Application of Available Climate Science to Assess the Impact of Climate Change on Spillway Adequacy

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Although there are considerable uncertainties in the science of climate change, there is a growing recognition of the importance of the issue. Incorporation of climate change impacts is now required in policy guidance from several government authorities and it is prudent risk management to consider the effects of climate change in planning for water resource infrastructure, including assessment and design of dam upgrades. This paper describes the potential impact of climate change on extreme flood estimates and provides a case study for Dartmouth Dam in south-eastern Australia. Three inputs to flood estimation were considered according to the projected impact of climate change; namely design rainfalls, modelled losses and initial reservoir level. The relative influence of each of these factors is explored. Rainfall and losses had a similar (and opposite) influence on results and for this dam the reservoir level prior to the flood event had the largest influence on results. This case study demonstrates that the insights of climate modellers and hydrologists need to be integrated in order to provide defensible estimates of the impact of climate change in flood hydrology studies. Credible projections of changes in design rainfall intensities are required for the full range of exceedance probabilities across Australia.

Keywords: *Risk management, climate change, flood estimates, spillway capacity.*

Introduction

Guidance for estimating large to extreme floods is given in Book VI of Australian Rainfall and Runoff, or ARR (Nathan and Weinmann, 2000). Current industry practice relies on recorded rainfall and streamflow data for extrapolating design rainfalls and calibration of rainfall-runoff models. As time passes and more recorded data accumulates, estimates based on historical data can be made with greater certainty. However, these studies assume a stationary climate, so the overall accuracy of the results may not improve with more historic data, given the potential impacts of climate change. The concept of climate change is problematic, because it means that the past may not be a good indicator of the future (Westra et al., 2010). This paper outlines a possible approach to this problem.

ARR Book VI, Section 7.7 (Nathan and Weinmann, 2000) acknowledges the difficulties in considering climate change and identifies the main difficulty as lack of information. In the intervening decade, climate research has continued to progress, and is now developed to a level that allows the impact of climate change on flood hydrology to be explored.

The case study used in this paper is Dartmouth Dam, which is located on the Mitta Mitta River in South East Australia. The embankment is of earth and rockfill construction, and has a storage capacity of approximately 3900GL. The catchment area is approximately 3500 km². The average annual inflows into the storage are only around 20% of the storage at Full Supply Level (FSL), so it is quite a large storage compared to its catchment. Prior to the current study, extreme flood estimates were derived using design inputs that assume a stationary climate. Those estimates provide a point of comparison with the new estimates reported in this paper.

Using the case study of Dartmouth Dam, a variety of inputs to flood estimation are examined and the possible impact of climate change on each input is considered.

Monte Carlo Framework for Flood Frequency Analysis

Design flood estimation has traditionally been based on the "design event" approach. A runoff routing model is used, and the rainfall depth is chosen to correspond to the specified design AEP. Then, the other inputs (losses, rainfall patterns) are chosen with the aim of the resulting modelled flood having a similar AEP to the rainfall input.

More comprehensive methods use joint probability techniques. A runoff routing model is still used, but the inputs to the model are not limited to single representative values. Instead, they are provided as distributions of possible values, and the distributions are chosen to reflect the observed variability. This is the approach adopted in this case study and RORB was the runoff routing model used. A Monte Carlo framework was used to run RORB many thousands of times, and with each run the inputs were chosen by randomly sampling each input distribution (Figure 1). The output of a joint probability technique is a distribution of outflows which can be presented as an outflow frequency curve. The AEP of interest can then be extracted from this curve. This method effectively mimics nature – for example, it allows for a flood of a particular magnitude to result from a moderate storm on a saturated basin, or a more intense storm on a dry basin. More information on joint probability techniques for design flood estimation can be found in Nathan et al. (2002; 2003).

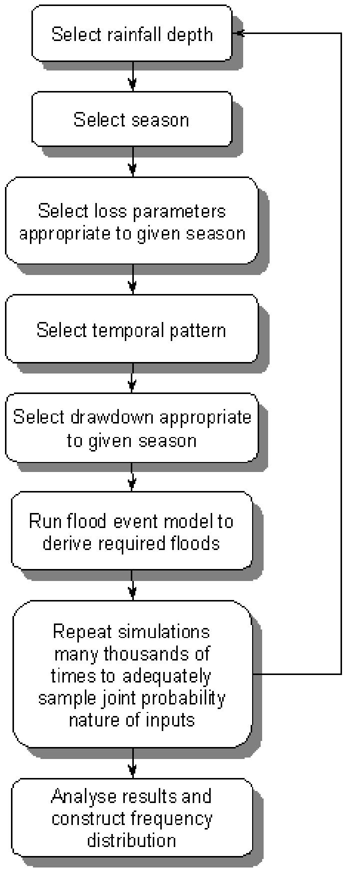

Figure 1: Process diagram for RORB Monte Carlo analysis (Nathan et al, 2002)

Since the inputs of interest in this study were provided as distributions, the main task described in this paper is estimating how these input distributions may change in response to climate change.

Method

Overview of Approach

Inputs into a flood runoff routing model typically include:

- Rainfall characteristics: depth, spatial pattern and temporal pattern;
- Spatial layout of the catchment (generally as a node-link network with attached sub catchment areas);
- Catchment losses reflecting partition of rainfall between infiltration/interception and overland flow; and
- Characteristics of any dams or storages (if applicable) including: spillway rating curves, storage capacity curves and initial storage levels prior to the flood event.

Some of these inputs will change little in response to climate change. The following three factors were selected for investigation in this study because they are considered to have the greatest potential for impacting on design flood estimates under climate change:

- Rainfall depths;
- Catchment losses; and
- Initial storage level.

These factors are discussed in turn below.

Rainfall Depths

A required input into the RORB Monte Carlo framework is an exceedance curve of rainfall depths for various storm durations. This input was derived for the Dartmouth catchment using the Bureau of Meteorology's published Intensity Frequency Duration (IFD) information and the CRC-FORGE procedure for Victoria (Weinmann et al., 1999). Revised design rainfall depths were under climate change required across the full frequency range from large events (1 in 50 to 1 in 100 AEP) all the way to extreme events (up to the PMP).

There is very limited credible information on changes in design rainfall depths. Plausible values for changes in rainfall depths due to climate change were then estimated with reference to a number of studies, as described below. Abbs (2009) performed an analysis of changes in design rainfall intensities for central Victoria and the Riverina area of southern NSW as part of the South-East Australia Climate Initiative (SEACI). This work, along with other similar studies (Abbs et al., 2006; Abbs and Rafter, 2008) used a high resolution (4km grid) limited area model that is embedded within boundary conditions from a Global Climate Model (GCM). A dynamic downscaling model was used to generate at least 100 events each for current, 2030 and 2070 climatic conditions and the maximum rainfall depths over windows of between 30 minutes and 96 hours in duration were then extracted for each model grid point. Abbs (2009) provides maps of the changes in rainfall depths over various durations. An example is reproduced in Figure 2 below.

By overlaying the catchment boundary onto these maps, the changes in rainfall depths can be estimated. Table 1 gives the estimates obtained for the study area. These results are consistent with general guidance that intensities of storm events are projected to increase under climate change (IPCC, 2007). However, for 2070, either little change or a decrease is projected. This result may be due to a reduction in the number of intense storm events even though events may become more intense when they do occur.

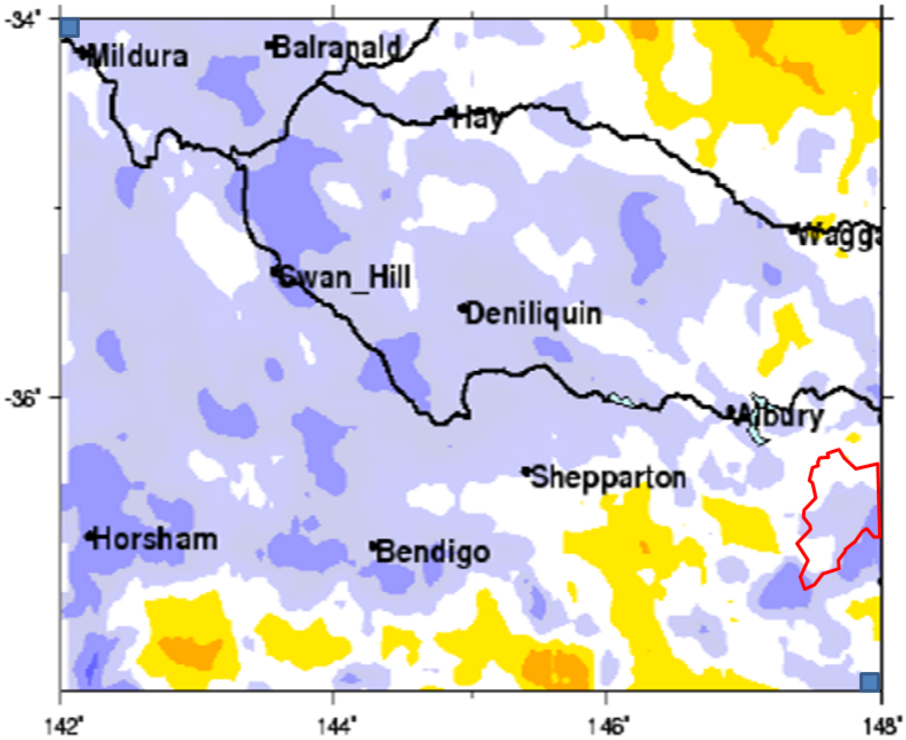

Figure 2: Projected percentage changes in design rainfall depths for the 24 hr duration under projected 2030 climate conditions, from Abbs (2009), with the Dartmouth Dam catchment area outlined in red.

Table 1: Estimated changes in large rainfall depths for the study catchment, based on Abbs (2009), for "large" rainfalls (AEP between 1 in 50 and 1 in 200)

Rainfall event duration	*Changes in rainfall depths from current to 2030*	*Changes in rainfall depths from current to 2070*
24 hours	+7%	+1%
72 hours	+5%	-9%

There are a number of sources of uncertainty to consider when using this data. The GCMs which provide the boundary conditions may be limited in their ability to correctly represent the frequency of occurrence of events of different synoptic types in the region (Abbs and Rafter, 2008). Furthermore, the considerable spatial variability in results (as per Figure 2) may be partly due to random sampling variability from having the intense rainfall storms occurring randomly in different locations in the 100 simulations for each climate scenario. Also, the detailed results from Abbs (2009) were not available, so the estimates for the study catchment were based on interpretation of the published maps only. Given these sources of uncertainty, additional estimates were sought from other sources.

New Zealand Climate Change Office (2004) includes a simple table that relates percentage changes in design rainfall depths to projected increases in annual temperature, based on high resolution atmospheric modelling of New Zealand. While this work is obviously not directly applicable to South East Australia, its simple method provides a useful comparison. Using projected temperature increases published by DSE (2008), the projected changes in rainfall using the New Zealand method were generally consistent with the estimates from Abbs (2009). The 1 in 100 AEP rainfall depths are predicted to increase by between 4% and 6%, depending on duration (Table 2).

Further verification was provided by CSIRO (2007a), which estimated changes in 1 in 40 AEP design rainfall intensities for the upper Murray catchment in South East Australia. These projections were based directly on results from GCM simulations and are therefore expected to be less accurate and display more variability. CSIRO (2007a) found that 1 in 40 year, 24 hour rainfall depths in the upper Murray catchment are likely to change by between -3% and +25% (2030 climate) and -7% and +29% (2070 climate). Although this represents a large range, the results are generally consistent with the two previous methods.

Table 2: Estimated changes in rainfall depths for the 24 hr duration in 2030

Method	*Description of result*	*Result*
Abbs (2009)	Increase in depths for large rainfalls.	+7%
NZCCO (2004)	Increase in depth for the 1 in 100 AEP assuming 0.9°C warming (DSE, 2008).	+6%

CSIRO (2007a)	Increase in depth for the 1 in 40 AEP.	Between 3% and +25%

Given the results above, it was decided to adopt a "best estimate" of likely changes in rainfall depths due to climate change of +7%. The plausible range of values was set as 0% to 15%. Due to the nature of historical data, the results above are generally based on storms in the AEP range of between 1 in 5 and 1 in 200. Very little guidance exists as to extrapolation into more extreme AEPs up to the Probable Maximum Precipitation (PMP). Jakob et al. (2008, 2009) completed a study of the implications of climate change for PMP estimation in Australia. They could not confirm that PMP depth estimates will definitely increase under a changing climate, and as a result the Bureau of Meteorology has not revised PMP estimates for effects of climate change. Even though the PMP depth may not change, there may be a change in the AEP of the PMP. It is possible that conditions of maximal moisture availability and storm efficiency may coincide more frequently in the future.

It was decided that design rainfall depths would be increased by the same percentage (a best estimate of +7%, with a plausible range of 0 to +15%) across the entire range of large, rare and extreme floods. As a result, the AEP of the PMP increased by approximately 1.3 times for the best estimate and up to 1.8 times for the +15% scenario. The PMP depth was not changed. In comparison, the uncertainty in the AEP of the PMP under current climate is an order of magnitude (+/- 10 times) (Laurenson and Kuczera, 1999).

Catchment Losses

For consistency with previous work in the Murray-Darling Basin, the scenarios adopted for estimating changes in catchment losses (and also storage drawdown, as discussed in the next section) correspond to scenarios in the Murray-Darling Basin Sustainable Yields (MDBSY) Project (CSIRO, 2007b). MDBSY scenarios used a 112 year run period, for which climate variability is based upon the climate for 1895-2006 and then adjusted differently for each scenario (Chiew et al., 2008). The following MDBSY scenarios were used in the current study:

- Scenario A – Historical climate (1895 to 2006) and current development;
- Scenario C Mid – Future climate (for around the year 2030) and current development, using downscaled GCM outputs that produce inflows near the best estimate of possible projections (approximate probability of exceedance of 50%); and
- Scenario C Dry – Future climate (for around the year 2030) and current development,using downscaled GCM outputs that produce inflows near the "dry" end of possible projections (approximate probability of exceedance of 95%).

As described above, the RORB Monte Carlo framework requires input of a probability distribution for both initial loss (in mm) and continuing loss (in mm/hour). The amounts by which these distributions might increase in value in response to climate change was estimated using the method described below.

During the initial study that did not consider climate change, the RORB Monte Carlo flood frequency curve for the study catchment was compared with the curve from flood frequency analysis to ensure an acceptable match. If a match was not achieved, the distribution of assumed losses was shifted up or down, as described in Nathan et al. (2003).

In the current study, this process was repeated, but the flood frequency analysis was not based on historic data, but rather on a synthetic timeseries derived from the MDBSY. Instead of matching peak flow rates (as per traditional frequency analysis) it was decided to match flow volumes since they are more sensitive to assumed losses. A period of 4 days was chosen as a representative flood duration.

For each of the above MDBSY scenarios, a timeseries of inflows to the storage was obtained from the Murray-Darling Basin Authority (MDBA). The volumes over rolling 4-day periods were totalled and a flood frequency analysis was performed on these totals. Within the Monte Carlo framework, the assumed loss distributions were altered so that the Monte Carlo 4-day volumes matched the MDBSY 4-day volumes. Table 3 contains the losses that were derived using the method above for each scenario. Quoted values correspond to medians in each distribution.

Table 3: Median catchment losses adopted for each climate change scenario.

Scenario	***Initial loss (mm)***	***Continuing Loss (mm/hour)***	***% change from Historic***
Scenario A	9.6	5.5	0%
Scenario C_{mid}	12.1	6.9	25%
Scenario C_{dry}	15.4	8.8	60%

Initial Reservoir Level

In the RORB model for this case study, the Monte Carlo framework allows consideration of a probability distribution for reservoir initial storage (or drawdown), rather than a single value. The model also takes seasonality into account, with a separate distribution specified for four different seasons.

As with losses, the changes in drawdown were estimated for each of MDBSY Scenarios A, Cmid and Cdry.

Outputs from the MSM-Bigmod model runs for storage levels were obtained from the MDBA for each scenario. In each case, daily values of storage volumes in the dam were obtained for the 112 year scenario duration. This data was analysed to provide a probability exceedance curve for drawdown in each of the four seasons (December-March, April-May, June-September, October-November). Figure 4 shows the combined (annual) drawdown distribution for each of the scenarios.

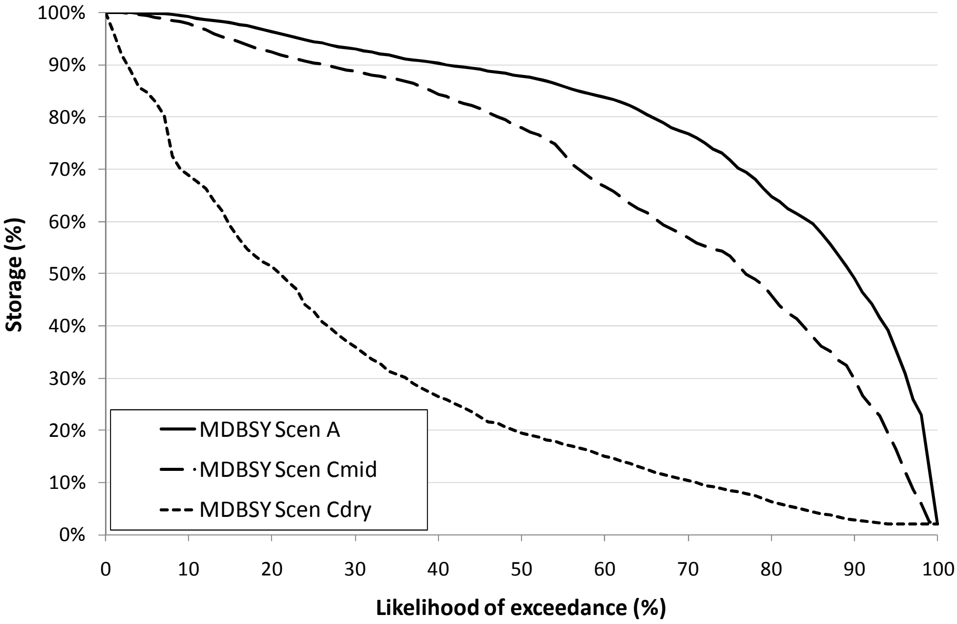

Figure 3: Drawdown probability distributions for various MDBSY scenarios

Figure 3 demonstrates that there is a much greater difference in drawdown between the two climate change scenarios Cmid and Cdry, than between the climate change scenario Cmid and Scenario A (historical climate). This demonstrates that, in terms of drawdown, the middle estimate of climate change (Cmid) is comparatively similar to the estimate of current conditions (Scenario A), but the range of climate change scenarios includes some where the drawdown is very different. For example, in Scenario Cdry Dartmouth Reservoir is less than 25% full for around half of the scenario duration. By comparison, Scenario A (historical climate) and Scenario Cmid have Dartmouth Reservoir around 90% and 80% full respectively, for around half of the scenario duration.

Scenarios

To analyse the sensitivity of the outflow frequency curve to the three different changes in inputs, nine separate Monte Carlo model runs were undertaken, each of which involved over 10,000 RORB model runs. This produced nine possible flood frequency curves. The inputs into the nine runs were produced by combining three possible future projections of changes in catchment losses and reservoir drawdown with three possible future projections of changes in design rainfall intensity. The reason why the losses and drawdown were linked together is that they were each derived with respect to Scenario A, Cmid and Cdry from MDBSY, whereas the design rainfalls are derived separately based on Abbs (2009), as described above. Scenario A0 assumes a stationary climate, so it provides a point of comparison for the other scenarios. The runs are summarised in Table 4.

Table 4: Scenario details for Monte Carlo Analysis

Scenario Name	***Change in design rainfall depths***	***Change in loss values***	***Drawdown curves from MDBSY scenario***
A0	0%	0%	A
A+7	+7%	0%	A
A+15	+15%	0%	A
Cmid 0	0%	+25%	Cmid
Cmid +7	+7%	+25%	Cmid
Cmid +15	+15%	+25%	Cmid
Cdry 0	0%	+60%	Cdry
Cdry +7	+7%	+60%	Cdry
Cdry +15	+15%	+60%	Cdry

Results

Inflow Frequency Curves

Although the outflow frequency curve is the primary output, the inflow frequency curve is still of interest because it is independent of assumed drawdown and hence it shows the influence of changes in losses and rainfall depths only. From Figure 4 it can be seen that neither losses nor depths are dominant in determining inflows; both have approximately the same order of impact (for the changes that have been assumed in this study). For example, the 1 in 100,000 AEP inflow is:

- Around 10,000m³/sec for A0 (losses Δ0, depths Δ0);
- Around 25% greater for A+15 (losses Δ0, depths ↑↑); and
- Around 20% less for Cdry + 0 (losses ↑↑, depths Δ0).

It is noted that flood routing through the storage tends to amplify these effects, meaning that the percentage impact on outflows will generally be greater than the percentage impact on inflows.

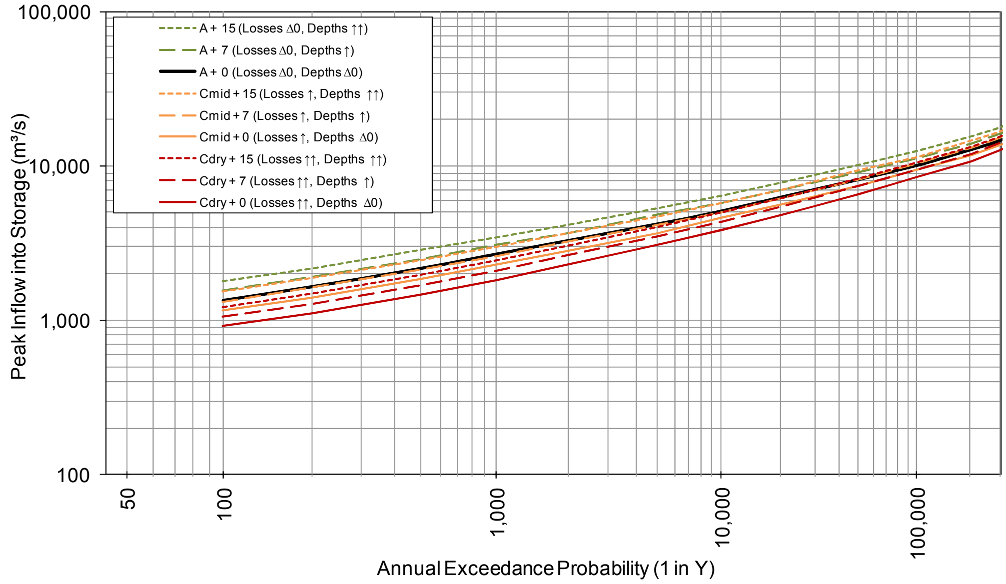

Figure 4: Dartmouth Dam inflow frequency curves for all scenarios

Outflow Frequency Curves

The outflow frequency curves are given in Figure 5. The curves are much more spread out for outflows than for inflows. For example, the 1 in 100 000 AEP outflow is:

- Approximately 3,000m3/sec for A+0 (losses Δ0, depths Δ0);
- Around 1.4 times greater for the highest scenario (A+15: drawdown Δ0, losses Δ0, depths ↑↑); and
- Around 6 times lower for the lowest scenario (Cdry + 0: drawdown ↑↑, losses ↑↑, depths Δ0)

The greater separation between Cmid, Cdry and A scenarios for outflows is due mainly to the influence of initial storage level on the results. The influence of initial storage level in this case study is greater than that of rainfall depths or losses, as discussed below.

Discussion

Table 5 splits the estimated impact of climate change into its constituent causes. The 1 in 100,000 AEP outflow is chosen as an indicative measure. As noted above, the rainfall depths and losses have a similar level of influence on inflows, of the order of 20-25%. Routing through the reservoir amplifies these effects, resulting in the figures shown in Table 5. The direction of change caused by the two is opposite – that is, rainfall depths are predicted to increase under climate change, causing larger floods; losses are predicted to increase, causing smaller floods. Initial storage levels (or drawdown) had the greatest impact on outflows. For Dartmouth Dam, drawdown was found to have around double the influence on the outflows compared the other two factors. This reflects the fact that this storage is large compared to its catchment, and relatively small drawdowns can provide large volumes of airspace to buffer incoming flows.

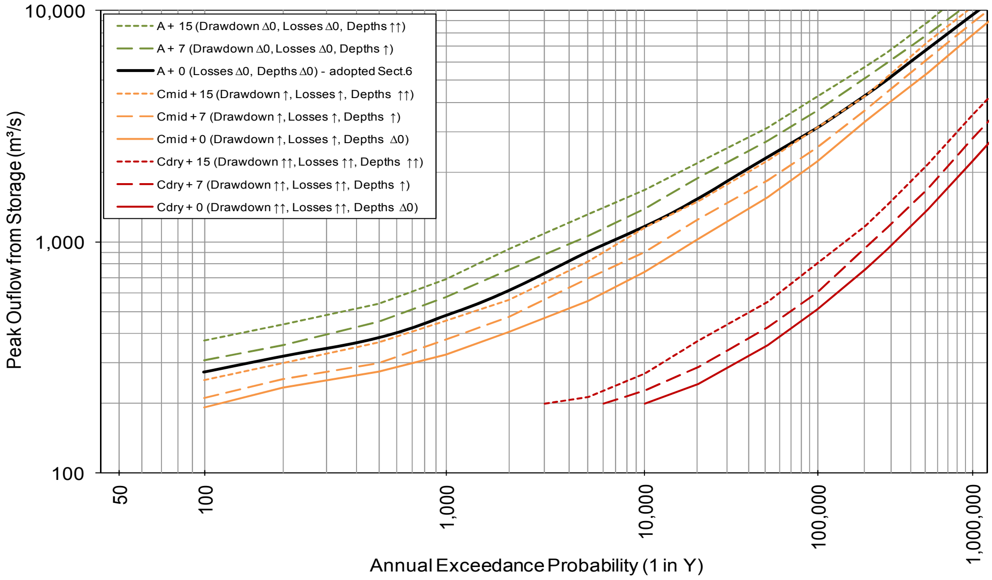

Figure 5: Dartmouth Dam outflow frequency curves for all scenarios

Table 5: Approximate impact on the 1 in 100,000 AEP Outflow of changes to inputs for Dartmouth Dam

Modelling input	***Largest flood risk scenario***	***Median flood risk scenario***	***Smallest flood risk scenario***
Rainfall depths	~35% increase	~15% increase	No change
Losses	No change	~10% decrease	~25% decrease
Initial storage level	No change	~25% decrease	~55% decrease
All three combined	~35% increase	~20% decrease	~80% decrease

The PMP Design Flood (PMPDF) refers to the flood with the same AEP as the PMP. For Dartmouth Dam, the PMPDF was estimated to be up to 16% lower on inflows and up to 81% lower on outflows due to the influence of climate change (Table 6).

The Dam Crest Flood (DCF) is the flood which causes the water level to rise as far as the embankment crest of the dam. In this case study, the DCF ranged between being twice as likely in the scenario with the largest flood risk, to 14 times less likely in the scenario with the least flood risk. It can be seen that the uncertainty associated with climate change leads to a wide range of possible estimates. However, it is noted that for Dartmouth Dam most (around two thirds) of the scenarios indicated a decrease in risk due to climate change.

Table 6: Impacts of climate change on selected indices for Dartmouth Dam

Design Flood	***Largest flood risk scenario***	***Median flood risk scenario***	***Smallest flood risk scenario***
PMPDF inflow	Negligible change	8% decrease	16% decrease
PMPDF outflow	Negligible change	20% decrease	81% decrease
Dam Crest Flood (DCF)	2.0 times more likely	1.4 times less likely	14 times less likely

It is noted that the level of uncertainty in extreme flood estimation is inherently quite high. The estimates of the extreme floods under climate change are within the 90% confidence limits of the non-climate change result, for most of the scenarios considered within this paper. Thus, uncertainty in estimating hydrologic risk is derived from these sources:

- Inherent uncertainty in the estimation of extreme floods in an unchanging climate; and
- Uncertainty introduced by climate change.

Conclusions

This paper described a framework for incorporating climate science into design flood estimates, and applied this framework to the case study of Dartmouth Dam. Three different inputs to flood estimation were considered: namely design rainfall depths, losses and initial storage level. In general, the scientific consensus is that design rainfall depths will probably increase under climate change, which will increase flood risk. In contrast, the effect of changes in losses and initial storage level is likely to decrease risk. The potential impacts on the initial storage level was found to have the greatest influence on outflow floods in this case study. Overall, the results indicate a likely reduction in flood risk due to climate change for this case study.

In general, there is a lack of qualitative information or research investigating the potential impacts of climate change on factors that affect flood magnitude. As such, the inputs were selected on a pragmatic basis using the best available information at the time of the study, and estimates should be revised as further information and research becomes available.

This case study demonstrates that the insights of climate modellers and hydrologists need to be integrated in order to provide defensible estimates of the impact of climate change in flood hydrology studies. Credible projections of changes in design rainfall intensities are required for the full range of exceedance probabilities across Australia.

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