd and lower order streams				
Current (varies between catchments)	✓	✓	✓	✓
25%	✓	✓	✓	✓
50%	✓	✓	✓	✓
75%	✓	✓	✓	✓
100%	✓	✓	✓	✓

Existing farm dams in a catchment may be used for a number of different purposes, including irrigation, stock and domestic water supply and for aesthetic visual amenity. Dams that were less than 5 ML in capacity were assumed to be for stock and domestic purposes, which was consistent with previous surveys of farm dam use. Existing dams larger than 5 ML in capacity were assumed to be for cropping. The crop type and hence irrigation demand pattern was estimated based upon the use in a 200 m radius of each farm dam, as recorded in the Australian Land Use Management Classification (ALUMC), version 8 (ABARES, 2016).

Construction of a farm dam may involve installation of additional infrastructure for irrigation and a conversion from one land use to another, for example dryland grazing to irrigation of tree crops. It was assumed that existing farm dams are meeting the current requirements for stock and domestic use in each catchment. It was assumed that the water usage from new dams would be assigned to higher value uses. The crop types to be assumed for new irrigation dams in each catchment were provided by the Water group of the former NSW Department of Primary Industries (now DPIE), based upon its officers' consultations with officers from the NSW Department of Primary Industries, Agriculture.

Analysis of potential mean annual impact of harvestable rights dams

Figure ES- 2 shows the variation in the current percentage of uptake of the existing HR (set at 10% of estimated mean annual runoff, abbreviated to EMAR) between the ten study catchments. Uptake of HR is currently highest in the Wollindilly (70%), Double (66%) and Bega-Bemboka (65%) catchments. By contrast the current percentage of uptake is lowest in the Bucca Bucca (1%), Allyn and Wollombi (both 13%) catchments.



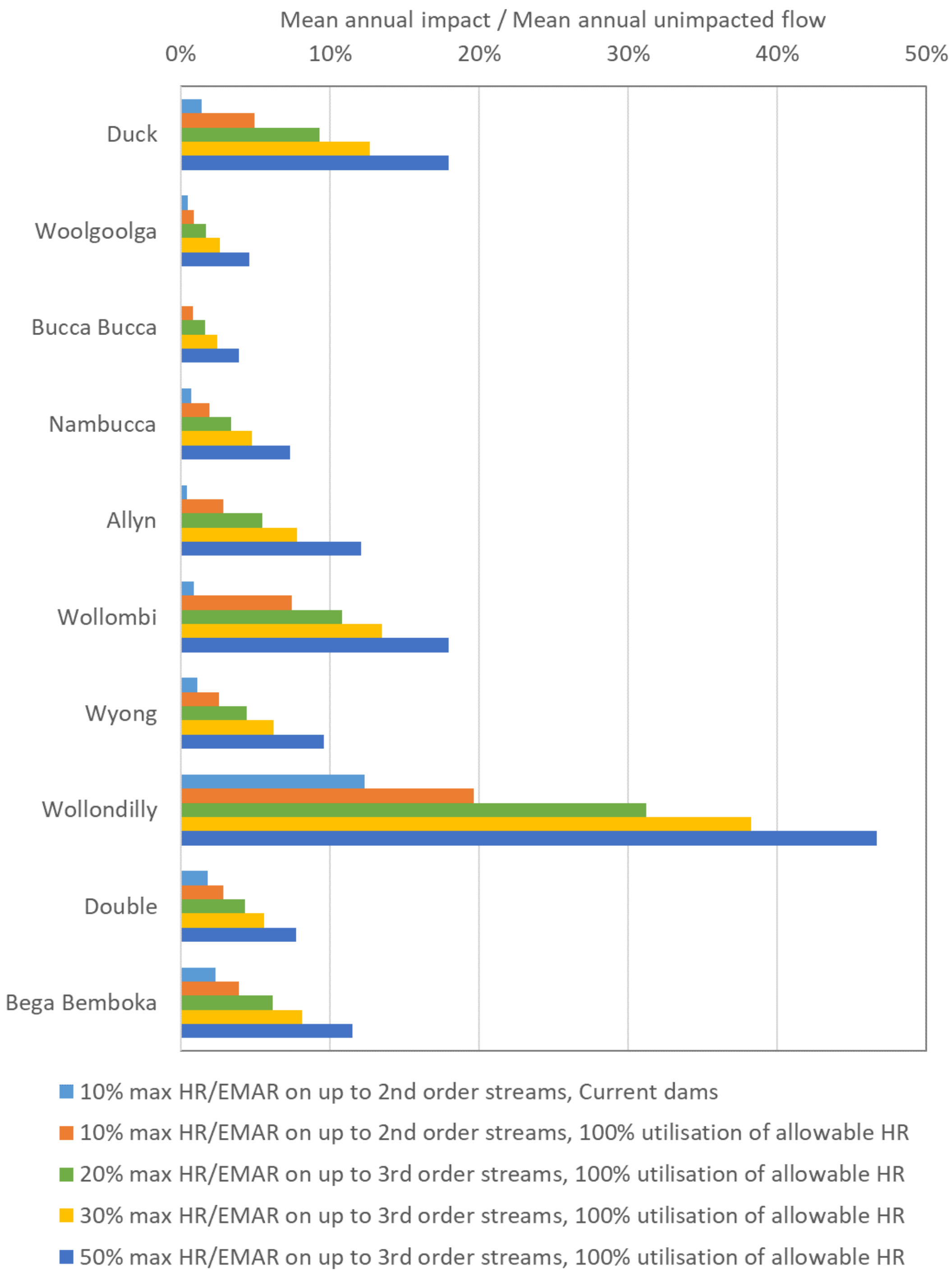
- **Figure ES- 2 Current proportion of uptake of harvestable right under the existing policy of permitting dam storage volumes at 10% of estimated mean annual regional runoff**

Figure ES- 3 shows the mean annual farm dam impact as a proportion of the unimpacted mean annual flow volume, for each of the study catchments and selected scenarios. Existing dams take between 0.01% (Bucca Bucca) and 12.3% (Wollondilly) of the mean annual flow. This would increase to between 0.8% (Bucca Bucca) and 19.6% (Wollondilly) of the mean annual flow if there was 100% utilisation of the existing 10% HR. Lower densities on this upper limit were identified in the catchments with larger proportions of state forest and national park, as it was assumed that there would be minimal development of new dams forested areas.

If the HR policy were to be modified to allow an increase in the HR as a proportion of Estimated Mean Annual Runoff (EMAR) and there was 100% uptake of HR, the mean annual impact as a proportion of mean annual flow would be given by the green, yellow and dark blue bars in Figure ES- 3. The mean annual impacts in the Wollondilly catchment, in particular, could be a very large proportion of the mean annual flow if there was full uptake, with impacts of 31.2% of mean annual flow for the 20% Harvestable Right (HR) / to estimated mean annual runoff (EMAR), 38.3% of mean annual flow for the 30% HR/EMAR and 46.7% of mean annual flow for the 50% HR/EMAR scenarios. For the other catchments, the mean annual impact as a percentage of mean annual flow are lower values. If there was full uptake of the HR and the HR was increased to 50% of EMAR, the mean annual impact would be 18% in the Duck and Wollombi catchments, down to 3.9% in the Bucca Bucca catchment.

For licensed diverters in many catchments, availability of water during dry years may be more critical than the availability of water in years with near-average or above average flows. Figure ES-4 shows the impact, as a proportion of unimpacted mean annual flow, in the driest 10% of years (driest four calendar years modelled) in each of the study catchments. The percentage impacts are much larger in dry years than if all years are considered. Existing HR dams already take 35% of mean annual flow in dry years in the Wollondilly catchment and about 10% of mean annual flow in dry years in the Duck, Double and Bega-Bemboka catchments. If there was to be 100% utilisation of the existing farm dams under the current policy (10% HR/EMAR), the impact of HR dams in dry years would be 50% in Wollondilly and they would exceed 10% of annual flow in dry years in eight of the catchments.

The storage volume of dams is a strong predictor of the mean annual impact in each catchment. The ratio of mean annual impact to volume of dams did not vary much between each of the scenarios in each catchment. On average, the mean annual impact of existing dams was 78% of the existing dam storage volume and this ratio typically only changed by a few percent across the scenarios modelled in each catchment. The variations in ratio between catchments were due to the differences in crop type, and hence demand factor, assumed between catchments, and variations in the characteristics of the stream network changing the typical area upstream of each dam (and hence inflow) relative to the dam storage volume. The relative consistency in the ratio of mean annual impact to storage volume provides the opportunity to regionalise the results from the detailed modelling (undertaken for this report) to other catchments across coastal NSW.



- **Figure ES- 3 Comparison of mean annual impact as a proportion of mean annual flow for all study catchments and for five selected key scenarios, where HR/EMAR stands for Harvestable Right / Estimated Mean Annual Runoff**

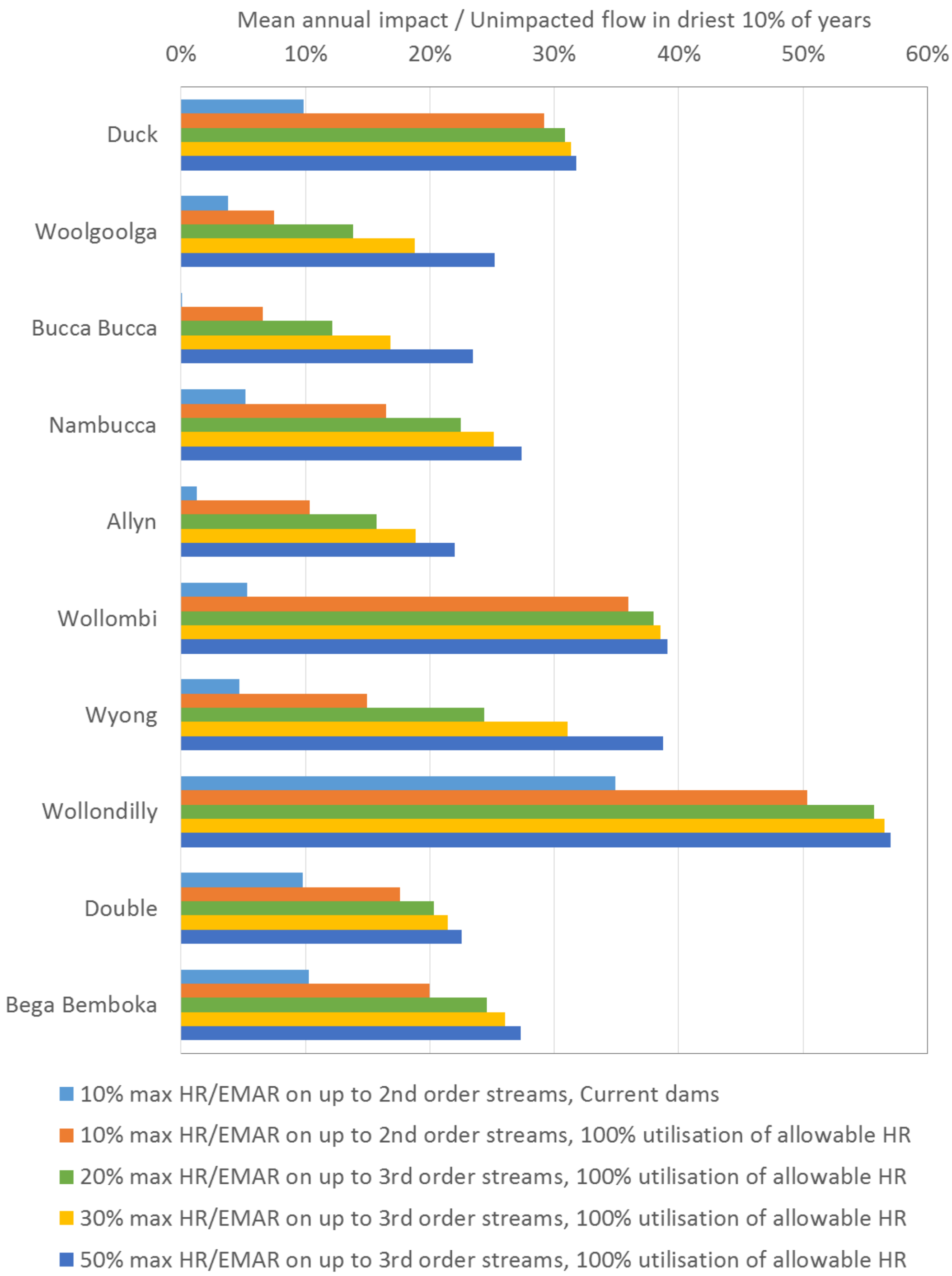


Figure ES- 4 Comparison of mean annual impact as a proportion of mean annual flow in the driest 10% of years for all study catchments and for five selected key scenarios, where HR/EMAR stands for Harvestable Right / Estimated Mean Annual Runoff

Analysis of potential impacts on licensed diversions from streams

Increasing the HR does cause some, usually relatively small, increases in the proportion of days when the flow would be below the cease to pump level (refer to charts in main report). The differences in proportion of days below the cease to pump level between catchments (for existing conditions), were a function of how the cease to pump level had been set in the WSP area planning process. So, for example, unregulated stream diverters in the Wollombi catchment (High Flow licences) would be prevented from diverting on 45.5% of days (when the flow was less than 18 ML/d), compared with very low flow class diverters in the Bega Bemboka catchment that would be prevented from diverting on 2.1% of days (when the flow was less than 2 ML/d). As a result, these frequencies of change to Cease to Pump should not be compared between catchments.

Analysis of potential impacts on environmental water

Impacts on a large variety of environmental flow statistics were calculated in each catchment and for each scenario modelled. The variations between scenarios within each catchment, for most of these statistics, were negligible.

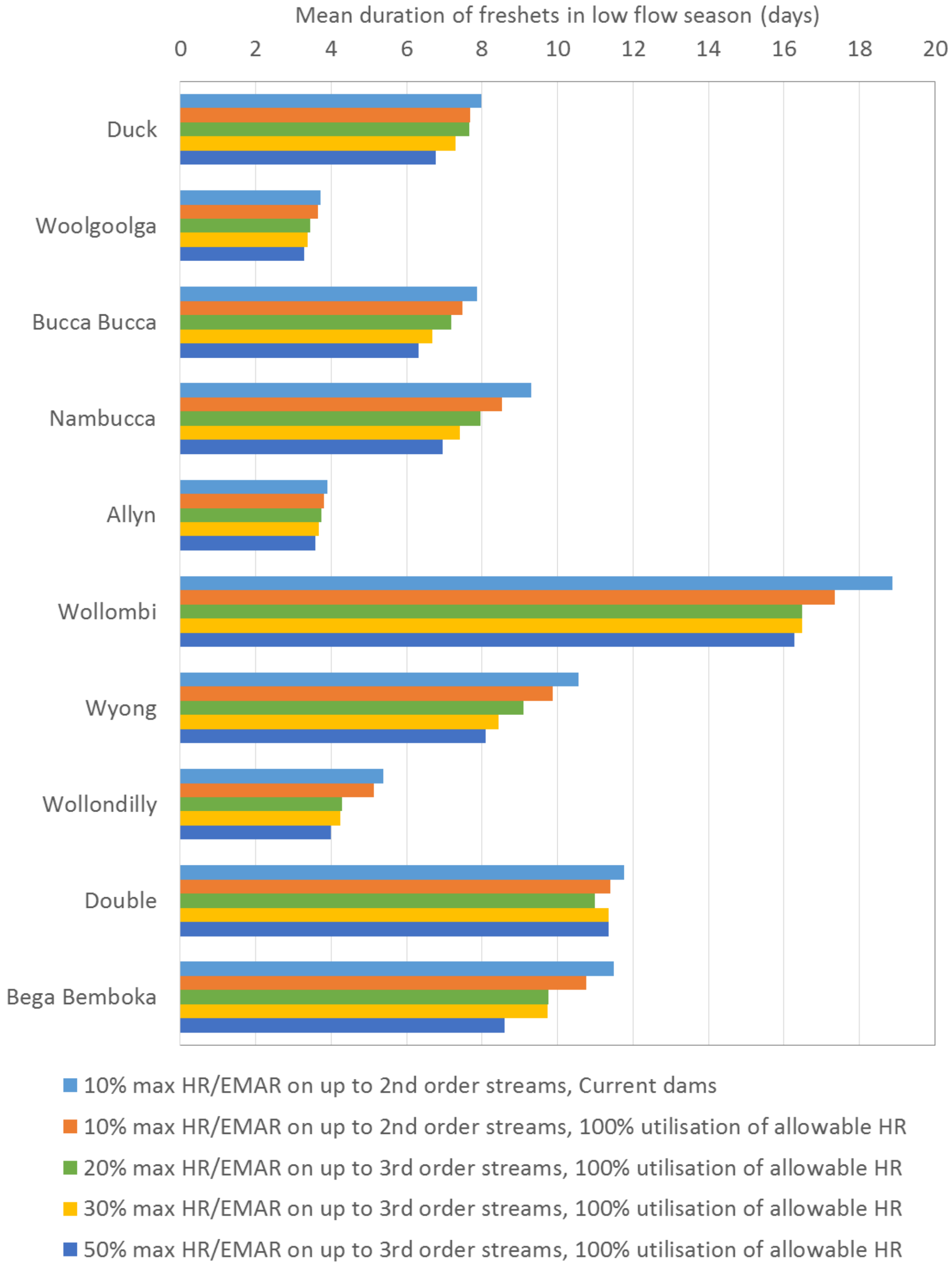
The one aspect of the flow regime where the different scenarios did appear to have an impact was on the mean duration of freshets. Figure ES- 5 shows the mean duration of freshets in the low flow season. The mean duration of freshets reduces as the HR and the uptake of the HR increases, particularly when dams are permitted on 3rd order as well as 2nd order streams. Farm dams are effective at capturing inflows from the first part of freshet events, hence reducing the duration of these regular small floods that remain.

Potential consequence of farm dam failure

Farm dams, including HR dams, may present a risk to people and property that are downstream of them, in the event that they were to fail. Under the Dams Safety Act (1978), dam owners are responsible for the safety of their dam(s) and for meeting the requirements of the NSW Dam Safety Committee.

The consequences of dam failure, in terms of potential loss of life, potential damage to property and potential damage to the environment normally increase with increasing storage volume and height of the dam structure. If HR were to be increased then it is likely that there would be an increasing number of larger farm dams constructed, which could then increase the consequences and risk to people and assets downstream of those dams.

Analysis of the changes in risk presented by potential dam failure, as a result of a change in HR policy, was outside of the scope of this project. It is recommended that analysis of the potential implications for dam safety management be considered as part of further consideration of changes in HR policy.



- **Figure ES- 5 Comparison of mean duration of freshets in the low flow season for all study catchments and for five selected key scenarios**

1. Introduction

1.1 Background

A NSW Farm Dam Policy was established in 1999 to allow landholders to build farm dams up to a certain size based on their property size and location. This policy was brought into the legislative framework as a form of basic landholder right under section 53 of the Water Management Act 2000. This 'harvestable right' gives andholders the right to capture water without the need for any access licence, water supply work approval or water use approval.

Under Section 54 of the *Water Management Act 2000,* the Minister can establish harvestable rights (HR) orders to specify conditions around the capture and storage of HR water, such as where dams can be constructed and the maximum HR volume. The HR order for the Eastern and Central Division of NSW specifies that landholders can build dams that can capture a volume no greater than a defined estimate of 10% of the average regional rain water runoff, provided that the dams are located only on hillsides or minor streams, i.e. streams defined as having a Strahler order of 1st or 2nd. The HR limit is implemented as a total dam capacity known as the Maximum Harvestable Right Dam Capacity (MHRDC). The MHRDC is calculated by multiplying a landholder's property size by the value for that property specified in the MHRDC Multiplier maps, publicly available from https://www.waternsw.com.au/customer-service/water-licensing/basic-landholder-rights/harvestable-rights-dams/maximum-harvestable-right-calculator.

The Farm Dam Policy was formulated to provide a balance between a landholder's reasonable requirement to use water on their property, and limiting impacts on downstream water users and the environment. Under the National Water Initiative (paragraphs 55-57) farms dams are considered a land use that have the potential to intercept significant volumes, and need to be managed based on their risk to the integrity of water access entitlements and the achievement of environmental objectives.

1.2 Purpose of this investigation

Concerns have been expressed by landholders on the coast that the current HR order is overly restrictive given high water availability from higher average rainfall relative to inland areas. The restrictions on locating a dam only on 1st and 2nd order streams or hillsides (zero-order streams) may impact coastal catchments unequally compared to inland catchments, with a lower rainfall, and hence lower drainage density. Higher drainage density means that properties in coastal catchments may be able to construct farm dams on 3rd order streams with downstream impacts that are proportionally less than in inland catchments. Regional economies in coastal NSW may benefit from having a less restrictive policy.

The purpose of this project was to investigate how potential changes in HR policy would modify end of catchment flows for ten case study catchments in the coastal region of New South Wales. The case study catchments are shown in Figure 1-1.

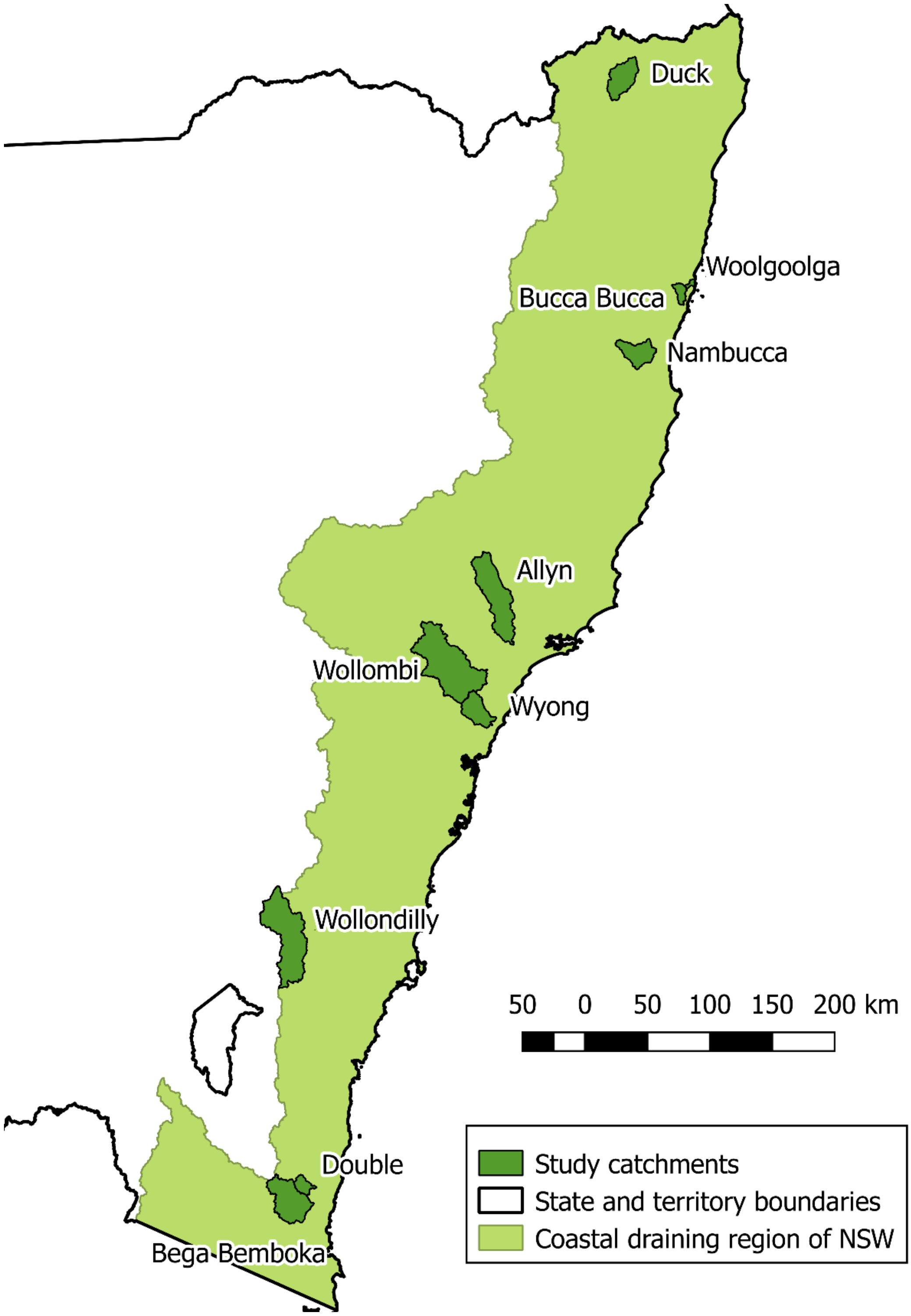


Figure 1-1 Map of catchments modelled in this study

Models were established in each of the case study catchments, first to derive the unimpacted streamflow time series, by removing the impact of existing dams on streamflow at the catchment outlet. The models were then run for 40 scenarios in each catchment, by including potential new farm dams that could be constructed under the existing HR policy and with the HR policy modified to permit larger dam volumes and/or dams located on up to either 2nd or 3rd order streams.

Modelling of farm dam impacts, under both existing conditions and for the HR scenarios, was conducted in the Spatial Tool for Estimation of Dam Impacts (STEDI).

This report represents the modelling component of the current DPIE review into its HR policy for coastal catchments. The outcomes of the scenario modelling (of which only some are presented in this report) will be used by DPIE to develop recommendations regarding its HR policy.

1.3 This report

In this report:

- Section 2 describes the method applied;
- Section 3 discusses the approach to assembly of gauged streamflow, rainfall and potential evaporation data, infilling of missing data and selection of a common climatic period for modelling;
- Section 4 explains the application of the STEDI models;
- Section 5 discusses the results from the STEDI modelling, for existing dams and for the scenarios; and
- Section 6 discusses limitations of the work and provides recommendations on further investigations.

2. Method

2.1 Estimating volume of existing farm dams

2.1.1 Farm dam characteristics

Existing farm dams within each gauged catchment were identified using the polygon and point layers of water bodies provided by the former NSW Department of Primary Industries (now DPIE). Quality control filters were applied to remove large regulated dams, natural lakes, billabongs, river channels and other water bodies that were not likely to be HR dams.

These were then intersected with the each of the study area catchments to locate the farm dams that were included in the STEDI models.

2.1.2 Surface area to volume relationships

GIS data sets identify the location and surface area of farm dam water bodies. For hydrological modelling purposes, the volumes of existing dams were estimated from their surface area. In the scenario modelling of potential future impacts, the surface areas of farm dams were estimated from the storage volume of the dam for the scenario.

There have been several Australian studies conducted over the last couple of decades that have estimated farm dam storage volumes from surface areas. These studies have normally drawn upon a data set of dams with measured surface area and volume, determined either from field survey or LIDAR data collected when the dams were empty or near-empty. A regression relationship (normally a power-law) was then fitted in each study to the available data set. Table 2-1 lists the equations that have been derived from previous studies. None of the previous studies had collected data in coastal NSW catchments, with a focus generally on the Murray Darling Basin (MDB).

Table 2-1 Relationships between surface area and storage volume for farm dams, extracted from Australian studies

Reference	Equation	Comment
Fowler et al. (2016)	$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.321}}{9600}$	Derived from a sample of 365 dams from seven LIDAR data sets and 42 field surveyed dams (total 407 dams) in Victoria. Adopted for Victorian baseline farm dam study in 11 catchments (HARC, 2017).
Lowe et al. (2005)	$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.314}}{6900}$	Derived from a sample of 152 field surveyed dams in Victoria. Fowler et al. (2011) also plotted this relationship against 106 dams in the Murrumbidgee catchment and found it to be suitable for application.
Srikanthan and Neil (1989)	$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.25}}{5348}$	Derived from a sample of dams in the Yass River catchment, NSW
Wiesenfeld et al. (2012)	$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.238}}{5263}$	Derived from a sample of 73 LIDAR surveyed dams in Queensland
Agrecon (2005)	$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.1147}}{1169}$	Derived from a sample of 5832 dams across the MDB, although the DEM used appears to have been relatively low resolution SRTM
McMurray (2004) [Low irrigation use]	$V = \begin{cases} \frac{SA^{1.25}}{5000} for\ SA < 15000m^2 \\ \frac{SA}{454} for\ SA \geq 15000m^2 \end{cases}$	Derived from a sample of dams in the Mount Lofty and Clare regions of South Australia, for dams in the overall data set that were deemed to have low irrigation usage.
McMurray (2004) [High irrigation use]	$V = \begin{cases} \frac{SA^{1.26}}{4651} for\ SA < 20000m^2 \\ \frac{SA}{357} for\ SA \geq 20000m^2 \end{cases}$	Derived from a sample of dams in the Mount Lofty and Clare regions of South Australia, for dams in the overall data set that were deemed to have high irrigation usage.
Gan (1988)	$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.00}}{233}$	Australia waide survey of larger dams (37 to 10,000 ML) volumes. Uses an older data set and for small dams in particular appears to overestimate volumes. Linear relationship also appears to be unrealistic, as it results in a constant depth of 4.3 m for all dams.
Department of Water (2007)	$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.071}}{1430}$	Derived for a sample of dams in South West Western Australia
Good and McMurray (1997)	$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.4}}{22727}$	Derived for a sample of dams in the Mount Lofty Ranges of South Australia

There was reasonable consistency between several of the fitted equations from the more recent and reliable studies, particularly when they are plotted on a log-log scale, as in Figure 2-1.

There were more apparent differences between the equations when plotted on a linear scale, as in Figure 2-2. Selection of an equation near the top of these plots (for example Agrecon, 2005 or Lowe et al., 2005) would produce a larger estimate of the total volume of existing dams in each catchment and hence a larger degree of estimated farm dam impact from existing dams. By contrast, selection of an equation near the bottom of these plots (for example Wiesenfeld, 2012) would produce a smaller estimate of the total volume of dams in each catchment and hence a smaller degree of estimated farm dam impact from existing dams. The converse of these statements would be true for the HR scenario modelling, where the volume of each farm dam would be set in response to the property area and the surface area derived for estimating hydrological impact. However, the selection of surface area-volume equation would have relatively minor impact on the scenarios for future policies and uptake of HR, as the equation selected would ultimately only modify net difference between direct rainfall and direct evaporation from the reservoir surface areas, which are typically about one quarter of the overall water balance.

For this study, the surface area-volume relationship that was recently adopted for farm dam modelling in eleven catchments in Victoria was adopted (Fowler et al., 2016), since it uses the largest relevant data set and fits in the middle of most of the distributions, as follows:

$$Volume\ (ML) = \frac{Surface\ area\ (m^2)^{1.321}}{9600}$$

Equation 2

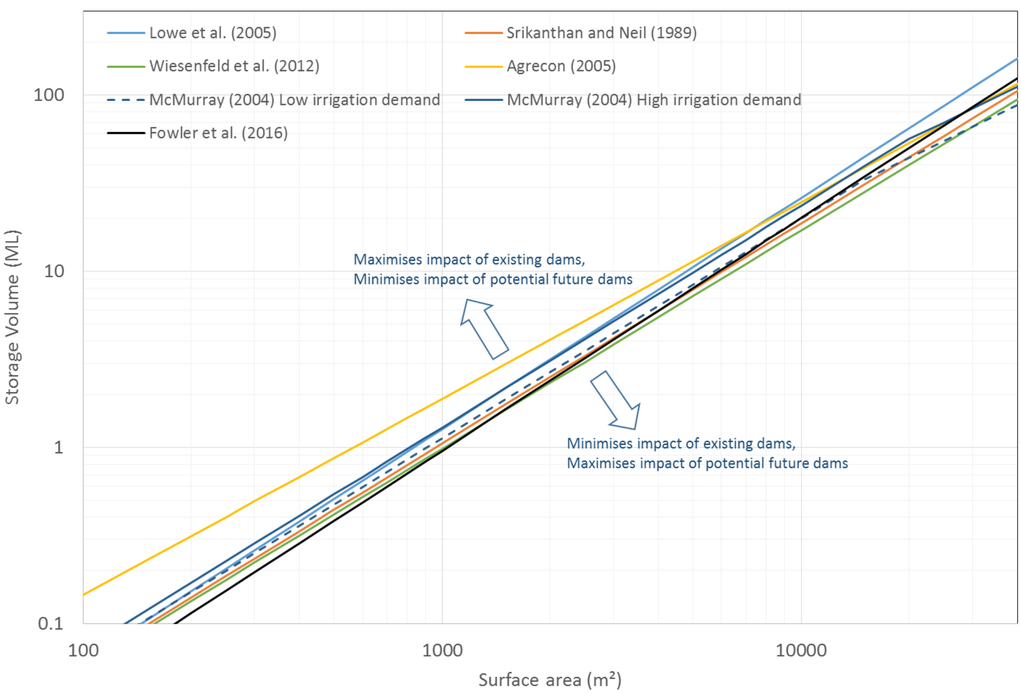
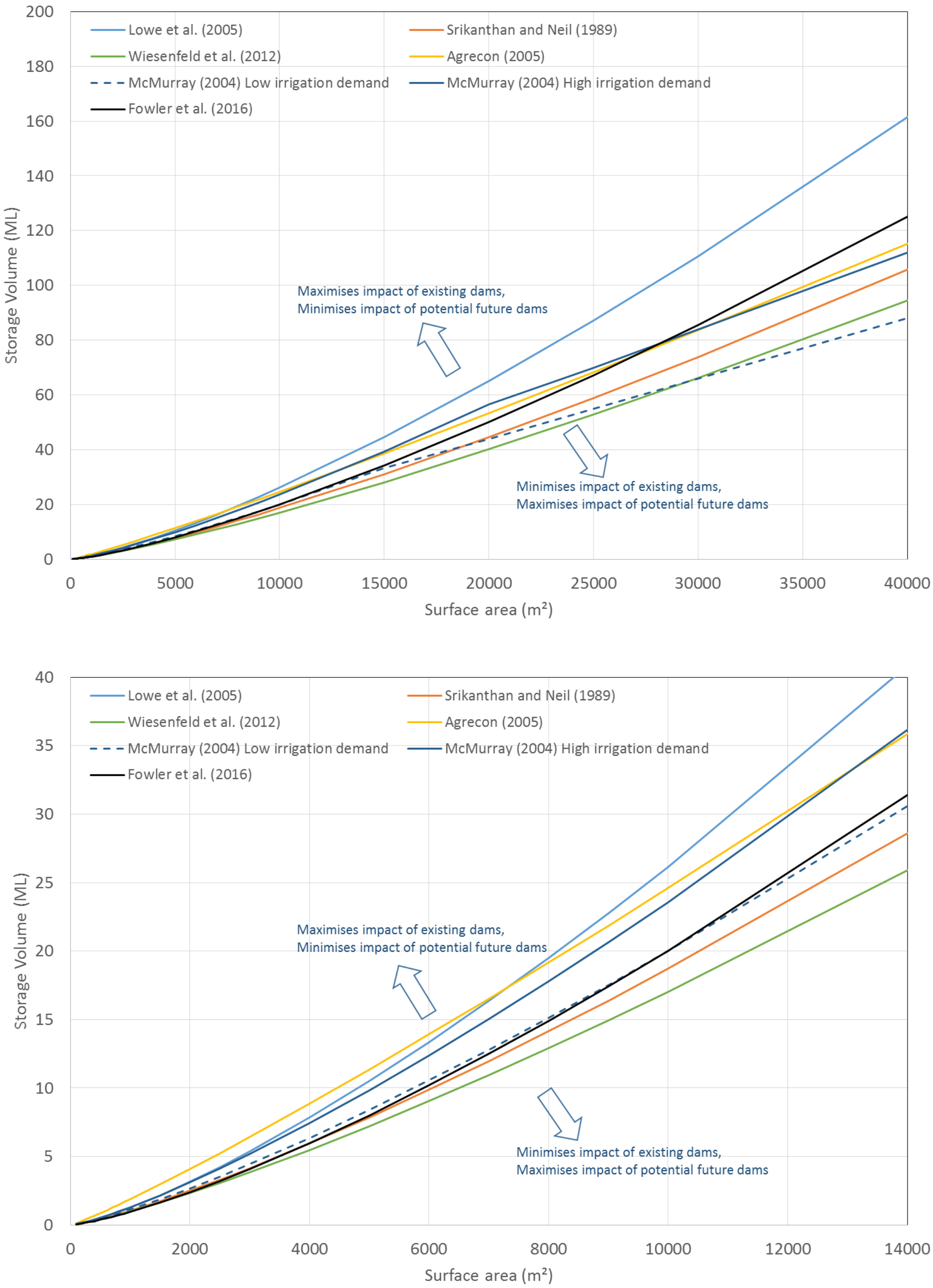


Figure 2-1 Comparison of surface area-volume relationships for farm dams from previous studies, shown on log-log scale



- **Figure 2-2 Comparison of surface area-volume relationships for farm dams from previous studies, shown on linear scale. The top panel shows the whole relevant range (to 200 ML volume), while the bottom panel concentrates on smaller dams (to 40 ML)**

2.1.3 Distribution of volumes for point dams

Spatial data on water bodies in NSW is comprised of two data sets: polygon features and point features. The water bodies captured as polygons are typically larger (in area) than the features captured as points. The storage volume of each polygon farm dam may be estimated from its surface area, using the equation discussed in Section 2.1.2. However, the same approach can not be taken with point farm dams, as their surface area is not identified in the spatial data.

Lowe et al. (2005), when faced with the same issue in Victoria, calculated a probability distribution for point farm dam features from a sample of point dams. This probability distribution has then been randomly sampled to assign a notional storage volume to each of the point dams for modelling purposes in Victoria (R. Morden, pers. comm.; HARC, 2017).

A sample of 100 point dams was randomly selected from among the ten catchments from Eastern NSW in this study. For these 100 sample dams, the surface area of each dam was digitised from Google and Bing imagery. The surface area was computed for each of the 100 digitised dams and the storage volume for each was estimated using Equation 1. A log-normal distribution (with mean of natural logarithm of volumes of -1.6226 and standard deviation of natural logarithm of volumes of 1.3137) was found to provide a good fit to the storage volumes of the 100 sampled dams, as shown in Figure 2-3. It was assumed that the largest feasible value of a point farm dam was 5 ML, as the largest of the 100 dams in the sample had an estimated volume of 4.4 ML.

It can be noted from Figure 2-3 that 90% of the point farm dams have a volume less than 1 ML. The mean volume is 0.44 ML. The dams volumes estimated for point dams in the NSW data are lower than the distribution identified by Lowe et al. (2005) from Victorian data, which was most likely due to differences in the mapping approach that had been applied between the NSW and Victorian spatial data sets. In other words, the NSW data was more likely to capture dams that were greater than about 1000 m^2 (or 1 ML estimated volume) as polygons rather than points, whereas this threshold was probably larger in the Victorian spatial data.

Notional storage volumes were randomly assigned to each of the point farm dams by randomly sampling from the log-normal distribution that was fitted to the sample of NSW data.

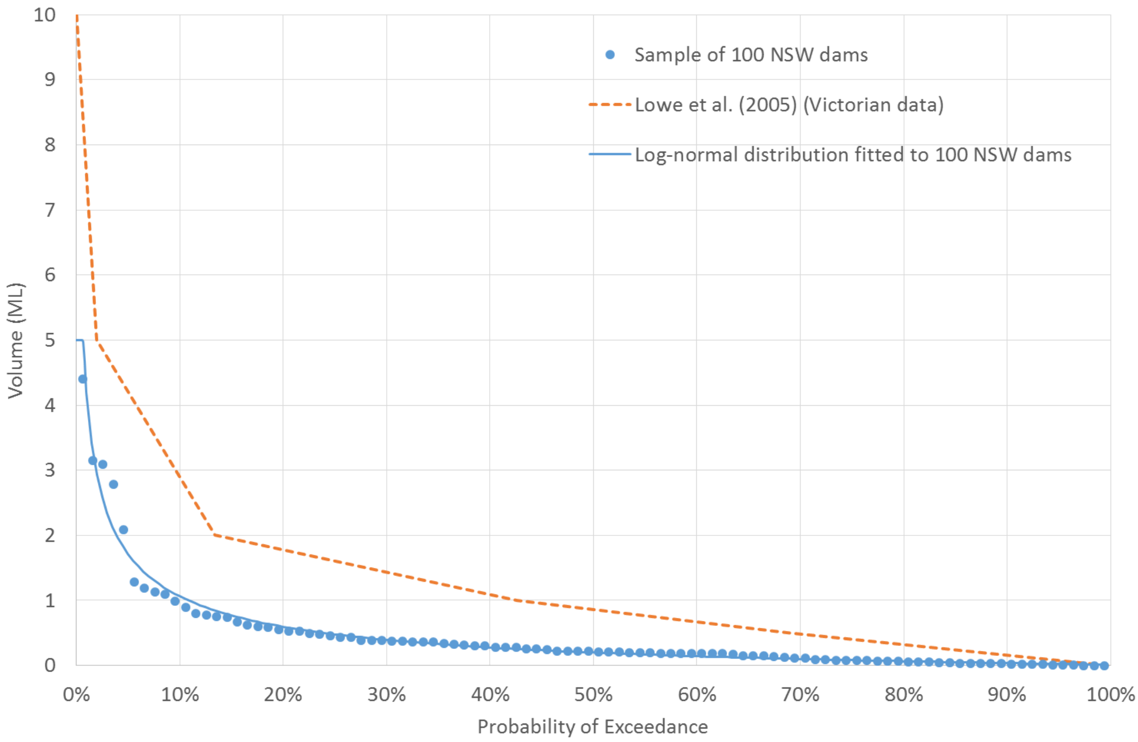


Figure 2-3 Probability distribution of storage volumes fitted to a sample of 100 point farm dam features in the study catchments

2.2 Scenarios for new harvestable rights dams

This study considered scenarios that would relax the HR policy: by increasing the MHRDC for each property and/or by permitting dams to be located on 3rd order as well as 1st and 2nd order streams. Scenarios also considered variations in the proportion of land holders that were assumed to utilise their maximum allowable HR. There were 40 scenarios that were modelled in each catchment, as shown in Table 2-2.

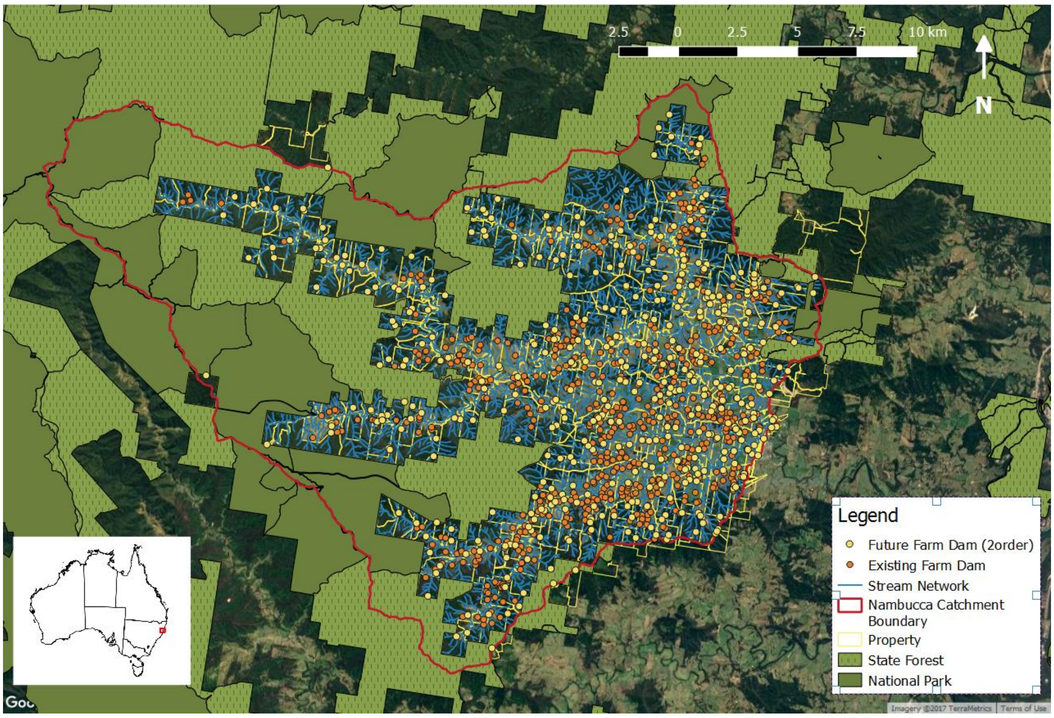
Table 2-2 Scenarios modelled in each catchment

Dams permitted on 2nd and lower order streams (existing policy)				
	Volume of dams as a proportion of estimated mean annual runoff			
Proportion of uptake of allowable harvestable right	10% (Existing policy)	20%	30%	50%
Current (varies between catchments)	✓	✓	✓	✓
25%	✓	✓	✓	✓
50%	✓	✓	✓	✓
75%	✓	✓	✓	✓
100%	✓	✓	✓	✓
Dams permitted on 3rd and lower order streams				
Current (varies between catchments)	✓	✓	✓	✓
25%	✓	✓	✓	✓
50%	✓	✓	✓	✓
75%	✓	✓	✓	✓
100%	✓	✓	✓	✓

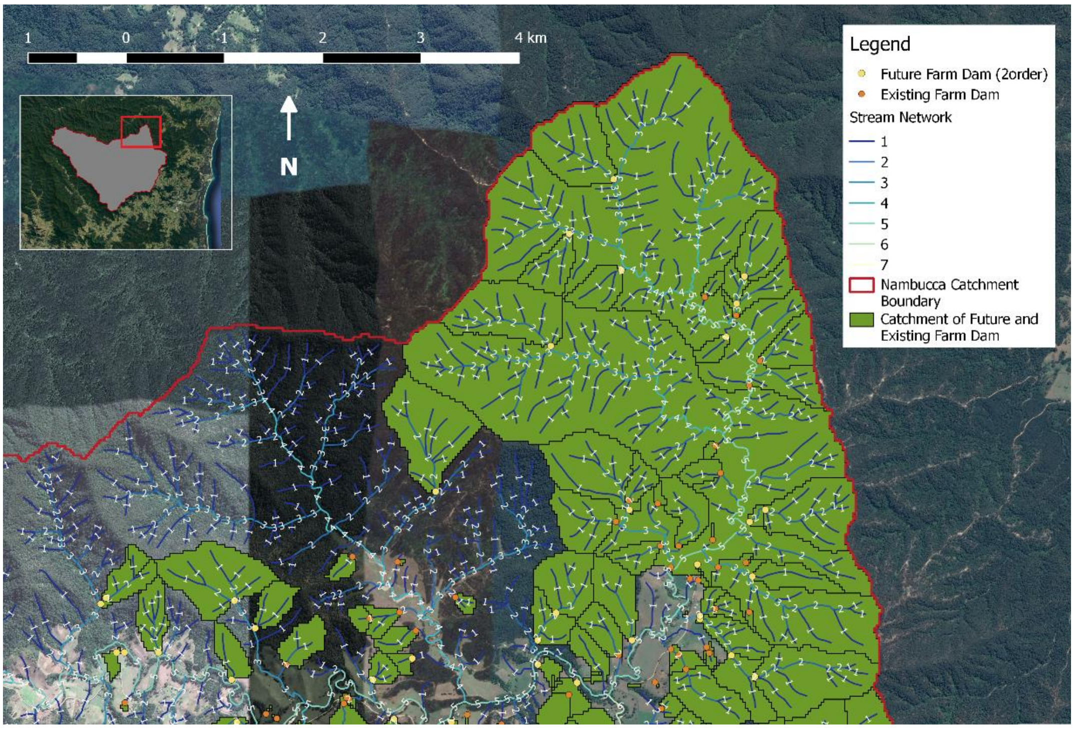
In all scenarios, the following assumptions were made about the volume and placement of HR dams:

- HR dams would not be added on land that is currently national park or state forest (see Figure 2-4);
- HR dams would not be added on land that were road reserves;
- harvestbale rights dams would not be added where the size of new or increased dams on a property was less than 1 ML;
- existing dams would remain in their existing locations, as identified in the GIS data layers; and
- new dams would be placed at the location of highest flow accumulation on the property, where that location was located on a 2rd order or lower / 3th order or lower stream (see Figure 2-5).

A flow chart that maps out the process that was applied is shown in Figure 2-6.



▪ **Figure 2-4 Farm dam locations avoiding state forest and national parks in Nambucca catchment**



▪ **Figure 2-5 Stream network order and chosen farm dam location in on 2 order and under in Nambucca catchment**

To model the proportion of uptake of HR dams, the positioning of dams for the 100% uptake scenarios were first modelled. Dams were then eliminated at random from the 100% uptake scenarios, to achieve uptakes of 25%, 50% and 75% of HR. Dams were also eliminated at random to achieve the same proportion of uptake as the existing uptake of HR (set at 10% of EMAR) in the catchment.

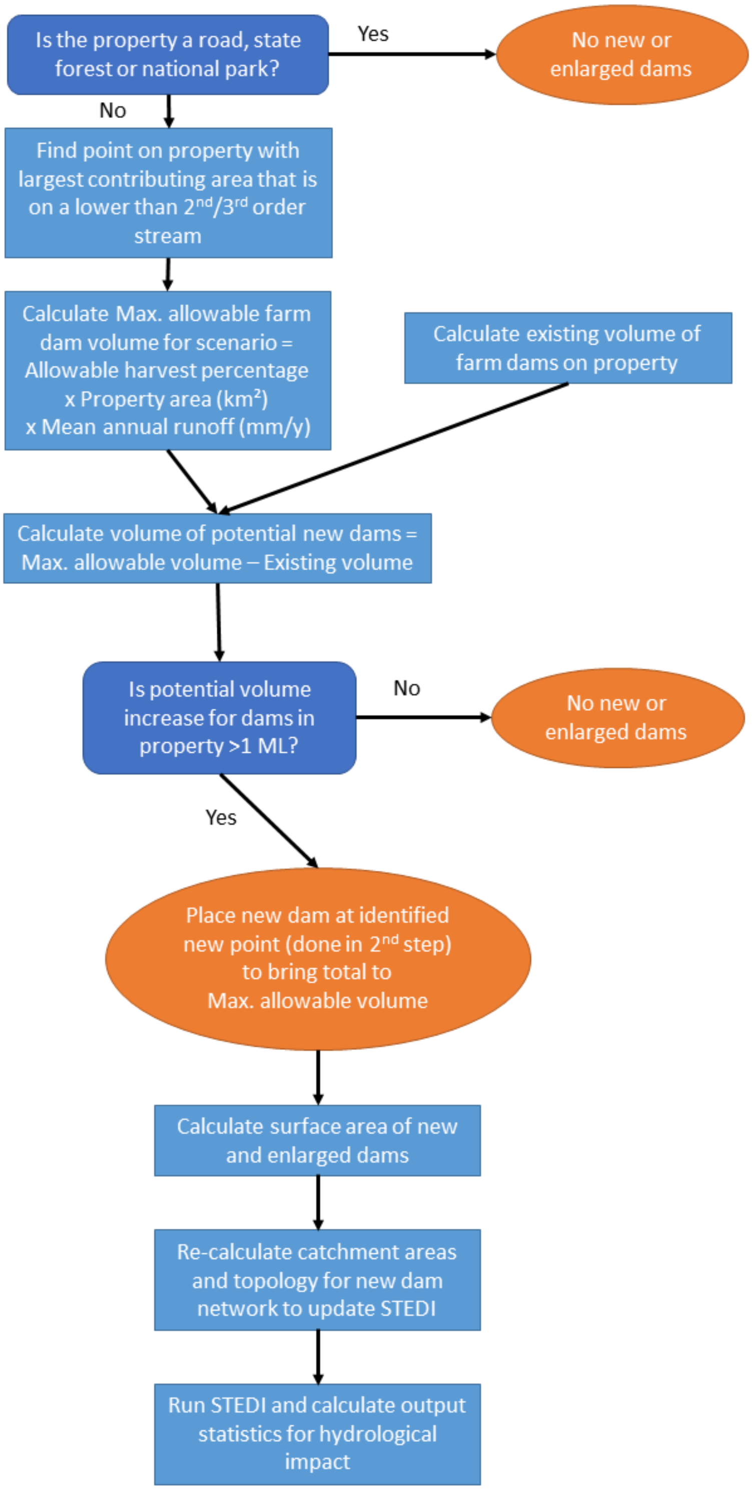
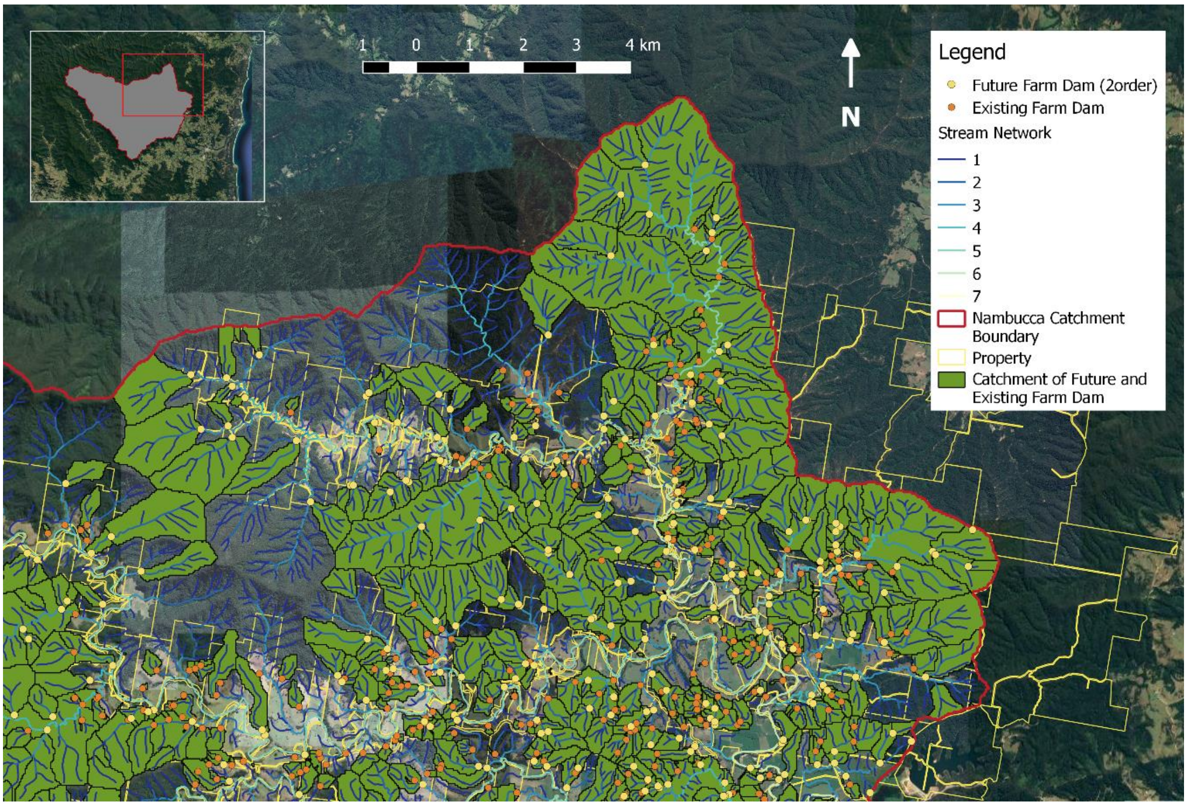


Figure 2-6: Flow chart for calculation of allowable volume and placement of farm dams for the harvestable rights scenarios

2.3 Catchment areas and connectivity of farm dams to the stream network

A digitial terrain model was derived for defining catchment areas of each dam using the 3 arc-second Shuttle Radar Terrain Mission (SRTM) digital elevation model, with stream enforcement using the Strahler stream layer provided by the former NSW Department of Primary Industries (now DPIE). The Terrain Analysis Using Digital Elevation Models (TauDEM) toolbox from the Hydrologic Research Group of Utah State University (http://hydrology.usu.edu/taudem/taudem5/) was used to define the farm dam catchment areas and connectivity. An example of farm dam network connectivity is shown in Figure 2-7.



- **Figure 2-7 Network connectivity of existing farm dams and future possible farm dams allowed up to 2nd order stream order in Nambucca catchment**

2.4 Modelling impacts on streamflow using STEDI

The following description of STEDI is taken from the user manual (SKM, 2011):

STEDI is a water balance model. It uses information regarding catchment outflows, dam sizes, demands and climate to simulate individual dams within a catchment. STEDI can be used to model:

- The impact of existing levels of dam development on the natural flow regime, and
- The impact of potential future dam development on the current flow regime

STEDI can run at a daily, weekly or monthly time-step, and if needed represent:

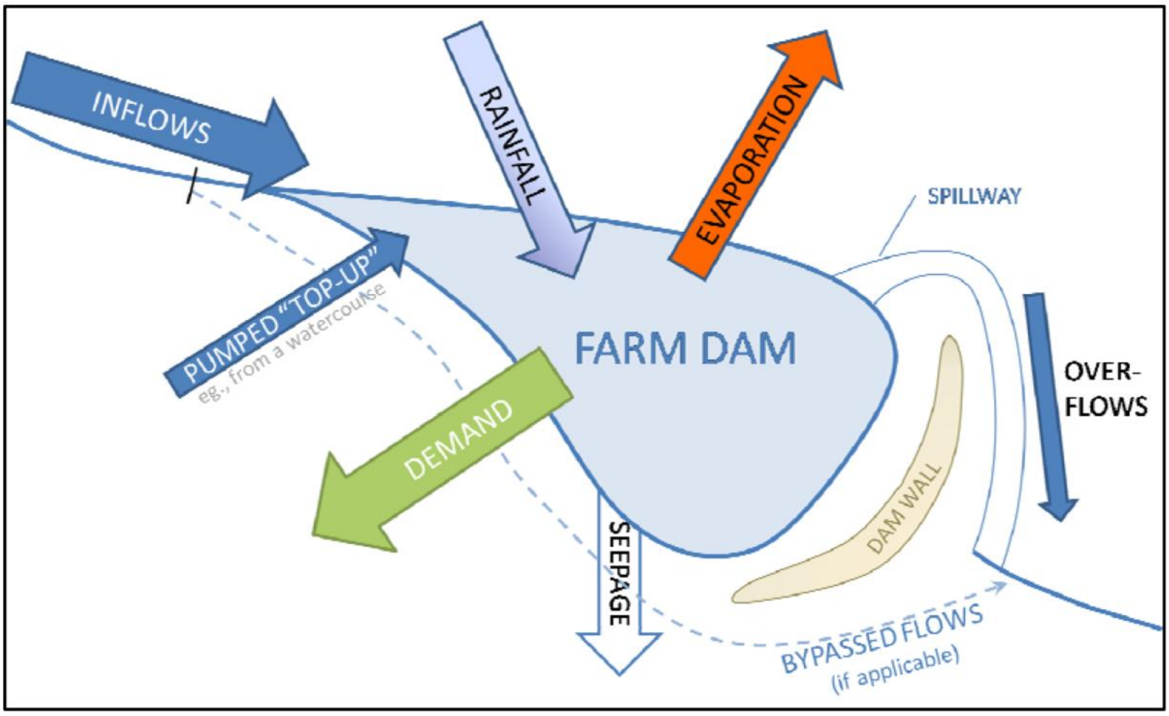
- Low flow bypasses around dams
- Dams that are topped up by pumping (e.g. from a local watercourse)
- Variations in demand from dam to dam and time-step to time-step
- The effect of flow routing from one dam to another through the stream network

For this project, the first two features were not required, but the latter two were implemented. The models were run on a daily time-step.

More detail on STEDI is available in the user manual (SKM, 2011). For additional background information, refer to the papers by Nathan et al. (2005) and Lowe et al. (2005).

It should be noted that there are some fixed limits on the maximum number of some of the inputs to STEDI, which are set by the current version of STEDI (SKM, 2011). These limits are:

- The maximum number of farm dams that can be modelled in any catchment is 9,999; and
- The maximum number of demand types is 6.



- **Figure 2-8: Simplified water balance for a farm dam. Source: SKM, 2011**

2.5 Demands

2.5.1 Demands on existing dams

Existing farm dams in a catchment may be used for a number of different purposes, including irrigation, stock and domestic water supply and for aesthetic visual amenity. Dams used for irrigation may be used to provide water for a variety of different crop types.

Land use in the area surrounding existing farm dams was used as an indicator of the potential use of water from the farm dams in the catchment. The most common land use in a 200 m radius of each farm dam was extracted from the Australian Land Use Management Classification (ALUMC), version 8 (ABARES, 2016).

The following report used Nambucca as a representative example of the ten catchments to demonstrate adopted analysis process and results interpretation in this project. Other catchments follow the same procedure.

Figure 2-9 shows that the overwhelming majority (92%) of the 633 existing farm dams in the Nambucca catchment were surrounded by a native or exotic pasture mosaic. Of dams that were surrounded by land uses that are likely to be irrigated, 9 of the 633 existing farm dams were in areas identified as grazing irrigated modified pastures, and 1 of the 633 dams was identified as being in a fruit tree area. It is possible that the ALUMC data is not ble to distinguish areas of irrigated pasture from areas that are not irrigated, particularly for areas that may only be irrigated for short periods of time. It is therefore likely that the native/exotic pasture mosaic land use includes some pasture that is irrigated from farm dams, and non-irrigated areas where the farm dams are used for stock and domestic purposes.

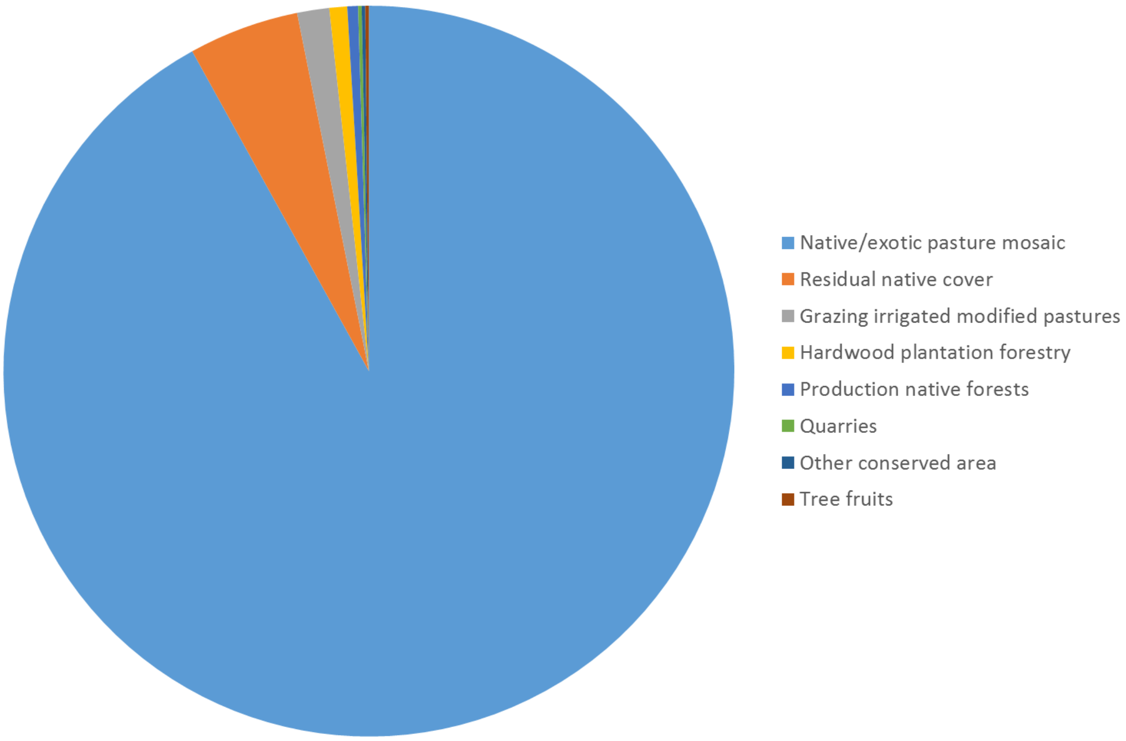


Figure 2-9 Most common land use found in a 200 m radius around each of the 633 existing farm dams in the Nambucca study catchment

Lowe et al. (2005) found that farm dams with smaller storage volumes were more likely to be used for stock and domestic purposes, whilst larger farm dams were more likely to be used for irrigation. Lowe at al. (2005) identified that 5 ML was a typical threshold between stock and domestic and irrigation dams. Applying the 5 ML threshold, 91% of the dams in the Nambucca catchment are assumed to be stock and domestic dams and the remaining 9% (57 dams) are assumed to be irrigation dams. Based upon the analysis of the ALUMC data, 9 of the 633 dams were surrounded mainly by irrigated pasture, with only 1 of the 633 dams surrounded mainly by fruit tree. Further analysis of the ALUMC data revealed that 11 of the dams in the Nambucca catchment had any area identified as fruit tree. It was therefore possible that about 11 of the existing dams in the catchment were being used to irrigate fruit tree, which would represent about 20% of the 57 dams that were greater than 5 ML in storage volume.

Fowler et al. (2016) summarises the literature on demand factors for farm dams expressed as a proportion of volume. Surveys by Fowler et al. (2012), Wiesenfeld et al. (2012) and Lowe et al. (2005) found mean demand factors for stock and domestic dams of 0.35, 0.48 and 0.50 respectively. Considerable variability was identified in the demand factor between stock and domestic dams in each of these studies, with the standard deviation in the demand factor ranging between 0.25 and 0.32. For stock and domestic dams, an annual demand equal to 0.5 of the farm dam volume was adopted in this project. The stock and domestic demand was assumed to be uniformly distributed throughout the year and uniformly between years.

The inter-annual variation in irrigation demand was estimated for the Nambucca catchment by calculating time-series of demand, for a nominal area of 1 ha using IQQM's crop model, for four different irrigated crop types: dairy pasture, blueberries, bananas and macadamias. The probability distribution of annual water demand was computed for each potential crop type, based upon an irrigation water year commencing in May and ending in April. Irrigators' decisions about the area of crop to irrigate and the size of their farm dam will be influenced by several factors. However, if we considered a hypothetical simplification, whereby the farm dam was assumed to be full at the start of the irrigation season (May), there were no inflows through the year and no net loss of evaporation from the dam surface area, then the volume of water used from the farm dam would be influenced only by annual variations in crop demand. If the farm dam was selected so that it could irrigate 1 ha of crop with 80% annual reliability, then size of the dam would be given by the second row of Table 2-3. In an average year, the demand used from the dam would be given by the first row of Table 2-3. For this hypothetical dam, the mean annual demand divided by the volume of the dam (sized to supply at 80% annual reliability) represents the demand factor, shown in the third row of Table 2-3. These notional demand factors range between 0.72 for macadamias and 0.84 for blueberries. The demand factors computed for this hypothetical example compare well with the median demand factor for irrigation dams of 0.83 found by Lowe et al. (2005) from surveys of farmers.

For permanent plantings, such as blueberries, bananas and macadamias, it would be reasonable to assume a higher level of reliability. Referring to the fourth and fifth rows of of Table 2-3, the demand factor for 95% annual reliability was estimated to be 0.54 for macadamias and 0.75 for blueberries in the Nambucca catchment.

Table 2-3: Estimation of irrigation demand factors for four crop types in the Nambucca catchment, computed from IQQM crop modelling

Statistic	Dairy pasture	Blueberries	Bananas	Macadamias
Mean annual demand per hectare	9.44	10.04	15.02	4.58
80th percentile of annual demand per hectare	11.59	11.99	18.72	6.34
Mean demand / 80th percentile demand	0.81	0.84	0.80	0.72
95th percentile of annual demand per hectare	13.32	13.30	19.88	8.43
Mean demand / 95th percentile demand	0.71	0.75	0.76	0.54

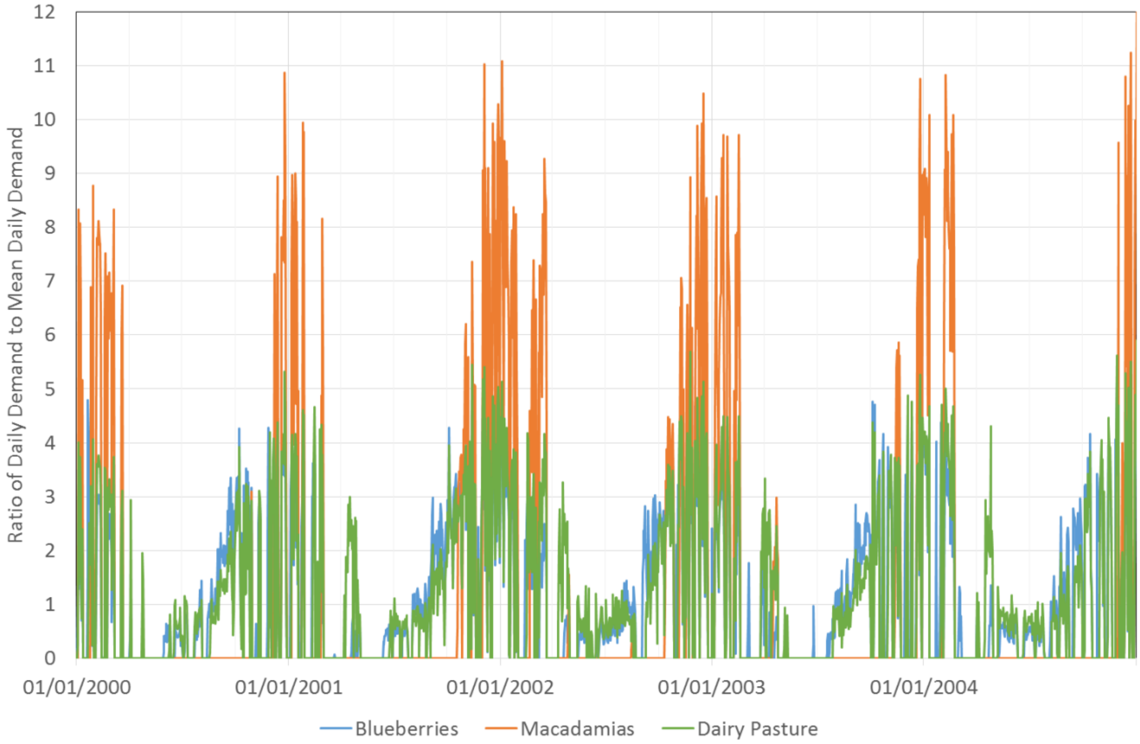
Table 2-4 summarises the assumptions that were made about demand factors and patterns for existing farm dams in the Nambucca catchment. As discussed above, all dams less than 5 ML in storage volume were assumed to be stock and domestic dams, having a demand factor of 0.5 and a uniform demand pattern. Dams greater than 5 ML were assumed to be irrigation dams, with 80% of these dams for pasture irrigation and the remaining 20% for permanent horticulture. A demand factor of 0.81 was assumed for the dairy pasture dams, based upon the analysis in Table 2-3 (for

80% reliability) and because it was relatively close to the value previously adopted by Lowe et al. (2005). A lower demand factor of 0.54 was adopted for the permanent horticulture dams, based upon an assumed 95% reliability (see Table 2-3). The demand temporal pattern for permanent horticulture was assumed to be Macadamias, as this would be relatively similar to other tree crops in the region, such as pecans, bananas and avocados.

Figure 2-10 shows a selected period of the temporal patterns that were applied to the demands for irrigated dairy pasture and irrigated permanent horticulture (macadamian nuts). Modelled water demands for macadamias demonstrate more variability than those for pasture and blueberries, both within years and between years.

Table 2-4: Demands adopted for existing farm dams in the Nambucca catchment

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	576	0.5	Uniform
Irrigation: pasture	80% of dams > 5 ML in volume	47	0.81	Daily pattern from IQQM crop model for dairy pasture
Irrigation: permanent horticulture	20% of dams > 5 ML in volume	11	0.54	Daily pattern from IQQM crop model for Macadamias



- **Figure 2-10 Temporal patterns of daily demand for blueberries, pecans and dairy pasture in the Nambucca catchment, derived from IQQM crop modelling**

Demand factors for future potential farm dams in other nine catchments were calculated and these are shown in Appendix A.

2.5.2 Demands on potential future harvestable rights dams

Construction of a farm dam may involve installation of additional infrastructure for irrigation and a conversion from one land use to another, for example dryland grazing to irrigation of tree crops. The existing land use in a catchment was not necessarily, therefore, a valid indicator of the demand factor or demand pattern that would be used by future farm dams that may be installed under the HR policy.

It was assumed that existing farm dams are meeting the current requirements for stock and domestic use in the catchment. It was therefore assumed that all new farm dams, installed under the HR policy, would be for irrigation. It was also assumed that the water usage from new dams would be assigned to higher value uses: irrigated dairy pasture, blueberries or permanent horticulture. Based upon discussions with NSW Department of Primary Industries Agriculture officers, it was assumed that the split in irrigation usage from new HR farm dams in Nambucca catchment would be 50% for irrigated pasture, 25% for irrigated blueberries and 25% irrigated permanent horticulture (represented by macadamias). This split and the adopted demand factors is given in Table 2-5.

Demand factors for future potential farm dams in other nine catchments were calculated and these are shown in Appendix B.

- **Table 2-5: Demands adopted for existing and potential future farm dams in the Nambucca catchment for harvestable rights scenarios**

Dam type	Method of selection	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	80% of existing dams in catchment that are > 5 ML in volume, PLUS 50% of new HR dams greater than 5 ML in volume (selected at random)	0.81	Daily pattern from IQQM crop model for dairy pasture
Irrigation: permanent horticulture	20% of existing dams in catchment that are > 5 ML in volume PLUS 25% of new HR dams greater than 5 ML in volume (selected at random)	0.54	Daily pattern from IQQM crop model for macadamias
Irrigation: blueberries	25% of new HR dams greater than 5 ML in volume (selected at random)	0.75	Daily pattern from IQQM crop model for blueberries

2.6 Statistical assessment of impact of farm dams

An increase in the volume of HR dams from the existing level will increase the impact of the dams on instream flows in the catchment. This may impact:

- The capacity of licensed diverters to access flows from the stream in the volume and frequency that they require, without additional restriction; and
- Water available to support the in-stream and riparian environment.

Impacts upon flows were only assessed at one location in each catchment, at the end of system of the designated WSP area.

2.6.1 Statistics for assessment of impact on direct diverters from streams

Water sharing rules are defined in each of the water source areas considered in this project. The water sharing rules define one or more cease to pump level at a reference flow gauge. When flows at the gauge fall below the defined cease to pump level(s), one or more classes of direct diversion from streams must cease.

WSP rules and the rules summary sheets may use a reference flow gauge that is the same one that was used for STEDI modelling in the relevant catchment for this study. For these catchments, the cease to pump rules at the flow gauge used for STEDI modelling were applied to directly estimate the potential impact on stream diversions. However, in several of the catchments modelled in this study, the WSP rules referred to different gauge(s) within the catchment to the gauge used for STEDI modelling or they may specify that pumping must cease when there is “no visible flow” at the pump site (or similar rules). The cease to pump levels that were applied to assess the duration and occurrence of potential cease to pump conditions, for this study, are summarised in Table 2-6. Appendix C details the cease to pump rules expressed in the rule summary sheets for each catchment, with Table C- 1 summarising cease to pump rules where the gauge was used for the STEDI modelling and Table C- 2 summarising cease to pump rules for catchments where was not possible to make a direct comparison between the STEDI model outputs and the specified conditions.

- **Table 2-6 Cease to pump level assigned to assess the occurrence of very low flows in modelling catchments**

Catchment	Approach	Reference flow location	Class of diverters	Cease to pump flow rate (ML/d)
Duck	0.01 mm/d x catchment area as indicator of low flow	Outlet of Duck Creek WSP area	Unregulated river access	5
Woolgoolga	0.01 mm/d x catchment area as indicator of low flow	Tidal limit on Woolgoolga Creek	Very low flow class	0.15
Bucca Bucca	0.01 mm/d x catchment area as indicator of low flow	Outlet of Bucca Bucca Creek WSP area	Unregulated river access	1
Nambucca	North Arm Nambucca River and Missabotti Creek WSP area plan	205006, Nambucca River at Bowraville as a proxy for 205015, Nambucca River North Arm upstream of Bowraville	Very low flow class	5
Allyn	0.01 mm/d x catchment area as indicator of low flow	Allyn at Flying Fox Lane	Very low flow class	12
Wollombi	0.01 mm/d x catchment area as indicator of low flow	210004, Wollombi Brook at Warkworth	Unregulated	18
Wyong	Wyong River WSP area plan	Combined flows at 211009, Wyong River at Gracemere gauge and 211010, Jilliby Jilliby Creek at upstream of Wyong River (Durren Lane) gauge.[1]	Very low flow class	4
			A class	13.5
			B class	26
Wollondilly	Upper Wollondilly River WSP area plan	2122711, Wollondilly River at Murrays Flat	Very low flow class	2
Double	Lower Bega / Lower Brogo Rivers tributaries WSP area plan	219017, Double Creek near Brogo	Very low flow class	2
	Upper Bega / Bemboka Rivers tributaries WSP area plan	219017, Double Creek near Brogo	Very low flow class	2
Upper Bega / Bemboka	Upper Bega / Bemboka Rivers WSP area plan	219032, Bega River at Kanoona	Very low flow class	2
			Low flow class	5
			A class	65
			B class	160

[1] Note that the reference point may change during the term of the plan to the Wyong River Weir, if appropriate.

2.6.2 Statistics for assessment of impact on flows for the environment

The geomorphological and biological responses in a stream and riparian zone are influenced by the flow regime in the river. The ecological health of a river is likely to be dependent on a range of different components of the flow regime, including maintenance of minimum passing flows, the frequency, duration and magnitude of freshets and frequency, duration and magnitude of small to moderate sized flood flows. These requirements may vary seasonally.

Ecological flow requirements may vary considerably between different rivers and catchments. However, for this study, no detailed ecological investigations were undertaken to assess the relative impacts of the HR scenarios on water available for the environment. Instead for this project, the former NSW Department of Primary Industries (now DPIE) provided a spreadsheet that specified the following indicators, as proxy measures of changes in ecological health between different flow scenarios:

- Mean daily flow exceeded on 80% of days in the low flow season (defined as the contiguous five months of the year that have the lowest total median flow volume);
- Mean daily flow exceeded on 80% of days in the high flow season (defined as the contiguous five months of the year that have the highest total median flow volume);
- Freshets in the low flow season (defined as events where flow exceeded the flow recorded on 20% of days in the low flow season, under existing conditions):
  - Proportion of years in the comparison period (1975-2016) when freshets occurred;
  - Mean number of freshets per low flow season;
  - Mean duration of freshets;
- Freshets in the high flow season (defined as events where flow exceeded the flow recorded on 20% of days in the high flow season, under existing conditions):
  - Proportion of years in the comparison period (1975-2016) when freshets occurred;
  - Mean number of freshets per high flow season;
  - Mean duration of freshets;
- Mean daily flow with an average recurrence interval (ARI) of 1.5 years, estimated from a partial series analysis;
- Mean daily flow with an ARI of 2.5 years, estimated from a partial series analysis; and
- Mean daily flow with an ARI of 5 years, estimated from a partial series analysis.

Low and high flow seasons were derived from analysis of the daily unimpacted flow time series in each catchment, for 1975-2016. Table 2-7 shows the high and low flow seasons by catchment. Most of the catchments north of Sydney have high flow seasons in either spring/summer or summer/autumn. Double Creek also has a high flow season over summer. Wollondilly and Bega Bemboka have high flow seasons in winter/spring (Wollondilly) and autumn/winter (Bega Bemboka).

Table 2-7 High and low flow seasons by catchment

Catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Duck	High		Low	Low	Low	Low	Low		High	High	High	High
Woolgoolga		High	High	High	High	High		Low	Low	Low	Low	Low
Bucca Bucca		High	High	High	High	High		Low	Low	Low	Low	Low
Nambucca	High	High	High	High	High		Low	Low	Low	Low	Low	
Allyn	High		Low	Low	Low	Low	Low		High	High	High	High
Wollombi	High	High	High	High	High		Low	Low	Low	Low	Low	
Wyong		High	High	High	High	High		Low	Low	Low	Low	Low
Wollondilly	Low	Low	Low	Low	Low		High	High	High	High	High	
Double	High	High	High		Low	Low	Low	Low	Low		High	High
Bega Bemboka	Low	Low		High	High	High	High	High		Low	Low	Low

Key: High flow season | Low flow season

3. Data collation and infilling

3.1 Existing dams

Existing dams were identified from spatial data and entered into the STEDI model input files. Table 3-1 summarises the number and volume of existing farm dams in the catchment to the reference gauge location used to derive uimpacted flows.

- **Table 3-1: Number and volume of existing farm dams upstream of the reference gauge location used to derive unimpacted flows**

Catchment	Area (km²)	Number of existing dams		Storage volume of existing dams	
			per km²	ML	ML/km²
Duck	336.47	933	2.77	1563	4.64
Woolgoolga	10.68	11	1.03	30.7	2.87
Bucca Bucca	21.04	7	0.33	10.4	0.49
Nambucca	431.10	633	1.47	1586	3.68
Allyn	435.44	1337	3.07	1470	3.38
Wollombi	1852.87	4054	2.19	13379	7.22
Wyong	329.81	864	2.62	1665	5.05
Wollondilly	1575.92	7762	4.93	11450	7.27
Double	152.29	262	1.72	667	4.38
Bemboka-Upper Bega	825.60	1788	2.17	4327	5.24

3.2 Streamflow

Table 3-2 and Figure 3-1 summarise the mean daily streamflow records available for the selected streamflow gauges in each of the catchments. The streamflow records were extented to a common period for STEDI modelling of 1975 to 2016 inclusive. Missing data in the streamflow records was also infilled. The approach to infilling and extension for each gauge is set out in Table 3-3. In most catchments, a calibrated SimHyd rainfall runoff model was applied on a daily time-step. Quantile-quantile regression was then applied to adjust the daily SimHyd model outputs to produce an excellent match to the daily flow duration curve for the period when gauged data was available. Table 3-3 also shows the monthly statistics for the model calibration and a comparison of these statistics against the criteria from Moriasi et al. (2007).

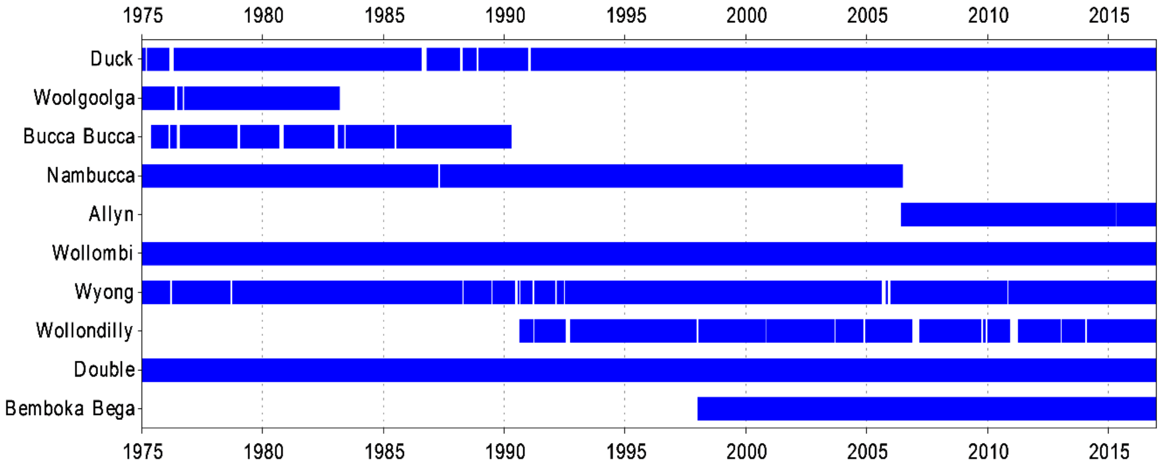


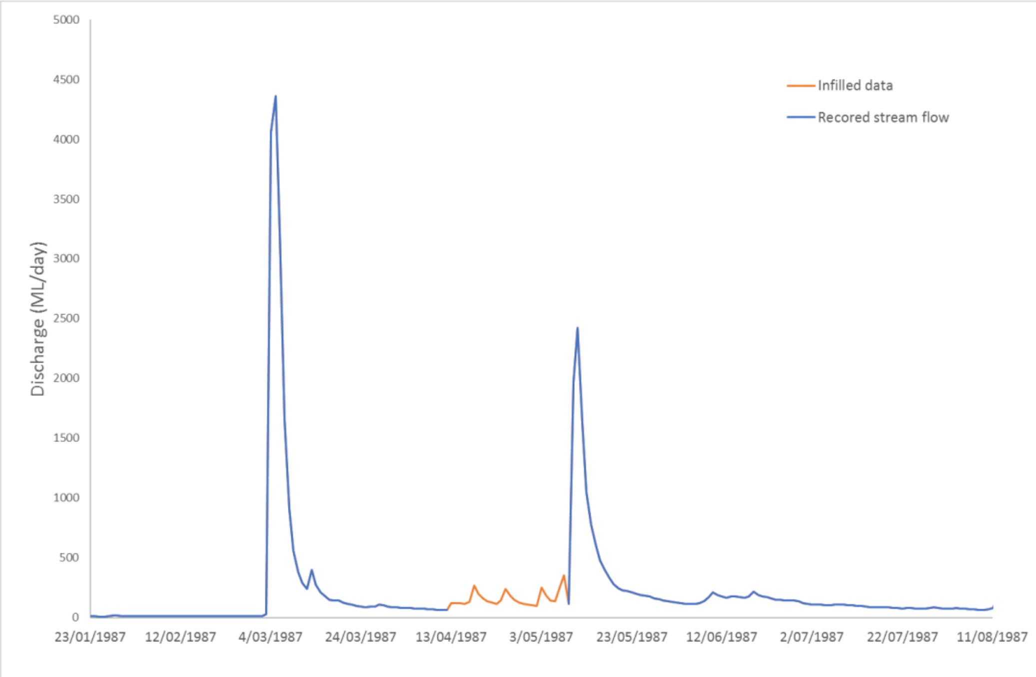
Figure 3-1 Gantt chart of available gauged streamflow data for each catchment

Table 3-2: Available daily gauged streamflow records for each catchment

Catchment	Gauge number	Gauge name	Period of record	% Missing Data	
				In gauge period	In 1975-2016
Duck	204049 (and regression with 204043)	Duck Creek at Capeen (after infilling with regression from Peacock Creek at Bonalbo)	Jan 1975-Dec 2016	1.8%	1.8%
Woolgoolga	205007	Woolgoolga Creek at Woolgoolga (near Freemans Road)	Jan 1975-Mar 1983	2.6%	80.9%
Bucca Bucca	204060	Bucca Creek at Central Bucca	May 1975-Apr 1990	5.7%	66.3%
Nambucca	205006	Nambucca River at Bowraville	Jan 1975-Jul 2006	0.5%	25.2%
Allyn	210143	Allyn River at Flying Fox Lane	Jun 2006-Dec 2016	0.2%	74.8%
Wollombi	210004	Wollombi Brook at Warkworth	Jan 1975-Dec 2016	0.0%	0.0%
Wyong	211009 and 211010 combined series	Wyong River and Jilliby Creek combined series	Jan 1975-Dec 2016	2.2%	2.2%
Wollondilly	2122711	Wollondilly River at Murrays Flat	Aug 1990-Dec 2016	5.7%	40.7%
Double	219017	Double Creek near Brogo	Jan 1975-Dec 2016	0.0%	0.0%
Bemboka Bega	219032	Bega River at Kanoona	Jan 1998-Dec 2016	0.0%	54.8%

Table 3-3 Calibration statistics for infilling of flow records at gauges

Gauge	Infilling method	% Missing in 1975-2016	Monthly Nash Sutcliffe Efficiency (Rating against Moriassi et al., 2007 criteria)	% Bias in Monthly Flows (Rating against Moriassi et al., 2007 criteria)
Duck Creek at Capeen (after infilling with regression from Peacock Creek at Bonalbo)	Regression from Peacock Creek at Bonalbo SimHyd model followed by daily quantile-quantile rescaling	1.8%	0.968 (Very good)	4.6% (Very good)
Woolgoolga Creek at Woolgoolga (near Freemans Road)	SimHyd model with daily quantile-quantile rescaling	80.9%	0.937 (Very good)	-0.5% (Very good)
Bucca Creek at Central Bucca	SimHyd model with daily quantile-quantile rescaling	66.3%	0.851 (Very good)	0.2% (Very good)
Nambucca River at Bowraville	SimHyd model with daily quantile-quantile rescaling	25.2%	0.968 (Very good)	4.6% (Very good)
Allyn River at Flying Fox Lane	SimHyd model with daily quantile-quantile rescaling	74.8%	0.572 (Satisfactory)	-0.1% (Very good)
Wollombi Brook at Warkworth	SimHyd model with daily quantile-quantile rescaling	0.0%	0.575 (Satisfactory)	0.0% (Very good)
Wyong River and Jilliby Creek combined series	SimHyd model with daily quantile-quantile rescaling	2.2%	0.834 (Very good)	0.7% (Very good)
Wollondilly River at Murrays Flat	SimHyd model with daily quantile-quantile rescaling	40.7%	0.605 (Satisfactory)	-10.9% (Good)
Double Creek near Brogo	Regression with IQQM daily inflow time series	0.0%	0.999 (Very good)	-0.1% (Very good)
Bega River at Kanoona	Regression with upstream gauge sites	54.8%	0.983 (Very good)	0.2% (Very good)



- **Figure 3-2 infilled stream flow using SIMHID model in Nambucca catchment**

3.3 Daily rainfall and evaporation data

Daily rainfall and evaporation data was extracted from the Australian Water Availability Project (AWAP) gridded daily rainfall dataset, compiled by the Bureau of Meteorology and CSIRO.

Daily time-series of potential evapotranspiration were extracted from the ARWA-L dataset at the centroid of each gauged catchment. In the remaining report sections, this dataset is referred to as potential evaporation. Table 3-4 summarises the climate characteristics of each catchment from 1/1/1975 to 31/12/2016.

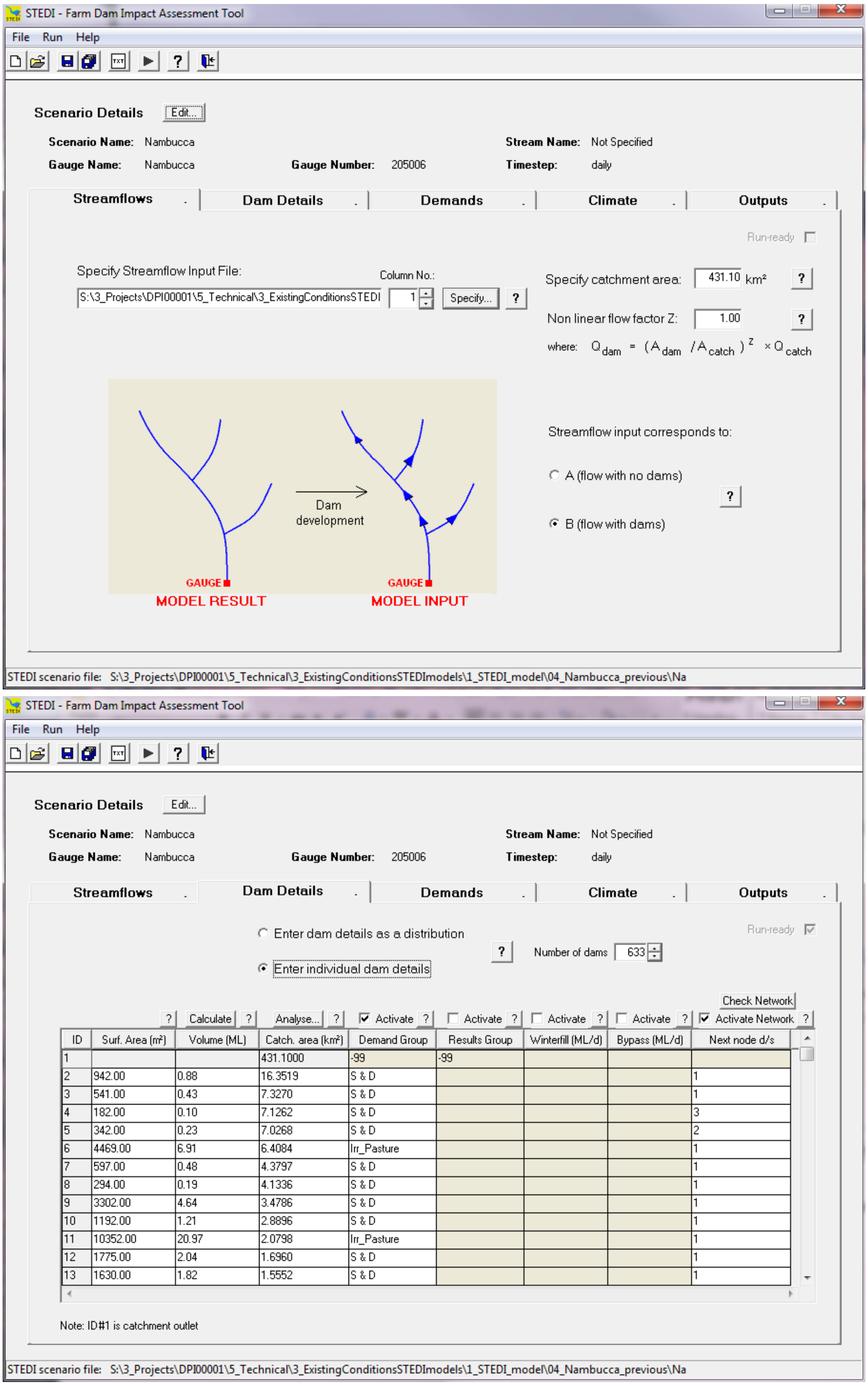
- **Table 3-4: Mean annual climate statistics for 1975 to 2016 (inclusive)**

Catchment	Mean annual depth (mm)		
	Rainfall	Potential Evaporation	Difference
Duck	958	1778	820
Woolgoolga	1548	1981	432
Bucca Bucca	1588	1960	372
Nambucca	1401	1750	348
Allyn	929	1634	705
Wollombi	829	1563	734
Wyong	1173	1567	394
Wollondilly	638	1478	840
Double	866	1528	662
Bemboka-Upper Bega	768	1456	688

4. Model development

After all the required inputs were prepared (Sections 2 and 3), the STEDI models for each catchment were set up in a manner consistent with the user manual (SKM, 2011). This involved entering the relevant information into each tab of the STEDI user interface (e.g. Figure 4-1 and Figure 4-2).

Each of the STEDI models simulate the farm dam impacts on a daily time-step based on historic climate conditions and adopted levels of farm dam development. A key assumption, in addition to those mentioned in Section 2, is that direct diversions from the waterways upstream of the flow gauges are negligible, and therefore do not need to be accounted for when modelling the farm dam impacts. And although the STEDI models have been developed on a daily time-step, it is important to remember that uncertainties associated with the inputs (particularly the demand factors and patterns), mean the predicted farm dam impacts will be more accurate when aggregated to longer time-steps (i.e. monthly and yearly).



- **Figure 4-1. Nambucca catchment STEDI model; streamflow inputs (top), dam details (bottom)**

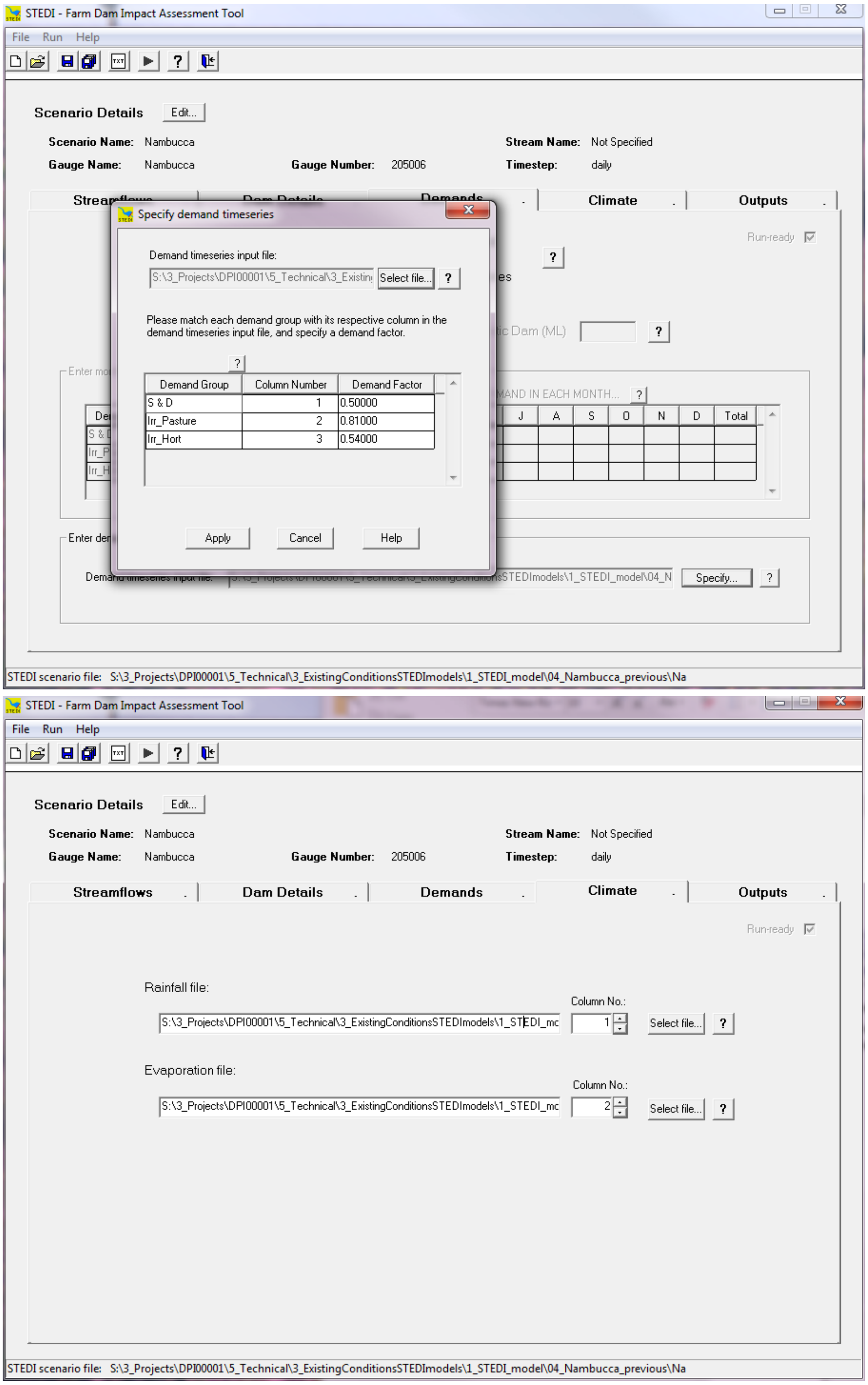


Figure 4-2. Nambucca catchment STEDI model: demand inputs (top), climate inputs (bottom)

5. Results and discussion

Results from the STEDI modelling were calculated for each of the 40 scenarios modelled, in each of the ten catchments, for the period from 1 January 1975 to 31 December 2016 (42 years). Full spreadsheets of all model results, including simulated daily streamflows and calculations of impacts of farm dams on daily flows were provided. Discussion of results in this report, for all 40 scenarios, is presented only for one catchment, normally the Nambucca River.

Comparisons for all catchments are presented, in this report, for the following five scenarios:

- Exitising farm dams;
- 100% uptake of HR at 10% of estimated mean annual runoff (EMAR), with dams permitted on up to 2nd order streams (full uptake of current policy);
- 100% uptake of HR at 20% of estimated mean annual runoff (EMAR), with dams permitted on up to 3rd order streams;
- 100% uptake of HR at 30% of estimated mean annual runoff (EMAR), with dams permitted on up to 3rd order streams; and
- 100% uptake of HR at 50% of estimated mean annual runoff (EMAR), with dams permitted on up to 3rd order streams.

Given the large number of results, this report concentrates mainly on outputs where there were significant differences between scenarios.

5.1 Storage volume and number of farm dams

The Nambucca catchment has 633 existing farm dams, with a total estimated storage volume of 1586 ML. The existing density of farm dams across the catchment is 3.65 ML/km². This is a moderate density, when compared with other catchments in South-Eastern Australia (refer for example to HARC, 2017). The existing dams are capturing water from an overall area of 96.4 km², or 22.2% of the total catchment area.

Under the existing HR policy (capturing 10% of EMAR), the allowable volume of havestable rights dams would be 4836 ML. The existing dams in the Nambucca catchment are therefore taking up 33% of the allowable volume under the existing HR policy. If all properties in the Nambucca catchment were to be developed up to their existing HR on 2nd order streams and above, the total area impounded by dams would almost double from it's current value, to 172.8 km² (or almost 40% of the total catchment area). If the HR policy were to be relaxed to permit dams on 3rd order streams as well, the total area impounded by dams would increase to 244.5 km² (or 56.3% of the total catchment area).

Figure 5-1 shows the volume of farm dams that were modelled for each of the HR scenarios in the Nambucca catchment.

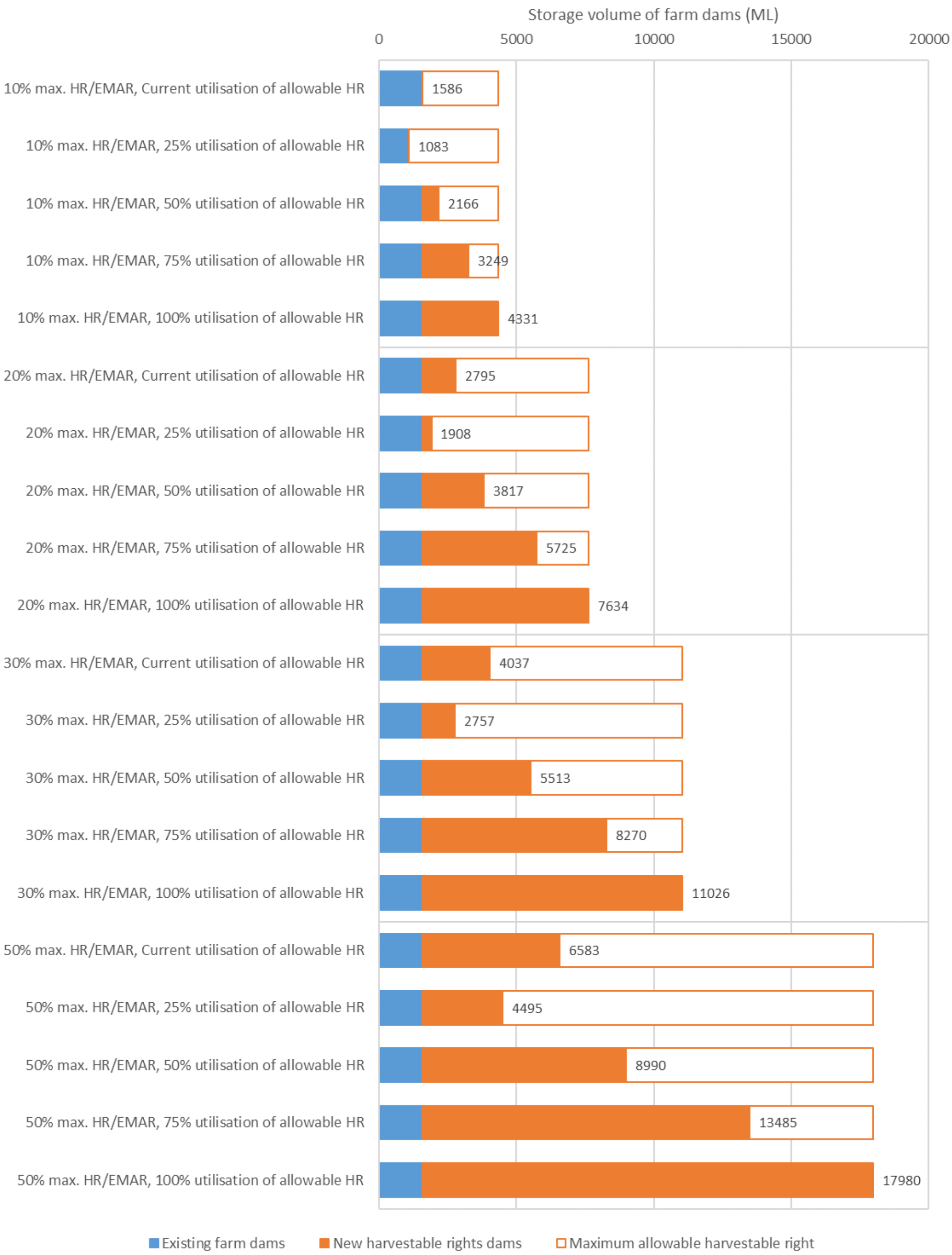
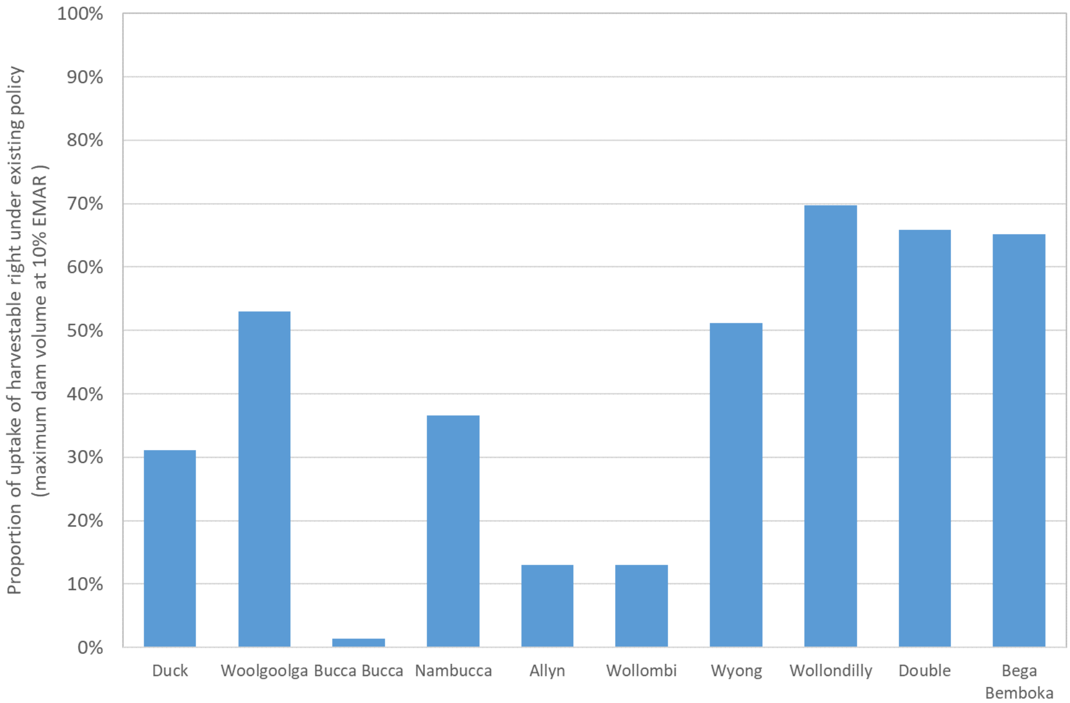


Figure 5-1 Storage volume of farm dams for harvestable rights scenarios modelled in the Nambucca River catchment

Figure 5-2 shows the variation in the current percentage of uptake of the existing HR (set at 10% of EMAR) between the ten study catchments. Uptake of HR is currently highest in the Wollindilly (70%), Double (66%) and Bega-Bemboka (65%) catchments. By contrast the current percentage of uptake is lowest in the Bucca Bucca (1%), Allyn and Wollombi (both 13%) catchments.



- **Figure 5-2 Current proportion of uptake of harvestable right under the existing policy of permitting dam storage volumes at 10% of estimated mean annual regional runoff**

Differences were observed between the unimpacted mean annual runoff, estimated from gauged flows for 1975-2016, and the volume of HR dams that would be calculated by multiplying the existing MHRDC contours by 10 in each catchment, as shown by the calculations in Table 5-1. The Table 5-1 shows that there are considerable differences between 10% of the EMAR calculated from gauged flows and the current HR. In eight of the catchments considered in this study, the EMAR from gauged flows is greater than the EMAR that would be derived from the MHRDC contours (see last column of Table 5-1). However, there are two catchments where the EMAR from gauged flows is less than the EMAR that would be derived from the MHRDC contours, with the gauged estimate 20% lower in the Wollombi catchment and less than half (52% lower) in the Wollondilly. The MHRDC contours were calculated using and approach that considered conversion of rainfall to runoff, regionalisation of the rainfall to runoff ratio, spatial varations in rainfall, variations in the typical usage of water from HR dams and the reliability of water supply from HR dams (Department of Industry, 2018). The differences in approach are likely to explain the differences in Table 5-1.

- **Table 5-1 Comparisons between unimpacted mean annual runoff, estimated from gauged flows for 1975-2016, and the estimated mean annual runoff that would be calculated by multiplying the existing MHRDC contours by 10 in each catchment**

Catchment Name	Catchment area (km²)	Unimpacted Mean Annual Flow, 1975-2016 (ML/y)	Unimpacted mean annual runoff depth (mm/y)	10% of unimpacted mean annual runoff depth (ML/ha/y)	MHRDC Contour for 10% EMAR (ML/ha)	% Difference
Duck	529.1	77882.5	147.20	0.147	0.107	38%
Woolgoolga	30.0	5962.8	198.50	0.198	0.130	52%
Bucca Bucca	118.0	76136.1	645.29	0.645	0.137	372%
Nambucca	434.2	180345.6	415.31	0.415	0.139	198%
Allyn	1185.3	370723.2	312.78	0.313	0.101	210%
Wollombi	1863.2	125486.1	67.35	0.067	0.084	-20%
Wyong	437.4	97986.7	224.05	0.224	0.113	98%
Wollondilly	1580.9	55582.6	35.16	0.035	0.073	-52%
Double	152.7	33259.3	217.84	0.218	0.089	144%
Bega Bemboka	827.5	159388.8	192.61	0.193	0.087	122%

The total storage volume of farm dams was divided by the total area of each study catchment for the five key scenarios. These comparisons are presented in Figure 5-3. The existing densities of farm dams (light blue bars for each catchment) vary between 0.09 ML/km² (Bucca Bucca) and 7.2 ML/km² (Wollondilly). These densities therefore cover the typical range of farm dam densities that have been observed in Victoria (HARC, 2017).

If there was to be full uptake of the existing HR (10% of EMAR on up to 2nd order streams), the results would be given by the orange bars in in Figure 5-3. The resulting farm dam densities would then range between 1.9 and 12 ML/km². Lower densities on this upper limit were identified in the catchments with larger proportions of state forest and national park, as it was assumed that there would be minimal development of new dams in these areas.

If the HR policies were to be modified to allow an increase in the HR as a proportion of EMAR and there was 100% uptake of HR, the dam volumes per unit catchment area would be given by the green, yellow and dark blue bars in Figure 5-3.

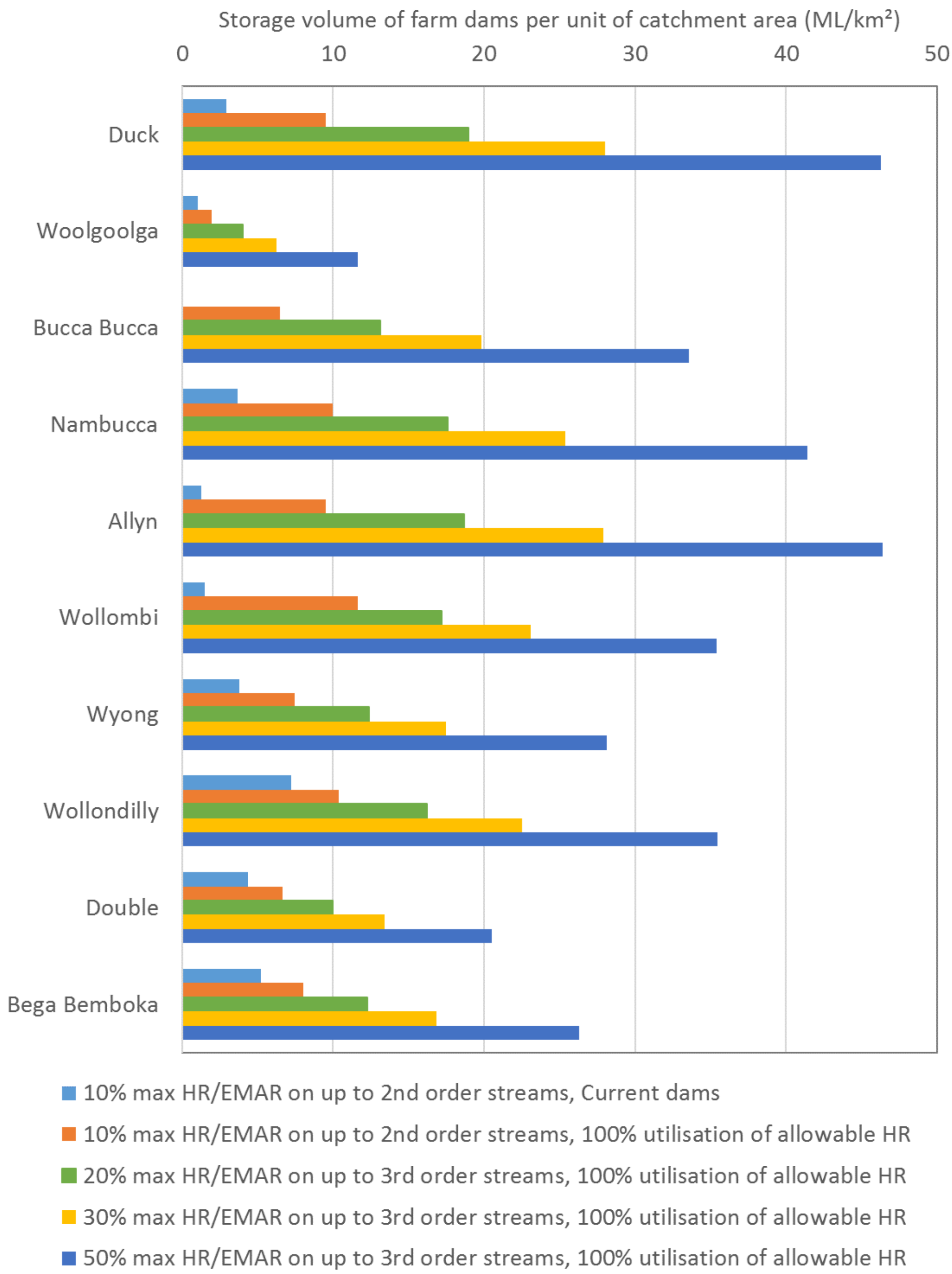


Figure 5-3 Comparison of storage capacity of farm dams per unit of catchment area for all study catchments and for five selected key scenarios

5.2 Mean annual impact of harvestable rights scenarios

5.2.1 Catchment Context

In this section, the impact of the different sceanrios on various hydrological indicators are discussed. Any change in the hydrological characteristics of a catchment will have an impact on either:

- Other catchment water users; and/or
- Water-dependent ecosystems.

In the case of catchment water users in unregulated streams, extractions are typically limited by Cease To Pump (CTP) conditions. CTP conditions limit the extraction by irrigation, town water supply and stock and domestic users. Any increase in the frequency and/or duration of these CTP periods will reduce the volume of water extracted. These impacts will be:

- Loss of economic productivity for irrigation and stock and domestic users; and
- Reduced reliability of town water supply – who typically rely on extractions to re-fill off-stream storages.

In cases where there town water supplies are provided by on-stream storages, reduced flows will also have an adverse impact on water security.

Urban communities rely of a reliable water supply to provide consumers with an agreed standard of service which in turn underpins local industry and commerce. Significant investment in water supply infrastructure (typically dams) is required to provide security of supply during periods of drought. With reduced access to low flows for filling storages, the capacity of the storage asset to provide supply can be significantly impacted. This will result in the need for immediate investment in additional storage or the advancement of future investment to increase supply security. In both cases these costs to water utilities will be significant and will result in higher water charges.

In cases where town water supplies rely on run-of-river flows (without storage), the increased frequency of low flow periods will increase periods of water restrictions which may in turn violate required standards of service. This in turn may precipitate the need to invest in water storage.

In the case of the environment, any permanent change in flow regime will results in an change in the equilibrium of water-dependent ecosystems. The extraction of water is already adversely impacting coastal ecosystems, where additional stress is placed on the environment through rural and urban land development. Typical impacts include:

- For fresh water environments, increased frequency of low flow periods that can impact on fish habitats and the viability of water-dependent vegetation communities;
- For estuarine environments, reduced frequency and volume of flushing flows that provide some relief from land use-induced stresses from pollutants and sediments.

While it is beyond the scope of this project to analyse these impacts in any detail, it is important that the potential impacts on water users and the environment are understood.

Table 5-2 outlines the types of impacts that increases in the development of farm dams would have in each catchment from four different perspecitves. These impacts have been broadly classified as:

- Nil, where there is no or negligible impact
- Unlikley, where an impact is unlikely, but if there is an impact it is likely to be insignificant.
- Limited, where there is some certainty of an impact, however it is likely to be minor
- Some – where there will be some impact of moderate or uncertain magnitude
- Likley – where there is likely to be an impact;
- Significant – where there is a liklihood of a significant impact.

Table 5-2 Potential impacts of additional farm dam development in study catchments

Catchment	Town Water Supply	Other Water Users	Riverine Ecosystems	Coastal Ecosystems
Duck	Nil. There are no town water supplies that are extracging downstream of this catchment.	Some. There is considerable water extracted both within and downstream of this catchment for stock and domestic and irrigation water use.	Some. Located in the larger Clarence River catchment, which although classified in good condition, any alteration of flow regimes can cause adverse impacts.	Unlikley. Located in the upstream reaches of a large coastal estuary.
Woolgoolga	Nil. There are no town water supplies that are extracting from this catchment.	Unlikely. There is little in the way of extractive water use in this catchment and downstream.	Some. A small coastal catchment, any change in flow regimes will have an adverse impact.	Likely. Catchment flows into Woolgoolga Lake which is an Intermittently Closed and Open Lagoon or Lake (ICOLL) serviced by a small catchment with urban development pressures. Any reduction in flows will have adverse impacts.
Bucca Bucca	Nil. All villages downstream on the Orara River are supplied by the regional water supply scheme.	Some. There is considerable water extracted both within and downstream of this catchment for stock and domestic and irrigation water use.	Some. Located in the larger Clarence River catchment, which although classified in good condition, any alteration of flow regimes can cause adverse impacts.	Unlikley. Located in the upstream reaches of a large coastal estuary.

Catchment	Town Water Supply	Other Water Users	Riverine Ecosystems	Coastal Ecosystems
Nambucca	Significant. Nambucca Shire Council water supply relies on access to flows from the river to fill an off-river storage. Increase in the duration of low flow periods will impact adversely on water security.	Some. There is considerable water extracted both within and downstream of this catchment for stock and domestic and irrigation water use.	Some. Any changes in flow regimes will have an adverse impact.	Some. Located in the upstream reaches of a medium-sized coastal estuary.
Allyn	Nil. Urban communities in the catchment are in the Hunter Water service area	Some. There is considerable water extracted both within and downstream of this catchment for stock and domestic and irrigation water use. Lostock Dam regulates some of the flow in the catchment so so regulated water users could be impacted.	Some. Any changes in flow regimes will have an adverse impact.	Unlikley. Located in the upstream reaches of the Hunter River, a large coastal estuary.
Wollombi	Nil. Town water supply throughout the region is provided by Hunter Water and is not sourced from the Wollombi River	Some. Likley to be extractions for irrigation, stock and domestic and mining water uses.	Some. Any changes in flow regimes will have an adverse impact.	Unlikley. Located in the upstream reaches of the Hunter River, a large coastal estuary.
Wyong	Some. While the Wyong River is utilised for the Central Coast water supply, the potential for additional farm dam development in upstream areas is limited by the terrain. Most of the potential for additional development is in the Jilby Jilby Creek arm and in the lower reaches of the catchment well downstream of the water supply offtake.	Some. There is some extraction of surface water for irrigation use in the Jilby Jilby Creek arm of the catchment with stock and domestic use throughout.	Some. Any changes in flow regimes will have an adverse impact.	Likely. Located upstream of the Tuggerah Lake, which already has ecosystems stresses caused by power station cooling uses and urban development.

Catchment	Town Water Supply	Other Water Users	Riverine Ecosystems	Coastal Ecosystems
Wollondilly	Significant. This catchment River provides water for the Goulburn and Marulan urban communities via on-stream storages. Any reduction in flows will reduce the security of supply. Would also have an impact on inflows to Sydney's water supply Lake Burragorang.	Limited, There is some limited extractive water use in this catchment.	Significant. This catchment is classified as being in moderate condition. With much of this catchment being comprised of perennial streams, increases in the frequency and duration of low flow periods will have an additional adverse impact.	Unikely. Located upstream of the large Hawkesbury-Nepean river system of which impacts of the Sydney metropolitan area are far more significant.
Double	Nil – water supply for for the Brogo-Bermagui water supply is from the regulated WaterNSW storage.	Likely. Extractive water use in the regulated catchment is dependent on the reliability of Brogo dam. There is considerable water extraction in the unregulated parts of the catchment which would be adversely impacted.	Some. Any changes in flow regimes will have an adverse impact, particularly given the developed state of water use in the catchment.	Some. Located in the upstream reaches of a medium-sized coastal estuary that already has significant amounts of water extraction.
Upper Bega / Bemboka	Nil – this catchment is adjacent to the Tantawanglo Creek Wier where water is extracted for the Tantawanglo-Kiah and Bega-Tathra water supplies.	Likely. There are significant extractions for irrigation, stock and domestic water uses.	Significant. Due to high levels of historical water extraction this catchment is a highly developed one. Further reductions in flows would have an additional adverse impact.	Some. Located in the upstream reaches of a medium-sized coastal estuary.

5.2.2 Flow Impact Results

Mean annual impacts of farm dams for the study catchments, as a proportion of catchment area, are shown in Figure 5-4. The current mean annual impacts range between 0.09 ML/year/km^2 (Bucca Bucca) and 4.66 ML/year/km^2 (Wollondilly), as shown by the light blue bars in Figure 5-4.

If there was to be full uptake of the existing HR (10% of EMAR on up to 2nd order streams), the results would be given by the orange bars in in Figure 5-4. The resulting impacts would then range between 1.7 and 8.9 ML/year/km^2. The lower values were for the catchments with larger proportions of state forest and national park, as it was assumed that there would be minimal development of new dams in these areas.

If the HR policies were to be modified to allow an increase in the HR as a proportion of EMAR and there was 100% uptake of HR, the mean annual impact per unit catchment area would be given by the green, yellow and dark blue bars in Figure 5-4.

Figure 5-5 shows the mean annual impact as a proportion of the unimpacted mean annual flow volume, for each of the study catchments and selected scenarios. Existing dams take between 0.01% (Bucca Bucca) and 12.3% (Wollondilly) of the mean annual flow. This would increase to between 0.8% (Bucca Bucca) and 19.6% (Wollondilly) of the mean annual flow if there was 100% utilisation of the existing 10% HR.

If the HR policies were to be modified to allow an increase in the HR as a proportion of EMAR and there was 100% uptake of HR, the mean annual impact as a proportion of mean annual flow would be given by the green, yellow and dark blue bars in Figure 5-5. The mean annual impacts in the Wollondilly catchment, in particular, could be a very large proportion of the mean annual flow if there was full uptake, with impacts of 31.2% of mean annual flow for the 20% HR/EMAR, 38.3% of mean annual flow for the 30% HR/EMAR and 46.7% of mean annual flow for the 50% HR/EMAR scenarios.

For the other catchments, the mean annual impact as a percentage of mean annual flow are lower values because the existing HR contours produce conservatively low estimates of EMAR, when compared with gauged flows over 1975-2016 (refer to Table 5-1). If there was full uptake of the HR and the HR was increased to 50% of EMAR, Figure 5-5 shows that the mean annual impact would be 18% in the Duck and Wollombi catchments, down to 3.9% in the Bucca Bucca catchment.

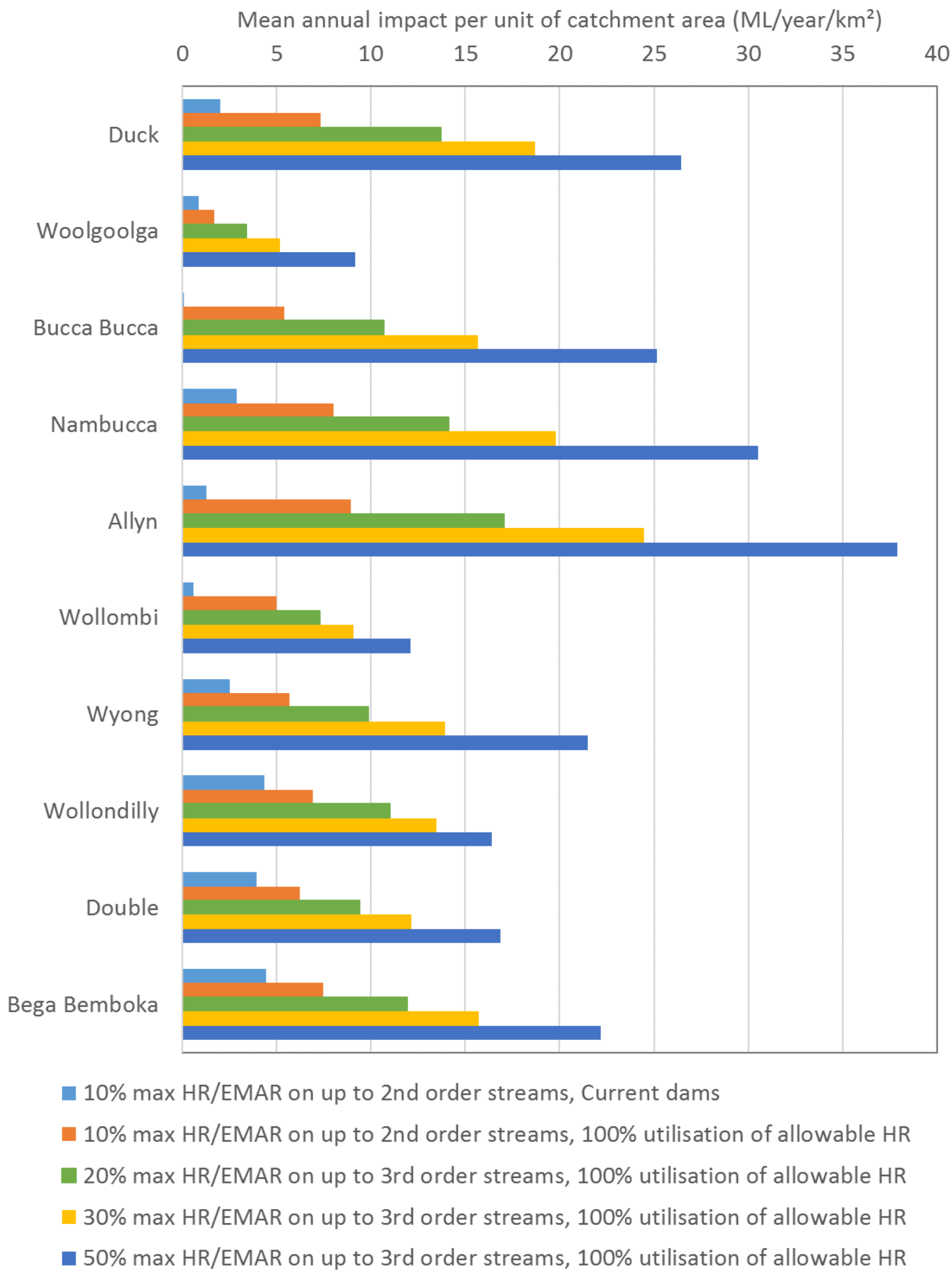


Figure 5-4 Comparison of mean annual impact per unit of catchment area for all study catchments and for five selected key scenarios

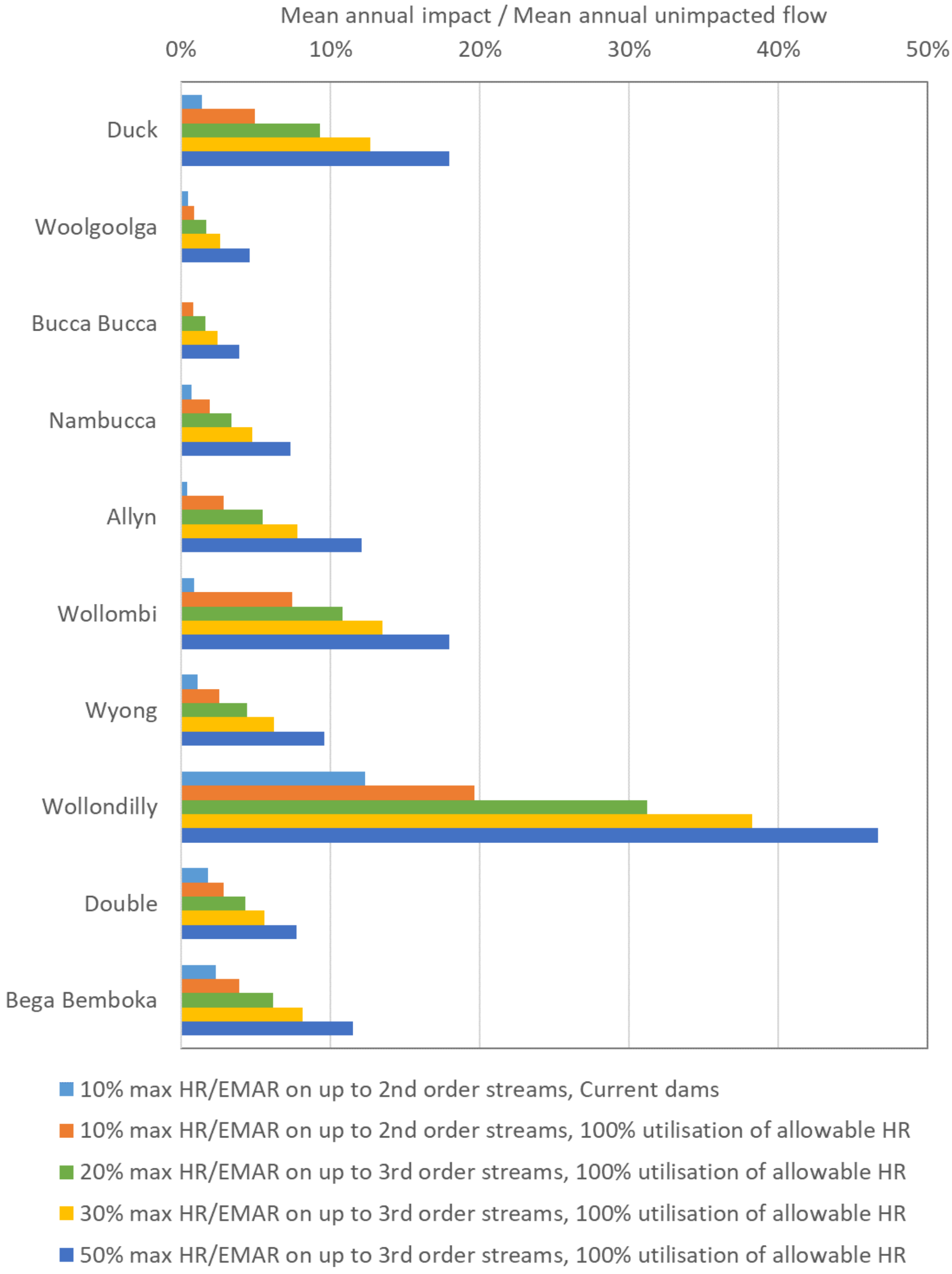
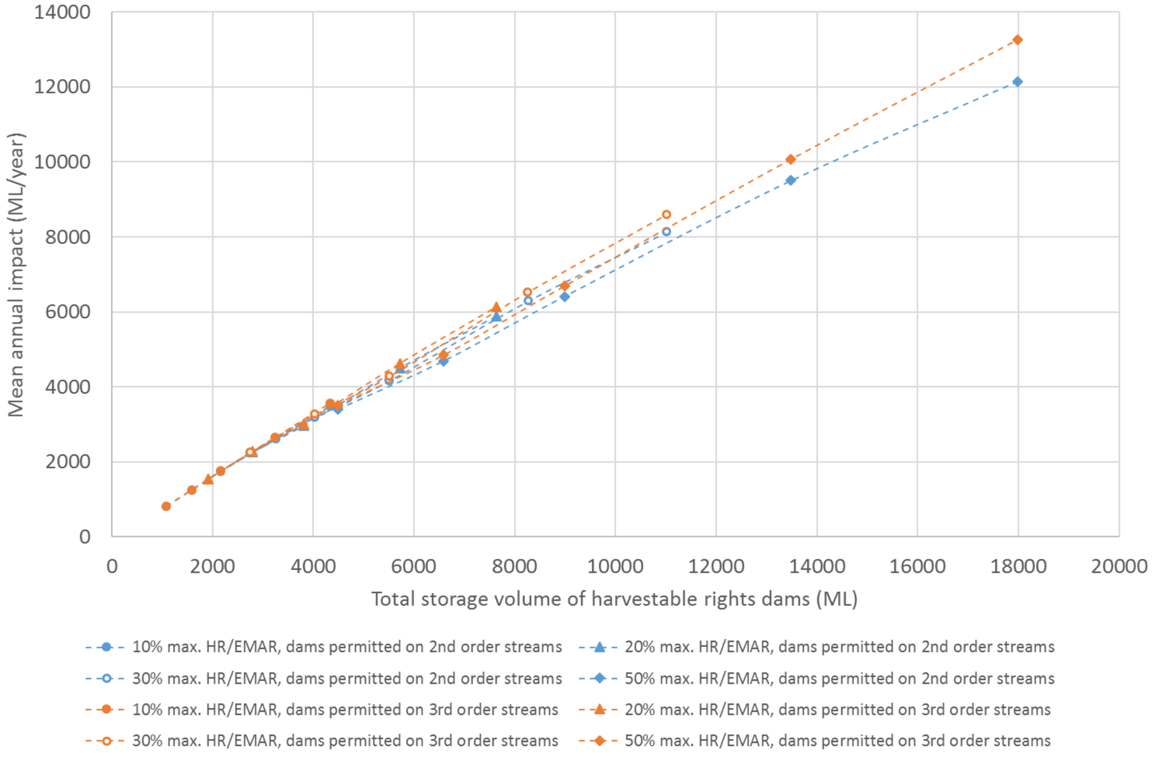


Figure 5-5 Comparison of mean annual impact as a proportion of mean annual flow for all study catchments and for five selected key scenarios

Figure 5-7 shows the modelled mean annual impact for each of the HR scenarios in the Nambucca catchment. The mean annual impact of farm dams is strongly correlated with the total storage volume of dams in each scenario. Allowing HR dams on 3rd order streams (in addition to 2nd order streams) has a much weaker influence on the mean annual impact than increasing the storage volume of dams.

The storage volume of dams is a strong predictor of the mean annual impact in each catchment, as shown in Figure 5-8. The ratio of mean annual impact to volume of dams does not vary much between each of the scenarios in each catchment, with the ratio dropping off slightly for higher HR/EMAR ratios as the additional dams start to cannibalise the inflow from downstream dams. The variations in ratio between catchments are due to the differences in crop type, and hence demand factor assumed between catchments, and variations in the characteristics of the stream network changing the typical area upstream of each dam (and hence inflow) relative to the dam storage volume.



- **Figure 5-6 Mean annual impact against total storage volume of harvestable rights dams for Nambucca catchment**

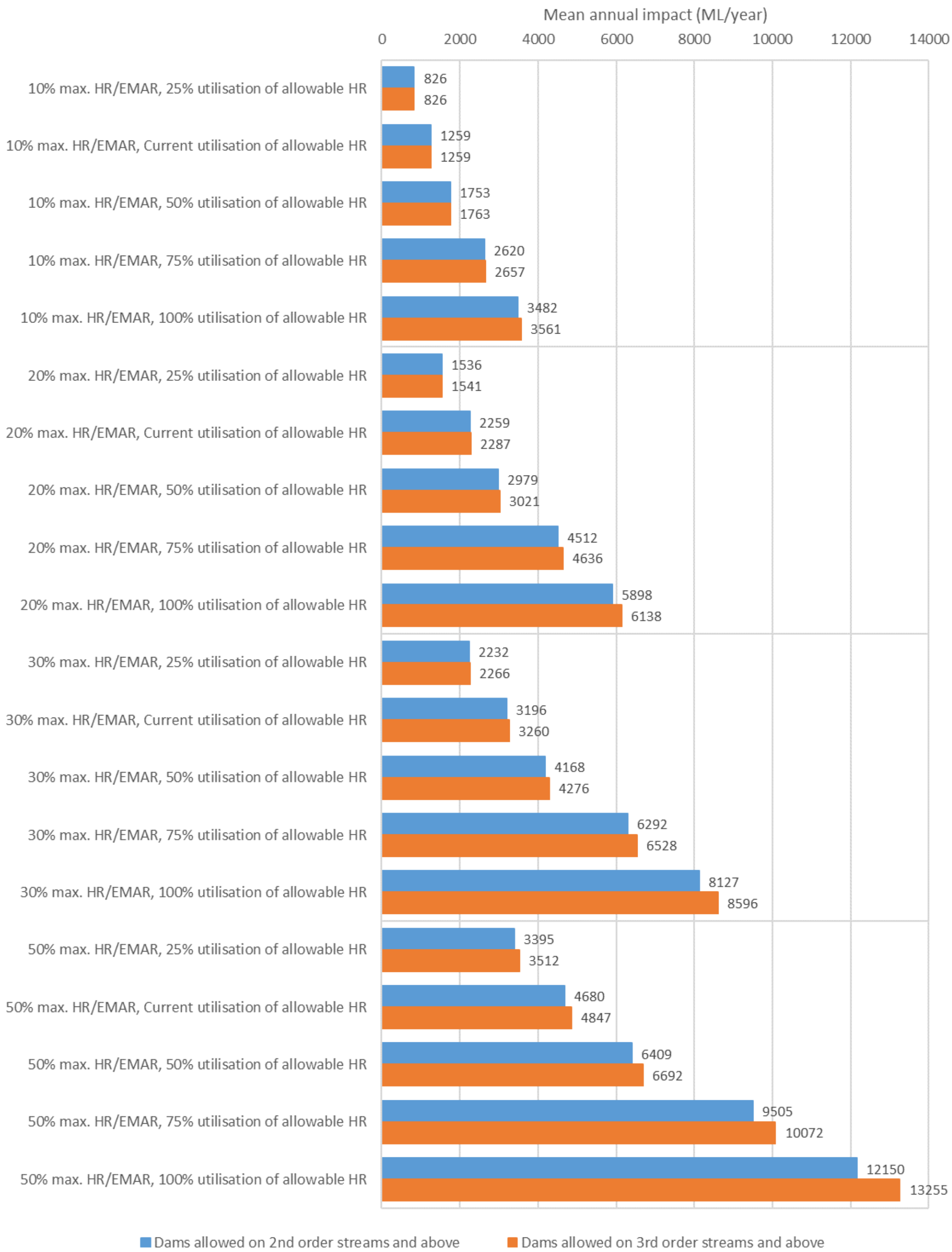
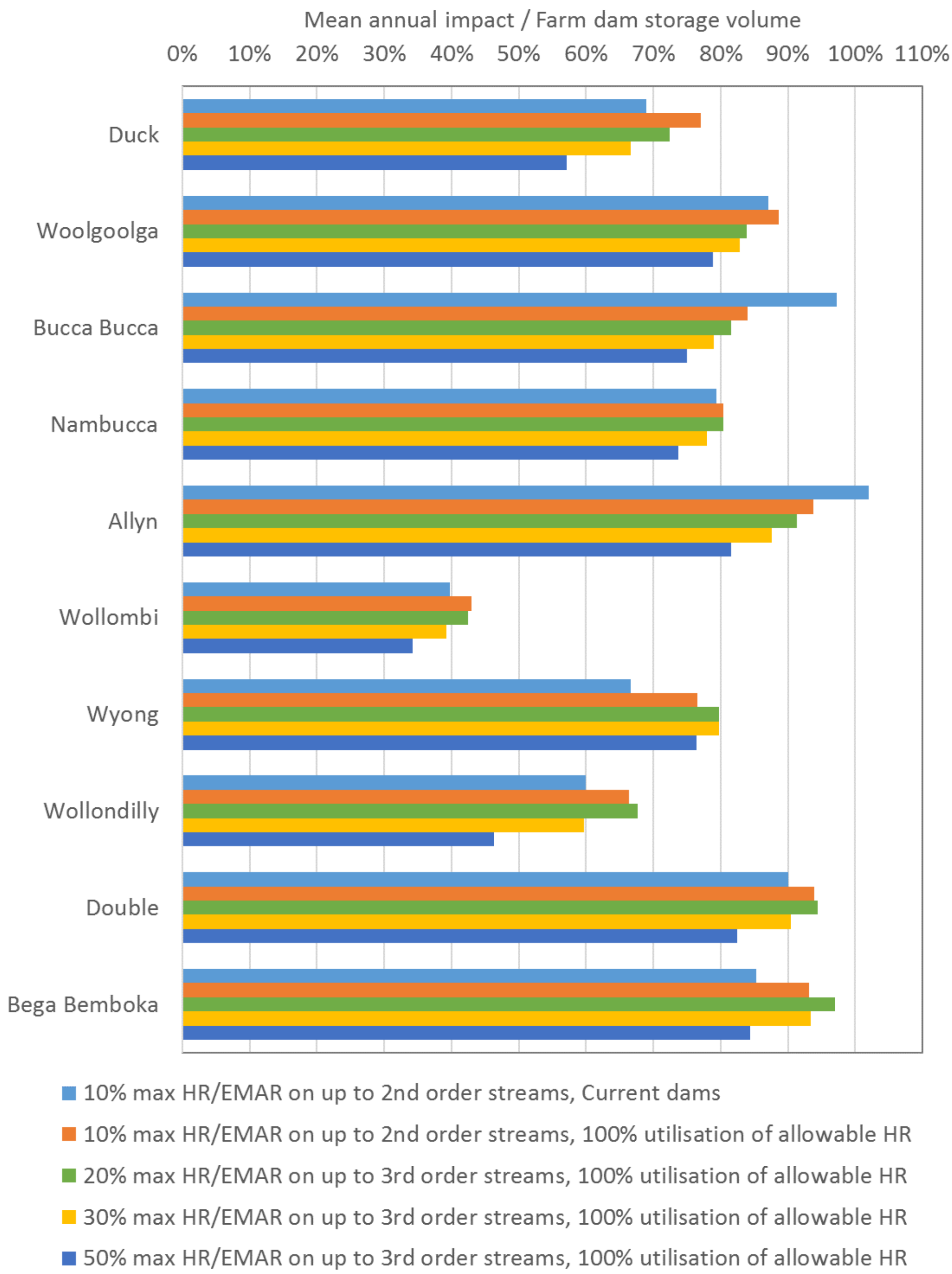


Figure 5-7 Modelled mean annual impact on streamflow for harvestable rights scenarios in the Nambucca River catchment

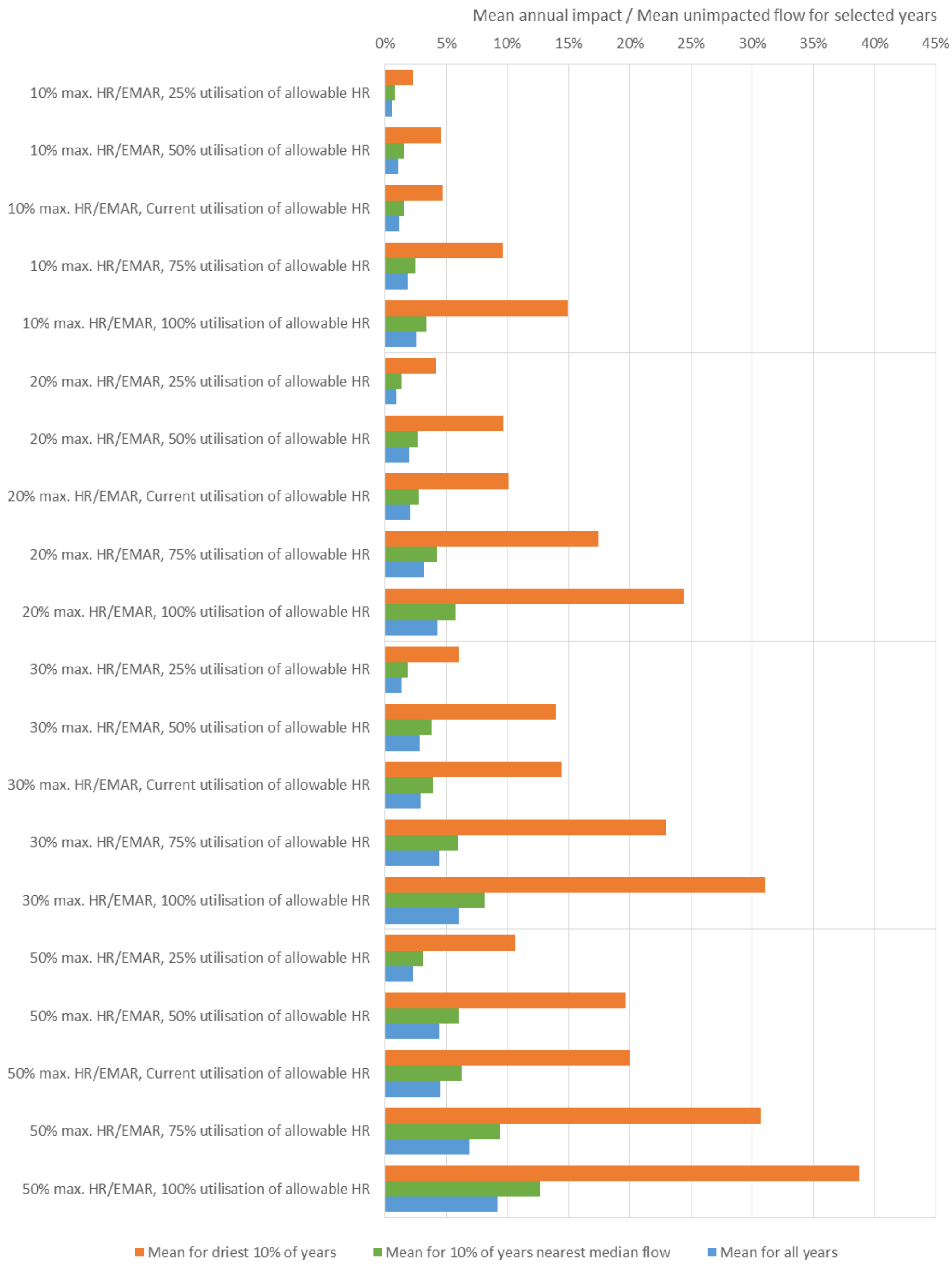


- **Figure 5-8 Comparison of mean annual impact as a ratio to the storage volume of farm dams for all study catchments and for five selected key scenarios**

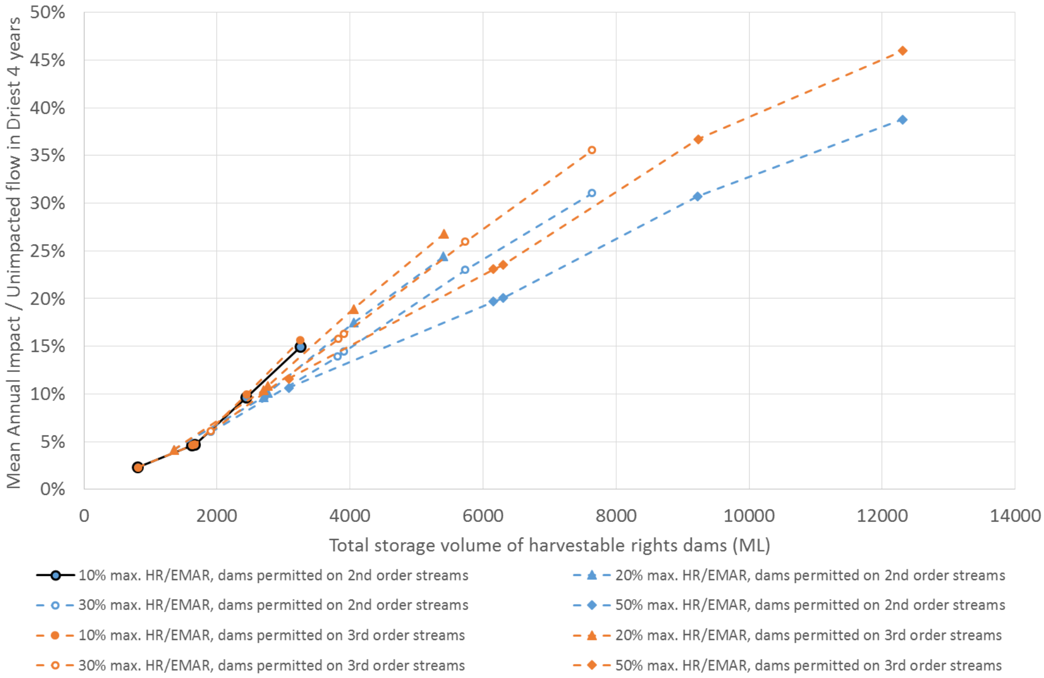
For licensed diverters in many catchments, availability of water during dry years may be more critical than the availability of water in years with near-average or above average flows. Mean annual impacts were therefore computed separately in the driest 10% of years in the simulation period (four calendar years in the period 1975-2016 with the lowest unimpacted annual flow volume), the 10% of years closest to the median flow (four calendar years in the period 1975-2016 ranked 20th to 23rd by unimpacted mean annual flow volume) and for all 42 years in the simulation period. Figure 5-9 shows that the mean annual volume of impact is a much larger proportion of the overall take in the driest 10% of years than in near median and all years.

In the Wyong catchment, the current volume of farm dams is 1665 ML, which represents 51% utilisation of the existing HR (2440 ML). The existing HR dams in the Wyong catchment take 1.6% of the flow volume in median years but 4.7% of the flow volume in the driest 10% of years (refer to third set of bars from top of Figure 5-9). Figure 5-10 shows that an increase in utilisation of HR dams or a change in policy to permit increased HR dams would increase the impact of dams as a proportion of total flow during dry years. If there was 100% utillisation of the exitisting HR (10% of EMAR), the volume of farm dams would increase to 3250 ML, which would result in 14.9% impact on mean flow in the driest 10% of years. Permitting HR dams in the Wyong catchment on 3rd order as well as 2nd order streams starts to have increasing impact on dry years once the total volume of HR dams exceeds about 4000 ML.

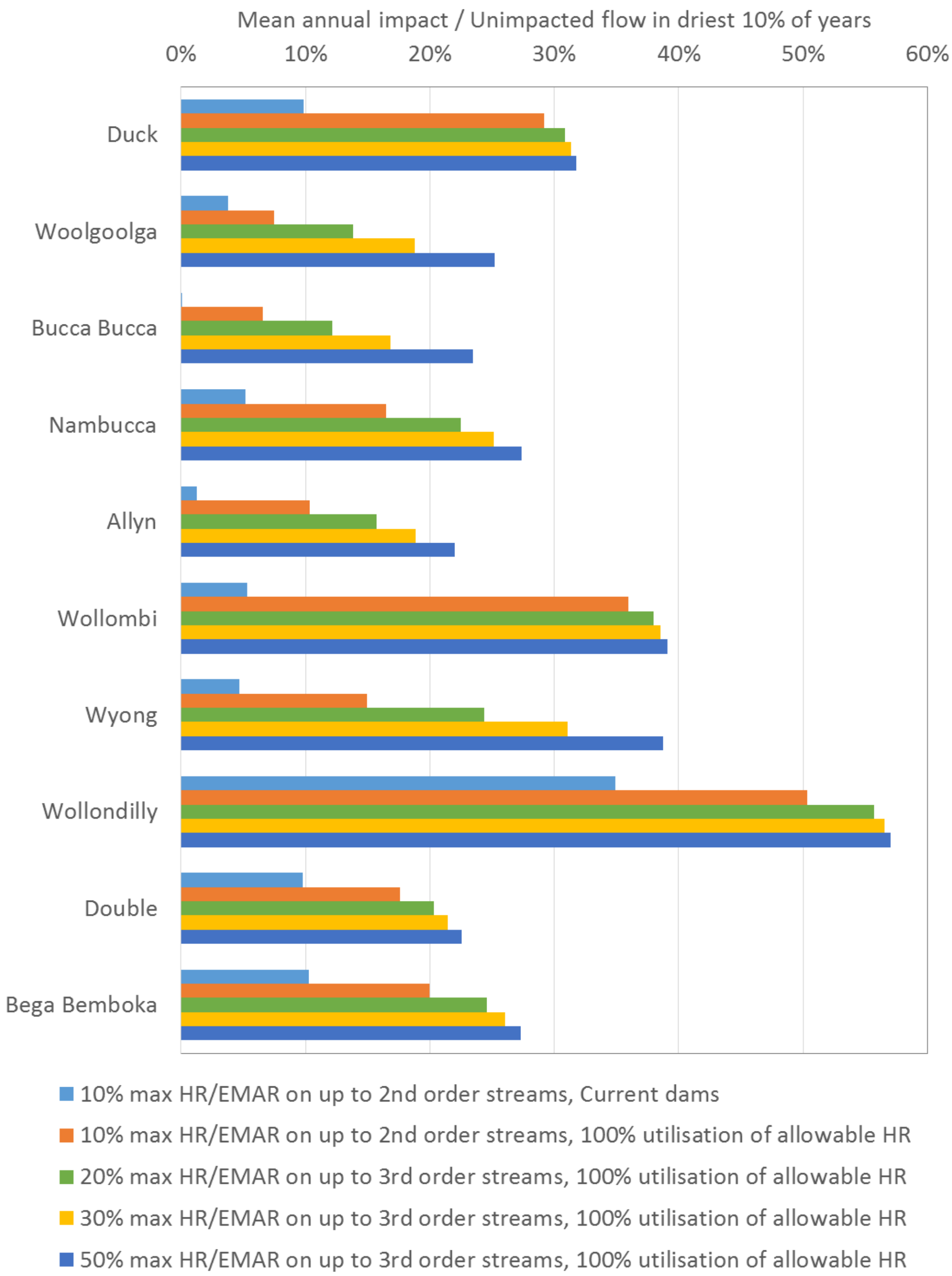
Figure 5-11 shows the impact, as a proportion of unimpacted mean annual flow, in the driest 10% of years (driest four calendar years modelled) in each of the study catchments. The percentage impacts are much larger in dry years than if all years are considered, as can be seen by comparing Figure 5-5 with Figure 5-11. Existing HR dams already take 35% of mean annual flow in dry years in the Wollondilly catchment and about 10% of mean annual flow in dry years in the Duck, Double and Bega-Bemboka catchments. If there was to be 100% utilisation of the existing farm dams under the current policy (10% HR/EMAR), the impact of HR dams in dry years would be 50% in Wollondilly and they would exceed 10% of annual flow in dry years in eight of the catchments.



- **Figure 5-9 Comparison of mean annual impact as a ratio to mean unimpacted flow for the driest 10% of years, near median 10% of years and all years for the Wyong catchment**



- **Figure 5-10 Mean annual impact as a ratio to mean unimpacted flow for the driest 10% of years compared with total storage volume of harvestable rights dams for the Wyong catchment**

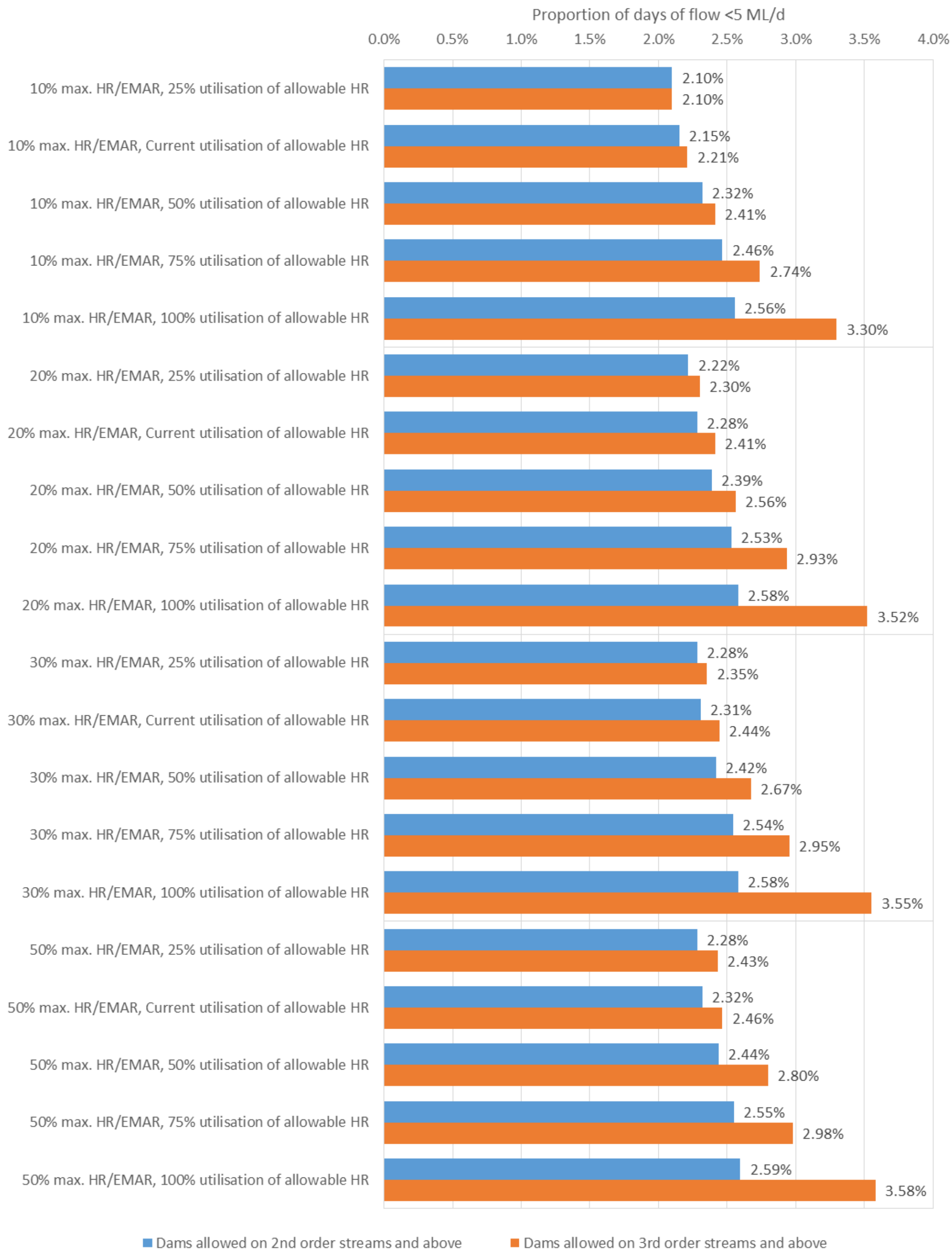


- **Figure 5-11 Mean annual impact as a ratio to mean unimpacted flow for the driest 10% of years for all study catchments and for five selected key scenarios**

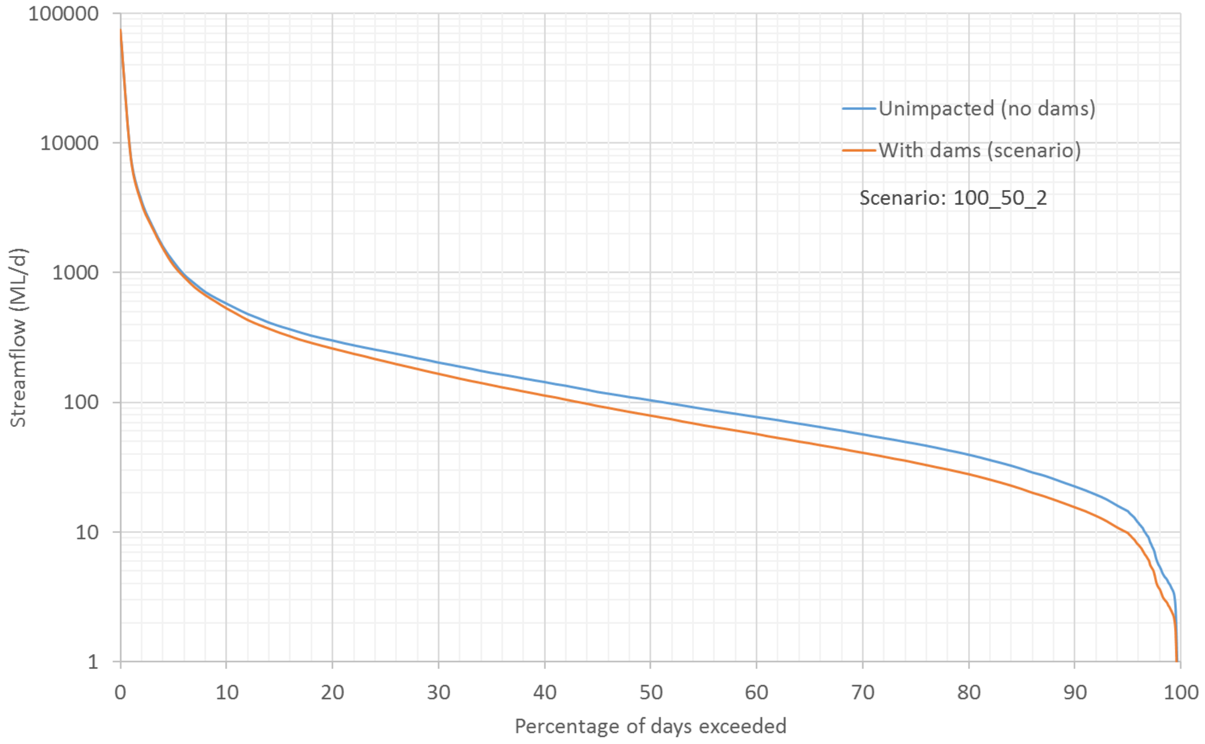
5.3 Impact of harvestable rights scenarios on licensed diversions from streams

Direct diverters from the Nambucca River and its major tributaries are required to stop diversions when streamflow is less than 5 ML/d at the Nambucca River North Arm upstream of Bowraville gauge. Figure 5-12 shows the proportion of days that this 5 ML/d cease to pump flow rate is exceeded for each scenario. Under existing conditions, streamflow is less than 5 ML/d on 2.2% of days. Under the most impacting scenario (100% uptake of allowable HR at 50% of EMAR, with dams allowed on 3rd order streams), the proportion of days below 5 ML/d would increase to 3.6% of days. Figure 5-13 shows an example of the flow duration curve for the scenario for 100% uptake of allowable HR at 50% of EMAR, with dams allowed on 2nd order streams.

Similar comparisons were performed in each catchment of the proportion of days when the flow would be above the cease to pump level. Figure 5-14 shows that increasing the HR does cause increases in the proportion of days when the flow would be below the cease to pump level in some catchments. The differences in proportion of days above the cease to pump level between catchments (for existing conditions), shown in Figure 5-14, were a function of how the cease to pump level had been set in the WSP area planning process. So, for example, unregulated stream diverters in the Wollombi catchment would not be able to divert on 45.5% of days (when the flow was less than 18 ML/d), compared with very low flow class diverters in the Bega Bemboka catchment that would be below the cease to pump level on 2.1% of days (when the flow was less than 2 ML/d). It was noted that some of the cease to pump levels presented are for different classes of licence, meaning that comparisons of total time below triggers between valleys should not be made. However, the modelling will indicate where significant changes may be expected for different licence classes within each valley.



- **Figure 5-12 Modelled proportion of days when flow would be below 5 ML/d for harvestable rights scenarios in the Nambucca River catchment**



- **Figure 5-13 Flow duration curves for the Nambucca River at Bowraville, showing the scenario for 100% uptake of allowable harvestable right at 50% of EMAR, with dams allowed on 2nd order streams**

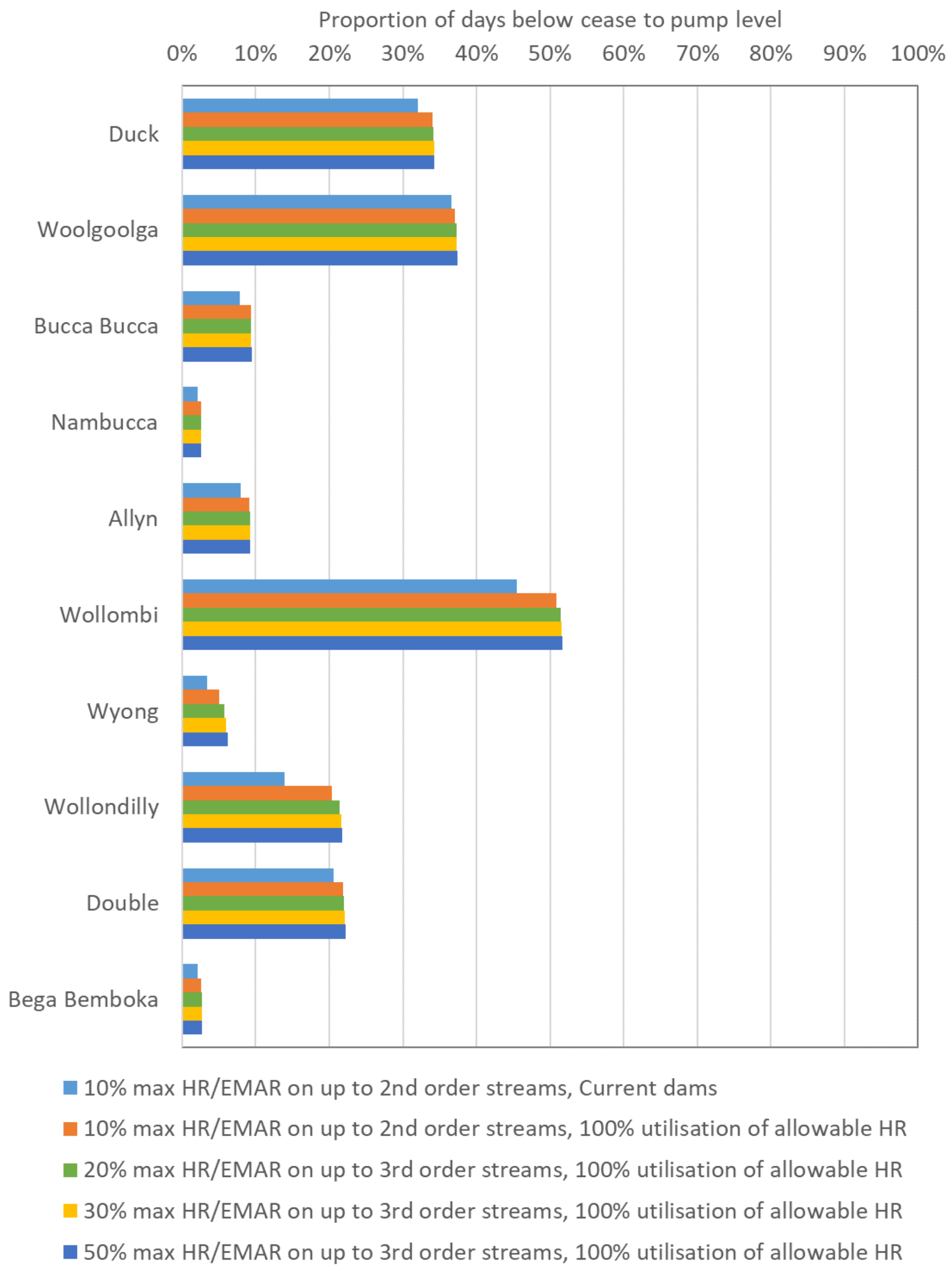
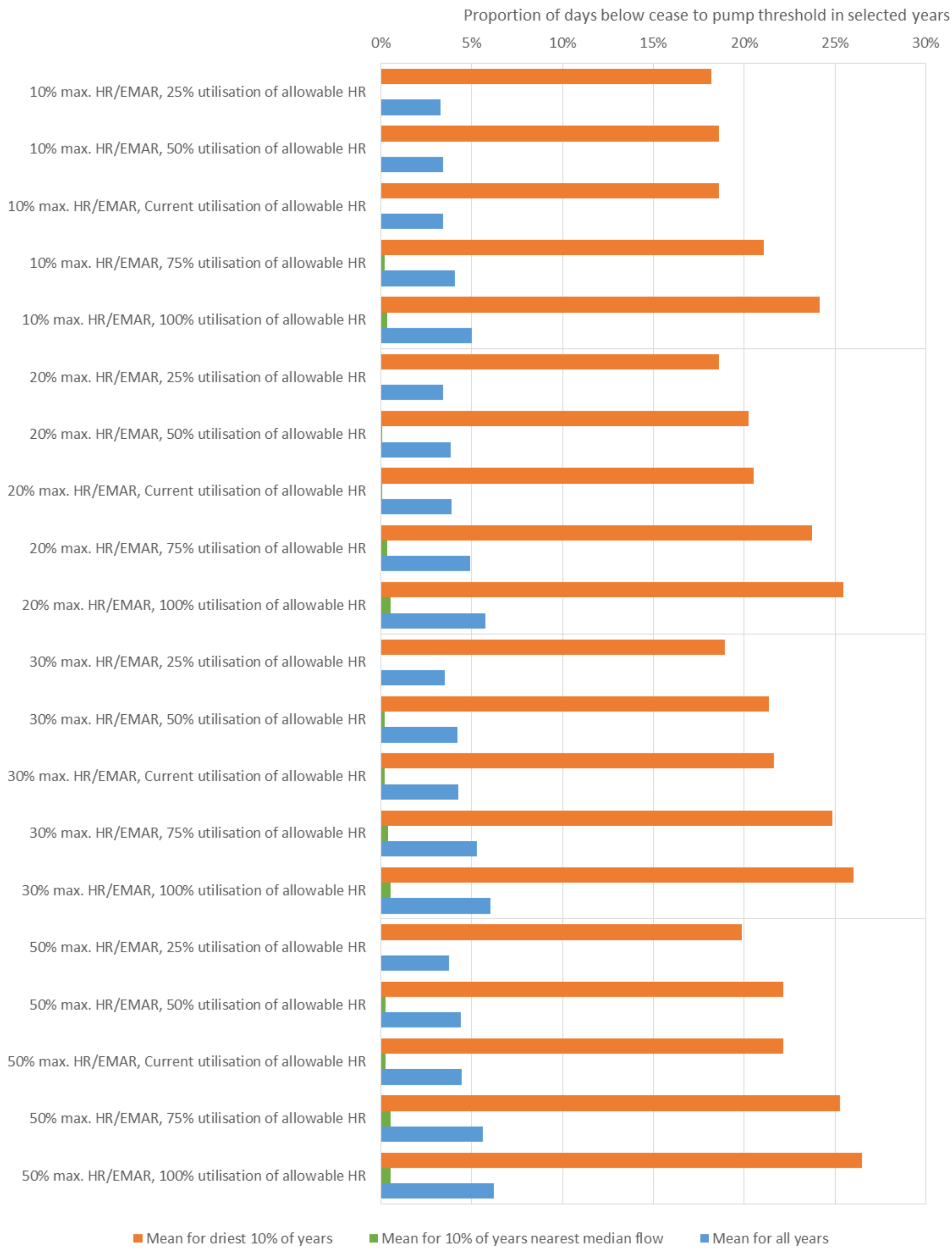


Figure 5-14 Comparison of proportion of days below the cease to pump level (lowest flow class) for all study catchments and for five selected key scenarios

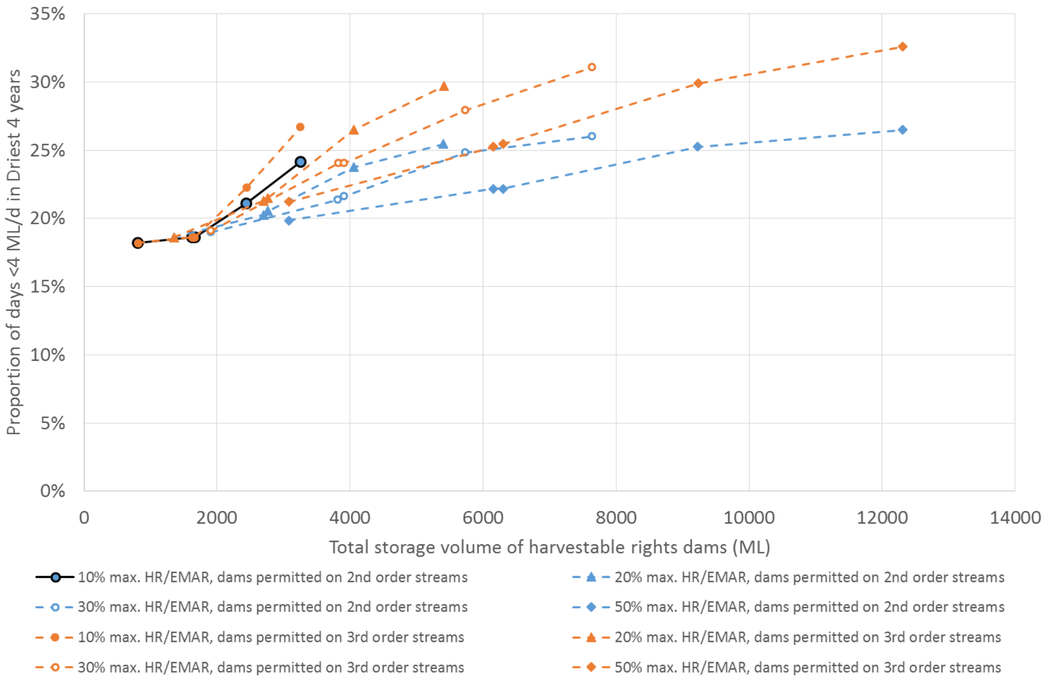
For licensed diverters in many catchments, availability of water during dry years may be more critical than the availability of water in years with near-average or above average flows. The number of days below the cease to pump threshold were therefore computed separately in the driest 10% of years in the simulation period (four calendar years in the period 1975-2016 with the lowest unimpacted annual flow volume), the 10% of years closest to the median flow (four calendar years in the period 1975-2016 ranked 20th to 23rd by unimpacted mean annual flow volume) and for all 42 years in the simulation period.

In the Wyong catchment, the current volume of farm dams is 1665 ML, which represents 51% utilisation of the existing HR (2440 ML). The third set of bars from the top of Figure 5-15 shows that number of days below the cease to pump threshold for the very low flow class in the Wyong catchment is much higher in the driest 10% of years (18.6% of days under current conditions) than in near-median years (0%) and all years (3.4% of days). The proportion of days below the cease to pump threshold in the Wyong catchment was much larger in dry years than in all years for all of the scenarios modelled. If there were 100% utilisation of the existing HR, the proportion of days impacted in the driest 10% of years would increase from the current level of 18.6% to 24.2%. These changes in the number of days below Cease to Pump may result in significant impacts for licensed irrigators and for the availability of water for Town Water supply. The potential for impacts on licensed irrigation crops, or on town water supply reliability has not been assessed as part of this study.

Figure 5-16 shows that an increase in utilisation of HR dams or a change in policy to permit increased HR dams would increase the number of days below the cease to pump threshold (4 ML/d) in the Wyong catchment in dry years. Permitting HR dams in the Wyong catchment on 3rd order as well as 2nd order streams would increase the number of days below the cease to pump threshold by between 3% and 6% of days, as shown by the orange coloured curves sitting above the blue coloured curves in Figure 5-16.



- **Figure 5-15 Comparison of proportion of days below the cease to pump threshold (4 ML/d) for the driest 10% of years, near median 10% of years and all years for the Wyong catchment**



- **Figure 5-16 Proportion of days below cease to pump threshold (4 ML/d) for the very low flow class for the driest 10% of years compared with total storage volume of harvestable rights dams for the Wyong catchment**

5.4 Impact of harvestable rights scenarios on environmental water

Impacts on a large variety of environmental flow statistics were calculated in each catchment and for each scenario modelled. The variations between scenarios within each catchment, for most of these statistics, were negligible.

The one aspect of the flow regime where the different scenarios did appear to have an impact was on the mean duration of freshets. Figure 5-17 and Figure 5-18 show the mean duration of freshets in the low and high flow seasons respectively. The mean duration of freshets reduces as the HR and the uptake of the HR increases, particularly when dams are permitted on 3rd order as well as 2nd order streams. Farm dams are effective at capturing inflows from the first part of freshet events, hence reducing the duration of these regular small floods.

Figure 5-19 demonstrates this effect on the mean duration of freshets in the low flow season for all 40 scenarios modelled in the Nambucca catchment. The relationship between the duration of freshets and the storage volume of HR dams for the Nambucca catchment are shown in Figure 5-20 and Figure 5-21, for the wet and dry seasons respectively. Increasing the volume of HR dams reduces the mean duration of freshets in both the low and high flow seasons. These figures demonstrate that in the Nambucca catchment, the mean duration of freshets was more sensitive to the volume of HR dams in the low flow season than in the high flow season.

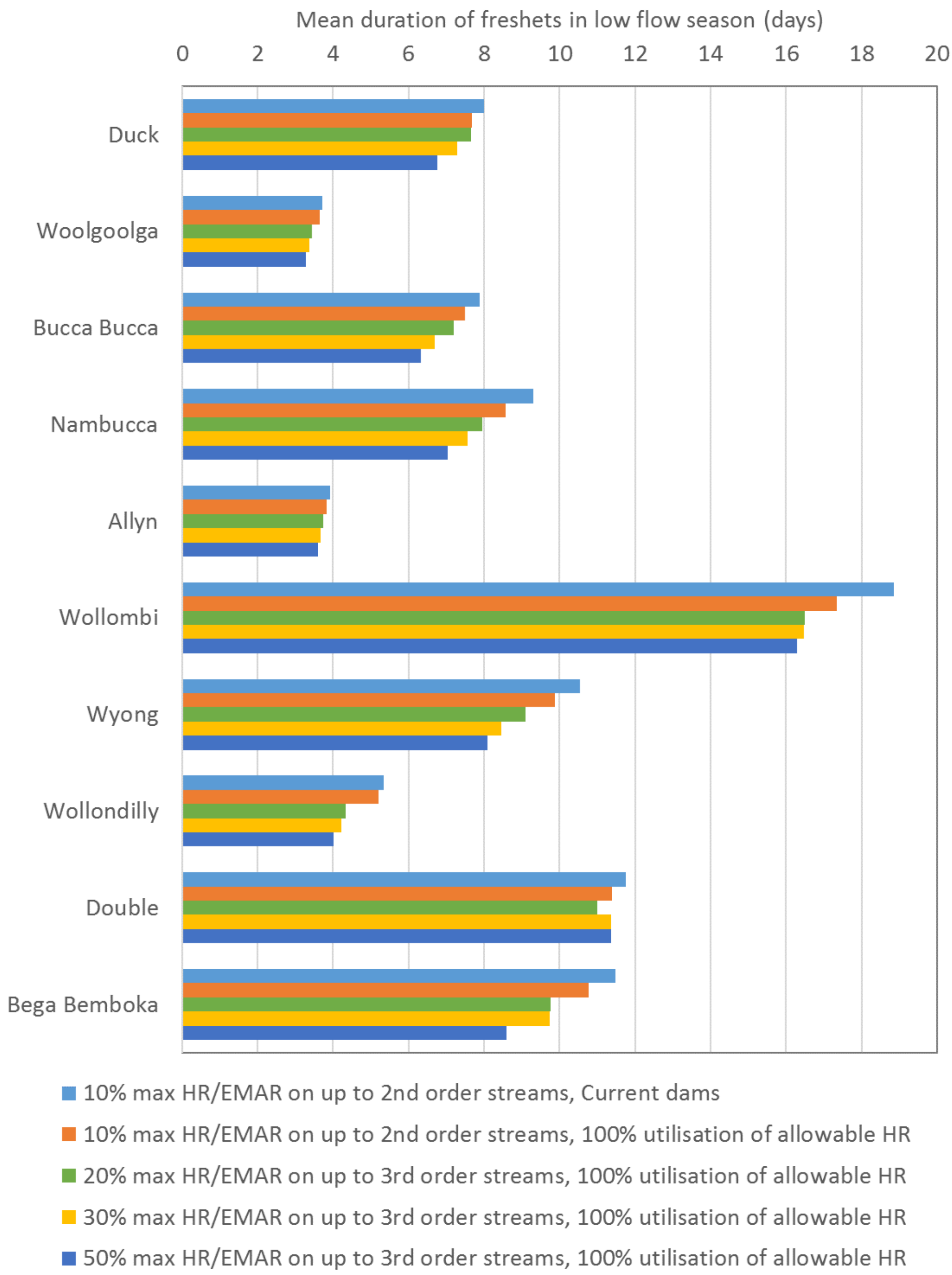


Figure 5-17 Comparison of mean duration of freshets in the low flow season for all study catchments and for five selected key scenarios

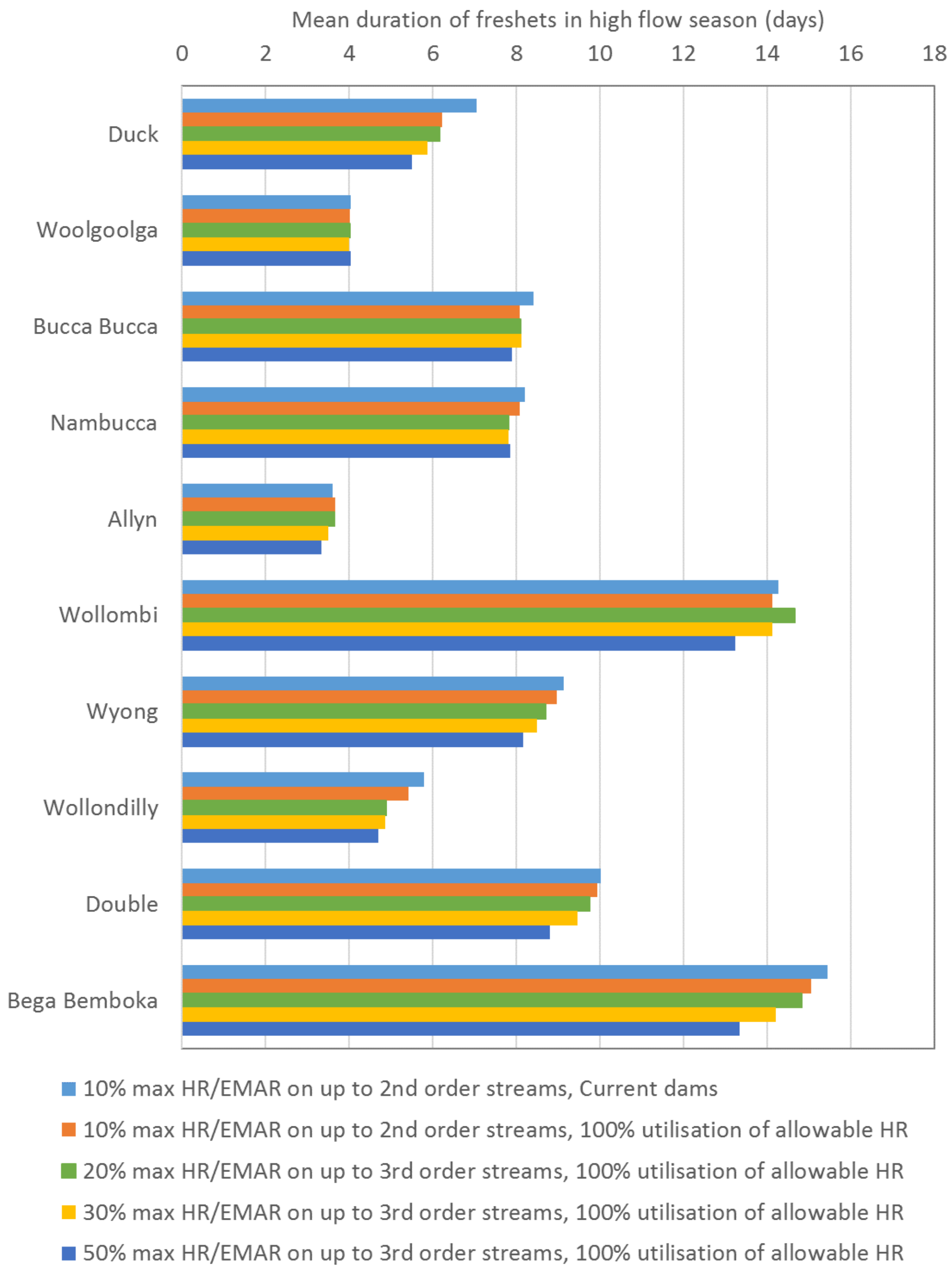
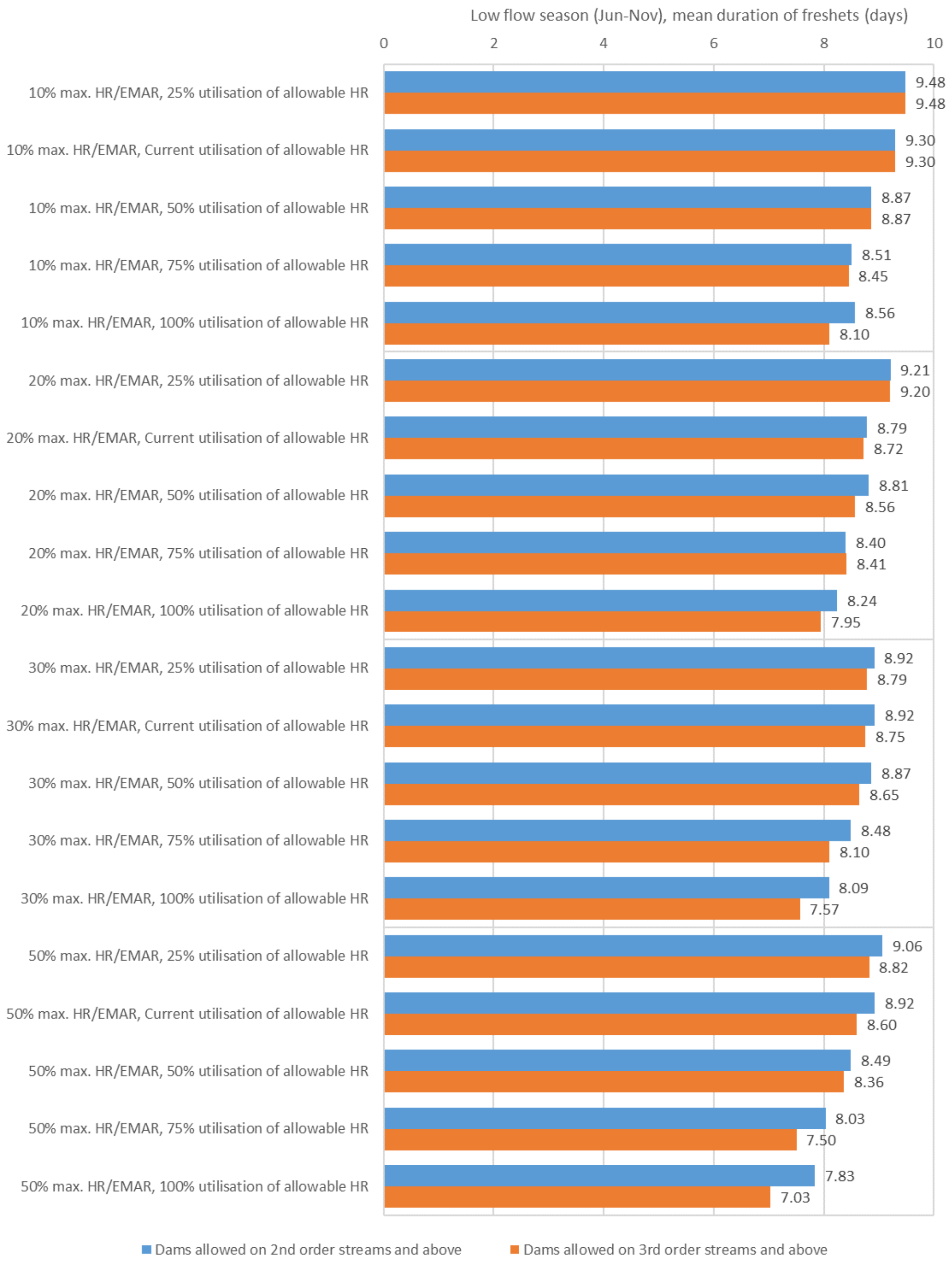
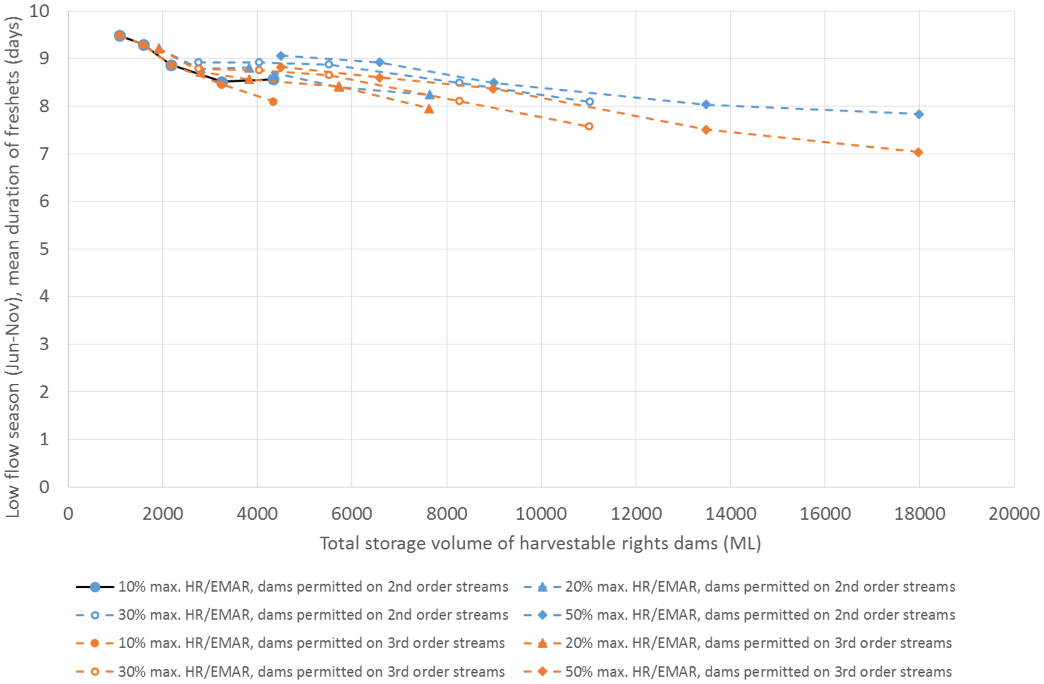


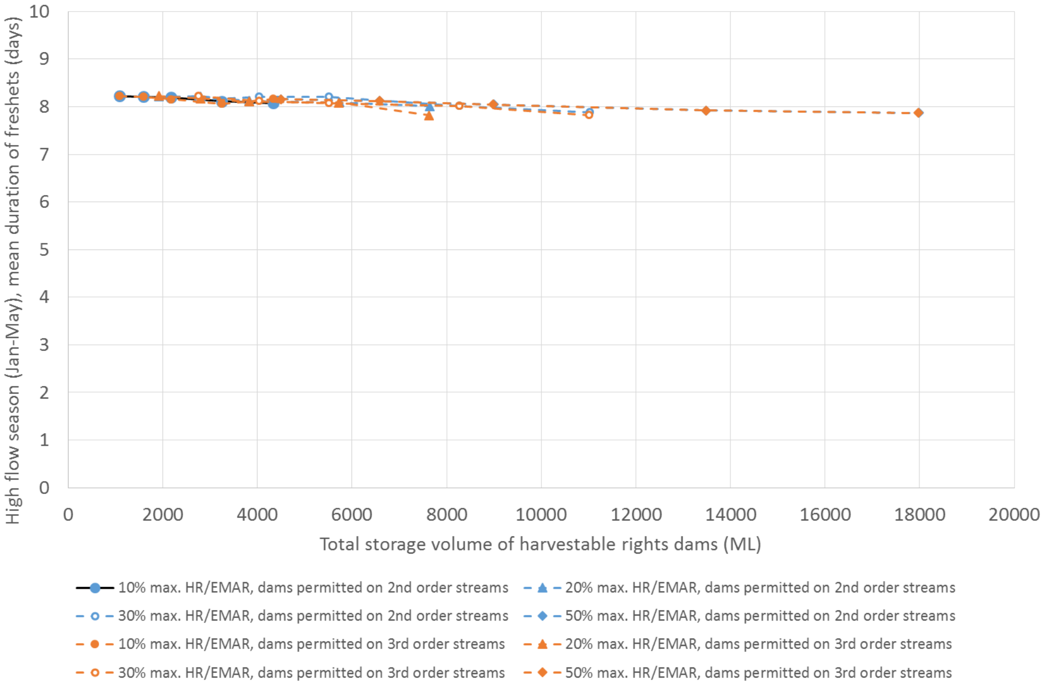
Figure 5-18 Comparison of mean duration of freshets in the high flow season for all study catchments and for five selected key scenarios



- **Figure 5-19 Mean duration of freshets in the low flow season for harvestable rights scenarios in the Nambucca River catchment**



- **Figure 5-20 Relationship between mean duration of freshets in the low flow season and storage volume of harvestable rights dams in the Nambucca River catchment**



- **Figure 5-21 Relationship between mean duration of freshets in the high flow season and storage volume of harvestable rights dams in the Nambucca River catchment**

5.5 Remarks on potential consequences of dam failure

Farm dams, including HR dams, may present a risk to people and property that are downstream of them, in the event that they were to fail. Under the Dams Safety Act (1978), dam owners are responsible for the safety of their dam(s) and for meeting the requirements of the NSW Dam Safety Committee.

The consequences of dam failure, in terms of potential loss of life, potential damage to property and potential damage to the environment normally increase with increasing storage volume and height of the dam structure. If HR were to be increased then it is likely that there would be an increasing number of larger farm dams constructed, which could then increase the consequences and risk to people and assets downstream of those dams.

6. Limitations and potential further work

This report has presented detailed modelling of potential impacts of changes in HR scenarios for ten catchments that are in basins that drain to the coast. A potential next step would be to regionalise these results to the rest of the coastal catchments in New South Wales. This would involve spatial analysis of the estimated storage volume of existing dams, which could then be used to estimate the impact of these dams on stream flows. Spatial analysis could also be conducted to estimate the HR volumes, under the various scenarios under consideration, hence permitting comparison between the existing and potential impact under each of these scenarios.

The modelling conducted for this study was conducted using streamflow and climate data over a 42 year period from 1975 to 2016 inclusive. Long-term climate variability and climate change may not be captured by the period used for this study. It is recommended that further modelling be conducted to confirm the robustness of the findings under reasonable projections of climate change.

Analysis of the changes in risk presented by potential dam failure, as a result of a change in HR policy, was outside of the scope of this project. It is recommended that analysis of the potential implications for dam safety management be considered as part of further consideration of changes in HR policy.

7. Conclusion and recommendations

The potential level of hydrological impact of changes to the harvestable rights (HR) policy varies between catchments, depending upon a number of factors. The impacts range from small to moderate, but may have a significant impact on parameters such as the number of days and duration below cease to pump, and the total annual flow during drier years. While the purpose of this study is limited to hydrologic change, these changes may have significant impacts on irrigation potential and ecological values.

Uptake of the existing HR varies between catchments, with currently the highest proportions in the Wollindilly (70%), Double (66%) and Bega-Bemboka (65%) catchments. By contrast the current percentage of uptake is lowest in the Bucca Bucca (1%), Allyn and Wollombi (both 13%) catchments.

Existing dams take between 0.01% (Bucca Bucca) and 12.3% (Wollondilly) of the mean annual flow. This would increase to between 0.8% (Bucca Bucca) and 19.6% (Wollondilly) of the mean annual flow if there was 100% utilisation of the existing 10% HR. Lower densities on this upper limit were identified in the catchments with larger proportions of state forest and national park, as it was assumed that there would be minimal development of new dams forested areas.

If the HR policy were to be modified to allow an increase in the HR as a proportion of Estimated Mean Annual Runoff (EMAR) and there was 100% uptake of HR, the mean annual volumes of water extracted by farm dams would increase appreciably in all catchments. The mean annual impacts in the Wollondilly catchment, in particular, could be a very large proportion of the mean annual flow if there was full uptake, with impacts of 31.2% of mean annual flow for the 20% Harvestable Right (HR) / to estimated mean annual runoff (EMAR), 38.3% of mean annual flow for the 30% HR/EMAR and 46.7% of mean annual flow for the 50% HR/EMAR scenarios.

For the other catchments, the mean annual impact as a percentage of mean annual flow are lower values. If there was full uptake of the HR and the HR was increased to 50% of EMAR, the mean annual impact would be 18% in the Duck and Wollombi catchments, down to 3.9% in the Bucca Bucca catchment.

For licensed diverters in many catchments, availability of water during dry years may be more critical than the availability of water in years with near-average or above average flows. The percentage impacts are much larger in dry years than if all years are considered. Existing HR dams already take 35% of mean annual flow in dry years in the Wollondilly catchment and about 10% of mean annual flow in dry years in the Duck, Double and Bega-Bemboka catchments. If there was to be 100% utilisation of the existing farm dams under the current policy (10% HR/EMAR), the impact of HR dams in dry years would be 50% in Wollondilly and they would exceed 10% of annual flow in dry years in eight of the catchments.

The storage volume of dams is a strong predictor of the mean annual impact in each catchment. The ratio of mean annual impact to volume of dams did not vary much between each of the scenarios in each catchment. On average, the mean annual impact of existing dams was 78% of the existing dam storage volume and this ratio typically only changed by a few percent across the scenarios modelled in each catchment. The variations in ratio between catchments were due to the differences in crop type, and hence demand factor, assumed between catchments, and variations in the characteristics of the stream network changing the typical area upstream of each dam (and hence inflow) relative to the dam storage volume. The relative consistency in the ratio of mean annual impact to storage volume provides the opportunity to regionalise the results from the detailed modelling (undertaken for this report) to other catchments across coastal NSW.

Increasing the HR does cause some, usually relatively small, increases in the proportion of days when the flow would be below the cease to pump level. The differences in proportion of days below the cease to pump level between catchments (for existing conditions), were a function of how the cease to pump level had been set in the WSP area planning process.

Ecological flow requirements may vary considerably between different rivers and catchments. However, for this study, no detailed ecological investigations were undertaken to assess the relative impacts of the HR scenarios on water available for the environment. Instead for this project, statistical measures representing the proportion of days of low flows, frequency, duration and magnitude of freshets and frequency, duration and magnitude of small to moderate sized flood flows were assessed in the high and low flow seasons. Impacts on a large variety of environmental flow statistics were calculated in each catchment and for each scenario modelled. The variations between scenarios within each catchment, for most of these statistics, were negligible.

The one aspect of the flow regime where the different scenarios did appear to have an impact was on the mean duration of freshets. The mean duration of freshets reduces as the HR and the uptake of the HR increases, particularly when dams are permitted on 3rd order as well as 2nd order streams. Farm dams are effective at capturing inflows from the first part of freshet events, hence reducing the duration of these regular small floods that remain.

It is recommended that more nuanced assessment of potential effects of farm dams on environmental flows be undertaken, i.e. assessment should be sought from ecologists and geomorphologists of the potential impacts on the flow regime for ecological outcomes under a range of scenarios. A possible template for this would be the work that was undertaken to establish sustainable diversion limits in unregulated catchments in Victoria (Nathan et al., 2002; NRE, 2002; NRE, 2003) and South-West Western Australia (Lang et al, 2008). Similarly, this report does not attempt to quantify the economic implications of increasing HR access, either positive - through the increased storage of water for irrigation, or negative – through the potential impact on water access for existing licence holders.

This report represents the modelling component of the current DPIE review into its HR policy for coastal catchments. The outcomes of the scenario modelling (of which only some are presented in this report) will be used by DPIE to develop recommendations regarding its HR policy.

In reviewing its HR policy, DPIE will focus on periods of low rainfall and runoff during which competition for water is greatest. Furthermore, in using this report to guide HR policy recommendations, it is important to recognise that the modelled outcomes represent end-of-system impacts. It is important to also consider the potential hydrologic impacts within each catchment. For example, an increase in water extracted may have a minimal impact on end-of-system flows but may have substantial hydrological impacts immediately downstream of the extraction point.

8. References

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Appendix A Demands adopted for existing dams

Table A-1 Demands adopted for existing farm dams in the Duck catchment

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	883	0.5	Uniform
Irrigation: pasture	All dams > 5 ML in volume	50	0.85	Daily pattern from IQQM crop model for dairy pasture

Table A-2 Demands adopted for existing farm dams in the Woolgoolga catchment

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	9	0.5	Uniform
Irrigation: pasture	38% of dams > 5 ML in volume	1	0.80	Daily pattern from IQQM crop model for dairy pasture
Irrigation: permanent horticulture	62% of dams > 5 ML in volume	1	0.56	Daily pattern from IQQM crop model for macadamias

Table A-3 Demands adopted for existing farm dams in the Bucca Bucca catchment

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	6	0.5	Uniform
Irrigation: pasture	All dams > 5 ML in volume	1	0.80	Daily pattern from IQQM crop model for dairy pasture

Table A- 4 Demands adopted for existing farm dams in the Allyn catchment

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	960	0.5	Uniform
Irrigation: pasture	All dams > 5 ML in volume	38	0.83	Daily pattern from IQQM crop model for dairy pasture

Table A- 5 Demands adopted for existing farm dams in the Wollombi catchment

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	721	0.5	Uniform
Irrigation: pasture	93% of dams > 5 ML in volume	258	0.87	Daily pattern from IQQM crop model for dairy pasture
Irrigation: permanent horticulture	7% of dams > 5 ML in volume	19	0.59	Daily pattern from IQQM crop model for Grape vines

Table A- 6 Demands adopted for existing farm dams in the Wyong catchment

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	799	0.5	Uniform
Irrigation: pasture	93% of dams > 5 ML in volume	62	0.86	Daily pattern from IQQM crop model for dairy pasture
Irrigation: turf	7% of dams > 5 ML in volume	3	0.75	Daily pattern from IQQM crop model for Turf

- **Table A- 7 Demands adopted for existing farm dams in the Wollondilly catchment**

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	7500	0.5	Uniform
Irrigation: pasture	All dams > 5 ML in volume	257	0.86	Daily pattern from IQQM crop model for dairy pasture

- **Table A- 8 Demands adopted for existing farm dams in the Double catchment**

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	253	0.5	Uniform
Irrigation: pasture	All dams > 5 ML in volume	9	0.84	Daily pattern from IQQM crop model for dairy pasture

- **Table A- 9 Demands adopted for existing farm dams in the Bemboka / Upper Bega catchment**

Dam type	Method of selection	Number of existing dams in catchment	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All dams < 5 ML in volume	1707	0.5	Uniform
Irrigation: pasture	All dams > 5 ML in volume	81	0.85	Daily pattern from IQQM crop model for dairy pasture

Appendix B Demands adopted for future possible dams

Table B- 1 Demands adopted for existing and potential future farm dams in the Duck catchment for HR scenarios

Dam type	Method of selection	Demand factor (Mean demand / dam storage volume)	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	All existing dams in catchment that are > 5 ML in volume, PLUS 40% of new HR dams greater than 5 ML in volume (selected at random)	0.85	Daily pattern from IQQM crop model for dairy pasture
Irrigation: macadamias	20% of new HR dams greater than 5 ML in volume (selected at random)	0.6	Daily pattern from IQQM crop model for macadamias
Irrigation: avocado	20% of new HR dams greater than 5 ML in volume (selected at random)	0.69	Daily pattern from IQQM crop model for avocado
Irrigation: vegetables	20% of new HR dams greater than 5 ML in volume (selected at random)	0.72	Daily pattern from IQQM crop model for vegetables

Table B- 2 Demands adopted for existing and potential future farm dams in the Woolgoolga catchment for HR scenarios

Dam type	Method of selection	Demand factor	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	38% existing dams in catchment that are > 5 ML in volume, PLUS 30% of new HR dams greater than 5 ML in volume (selected at random)	0.8	Daily pattern from IQQM crop model for dairy pasture
Irrigation: permanent horticulture	62% existing dams in catchment that are > 5 ML in volume, PLUS 25% of new HR dams greater than 5 ML in volume (selected at random)	0.56	Daily pattern from IQQM crop model for macadamias
Irrigation: citrus	20% of new HR dams greater than 5 ML in volume (selected at random)	0.54	Daily pattern from IQQM crop model for citrus
Irrigation: bluberries	25% of new HR dams greater than 5 ML in volume (selected at random)	0.74	Daily pattern from IQQM crop model for bluberries

Table B- 3 Demands adopted for existing and potential future farm dams in the Bucca Bucca catchment for HR scenarios

Dam type	Method of selection	Demand factor	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	All existing dams in catchment that are > 5 ML in volume, PLUS 30% of new HR dams greater than 5 ML in volume (selected at random)	0.8	Daily pattern from IQQM crop model for dairy pasture
Irrigation: macadamias	25% of new HR dams greater than 5 ML in volume (selected at random)	0.54	Daily pattern from IQQM crop model for macadamias
Irrigation: citrus	20% of new HR dams greater than 5 ML in volume (selected at random)	0.55	Daily pattern from IQQM crop model for citrus
Irrigation: bluberries	25% of new HR dams greater than 5 ML in volume (selected at random)	0.73	Daily pattern from IQQM crop model for bluberries

Table B- 4 Demands adopted for existing and potential future farm dams in the Allyn catchment for HR scenarios

Dam type	Method of selection	Demand factor	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	All existing dams in catchment that are > 5 ML in volume, PLUS 40% of new HR dams greater than 5 ML in volume (selected at random)	0.83	Daily pattern from IQQM crop model for dairy pasture
Irrigation: olives	20% of new HR dams greater than 5 ML in volume (selected at random)	0.63	Daily pattern from IQQM crop model for olives
Irrigation: nurseries	20% of new HR dams greater than 5 ML in volume (selected at random)	0.59	Daily pattern from IQQM crop model for nurseries
Irrigation: grapes	10% of new HR dams greater than 5 ML in volume (selected at random)	0.59	Daily pattern from IQQM crop model for grape
Eggs	10% of new HR dams greater than 5 ML in volume (selected at random)	0.5	Uniform

- **Table B- 5 Demands adopted for existing and potential future farm dams in the Wollombi catchment for HR scenarios**

Dam type	Method of selection	Demand factor	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	93% existing dams in catchment that are > 5 ML in volume, PLUS 20% of new HR dams greater than 5 ML in volume (selected at random)	0.87	Daily pattern from IQQM crop model for dairy pasture
Irrigation: permanent horticulture	7% existing dams in catchment that are > 5 ML in volume, PLUS 10% of new HR dams greater than 5 ML in volume (selected at random)	0.59	Daily pattern from IQQM crop model for grape
Irrigation: olives	10% of new HR dams greater than 5 ML in volume (selected at random)	0.67	Daily pattern from IQQM crop model for olives
Irrigation: nurseries	10% of new HR dams greater than 5 ML in volume (selected at random)	0.82	Daily pattern from IQQM crop model for nurseries
Eggs	10% of new HR dams greater than 5 ML in volume (selected at random)	0.5	Uniform
Mining	40% of new HR dams greater than 5 ML in volume (selected at random)	0.8	Uniform

- **Table B- 6 Demands adopted for existing and potential future farm dams in the Wyong catchment for HR scenarios**

Dam type	Method of selection	Demand factor	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	93% existing dams in catchment that are > 5 ML in volume	0.86	Daily pattern from IQQM crop model for dairy pasture
Irrigation: turf	7% existing dams in catchment that are > 5 ML in volume, PLUS 30% of new HR dams greater than 5 ML in volume (selected at random)	0.75	Daily pattern from IQQM crop model for turf
Irrigation: avocado	25% of new HR dams greater than 5 ML in volume (selected at random)	0.58	Daily pattern from IQQM crop model for avocado
Irrigation: vegetables	15% of new HR dams greater than 5 ML in volume (selected at random)	0.68	Daily pattern from IQQM crop model for vegetables
Irrigation: nurseries	30% of new HR dams greater than 5 ML in volume (selected at random)	0.79	Daily pattern from IQQM crop model for nurseries

- **Table B- 7 Demands adopted for existing and potential future farm dams in the Wolondilly catchment for HR scenarios**

Dam type	Method of selection	Demand factor	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	All existing dams in catchment that are > 5 ML in volume	0.86	Daily pattern from IQQM crop model for dairy pasture
Irrigation: vegetables	10% of new HR dams greater than 5 ML in volume (selected at random)	0.77	Daily pattern from IQQM crop model for vegetables
Irrigation: olives	40% of new HR dams greater than 5 ML in volume (selected at random)	0.71	Daily pattern from IQQM crop model for olives
Irrigation: nurseries	10% of new HR dams greater than 5 ML in volume (selected at random)	0.84	Daily pattern from IQQM crop model for nurseries
Eggs	40% of new HR dams greater than 5 ML in volume (selected at random)	0.5	Uniform

- **Table B- 8 Demands adopted for existing and potential future farm dams in the Double catchment for HR scenarios**

Dam type	Method of selection	Demand factor	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	All existing dams in catchment that are > 5 ML in volume, PLUS 60% of new HR dams greater than 5 ML in volume (selected at random)	0.84	Daily pattern from IQQM crop model for dairy pasture
Irrigation: stone fruit	20% of new HR dams greater than 5 ML in volume (selected at random)	0.61	Daily pattern from IQQM crop model for stone fruit
Irrigation: apple	20% of new HR dams greater than 5 ML in volume (selected at random)	0.69	Daily pattern from IQQM crop model for apple

- **Table B- 9 Demands adopted for existing and potential future farm dams in the Bemboka / Upper Bega catchment for HR scenarios**

Dam type	Method of selection	Demand factor	Demand temporal pattern
Stock and domestic	All existing dams < 5 ML in volume PLUS All new HR dams less than 5 ML in volume	0.5	Uniform
Irrigation: pasture	All existing dams in catchment that are > 5 ML in volume, PLUS 60% of new HR dams greater than 5 ML in volume (selected at random)	0.85	Daily pattern from IQQM crop model for dairy pasture
Irrigation: stone fruit	20% of new HR dams greater than 5 ML in volume (selected at random)	0.61	Daily pattern from IQQM crop model for stone fruit
Irrigation: apple	20% of new HR dams greater than 5 ML in volume (selected at random)	0.7	Daily pattern from IQQM crop model for apple

Appendix C Cease to pump levels specified in water sharing plans

Table C- 1 Cease to pump thresholds specified in water sharing plans for study catchments

Catchment	Water Source	Reference flow gauge	Class of diverters	Cease to pump flow rate (ML/d)
Nambucca	North Arm Nambucca River and Missabotti Creek	205006, Nambucca River at Bowraville as a proxy for 205015, Nambucca River North Arm upstream of Bowraville	Very low flow class	5
	South Creek and Buckrabendinni Creek	205018, South Creek at Bowraville	Unregulated river access	No visible flow at pumping site
Wyong	Wyong River	Combined flows at 211009, Wyong River at Gracemere gauge and 211010, Jilliby Jilliby Creek at upstream of Wyong River (Durren Lane) gauge.[2]	Very low flow class	4
			A class	13.5
			B class	26
Wollondilly	Upper Wollondilly River	2122711, Wollondilly River at Murrays Flat	Very low flow class	2
Double	Lower Bega / Lower Brogo Rivers tributaries	219017, Double Creek near Brogo	Very low flow class	2
	Upper Bega / Bemboka Rivers tributaries	219017, Double Creek near Brogo	Very low flow class	2
Upper Bega / Bemboka	Upper Bega / Bemboka Rivers	219032, Bega River at Kanoona	Very low flow class	2
			Low flow class	5
			A class	65
			B class	160

[2] Note that the reference point may change during the term of the plan to the Wyong River Weir, if appropriate.

- **Table C- 2 Cease to pump thresholds specified in water sharing plans for study catchments, which were not able to be assessed against flows modelled at catchment outlet locations, due to the location of the reference point or nature of the condition in the water sharing plan**

Catchment	Water Source	Reference flow gauge	Class of diverters	Cease to pump flow rate (ML/d)
Duck	Duck Creek	Not applicable	Unregulated river access	"No visible flow"[3] at pumping site
Woolgoolga	Woolgoolga Creek	(No gauge number) Woolgoolga Creek at Reserve upstream of Pacific Highway	Very low flow class	"No visible flow"[4]
Bucca Bucca	Bucca Bucca River	Not applicable	Unregulated river access	"No visible flow"[5] at pumping site
Nambucca	Coastal Nambucca River	Not applicable	Unregulated river access	"No visible flow"[6] at pumping site
Allyn	Paterson/Allyn	210022, Allyn River at Halton	Very low flow class	7 ML/d OR there is no visible flow at the Allyn River at Flying Fox Lane (210143)
Wyong	Jilliby Jilliby Creek	211010, Jilliby Jilliby Creek at upstream Wyong gauge (Durren Lane)	Very low flow class	1
Wollondilly	Lower Wollondilly River	212271, Wollondilly River at Golden Valley	Very low flow class	3 (commence to pump at flows greater than 5 ML/d)

[3] The rules summary sheet for the Duck Creek water source states that cease to pump occurs when there is, "No visible flow at the pump site."

[4] The rules summary sheet for the Woolgoolga Creek water source states that, "All licence holders must cease to pump:
(a) when there is no visible flow immediately downstream of their pump site or into and out of the pumping pool, or
(b) when there is no visible flow at the reference point."

[5] The rules summary sheet for the Bucca Bucca River water source states that cease to pump occurs when there is, "No visible flow at the pump site."

[6] The rules summary sheet for the Coastal Nambucca River water source states that, "Licence holders are not permitted to take water when there is no visible flow at the pump site, or where water is being taken from a pool, when there is no outflow from the pool."