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A novel and efficient approach to estimate lifetime exposure risk with changing flood probabilities

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ABSTRACT

The widely adopted 1% AEP design flood level has been the backbone of flooding and stormwater design standards for over 50 years. The choice of the 1% AEP design flood was often justified by its equivalent "lifetime flood exposure risk" which is equal to (approximately) a 50% chance of experiencing one or more floods over a typical 70-year life. Lifetime exposure risk is simply calculated using the binomial distribution with the core assumption that flood probabilities do not change over the design life. The impact of climate change on flood producing rainfall has been a concern in Australia since 1987 with adjustment factors being introduced in 2016. The design rainfall increases in the future, in most of climate change scenarios. Therefore, assessing lifetime flood exposure risk using the binomial theorem is no longer valid. As the probability of design rainfalls and flood levels are changing every year, estimation of lifetime exposure risk presents additional computational complexity. This paper presents a novel and practical method for evaluating lifetime flood exposure risk using a full solution to the Poisson binomial formula. The solution is complete and computationally viable using a discrete Fourier transform. The technique also allows a better understanding of the mean exceedance chance over an exposure risk period rather than a fixed chance. The approach has also been adapted for use outside Australia and can be applied to any situation where the change in flood probability can be defined over time.

KEYWORDS: flood, lifetime exposure, risk, changing climate

1 INTRODUCTION

Design standards like the 1% AEP flood level have been the backbone of flooding and stormwater design for over 50 years and was widely adopted in Australia in the 1970s (Cardno, 2015). Similar 1% AEP design standards have found wide use in the United States of America, United Kingdom, New Zealand and Canada. Drainage standards around Australia were widely adopted at that time but with design standards varying between states and local government areas. Australian Rainfall and Runoff (ARR) 1987 (Pilgrim Ed.(1987) lists some typical drainage standard values of 20%-10% AEP for residential areas.

Standards based approaches for floodplain management assume the consequences of flooding and the overall risk can be managed by a 1% likelihood (NSW Government, 2005) and 1% is considered a reliable balance between acceptable and unacceptable flood risk (NSW Government, 2005). For stormwater systems this is less of a problem, as pipe capacity based on likelihood is really a measure of how frequent a major inconvenience will occur as events exceed the pipe drainage capacity (Ball Et al., 2019). Australian stormwater design standards tend to vary with the intensity of design rainfall, with locations of higher design rainfalls generally having a lower standard, as it is difficult to fit the higher design flows that occur as a result of the higher rainfall into a stormwater pipe system (Pilgrim Ed. 1986). Ironically, locations with lower pipe standards tend to have better regulated overland flow paths for when the stormwater system capacity is exceeded (QLD Department of Energy and Water Supply, 2013).

The impact of climate change on flood producing rainfall has been a concern in practice since ARR 1987 (Pilgrim Ed., 1987). ARR1987 (Pilgrim Ed. (1987) stated:

> "*It should be noted that no consideration has been given to the long term effects of climatic change, a topic which is receiving increasing attention in the scientific literature.*"

ARR1987 (Pilgrim Ed.(1987) then quotes the conference statement from the 1985 Villach WMO conference (International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts, (1985 : Villach, Austria), 1986):.

> "*Many important economic and social decisions are being made today on long term projects based on the assumption that past climatic data, without modification, are a reliable guide to the future. This is no longer a good assumption since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century. It is a matter of urgency to refine estimates of future climate conditions to improve these decisions.*"

ARR1987 (Pilgrim Ed., 1987) continues:

> *"As no reliable estimates of climatic change are available, it has been assumed that the statistical characteristics of heavy rainfall and floods remain constant throughout the design life of projects. This is implied in the use of all of the probability terms in ARR"*

Approaches to estimate the impact of climate change on rainfall only became available in Australian Rainfall and Runoff (Australian flood design standard) in 2016 (Ball Et al. (2016) and for Probable Maximum Precipitation (PMP) in 2024 (Ball Et al, 2019). The 2024 update provides additional advice on adjusting antecedent conditions and incorporating these changes into design event modelling.

The choice of the 1% AEP design flood was often justified by its equivalent "lifetime flood exposure risk" which is equal to (approximately) 50% chance of experiencing one or more floods over a typical 70-year life (Pilgrim Ed.(1987), SCARM (2000), Commonwealth of Australia, (2018)). With an assumption of stationarity, lifetime exposure risk is simply calculated using the binomial distribution.

2 BACKGROUND

Lifetime exposure risk is presented in many Australian flood and floodplain management guidelines., including ARR 1987 (Pilgrim Ed. (1987) and SCARM (2000). This includes all versions of the NSW Floodplain Management Manual (NSW Government, 1986, 2001, 2005), and the national guideline (Handbook 7 Managing the Floodplain; Commonwealth of Australia, 2018). Table 1 provides the lifetime exposure risk from NSW Floodplain Development Manual (NSW Government, 2005) which uses a 70-year design life, and Table 2 is based on an 80-year design life in the Handbook 7: Managing the Floodplain (Commonwealth of Australia, 2018). Lifetime exposure to flood risk is considered a better measure than annual risk because it accurately reflects the cumulative probability of experiencing a flood over the duration of home ownership or a lifetime.

The Commonwealth of Australia (2018) updated the design life from 70 to 80 years to accommodate changes in Australian life expectancy (Australian Bureau of Statistics (ABS), 2024). Similar increases in life expectancy have occurred in many western countries (Leon et al, 2019). The examples in this paper are restricted to 70 years as most IPCC and Australian climate change predictions either do not extend past 2099 or are considered too uncertain that their use is discouraged (Ball Et al, 2019).

Under stationary conditions, exposure risk is simple to calculate using the binomial formula; where the probability of n exceedances over y years is for an annual Probability p is:

$$\text{Exposure probability} = p^{n} * (1-p)^{(y-n)} * \frac{y!}{n! * (y-n)!} \qquad (1)$$

For the case of one or more floods this can be reduced to:

$$\text{Exposure probability} = 1 - (1-p)^{y} \qquad (2)$$

Table 1: Lifetime risk exposure table adapted from Floodplain Development Manual (NSW Government, 2005)

Chance of occurrence in any year (ARI/AEP)	Probability of experiencing the given flood in a period of 70 years	
	At least once (%)	At least twice (%)
1 in 10 (10%)	99.9	99.3
1 in 20 (5%)	97.0	86.4
1 in 50 (2%)	75.3	40.8
1 in 100 (1%)	50.3	15.6
1 in 200 (0.5)	29.5	4.9

Table 2: Flood Risk recurrences table adapted from Handbook 7 Managing the Floodplain Best Practice (Commonwealth of Australia, 2018)

Annual Exceedance probability (%)	Approximate Average recurrence interval (years)	Probability of experiencing a given sized flood in an 80 year period	
		At least once (%)	At least twice (%)
20	5	100	100
10	10	99.9	99.8
5	20	98.4	91.4
2	50	80.1	47.7
1	100	55.3	19.1
0.5	200	33.0	6.11
0.2	500	14.8	1.14
0.1	1000	7.69	0.30
0.01	10000	0.80	0.003

The binomial formula (Eq. 1) is simple to calculate with the combinational part of the formula calculating the unique number of ways a fixed number of floods can occur. This can be explained with the example of 10 floods in 70 years when assessing a 1 in 5 AEP level bridge performance over a 70-year design life. There are $3.96*10^{11} = (70!/(10!\times(70-10)!))$ combinations where 10 floods exceeding a specific threshold can occur in 70 years. With fixed probabilities in a stationary climate there is no need to calculate each separately. With climate change, each of the $3.96*10^{11}$ combinations has a unique probability and must be calculated separately to address non stationarity. That is not trivial, as 70 unique probabilities need to be multiplied for each case and summed. To calculate the probability of 10 or more floods one would also need to work out the probabilities for 0 to 9 exceedances. In a stationary climate with fixed probabilities there are 70 unique combinations but with changing probabilities there are 2^{70} ($1.181*10^{21}$) unique combinations.

The Poisson binomial distribution formula is written below:

$$P(Y \leq y) = \sum_{s=0}^{y} \sum_{A \in F_s} \prod_{i \in A} P_i \prod_{i \in A^c} (1-P_i) \tag{3}$$

Where F_s is defined as the set of all subsets of size s that can be chosen from the set $\{1,2 \dots n\}$, P_i is the probability of failure or exceedance in year i and Y is the number of failures in y years. Where the first sum operator sums the probability of 1 to Y failures, the 2nd sums all the combination of a fixed number of failures, that were identical in the simple binomial case. The two product operators multiply the probability of failures and non failures over y years. This case can be calculated by the Poisson binomial distribution formula. As the direct calculation is numerically intractable, various approximations have been proposed as well as recursive approaches tested to reduce the number of calculations required. For small number of failures the numerical overhead can be improved by multiplying the no failure case in equation 4:

$$\prod_{i=1}^{y}(1 - p_i) \qquad (4)$$

by the sum of the n cases of the product of the ratio of the failure over the non failure. The formula for the simple case of 2 failures (n=2), where the first failure is i and the second is j becomes:

$$\sum_{i=1}^{y-1}\sum_{j=i+1}^{y}(p_i) * \frac{p_j}{(1 - p_i) * (1 - p_j)} \qquad (5)$$

This reduces the numerical load from 2415 combinations of multiplying 70 probabilities to multiplying 70 probabilities once and multiplying this by the sum of 2415 combinations of 2 probability ratios. This increases speed for small values of n but is still too computationally complex for an online calculator where multiple future scenarios are considered. The numerical overhead can also be reduced by working in log space. The problem is further complicated by the need to sum a very large number of small probabilities together, which if not done carefully can lead to numerical rounding errors.

There are approximation formulas (Hong, 2013), that include very simple approaches based on the mean failure probability, but using an accurate formula was too slow and approximation methods too inaccurate, for a successful online calculator. Hong (2013) and Biscarri et al. (2017) presented accurate, computationally efficient methods based on a Fourier transformation. Hong's approach is available as Python functions (Straka, 2016) and provides exact solutions.

Some Australian design standards require performance over a design life without providing advice on how this should be carried out (for example Ball et al, 2019). Common approaches include design for adequate performance on the last day of the design life or designing for adequate performance at the midpoint of the design life. The geometric mean of the failure probabilities over a given design life can also be used as a more realistic design input if average performance over the design life is required. For the example of a 70 year design life equation 6 gives the geometric mean of the failure probabilities.

$$p = \sqrt[70]{\prod_{i=1}^{70} p_i} \qquad (6)$$

Where p is the average risk that will occur across the design life.

3 RISK EXPOSURE TOOL

A lifetime exposure tool was original developed for the Australian climate change calculator (Babister et al. 2024), and has now been generalised for broader application where the user defines the change in probability of failure over time. The tool is available at exposure.wmawater.com.au. Once the change in future flood risk has been uploaded the user can explore how lifetime exposure changes and compare this to the traditional stationary climate case.

This tool can calculate the change in probability over time from three or more points by fitting a curve through these points. The tool then applies the Poisson binomial formula to the selected design life. Testing found that the change in flood risk under Shared Socioeconomic Pathway (SSP) is well described by a simple 2nd order polynomial (Figure 1). This example is for the 11,500km^2 Hawkesbury Nepean catchment to Penrith in Western Sydney, Australia. Figure 1 shows how smooth probability change curves can be fitted to climate change results for different SSPs. The 2nd order polynomial through data for 2025, 2030, 2050 and 2090 for each SSP is a good approximation of the intermediate decadal values.

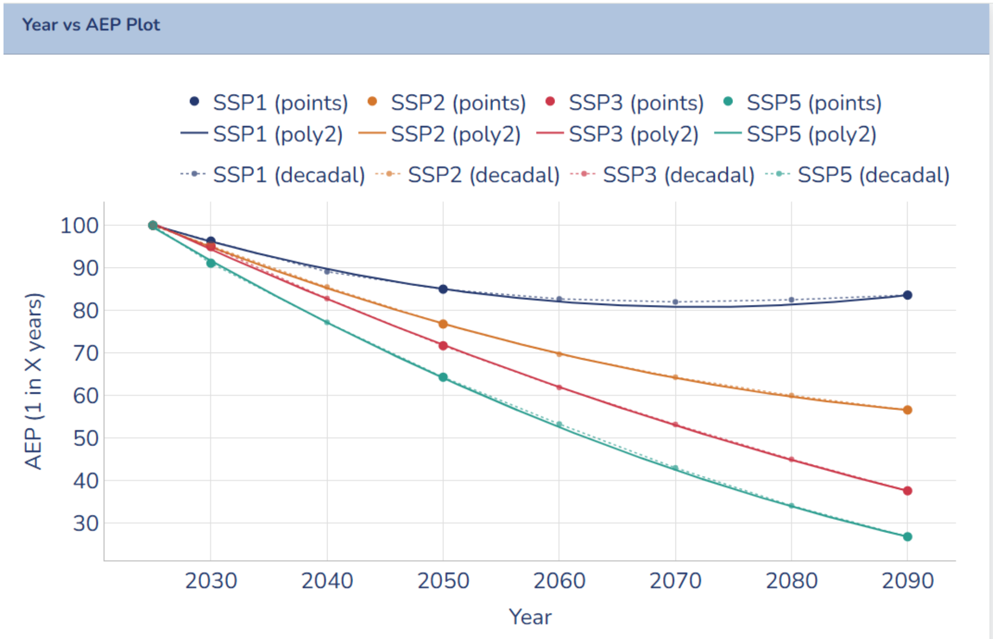
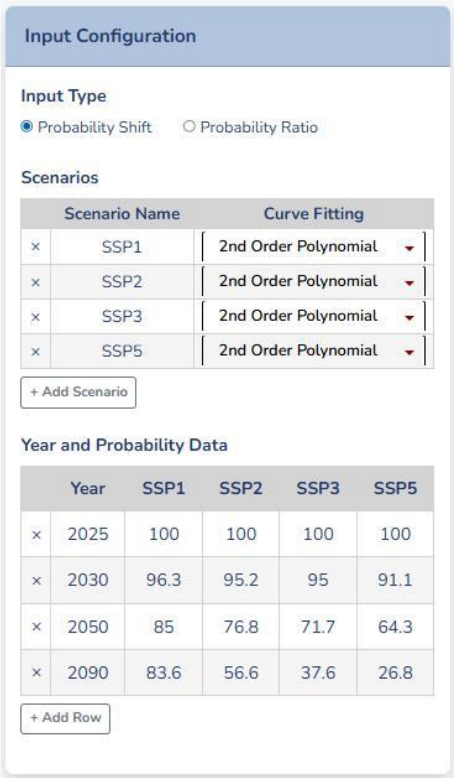


Figure 1: Change in probability of a 2025 1% AEP flow estimate for various SSP – decadal data fitted with 2nd order polynomial

The tool also allows the uses of a piecewise spline or simple linear segment interpolation (Figure 2) for cases where mitigation measures or other works cause more abrupt changes in probability over time. Figure 2 shows the landing page, how future flood risk is uploaded, and fitting method selected along with exposure period.



Input Configuration

Input Type

● Probability Shift ○ Probability Ratio

Scenarios

	Scenario Name	Curve Fitting
×	SSP1	2nd Order Polynomial
×	SSP2	2nd Order Polynomial
×	SSP3	2nd Order Polynomial
×	SSP5	2nd Order Polynomial

Year and Probability Data

	Year	SSP1	SSP2	SSP3	SSP5
×	2025	100	100	100	100
×	2030	96.3	95.2	95	91.1
×	2050	85	76.8	71.7	64.3
×	2090	83.6	56.6	37.6	26.8

Figure 2: Tool input configuration.

The steps in the tool are:

1. Upload the change in failure risk at discrete intervals (such as SSP2 2030,2050 2090). Up to 4 scenarios can be included. Changes in future flood risk can be uploaded as either probabilities or ratios
2. Fit a smooth relationship so annualised change in risk can be calculated. While a 2nd order polynomial is recommended other options include a piecewise spline or simple linear segment.
3. Fit statistics and graphs are produced to aid in the selection final section of fitting method.
4. Selected the start and finish year for exposure risk calculation.
5. After submitting tabulated and graphic exposure risk is calculated

4 RESULTS

Results are presented for two examples using the current Australian climate change guidance (Ball et al., 2019) for SSP1, SSP2, SSP3 and SSP5. The examples use a 70-year design life. For each example the change in flood probability is shown graphically along with graphs and tables of exposure risk. The two examples are:

1. A development at the 1% AEP level in a catchment with a 24-hour critical storm duration
2. A development at the 1% AEP level in a catchment with a 1-hour critical storm duration

These examples have been selected to show how the exposure risk under current guidance changes more dramatically on catchments with a shorter response time.

Example 1 - For a development built at the 1% AEP level in a catchment with a 24-hour critical storm duration the chance of 1 or more exceedances in the 70-year design life goes from around 50% under historic conditions to approximately 82% in SSP5 (Figure 3 and Table 3).

Example 2 - For a similar development built in a catchment with a 1-hour critical duration at the 1% AEP level the chance of 1 or more exceedances in the 70-year design life goes from around 50% under historic conditions to approximately 99% in SSP5 (Figure 4 and

Table **4**).

When undertaking risk or design life assessment in a non-stationary climate it is common to undertake an assessment at a representative point in the project's life, with the midpoint often being used. The midpoint works well when the rate of change is relatively linear. However, as SSP1 peaks and drops off and SSP5 shows an increasing rate of change in rainfall, a midpoint can be a poor choice. For a 70-year design life on a catchment with a 24-hour critical duration the use of the midpoint produces the following errors, SSP1 and SSP2 overestimate the frequency of events by 5.6% and 3.2%, respectively and SSP3 and SSP5 underestimate the frequency by 2.7% and 2.8% respectively.

5 CONCLUSIONS

Before now, it has not been practical to accurately calculate the exposure risk for reasonable values of n exceedances in non-stationary conditions. Previous solutions to calculating the probability mass function of a Poisson binomial distribution were largely intractable for large values of n. Accurate methods were computationally intensive and approximation methods inaccurate. With new approaches (Hong 2013) it is now practical to calculate exposure risk under climate change. This approach has been built into the Australian Climate Change Calculator (ccc.wmawater.com.au). This allows the tool to calculate the expected number of exceedances in a changing climate and is increasingly important to flood planning in a changing climate.

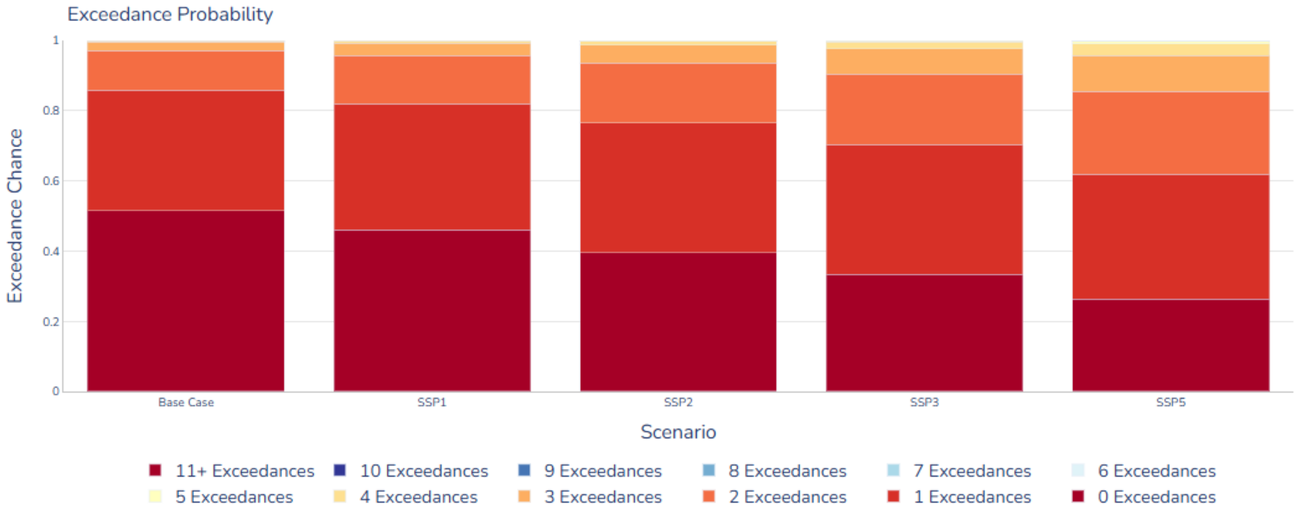


Figure 3: Number of exceedances in a 24-hour catchment over a 70-year design life

Table 3: Exceedance Probability (%) for 24-hour catchment over a 70-year design life

Number of Exceedances	Historic	SSP1	SSP2	SSP3	SSP5
0 Exceedances	49.48	46	40	33	26
1 Exceedance	34.99	36	37	37	36
2 Exceedances	12.19	14	17	20	24
3 Exceedances	2.79	3.5	5.1	7.2	10

4 Exceedances	0.47	0.65	1.1	1.9	3.3
5 Exceedances	0.06	0.096	0.2	0.39	0.82
6 Exceedances	0.01	0.012	0.029	0.066	0.17
7 Exceedances	0.00	0.0012	0.0035	0.0094	0.029
8 Exceedances	0.00	0.0001	0.00036	0.0011	0.0043
9 Exceedances	0.00	7.8E-06	0.000033	0.00012	0.00055
Ten or More	0.00	5.2E-07	2.6E-06	0.000012	0.000063

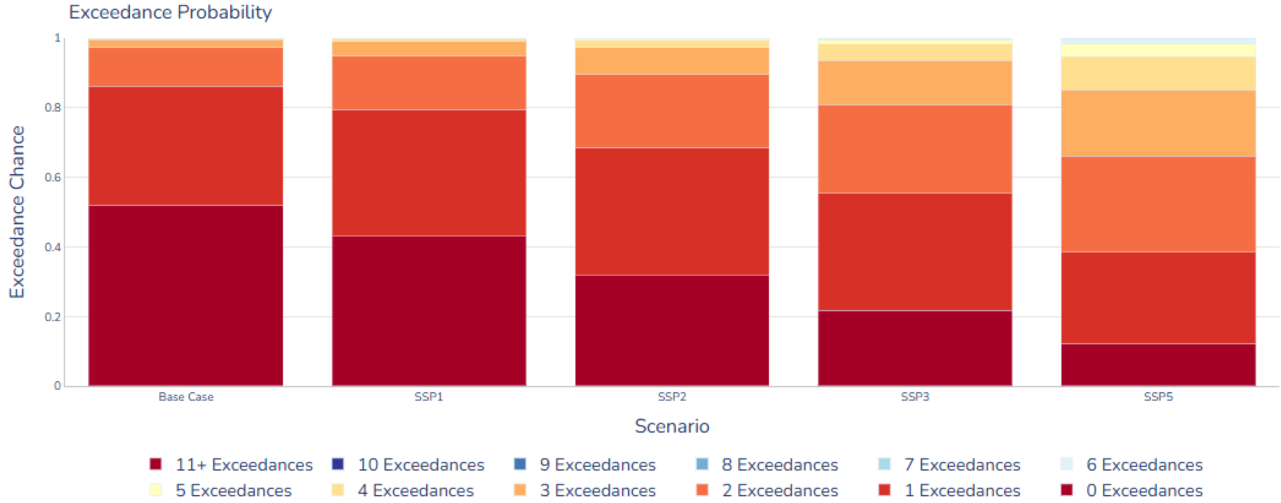


Figure 4: Number of exceedances in a 1-hour catchment over a 70-year design life

Table 4: Exceedance probability (%) for 1-hour catchment over a 70-year design life

Number of Exceedances	Historic	SSP1	SSP2	SSP3	SSP5
0 Exceedances	49.48	43	32	22	12
1 Exceedances	34.99	37	37	34	26
2 Exceedances	12.19	15	21	26	28
3 Exceedances	2.79	4.2	7.8	13	19
4 Exceedances	0.47	0.85	2.1	4.6	9.5
5 Exceedances	0.06	0.13	0.46	1.3	3.8
6 Exceedances	0.01	0.018	0.082	0.31	1.2
7 Exceedances	0	0.0019	0.012	0.061	0.33
8 Exceedances	0	0.00018	0.0016	0.01	0.075
9 Exceedances	0	0.000015	0.00017	0.0015	0.015
Ten or More	0	0.0000011	0.000017	0.0002	0.0026

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