Helping farmers and regulators manage and assure the cumulative flood safety of agricultural dams: a cost-effective regionalised review/design tool from Australia

John D. Pisaniello

ABSTRACT

In Australia and other countries, small private dams in agricultural catchments pose both disastrous individual and cumulative dam failure flood threats to downstream communities; threats that can be exacerbated by increased rainfall intensities caused by climate change. This paper addresses the need for a low cost, scientifically acceptable mechanism and policy guidance to help dam owners and governments better understand and manage these risks and assure community safety. To this end an innovative, cost-effective farm dam flood safety review/design tool is developed and tested in Australia, including hydrology-diverse Tasmania, to complement best practice dam safety assurance policy. The tool's development involved generating complex catchment data to represent hydrologically homogenous regions using best practice water engineering methods, to derive simple regionalised dam flood capability prediction relationships of acceptable accuracy. Results demonstrate the tool's successful development and potential transferability to different hydrological regions; how the relationships can be refined by future research and potentially made to account for climate change; and how the tool can be applied within a best practice dam safety assurance policy which includes additional farmer-friendly elements. The findings are potentially transferable to any region to assure communities that cumulative safety threats posed by rural catchment dams are minimised.

Key words | best practice assurance policy, cost-effective hydrological tool, cumulative flood threats, farm dams, flood safety engineering

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INTRODUCTION

Floods from dam failures constitute a widespread hazard to people, property and the environment (Walder & O'Connor 1997; Chang *et al.* 2011). Failures of large dams (commonly those higher than 15 m) are spectacular and receive greater attention than those of smaller dams. However, small dam failures, particularly those of privately-owned farm dams, occur with greater frequency (Lewis & Harrison 2002; Pisaniello 2011) and overtopping due to inadequate spillway flood capability is their most common cause of failure (Foster *et al.* 2000).

Small farm dams are usually earthen embankments and therefore, unlike masonry dams must not be allowed to overtop (ANCOLD 2000; Foster *et al.* 2000). Prior research and evidence demonstrates that without appropriate design, construction, maintenance, surveillance, review and upgrading, poorly managed small dams pose both significant individual and cumulative flood safety threats, and can cause considerable losses to the communities and environments downstream (Pisaniello & McKay 2007; Pisaniello *et al.* 2012; Tingey-Holyoak *et al.* 2013). Even more likely in catchments of undulating topography (Bodoque *et al.* 2014), these threats and losses are only exacerbated by climate change due to the significant predicted increases in rainfalls in many regions both in Australia and around the

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world (UN IPCC 2007, Veijalainen & Vehviläinen 2008; Engineers Australia 2014).

Small dam failures internationally have had disastrous consequences (Silveira 2008; Pisaniello *et al.* 2012). For example, in China, the Shimantan and Banquia dams failed in 1975 because of the cumulative failure of 60 smaller dams, resulting in the death of 230,000 people (Si & Qing 1998). In Italy, the Stava dam near Trento failed in 1985 and while releasing only 180 ML of tailings material, it killed 268 people and caused serious environmental damage (Engels 2005). In Brazil in 2010, a cumulative series of private dam bursts left 50 people dead and an estimated 150,000 homeless (Pottinger 2010). A study by Graham (1999) of dam failures in the United States from 1960 to 1998, found that small dams (less than 15 m high) caused 88% of the deaths resulting from all the dam failures studied. Furthermore, these structures not only age, but over time the physical areas of catchments have changed and continue to change significantly due to human activity meaning dam failure flood disasters that threaten life may increase (Jothityangkoon *et al.* 2013).

A clear problem exists with Australian small dam safety because privately owned dams (farm dams especially) are in great abundance (Finch 1997) and have failed in the thousands (Pisaniello & McKay 2007). Australia has in excess of 735,000 farm dams (Baillie 2008), and from these data it is estimated that around 10% are larger than 5 ML in size and around 0.5% are larger than 50 ML. For example, Victoria alone has 300,000 (Lake & Bond 2006) and around 1,000 are large enough (i.e. larger than 5 m high and 50 ML capacity) to cause significant consequences if they fail (Murley 1987). Lewis & Harrison (2002) reported that at least ten significant failures occurred in Victoria in the previous decade. In Tasmania private dams have failed in the past 80 years with serious consequences, including loss of life (Ingles 1984; Pisaniello *et al.* 2012), and currently some 500 of the 8,000 registered dams pose significant safety risks (DPIWE 2005, p. 21; Pisaniello *et al.* 2012). ANCOLD (1992) estimated a 23% failure rate for farm dams in NSW alone which, when considered on a cumulative level in a catchment above a large public dam (i.e. commonly a highly hazardous water supply dam owned and managed by the government), would have catastrophic consequences for property and lives downstream (Pisaniello *et al.* 2012).

Hence, catchment basins and communities are at threat because of the potential and severe consequences of farm dam failure at both the individual and cumulative levels. A need has developed for (i) owners to manage their dams in line with current standards and design rainfalls (including any updates from climate change, e.g. Engineers Australia (2014)) in order to improve safety and reduce the risks involved from dam failures in extreme circumstances, and (ii) governments to account for, supervise and assist in management of the risks in order to provide increased dam safety assurance to downstream communities. The paper aims to address this dual-need by developing a cost-effective flood safety review/design tool that links to best practice dam safety assurance policy to help minimise both individual and cumulative flood risks posed by rural catchment dams. To this end, the research also responds to the need for consistent regionalised local flood knowledge (McEwen & Jones 2012) and technical tools (Finch 1997; Tan *et al.* 2012) in addressing contemporary issues specific to small private dams.

The remainder of the paper firstly outlines the research context and scope, followed by the research design and methods used, the results and their applicability are then considered, and finally discussion, implications and conclusions are provided.

RESEARCH CONTEXT, SCOPE AND STUDY REGION

In Australia, minimum dam safety standards are set by the Australian National Committee on Large Dams (ANCOLD) whilst acceptable dam flood engineering methods and procedures are set by the Institution of Engineers, Australia (IEAust 1987, 1999). The Bureau of Meteorology (BoM) generates and provides guidance on Australian rainfall data for use by the water/dams engineering profession (e.g. BoM 1994).

Past research has demonstrated the serious individual and cumulative dam failure threats posed by small dams not meeting minimum design flood standards, and therefore the need to regulate even the smallest of dams (Pisaniello *et al.* 1999, 2012; Pisaniello 2011). However, administering and enforcing such regulation can be difficult and politically challenging (Pisaniello 2011). This is because the engineering consulting involved in modern flood capability design/review is expensive and often not affordable by private owners (Pisaniello *et al.* 1999, 2012). Hence, there is a need for appropriate cost-effective technology to complement best practice dam safety assurance policy.

Pisaniello *et al.* (1999) assisted in this area by successfully developing a cost-effective, regionalised farm dam spillway design/review technology for South Australia (Figure 1) and successfully transferred it to similar regions in Victoria and New South Wales (Pisaniello & McKay 2007; Pisaniello *et al.* 2012). The scope of this paper is to (i) demonstrate and test the technology's transferability to different regions with highly varying catchment hydrology characteristics and (ii) illustrate the technology's potential integration with best practice cost-effective dam safety assurance policy.

Tasmania provides both the best practice policy and the highly varying topographic, morphological and meteorological (i.e. catchment hydrology) characteristics necessary for the regional diversity of this study. Compared with mainland Australia, Tasmania's topography is very mountainous and undulating over a very small area (Figure 1) and its geology also varies significantly ranging from rich, fertile basalt in the north-west to dolerite and sandy soils scattered throughout other areas (DoM 1983; DPIW 2007). The state has a temperate climate and variable rainfall: up to 2,500 mm per year in the west, to as low as 600 mm in the Midlands and south east (BoM 2009). Farming activity is scattered as reflected by the density of farm dams in different regions (see Figure 2).

Pisaniello (2011) and Pisaniello *et al.* (2012) provide comprehensive description and analysis of each provision of Tasmanian policy against leading international practices, finding that it represents a best practice model benchmark. The Tasmanian policy addresses both the individual and cumulative threats of catchment dams by regulating dams as small as 1 ML (Pisaniello 2011) and is in line with the socio-ecological objective to balance the need for public and environmental protection (Sanchez *et al.* 2014) with the imposition of restrictive and expensive requirements on builders and owners (DPIWE 2003). To avoid placing significant cost on owners, smaller, less hazardous dams do not require

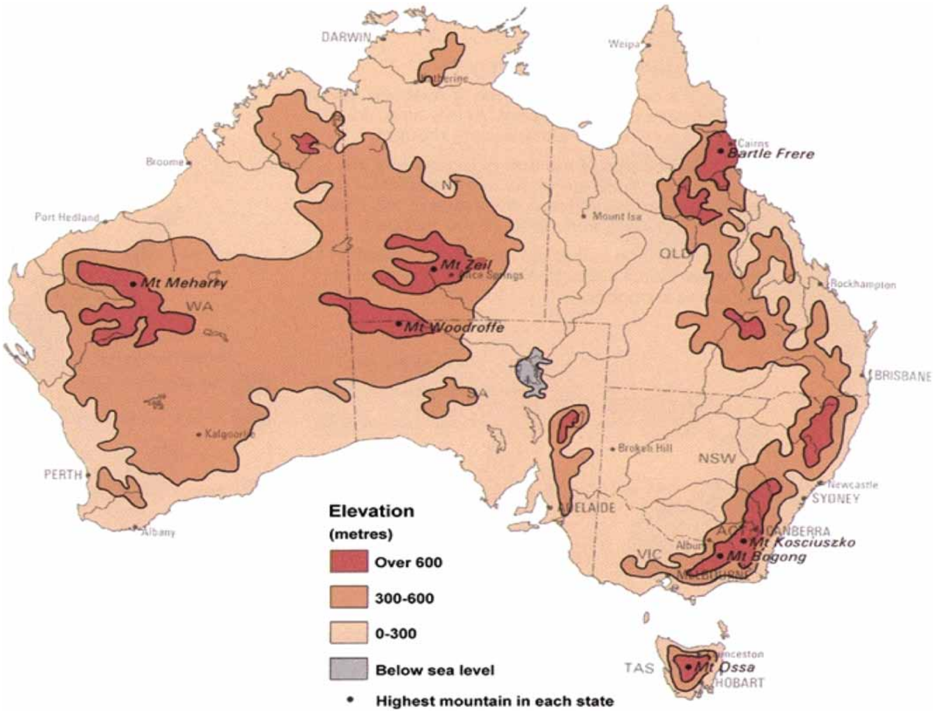


Figure 1 | Elevation map of Australia illustrating the very mountainous elevation of Tasmania (TAS in bottom right hand corner) compared to the rest of Australia, especially South Australia (SA) (*Source:* Geoscience Australia 2014).

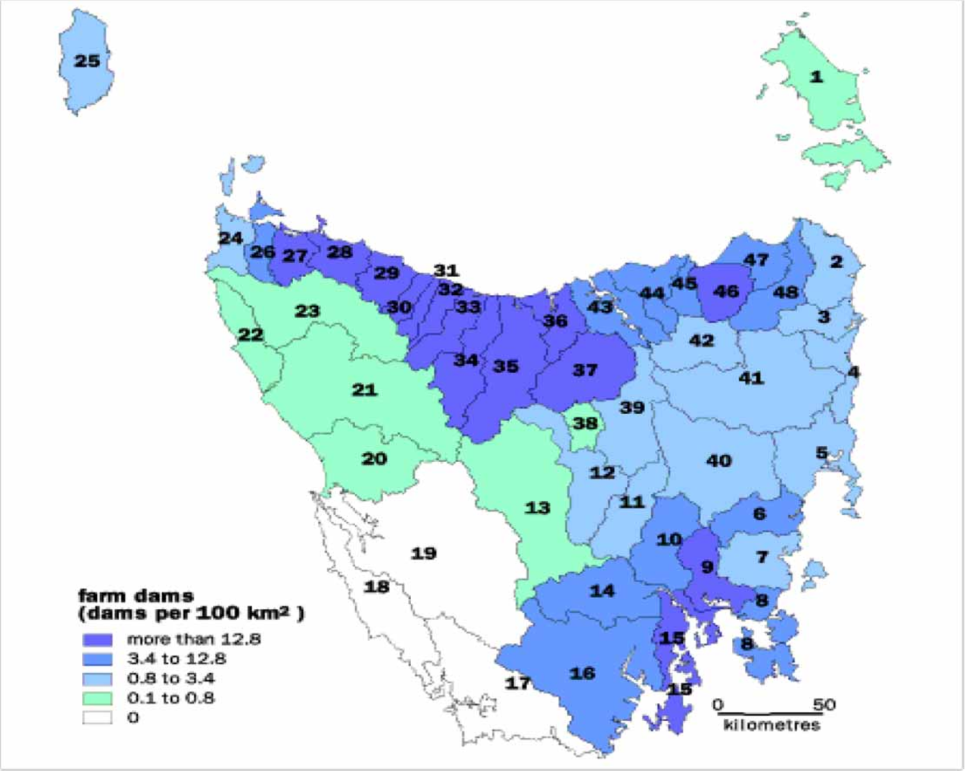


Figure 2 | Concentration of farm dams in Tasmanian planning and management catchments (numbered 1 to 48) with selected study regions comprising Central Region (catchments 4, 5, 11, 12, 39–42), Southern/Hobart Region (6–10, 14–16) and North-West Basalt Region (24, 26–34, 35–37) (*Source:* State of Environment Tasmania 2006).

sophisticated engineering reports but owners may prepare the report with a guided user-friendly and cost-effective pro-forma (DPIW 2009). Hence, the study reported below complements this cost-effective process from Tasmania.

METHOD FOR DEVELOPING THE COST-EFFECTIVE FLOOD SAFETY REVIEW/DESIGN TOOL

The study was based on the Pisaniello (1997) regionalised method as reported in Pisaniello *et al.* (1999), which was developed using the Dimensional Analysis technique (see also Pisaniello 1997, p. 193; Pisaniello *et al.* 2012). This method complies with Australian best practice dam flood engineering, including catchment analysis, modelling and calibration, extreme flood hydrology and reservoir/dam hydraulics per IEAust (1987, 1999) and Bulletin 53 (BoM 1994). It is also in line with overseas practice, for example the rainfall-runoff and reservoir routing modelling adopted recently by Saghafian *et al.* (2014) in Iran and the probability-based risk analysis methodology adopted by Sun *et al.* (2012) to evaluate an earth dam's overtopping risk in China.

Background to Pisaniello *et al.* (1999)

As part of a case study investigating private dam safety management practices in South Australia, the modern flood capabilities were determined of a sample of eleven hazardous private reservoirs located in the Mount Lofty Ranges of South Australia (Pisaniello *et al.* 1999). Given the foundational importance of this work, a brief summary outline is provided below.

- The eleven dams were selected on the basis that they be referable in size (i.e. larger than 5 m high and 50 ML capacity) and rated as either significant or high hazard in accordance with ANCOLD (1986) guidelines.
- The sample dams were all embankment-type structures with typical spillways that were free flowing and weir-type in nature. Maximum wall heights ranged from 5.5

to 10.7 m; storage capacities from 50 to 250 ML; and their catchments from 0.256 to 5.141 km^2.

- Hydrological/hydraulic models of the dams and their catchments were constructed using the RORB runoff routing package (recommended by IEAust (1987)), based on procedures described in Laurenson & Mein (1990).
- Design rainfall information was derived using standard procedures in IEAust (1987) and Bulletin 53 (BoM 1994) for events between the 10 year ARI and the probable maximum flood (PMF).
- The RORB catchment model parameters (catchment non-linearity, storage and catchment losses) represented by k_c, m and initial loss (IL) and continuing loss (CL), were determined for each case in accord with procedures described in IEAust (1987).
- An annual exceedance probability (AEP) for the probable maximum precipitation (PMP) was determined for each sample dam using the procedures outlined in IEAust (1987). Eight sample catchments attracted an AEP of PMP of 1 in 10^7 while the remainder attracted 1 in 10^6.
- ANCOLD (1986, and as updated in 2000) guidelines recommend that unless normal operating conditions indicate otherwise, a 100% full storage level should be assumed when assessing spillway flood capability of embankment dams.
- The RORB model was used to determine peak inflows to the reservoirs for all events possible up to the PMF. This enabled an inflow flood frequency curve to be established for each dam.
- The resulting peak outflows and corresponding peak water levels obtained for all recurrence intervals up to the PMF enabled an outflow flood frequency curve and elevation frequency relationship to be established for each dam.
- The imminent failure flood (IFF) capability, being the flood which when routed through the reservoir results in a peak storage level equal to the lowest elevation on the non-overflow crest (as recommended by ANCOLD (1986, 2000) for embankment dams), was determined in each case from the associated elevation frequency relationships of the dams.

The results of the case study were analysed by comparing them against ANCOLD criteria as illustrated in Table 1. The comparison in Table 1 demonstrates that many hazardous private reservoirs with inadequate spillway capacities do exist in the Mount Lofty Ranges of South Australia. These disturbing results together with two later follow-up studies displaying similar results (see Pisaniello & McKay 2005; Tingey-Holyoak *et al.* 2013) demonstrate that owners are not taking action in terms of analysis and upgrading of their structures and that the need for a dam safety assurance policy in South Australia is urgent. The results presented in Table 1 also provided a foundation for developing regionalised flood capability prediction relationships as follows.

Cost-effective regionalised flood capability prediction relationships for South Australia: sampling and development

In order to readily predict the flood capability of private dams on small catchments in line with modern best practice, a regional relationship was sought, incorporating easily measured variables such as spillway discharge capacity, reservoir area, catchment area, etc. This necessitated the establishment of an adequate sample as follows.

To derive a regional relationship for the prediction of flood-based outcomes involves selecting a homogeneous sample from which possible prediction equations can be derived. The homogenous sample should consist of dams

Table 1 | Comparison of flood capability results with ANCOLD (1986, and as per 2000 update) guidelines for Pisaniello *et al.* (1999) study in South Australia

Dam no.	Minimum hazard rating (high/sig.)	IFF 1/AEP (years)	ANCOLD guidelines IFF range 1/AEP (years)	Acceptable under ANCOLD guidelines? (Yes/No)
1	High	40	PMF-10,000	No
2	High	80	PMF-10,000	No
3	High	97	PMF-10,000	No
4	High	150	PMF-10,000	No
5	High	320	PMF-10,000	No
6	High	2,750	PMF-10,000	No
7	Sig.	190	10,000–1,000	No
8	Sig.	130	10,000–1,000	No
9	Sig.	280	10,000–1,000	No
10	Sig.	500	10,000–1,000	No
11	Sig.	1,400	10,000–1,000	Yes

with catchments exhibiting similar flood responses. The eleven dams reported above were considered to be a homogenous sample in this regard because:

- their catchments had similar physical characteristics and were generally free of other significant flow attenuating storages,
- consistent modelling procedures and parameters were adopted in their analyses, and
- similar design rainfall information applied to each of their catchments, particularly for extreme events.

However, as they stood, the results presented in Table 1 would only have been useful to develop a relationship for Low Hazard dams as most of the flood capability outcomes did not exceed the 1,000 year frequency. The data were limited by the size of the sample reservoirs and their spillways. As the research was mostly concerned with significant and high hazard dams with required flood capabilities beyond 0.1% AEP, the sample data required supplementing with a wider range of outcomes up to the PMF.

To achieve this, further flood capability studies were performed in the sample region based on hypothetical cases involving larger reservoirs and spillways with larger flood capabilities. These cases were created by altering four of the sample dams within their respective RORB data files by incrementally increasing the size of the spillway (i.e. height and width) and size of the reservoir which increases dam capability to attenuate flooding. The four dams were selected based on:

- their catchments being the most evenly spread in the study region,
- a good range of catchment sizes was represented between 1 and 10 km^2, and
- both cases of 1 in 10^6 and 1 in 10^7 AEP of PMF were represented.

In all, 33 new hypothetical dam cases were created. The IFF capabilities of the hypothetical dam cases were then determined in an identical manner to that described above. The results supplemented the flood capability outcomes determined for the real sample dams, providing a total sample space of $n = 44$ for developing prediction relationships.

A dimensional analysis of the results was conducted to explore any possible relationships between dimensionless ratios containing basic hydrological/hydraulic variables and reservoir flood capability (see also Pisaniello 1997, p. 195). Relationships were plotted in the logarithmic domain because of the great range of orders of magnitude associated with flood-based outcomes. The ratio determined to produce the most satisfactory line of best fit from dimensional parameter considerations was named the Reservoir Catchment Ratio (RCR):

$$RCR = \frac{SC}{PI_{PMF}} \cdot \sqrt{\frac{\sqrt{RA} \cdot SH}{1,000 \cdot CA}} \cdot \frac{\log\left\{\frac{PI_{PMF}}{PI_{100}}\right\}}{\log\left\{\frac{PI_{100}}{PI_{50}}\right\}} \tag{1}$$

where $SC =$ spillway overflow capacity (m^3/s); $PI_{PMF} =$ peak inflow for the PMF event (m^3/s); $RA =$ reservoir area at Full Supply Level (km^2); $SH =$ maximum height of spillway overflow (m); $CA =$ catchment area (km^2); $PI_{100} =$ peak inflow for the 100 year average recurrence interval (ARI) event (m^3/s); $PI_{50} =$ peak inflow for the 50 year ARI event (m^3/s).

For regions where no variation amongst sample catchments is observed in the AEP of PMP, the RCR can take on the compact form (Pisaniello *et al.* 1999, 2012):

$$RCR = \frac{SC}{PI_{PMF}} \cdot \sqrt{\frac{\sqrt{RA} \cdot SH}{1,000 \cdot CA}} \tag{2}$$

However, the RCR requires also being able to predict the peak PMF, 100 year ARI and 50 year ARI inflows associated with a dam. Nathan *et al.* (1994) found that empirical relationships for maximum floods are most commonly based on scatter plots of peak flow versus catchment area plotted in the logarithmic domain. Therefore, such relationships for the peak PMF, 100 year and 50 year inflows were derived for the eleven sample catchments (see Pisaniello *et al.* 1999) and substituted into the RCR (Equation (1)) to produce a Regionalised Reservoir Catchment Ratio (RRCR) applicable to the sample region as follows:

$$RRCR = \frac{SC}{97.805 \cdot CA^{0.7747}} \cdot \sqrt{\frac{\sqrt{RA} \cdot SH}{1,000 \cdot CA}} \cdot \frac{\log\left\{\frac{97.805 \cdot CA^{0.7747}}{5.2404 \cdot CA^{0.7453}}\right\}}{\log\left\{\frac{5.2404 \cdot CA^{0.7453}}{4.0985 \cdot CA^{0.7799}}\right\}} \tag{3}$$

A flood capability prediction relationship was then constructed via scatter plot of RRCR versus IFF Capability (1/AEP, years) as presented in Figure 3. This figure shows that a strong relationship exists between RRCR and IFF, consisting of three linear segments with different slopes over the range of AEPs up to the PMF.

The regressions in Figure 3 ($n = 44$ total) are defined by the following power functions (Pisaniello *et al.* 1999):

- Regression for data outcomes up to 1 in 1,000 AEP

$$IFF = 2 \times 10^{8} \cdot RRCR^{2.59} \quad (R^2 = 0.93,\ s.e. = +11.9/-7.2\%,\ n = 10) \tag{4}$$

- Regression for data outcomes from 1 in 1,000 to 1 in 10,000 AEP

$$IFF = 366,518 \cdot RRCR^{1.2191} \quad (R^2 = 0.98,\ s.e. = +2.1/-2.2\%,\ n = 11) \tag{5}$$

- Regression for data outcomes beyond 1 in 10,000 AEP

$$IFF = 3 \times 10^{10} \cdot RRCR^{4.9671} \quad (R^2 = 0.98,\ s.e. = +6.6/-4.3\%,\ n = 23) \tag{6}$$

The coefficient of determination (R^2) and standard error of logarithmic estimate (s.e.) for the above equations suggest that the overall relationship presented in Figure 3 provides a high level of predictive accuracy, particularly for IFF capabilities in the extreme domain. This level of accuracy was considered acceptable for predicting the flood capability of reservoirs on small catchments in the sample region.

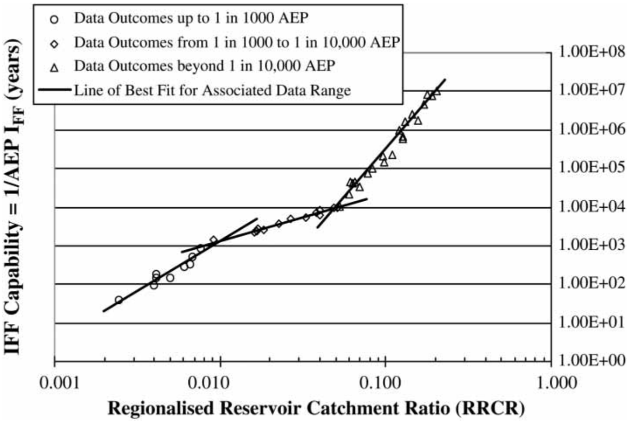


Figure 3 | Sample data ($n = 44$) and segmented lines of best fit for IFF capability prediction in the Mount Lofty Ranges region of South Australia (*Source:* Pisaniello *et al.* 1999).

How to transfer the Pisaniello *et al.* (1999) method to other regions

The above overall development process can be followed to derive similar relationships for any region. It should be noted that the flood capability of a dam, IFF, is now also known as dam crest flood (DCF) per ANCOLD (2000).

Developing the RRCR for the prediction of flood-based outcomes for a selected region involves selecting a homogeneous sample of catchments from which possible prediction equations can be derived. In order to then create the main flood capability prediction relationships (i.e. Figure 3 and Equations (4)–(6)), it is necessary to produce a wide range of flood capability outcomes relating to typical embankment dams hypothetically placed at the outlets of the regional catchments. The aim is to represent the hydraulic response of any size reservoir and spillway(s) relative to the hydrological flood response of any small rural catchment within the selected 'hydrologically homogenous' region.

A regional relationship of RRCR versus IFF/DCF is primarily developed to represent an entire study area based on four to six sample catchments of varying size (up to 10 km^2 and possibly 25 km^2) that are relatively well spread throughout the area, and the relationship is tested for predictive accuracy (see also Pisaniello 1997, p. 233). If the accuracy of this relationship is unacceptable, the initial study area will need to be broken down into smaller sub-regional areas for which relationships of increased predictive accuracy are developed. The aim is to achieve relationships for sub-regional areas that are each based on their own four to six representative sample catchments and that are of acceptable predictive accuracy, that is with R^2 of around 0.95 or better and with s.e. of no more than, say, ±10% in line with the results obtained by Pisaniello *et al.* (1999) (see Figure 3 and Equations (4)–(6) and also Pisaniello (1997, p. 223)). If at this point satisfactory predictive accuracy still cannot be achieved (either to the level established by Pisaniello *et al.* (1999), or higher if desired) the process is simply repeated whereby even smaller subregions are created, with more representative sample catchments (i.e. 4–6) established in each sub-region, until sufficient data and satisfactory prediction relationships are achieved.

The Tasmania study looked to generate such data and apply and test this process for Tasmania's more diverse range of hydrology-variant regions as follows.

Selection of sample regions and catchments for Tasmania case study

Six study catchments in Tasmania were initially used for developing a preliminary flood capability prediction relationship representing the whole state. Preliminary prediction relationships were also to be developed in at least three sub-regions where farm dam concentration is greater than 0.8 dams per 100 km^2 (Figure 2). Figure 2 provides useful guidance in the region delineation process. The three selected study sub-regions are represented by the following Tasmanian planning and management catchments in Figure 2:

- Central Region: 4, 5, 11, 12, 39–42.
- Southern/Hobart Region: 6–10, 14–16.
- North-West Basalt Region: 24, 26–34, 35–37.

The six initial representative sample catchments were selected to provide reasonable location spread throughout Tasmania with at least two catchments representing each sub-region (Figure 2), whilst ensuring availability of on-site or nearby gauged streamflow data for calibration purposes (Pisaniello *et al.* 1999). Selected sizes range from 1 to 25 km^2 (see Table 2), enabling a larger range to be tested compared to Pisaniello *et al.* (1999) who worked with catchments up to 10 km^2.

Table 2 | Summary of Tasmanian study catchments

Catchment no.	Catchment name	Catchment location/ region (see Figure 2)	Catchment area (km^2)
1	Ouse River	Central	1.75
2	Ross Creek	Central	8.23
3	Allens Rivulet	Southern/Hobart	12.80
4	Mountain River	Southern/Hobart	24.25
5	Wilson's Creek	North-West Basalt	1.3
6	Port Creek	North-West Basalt	5.44

Modelling and calibration of study catchments in Tasmania

The RORB v.5 program (Monash University & SKM 2005), a computer based, non-linear catchment runoff routing model, was used for modelling as it is recommended by IEAust (1999) for Australian rural catchments. The RORB model input parameters (i.e. k_c, m, IL and CL, as discussed above) were derived via one or a combination of the following methods in line with IEAust (1999): (i) direct calibration where actual gauged rainfall and streamflow data were available for the catchment being modelled, (ii) where gauged data were not available, modelling and calibration of similar nearby gauged catchments and transfer of the resulting data to the sample ungauged catchments, and/or (iii) using previously developed regionalised prediction methods, e.g. Dyer *et al.* (1994), Pearse *et al.* (2002) and Hill *et al.* (1996).

Catchment and sub-area delineations for the RORB models were made using 1:25,000 scale topographic maps (DPIW 2007). Catchment characteristics used for modelling (e.g. elevation, ground slope, vegetation, geology, etc.) were all derived from topographic and geological maps and past studies of the region (e.g. Dyer *et al.* 1994). The necessary design rainfall pluviographs applied to the sample catchment models were derived from IEAust (1999) for events in the observed range (i.e. up to 1-in-100 years) and also (BoM 1994) for storm events in the extreme domain (i.e. 1-in-100 years to the PMP).

Development of flood capability prediction relationships for Tasmania

As discussed in the Background section above, in order to create the flood capability prediction relationships based on the RRCR, it was necessary to produce a wide range of flood capability outcomes relating to embankment dams placed at the outlets of the regional calibrated sample catchments (Pisaniello *et al.* 1999). This was achieved for Tasmania by generating, in the created RORB catchment models, at least 20–30 hypothetical dam cases at the outlets of the selected study catchments, comprising varying size reservoirs and free flowing, weir-type spillways which would produce the necessary wide range of DCF capability outcomes up to the PMP, for the analysis that follows.

RESULTS OF REGIONALISED FLOOD CAPABILITY PREDICTION FOR TASMANIA

This section details the results of the main regionalised flood capability prediction relationships for Tasmania.

Preliminary results

Over 150 hypothetical dam cases were created in total on the initial six study catchments, and flood capability studies were undertaken for each case per the above method, generating a full range of DCF outcomes. All cases resulted in an AEP of PMP of 1 in 10^7 using the procedure in IEAust (1999): this therefore led to the RCR taking on the compact form, i.e. Equation (2).

The necessary peak PMF prediction equation for the six study catchments was then determined and substituted into the RCR to produce the RRCR applicable to the sample region as follows:

$$RRCR = \frac{SC}{52.857 \cdot CA^{0.8774}} \cdot \sqrt{\frac{\sqrt{RA} \cdot SH}{1000 \cdot CA}} \tag{7}$$

The flood capability (DCF) outcomes for the six study catchments were then used to create a scatter plot of RRCR versus DCF and the line of best fit is presented in Figure 4. The relationship in Figure 4 has an $R^2 = 0.85$ and s.e. $= +15.5/–28.8\%$ ($n = 174$) which is insufficient to declare it a reliable predictor of DCF at the state level. When the state relationship is broken down into three sub-regional relationships and simple comparable linear regressions were used, much improved R^2 and s.e. values are obtained, as illustrated in Figure 5. However, the sub-regional relationships need to each be based on a larger range of representative catchment sizes and locations (i.e. four to six catchments per sub-region) via future research in order to ensure their credibility as follows.

Refinement of the developed relationships and a demonstrative example

The relationships presented in Figure 5 are only rough preliminary representations of flood capability prediction in the selected study regions of Tasmania, but they well illuminate the potential and scope of future research to fully

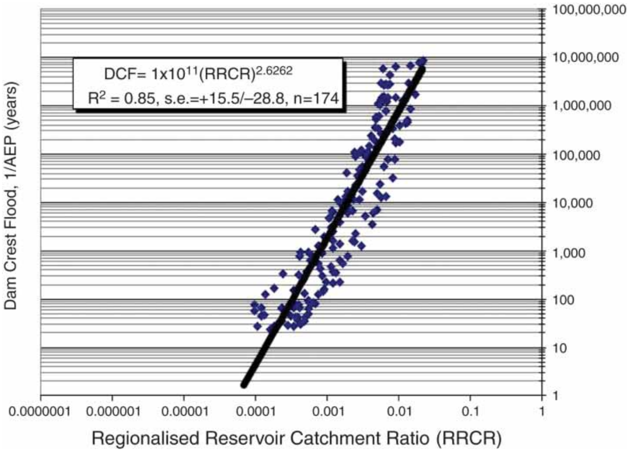


Figure 4 | Sample data ($n = 174$) and line of best fit for DCF prediction based on the RRCR representing the entire state of Tasmania.

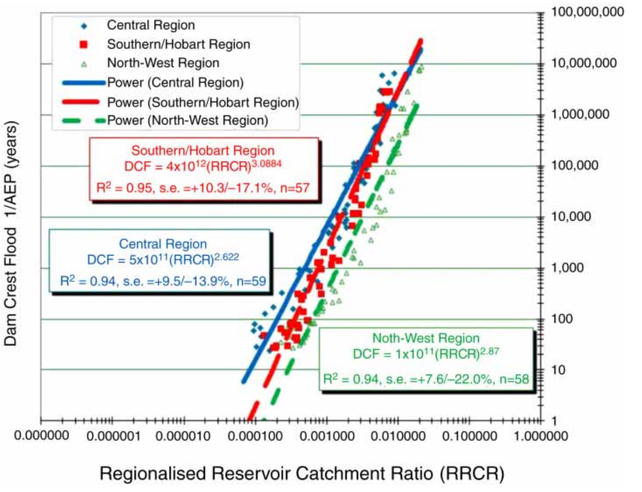


Figure 5 | Flood capability prediction in the form of more accurate sub-regional relationships for Tasmania.

develop the relationships (as demonstrated for one region below) which underpin the overall cost-effective flood safety review/design tool discussed further below.

As a starting point, the study developed a finalised prediction relationship for only the North-West Region (Figure 2). This was undertaken by establishing an additional four study catchments in this region (i.e. six in total with the preliminary two catchments re-used) as detailed in Table 3. Then repeating the above method, over 150 hypothetical dam cases were created in total on the six study catchments in this region representing all the possible combinations of reservoir size and spillway capacity to pass the entire range of AEP design floods up to the PMP. Flood capability studies were again undertaken for each case generating a full range of DCF outcomes.

When design peak PMF flow was plotted against catchment area in the logarithmic domain (Figure 6) the following line-of-best-fit relationship was obtained:

$$PI_{PMF} = 84.011 \cdot CA^{0.7397} \quad (R^2 = 0.99, \; s.e. = +0.8/-1.6\%, n = 6) \tag{8}$$

Nathan *et al.* (1994) derived a similar equation based on a sample of 56 catchments in South-Eastern Australia, ranging in size from 1 to 10,000 km^2:

$$PI_{PMF} = 129.1 \cdot CA^{0.616} \quad (R^2 = 0.95, \; s.e. = +36\%, -26\%, n = 56) \tag{9}$$

Table 3 | Summary of Tasmanian North-West Basalt Region study catchments (well spread from left to right of region, see Figure 2)

Catchment no.	Catchment name	Location in North-West Basalt Region	Catchment area (km^2)
1	Ghost Creek	Far left	4.1
2	Wilson's Creek	Central left	1.2
3	Sisters Creek	Central	15.2
4	Port Creek	Central	5.5
5	Claytons River	Central right	25.0
6	Yaxleys River	Far right	2.7

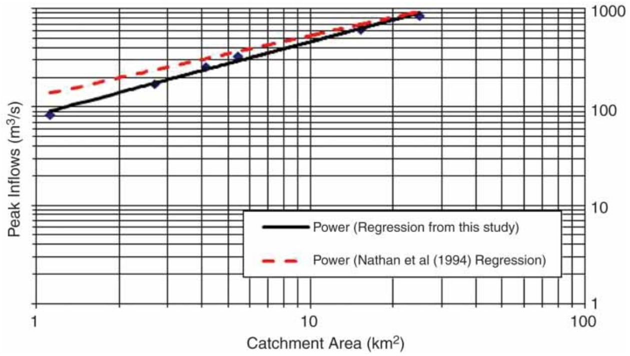


Figure 6 | Comparison of peak PMF prediction relationships from two sources: Tasmanian North-West Region of this study and the Nathan *et al.* (1994) study.

It was considered interesting, given the coincidence of regions, to compare the Nathan *et al.* (1994) prediction equation with that derived for this study region. This comparison is presented in Figure 6 and shows that the Nathan *et al.* (1994) equation, if applied directly to the Tasmania cases of this study, would slightly overestimate the peak PMF flows of the smaller catchments. This may be accounted for by either differences in hydrological regimes (South-Eastern Australia versus North-West Tasmania) or differences in catchment sizes examined in the two studies. However, for catchment areas between 10 and 25 km^2, the relationships converge.

When Equation (8) was substituted into the RCR, the following RRCR applicable to the sample region was generated:

$$RRCR = \frac{SC}{84.011 \cdot CA^{0.7397}} \cdot \sqrt{\frac{\sqrt{RA} \cdot SH}{1000 \cdot CA}}. \tag{10}$$

The flood capability (DCF) outcomes for the six study catchments were then used to create a scatter plot of RRCR versus DCF, as shown in Figure 7. A flood capability prediction relationship was constructed using all the sample outcomes and the resulting scatter plot and line of best fit representing the whole sub-region is presented in Figure 8.

Figure 8 displays an $R^2 = 0.90$ and s.e. = +11.4/–26.3% ($n = 164$) which is insufficient to declare it a reliable predictor of DCF at the region level. As described previously, the next possible step to achieve the necessary accuracy in this region would be to increase the number of representative

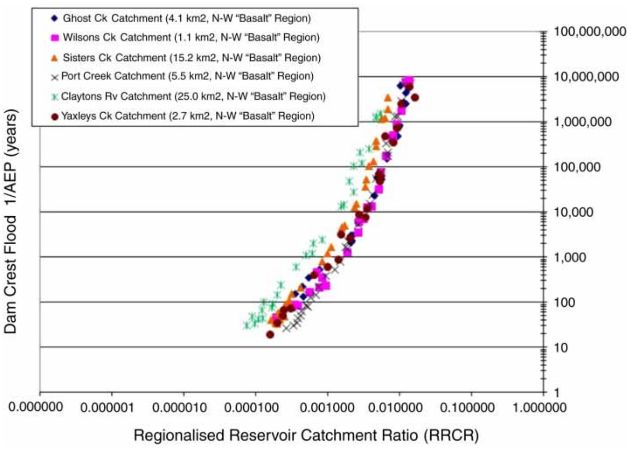


Figure 7 | RRCR sample data according to each of the study catchments in the North-West Region.

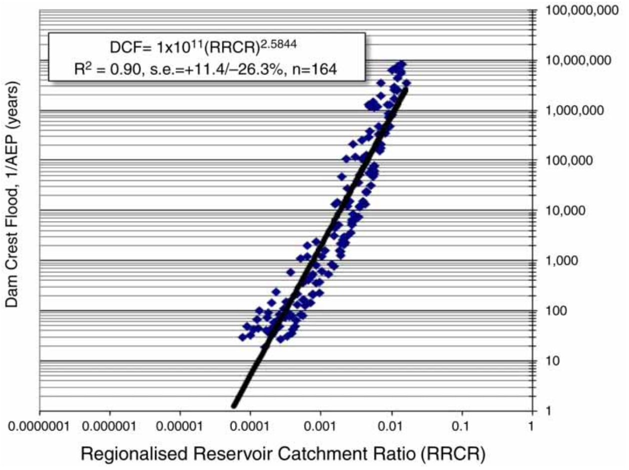


Figure 8 | Sample data ($n = 164$) and line of best fit for DCF prediction based on the RRCR representing North-West Region for catchments up to 25 km^2.

sub-regions within this region, with more representative sample catchments established in each sub-region (i.e. 4–6), until sufficiently accurate prediction relationships are achieved. Whilst this is an option open to future research, for now it was decided to achieve the necessary accuracy by simply removing the larger catchments that were clearly causing the unsatisfactory accuracy in Figures 7 and 8. Firstly the largest catchment was removed (Claytons Rv Catchment = 25 km^2) and the resulting prediction relationship provided an $R^2 = 0.93$ and s.e. = +10.1/–15.5% ($n = 137$) which is already much improved but is still not quite sufficiently accurate. Hence, the next largest study catchment (Sisters Ck = 15.2 km^2) was removed from the sample data and the resulting prediction relationship is presented in Figure 9. This figure displays an $R^2 = 0.94$ and s.e. = +8.6/–11.9% ($n = 108$) which more or less provides satisfactory predictive accuracy. However, Figure 9 also indicates potential of further improving this accuracy if segmented lines of best fit are used (as illustrated in Figure 3, Equations (4)–(6)). When this was performed on the Figure 9 data, the resultant segmented relationships are presented in Figure 10 and display the following substantially increased accuracies:

- Regression for data outcomes up to 1 in 10,000 AEP

$$DCF = 6 \times 10^{8} \cdot RRCR^{2.0006} \quad (R^2 = 0.94, \; s.e. = +6.6/-7.1\%, \; n = 54) \tag{11}$$

- Regression for data outcomes from 1 in 10,000 AEP and beyond

$$DCF = 6 \times 10^{15} \cdot RRCR^{4.7995} \quad (R^2 = 0.95, \; s.e. = +2.3/-2.9\%, \; n = 54) \tag{12}$$

When such segmentation was performed on Figure 8 representing the larger catchments, the improvement in accuracy was insufficient. Hence, if catchments up to 25 km^2 are to be represented, further sub-region division and data generation

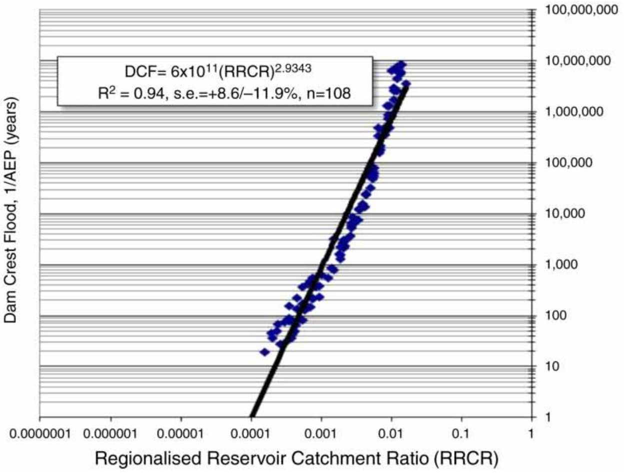


Figure 9 | Sample data with two largest catchments removed ($n = 108$) and line of best fit for DCF prediction based on the RRCR representing the entire North-West Region.

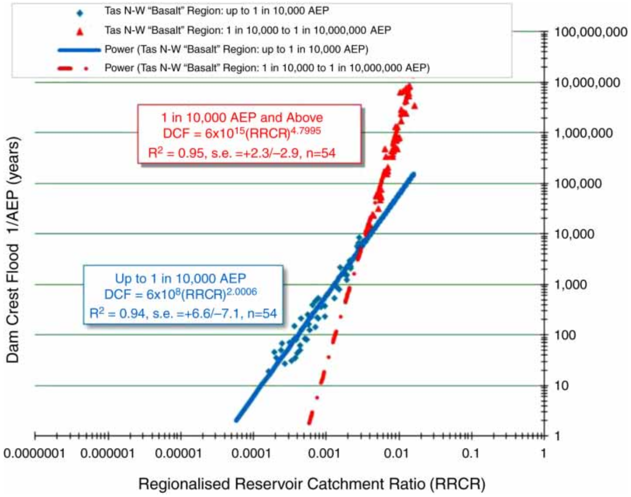


Figure 10 | Sample data ($n = 108$) and segmented lines of best fit ($2 \times n = 54$) for DCF prediction based on RRCR representing North-West Region for catchments up to 10 km^2.

would need to be undertaken per the main development method described above. However, as was found by Pisaniello *et al.* (1999) catchments up to 10 km^2 are usually more than representative of farm dam catchments and so for the purposes of this study, the Figure 10 relationships were representative of such small catchments and therefore satisfactory. At the same time, the Figure 8 relationship could in the interim still be used for larger catchments, especially for preliminary indicative purposes, provided that the reduced accuracy is accepted by the user.

A useful relationship for determining flood capability as %PMF

In the flood capability studies undertaken for each case above in the North-West region, DCF capability was also determined as %PMF. These outcomes ($n = 164$) were plotted against the RRCR in order to establish the relationship presented in Figure 11. The R^2 for this relationship is 0.98 and s.e. = +3.9/–5.9%, which is also of acceptable accuracy. This relationship provides the option of determining any flood capability as %PMF Inflow, which is useful in jurisdictions where flood capability standards are expressed in this way, for example Michigan, USA and South Africa (Pisaniello 2011).

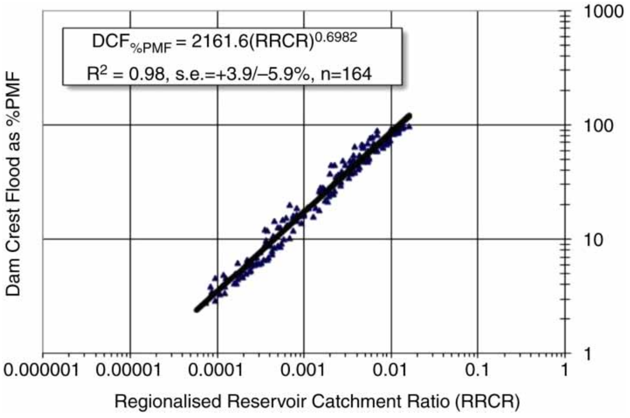


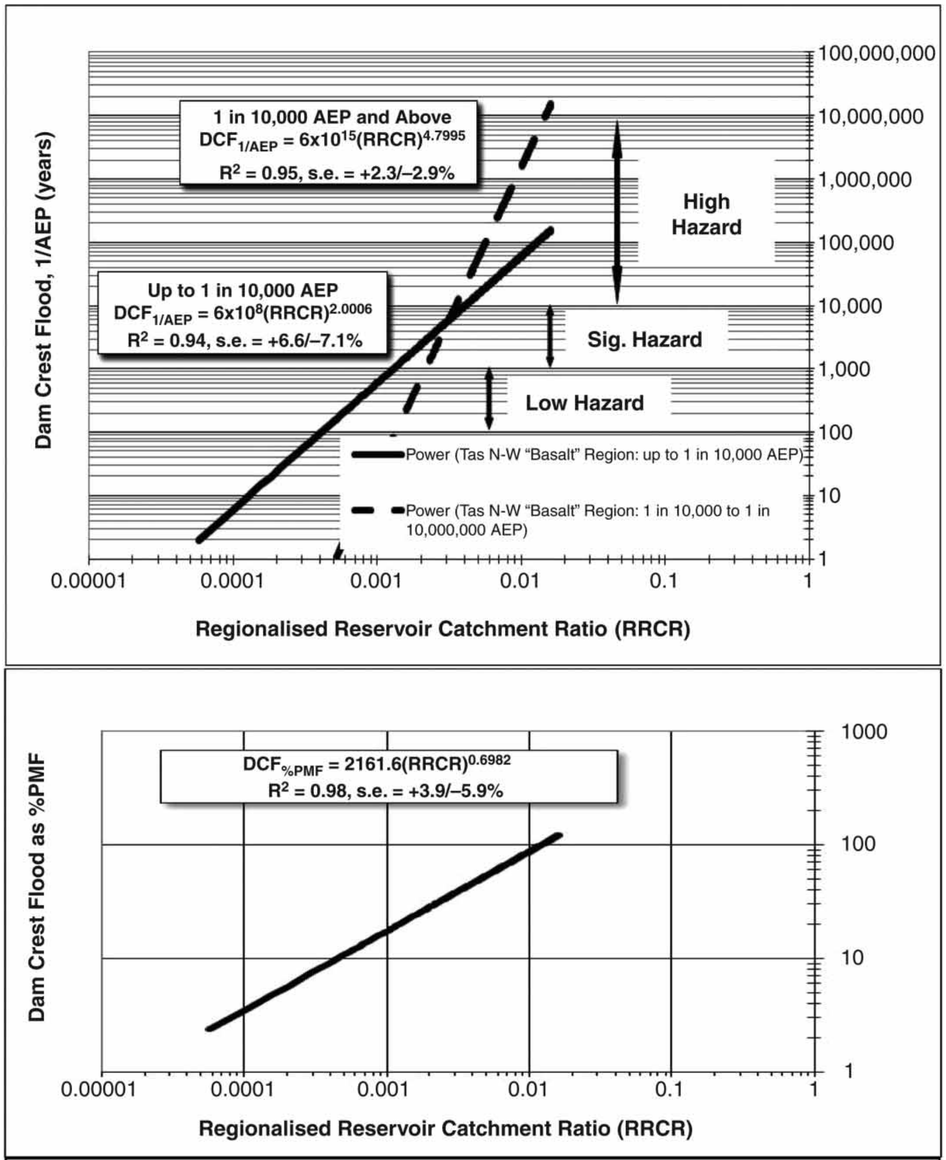
Figure 11 | Sample data ($n = 164$) and line of best fit for DCF prediction as %PMF: Tasmania North-West Region for catchments up to 25 km^2.

APPLICABILITY OF THE DEVELOPED RELATIONSHIPS: A COST-EFFECTIVE SPILLWAY REVIEW/DESIGN TOOL

The finalised relationships presented in Figures 10 and 11, as well as the preliminary relationships presented in Figures 5 and 8 (once fully developed), provide a procedure to engineers, authorities and dam owners to readily and effectively review and/or design the spillway flood capability of reservoirs on small catchments (area up to 25 km^2) in Tasmania. For example, ANCOLD (2000) acceptable flood capacity criteria can be incorporated into Figure 10 and combined with Figure 11 to create Figure 12: the principal cost-effective flood safety engineering review/design tool.

However, the following four conditions are associated with the tool:

1. It is based on the 100% full storage level conservative assumption which is recommended by ANCOLD (2000) as appropriate for embankment dams.
2. If any dams are located upstream of the subject dam, the tool should first be applied to each upstream dam to ensure their spillway capability is adequate.
3. The principal spillway(s) must be free flowing and weir-type in nature.
4. The DCF capability must be taken as the smallest flood which peaks at the lowest point of the non-overflow crest in line with ANCOLD (2000, p. 21) guidelines.



$$RRCR = \frac{SC}{84.011 \cdot CA^{0.7397}} \cdot \sqrt{\frac{\sqrt{RA} \cdot SH}{1000 \cdot CA}}$$

where:

SC = spillway overflow capacity (m^3/s), and commonly for farm dams the broad crested weir type spillway formulae applies: SC = 1.69SW.(SH)$^{1.5}$ (IEAust, 1987; 1999)

SW = average spillway width (m)

SH = maximum height of spillway overflow (m)

RA = reservoir area at full supply level (km^2)

CA = catchment area (km^2)

Figure 12 | Final reservoir flood capability design/review tool incorporating ANCOLD (2000) criteria: Tasmania North-West Region for catchments up to 10 km^2.

The hazard category for a dam for use in Figure 12 can be assessed using ANCOLD (2012) based on consideration of the dam failure flood affected zone against a matrix of both population at risk and severity of damage and loss. DSE (2012) makes available a simple and user-friendly Consequence Screening Tool for Small Dams for undertaking this hazard assessment process in line with ANCOLD (2012). DPIW (2009) makes available a similar simple on-line spreadsheet for undertaking this hazard assessment process. This is a further farmer-friendly element of the Tasmanian best practice dam safety policy (in addition to the guided reporting pro-forma discussed previously) that would link well with the cost-effective tool to minimise review/design cost burdens for dam owners.

When using the tool in review mode, the parameters required in the RRCR in Figure 12 must be first determined for an existing reservoir. These parameters are then put into the applicable prediction relationship to read off the corresponding flood capability (DCF) as 1/AEP (years) (or optionally as %PMF), which is automatically checked against the displayed ANCOLD criteria. When used in design mode, the same basic parameters are related to a proposed reservoir, or upgrade of an existing reservoir. The parameters must be varied iteratively in the RRCR until the ANCOLD safety criteria together with the owner's storage needs are satisfied. Both review and design mode worked examples are provided in Pisaniello (1997, Appendix H).

DISCUSSION OF RESULTS AND IMPLICATIONS

The reservoir flood capability design/review relationships presented above are only applicable to small rural catchments in the study regions because the flood capability studies used in the development process were based on (1) private reservoirs on small rural type catchments up to 10–25 km^2 and (2) region-specific hydrological modelling parameters. The relationships are limited to such small rural catchments as larger catchments usually contain other flow attenuating conditions upstream of the principal reservoir such as urbanised sub-catchments and/or large public reservoirs which contribute to a non-systematic, case specific type flood response. Region-specific hydrological parameters include rainfall magnitudes and distributions and catchment characteristics such as losses, storage and non-linearity. In Australia, these parameters vary from one region to another in line with the state-of-the-art procedures outlined in IEAust (1987, 1999) and rainfall information supplied by the BoM. In overseas countries these parameters would vary according to the standard hydrological engineering and meteorological procedures that prevail in those countries. Ultimately, different regions in Australia and in different countries could produce their own relationships with segments of different slope as illustrated in Figures 3, 5 and 10. Of greatest significance is that the overall mechanism (Figure 12) could be developed for any region in Australia or overseas by following a procedure based on the RRCR similar to that applied to South Australia and Tasmania above.

In Tasmania, once fully developed by future works (as illustrated here for the North-West Region) the tool will provide a number of important benefits. Firstly, the tool minimises costs to dam owners due to its ease of application. For example, consulting an engineer to undertake equivalent modern flood capability modelling and analysis can cost up to AU$10,000; the tool can reduce this fee significantly (Pisaniello & McKay 2007). This helps address the concern for government that dam safety assurance policy may place unacceptably high cost burdens on rural communities. This concern is further alleviated when the tool is used to complement the Tasmanian Government's farmer-friendly dam safety reporting approach. Secondly, the tool is easily applicable in either review and/or design mode. In design mode, the simple on-site input parameters can be selectively varied by the user to satisfy not only flood capability, but also other practical on-site factors, e.g. a farmer's minimum storage requirements for irrigation and fitting the spillway into the physical constraints of the valley with minimal excavation. Thirdly, the tool promotes consistency and uniform standards because the tool has embedded in it the complex best practice engineering processes required to review or design spillways. Finally, the Tasmanian dam safety authority is provided with a useful in-house auditing/checking tool for when it receives assessment reports for farm dams.

The technology, once established in a region, could also serve as a useful tool for planning authorities and developers to readily determine by how much a dam's flood capability would need to be upgraded as a result of the increased hazard from a new land development downstream. This would assist both land use planning and safety assurance policy in an integrated way, enabling the extra cost burdens on the owner to be accounted appropriately. Similarly the technology could be useful to insurance providers to readily audit/check reported flood capability risk levels for setting reduced premiums.

An additional important benefit is that the technology can also potentially be developed to account for climate change. For example, in Australia there is a national increase in temperature projected for around 1° by 2030, 2° by 2050, 3° by 2070 and 4° by 2100 (Garnaut 2008; Climate Change in Australia 2014). The interim guidance is a 5% increase in rainfall intensities predicted for every 1° of climate change induced temperature increase (Engineers Australia 2014). Hence, based on such projections the cost-effective tool presented here can be developed in any region to provide additional optional prediction curves (e.g. additional to those illustrated in Figure 12) for, say, 2030 (5% increase), 2050 (10% increase), 2070 (15% increase) and 2100 (20% increase). Dam owners would then have the added optional benefit of designing in advance for the optimal rainfall increase prediction after weighing up the construction costs against the risk reduction benefits over time (Engineers Australia 2014, p. iv).

In general, there is a clear need to mandate private owners to review the spillway flood capabilities of their dams in line with modern acceptable practice and to take appropriate remedial action where necessary. This is especially so when numerous private dams pose a cumulative threat within the catchment of a large hazardous public dam, such as South Australia's Kangaroo Creek Dam (Pisaniello 2011; Tingey-Holyoak *et al.* 2013). This is a large, high hazard public dam (65 m high, 19,000 ML capacity) in the River Torrens catchment of South Australia. A flood study by LDC & SMEC (1995) found the dam's peak inflow would increase four-fold assuming all small dams (>1,000) in the catchment failed at the same time in a 1-in-200 years flood event: a reasonable assumption as Pisaniello *et al.* (1999) and Pisaniello & McKay (2005, 2007) later found most small dams cannot pass such an event. This additional flow to Kangaroo Creek dam would exceed its spillway capacity, which should otherwise be capable of passing at least a 1-in-10,000 years flood event, putting downstream communities and the environment at unacceptable risk. The study thus recommended dam safety policy be implemented for 'controlling the standard of construction of farm dams and their spillways'. Kangaroo Creek Dam is currently in the process of being reviewed and upgraded to meet current ANCOLD guidelines (SA Water 2015), but the 1995 policy recommendation in regard to private dams is yet to be implemented (Pisaniello 2011; Tingey-Holyoak *et al.* 2013). The guidance provided in this paper should now encourage the South Australian Government to also act upon that recommendation. The regionalised tool developed here together with farmer-friendly dam safety reporting and hazard assessment processes established within best practice model policy can assist to achieve such a mandate in a cost-effective way. Both the preliminary relationships and example finalised relationships upon which the tool is based display excellent predictive accuracies for rural catchments up to 25 km^2 in size and for a diverse range of regional characteristics: this demonstrates their potential and scope for future development and the potential transferability of the tool's development process to other regions.

CONCLUSIONS

This paper helps to address both individual and cumulative flood threats posed by rural catchment dams. The research has found that a cost-effective flood safety engineering tool can be successfully developed on a regional basis to help minimise these threats. The reported regionalised preliminary relationships and example finalised relationships upon which the tool is based display excellent predictive accuracies, demonstrating the future potential and scope for finalising their development in the study area of Tasmania, as well as the potential transferability of the tool's development process to other regions in Australia and potentially abroad.

When the tool is used in conjunction with cost-effective, best practice dam safety assurance policy, such as Tasmania's farmer-friendly hazard assessment and reporting processes, dam review and design costs to private owners, and assurance/supervision costs to government can be minimised. As such, the cost-effective tool is capable of (i) encouraging and assisting farmers to review/design their spillways to minimise hazardous farm dams' risk of flood failure at the individual level and (ii) assisting authorities to readily account for, supervise and assure the flood capability of all farm dams within larger catchments in order to minimise the risk of catastrophic dam flood failure at the cumulative level. Added benefits include the potential for the tool to optionally account for climate change as well as assisting both land use planning policy and safety assurance policy in an integrated way.

Overall, this research shows that governments can provide for an adequate yet cost-effective level of dam safety policy to assure that not only individual hazardous dams are kept safe, but also the cumulative safety threats posed by rural catchment dams are kept in check. Development of the cost-effective flood safety engineering tool to complement best practice dam safety assurance policy that includes farmer-friendly hazard assessment and reporting processes provides an exemplar for others to follow.

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