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A model for assessing the impacts of farm dams on surface waters in the WaterCAST catchment modelling framework

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Abstract: With the continuing pressure on Australia's water resources farmers in many catchments are turning to farm dams as a means of providing additional sources of water for irrigation and stock. However, excessive farm dam development has been shown to have significant impacts on streamflow in many parts of Australia. The density and distribution of farm dams is related to the type and degree of change in land use. Therefore, there is a need to incorporate into catchment scale models links between catchment hydrology, farm dams and land use characteristics. This paper discusses the development of a farm dam model in the WaterCAST catchment modelling framework, for the assessment of farm dam impacts on stream flow at finer catchment scales that capture changes in land use and land management.

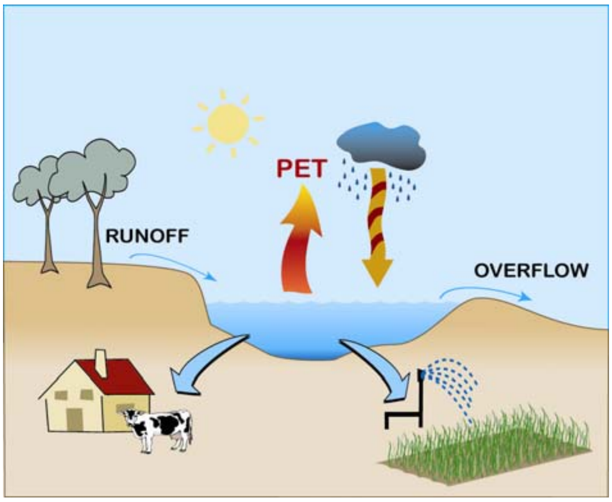

Figure 1. Conceptual diagram of farm dam water balance processes.

WaterCAST's farm dam model is based on the TEDI model (Tool for Estimating Dam Impacts). The TEDI model is conceptually simple, but has been designed with a level of complexity that is appropriate for the nature of available farm dam data. This flexibility has been replicated in WaterCAST. For instance, the specific sizes and spatial extent of every dam in a catchment is not explicitly represented. Instead, a distribution of farm dam sizes is split into a number of classes and the proportion of farm dams within each size class is entered into the model. The model then stochastically generates a sample of individual dams from this distribution until the required level of development has been reached. A water balance is then calculated for each dam in the generated sample (Figure 1). The WaterCAST farm dam model gives users the ability to configure farm dam characteristics for certain functional unit types, such as land use, to give a more detailed understanding on catchment response to alterations in stream flow. The model assesses the impact on catchment water quantity only, not water quality, such as sediment trapping.

The results show that the WaterCAST farm dam model can reproduce outputs generated by TEDI. The successful model validation gives confidence in the WaterCAST farm dam model as a robust tool for investigating farm dam impacts on catchment hydrology. A case study of the Campaspe River catchment (Victoria, Australia) demonstrates how farm dams can be customised for different land use types and the affects on catchment runoff explored within the WaterCAST modelling framework.

Keywords: *TEDI, CHEAT, land use, land management, on-farm storages, farm pond, runoff*

1. INTRODUCTION

With the continuing pressure on Australia's water resources farmers in many catchments are turning to farm dams as a means of providing additional sources of water for irrigation and stock. However, excessive farm dam development has been shown to have significant impacts on streamflow in many parts of Australia (Neal et al, 2002). This is particularly significant for catchments with low yields of runoff. Recently, there has been a push by government agencies and natural resource management agencies to understand and quantify the cumulative impact of farm dams on catchment hydrology, in particular in response to land use and climate change. Previous studies using WaterCress (Cresswell, 2002) have focused on investigating individual catchments with high farm dam densities and intensive agricultural land uses (Teoh, 2002; McMurray, 2004; Alcorn, 2006). More recently a whole basin approach has been targeted, such as the CSIRO Sustainable Yields project for the Murray-Darling Basin (MDB), which assessed the impact of farm dams on surface water resources of the MDB under current and future climate scenarios and possible land management changes (Chiew et al, 2008; MDBC, 2006). Therefore, there is a need to incorporate into catchment scale models links between catchment hydrology, farm dams and land use characteristics (Neal et al, 2002). This paper discusses the development of a farm dam model in the WaterCAST catchment modelling framework, for the assessment of farm dam impacts on stream flow at finer catchment scales that capture changes in land use and land management.

The approach to assessing farm dam impacts on catchment hydrology has been through the use of computer models, where a water balance for individual farm dams is computed for either a whole catchment, or for smaller subcatchments. For example, the TEDI model (**T**ool for **E**stimating **D**am **I**mpacts) is a simple computer program that assesses the impacts of farm dams on stream flow at catchment scales (Nathan et al, 2005). The TEDI model is conceptually simple, but it has been designed with a level of complexity that is appropriate for the nature of available data. Rather than representing dams in a spatially explicit manner, TEDI calculates the individual capacities of farm dams by stochastically sampling from a known distribution of dam sizes until the required level of development has been reached. A water balance is then computed for each individual dam that TEDI has generated. The CHEAT model (**C**omplete **H**ydrological **E**valuation of the **A**ssumptions in **T**EDI) is a progression from TEDI that uses a spatially explicit network of all farm dams in a study catchment. Therefore, the location and characteristics (e.g. total volume, demand, up-slope area) of each dam is specified and used as an input to a water balance model of the catchment (Jordan et al, 2004). TEDI and CHEAT are considered as the standard tool for assessing farm dam impacts on streamflow, and have been applied to many catchments in Australia, particularly in Victoria and New South Wales.

2. THE WATERCAST FARM DAM MODEL

2.1. Overview

WaterCAST is a whole-of-catchment modelling framework that represents a catchments' hydrology using a lumped approach (Argent et al, 2008). The node-link network links subcatchments, which are delineated via Functional Units (FU), which are areas within a sub catchment with a common hydrological response. Commonly, they are differentiated based on land use, providing a means for investigating catchment response to land use change. FUs generate runoff and constituents, which can then be modified by storage, demand, in-stream and filtering models. WaterCAST offers a choice of models for rainfall-runoff and constituent (such as nutrients and sediment) generation, and filtering models that can be "plugged-in" to the modelling framework.

The WaterCAST farm dam model has been developed by integrating the TEDI model into the WaterCAST modelling framework. The WaterCAST farm dam model has adopted from TEDI the same stochastic method of generating farm dam numbers, but applies this at the Functional Unit scale. This way the farm dam models can be configured for specific Functional Unit types, which may have different water demand patterns or different proportions of small and large dams. Once a sample of farm dams and corresponding capacities has been generated a daily water balance is calculated for each dam (Figure1). The water balance for each dam considers inflows from the local catchment area, rainfall falling directly on the dam surface, evaporation losses from the dam, and consumption from the dam to meet irrigation and stock and domestic demands. Demands are extracted from the dams uniformly throughout the year for small dams used mostly for stock & domestic consumption, whilst a seasonal pattern of demands for irrigation purposes is specified for dams over a nominated size. The water balance computes the storage in each dam at the end of the time step and the volume of any spills from each dam. Seepage losses from the dams are assumed to be negligible and are ignored at this stage of development (Nathan et al, 2005). Farm dams modelled by WaterCAST refer to those dams that collect water from their own catchment, not those that store water diverted from a nearby river, which are usually included within existing river system models.

The main assumptions used in the WaterCAST farm dam model can be summarised as follows:

1. The capacities of dams within the model are generated stochastically from the observed distribution of dam sizes within the catchment;
2. Spills from each farm dam flows directly to the next sub catchment downstream, without being lost or captured by other dams within the functional unit;
3. The total flow harvested by each dam is directly proportional to the dam size and its catchment area;
4. The local catchment area corresponding to each farm dam is assumed to be represented by a relationship with farm dam capacity (see Nathan *et al*., 2005);
5. The annual demand to be satisfied by each dam is known, and is assumed to be a constant proportion of the dam storage capacity;
6. Dams less than a given capacity (typically 5 ML) are used for stock & domestic purposes, while dams larger than this are used for irrigation, which influences the monthly pattern of demands from the dam assumed by the model; and
7. The surface area of each farm dam can be estimated using a non-linear relationship with the capacity of the dam.

The user interface for the farm dam model parameterisation allows any number of FUs to be parameterised with farm dams, and has the scope to allow parameters to be customised for different functional unit types. For instance, an “Irrigated Agriculture” FU may have few stock & domestic dams, therefore the proportion of irrigation dams can be increased to reflect large dam size and volumes, and the demand patterns customised to reflect intense irrigation use. In order to keep the model set-up simple and easy to apply across the whole catchment the farm dams parameterised for each FU are allocated to all sub catchments.

Data requirements for the WaterCAST farm dam model are listed below:

- Farm dam density per FU (ML/km^2)
- Function representing the catchment area corresponding to a 5 ML and 100 ML dam. The model assuming a linear relationship between dam volume and catchment area, defined by the catchment area of a 5 ML (small dams) and a 100 ML (larger) dam. This is based on previous Victorian studies (see SKM, 2004; Nathan et al, 2005).
- Average monthly demand pattern for irrigation and stock & domestic dams
- Capacity threshold between large irrigation dams and smaller stock / domestic dams (Default = 5 ML)
- Usage factor representing the proportion of water used as a proportion of dam volume
- A distribution of the proportion of farm dam numbers and average volumes within each size class to stochastically generate the farm dam network.
- Parameters (a and b) for relating dam surface area and volume (regression relationship) Surface Area = aVolume^b (Nathan et al., 2005).

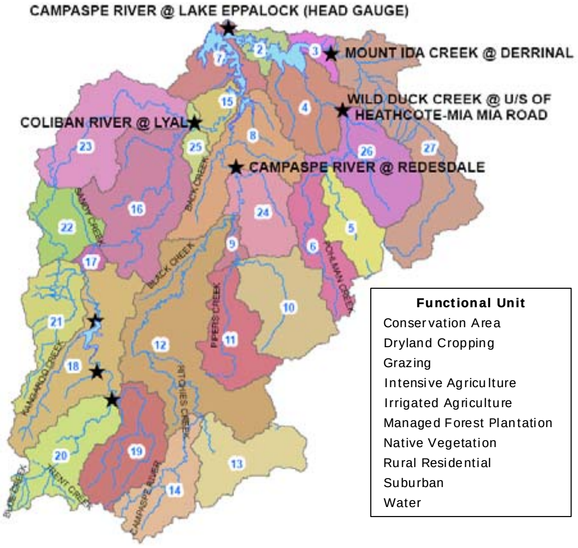

Figure 2. Campaspe River Catchment, upstream of Lake Eppalock, showing sub catchment divisions, major tributaries and stream flow gauging stations (Huider, 2008).

2.2. Experimental procedure for testing the WaterCAST farm dam model

The Campaspe River Basin was chosen for this study as a test case. The Campaspe River Basin covers an area of approximately 4,000 km^2 of north central Victoria, Australia, and flows north from its source in the Great Dividing Range to the Murray River. The Campaspe River experiences extreme variations in flow from year to year. The Campaspe basin has a very high density of farm dams relative to other basins in Victoria (SKM, 2008).

Farm dam data for the Campaspe River Basin was taken from an SKM study (SKM 2008) carried out on behalf of the Victorian Department of Sustainability & Environment (DSE). CHEAT models were constructed to assess farm dam impacts on stream flows in 12 sub catchments of the Campaspe River Basin. CHEAT calculated farm dam impacts at each sub catchment outlet, rather than considering flows cascading from dam to dam. For this study only data for those sub catchments upstream of Lake Eppalock were utilised (Figure 2). To effectively test the farm dam model in WaterCAST two experiments were designed:

2.3. Part 1: Comparison of TEDI and WaterCAST farm dam model performance

A simple experiment was designed to directly compare the TEDI model and the WaterCAST farm dam model performance. All inputs to TEDI and the WaterCAST farm dam model were standardised in order to compare model outputs at the catchment outlet. Therefore, climate data, the farm dam size class/volume distribution, catchment area/storage capacity relationship, monthly demand patterns and constant parameters were kept the same. Stream flow input into TEDI, which would normally be a continuous time series of measured stream flow at a gauge, was derived from WaterCAST as the total runoff generated from all 28 sub catchments. One functional unit was included in order to compare the same catchment areas. A farm dam density of 11 ML/km^2 was applied to the whole catchment, which is the mean dam density found by the SKM (2008) study for the Campaspe River catchments upstream of Lake Eppalock. A single, spatially averaged daily time series of rainfall (mm) and potential evaporation was used as climate inputs into both models. CHEAT parameters were applied to all sub catchments modelled in WaterCAST (Tables 1, 2 & 4; Figure 3). Both WaterCAST and TEDI models were run on a daily time step for a 21 year period (1st January 1982 to 31st December 2002).

Table 1. Parameters common to all WaterCAST farm dam models.

Parameter	Value
Capacity threshold for dam sizes (ML)	5
Surface Area parameter a	834.3
Surface Area parameter b	0.761
Usage factor – stock & domestic	0.5
Usage factor - Irrigation	0.84

Table 2. Dam volume and upstream catchment area relation (SKM, 2008).

Dam volume (ML)	Upstream Catchment Area (km^2)
0	0
5	0.26
10	0.42
100	1

Table 3. Farm dam densities applied to specific Functional Units

Functional Unit	Farm Dam Density (ML/km^2)
Conservation Area	2
Grazing	15
Intensive Agriculture	10
Irrigation Agriculture	7

Table 4. The number of farm dams and average volume in each size class as applied for all subcatchments of the Campaspe River Catchment (SKM, 2008).

Size class (ML)	0 – 0.5	0.5 - 1	1 - 2	2 - 5	5 - 10	10 - 20	20 - 40	40 -60	40 - 80	80-100	100-140	140+
Number	3888	2779	2559	2203	796	395	224	56	25	11	15	5
Average volume (ML)	0.25	0.75	1.51	3.42	6.97	14.08	27.57	49.05	69.08	88.73	114.53	188.60

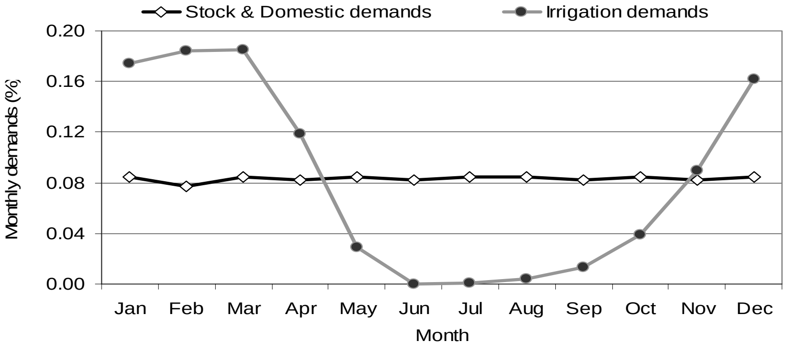

Figure 3. Monthly irrigation and stock & domestic demands from farm dams. The same data set is applied to all sub catchments in the WaterCAST and TEDI farm dam models (SKM, 2008).

2.4. Part 2: Campaspe River Catchment case study

A case study using the Campaspe River WaterCAST model, developed by Goulburn-Murray Water (Huider, 2008), was carried out where the WaterCAST farm dam model was applied. The model is applied to the Campaspe River sub catchments upstream of Lake Eppalock (Figure 2), with a total catchment area of 2065 km^2 and the outlet is located at Lake Eppalock's head gauge. Ten functional units are considered for each of the twenty-eight sub catchments, and the model has been calibrated using the SIMHYD rainfall-runoff model. Climate input data is from spatially gridded (SILO) rainfall and monthly potential evapotranspiration. Model scenarios were run on a daily time step for a 21 year period (1st January 1982 to 31st December 2002).

Farm dam densities (Table 3) and demand patterns (Figure 4) were customised for 4 land use FUs. Farm dams were applied to 72% of the total catchment area, eliminating areas unlikely to include farm dams. Dam densities were derived by comparing farm dam numbers and land use maps, and calculating densities in ML/km^2. Data from the SKM (2008) study was used as a base line from which to derive customised farm dam demand patterns for different land uses, by increasing or decreasing monthly demand percentages by a realistic amount for different land use types. The demand patterns applied to certain FUs should be considered hypothetical, but based on typical dam use patterns for certain land use types in the Campaspe Basin, as specific data was not available. For example, for Grazing FUs dam demands would be expected to have a low proportion of irrigation use, and a higher proportion of stock & domestic use compared to the baseline data (Figure 4).

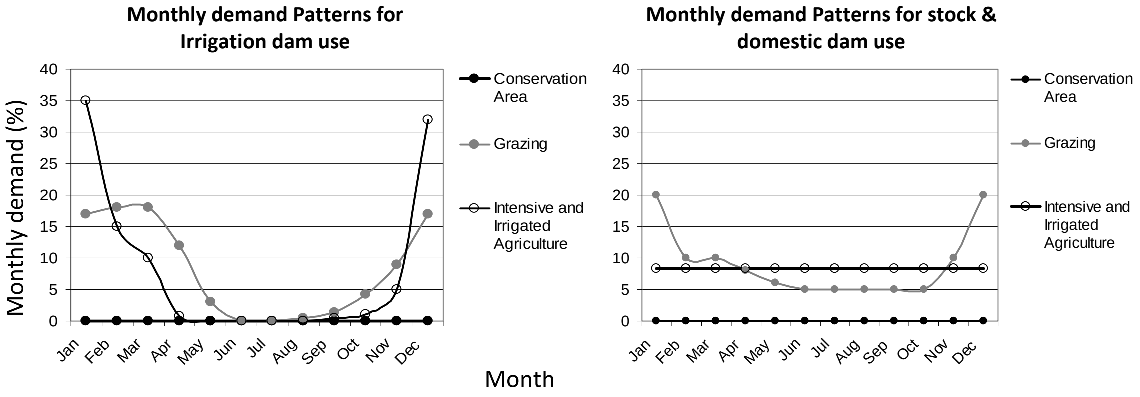

Figure 4. Farm dam demand patterns for stock and domestic dams and irrigation dams as applied per functional unit.

3. RESULTS AND DISCUSSION

3.1. Part 1: Comparison of TEDI and WaterCAST farm dam model performance

Comparisons of TEDI and WaterCAST farm dam model outputs at the catchment outlet show that WaterCAST performs as well as TEDI using the same data (Figure 5). The exceedance curve demonstrates the close fit between TEDI and WaterCAST, therefore giving us confidence that the algorithms taken from

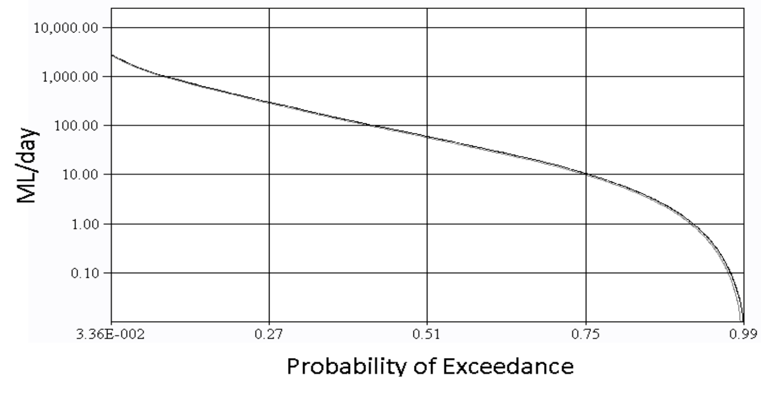

Figure 5. Exceedance curve of TEDI (grey line) and WaterCAST (black line) modified flow at the catchment outlet for the Campaspe River Catchments upstream of Lake Eppalock. Mean: WaterCAST = 471.3 ± 1699.9; TEDI = 454.69 ± 1671.25. R^2 = 1; y = 0.9998x. Data set for 1982 – 2002.

TEDI are working correctly and as expected in WaterCAST. TEDI generates 7082 dams for a catchment area of 2065.05 km^2 and a total capacity of farm dams of 22715.5 ML. WaterCAST, for the same catchment area and total farm dam capacity values, generates 6982 farm dams. There is a small discrepancy between the numbers of dams generated, which could be attributed to the different random number generator adopted by each model. However, the difference in dam numbers is acceptable given the close fit between the runoff simulated by TEDI and WaterCAST.

3.2. Part 2: Campaspe River Catchment case study

The results of the WaterCAST Campaspe case study predict that farm dams reduce average annual catchment runoff by 7%, with minimum and maximum monthly reductions of 4% and 22% respectively. The annual impact by farm dams is less then that suggested by the SKM (2008) study (Mean = 10%, min = 6%; max = 40%). However, farm dam models were only applied to 72% of the total catchment area, as farm dams would not be present in some areas such as forests. Whereas the SKM (2008) study applied farm dam models to 100% of the catchment area. Therefore, adjusting for the total catchment area by 0.28 gives a mean annual impacted flow of 9%, with a minimum and maximum of 5% and 28%. The mean and minimum annual impacted flow compares favourably with the SKM study, however, the maximum impacted flow given by WaterCAST is considerable less then that found in the SKM study. This may be due to modelling uncertainty at high flows, which could indicate that further model calibration is needed to take into account the influences of farm dams. Calibration implications are a focus of on-going work in testing the WaterCAST farm dam model. Although the SKM (2008) study uses gauged flow as an input to CHEAT and uses a spatial layer of farm dams from which to calculate a water balance, WaterCAST can still successfully reproduce similar results. This also indicates that stochastically generating a farm dam network from a size class – dam volume distribution can realistically represent the impacts of farm dams on catchment streamflow, reducing the need for complex data.

Previous catchment-scale farm dam models tend to parameterise farm dam demands as a constant annual percentage of the total volume for both irrigation and stock & domestic dams (Teoh, 2002). TEDI and CHEAT vary irrigation demand patterns by month, but previous applications of TEDI and CHEAT have assumed a constant pattern of stock & domestic demands. Figure 6 demonstrates how farm dam models applied to certain land use types affect the magnitude of catchment runoff downstream. Grazing is the dominant land use upstream of Lake Eppalock, with the highest density of farm dams, the demand patterns tend to be higher for stock & domestic use rather then for irrigation use. Conversely, Irrigation FUs occupy a smaller area of the catchment, where farm dam demands are much higher for irrigation use then stock & domestic demands. Farm dams in Conservation Areas are few in number, but will still intercept catchment runoff. Farm dam usage is mostly by wildlife, with no extractions for irrigation or domestic use. On a comparable area, Grazing FUs capture a greater proportion of runoff then Irrigation FUs, which exhibit a sharper decrease in runoff capture during the winter months. Farm dams in Conservation Area FUs intercept a small proportion of the total runoff (less then 8% of total impact). These results demonstrate how WaterCAST can be used to realistically explore hydrological impacts of dams by land use in a transparent manner.

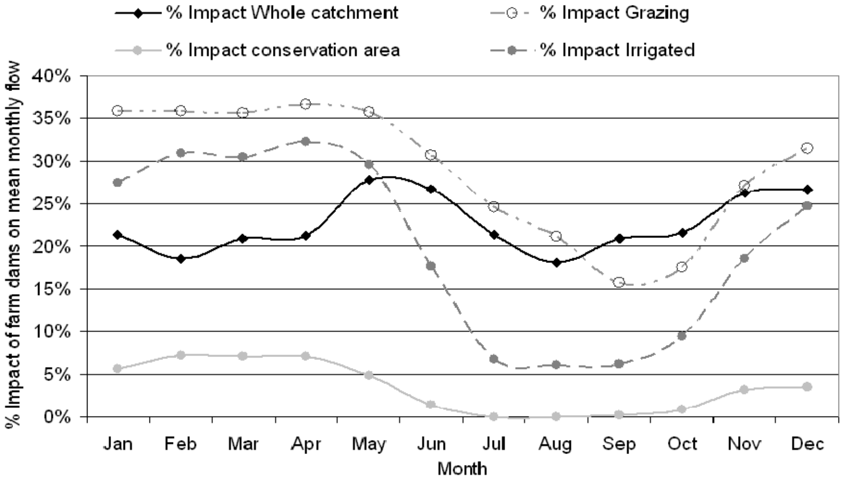

Figure 6. The percent difference in monthly impacted flow for catchment outflow, Grazing FU and Irrigated Agriculture FU at the catchment outlet.

4. CONCLUSIONS

The WaterCAST farm dam model aims to provide users with the ability to assess farm dam impacts on streamflow at catchment scales. This is achieved by integrating the TEDI farm dam model algorithms into the WaterCAST modelling framework. WaterCAST goes a step further by allowing farm dam models to be customised for certain functional unit types, such as land use, to give a more detailed understanding on catchment response to alterations in stream flow. Although TEDI and CHEAT are simplifications of a complex system and do have some limitations in their modelling capabilities, the successful model verification against the best available farm dam models gives confidence in the WaterCAST farm dam model as a robust tool for investigating impacts on catchment hydrology. Future work will focus on improving the usability of the farm dam model and investigating the further potential for customising farm dam characteristics, such as altering the size class-dam volume relationships.

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