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Cost-effective Private Dam Safety Assurance Policy and Spillway Design/Review

JOHN D. PISANIELLO & JENNIFER M. McKAY

University of South Australia, School of International Business, Division of Business and Enterprise, Way Lee Building, City West Campus, North Terrace, Adelaide SA 5000, Australia

ABSTRACT *Owner-obligation exists under common law to take reasonable care of dams according to current prevailing standards. However, this obligation may not be met in places where there is an absence of private dam safety assurance policy, which creates the possibility of placing the public at risk. To explore the potential seriousness of this problem, a case study has been conducted in the policy-absent state of South Australia where 11 hazardous private reservoirs have been investigated for spillway adequacy in line with state-of-the-art practice. Common high levels of deficiency have been discovered. Extended flood studies of hypothetical dams placed on the same catchments, bearing a wide range of spillway capacities and reservoir conditions, have then been conducted. Appropriate analysis has led to the derivation of regionalized relationships based on simple hydrological/hydraulic variables, for predicting reservoir flood capability as either 1/AEP or %PMF. The relationships have been utilized to develop a simple and cost-effective flood capability design/review procedure for reservoirs on small catchments which is compatible with any design flood standards. The paper also provides guidelines and criteria, based on international experience and practice, for government to readily explore an 'appropriate' private dam safety assurance policy for any jurisdiction. The guidelines, incorporating the cost-effective flood capability design/review procedure, aim to minimize review costs to private owners and ensure an acceptable level of private dam safety management.*

Introduction

While failures of large dams are generally more spectacular than those of smaller dams and receive much more attention, small dam failures, particularly those of privately owned farm dams, occur far more frequently. Therefore, in many cases, the total annual cost of small dam failures is more serious than the rare failures of large dams, especially in relation to government owned infrastructure. Also, past events have occurred where failures of relatively small dams have caused quite disastrous consequences. In the USA for example: a 19 m high earth dam failed in Pennsylvania in 1889 leading to the destruction of Johnstown and killing of around 3000 people, this being, in terms of lives lost, the second largest disaster of all time in the USA (Sowers, 1974); the Bear Wallow dam, 10 m high and with a catchment area of only 0.25 km^2, failed in 1976 killing 4 people (Joy, 1983); the Kelly Barnes Lake dam, only 8 m high, failed in 1977 killing a total of 39 people; and the Lake Lawn dam in Colorado,

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Table 1. PMF estimates for Burrinjuck Dam at different periods in time

Year	Estimated PMF (m^3/s)
1971	19 800
1982	23 000
1986	38 000

Source: After Wright (1988).

which was also 8 m high and stored only 830 ML, failed in 1982 drowning 3 people and causing US$31 million in damage despite warnings and evacuation (Hiser & McDonald, 1989). Such events suggest that without appropriate design, construction and maintenance, poorly managed small dams can cause significant human and property losses to the community.

Australia has a large number of relatively small, privately owned dams (farm dams in particular); those which have failed number in the thousands. For example, Victoria has an estimated 170 000 farm dams, 800 of which are large enough to cause serious consequences downstream if they failed, while in New South Wales (NSW), a recent study revealed a 23% failure rate for the state's farm dams (ANCOLD, 1992). When these private dams were constructed, the majority more than 20 years ago, their designs could only be based on rainfall frequencies and intensities and standards of risk available at the time. However, many aspects have changed over time such as population distributions, infrastructure patterns, meteorological information, engineering methods and design standards, together with the condition of the dams, raising serious doubts about dam adequacy.

In particular, significant advances made in the fields of meteorology and flood hydrology have updated both maximum probable rainfalls and design flood levels above those on which most existing dams were based. In effect, a spillway designed for the PMF in, say, 1970 may now be seen to have a capacity significantly less than today's probable maximum flood (PMF): this is illustrated in Table 1 where PMF estimates for Burrinjuck Dam in NSW are presented over three different time periods. As a result of such revisions, many dams have inappropriate spillway capacities. This is an issue receiving much concern and attention worldwide.

Consequently, the recognition of risks associated with dams has increased greatly. A need has therefore developed for owners to manage their dams appropriately in line with current standards in order to reduce the risks involved, reflect community standards and provide increased dam safety assurance to downstream communities.

However, the procedures associated with 'modern' dam safety management represent significant cost burdens to private owners. Consequently, private owners in general are ignoring, underestimating or simply remain unaware of the risks and hazards associated with their dams and are frequently guilty of not maintaining the structures. Therefore, as it is the role of government to protect the community, an associated need has also developed for government to provide both (1) appropriate policies which assure the community of owner participation and which protect them from unacceptable dam safety management practices and (2) cost-effective design/review procedures which minimize cost burdens to private owners and encourage better dam safety management. A case study reported in this paper demonstrates these needs. The paper also provides 'appropriate policy exploration and selection' guidelines and a cost-effective regionalized flood capability design/review procedure which, together, represent a mechanism to help address the needs.

Dam Safety Management in Australia

In Australia, as in most countries, owner obligation exists under common law to take reasonable care of dams according to *current prevailing standards*. Hence, owners should review their dams, and take appropriate action where necessary, in order to avoid liability for possible failure consequences (McKay & Pisaniello, 1995). The status with regard to this in Australia is discussed in the following sections, with particular emphasis placed upon spillway standards, review and upgrading.

Safety Assurance Policy and the Role of Government

Throughout Australia, most government dam-owning agencies have assumed the responsibility of evaluating public dams in terms of risk in accordance with current guidelines, and subsequently have either undertaken or are in the process of implementing appropriate action to reduce the risks to modern acceptable standards. For example, in NSW works on Pindari Dam to upgrade the spillway and increase the storage capacity of the dam were recently completed at an overall cost of A$68.8 million over a period of approximately four years (NSW Department of Land and Water Conservation, 1995). This came on top of Burrinjuck, the major upgrading works of which were completed in August 1994 at a cost to the state of $73.8 million over approximately six years (NSW Department of Water Resources, 1994). The costs of upgrading these two dams alone represent 0.10% and 0.08% of NSW government revenue over each period respectively (NSW Parliament, 1988–95).

NSW is also taking a responsible approach to the problem of safety of its privately owned dams (Pisaniello & McKay, 1996). Elsewhere in Australia there is no supervision of the management of these structures. Webster & Wark (1987) report that owners of private dams are wary of any controls which are likely to add significantly to their costs. Consequently, private owners in general are either ignoring, underestimating or simply remain unaware of the risks and hazards associated with their dams and are frequently guilty of not maintaining the structures. Too often, owners look only upon the benefits gained from their dams and not the hazards which the dams could generate. Local government bodies are unable to rectify the situation as they lack the power to ensure that owners take remedial action. As a consequence, potential hazards to neighbouring residents and properties exist, placing people and community infrastructure at unnecessary risk.

For some time, the Australian National Committee on Large Dams (ANCOLD) has been aware of this problem and has continually expressed concern over the matter. ANCOLD believes that there is a need for regulation and supervision and that this is best provided through uniform dam safety legislation. In 1972, ANCOLD prepared guidelines for dam safety legislation, and proposed that each state should implement such legislation together with establishing an independent control authority. In response, virtually all of the state governments have acknowledged and attempted to act upon these concerns and proposals by drafting and submitting varying forms of dam safety Bills to their respective parliaments. Unfortunately, owing to a high level of political ambivalence, attempts to enact these Bills have not been successful in all states.

To date, only three of the six states and two territories have been successful in establishing sound statutory control over dam management. However, while Queensland and Victoria have incorporated workable dam safety provisions within existing statutes, NSW is the only state to implement a specific dam safety Act under which an independent dam safety enforcement committee is constituted. Therefore, despite ANCOLD recommendations, there is still a need to ensure that communities are protected against dam management practices leading to unreasonable risk. States which fail to establish some form of safety assurance policy on the management of potentially hazardous private dams are, in effect, unconsciously devaluing the lives of people living downstream of these dams compared with the lives of those living downstream of public dams to which attention has or is being given: South Australia is one of these states.

Reservoir Flood Capability Standards and Review

The Australian National Committee on Large Dams sets the standard for modern acceptable practice in dam safety management in Australia. ANCOLD (1986) provides minimum prescriptive standards on appropriate design floods for dams, known as recommended design flood (RDF) standards. ANCOLD relates RDF to dam hazard potential based on a three-level hazard rating system as illustrated in Table 2. The criteria used by ANCOLD for the three hazard categories can be summarized as follows:

- *high hazard potential*—failure will endanger many lives in a downstream community and will cause extensive damage;
- *significant hazard potential*—failure may endanger some lives and will cause extensive damage;
- *low hazard potential*—failure poses negligible risk to life and will cause limited damage.

The acceptable RDF determined from Table 2 can be compared with the Imminent Failure Flood (IFF) of an existing dam to determine whether its spillway flood capability is adequate. Guidelines for determining the IFF of a dam are provided in ANCOLD (1986). In line with modern acceptable practice, these guidelines must be used in association with both: Australian rainfall and runoff (AR&R) (IEAust, 1987), which provides state-of-the-art engineering methods and design criteria for hydrological/hydraulic reservoir flood studies; and modern generalized probable maximum precipitation (PMP) estimates determined by the Bureau of Meteorology as described by Pearce & Kennedy (1993).

Unfortunately, these engineering processes are highly rigorous and time-consuming in practice and therefore generate high consulting fees. For this reason, owners tend to neglect the need for reviewing their dams and instead develop a sense of complacency, believing that as the dams have not failed up to now, then they will never fail. The result is that dams are deprived of necessary upgrading and downstream communities are placed at risk. The case study

Table 2. ANCOLD (1986) recommended design flood exceedance probability standards

Incremental flood hazard category	Annual exceedance probability
High	PMF to 1 in 10 000
Significant	1 in 10 000 to 1 in 1000
Low	1 in 1000 to 1 in 100

reported below, based on the policy-absent state of South Australia, demonstrates the potential seriousness of this problem. As indicated previously, a need has therefore developed for a mechanism that minimizes review costs to private owners and in turn encourages better dam safety management: the regionalized flood capability design/review procedure described later represents such a mechanism.

A Demonstrative and "Foundation Setting" Case Study

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 11 hazardous private reservoirs located in the Mount Lofty Ranges of South Australia (Pisaniello, 1997). A brief outline of this work is given below.

- The 11 dams were selected on the basis that they be 'referable' in size and rated as either 'significant' or 'high' hazard in accordance with ANCOLD (1986) guidelines.
- The sample dams were all embankment-type structures and had typical spillways that were free-flowing and weir-type in nature. The maximum wall heights of the dams ranged from 5.5 m to 10.7 m; their storage capacities ranged from 50 ML to 250 ML; the size of their catchments ranged from 0.256 km^2 to 5.141 km^2.
- Hydrological/hydraulic models of the dams and their catchments were constructed using the RORB runoff routing package, based on procedures described in Laurenson & Mein (1990).
- Design rainfall information was derived as follows:
  (1) from AR&R (IEAust, 1987) for storm events in the observed range (i.e. up to 100 year ARI);
  (2) from Bulletin 53 (Bureau of Meteorology, 1994) for the PMF event; and
  (3) using interpolation procedures described in AR&R (IEAust, 1987) for events between the 100 year ARI and the PMF.
- The RORB catchment model parameters, k_c, m and catchment losses, initial loss (IL) and continuing loss (CL), were determined for each case in accordance with procedures described in AR&R (IEAust, 1987). As each sample catchment was ungauged, k_c and m were determined from regionalized information provided in AR&R. Catchment losses for events in the observed range were transposed from neighbouring gauged catchments of similar size and with similar physical characteristics, while, for events in the extreme domain, IL/CL = 0/1 (mm, mm/hr) was consistently adopted in line with AR&R guidelines.

- An annual exceedance probability (AEP) for the probable maximum event (PME) was determined for each sample dam using the procedures outlined in AR&R (IEAust, 1987). For small catchments up to 100 km^2, this is mainly dependant on the value of the following ratio:

  $$\log (X_{PM}/X_{100})/\log (X_{100}/X_{50}) \qquad (1)$$

  where:

  X represents the peak event magnitude for either rainfalls, flows, or flood volumes;
  X_{PM} denotes the probable maximum event;
  X_{100} denotes the 100 year ARI event;
  X_{50} denotes the 50 year ARI event.

  AR&R divides Australia into two zones and provides limiting AEP of PME criteria for each based on the value of equation 1. In line with these criteria, eight sample catchments attracted an AEP of PME of 1 in 10^7 while the remainder attracted 1 in 10^6.
- The RORB model was used to determine peak inflows to the reservoirs for all events necessary up to the PMF. This enabled an inflow flood frequency curve to be established for each dam.
- The RORB model was then used to route all inflow hydrographs through the reservoirs for both an upper bound and lower bound 'start' storage level case:
  (1) upper bound case—initial storage level assumed 100% full:
  (2) lower bound case—initial storage level assumed 33% full.
  The lower bound case was checked simply to eliminate uncertainty.
- 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 for both cases of 'start' storage level.
- The 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] 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 3.

ANCOLD (1986) guidelines recommend that unless normal operating conditions indicate otherwise, a 100% full 'start' storage level should be assumed when assessing spillway flood capability of embankment dams. The comparison in Table 3 demonstrates that regardless of the 'start' storage level assumed, many hazardous private reservoirs with inadequate spillway capacities do exist in the Mount Lofty Ranges of South Australia. The risk of failure from overtopping is consistently unacceptable for 91% of the total sample and 100% of the high hazard sample. In particular, the flood capabilities of five of the six high hazard dams (83%) displayed exceedance probabilities in the order of those required for *low* hazard dams under ANCOLD requirements (i.e. 1 in 100 to 1 in 1000 AEP). It is important to note that three of these dams (dam numbers 1, 2 and 3) *do not* even satisfy the required criteria for low hazard dams. These disturbing results demonstrate that owners are not taking action in terms of

Table 3. Comparison of flood capability results with ANCOLD guidelines

Dam no.	Minimum hazard rating (High/Sig.)	IFF if 100% full 1/AEP (years)	IFF if 33% full 1/AEP (years)	ANCOLD guidelines IFF range 1/AEP (years)	Acceptable under ANCOLD guidelines? (Yes/No)
1	High	40	800	PMF-10 000	No
2	High	80	290	PMF-10 000	No
3	High	97	1600	PMF-10 000	No
4	High	150	1150	PMF-10 000	No
5	High	320	680	PMF-10 000	No
6	High	2750	3300	PMF-10 000	No
7	Sig.	190	2000	10 000-1000	No
8	Sig.	130	570	10 000-1000	No
9	Sig.	280	2300	10 000-1000	No
10	Sig.	500	2700	10 000-1000	No
11	Sig.	1400	6400	10 000-1000	Yes

analysis and upgrading of their structures and that the need for some form of private dam safety assurance policy in South Australia is urgent. In more general terms the case study shows the importance of exploring the scope of the private dam safety problem in any 'policy absent' or 'policy deficient' country or state; recently developed policy exploration guidelines and selection criteria are presented later to help determine 'appropriate' safety assurance policy for varying circumstances.

The results presented in Table 3 also provided a foundation for developing regionalized flood capability prediction relationships upon which the final cost-effective design/review procedure is based, as described in the following section.

A Cost-effective Regionalized Flood Capability Design/Review Procedure for Private Dams

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 described below.

Establishing a Sufficient Sample

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 with catchments exhibiting similar flood responses. The 11 reported earlier 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;
- similar design rainfall information applied to each of their catchments, particularly for extreme events.

However, as they stood, the results presented in Table 3 would have been useful only to develop a relationship for low hazard dams as most of the flood capability outcomes did not exceed the 1000 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. These cases were created by altering the spillway and reservoir sizes of a number of the sample dams within their respective RORB data files. The alterations were made by either one or a combination of the following:

- widening the spillway;
- raising the top of the crest, thereby increasing spillway height;
- deepening the spillway which increases spillway height and decreases reservoir surface area and storage capacity;
- raising the entire embankment and spillway, thereby increasing reservoir surface area and storage capacity.

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 earlier for both the 100% full and 33% full 'start' storage level extremes. The results supplemented the flood capability outcomes determined for the real sample dams, providing a total sample space of $n = 44$ (for each 'start' storage level case) for developing prediction relationships.

Development of Regionalized Prediction Relationships

A dimensional analysis of the results discussed above was conducted to explore any possible relationships between dimensionless ratios containing basic hydrological/hydraulic variables and reservoir flood capability. Relationships were plotted in the logarithmic domain because of the great range of orders of magnitude associated with flood-based outcomes. This led to the development of regionalized flood capability prediction relationships for the 100% full 'start' storage level case for the Mount Lofty Ranges. This overall development process can be followed to derive similar relationships for any region. The relationships developed for the Mount Lofty Ranges of South Australia are presented below.

Flood capability prediction relationship for the 100% full 'start' storage level case: Mt. Lofty Ranges The ratio determined to produce the most satisfactory line of best fit from dimensional parameter considerations was named the *reservoir catchment ratio* (RCR):

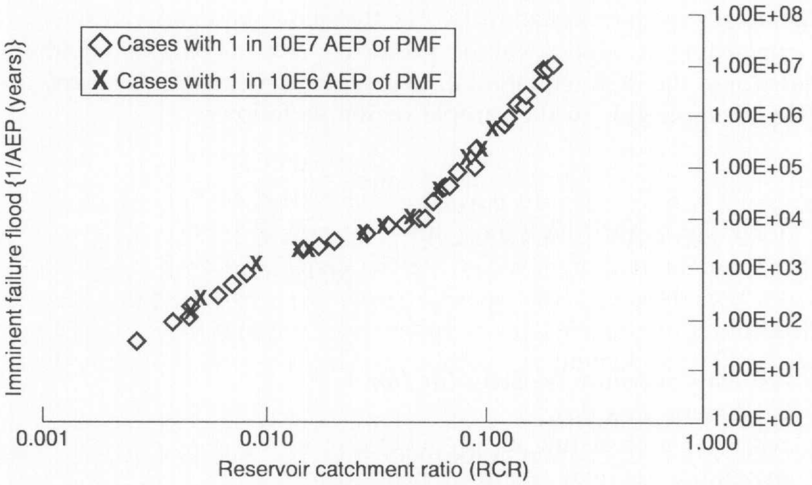

Figure 1. Scatter plot of RCR versus IFF capability.

$$RCR = \frac{SC}{PI_{PMF}} \cdot \sqrt{\frac{\sqrt{RA \cdot SH}}{1000 \cdot CA}} \cdot \frac{\log\left\{\dfrac{PI_{PMF}}{PI_{100}}\right\}}{\log\left\{\dfrac{PI_{100}}{PI_{50}}\right\}} \tag{2}$$

where:

SC = spillway overflow capacity (m^3/s);
PI_{PMF} = peak PMF inflow (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 100 year ARI inflow (m^3/s);
PI_{50} = peak 50 year ARI inflow (m^3/s).

The scatter plot of RCR versus IFF capability 1/AEP (years) is presented in Figure 1. This figure shows that a strong relationship exists between RCR and IFF, consisting of three 'straight line' segments with different skewness over the range of AEPs up to the PMF.

It becomes apparent from equation 2 that equation 1 is part of the RCR. This attribute was found to account fully for the effects of different AEPs of PMF for different dam cases as illustrated in Figure 1.

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) state 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, the peak PMF, 100 year and 50 year inflows determined for the 11 sample catchments (discussed earlier) were plotted against their areas and fitted with lines of best fit. The peak PMF inflow (PI_{PMF}, m^3/s), peak 100 year inflow (PI_{100}, m^3/s) and peak 50 year inflow (PI_{50}, m^3/s) were found to be functions of catchment area (CA, km^2) for the lines of best fit as follows:

$$PI_{PMF} = 97.805 \cdot CA^{0.7747} \qquad (R^2 = 0.9941) \tag{3}$$

$$PI_{100} = 5.2404 \cdot CA^{0.7453} \qquad (R^2 = 0.9901) \tag{4}$$

$$PI_{50} = 4.0985 \cdot CA^{0.7799} \qquad (R^2 = 0.9872) \tag{5}$$

The coefficients of determination (R^2) of the above equations are very close to unity, suggesting a high level of predictive accuracy. The equations were substituted into the RCR (equation 2) to produce a *regionalized reservoir catchment ratio* (RRCR) applicable to the sample region as follows:

$$RRCR = \frac{SC}{97.805 \cdot CA^{0.7747}} \cdot \sqrt{\frac{\sqrt{RA} \cdot SH}{1000 \cdot CA}} \cdot \frac{\log\left\{\dfrac{97.805 \cdot CA^{0.7747}}{5.2404 \cdot CA^{0.7453}}\right\}}{\log\left\{\dfrac{5.2404 \cdot CA^{0.7453}}{4.0985 \cdot CA^{0.7799}}\right\}} \tag{6}$$

where:

SC = spillway overflow capacity (m^3/s);
CA = catchment area (km^2);
RA = reservoir area at full supply level (km^2);
SH = maximum spillway overflow height (m).

A new flood capability prediction relationship was constructed using the same sample outcomes but based on the above RRCR. The resulting scatter plot and lines of best fit are presented in Figure 2. The overall shape of this relationship is similar to that presented in Figure 1 (based on RCR); however, the skewness of the three segments is altered. The skewness of the relationship changes at AEPs of 1 in 1000 and 1 in 10 000. This was attributed to the significant difference between catchment losses used for events in the observed range and those used for events in the extreme domain in line with AR&R (IEAust, 1987) guidelines. The regressions in Figure 2 are defined by the following power functions:

- Regression for data outcomes up to 1 in 1000 AEP
  $$IFF = 2 \times 10^8 \cdot RRCR^{2.59} \tag{7}$$
  $R^2 = 0.9265$, s.e. = $+11.9/-7.2\%$
- Regression for data outcomes from 1 in 1000 to 1 in 10 000 AEP
  $$IFF = 366518 \cdot RRCR^{1.2191} \tag{8}$$
  $R^2 = 0.9809$, s.e. = ; $+2.1/-2.2\%$
- Regression for data outcomes beyond 1 in 10 000 AEP
  $$IFF = 3 \times 10^{10} \cdot RRCR^{4.9671} \tag{9}$$
  $R^2 = 0.9760$, s.e. = $+6.6/--4.3\%$

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 2 provides a high level of predictive accuracy, particularly for IFF capabilities in the extreme domain. This level of accuracy is considered acceptable for predicting the flood capability of reservoirs on small catchments in the sample region.

A relationship for converting flood capability from 1/AEP to %PMF: Mt. Lofty Ranges. Given the development of the food capability prediction relationship presented in Figure 2, it was considered appropriate to also provide an associated relationship enabling the option of converting any flood capability from 1/AEP to '% PMF inflow'. Therefore, using all the previous sample outcomes for both the 100% full and 33% full 'start' storage level cases ($n = 84$), flood

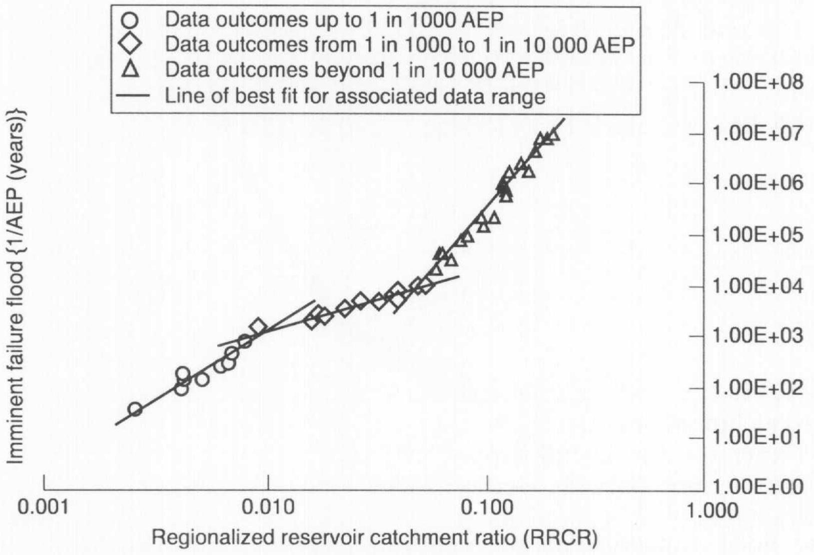

Figure 2. Sample data and line of best fit for IFF prediction based on the RRCR.

capability as 1/AEP (years) was plotted against flood capability as % PMF. The resulting scatter plot is presented in Figure 3.

A strong segmented relationship is again evident over the entire range of AEPs. Figure 3 illustrates this with a line of best fit through the scatter plot. However, the relationship separates at around 1 in 1000 AEP where it distinguishes between cases with 1 in 10^7 AEP of PMF and those with 1 in 10^6 AEP of PMF. The relationship separates at this point because the magnitudes of rainfalls for *extreme events* are dependent on the assigned AEP of PMF of a dam (see earlier and equation 1). Therefore, to be able to utilize this relationship, the AEP of PMF of a dam must first be determined using equation 1 in association with equations 3, 4, and 5.

From Figure 3, the lines of best fit of the five labelled segments are defined by the following power functions:

- Segment No. 1

$$IFF_{1/AEP} = 0.7135 \cdot (IFF_{\%PMF})^{2.9544} \qquad (R^2 = 0.9767) \tag{14}$$

- Segment No. 2

$$IFF_{1/AEP} = 6.3628 \cdot (IFF_{\%PMF})^{2.0607} \qquad (R^2 = 0.9949) \tag{15}$$

- Segment No. 3

$$IFF_{1/AEP} = 2 \times 10^{-7} \cdot (IFF_{\%PMF})^{6.7587} \qquad (R^2 = 0.995) \tag{16}$$

- Segment No. 4

$$IFF_{1/AEP} = 8.6657 \cdot (IFF_{\%PMF})^{1.8585} \qquad (R^2 = 0.9925) \tag{17}$$

- Segment No. 5

$$IFF_{1/AEP} = 1 \times 10^{-5} \cdot (IFF_{\%PMF})^{5.4781} \qquad (R^2 = 0.9962) \tag{18}$$

The coefficients of determination of the above equations are all extremely close to unity. Therefore, the regressions enable satisfactory conversion of flood capability from 1/AEP to %PMF. It is important to note that the conversion relationship presented in Figure 3 can be used for any case of 'start' storage level as flood capability outcomes are converted from 1/AEP to '%PMF inflow' using inflow flood frequency curves which are independent of 'start' storage level. The

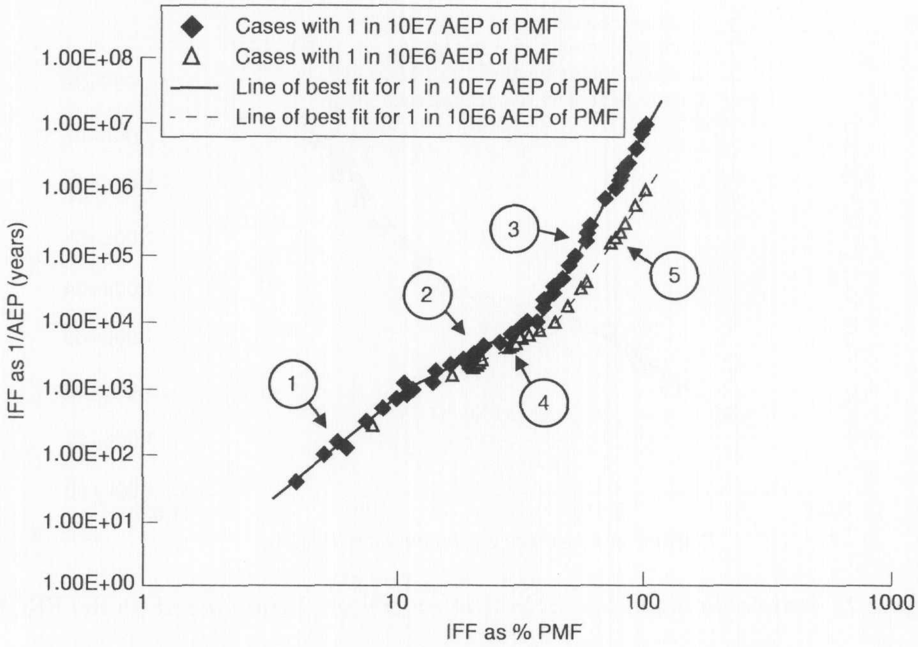

Figure 3. Sample data and line of best fit for conversion of flood capability from 1/AEP to %PMF.

final and most usable form of the overall conversion relationship is presented in Figure 4.

Description of the Regionalized Flood Capability Design/Review Procedure

The relationships presented in the foregoing section provide a procedure to engineers and dam owners to readily and effectively review and/or design the spillway flood capability of reservoirs on small catchments (area up to 10 km^2) in the Mount Lofty Ranges of South Australia. ANCOLD criteria on design floods for dams can be incorporated into Figure 2 to create Figure 5: the principle design/review tool.

The procedure can be used in either review or design mode. However, the following three main conditions are associated with the mechanism:

(1) The catchment must be free of any significant flow attenuating storages upstream of the principal reservoir.
(2) The spillway(s) must be free flowing and weir-type in nature.
(3) The IFF must be taken as the smallest flood which peaks at the *lowest point* of the non-overflow crest. Providing this conservative condition is acceptable, the mechanism can be applied to any dam-type structure. ANCOLD (1986) suggests that this condition is appropriate for embankment-type dams.

When using the procedure in review mode, the simple parameters required in the associated dimensionless ratio (see equation 6) must first be determined for an existing reservoir. These parameters are then put into the prediction relationship to read off the corresponding flood capability, which is automatically

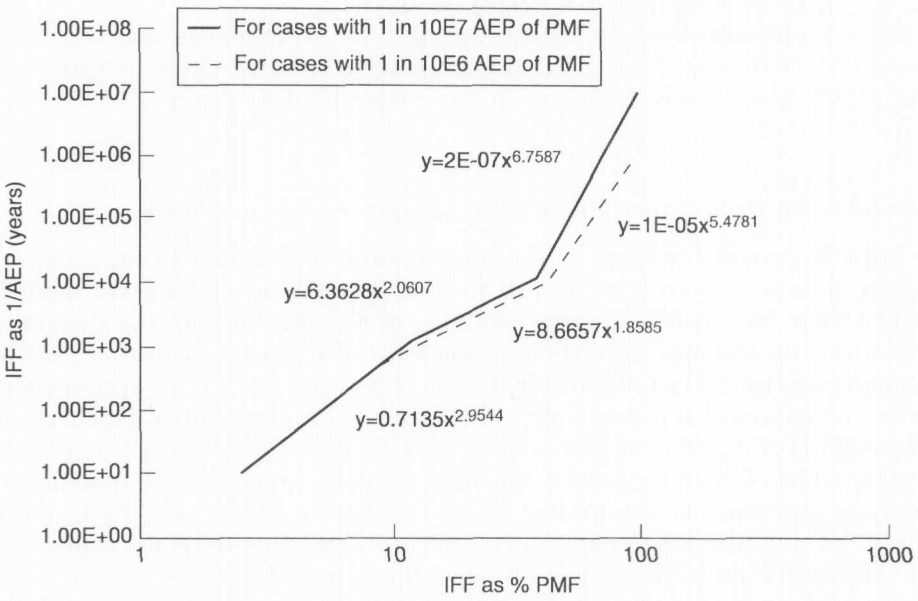

Figure 4. Relationship for converting IFF flood capability from 1/AEP to %PMF for reservoirs on small catchments in the Mount Lofty Ranges of South Australia.

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 associated dimensionless ratio until the ANCOLD safety criteria and the owner's storage needs are satisfied.

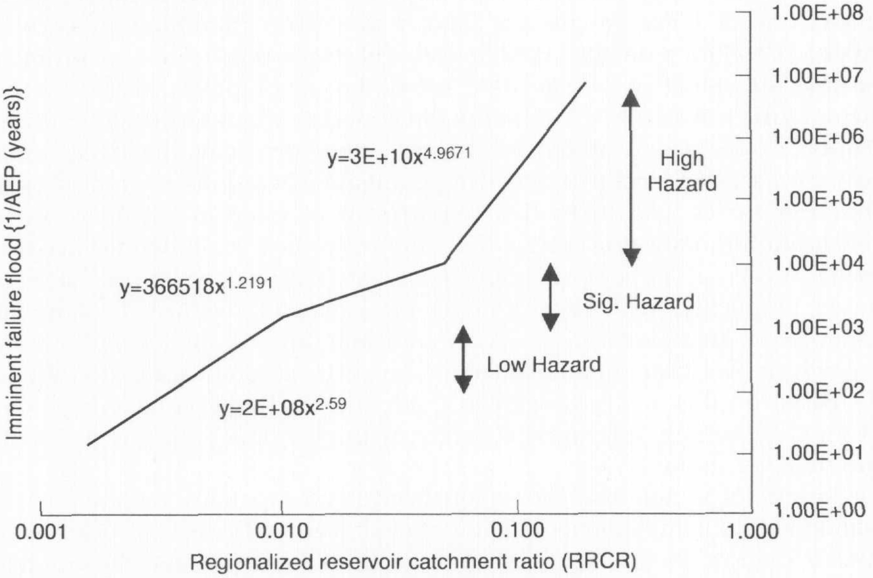

Figure 5. Reservoir flood capability design/review relationship incorporating ANCOLD criteria (from Table 1).

If for any circumstance the flood capability of a reservoir is to be known in terms of %PMF, say for example, to compare with NSW safety criteria (NSW DSC, 1993), then Figure 5 can be used to make the conversion.

Providing an Appropriate Private Dam Safety Assurance Policy

In order to provide increased dam safety assurance to downstream communities, it is necessary to educate private dam owners so as they are made to realize their responsibilities and liabilities in accordance with the dictates of common law, and also to establish some form of regulatory control over dam management practices to ensure that owners manage their dams appropriately in line with current standards. A detailed review of international practices (see Pisaniello [1997] and also Pisaniello & McKay [1996]), indicates that this can best be achieved with the establishment of properly organized, systematic dam safety programmes based on dam safety legislation. At the very least, considering that downstream communities ultimately bear the risks associated with dams, they should have the 'right to now' the potential dangers they are living under and be provided with the opportunity for salvation in the event of failure though appropriate Emergency Preparedness Procedures provided for under legislation.

Overseas experience, together with the experience of NSW, clearly demonstrates that dam safety programmes are workable and not too costly. Elements of best practice can and do exist successfully to control the safety management of private dams and in turn provide increased dam safety assurance to the public and promote the ideals of reducing loss of life as well as environmental and economic losses.

Based on the above, three safety assurance policy models have been developed which can be implemented in any country or state: a model of 'best practice', one of 'average practice' and a model of 'minimum practice' (see Pisaniello [1997] for a detailed description of these models). For a government to determine the extent of private dam safety assurance policy necessary for its particular jurisdiction (i.e. which of the three models should be used) requires an indication of the scope of the local dam safety problem; the most accurate indicator for this is 'density of deficient potentially hazardous reservoirs' as used in the USA in the late 1970s (US Department of Interior, 1980). In order to establish limiting indicator criteria (i.e. limiting values which would necessitate differing levels of policy), a number of international practices have been analysed, implicitly, with regard to (1) the extent of the private dam safety problem in the area based on the above indicator, and (2) the level of assurance policy which has been implemented in order to accommodate it (Pisaniello, 1997). Based on this analysis, detailed guidelines and criteria have been developed for determining 'appropriate' safety assurance policy for any jurisdiction, as summarized in Table 4.

It is important to note that the regionalized flood capability review procedure presented earlier complements the guidelines given in Table 4 as it can be used to *readily* determine the 'number of deficient dams' (i.e. for the guidelines indicator). This should encourage government to explore the status of private dam safety in any particular area and, if necessary, resolve the problem by appropriate policy implementation.

Table 4. Guidelines for determining an 'appropriate' private dam safety assurance policy for any jurisdiction

No. of potentially hazardous private dams*	No. of deficient** potentially hazardous private dams	Equivalent policy model to be implemented (see Pisaniello, 1997)
>70	>20	Model of best practice
>70	<20	Model of average practice (review situation in 15 years)
20–70	>20	Model of average practice (but review no. of deficient dams in 5 *years*: if still >20, upgrade to best practice)
20–70	10–20	Model of average practice (review situation in 15 years)
20–70	<10	Model of minimum practice (review situation in 10 years)
<20	>2	Model of minimum practice (review situation in 5 years)
<20	0, 1 or 2	Do nothing—advise owners of the deficient dams of their responsibility under common law (review situation in 10 years)

Notes:*This refers to the *total* number of potentially hazardous private dams contained within a county or state. For initial exploration, 'potentially hazardous dams' can be taken as those which are referable in size (ANCOLD, 1986) and pose either a high or significant hazard potential.

** Deficiency can result from either inadequate structural integrity, insufficient spillway flood capability or inadequate earthquake resistivity, as determined from a safety review.

Conclusion

There is a clear need in states where hazardous private dams exist to ensure that owners review and maintain their dams in line with current acceptable practice and take appropriate remedial action where necessary. Adequate assurance can only be provided through the implementation of appropriate policy, which requires the backing of law makers. The results of the case study reported in this paper, together with the cost-effective regionalized procedure and policy exploration guidelines, should encourage such backing.

The regionalized procedure described here, which is applicable only to the Mount Lofty Ranges of South Australia but derivable for any other region, can be used for dams on small catchments up to 10 km^2 in size; this will usually cater for most private dam cases in a particular area. The main benefit of the procedure is its simplicity, which dramatically reduces the great effort and resource that is normally required for conducting a 'state-of-the-art' reservoir flood capability study. The procedure provides a basis for quick yet accurate review and/or design of private dam spillways against any design flood standards, therefore complementing the policy exploration guidelines, and is in line with modern acceptable practice, which is of critical importance in a court of law.

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