INFRASTRUCTURE NSW

CLIMATE CHANGE AND FLOODING EFFECTS ON THE HAWKESBURY-NEPEAN

FINAL REPORT

SEPTEMBER 2021

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Project Climate Change and flooding effects on the Hawkesbury-Nepean	**Project Number** 113031-07
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AEP	Annual Exceedance Probability
ARI	Average Recurrence Interval
ARR	Australian Rainfall and Runoff
BOM	Bureau of Meteorology
DTM	Digital Terrain Model
GIS	Geographic Information System
IFD	Intensity, Frequency and Duration (Rainfall)
m AHD	meters above Australian Height Datum
OEH	Office of Environment and Heritage
PMF	Probable Maximum Flood

ADOPTED TERMINOLOGY

Australian Rainfall and Runoff (ARR, ed Ball et al, 2016) recommends terminology that is not misleading to the public and stakeholders. Therefore, the use of terms such as “recurrence interval” and “return period” are no longer recommended as they imply that a given event magnitude is only exceeded at regular intervals such as every 100 years. However, rare events may occur in clusters. For example, there are several instances of an event with a 1% chance of occurring within a short period, for example the 1949 and 1950 events at Kempsey. Historically the term Average Recurrence Interval (ARI) has been used.

ARR 2016 recommends the use of Annual Exceedance Probability (AEP). Annual Exceedance Probability (AEP) is the probability of an event being equalled or exceeded within a year. AEP may be expressed as either a percentage (%) or 1 in X. Floodplain management typically uses the percentage form of terminology. Therefore a 1% AEP event or 1 in 100 AEP has a 1% chance of being equalled or exceeded in any year.

ARI and AEP are often mistaken as being interchangeable for events equal to or more frequent than 10% AEP. The table below describes how they are subtly different. While AEP is recognised as an industry standard, ARI terminology has been adopted for the communication of non-standard frequencies such as those observed in the conversion of design flood frequencies to those under a climate change scenario.

For events more frequent than 50% AEP, expressing frequency in terms of Annual Exceedance Probability is not meaningful and misleading particularly in areas with strong seasonality. Therefore, the term Exceedances per Year (EY) is recommended. Statistically a 0.5 EY event is not the same as a 50% AEP event, and likewise an event with a 20% AEP is not the same as a 0.2 EY event. For example, an event of 0.5 EY is an event which would, on average, occur every two years. A 2 EY event is equivalent to a design event with a 6 month Average Recurrence Interval where there is no seasonality, or an event that is likely to occur twice in one year.

The Probable Maximum Flood is the largest flood that could possibly occur on a catchment. It is related to the Probable Maximum Precipitation (PMP). The PMP has an approximate probability. Due to the conservativeness applied to other factors influencing flooding a PMP does not translate to a PMF of the same AEP. Therefore, an AEP is not assigned to the PMF.

Frequency Descriptor	EY	AEP (%)	AEP (1 in x)	ARI
Very Frequent	12			
	6	99.75	1.002	0.17
	4	98.17	1.02	0.25
	3	95.02	1.05	0.33
	2	86.47	1.16	0.5
	1	63.21	1.58	1
	0.69	50	2	1.44
Frequent	0.5	39.35	2.54	2
	0.22	20	5	4.48
	0.2	18.13	5.52	5
	0.11	10	10	9.49
	0.05	5	20	20
Rare	0.02	2	50	50
	0.01	1	100	100
	0.005	0.5	200	200
	0.002	0.2	500	500
Very Rare	0.001	0.1	1000	1000
	0.0005	0.05	2000	2000
	0.0002	0.02	5000	5000
Extreme			↓	
			PMP/ PMPDF	

EXECUTIVE SUMMARY

In May 2017, the NSW Government released *Resilient Valley, Resilient Communities Hawkesbury-Nepean Valley Flood Risk Management Strategy* (Flood Strategy). The Flood Strategy is a comprehensive long-term framework for the NSW Government, local councils, businesses and the community to work together to reduce flood risk, building a more flood resilient Hawkesbury-Nepean Valley. It includes a range of targeted actions delivering nine outcomes across the prevention, preparedness, response and recovery spectrum of disaster risk management. Outcome nine requires the Flood Strategy be periodically reviewed to ensure that the objectives are being realised, taking into consideration a number of issues including the impact of projected climate change on flood risk. More detailed climate change analysis is a consideration in the development of the detailed concept design, and required under the Secretaries Environmental Assessment Requirements (SEARs) for the proposed raising of Warragamba Dam.

This report outlines the assessment of the impact of projected climate change on the flood mitigation benefits of various raising levels for Warragamba Dam that led up to the preferred 14 metre raising option, and investigates the 14 metre dam raising in detail including other related factors that influence dam and spillway levels. These factors include the distinct wet and dry periods that dominate the Hawkesbury-Nepean Valley flood record, and the option of having the two spillways operate at different levels so that the side spillway operates less frequently and closer to its original design.

The impact of climate change on flood producing rainfall is quite complex and there is still considerable uncertainty around exactly how a warming climate will influence flood behaviour. Warmer temperatures increase the moisture carrying capacity of the atmosphere and theoretically will lead to higher rainfall but the causes of rare floods are more complex. Nearly all major floods in the Hawkesbury-Nepean are caused by an east coast low, an intense low pressure weather system that can occur on average several times each year off the eastern coast of Australia. The overall frequency of this weather system and how often they impact the Hawkesbury-Nepean is also likely to change along with how dry catchments are and the dam levels prior to a flood event. It is also likely that climate change will cause proportionally higher increases in rainfall in locations where the terrain orographically enhances rainfall for example the eastern part of the catchment on the Woronora Plateau. While there is some uncertainty about how climate change will affect rainfall, this report assesses the current best estimates of how climate change will affect flooding based on work by CSIRO, BoM and the NSW NARCliM project.

Diagram 2 shows the surface temperature anomaly in the Oceania region from 1910 to 2010 (NOAA) along with projected warming for the east coast region for high (8.5 RCP), low (4.5 RCP) and an interpolated medium representative climate pathway (RCP) from the CSIRO climate modelling work. These two data sets align well at the common cross over point of 1995. Current research suggests that regional scale flood producing rainfalls will increase proportionally with temperature. On this basis the historical rainfall and streamflow record contains some warming effects and the current flood behaviour is already significantly affected.

The flood record at Windsor dates back to 1790 and is the longest in Australia and shows distinct wet and dry periods that last for approximately 40 years. Nearly all the moderate and all the major floods have occurred in the wet period with only a handful of isolated events in the dry periods. The current dry period commenced 25 years ago in 1993, while the only two complete, recorded dry periods both lasted 38 years.

The initial dam raising options assumed the main central spillway and the larger auxiliary, or side spillway, will start operating at similar levels. The current preferred design (known as A7 or AS 130.6) has these offset. This design operates with uncontrolled (non-gated) spillways set at 128.45m AHD for the centre spillway, and 130.6m AHD for the side spillway. The layout of the preferred raised dam design is illustrated in Diagram 1.

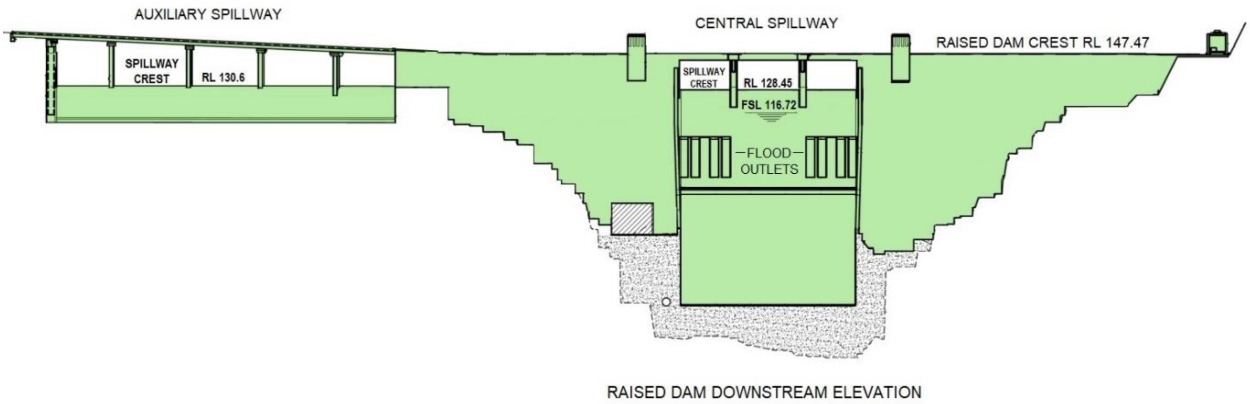
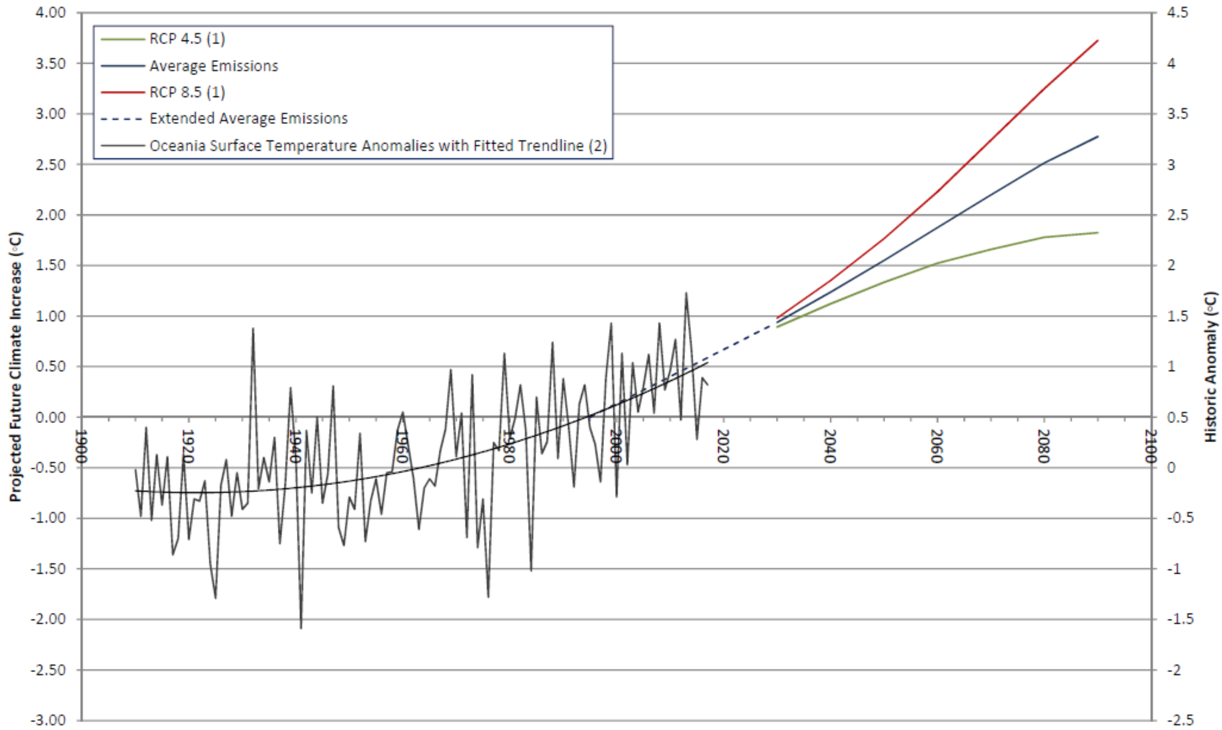


Diagram 1: Preferred dam design (A7) layout

There are good practical reasons why the levels at which the spillways operate should be set at different levels. The current auxiliary spillway was designed to only operate in rare floods and is untested, unlike the main spillway that has passed quite high flows. The practical issue is not with the design of the spillway but the dissipation of energy that occurs at the bottom of the spillway. The main spillway energy dissipater has performed quite well but the auxiliary spillway design assumes that the river will be quite high before it operates.



Source:
(1) ARR Data Hub, sourced from the Climate Futures tool acessed: https://www.climatechangeinaustralia.gov.au/en/climate-projections/future-climate/. Average based on East Coast South climate from 1986 to 2005.
(2) NOAA, Oceania Land Temperature Anomalies accessed: https://www.ncdc.noaa.gov/. Anomaly measured from 1910 to 2000.

Diagram 2: Surface Ocean temperature anomalies with projected climate change

This report investigates dam raising options under historic, current and future climate change conditions. Under all climate projections flood levels increase for both the existing dam and various mitigation dams. Under a medium climate change projection (14.6% increase in rainfall by 2090), for example, the 1% AEP or 100 year ARI flood level at Windsor is projected to increase from 17.32m to 18.43m. A 14m raised dam will reduce the flood level at Windsor to 13.25m under historical conditions, and 14.88m under this medium climate change projection.

This report was undertaken over several stages throughout the dam design optimisation process. As a result, not all analysis presented in the report has been reproduced in each evolution of the report. Following the review of the report by expert reviewers the climate change scenarios from the various sources were adjusted to a common baseline. Only the existing dam and the currently preferred 14m raising design runs were updated for these common baseline climate change scenarios. The assessment of different dam raising heights was not updated and has been moved to an appendix for clarity.

Table 1 summarises the results for existing, and 14m dam under historical, under different climate projections. The unique topography of the Hawkesbury-Nepean Valley means that the impacts of climate change are larger than in many other NSW catchments.

Table 1: Summary of Flood Levels (m) under a range of rainfall increases, for existing and 14m raised (A7) dam configurations

Scenario	1% AEP Windsor Bridge Levels		1% AEP Penrith Levels	
	Existing	A7	Existing	A7
Base	17.32	13.25	25.78	21.58
4.9%	17.71	13.78	26.09	22.24
7.33%	17.90	14.03	26.21	22.58
9.5%	18.06	14.29	26.31	22.86
13.4%	18.34	14.73	26.47	23.37
14.6%	18.43	14.88	26.52	23.52
18.6%	18.72	15.33	26.68	23.99
19.7%	18.80	15.45	26.72	24.12
23.9%	19.11	15.92	26.87	24.60
32.7%	19.71	16.84	27.13	25.52

Diagram 3 shows the impact of climate change from low to high rainfall increases and over different time horizons. The red bar shows changes in the current 100 year ARI flood level at Windsor (a major population centre) with a raised dam for different climate change scenarios. The blue bar shows the increase in flood levels for different climate change scenarios for the existing dam. Similar trends are shown at Penrith.

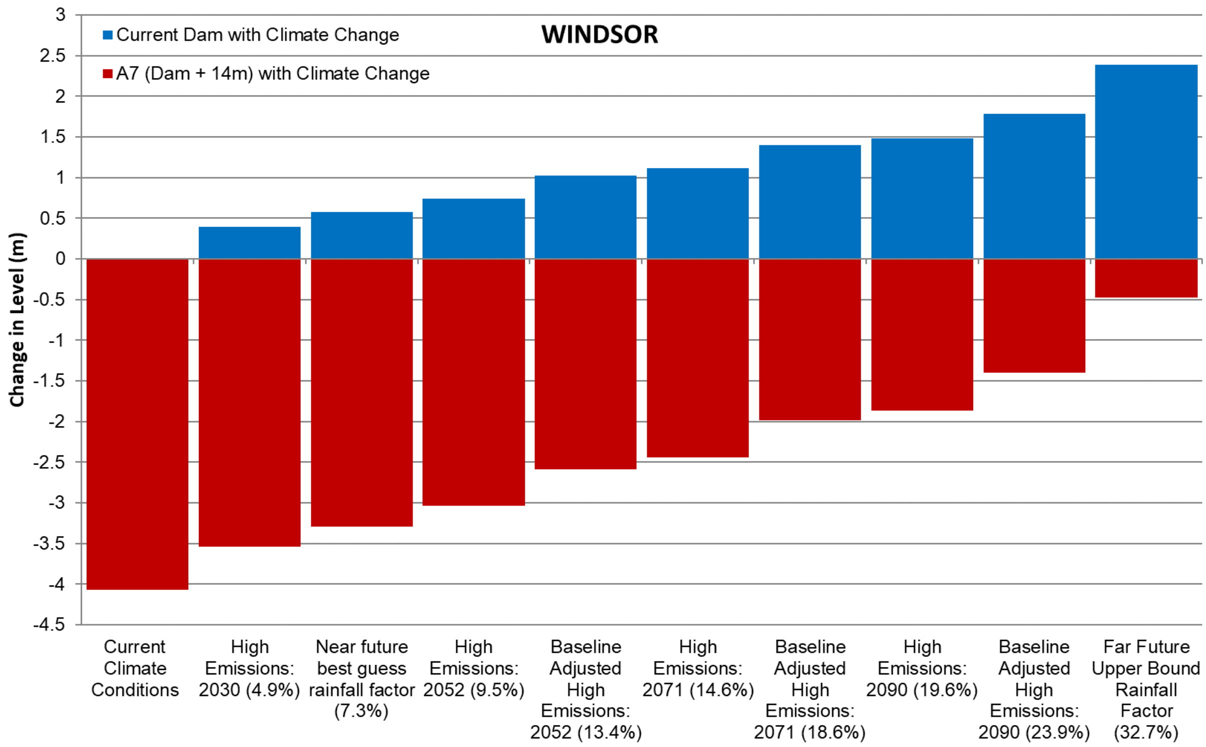


Diagram 3: 100 year ARI Level Impact of Climate Change on Existing Dam and A7 (Dam +14m) Scenarios at Windsor

1. INTRODUCTION

In May 2017, the NSW Government released the *Resilient Valley, Resilient Communities Hawkesbury-Nepean Valley Flood Risk Management Strategy* (Flood Strategy, INSW 2017). The Flood Strategy addresses flooding over 425 km^2 of floodplain within an area with a large and growing population including Penrith, Richmond, Windsor and surrounding suburbs. The Flood Strategy includes a range of targeted actions designed to deliver nine key outcomes that fulfil the National Strategy for Disaster Resilience roles for Government. Outcome nine requires the Flood Strategy be periodically reviewed to ensure that the objectives are being realised, taking into consideration the impact of projected climate change on flood risk.

More detailed climate change analysis is a consideration in the development of the detailed concept design, and required under the Secretaries Environmental Assessment Requirements (SEARs) for the proposed raising of Warragamba Dam. This report assesses the impact of climate change on flood risk with the current and proposed raised Warragamba Dam, and investigates several other related factors that influence dam and spillway levels. These factors include wet and dry periods that dominate the Hawkesbury-Nepean Valley flood record, and the option of having the two spillways operate at different levels so that the auxiliary spillway operates less frequently and closer to its original design.

1.1. Climate change and flooding

There is strong evidence that increases in global temperatures will lead to an increase in the intensity of rare rainfall, and that extreme flooding globally has increased over the 20th century (Trenberth, 2011; Wasko and Sharma, 2017). Global warming has been observed for several decades and has been linked to changes in key parts of the hydrologic cycle including changes in rainfall behaviour, rainfall intensity, soil moisture and runoff (Bates et al, 2008).

The hydrologic profession has been concerned about climate change for over three decades. Until recently nearly all hydrologic analysis techniques assumed a stable climate and that historical climate and rainfall records could be used as a robust indicator of future runoff. This has troubled the profession as most large projects involve construction of major assets, including dams, bridges or pipelines, that will have a design life of over 100 years. In most cases, minor increases in the size or capacity of these structures in the future will cost the same or more than the original structure. These structures are often built in the most efficient location, so an augmentation or upgrading in a less efficient location is considerably more expensive.

In 1987 the national guideline on flood estimation, Australian Rainfall and Runoff (ARR) (Pilgrim, 1987), warned practitioners about the long-term risk of climate change on rainfall, floods and sea level. ARR (1987) included the first of three conclusions from the 1985 International Climate Conference in Villard Austria.

> *"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."

Over the past three decades, there has been considerable research into climate change and the effect on hydrologic cycle and flooding. There is evidence of consistent intensification of large precipitation events over the past century in NSW and ACT, and studies show large rainfalls are projected to increase in the near and far future (Evans et.al. 2014; Bates et.al. 2015). The impact of climate change on flood producing rainfall globally is complex and there is still considerable uncertainty around exactly how a warming climate will influence flood behaviour in specific regions (IPCC, 2014). While there remains a high level of uncertainty about the exact changes to flooding and when they will occur, research and modelling indicate that flood risk on the east coast of Australia is likely to increase (e.g. Evans et.al. 2014). This report openly discusses the uncertainty in projected changes to rainfall intensity and how this may affect flood behaviour.

The Hawkesbury-Nepean Valley is particularly sensitive to small changes in rainfall as it has one of the largest flood ranges in Australia. In most NSW coastal rivers the 100 year ARI or 1 in 100 AEP flood level is 3-8 metres above the normal water level, however at Windsor it is 17m. The river at Windsor is tidal and is usually a few hundred millimetres above normal sea level, but on five occasions since 1977 the river has risen above 10m, and in 1867 reached 19.7m. Even with the construction of the Warragamba Dam for water supply in the 1950s, the equivalent of the 1867 flood would still reach 19.2m AHD at Windsor.

1.2. Terminology: Hydrology vs Climate Change science

The climate science and hydrologic communities use similar frequency descriptors to define very different probabilities and this has caused considerable confusion to both professions, related groups and the community. The terms "extreme" and "extreme rainfall" have a very different meaning to the two groups.

The hydrologic community defines an extreme rainfall or flood as an event with an annualized risk of 1 in 2,000 or an average recurrence interval of 2,000 years or greater. Over a typical 80 year life span, an individual has 3.92% probability of experiencing one or more such flood events. This type of event is used to design major road and rail bridges, while much rarer events are used to design large dams. The frequency descriptors as used in Australian Rainfall and Runoff (Ball et al, 2019) are shown in the adopted terminology section of this report.

The climate science community, like other groups, often defines an extreme event as an event with a 1% chance of happening. This is often defined on a daily basis, not an annual basis. On this basis, an extreme rain day would be a daily rainfall that is exceeded on average 3.65 times per year. Such an event is something that over a typical 80 year life span would be experienced approximately 292 times. This is the basis of analysis for the change in extreme rain days in most climate change reports.

1.3. Hydrologic cycle

The hydrologic or water cycle describes the movement of water between the Earth's atmosphere, the land surface and oceans, shown diagrammatically in Diagram 4. The key water states include moisture in the Earth's atmosphere, surface water including runoff, flow in creeks and rivers and the water stored in lakes and the ocean. The key processes include precipitation such as rainfall and snow, evapotranspiration including evaporation and transpiration, infiltration of water into the ground and the movement of water in the atmosphere, along the ground surface and within the ground. Many of these processes are driven or influenced by temperature and are likely to be affected by climate change. While rainfall is the dominant driver of flooding and climate change is likely to affect how much rainfall occurs during floods, climate change is also likely to affect how much water infiltrates, as well as when and where rainfall occurs.

Human modification of the water cycle by capturing, harvesting, retarding and/ or storing flows through structures such as dams and extracting water from ground and surface waters has been a long-term water management practice to provide greater water security and reliability of water supplies. Highly variable climates, long-term inflows and human demand will change the probability of different water levels in dams before an event.

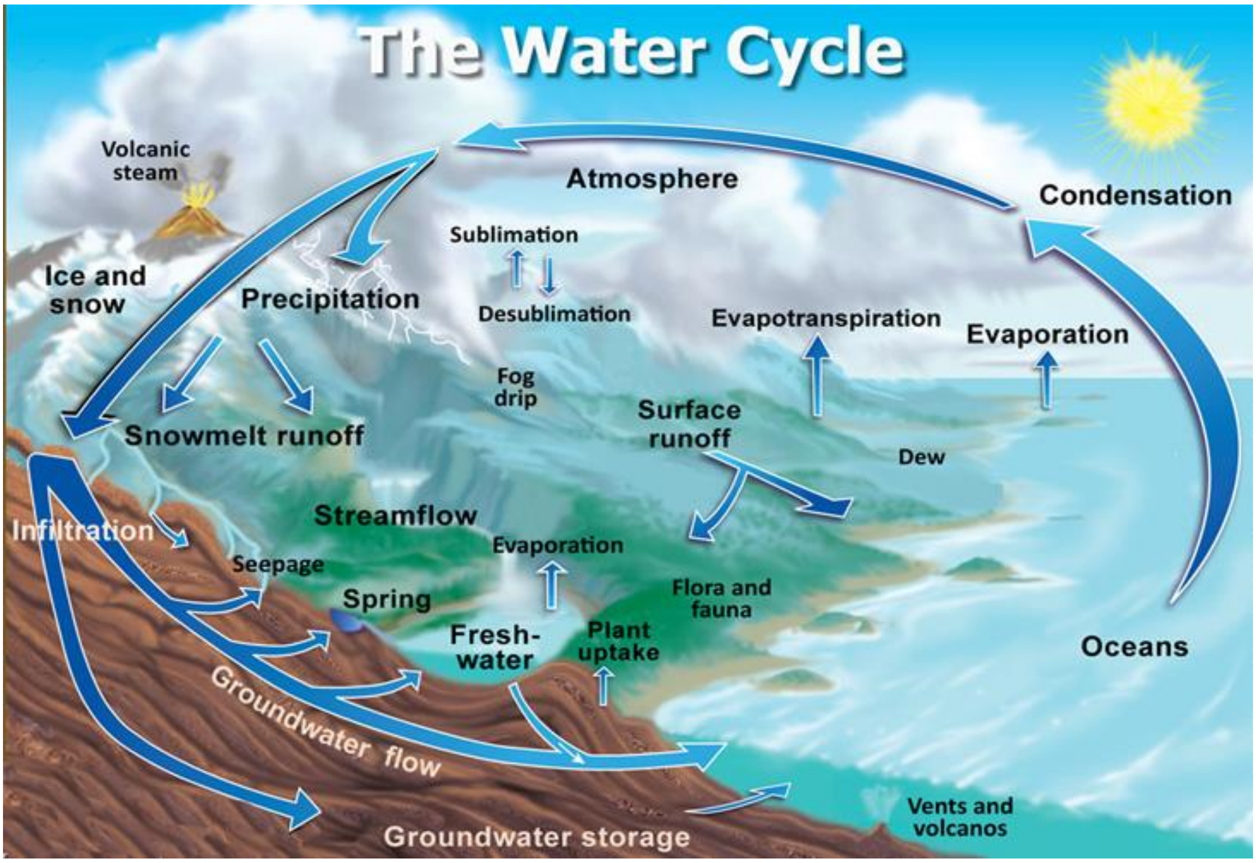


Diagram 4: Hydrologic Cycle (source http://ga.water.usgs.gov/edu/watercycle.html)

1.4. Climate cycles – ENSO and IPO

The flood record on the east coast of Australia exhibits periods of a decade or longer timescale that are flood or drought dominated. This was first recognised by Erskine and Warner in 1988.

Short term climate variability on the east coast of Australia is characterised by the inter-annual El Nino/Southern Oscillation (ENSO). There is a marked increase in flood risk in Eastern Australia during the La Nina phase. The El Nino phase typically contains few major floods (Trenberth, 2011). While ENSO correlates well with rainfall for large parts of Australia, this is often not the case on the eastern seaboard (Murphy and Timbal, 2008, Dowdy et. al., 2015). Occurrence of East Coast Low rainfalls that are associated with flooding in the Hawkesbury-Nepean Valley show no correlation with ENSO (Pepler et.al., 2014).

There is also considerable evidence that longer term processes have a major impact on flood risk. The Inter-decadal Pacific Oscillation (IPO) is a pattern of Pacific Ocean temperature variation that shifts phase at a timescale typically lasting 15-30 years. There is some evidence of an increase in flood risk during an IPO negative period on the east coast of Australia (Micevshi et al., 2006).

Diagram 5 shows the IPO index from 1880 to 2000 with several large Hawkesbury-Nepean floods. Figure 23 shows the IPO record along with floods above 10m at Windsor with the modern events adjusted for the impact of Warragamba Dam. Figure 23 plots the frequency of these events in IPO negative, neutral and positive periods. It is worth noting that the three largest events 1867, 1864 and 1961 all occurred in IPO negative periods.

Understanding the influence of ENSO and IPO, and how the IPO modulates individual ENSO events is very important to understanding how changes to the broader climate will affect flood risk. While there is a well-understood relationship between IPO negative periods and flooding, the interaction is complex. The La Nina phase and IPO negative phase can result in higher than average rainfall and this has a two-fold effect, as not only does the probability of flood producing rainfall increase, but more importantly this rainfall is more likely to occur during a period when the catchment is considerably wetter than average. Wet antecedent conditions are well documented as having a strong influence on the resulting flood magnitude as much more of the rainfall becomes runoff.

ENSO and IPO could influence dam levels before a major flood event as dam level behaves in a similar way to soil wetness although with a much longer memory, with dam levels being much higher during wet periods. In the Hawkesbury-Nepean there is a strong multidecadal wet dry cycle that partially aligns with the IPO cycle. This is discussed in detail in Section 4.2.4.

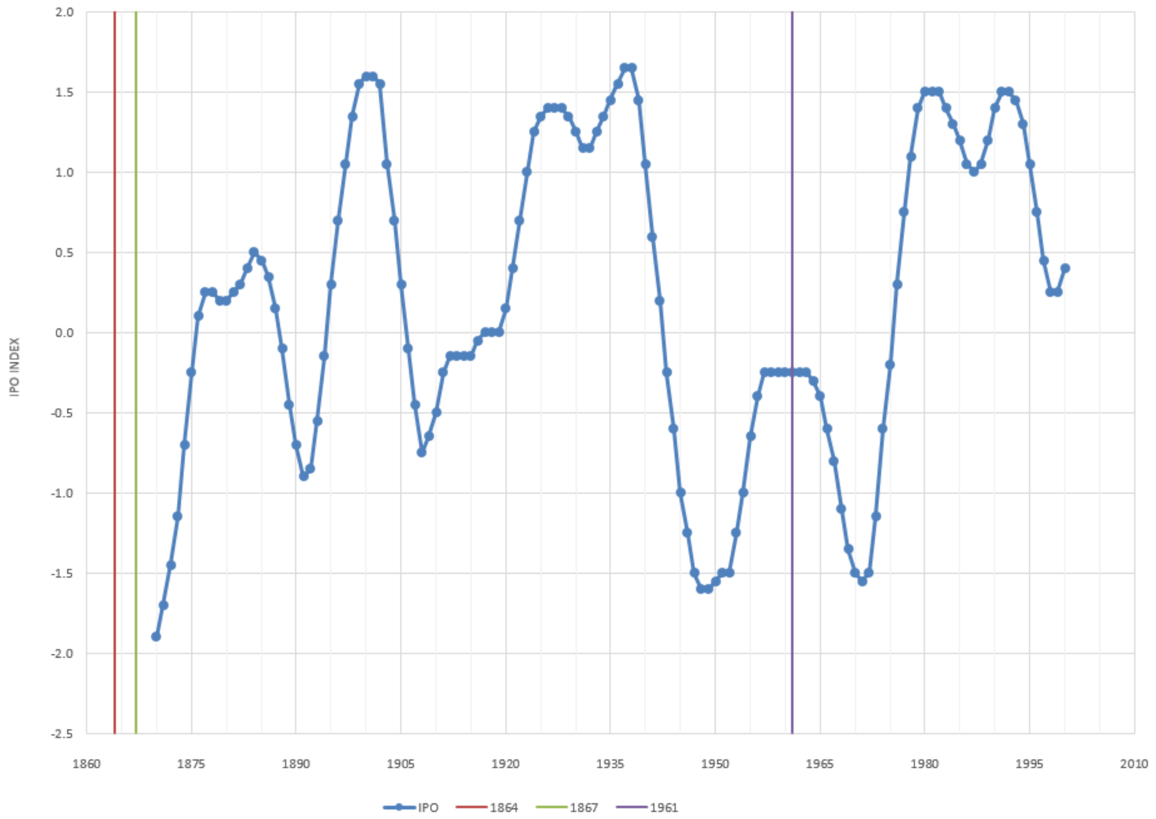


Diagram 5: IPO Index 1880-2000

1.5. Review Process

During the course of this work an early draft of the report prior to the inclusion of the NARCliM work was provided to Associate Professor Rory Nathan of University of Melbourne. This report produced a series of recommendations that are included in Appendix B along with a response. Those recommendations that could be carried out without a detailed research project were undertaken, other than one recommendation where the design input is currently not available from WaterNSW. Several of the recommendations require substantial amounts of work. Climate change may lead to a reduction in soil moisture levels and dam levels prior to flood events, that could partially offset some of the impact of the increased flood producing rainfall. Earlier work investigating lowering the full supply level of the dam by 16.9% and 37.8% showed that while lowering the full supply level had an effect on small flood events downstream of the dam, it had a relatively minor effect on large flood events.

2. CLIMATE CHANGE AND FLOOD PRODUCING RAINFALL

2.1. Theory

There is strong evidence that increases in global temperatures will lead to an increase in the intensity of rare rainfall, and that extreme flooding globally has increased over the 20th century (Trenberth, 2011). Global warming has been observed for several decades and has been linked to changes in key parts of the hydrologic cycle including changes in rainfall behaviour, rainfall intensity, soil moisture and runoff (Bates et al., 2008).

Climate change can alter flood behaviour in the Hawkesbury-Nepean by changing:

- Probability of long duration rainfall intensities;
- Storm type and frequency;
- Rainfall spatial and temporal patterns;
- Antecedent conditions; and
- Dam levels prior to flood producing rainfall.

The interaction of these characteristics makes predicting the impact of climate change on flood behaviour complex.

2.2. Rainfall depth and frequency

The interaction between a warming climate and rainfall is complex. A warmer climate leads to an increase in the potential moisture-holding capacity of the atmosphere, which is one of the key factors in the depth of precipitation in rarer rainfall events. However on large catchments like the Hawkesbury-Nepean, long duration rainfall events are also dependant on sources of moisture and transport of moist air. Statistically significant increases in rainfall intensity have been detected in Australia for short duration rainfall events and are likely to become more evident towards the end of the 21st century (Westra et al., 2013). Changes in long duration events of relevance to the Hawkesbury-Nepean are expected to be smaller and harder to detect, but projections analysed by CSIRO (2007) showed that an increase in daily precipitation intensity is likely under climate change. It is worth noting that a warming climate can lead to decreases in annual rainfall along with increases in flood producing rainfall.

2.3. Storm type, frequency and seasonality

Nearly all of the large flood-producing events on the Hawkesbury-Nepean catchment have occurred in late Autumn or Winter and have been either caused by East Coast Lows (ECLs) or the interaction of ECLs and other rain-producing systems (Callaghan and Power, 2014; (Kiem et al. 2016). The ECL weather system accounts for a significant proportion of rainfall on the south east coast of Australia (Pepler et al., 2014, Dowdy et al., 2013). ECLs do not correlate well with climate drivers such as ENSO, making them hard to predict.

Researchers have identified a likely annual decrease in ECLs with climate change, dominated by a reduction in cool season ECLs (Pepler et al., 2013, Dowdy et al., 2013, 2015). This reduction is in the frequency of weak ECL events; ECLs that produce the heaviest rainfalls show no change in frequency in future. Pepler et al. (2016) provide strong evidence that ECL frequency will increase in the Summer and Autumn months. This could have further implications for antecedent catchment conditions.

2.4. Spatial and temporal rainfall behaviour

The influence of warmer climate on the spatial and temporal aspects of rainfall is not as well understood as changes in intensity. Work by Abs and Rafter (2009) suggests that increases will be more pronounced in areas with strong orographic enhancement, which could lead to larger increases in the Nepean catchment than the Warragamba catchment. This would lead to a mitigation dam on the Warragamba River being slightly less able to control downstream flooding. Work by Wasco and Sharma (2015) analysing historical storms found that, regardless of the climate region or season, temperature increases are associated with rainfall temporal patterns becoming less uniform, with the periods of the storm with the largest rainfall increasing in rainfall intensity and the periods of the storm with lower rainfall decreasing. Wasco and Sharma (2016) found that the spatial extent of storms can decrease with higher temperatures. This is likely to lead to higher rainfalls.

2.5. Antecedent conditions

Changes to rainfall and evaporation as a result of climate change may result in a change in the antecedent conditions prior to a flood event. It is likely that annual evaporation over Australia will increase (Bates et al., 2008) by 2030, and by 2070 it is likely to increase by approximately 2%. Evans et al. (2017) also show that there is projected to be increases in the maximum consecutive dry days between storms over south east Australia. Increased evaporation in combination with decreased annual rainfall could result in decreases in annual runoff but the impact on flood events is likely to be less pronounced. The increase in dry spells between storms may result in drier antecedent conditions. This is likely to affect more frequent events.

2.6. Dam levels prior to flood producing rainfall

Along with changing antecedent conditions, a warming climate could change pre-event levels in Warragamba Dam. This aspect is complex as runoff into the dam may change (including the large events that often fill the dam) as well as the operational response to any changes. A decrease in inflows to the dam could result in more frequent pumping from the Shoalhaven River, leading to higher dam storage levels. Results of dam operation modelling (WATHNET) under future climate conditions were not available at the time of this study and pre-event levels were assumed to be the same as under current conditions, as operational changes could be made to keep levels the same under current and future climate conditions.

Dam storage levels prior to flood producing rainfall event can impact the downstream flood levels during the flood event. Although there are a number of dams in the Hawkesbury-Nepean catchment, only the Warragamba Dam has the catchment area and capacity to significantly impact the flood levels in the Penrith and Richmond/Windsor floodplains.

Warragamba Dam is a water supply dam, providing around 80% of Sydney's water supply (INSW, 2017). It is not designed or operated for flood mitigation. Warragamba Dam is a concrete gravity dam on the Warragamba River, impounding Lake Burragorang. The dam was built between 1948 and 1960, and was upgraded in the late 1980s with strengthening of the dam wall and raising the dam wall by five metres. In the early 2000s an auxiliary spillway was built to protect the dam during rare and extreme flood events by diverting floodwaters around the dam. Warragamba Dam is 142m high with a crest length of 351m. There are five crest gates on the main spillway – a central drum gate and two pairs of radial gates.

The locations of the Hawkesbury-Nepean Valley and Warragamba Dam are shown in Figure 1.

2.7. NARCliM and ARR Research

The coarse resolution (200-300km grids) of Global Climate Models (GCMs) means that they have limited ability to model climate extremes, such as rainfall, on a regional or catchment scale. Statistical and dynamic downscaling are two basic approaches used to model how climate change will affect flood producing rainfall from GCMs.

Dynamic downscaling approaches take the coarse GCMs and use them as boundary conditions for local fine scale models that reproduce atmospheric processes at a much finer scale. These models can be used with GCM historical hindcasts or future climate conditions. While GCMs are calibrated to historical weather and are used in weather forecasting, they are better at predicting temperature and everyday rainfall than exactly when and where flood producing rainfall will occur. GCMs are unable to simulate the local and regional circulations which can combine with larger scale forcings to produce extreme rainfalls. Another significant challenge is that, by its very definition, the historical record contains only a small number of "rare" events, which makes the parameterising of models for rare events difficult.

Statistical downscaling takes a different approach where the correlation structure between the information produced by the GCM and observed rainfall statistics is calculated and then used to predict how future rainfall will change for different future GCM model results. Fundamental limitations of statistical downscaling include the assumption that the identified empirical relationship does not change in a future warmer world. Examples of shifts in precipitation regimes have occurred making this assumption questionable. Statistical methods also need to identify large-scale predictands to use to form this relationship. Research has shown that small differences in predictands chosen can alter the sign of the projected future change (Fu et al., 2018). This lowers the confidence in the majority of statistically downscaled projections. There is considerable uncertainty in the results of downscaled modelling as not only are downscaling and GCM approaches imperfect, but there is still no certainty over how the world will manage CO_2 emissions.

To better understand the influence of different downscaling approaches and models a benchmarking study was carried out as part of the Australian Rainfall and Runoff project (Engineers Australia, 2014). This study brought together experts from BOM, CSIRO, UNSW and University of Adelaide and the NSW/ACT NARCliM project (a research project between the NSW and ACT governments and Climate Change Research Centre at University of NSW). The aim of the benchmarking project was to determine how the results varied from other downscaling approaches (statistical and dynamic), and even different downscaling models and model resolutions. The project used the greater Sydney region as a case study because of the extensive data set already available from the previous CSIRO work and the NARCliM project.

The outcome from this project was that many of the results were method dependent and while there were similar rainfall trends on a broad spatial basis, locational specific results varied considerably. The influence of terrain was a major factor as even the high resolution models needed to smooth extreme topographic features, such as the Illawarra Escarpment that is immediately adjacent to the upper reaches of the Nepean and Wollondilly catchments of the Hawkesbury-Nepean.

Another part of this project investigated if a statistically significant increase in flood producing rainfall could be found in the historical record. This part of the study found there was evidence of short duration rainfall (of 30 minutes to 1 hour) increasing due to climate change.

3. ASSESSMENT OF CLIMATE CHANGE IMPACT ON THE HAWKESBURY-NEPEAN

3.1. Australian Rainfall and Runoff Method for Rainfall Estimation

One approach to investigating climate change impacts on flood producing rainfall is based on research projects by Commonwealth Science and Industrial Research Organisation (CSIRO) and others as part of ARR (Engineers Australia, 2014 and Ball et al., 2019). This work recommends an interim approach based on simple temperature scaling using temperature projections from the CSIRO future climates tool (www.climatechangeinaustralia.gov.au). For each NRM cluster, the GCM consensus cases are listed for four class intervals (or ranges) of projected annual mean surface temperature increases for RCPs 4.5 and 8.5 relative to the 1986 to 2005 baseline.

Scaling based on temperature is recommended as climate models are much more reliable at producing temperature estimates than rainfall, and an ensemble of climate models can be used to estimate annual mean surface temperature. It is noted in ARR that this approach considers only the change in rainfall intensity due to climate change, given the paucity of climate change projections for other factors the influence flood risk. The simple scaling approach is undertaken using the following formula:

$$I_P = I_{ARR} \times 1.05^{T_m}$$

Where:

I_P is the projected rainfall intensity or depth

I_{ARR} is the design rainfall intensity or depth for current climate conditions

1.05 is the assumed temperature scaling based on the approximately exponential relationship between temperature and humidity

T_m is the temperature at the midpoint of the selected class interval.

Using several Representative Climate Pathways (RCP), projected increases in temperature and rainfall for the NRM cluster that includes the Warragamba Dam catchment are shown in Table 2 for 2050 and 2090. These were obtained from the ARR datahub (Babister et al., 2016) which provides a practical implementation of the ARR procedure. This is relative to temperature for a baseline period of 1986-2005. ARR recommends that RCP 4.5 and 8.5 be used for impact assessment as the RCP 6 results are based on a small sample of GCM results and are considered less reliable. RCP 4.5 is recommended as a low emissions pathway as RCP 2.6 is considered too optimistic (requires global emissions to peak by 2020). RCP 8.5 is recommended for consideration where the expense of considering it can be justified on socioeconomic and environmental grounds. This first pass estimate does not account for increases being expected to be higher for shorter duration events, and smaller for large catchments like the Hawkesbury-Nepean.

Between 2030 and 2060 the RCP 6 results are inconsistent with the RCP 4.5 and 8.5 results. To remove this inconsistency a medium emissions scenario was created by averaging the 4.5 and 8.5 scenarios (Table 3).

Table 2: Climate futures tool – Sydney. Projected increases in temperature and rainfall (shown in brackets).

Year	Representative Concentration Pathway		
	RCP 4.5	RCP 6	RCP 8.5
2030	0.869 (4.3%)	0.783 (3.9%)	0.983 (4.9%)
2040	1.057 (5.3%)	1.014 (5.1%)	1.349 (6.8%)
2050	1.272 (6.4%)	1.236 (6.2%)	1.773 (9.0%)
2060	1.488 (7.5%)	1.458 (7.4%)	2.237 (11.5%)
2070	1.676 (8.5%)	1.691 (8.6%)	2.722 (14.2%)
2080	1.810 (9.2%)	1.944 (9.9%)	3.209 (16.9%)
2090	1.862 (9.5%)	2.227 (11.5%)	3.679 (19.7%)

() indicate the projected rainfall increase

If a modelled flood event had 100 mm of rainfall in a catchment under “2016” or historic average climate conditions, under a 4.9% rainfall increase scenario that same modelled event would have 104.9 mm of rainfall in the same catchment over the same time period.

Table 3: Climate futures tool – Sydney- with approx medium emission scenario

Year	Low (based on RCP 4.5)	Medium (average of RCP 4.5 and 8.5)	High (based on RCP 8.5)
2030	0.869 (4.3%)	4.60%	0.983 (4.9%)
2040	1.057 (5.3%)	6.05%	1.349 (6.8%)
2050	1.272 (6.4%)	7.70%	1.773 (9.0%)
2060	1.488 (7.5%)	9.50%	2.237 (11.5%)
2070	1.676 (8.5%)	11.35%	2.722 (14.2%)
2080	1.810 (9.2%)	13.05%	3.209 (16.9%)
2090	1.862 (9.5%)	14.60%	3.679 (19.7%)

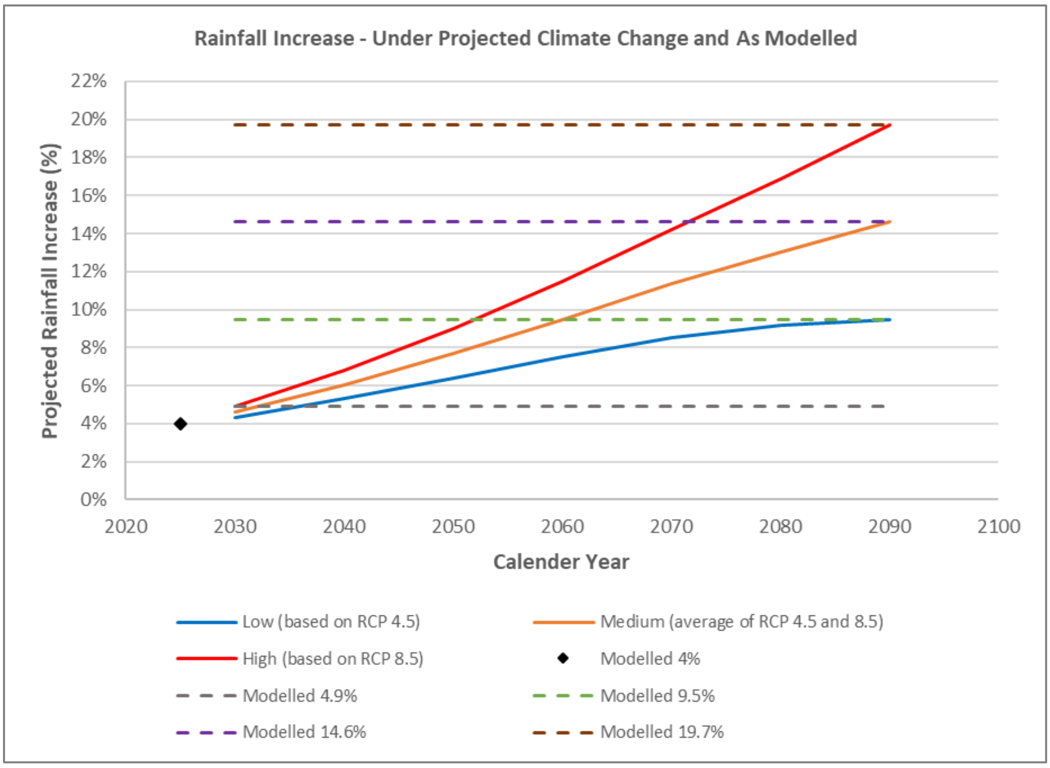


Diagram 6: Projected and modelled rainfall increases with climate change

These scenarios can be directly used to represent 2030 conditions and low, medium and high emissions 2090 conditions, but more importantly they allow for interpolation at decades time scales. These rainfall increases can be represented as the approximate time scales when they may occur in Table 4. It is noted that the last decade has seen emissions tracking towards the upper end of the RCPs (Sanderson et al., 2016).

Table 4: Climate change pathways, rainfall increases and approximate time scales

Modelled Climate Change Rainfall Increase	**Expected Year when rainfall increase realised under different climate change projections**		
	Low Emissions	**Medium Emissions**	**High Emissions**
	RCP 4.5		**RCP 8.5**
4.9%	2036	2032^	2030
9.5%	2090	2060^	2052
14.6%	2260*	2090*^	2071
19.7%	2430*	2120*^	2090
* Extrapolation based on low emissions 2090 increase			
^ Average of low and high emissions			

The design rainfall and streamflow data used to inform the modelling can be thought of as representing a certain point in time. While there is limited rainfall data back to 1850 with many stations installed around 1900, the average date of the rainfall data used for the Hawkesbury-Nepean Valley is 1966. The stream flow data used in the catchment has an average date of 1935.

The ARR method of rainfall increases were adjusted to account for the temperature increase that has already occurred, to make them directly comparable to the existing rainfalls that are used on the catchment. This resulting in the rainfall increases documented in Table 5.

While the climate change projections are based on the base condition representing the decade either side of 1995. Diagram 2 combines the surface ocean temperature anomalies with projected climate change. A simple trendline through the historic anomaly suggests approximately 0.7 degrees of warming has occurred between 1935 and 1995. An interpolation of the climate when the dam is complete (2025) can then be undertaken. This method gives a rainfall increase of nearly 4% by the time the dam is completed. This means that the base case at that point in time would be close to the 4.9% scenario.

Table 5: Baseline Adjusted ARR rainfall increase percentages

Year	**Low (based on RCP 4.5)**	**Medium (average of RCP 4.5 and 8.5)**	**High (based on RCP 8.5)**
2030	8.1	8.4	8.7
2040	9.1	9.8	10.6
2050	10.2	11.6	12.9
2060	11.4	13.4	15.5
2070	12.4	15.3	18.3
2080	13.1	17.1	21.1
2090	13.4	18.6	23.9

The baseline adjusted 2090 low, medium and high values from Table 5 were run for comparison purposes (i.e. 13.4, 18.6 and 23.9%).

3.2. NARCliM Calculated Rainfall Increases

As an alternative method for determining the extreme rainfall increases associated with climate change, the NARCliM dataset (Willgoose et al. 2014) was obtained from the then Office of Environment and Heritage and analysed. This dataset was produced by dynamical downscaling of four General Circulation Models using three Regional Climate Models at the date ranges of 1990-2009 (existing climate), 2020-2039 (near future climate) and 2060-2079 (far future climate). Daily rainfall totals from 12 ensembles of runs at each date range were analysed and rainfall frequencies determined. A comparison of the rainfall frequencies for each date range was undertaken. Temperature data were also analysed by determining the average temperatures of the datasets and determining the associated rainfall increases through time.

The NARCliM rainfall data set is publicly available in two formats, bias corrected and raw. The bias correction process involves filtering out grid cells with greater than 1,200mm of rainfall per day (Evans and Argueso, 2014) and setting them to the average of the surrounding eight grid cells. Then rainfall days greater than 0.2mm at all grid cells are ordered and scaled to match an observed ordered rainfall set of the same grid cell. This process potentially alters the temporal and spatial consistency of the raw rainfalls and hence was not used, although the raw data was altered to include the adjustment to extremely high rainfalls. The following rainfall analysis is based on the method used by Evans and Argueso (2015).

Annual maximum areal three day rainfalls were then derived from the NARCliM data by averaging daily rainfalls at all grid cells within the range of catchments of interest shown in Figure 1. Using the areal rainfalls in the analysis is preferable to using the point rainfalls at the grid cell scale, as areal reduction effects are included and the consistency of the dataset is improved with the spatial averaging acting as a form of space for time substitution. The three day rainfall totals were calculated over the 20 year periods and the yearly maximums were sampled to make an Annual Maxima Series (AMS). For each climate model, time-span and scenario L-moments were calculated for the AMS sets and were used to derive GEV distribution parameters and rainfall quantiles. The fitted distributions for all the models, scenarios and date ranges can be seen in Figure 2, Figure 3 and Figure 4 for the catchment to Penrith. Also shown on Figure 2, Figure 3 and Figure 4 are observed spatial rainfall quantiles from the historic record for the catchments of interest, which were derived using the same GEV fitted with L-moments technique.

Long record lengths are desirable when estimating Intensity Frequency Duration (IFD) curves for design flood estimation. The current IFD estimates for Australia (Green et al. 2012) require a minimum of 30 years of AMS for the site's data to be included in the analysis. For the higher order L-moments which define slope and curvature, a pool of 500 to 2,000 station years AMS is taken and the estimates from multiple sites are combined, which is vastly more restrictive than the use of a 20 year window adopted for the NARCliM data. Although pooling can be done on the NARCliM dataset, it only increases effective record length for spatially independent rainfall events and often does so at the expense of homogeneity. Therefore, it is not reasonable to expect the same degree of confidence from rainfall quantiles derived from the NARCliM data as can be taken from the historical record.

For the 1990-2009 date range, fitted rainfall frequency distributions to climate models demonstrated large amounts of variability. L-moments were averaged for the 12 combinations of climate model and scenario in a method similar that was used in the regionalisation of the BoM IFDs (Green et al. 2012) and used to derive new GEV distributions. This averaging may increase the effective record length of the date ranges for the NARCliM dataset. Figure 5 shows the average of the NARCliM data for the 1990-2009 date range is within the confidence limits of the observed rainfall frequency distribution but slightly low on the frequent end. The NARCliM 1990-2009 data has a steeper gradient than the observed data, which results in a slight overestimation on the rare end.

Since there is very high confidence in the observed index rainfall (the first L-moment), it is reasonable to force the index rainfall produced from the NARCliM data to match the observed. A scaling factor was derived by dividing the observed index rainfall by the NARCliM 1990-2009 averaged index rainfall. Figure 5 shows the fit that is obtained when the index rainfall of the NARCliM 1990-2009 data is scaled using this scaling factor. Although the NARCliM rainfall frequency curve has a higher gradient than the observed, the fits are very similar.

To compare the existing data to the near and far future estimates, the future values were divided by the existing date range estimates to obtain scaling factors. The near and far future date ranges show very similar estimates on average and suggest that rainfall frequency estimates will be smaller in the far future than they will be in the near future. This suggests the assumptions used for methods where rare rainfalls increase with temperature are not fully accurate. It is known that precipitation changes in a non-linear way in response to global warming. Future precipitation changes can be broken down into two main components: thermodynamic and circulation (dynamic) changes (e.g. Pfahl et al., 2017). The thermodynamic changes scale with temperature and are associated with the increasing water holding capacity of the air as temperatures rise; but circulation changes can have very different impacts on precipitation depending on location and time frame. At short time scales (hourly) the thermodynamic effect dominates, while at longer time scales (multiple days) circulation changes have larger impact.

There are high levels of uncertainties in these results however, and fitting GEV distributions to the 20 year samples will give vastly different rainfall frequency estimates if based on using different portions of the observed sample, as can be seen in Figure 2 which shows the GEV fit to observed AMS from 1990-2009. This noise is likely to be partly responsible for the observed inconsistency in the various models and scenarios of the NARCliM data.

The inconsistency in these results could also be due to differences in individual climate models. To test if more consistent results can be derived, the scaling factor of current to future index rainfall for each individual climate model and scenario for each date range was calculated and can be seen in Table 5. R1, R2 and R3 are the three different regional models run. The mean of each climate model set was calculated and is displayed in Table 6. There appear to be two main levels of inconsistency in this data, one is between the climate models and the other is within the scenarios for each climate model. The means of each climate model vary considerably, which could be due to differences in how each model works. The other inconsistency is the high variability between scenarios for each climate model, which is possibly due to the mechanics of each model but is also likely a result of the short record length. This high variability in the fitting parameter that has the highest confidence, creates very large uncertainty in rainfall increases with climate change using this method.

Table 6: Mean index rainfall scaling factors for the NARCliM models and scenarios

Date Range	Scenario	CCCMA3.1	CSIRO.MK3.0	ECHAM5	MIROC3.2
2020-2039	**R1**	1.393	0.869	1.138	1.145
	R2	1.484	0.976	1.208	1.041
	R3	1.105	0.794	1.098	1.042
	Mean	1.327	0.880	1.148	1.076
2060-2079	**R1**	1.161	0.908	1.248	1.098
	R2	1.113	0.940	1.044	1.087
	R3	0.983	1.139	1.266	1.118
	Mean	1.085	0.996	1.186	1.101

One important aspect of changes in extreme rainfalls with climate change is how it is distributed spatially. As the temperature increases, so does the moisture holding capacity of the air, and hence when it is forced to rise by mechanisms such as orographic enhancement, the potential for extreme rainfalls is increased. Areas of steep terrain and known orographic enhancement may experience higher increases to extreme rainfalls than areas with flatter terrain (Shi and Durran, 2015). The representation of this in the NARCliM data was investigated by comparing the index rainfall scaling factors for a number of sub-catchments with different topographical features of the Hawkesbury-Nepean catchment. The catchments investigated can be seen in
Figure 1 and their scaling factors are shown in Table 7.

Some subcatchments affected by orographic enhancement are subject to increased rainfall in the NARCliM model. The Coxs, Grose and the Kowmung catchments exhibiting larger rainfall increases than the catchment to Golden Valley and Jooriland. Some catchments which are subject to significant orographic enhancement such as Nepean, Maldon and Nattai Causeway demonstrate some of the lowest increased rainfalls. This is possibly due to the climate models smoothing of the steep topographical features of the Illawarra escarpment. This makes it impractical to use the NARCliM data to determine the distribution of rainfall increases spatially, and this type of analysis is best done by making any necessary assumptions and using the results to determine the sensitivity of the system to alternate spatial distributions of rainfall increases. A sensitivity assessment of climate change causing greater rainfall increases in areas subject to orographic enhancement is contained in Appendix A.

Table 7: Multi-model average index rainfall scaling factors for catchments of interest

Date Range	Colo River	Coxs River	Golden Valley	Grose	Jooriland	Kowmung Cedarford	Nattai Causeway	Nepean Maldon	Nepean Wallacia
2020 - 2039	1.119	1.114	1.052	1.111	1.067	1.120	1.054	1.055	1.056
2060 - 2079	1.124	1.116	1.095	1.139	1.090	1.122	1.049	1.017	1.053

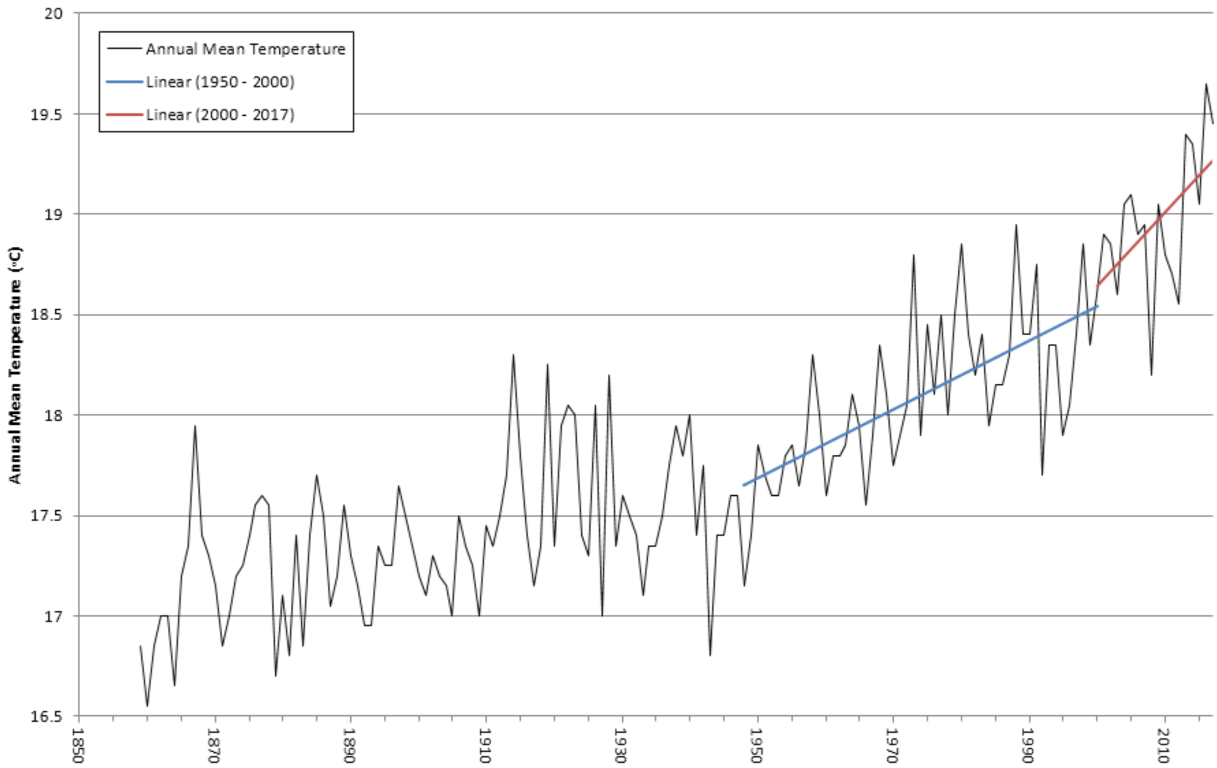


Diagram 7: Average annual Sydney Observatory Hill temperatures

The NARCliM temperature increases were converted to increases in rainfall extremes by applying the ARR method to convert temperature increases to increases in extreme rainfall depths. Average temperatures were calculated for the NARCliM data for the entire daily mean temperature dataset for each model, scenario and date range. The mean temperatures of the 1990-2009 date range were subtracted from the future date ranges.

As for the rainfall increases derived using the ARR method, the temperature increases were adjusted to a baseline of 1950-2000, to make them directly comparable to the existing rainfalls that are used on the catchment. The adjustment was based on averaging the minimum and maximum daily temperatures at Sydney Observatory Hill. All days within each year were averaged to create the annual mean temperature values shown in Diagram 7. A line was then fitted to the 1950 to 2000 date range and the temperature increase was determined to be 0.8°C. The resultant temperature increases and associated rainfall increases for NARCliM data is shown in Table 8. Stronger agreement occurs between climate models when using the temperature data to estimate rainfall increases (Figure 6).

Table 8: Temperature and associated rainfall increases derived from the NARCliM data

Date Range	Temperature Increase (°C)	Rainfall Increase (%)
2020-2039	1.45	7.33
2060-2079	2.76	14.41

The mid range NARCliM estimate was converted to a rainfall increase using the ARR procedure assuming a 5% rainfall increase per °C of warming. While the temperature scaling of the NARCliM results give a good mid range estimate, upper and lower bound estimates were also tested. ARR states that "*the expected change in heavy rainfalls is between 2% and 15% per °C of warming*"

(Bates et al., 2016). A lower bound estimate using the 2% per degree of warming corresponds to a 2.9% increase in rainfall for the near future (not run in the Monte Carlo framework) and 5.62% increase for the far future (not presented in the current assessment). The upper bound estimate was calculated using the model mean of CCCMA3.1 for the near future climate to obtain an increase of 32.7%. As this estimate is higher in the near future than the far future in this model, a far future estimate run was not calculated.

3.3. Adopted model runs

In order to reduce the number of flood hydrology model runs and cover the full range of possible climate change scenarios the following rainfall increases were chosen for the final assessment documented in this report:

Table 9: Adopted Model Runs

Percentage Rainfall Increase (%)	Source	Alternate name
4.9	ARR Data Hub	High Emissions: 2030
7.3	NARCLiM	Near Future best guess rainfall factor
9.5	ARR Data Hub	High Emissions: 2052
13.4	Baseline Adjusted ARR Data Hub	Baseline Adjusted High Emissions: 2052
14.6	ARR Data Hub (close to NARCLiM 14.4 so 14.4 wasn't run)	High Emissions: 2071
18.6	Baseline Adjusted ARR Data Hub	Baseline Adjusted High Emissions: 2071
19.7	ARR Data Hub	High Emissions: 2090
23.9	Baseline Adjusted ARR Data Hub	Baseline Adjusted High Emissions: 2090
32.7	NARCLiM	Far Future upper bound rainfall factor

The standard approach is to factor up the rainfall equally at each location within the catchment. This was undertaken for the chosen climate change scenarios. The 9.5% rainfall increase is considered to be a reasonable midway estimate and was chosen for most of the reporting contained herein.

3.4. Flood modelling

The impact of climate change on flood mitigation provided by Warragamba Dam was modelled using hydrologic and hydraulic models developed for previous studies (WMAwater, 2019). A hydrologic model was used to model the catchments upstream of Warragamba Dam and routing through the reservoir. A hydraulic model was used to model the river system downstream of the dam. These models have been well calibrated to a range of flood events and closely reproduce flood levels at Windsor and Penrith.

The hydrologic model used is a RORB model. The standard package was modified to allow large sub-catchments to be independently modelled and to simulate the impact of Warragamba Dam and the implemented procedure for operating its gates during flood events, known as the 'H14 protocol'. The final model layout consists of 121 sub-areas.

The model was calibrated to available streamflow and rainfall data, mainly at stations upstream of the dam, and the calibration parameters were used to estimate suitable parameters in uncalibrated catchments in the downstream valley.

The distance from Warragamba Dam to the ocean is approximately 200 kilometres and includes:

- narrow incised valleys (from Warragamba to Penrith)
- deep river channels that can convey a 1 in 50 AEP flood (Penrith)
- wide floodplains with a large flood range (Windsor)
- a choked river valley that transitions into a drowned river valley (downstream of Windsor to the ocean).

These diverse hydraulic features mean that, until the recent invention of high capacity Graphics Processing Unit (GPU) and GPU-based hydrodynamic models such as TUFLOW HPC (Heavily Parallelised Compute), two-dimensional modelling of the entire valley was not possible. Even with current GPUs, it is necessary to represent the gorge upstream of Penrith in a relatively simplistic representation. While this floodplain is challenging for two-dimensional models, the quasi two-dimensional model developed in the earlier studies (RUBICON) can be run fast enough (5,000 times faster than the two-dimensional model) that it can be used in a Monte Carlo environment.

The adopted RUBICON model is as developed for the 1996 Flood Study and modified for the 2019 Hawkesbury-Nepean Valley Interim Flood Study. Ten historic flood events were used to calibrate the hydraulic model. These ranged in size from the November 1961 flood, which was the second largest in the valley in the past 200 years, to a small fresh in October 1987, which produced no outflow from Warragamba Dam. The model and calibration process is described in detail in WMAwater, 2019.

Whilst these models have been well calibrated to historical flood events, climate change could result in conditions outside those observed in the historic record. In particular, the impacts of climate change on antecedent rainfalls may change the losses assumed in the modelling. This is acknowledged as an area for further research in ARR 2019, and is not considered in the modelling in this study. Antecedent conditions will have more influence on small, more frequent, flood events than large events, as losses will be a larger proportion of the volume of small events.

Real flood events exhibit an enormous degree of variability, most of which is determined by exactly when and where rainfall falls. Flood events are also influenced by how wet the catchment is. To better capture this variability, design flood estimation in Australia is moving from a single event per quantile (such as the 1 in 100 AEP) to Monte Carlo modelling where thousands of events are run. For the dam operations study (WMAwater, 2017), the variability in key input variables was estimated from observed events and a Monte Carlo framework was established. The framework samples rainfall temporal patterns and from distributions of losses and pre-burst rainfalls. The adopted modelling framework is consistent with emerging best practice in flood estimation, and has been demonstrated to reproduce a range of flood characteristics that are important for evaluating mitigation options and evacuation strategies. This framework has been used for this study.

3.5. Climate change and existing dam

This increase in rainfall intensity with projected climate change will alter the frequency of large inflows into the dam and the subsequent downstream flooding. In order to establish a base case, climate change scenarios were applied to the existing dam. Figure 7 and Figure 8 show the flood stage frequency curve for Penrith and Windsor for the existing climate and the climate change scenarios, with the existing dam. Throughout this report, the focus is on the 100 year ARI (1% AEP) flood event as this is a key event for damage assessment and setting flood planning levels. A 100 year ARI (1% AEP) event at Windsor under existing climate becomes an 80 year ARI event with 4.9% rainfall increase and a 64 year ARI event with 9.5% rainfall increase. A 100 year ARI (1% AEP) event at Penrith under existing climate becomes a 78 year ARI event with 4.9% rainfall increase and a 64 year ARI event with 9.5% rainfall increase. In the far future upper bound case of 32.7% rainfall increase a 100 year ARI (1% AEP) event at Windsor under existing climate becomes a 28 year ARI event. The change in probability of the current 100 year ARI event under different climate change rainfall increases is presented in Table 10.

Diagram 8 and Diagram 9 present the change in flood level from the existing 1% AEP level for the various climate change scenarios for the existing dam case (blue) for Windsor and Penrith respectively. Under 9.5% climate change for the existing dam, 1% AEP flood levels at Windsor increase by 0.74m.

Table 10: Probability of the current 100 year ARI event by scenario - existing dam and climate change

Location	Current 2016 average climate	Climate change scenario (Year ARI)								
		4.9 %	7.3 %	9.5 %	13.4 %	14.6 %	18.6 %	19.7 %	23.9 %	32.7 %
WINDSOR	100	80	70	64	55	52	44	42	37	28
PENRITH	100	78	70	64	55	52	45	44	38	30

Table 11: Change in probability of a 100 year ARI event by scenario (ratio compared to current climate)

Location	Current 2016 average climate	Climate change scenario (ratio)								
		4.9 %	7.3 %	9.5 %	13.4 %	14.6 %	18.6 %	19.7 %	23.9 %	32.7 %
WINDSOR	1.00	1.25	1.43	1.56	1.82	1.92	2.27	2.38	2.70	3.57
PENRITH	1.00	1.28	1.43	1.56	1.82	1.92	2.22	2.27	2.63	3.33

Figure 9 presents the time for floods to rise from 4.0 m AHD to 17.3 m AHD at Windsor for the existing dam under climate change. As rainfall increases the number of events that reach 17.3m AHD increases. With climate change, the number of events that take 15-24 hours to reach 17.3m AHD increases, which is important for evacuation.

Figure 10 presents the upstream inundation for the existing case and the 9.5% climate change scenario. With climate change the length of time inundation occurs upstream of the dam increases for certain flood levels.

Figure 11 depicts the two day inflow volume to Warragamba Dam and Wallacia under existing climate and climate change conditions. A larger increase is shown in the dam inflows compared to flows at Wallacia, as the dam has a larger contributing catchment.

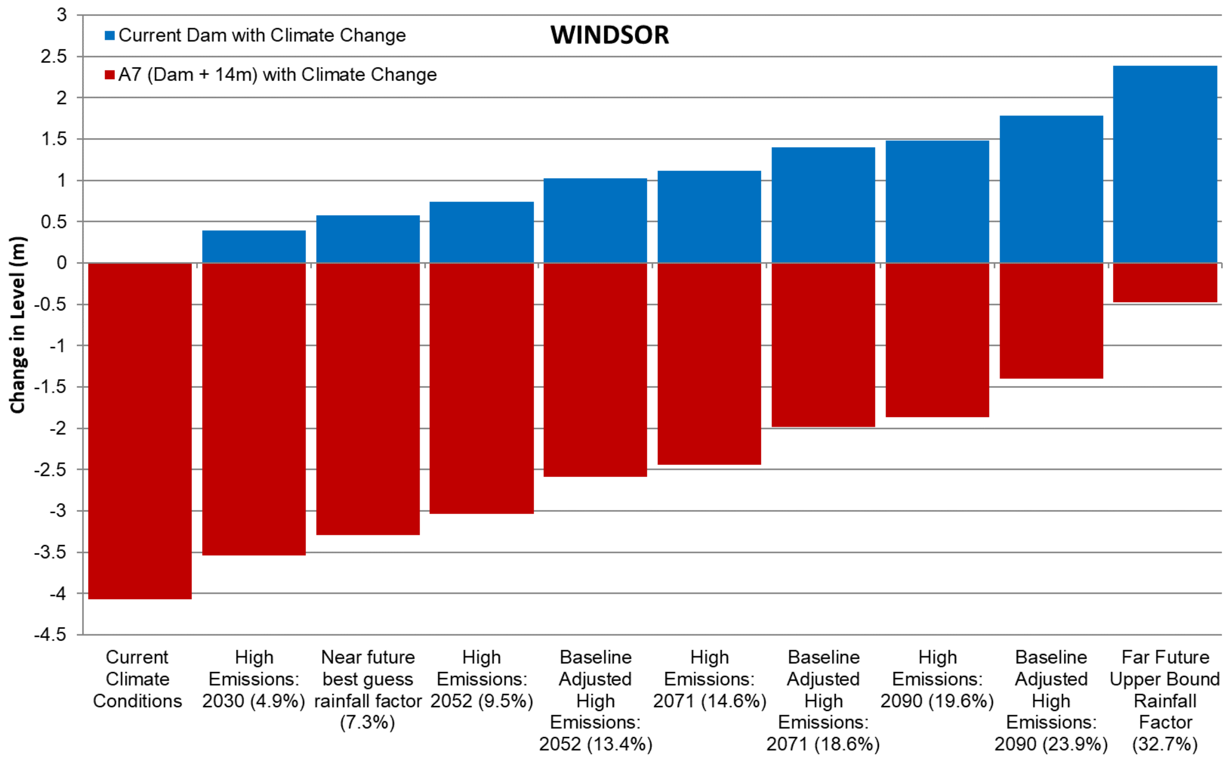


Diagram 8: 100 year ARI Level Impact of Climate Change on Existing Dam and A7 (Dam +14m) Scenarios at Windsor

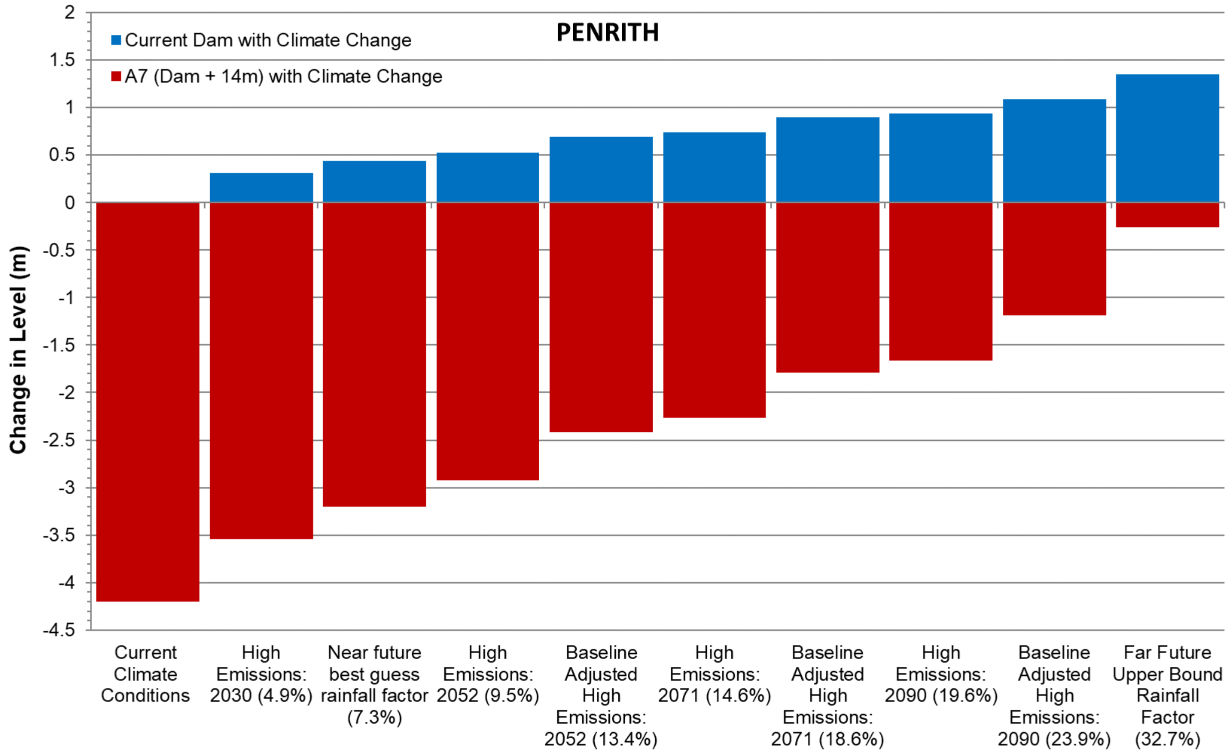


Diagram 9: 100 year ARI Level Impact of Climate Change on Existing Dam and A7 (Dam +14m) Scenarios at Penrith

3.6. System response

The Sydney Water supply network is a complex system where water can be supplied from various sources. The system can also transfer water from the Shoalhaven River to the Warragamba and Nepean dams. The more expensive supply sources are generally only triggered when overall storage or key reservoirs drop below key operational water supply trigger levels. This can make the system response quite complex and often non-intuitive, as under some climate change scenarios the current operational rules are triggered more often which increases the probability of the dam being above key levels prior to a flood event. Increasing the trigger levels can lead to the dam being at a higher level before a flood event. It is highly likely that operational rules will be fine-tuned as climate change impacts are better understood. This will affect more frequent floods, as most large events occur during wet phases when the dam level is high.

3.7. Uncertainties

This study follows current best practice and uses methods from current guidelines and well calibrated hydrologic and hydraulic models to model floods. Despite this, modelling of the impacts of climate change on flooding includes inherent and unavoidable uncertainties.

There are a range of uncertainties in modelling the possible impacts of climate change on flooding in the Hawkesbury-Nepean Valley, and the mitigation provided by Warragamba Dam. These include:

- Uncertainty in the Representative Concentration Pathways and how the climate will respond, modelled using GCMs
- Uncertainty in projected increases in rainfall calculated using the ARR method due to the

simple assumption of rainfall scaling with temperature, and uncertainty in the magnitude of temperature increases at different time slices in the future
- Uncertainty associated with downscaling and modelling in the NARCliM outputs
- The consideration of the impact of climate change on rainfall intensity only, without allowance for changes in temporal and spatial distribution of rainfall
- Uncertainty in the hydrologic and hydraulic models, in particular how changed antecedent conditions under future climate will impact the performance of the hydrologic model.

While small floods are sensitive to changes in dam levels prior to a flood, large floods are generally insensitive to changes in dam level prior to flood events. Other simulations assuming full supply level and a 5m draw down prior to a flood, show very little difference in peak flood levels for floods of 1% AEP or rarer.

4. EFFECTS OF CLIMATE CHANGE AND A RAISED DAM

4.1. Climate change and a 14m raised dam

The Flood Strategy (INSW 2017) requires that engineering design, environmental and planning approvals and business case be prepared for raising Warragamba Dam by around 14 metres. The Secretaries Environmental Assessment Requirements (SEARs) for the environmental assessment for the proposed raising of Warragamba Dam require a detailed investigation into the impact of projected climate change on the proposal. The details of the dam raising and the operating rules derived for the 14m raised dam are described in (WMAwater, 2017), however the layout of the preferred raised dam design is illustrated in Diagram 1. Table 12 presents the change in the probability of the 100 year ARI (1% AEP) flood for the A7 (Dam +14m) scenario compared to the existing dam.

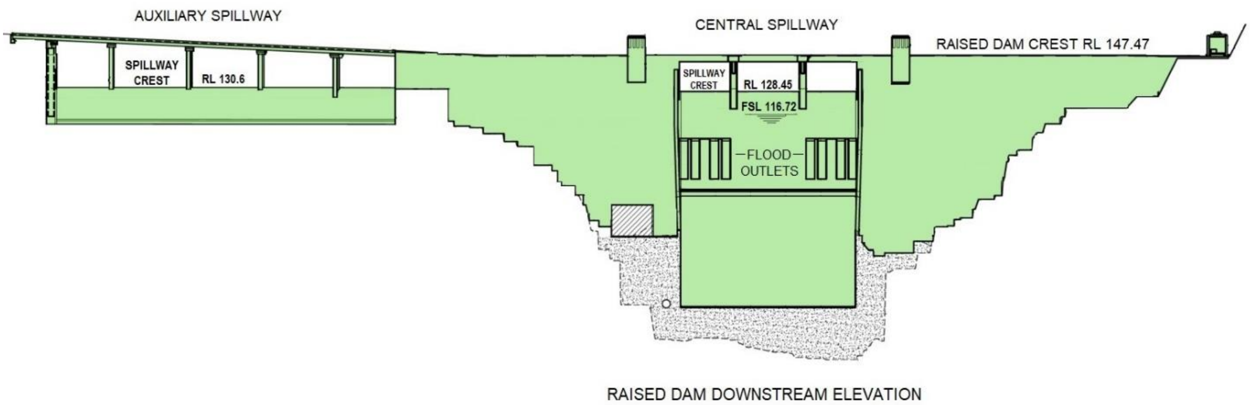


Diagram 10: Preferred dam design (A7) layout

Raising the dam by 14m changes the probability of a 100 year ARI flood level at Windsor to a 716 year ARI. This is a substantial reduction in flood risk for downstream properties. Under a climate change scenario with an 9.5% rainfall increase, this benefit is eroded to a 367 year ARI. However if the dam is not raised, then under 9.5% climate change scenario, a 100 year ARI event is changed to a 64 year ARI. A similar pattern occurs at Penrith. For the high emissions scenario (18.6% increase) the benefit is further eroded to a 232 year ARI. However if the dam is not raised, then under 18.6% climate change scenario, a 100 year ARI event is changed to a 44 year ARI.

The red bar in Diagram 8 and Diagram 9 shows changes in the current 100 year ARI flood level at Windsor and Penrith with a raised dam for different climate change scenarios. The blue bar shows the increase in flood levels for different climate change scenarios for the existing dam. These were derived from stage frequency curves fitted to the Monte Carlo flood model results (Figure 12 and Figure 13). The A7 (Dam +14m) scenario provides a 4.07m reduction in flood levels under current climate conditions at Windsor. Under the 18.6% rainfall increase scenario a 14m raised mitigation dam would reduce the current 100 year ARI flood level by 2.0m whereas without a mitigation dam, levels would increase by 1.4m.

Figure 12 and Figure 13 present the A7 (Dam +14m) stage frequency curve under the various climate change scenarios compared to the existing scenario for Windsor and Penrith respectively. Only under extreme climate change conditions (23.9% rainfall increase) for very rare events will the benefits of the dam raising be negated. Under 23.9% climate change conditions without the dam raising, the current 100 year ARI flood event would become a 37 year ARI event at Windsor. The dam raising would still reduce the climate change impacted 100 year ARI flood level by 3 to 4 metres.

Figure 14 presents the time for flood levels to rise between 4.0m and 17.3m AHD at Windsor for the existing and A7 (Dam +14m) cases, for current climate and 9.5% increase in rainfall under climate change. This figure is derived from running the flood models in Monte Carlo mode and shows the number of runs (events) in the 200,000 for different times to rise from 4m to 17.3 at Windsor. Raising the dam by 14m significantly reduces the number of cases where the flood level reaches 17.3m AHD, and also the number of events that are difficult for evacuation (15-24hrs lead time). Under the climate change scenario, the number of 15-24hr lead time events for the A7 (Dam +14m) case increases, which would reduce flood warning time and significantly increase the flood evacuation risk.

Figure 15 presents the upstream inundation for the A7 (Dam +14m) case. With the operating rules that have been derived for the A7 (Dam +14m) case, the dam is drawn down within 14 days. Figure 16 presents the upstream inundation curves for the Dam +14m with 9.5% increase in rainfall under climate change. For the A7 (Dam +14m case), there are some cases where it is difficult to draw the dam down to 120m AHD in 14 days. However with changes to the operating rules this can be achieved. This is typically caused by events where there is a small flood on the Nepean River and the dam just spills.

Table 12: Change in probability of current flood planning level under climate change (Year ARI) – Existing dam and 14m raised dam

Location	Dam Scenario	Current 2016 average climate	Climate change scenario (Year ARI)								
			4.9%	7.3%	9.5%	13.4%	14.6%	18.6%	19.7%	23.9%	32.7%
WINDSOR	Existing Dam	100 (at 17.3m)	80	70	64	55	52	44	42	37	28
	A7 (Dam +14m)	716	486	422	367	299	282	232	220	183	123
PENRITH	Existing Dam	100 (at 25.8m)	78	70	64	55	52	45	44	38	30
	A7 (Dam +14m)	602	440	380	337	275	258	214	202	165	112

Table 13: Ratio of change in ARI under climate change compared to current 2016 average climate

Location	Dam Scenario	Current 2016 average climate	Climate change scenario (ratio)								
			4.9%	7.3%	9.5%	13.4%	14.6%	18.6%	19.7%	23.9%	32.7%
WINDSOR	Existing Dam	1.00	1.25	1.43	1.56	1.82	1.92	2.27	2.38	2.70	3.57
	A7 (Dam +14m)	1.00	1.47	1.70	1.95	2.39	2.54	3.09	3.25	3.91	5.82
PENRITH	Existing Dam	1.00	1.28	1.43	1.56	1.82	1.92	2.22	2.27	2.63	3.33
	A7 (Dam +14m)	1.00	1.37	1.58	1.79	2.19	2.33	2.81	2.98	3.65	5.38

4.2. Climate change and a raised dam

4.2.1. Changes to dam operating rules for a raised dam

4.2.1.1. Operating rules changes

The operation rules presented in this assessment have been developed to inform the dam design and the associated climate change impact assessment. While this report includes results from the current preferred dam spillway design (A7), these operating rules are likely to be further optimised once the final dam design is determined.

The Taskforce adopted up to 14 days of upstream inundation above 120m AHD as a preliminary threshold for upstream environmental impacts based on the work undertaken for the 1995 EIS. The area below 120 mAHD has previously been inundated by the current dam and the time to return to FSL from this level is similar to the existing dam. To minimise the upstream inundation duration, the Taskforce design was based on releasing temporarily captured large inflows at 50 per cent of the peak spill of the dam during that event. For a 14m raised dam case, there are no events where the draw down to 120m AHD exceeds 14 days.

Preliminary investigations into larger mitigation raising (higher dam raising) found that two events slightly exceed 14 days above 120m AHD, with the largest exceedance by 3 hours. These complex events (which need to be carefully managed) were cases where it is not possible to draw down the dam level to 120m AHD within 14 days without exceeding the 50% rule, described in the following section. These events tend to be in the order of 20-50 year ARI events where the majority of rainfall falls upstream of the dam and there is little or no spill from the dam. These difficult cases were initially addressed by a complex set of rules, but it was found that it was easier to mandate minimum discharges that depend on the maximum level in the dam. These events that exceed 14 days are expected to be eliminated by further optimisation of the operating rules.

4.2.1.2. Simplified lookup table

Depending upon the peak dam level, one or two mandated minimum discharges are applied to draw the dam water level back down to Full Supply Level (FSL). For large events the drawdown is separated into two phases. The first phase (flow 1) aims to rapidly drawdown the dam water level on the back of the flood so that the majority of the storage is recovered and upstream impacts are minimized. Once this is achieved, the road bridge at Windsor can be opened and, in the second phase (flow 2), the residual stored water in the dam is drawn down at a rate not exceeding 100GL/d (keeping the bridge open) until the level reaches FSL.

These discharges are shown in Table 14. One additional rule was used to address longer events. For longer events the switch between flow 1 (the 50%) rule and flow 2 was delayed to ensure the dam returned to 120mAHD in 14 days.

Figure 17 shows the time the dam is above 120m AHD and FSL for the 20,000 simulation events. Some events where it was more difficult to draw the water level down to below 120m AHD are shown in Diagram 11 to Diagram 13. Under climate change the number of these difficult draw down cases increases significantly. The more difficult events are generally those where the dam has significantly mitigated the flood, resulting in a large amount of temporarily stored water that needs to be discharged from the dam.

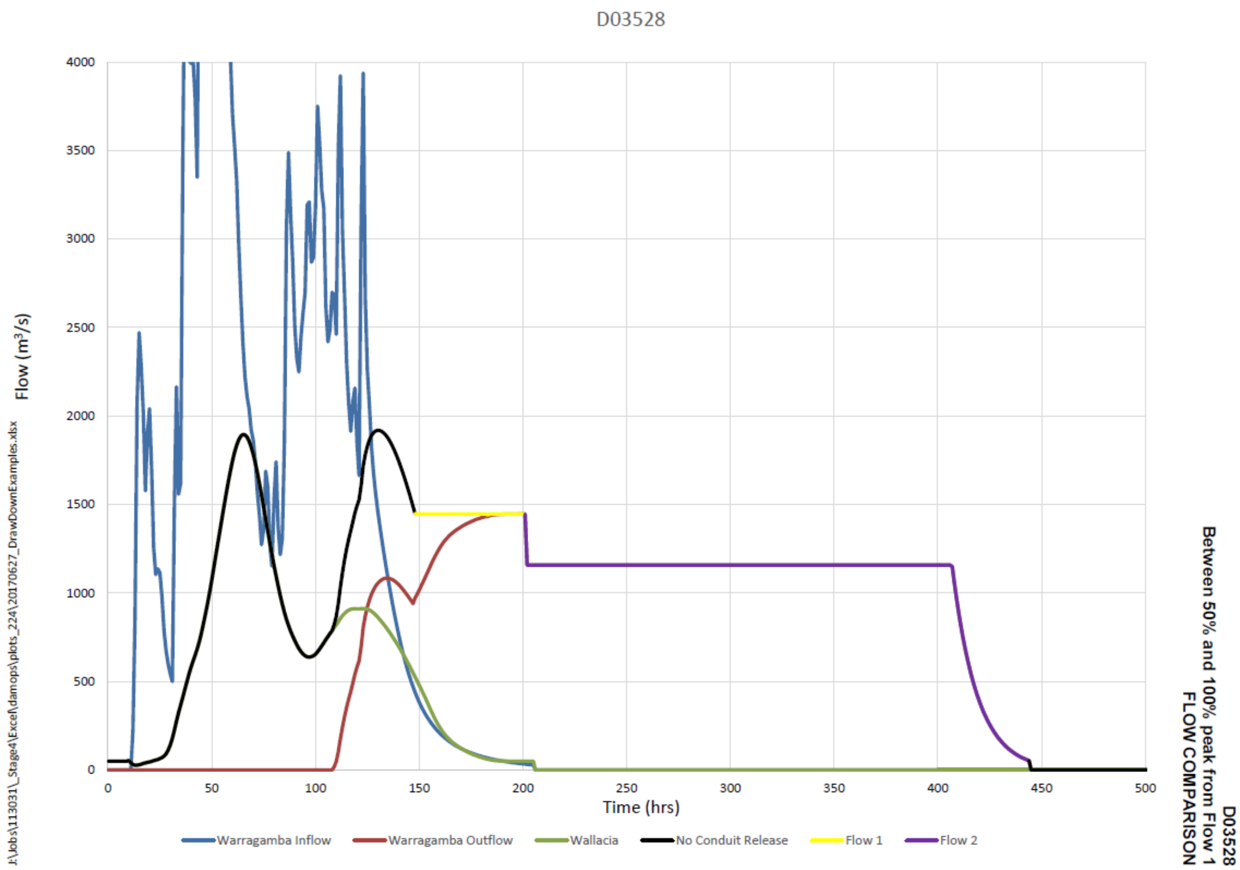


Diagram 11: Example Event 1, Dam raising, level spillways

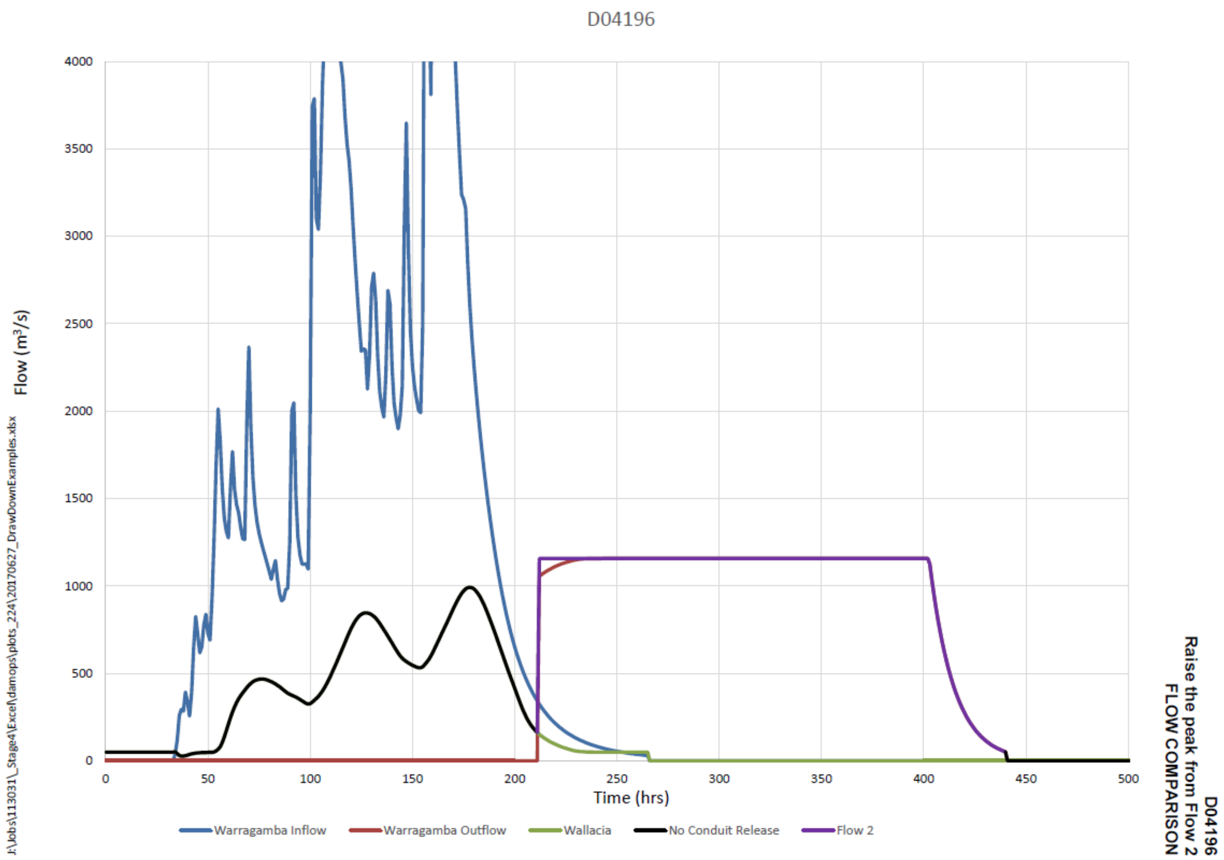


Diagram 12: Example Event 2, Dam raising, level spillways

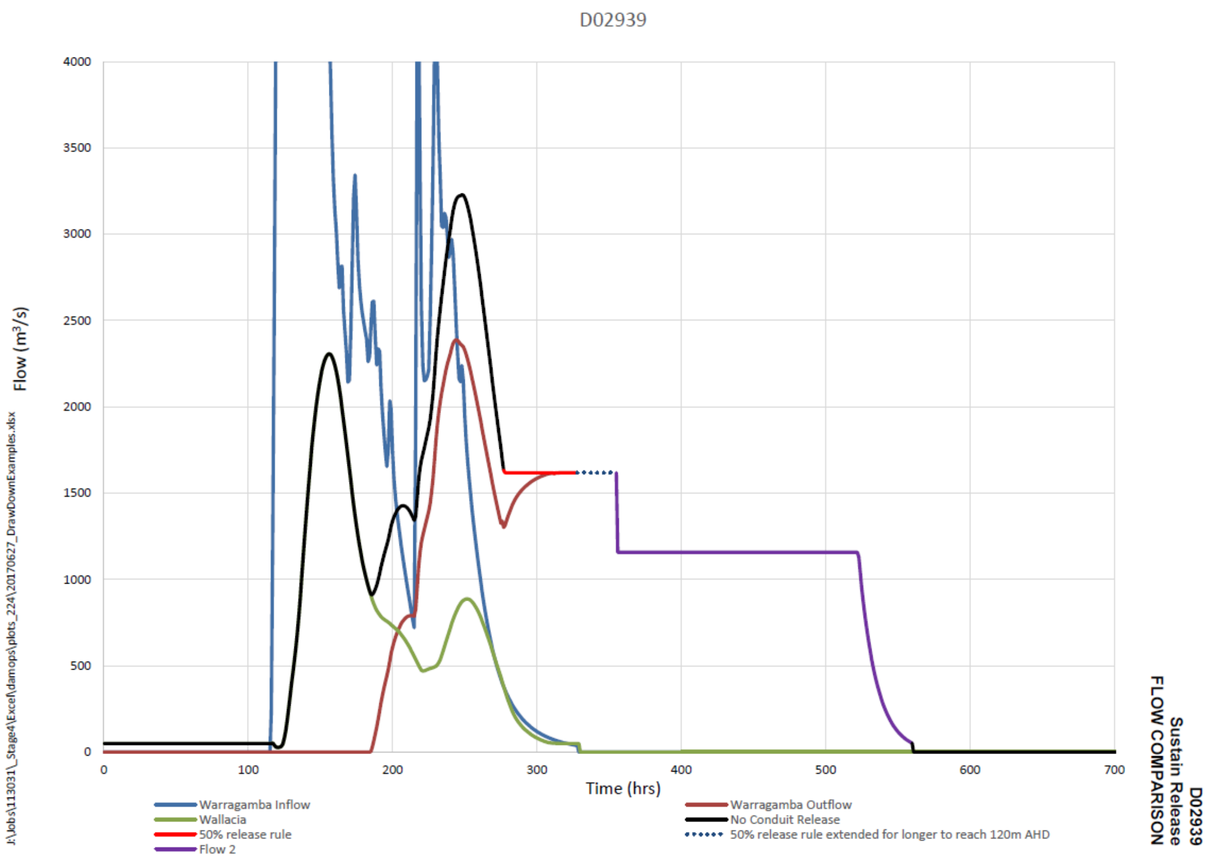


Diagram 13: Example Event 3, Dam raising, level spillways

Figure 18 and Figure 19 show the peak discharge resulting from the dam releases at Penrith and Windsor, compared to the case where no water is discharged from the dam. Points below the 1:1 line are where the drawdown generates the peak flow.

4.2.2. Consideration of different raised dam heights

Table 11 shows that increases in rainfall intensity associated with climate change, increases the frequency of floods reaching the flood planning level. This also means that some flood events will rise faster and evacuation roads would be cut earlier.

Different dam raising options ranging from 14 to 20 metres were considered by the Taskforce (2014-16) for determining a preferred mitigation zone that would significantly reduce the regional flood risk in the valley while limiting the temporary upstream inundation impacts. The resultant 2017 Flood Strategy required that WaterNSW complete a detailed concept design and submit environmental and planning approvals for raising Warragamba Dam by around 14 metres. The recommendation "around" 14 metres was in recognition that additional assessment including consideration of spillway heights, release rules and more detailed analysis of climate change impacts would be required to determine the optimal dam raising height and design.

As part of the detailed climate change analysis for the final dam design, different dam heights were examined to determine the relationship between changes in mitigation benefits under the full range of climate scenarios to 2090. This assessment of dam raisings up to 20 metres was for comparative purposes and does not change the Flood Strategy's commitment to proceeding with design and approvals for a dam raising of around 14 metres.

By 2060 under a medium climate change (9.5%), flooding at the current 1 in 100 ARI level at Windsor (17.3 m AHD) will become a 1 in 370 ARI event (with the current A7 design). However, with medium climate change by 2090 a dam raising in the order of 17m would be required to maintain the probability of flooding at 17.3 m with a 1 in 370 ARI.

The analysis of preliminary dam raising designs with offset main and auxiliary spillway levels is discussed in Appendix A.

4.2.3. Spatially Varying Climate Change Rainfall Increase

Dynamic downscaling research suggests areas subject to orographic rainfall enhancement will experience proportionally higher rainfall increases than other areas. While standard practice is to uniformly scale rainfall, it was considered prudent to test the performance of different mitigation dams under a scenario where rainfall increases were higher in these orographically enhanced areas, as many of these areas are not controlled by Warragamba Dam. This is particularly apparent for the Nepean system, where the upper reaches are subject to some of the most orographically enhanced rainfall. While 4 major water supply dams are in the Upper Nepean Catchment, their combined storage is relatively small compared to Warragamba Dam. Figure 20 depicts the relative orographic enhancement. In Figure 20, the areas subject to orographic enhancement (calculated as the top 1/3 of 1% AEP IFD values) are shown in the first panel, whilst the second panel depicts the percentage of area in each sub-catchment subject to orographic enhancement. The rainfall was increased in these areas, and proportionally decreased over the remaining catchment so that the overall rainfall increase in the catchment remained the same.

The spatially varying rainfall increase cases were run as a sensitivity analysis. The results of this analysis were not updated for the latest design and are contained in Appendix A. For frequent events there is very little change in flood levels between the two cases. For events from 5% AEP to 0.5% AEP at Windsor, flood levels are slightly higher when a spatially varying rainfall increase is applied. At Penrith, flood levels are slightly higher when a spatially varying rainfall increase is applied for events from around 5% AEP to 2% AEP. For very rare events applying the spatially varying rainfall results in a lower flood level for the same AEP event.

Table 14: Dam Operations - Minimum discharge look up table applied for all raised dam designs

Peak level (m AHD)	Name/flow description	Flow 1 (GL/D)	Minimum days at flow 1	Change to flow 2 at (m)	Mandated minimum Flow 2 (GL/D)	Minimum days at flow 2	Minimum total days	Finish level (m AHD)	Minimum Days to 120m AHD
117.00	low flow	10.0	2.28	117.0			2.28	116.72	
117.50	low flow	20.0	3.06	117.5			3.06	116.72	
118.00	low flow	30.0	3.33	118.0			3.33	116.72	
119.00	low flow	50.0	3.57	119.0			3.57	116.72	
120.00	low flow	60.0	4.32	120.0			4.32	116.72	
121.00	low flow	70.0	4.87	121.0			4.87	116.72	0.59
122.00	low flow	80.0	5.30	122.0			5.30	116.72	1.45
123.00	low flow	90.0	5.65	123.0			5.65	116.72	2.14
124.00	100	100.0	5.94	124.0			5.94	116.72	2.70
125.00	100	100.0	6.81	125.0			6.81	116.72	3.49
126.00	100	100.0	7.70	126.0			7.70	116.72	4.29
127.00	100	100.0	8.60	127.0			8.60	116.72	5.10
128.00	100	100.0	9.51	127.5			9.51	116.72	5.94
129.00	100	100.0	10.45	127.5			10.45	116.72	6.79
130.00	100	100.0	11.41	127.5			11.41	116.72	7.67
131.00	125/100	125.0	2.67	127.5	100.0	9.05	11.72	116.72	7.90
132.00	125/100	125.0	3.47	127.5	100.0	9.05	12.53	116.72	8.62
133.00	150/100	150.0	4.12	126.65	100.0	8.23	12.35	116.72	8.36
134.00	162.5/100	162.5	5.10	125.42	100.0	7.17	12.26	116.72	8.19
135.00	175/100	175.0	5.03	126.02	100.0	7.70	12.73	116.72	8.57
136.00	175/100	175.0	6.55	124.22	100.0	6.12	12.66	116.72	8.42
137.00	200/100	200.0	6.01	124.82	100.0	6.64	12.65	116.72	8.32
138.00	200/100	200.0	7.04	123.72	100.0	5.69	12.73	116.72	8.32
139.00	full/100	262.0	3.58	123.02	100.0	5.09	8.66	116.72	6.63

140.00	full/100	266.1	3.18	122.82	100.0	4.92	8.10	116.72	6.78
141.00	full/100	270.1	2.87	122.72	100.0	4.83	7.70	116.72	6.98
142.00	full/100	274.2	2.78	121.22	100.0	3.57	6.36	116.72	6.44
143.00	full/100	278.2	2.67	120.0	100.0	2.59	5.26	116.72	6.05
144.00	full/100	282.3	2.47	120.0	100.0	2.59	5.06	116.72	6.29
145.00	full/100	286.4	2.31	120.0	100.0	2.59	4.90	116.72	6.53
146.00	full/100	290.4	2.18	120.0	100.0	2.59	4.77	116.72	6.77
147.00	full/100	294.5	2.06	120.0	100.0	2.59	4.65	116.72	7.01

Where:

Drain down times

- Less than 7 days to FSL bridges open
- 7-14 day to FSL bridges open
- Bridges shut < 7 days
- Fully open bridges shut < 10 days
- Fully open bridges shut till 120m AHD reached in dam

4.2.4. Interpolation Calculations for Decades and Climate Change for Damages Calculations

To allow the economic assessment to account for the gradual increase in flood risk due to climate change, an approach was adopted where instead of running the full ensemble of events for decade and emissions scenarios, results were interpolated by calculating the probability shift in flood risk. This also removed the noise from each ensemble run and allowed the flood damages curves to be integrated in a more consistent manner. Figure 29 and Figure 30 show the previous stage damage curves shift for low and high climate change emissions scenarios interpolated by decade. Note that under current practice the PMF does not change with climate change.

5. FLOOD AND DROUGHT DOMINATED REGIMES

The flood record at Windsor and other parts of the NSW East Coast exhibits distinct wet and dry periods that show considerable persistence. The chance of a flood is much higher if there was flooding in the previous 5 years and, similarly, the chance of not having a flood is much higher if none have occurred in previous years. This persistence cannot be explained by random chance.

Hall (1927) carried out an assessment of rainfall and flood records and concluded that the magnitude and frequency of floods at Windsor was reflected in the trends in rainfall and that there were distinct historical periods characterised by many floods and high rainfall. Cornish (1977) first proposed that there were distinct regimes. Erskine and Warner (1988) carried out a detailed analysis of flood dominated regimes (FDR) and drought dominated regimes (DDR).

The long flood record at Windsor shows multi decadal periods with very few major floods and similar length periods with a very large number of major floods. A near complete record of large floods over 10m can be constructed at Windsor back to 1790 by adjusting recent floods for the construction of Warragamba Dam and careful analysis of historical records for early events, though some uncertainty does exist about two events in 1830s. A 10m flood at Windsor under pre-dam conditions is approximately a 5 year ARI event. A record using an 8m threshold can only be constructed back to 1857. This data is plotted on Figure 21 with years with multiple events highlighted. The interarrival time for events above 8m and 10m is shown on Figure 22. These graphs show distinct flood and drought dominated periods. Table 15 shows the classification if a FDR is defined as a period with 10m floods more frequent than every 5 years, a DDR is defined as a period with floods less frequent than every 10 years and a transition occurs when the other threshold is reached.

Table 15: FDR and DDR – Windsor

Period	Regime	Duration (years)
1790 - 1799	Drought?	>9
1799 – 1818	Flood	21
1819 - 1856	Drought	38
1867 - 1904	Flood	47
1905 - 1942	Drought	38
1943 - 1992	Flood	51
1993 - present	Drought	>= 24

While it is possible to use other definitions that result in slightly different periods of flood and drought, the general trend in the flood record is clear and the 10 year transition from flood to drought dominated nicely deals with the flood free periods from 1880 to 1889 and 1978 to 1986, both of which are bookended by a series of large events.

The period from 1992 to February 2021 when this report was finalised has persisted without a large flood. No event during this period reached 10m at Windsor, although the February 2020 flood event would have exceeded that level if the storage level in Warragamba Dam was higher at the beginning of that event. The historical sample provides only two complete Flood Dominated

Periods and Drought Dominated Periods.

It has long been suggested that the flooding regime is characterised by periods of the negative inter decadal pacific oscillation (IPO). However, Figure 23 shows that while there is a strong correlation between IPO positive and DDR from 1904-1943 and the first half of the FDR from 1944 - 1975, other periods show no correlation, with the period from 1975 onwards showing nearly the reverse relationship.

To estimate the probability of flooding in each regime the flood record was split into flood and drought dominated records. Initially both periods were analysed but because nearly all the large events occur in the flood period, which is about half the length of the total record, an approach was adopted where the complete record and the FDR were fitted using a similar growth curve and the DDR distribution was calculated using these results and the total probability theorem. This resulted in the curves in Figure 24 where the complete record and FDR fit well but the DDR fit is poor. This is not unexpected with a small sample size. Figure 25 shows how the fit would improve with just one more 12m event recorded in the drought period.

To better understand the persistence several sampling experiments were carried out where no persistence was assumed and flood and drought dominated periods were assumed to persist for 5, 10, 20 and 40 years. This approach is somewhat simplified as the flood and drought dominated periods are probably better described by a Markov process where instead of having a fixed length, there is a small probability of changing states. Figure 26 shows the interarrival times compared to the reliable record since 1857 and the longer record from 1790. While not conclusive, the observed data is well described by a wet and dry period approaching 40 years.

5.1. Sensitivity of results to regime change

The current DDR has persisted for the last 27 years while the two previously observed periods have lasted for 38 years. While there is insufficient evidence to draw any conclusions about causes of previous flood dominated periods or the likelihood of the current drought dominated period ending or even the future climate having such distinct flood and drought dominated behaviour, it was considered prudent to test the performance of a 14m raising in a flood dominated period. If the current drought dominated period persists for a similar period as the previous two its ending would coincide with the completion of construction.

While it is unclear if flood and drought dominated regimes are a true cyclic behaviour or just an artefact of our relatively short flood record, flood risk nearly doubles in a flood dominated regime. Figure 27 and Figure 28 compare the probability of flood levels for the existing dam and a 14m mitigation dam during a FDR and their overall probability. Note that this analysis has not been updated for the current 14m raising case.

6. CONCLUSIONS

This study has investigated the potential impacts of climate change on flood risk in the Hawkesbury-Nepean Valley for the current and proposed raised Warragamba Dam. The extreme flood range at Wallacia, Penrith and Windsor makes the flood behaviour very sensitive to minor changes in flood producing runoff. Unless mitigated projected climate change will significantly increase the flood risk to life and property in these areas. While it is likely that the reduction in flood levels from a mitigation dam will be eroded with climate change, the proposed raising of Warragamba Dam by 14 metres will continue to provide mitigation of the current flood risk even under the most extreme climate change projections until the end of the century.

The impacts of climate change on flood producing rainfall (design rainfalls) in the Hawkesbury-Nepean Valley were estimated using two methods. The first is a simple temperature scaling method recommended in Australian Rainfall and Runoff. Representative Climate Pathways 4.5 and 8.5 were used, and a medium scenario between these two pathways. Using this method, design rainfall intensities are projected to increase by approximately 4.9% by 2030, and between 9.5% and 18.6% by 2090. The second method used the NARCliM dataset results (Willgoose et.al., 2014) generated by dynamical downscaling of four General Circulation Models (GCMs) using three Regional Climate Models.

The results showed change in rainfall intensity of between -20% to +48% by 2020-2039, and -9% to +16% by 2060-2079. Only one of the four downscaled GCMs showed a reduction in rainfall intensity over the future time slices. The uncertainty in the projected impacts of climate change on rainfall intensity is clearly evident in the results of the analysis. However the results indicate that a significant increase in rainfall intensity is likely. The impact on flooding in the Hawkesbury-Nepean Valley was assessed by running a range of future rainfalls, generated by the two different methods, through hydrologic, reservoir and hydraulic models of the catchment and dam.

The assessment of different dam raising heights in Appendix A is based on the central and auxiliary spillways being at the same heights to maximise flood mitigation. In Appendix A for a low climate change increase by 2090, a 17m dam raise is required to achieve similar benefits in 2090 as a 14m dam raise under historical conditions. It is likely to be unfeasible to further raise the spillways for a 14m dam raising in future unless the abutments have been designed to allow this raising. Therefore, there is a strong case for either raising the dam by 17m now or designing a 14m raised dam that has abutment walls that allow for the spillway to be raised another 3m if greenhouse gas emissions are unable to sufficiently reduce climate change impacts in the future.

An offset spillway arrangement, which has the central and auxiliary spillways at different heights, can reduce the frequency of the side spillway operating. The proposed A7 design for the dam raising EIS has an offset spillway arrangement that reduces the temporary upstream inundation while only having a small reduction in downstream flood mitigation benefits. This offset design also makes it easier to draw the dam down and reduces the number of events where the peak flood level is caused by draw down.

The historic flow record shows distinct periods of wet and dry climate in the Hawkesbury-Nepean Valley, with the current drought dominated period commencing in 1992. If the current drought dominated period persists for a similar period as the previous two recorded in the historical record, it is possible that the Hawkesbury-Nepean Valley climate will return to a wet period in the near future. These wet periods contain nearly all the medium floods and all the large floods in the Hawkesbury-Nepean Valley.

While there will continue to be uncertainty about the impact of climate change on flood behaviour, some of the uncertainty can be reduced by further work and research. The flood mitigation provided by the final preferred dam raising option with the latest dam drawdown information has been modelled under a changed climate. Further research is recommended into understanding the sensitivity of flood behaviour to changes in antecedent conditions, due to changes in rainfalls and east coast lows. However, this is not expected to change the reports main conclusions on the impact of climate change on flood risk.

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Figures

FIGURE 1
STUDY AREA

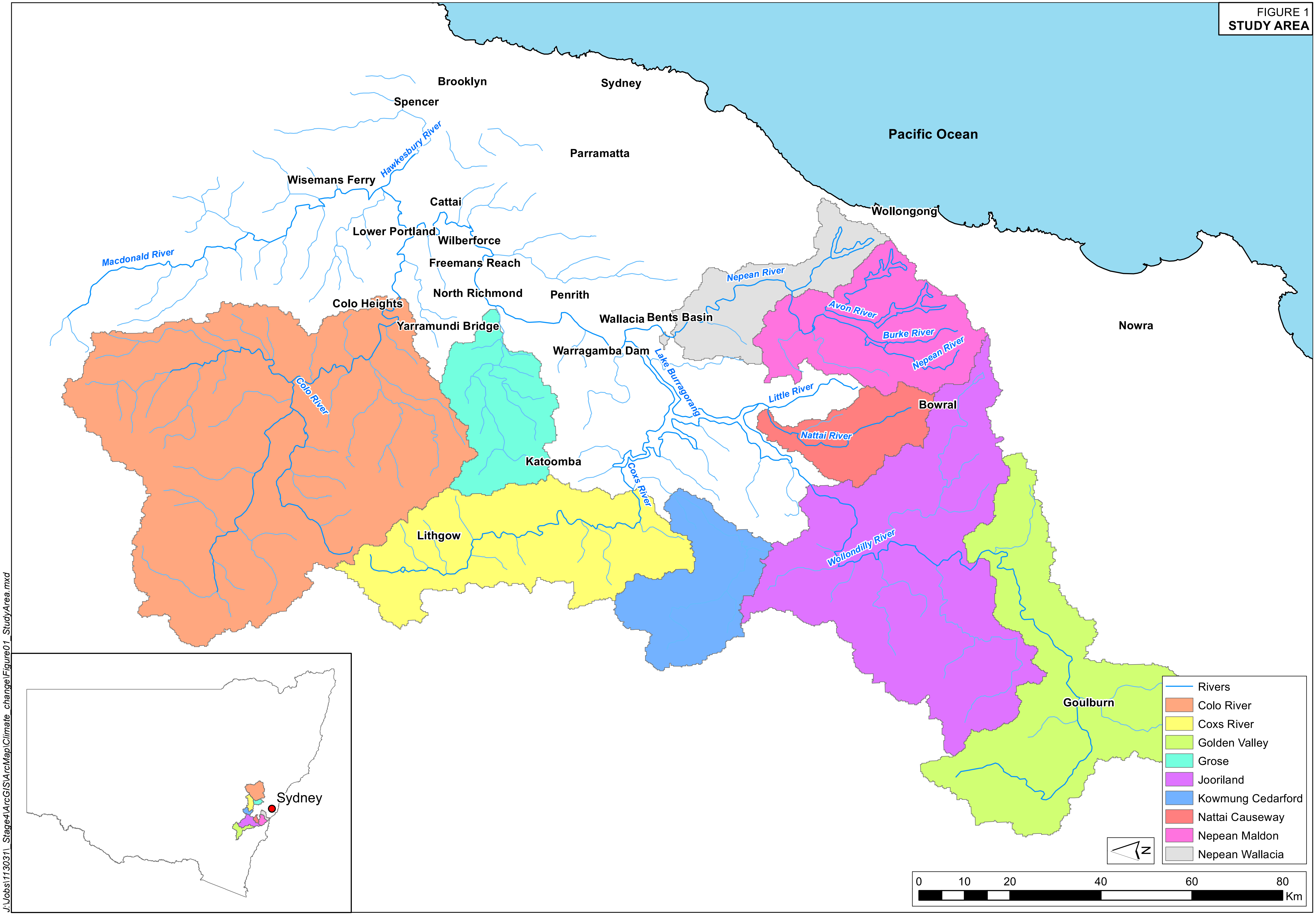

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FIGURE 2

NARCLIM RAINFALL FREQUENCY CURVES

1990–2009

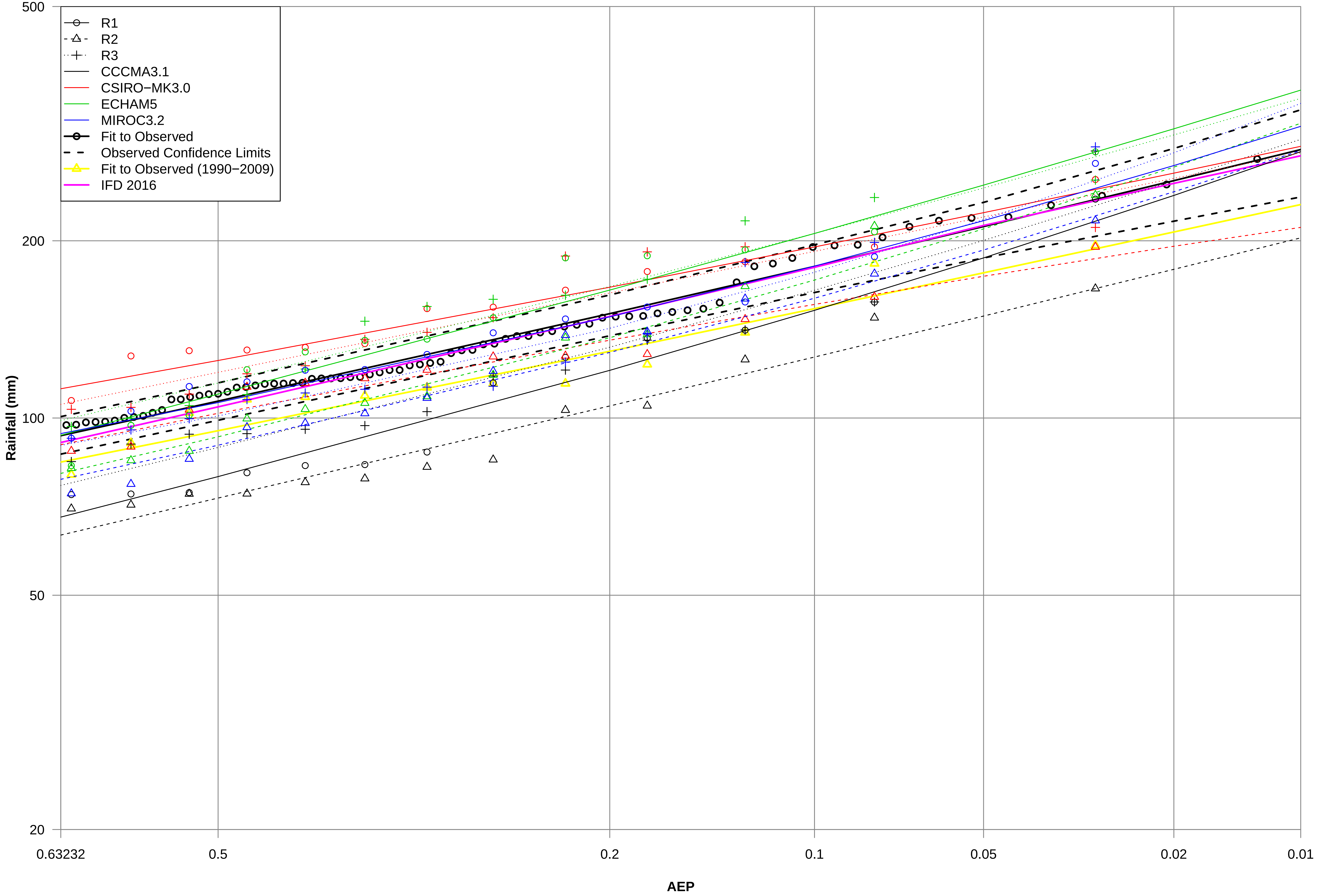


FIGURE 3

NARCLIM RAINFALL FREQUENCY CURVES

2020–2039

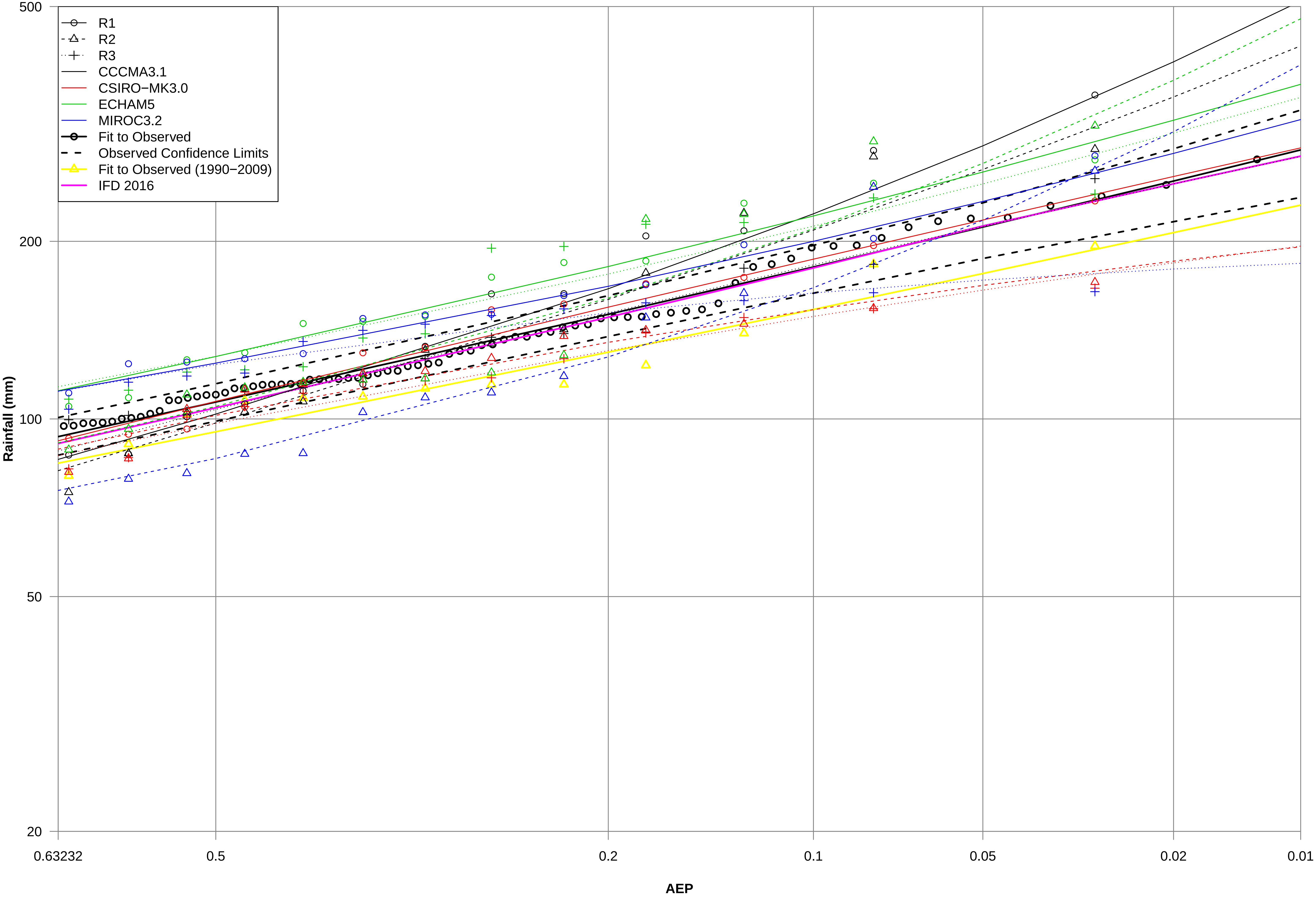


FIGURE 4

NARCLIM RAINFALL FREQUENCY CURVES

2060−2079

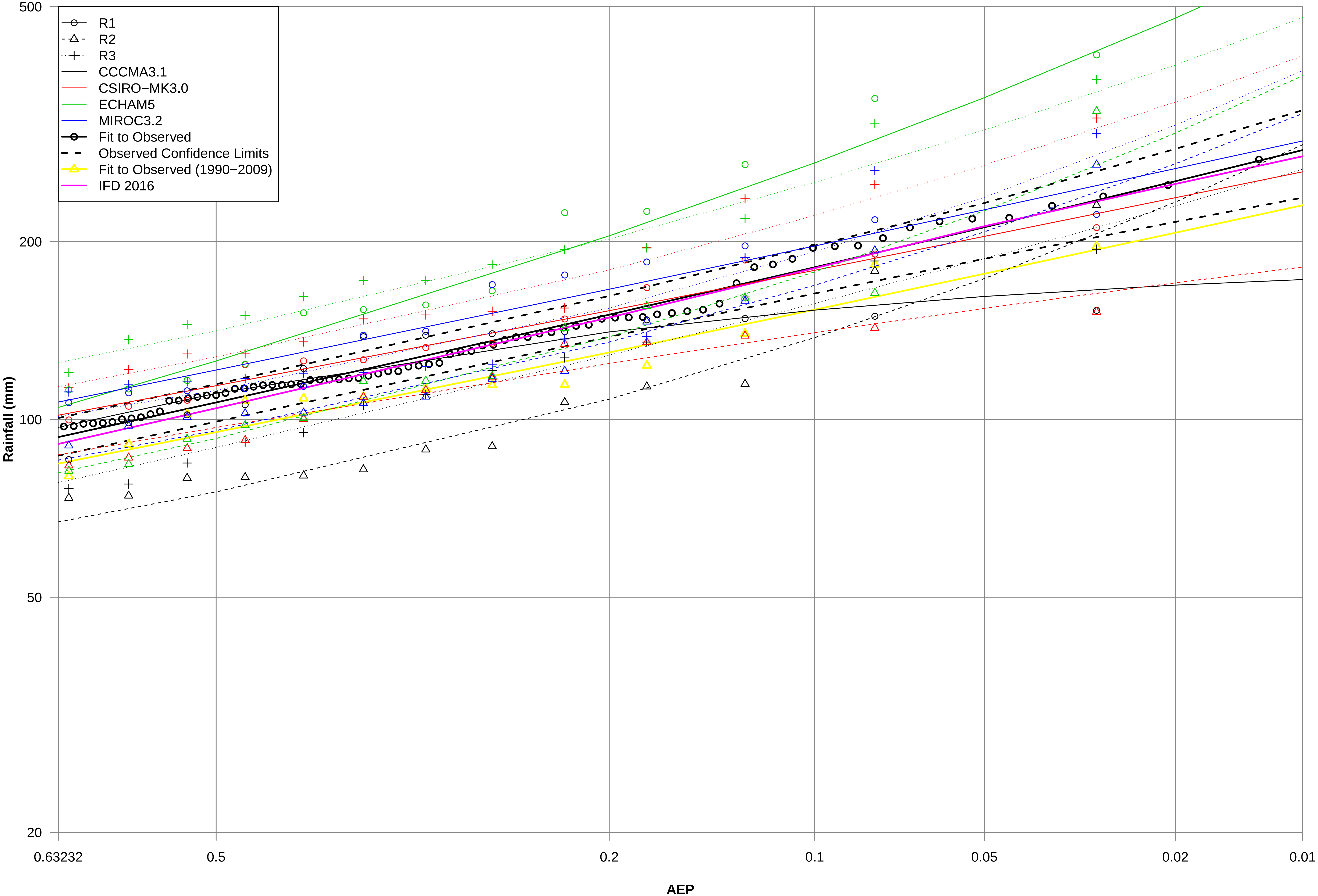
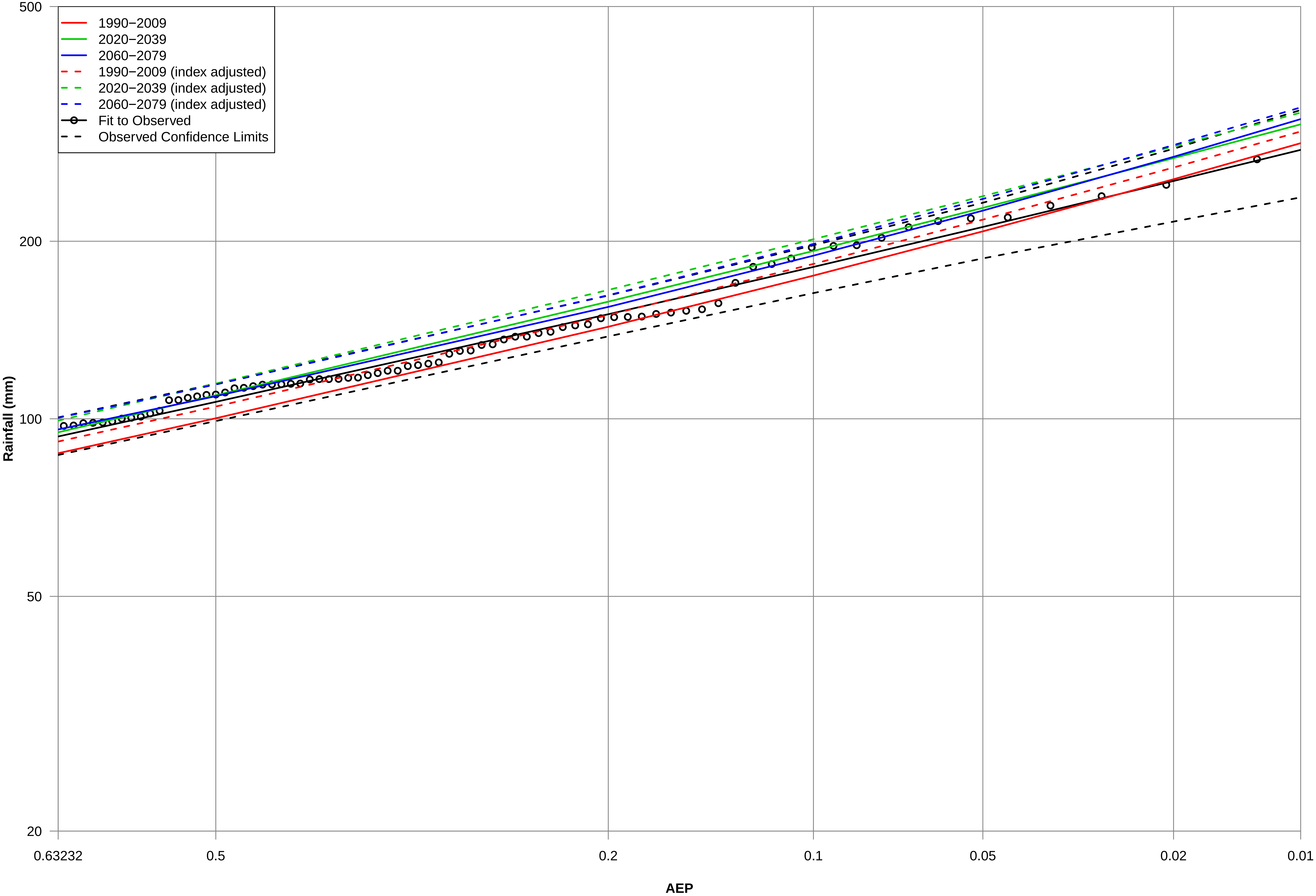
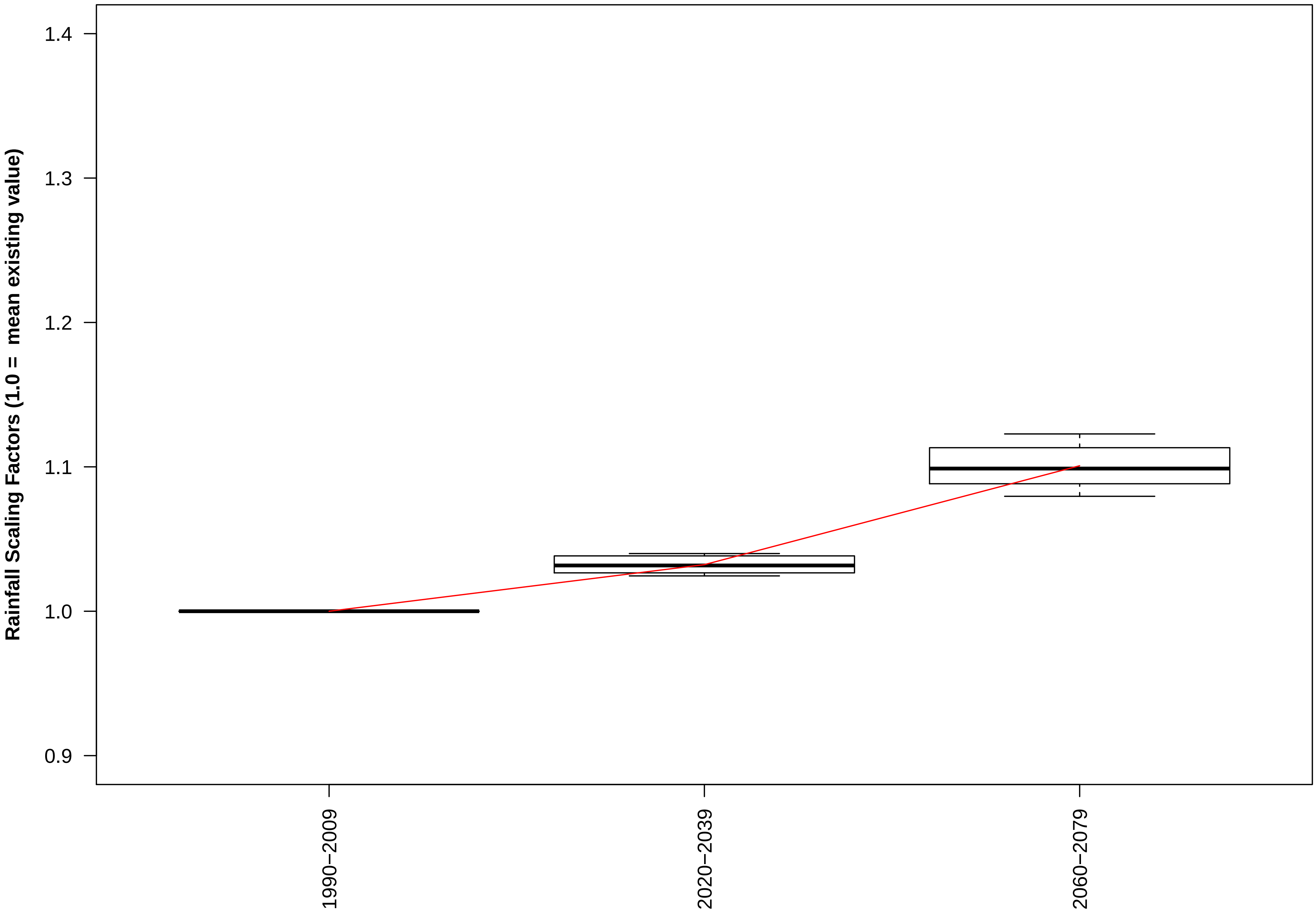


FIGURE 5

NARCLIM MULTI−MODEL AVERAGE RAINFALL FREQUENCY CURVES





NARCLIM TEMPERATURE DERIVED RAINFALL SCALING FACTORS

FIGURE 6

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FIGURE 7

STAGE FREQUENCY CURVE
EXISTING DAM AND CLIMATE CHANGE
WINDSOR

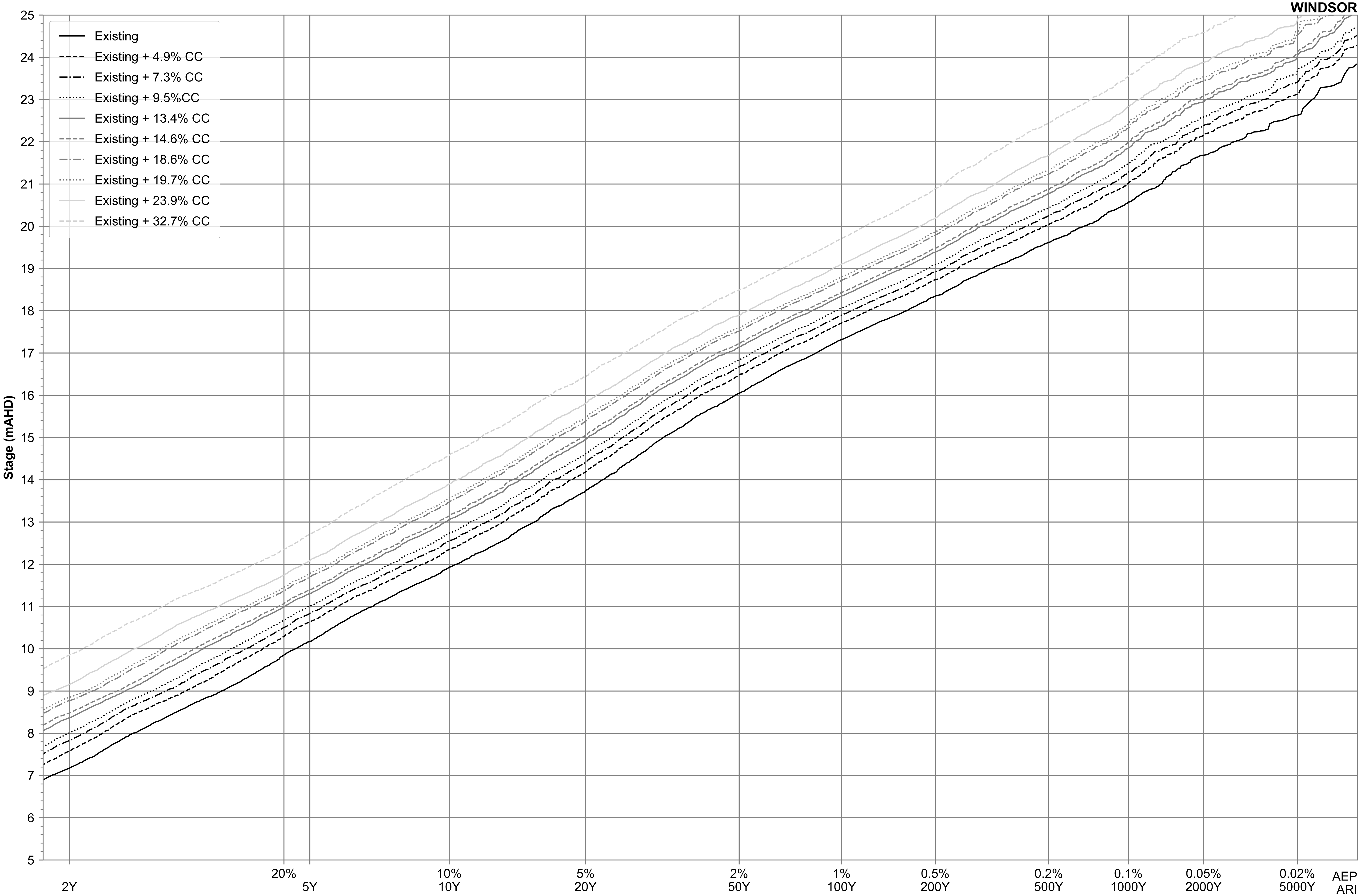

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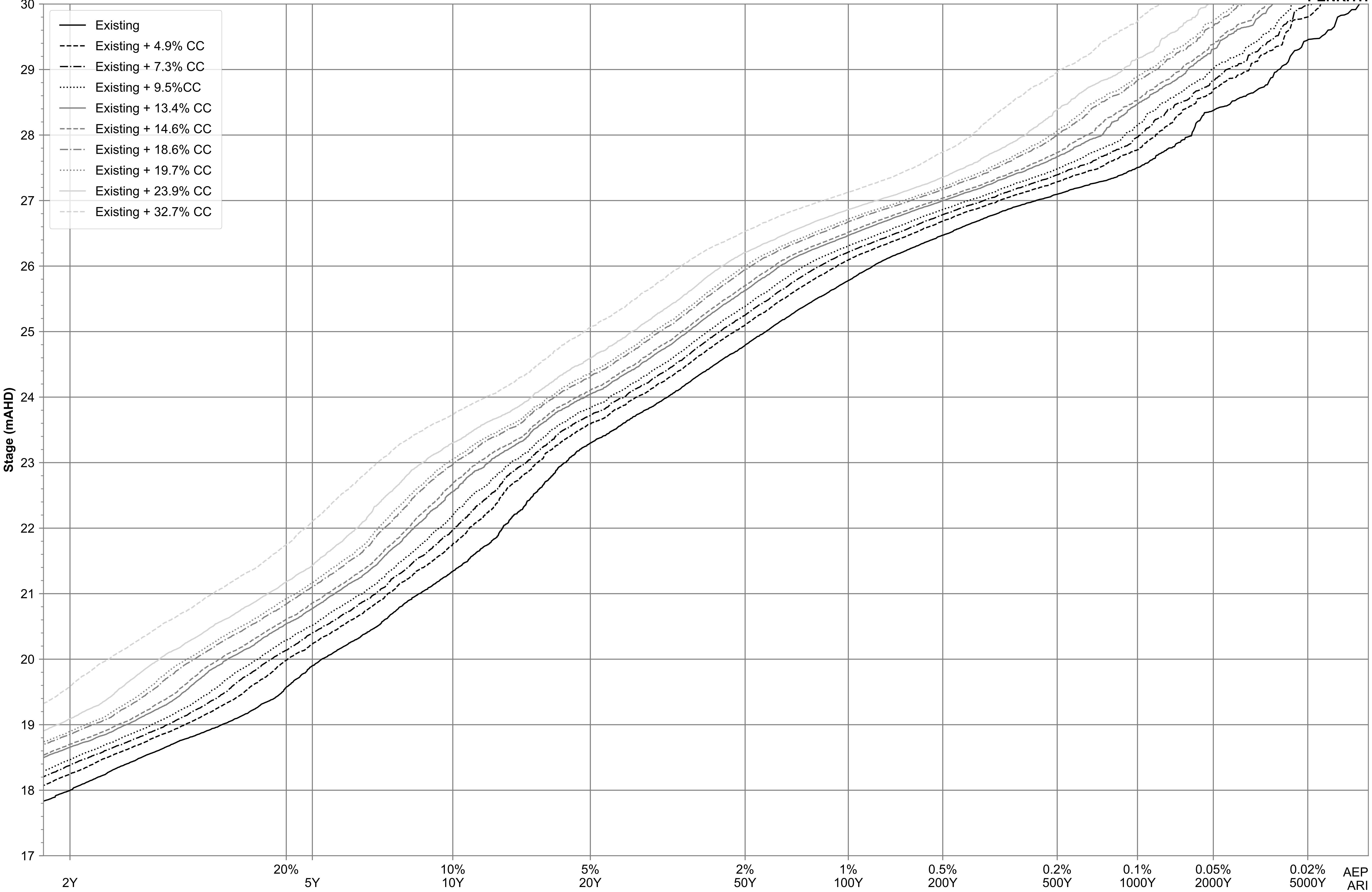
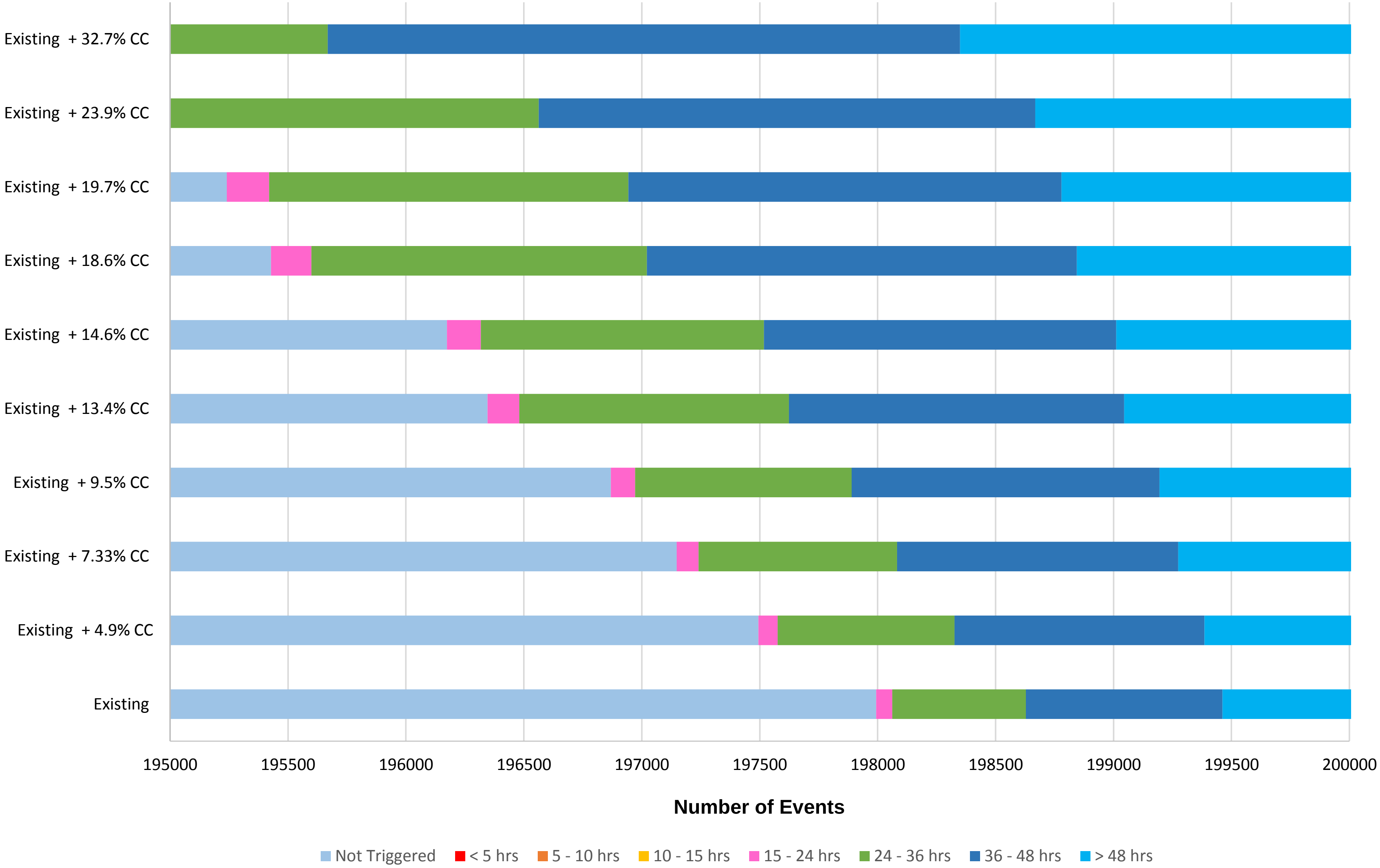
FIGURE 8

STAGE FREQUENCY CURVE
EXISTING DAM AND CLIMATE CHANGE
PENRITH





NOTE: Some events that are not triggered and therefore are not shown for clarity.

FIGURE 9
TIME FROM 4m TO 17.3mAHD
EXISTING DAM AND CLIMATE CHANGE

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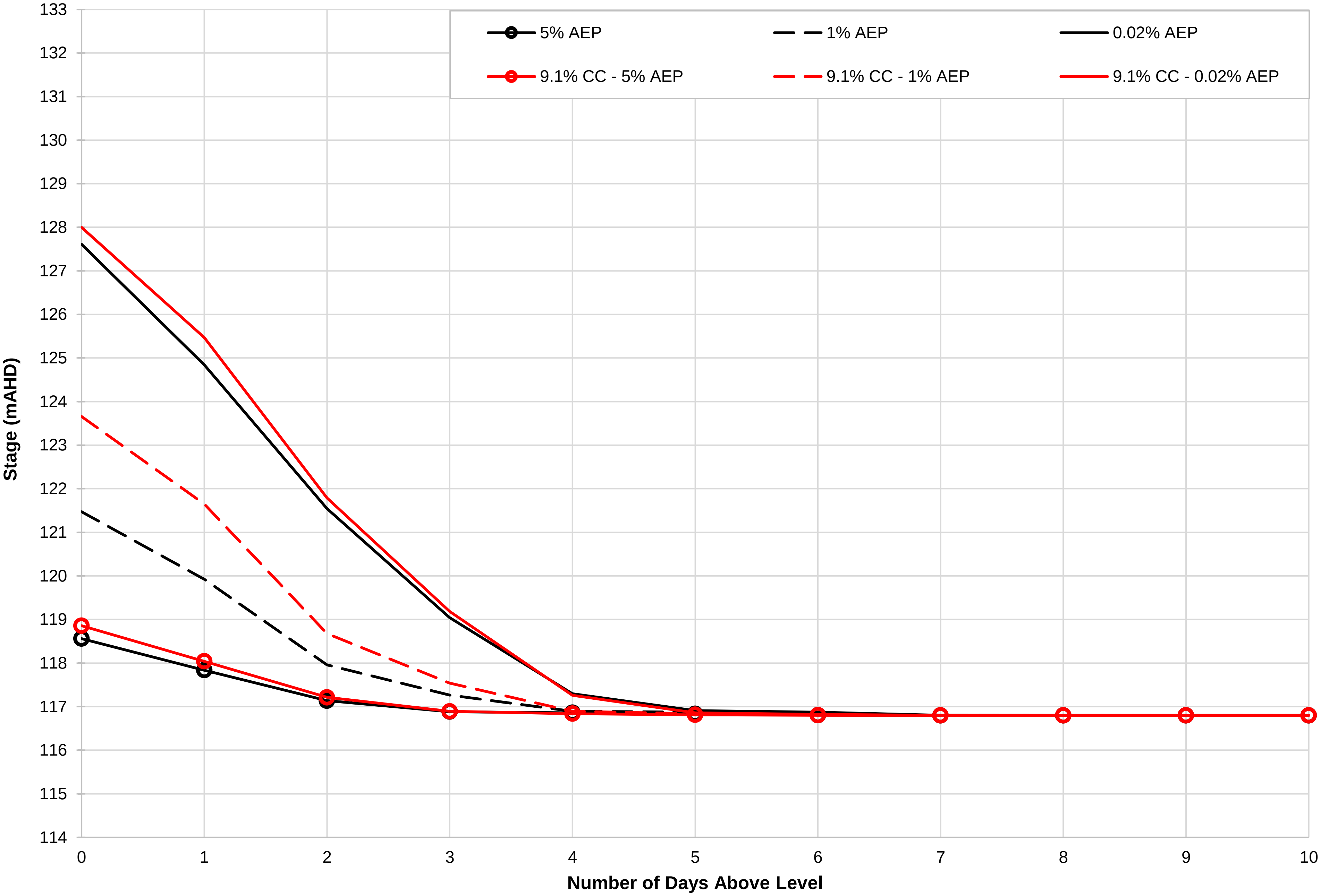

FIGURE 10
UPSTREAM INUNDATION
EXISTING CONDITIONS

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FIGURE 11

CHANGE IN INFLOW VOLUME TO DAM DUE TO CLIMATE CHANGE

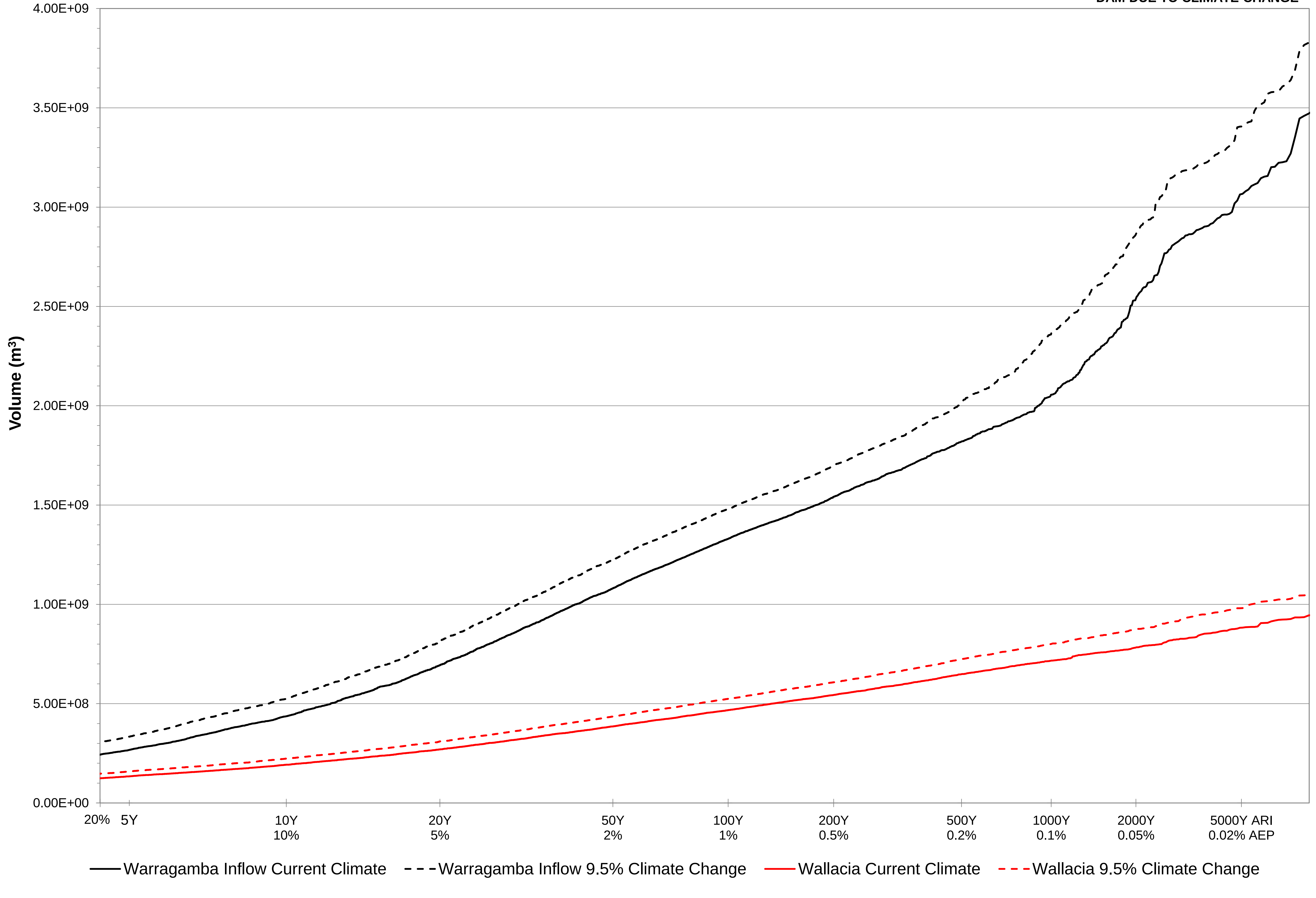

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FIGURE 12

STAGE FREQUENCY CURVE
A7 (DAM +14M) AND CLIMATE CHANGE VS EXISTING
WINDSOR

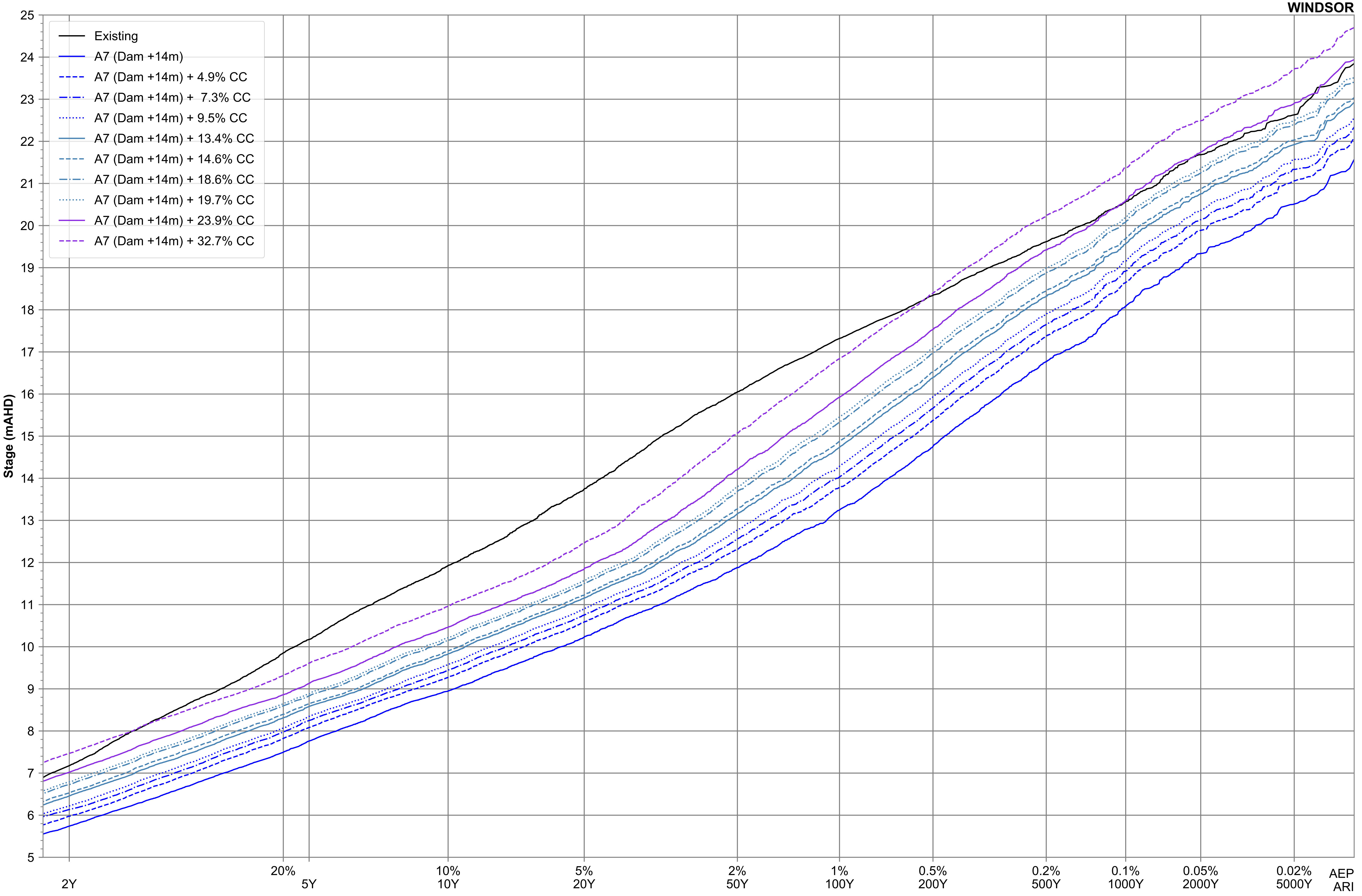

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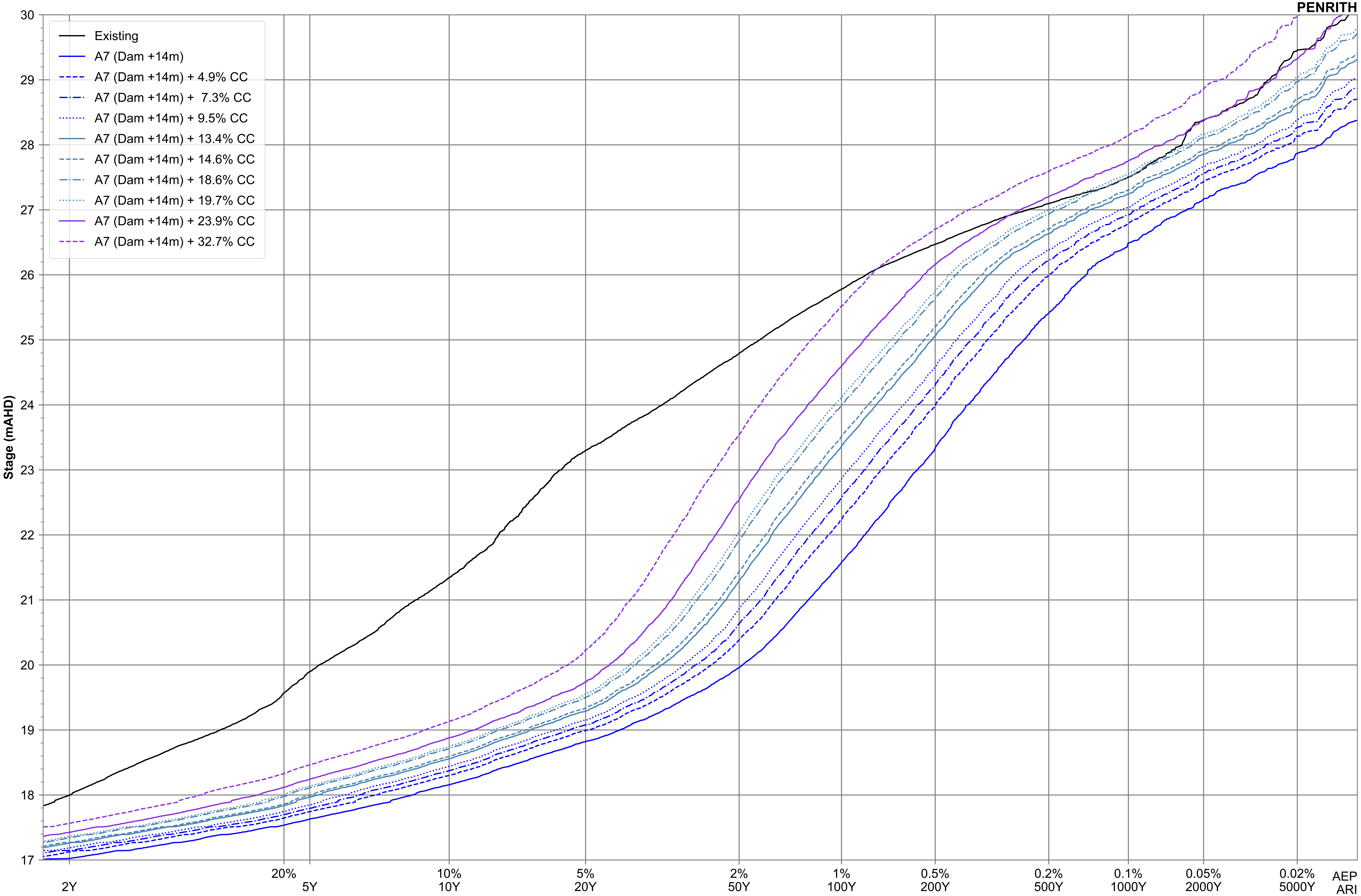
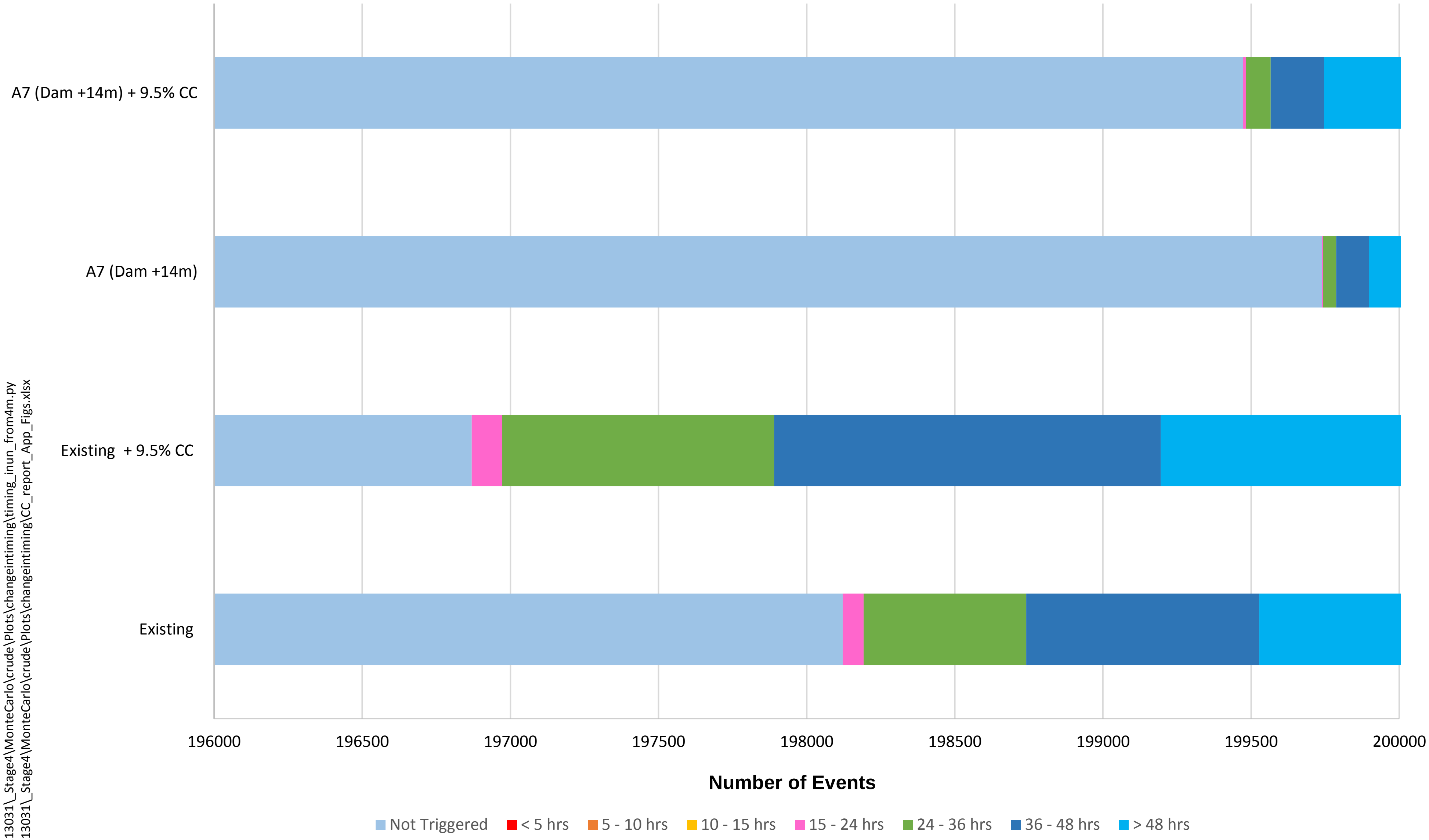
FIGURE 13

STAGE FREQUENCY CURVE
A7 (DAM +14M) AND CLIMATE CHANGE VS EXISTING
PENRITH





NOTE: Some events that are not triggered and therefore are not shown for clarity.

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FIGURE 14
TIME FROM 4m TO 17.3mAHD AS130.6 (DAM +14m) VS EXISTING WITH AND WITHOUT CLIMATE CHANGE

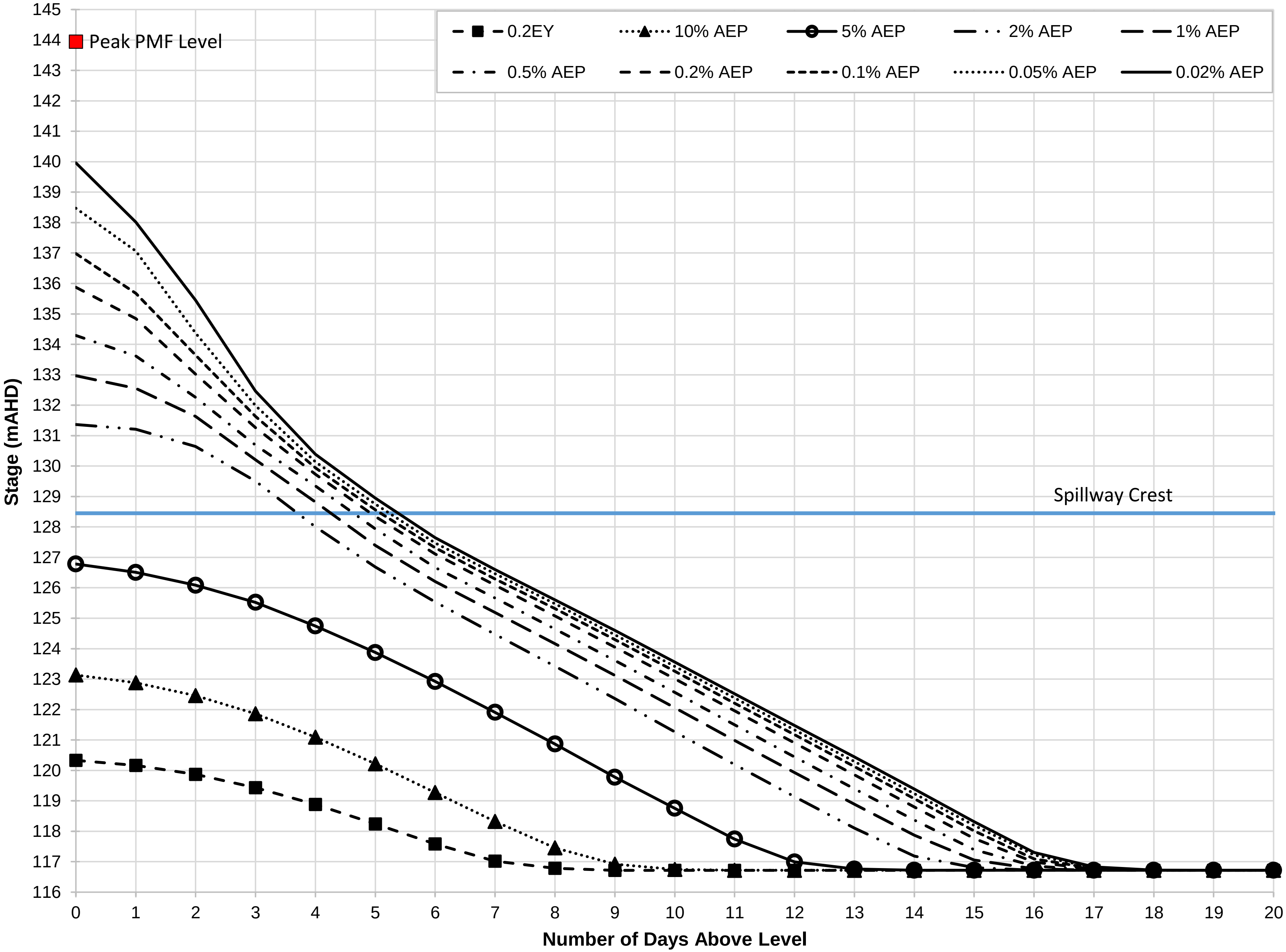

FIGURE 15
UPSTREAM INUNDATION
A7 (DAM +14M)

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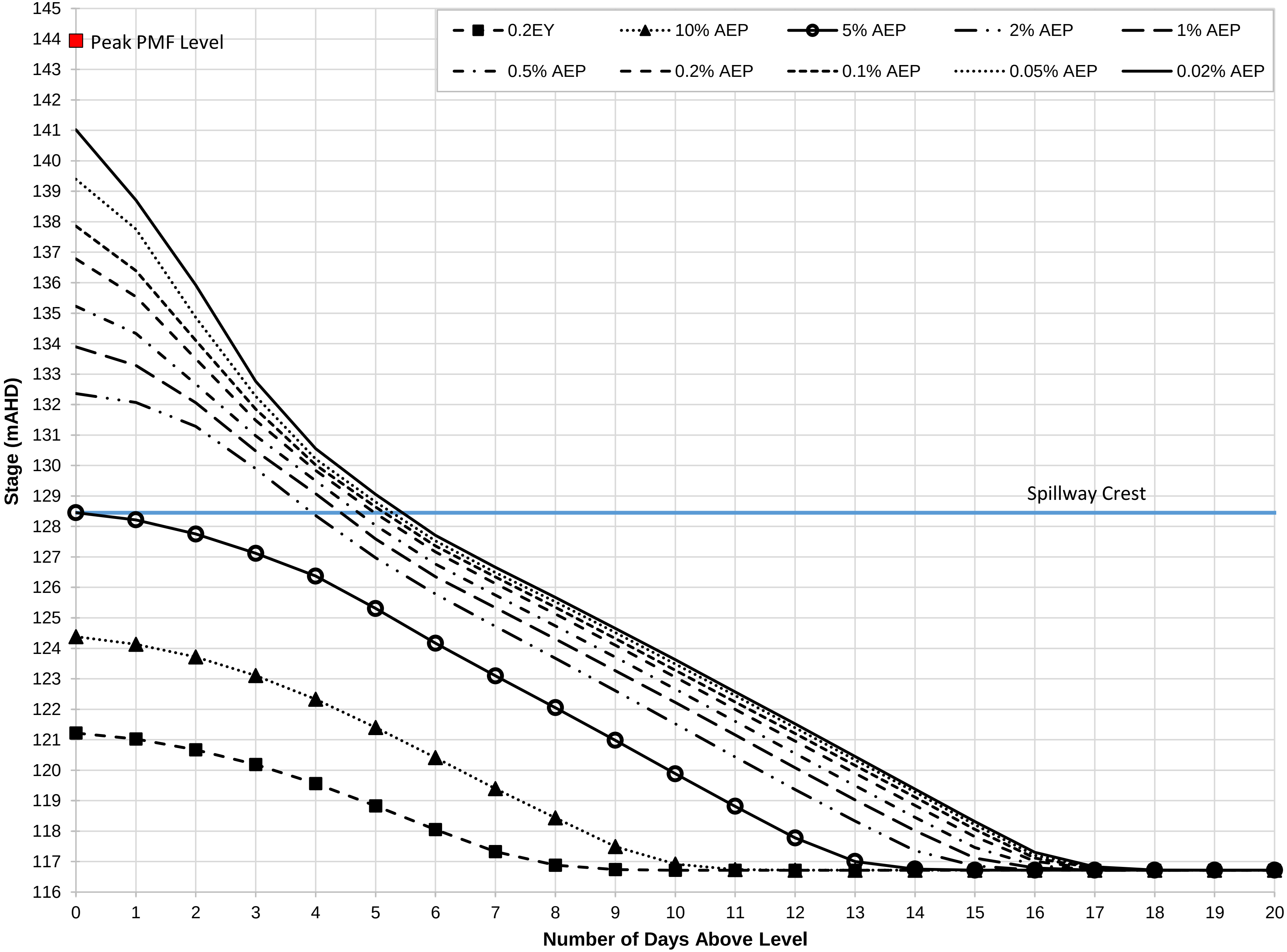

FIGURE 16
UPSTREAM INUNDATION
A7 (DAM +14M) - 9.5% CC

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FIGURE 17
DAYS ABOVE 120 MAHD DAM LEVEL VS PEAK DAM LEVEL AEP
DAM +17M

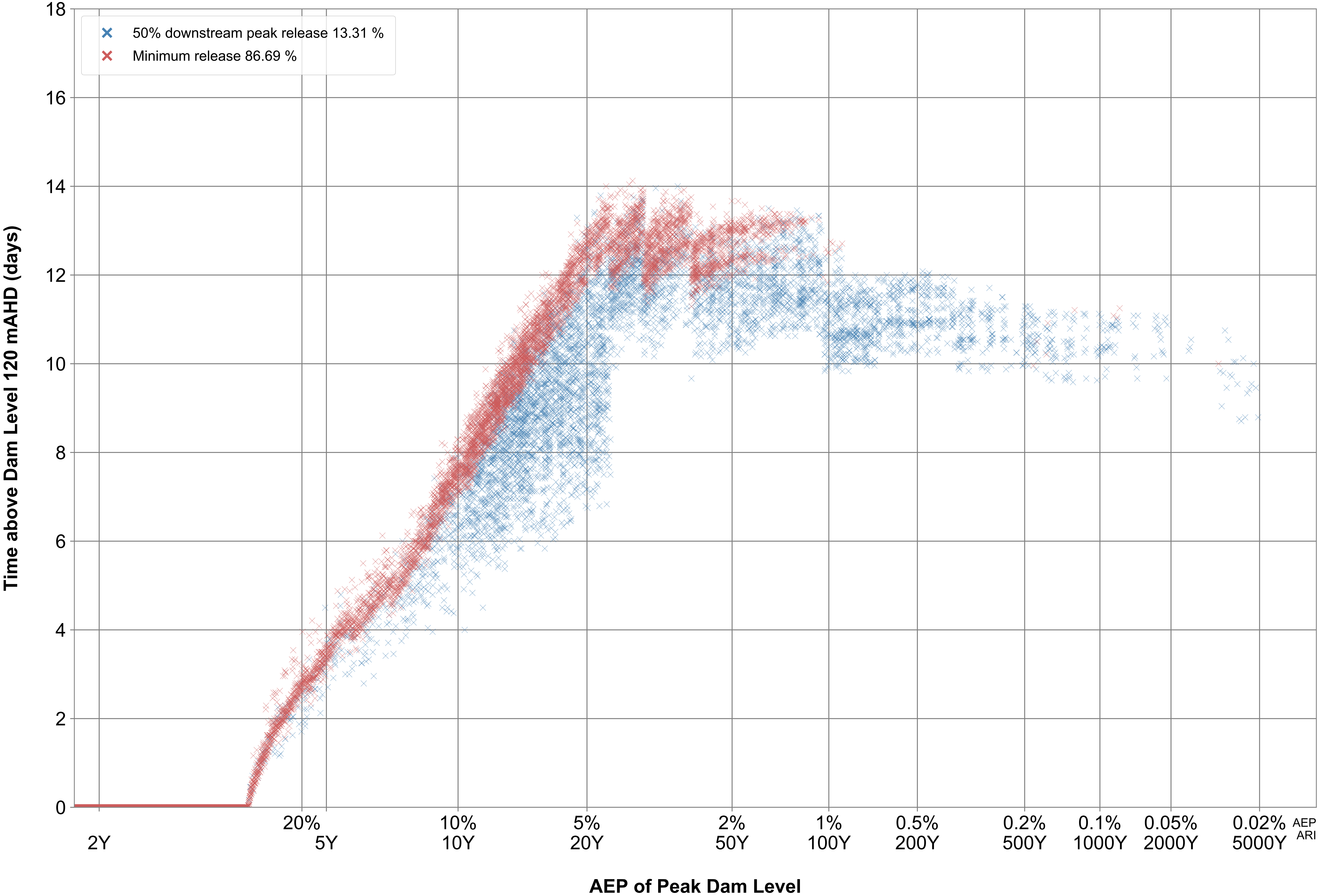


FIGURE 18

PEAK FLOW DAM OPERATIONS VS NO RELEASES – A7 (DAM +14M)
WINDSOR

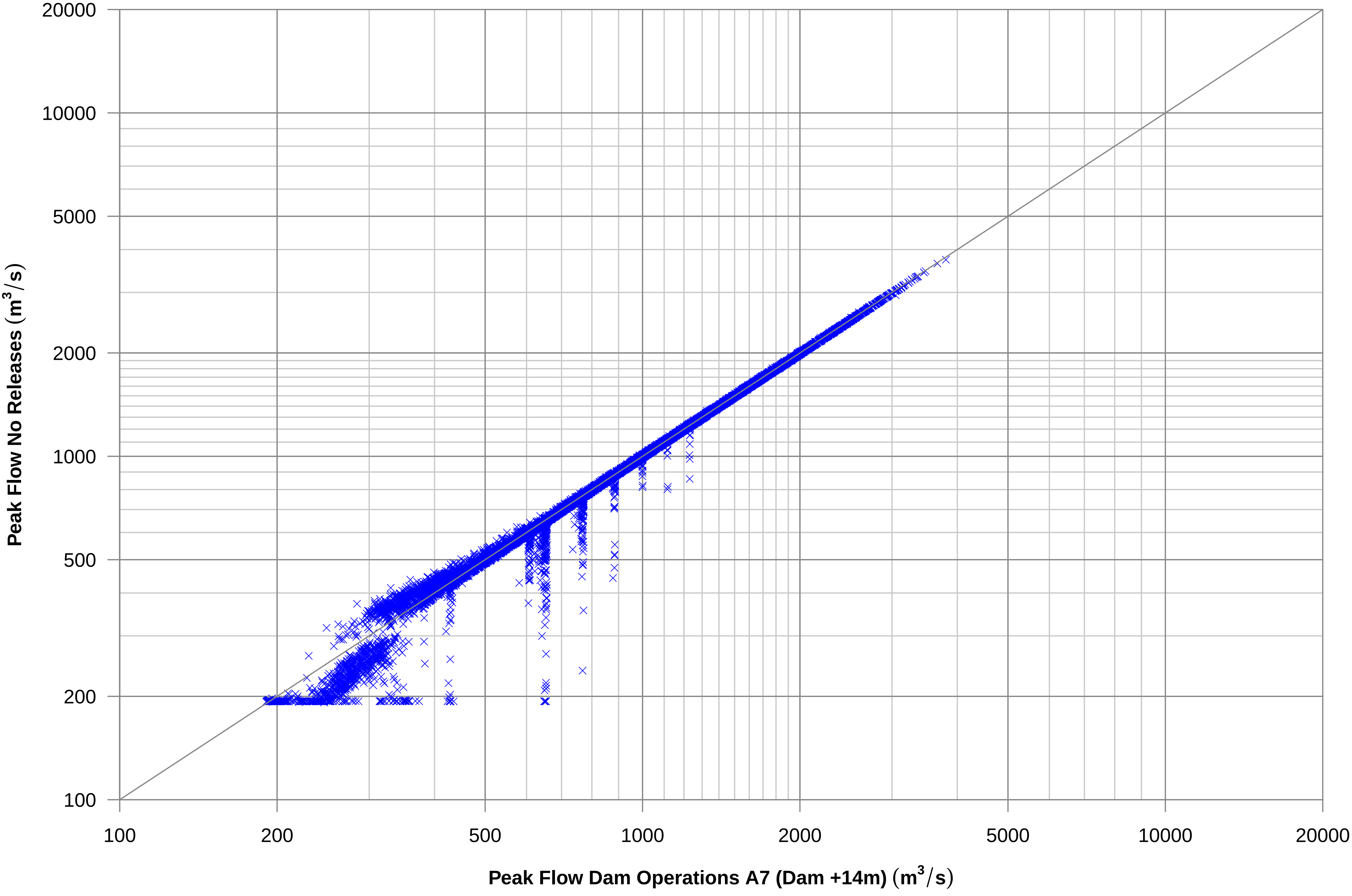


FIGURE 19

PEAK FLOW DAM OPERATIONS VS NO RELEASES – A7 (DAM +14M)
PENRITH

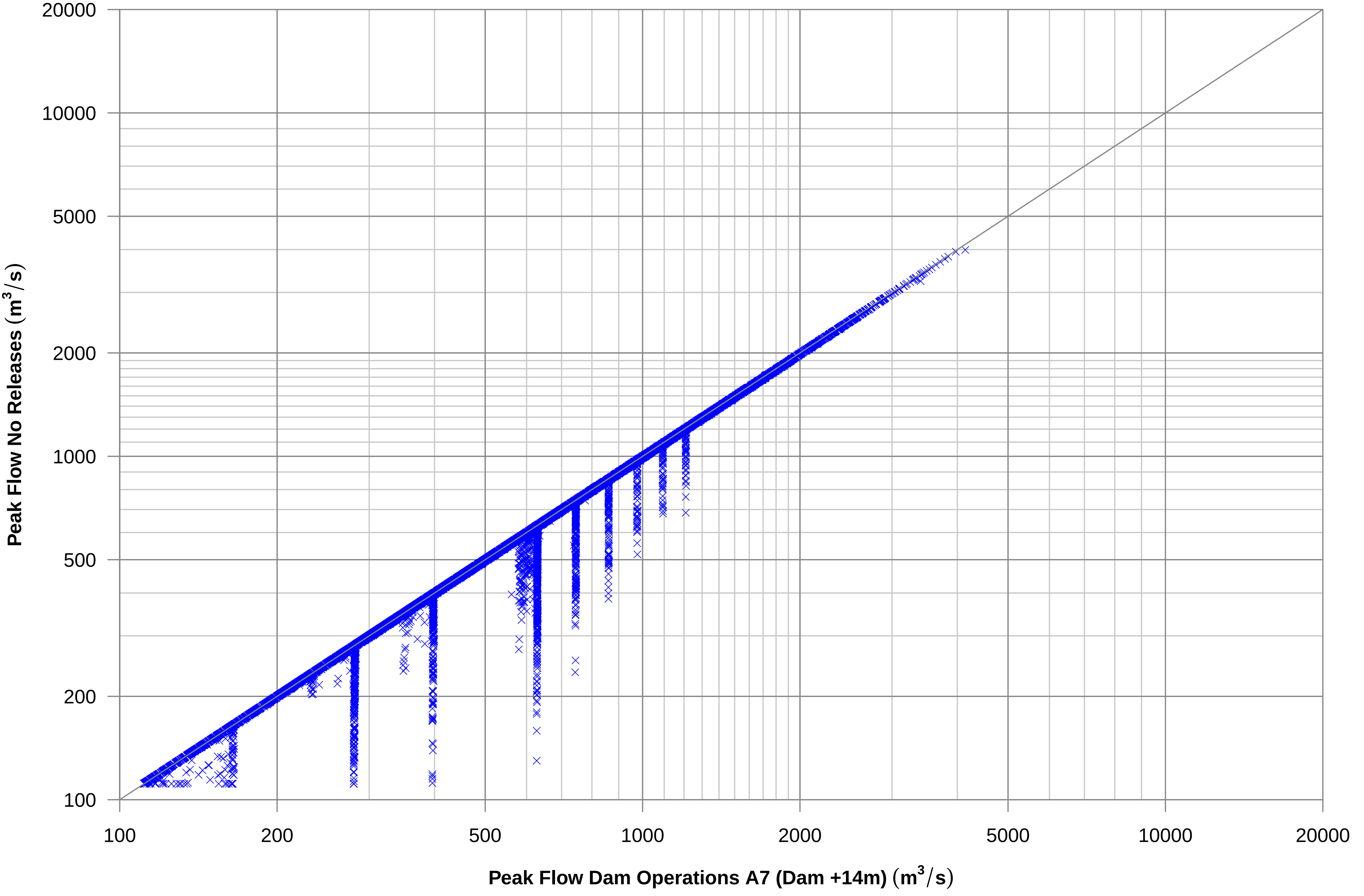
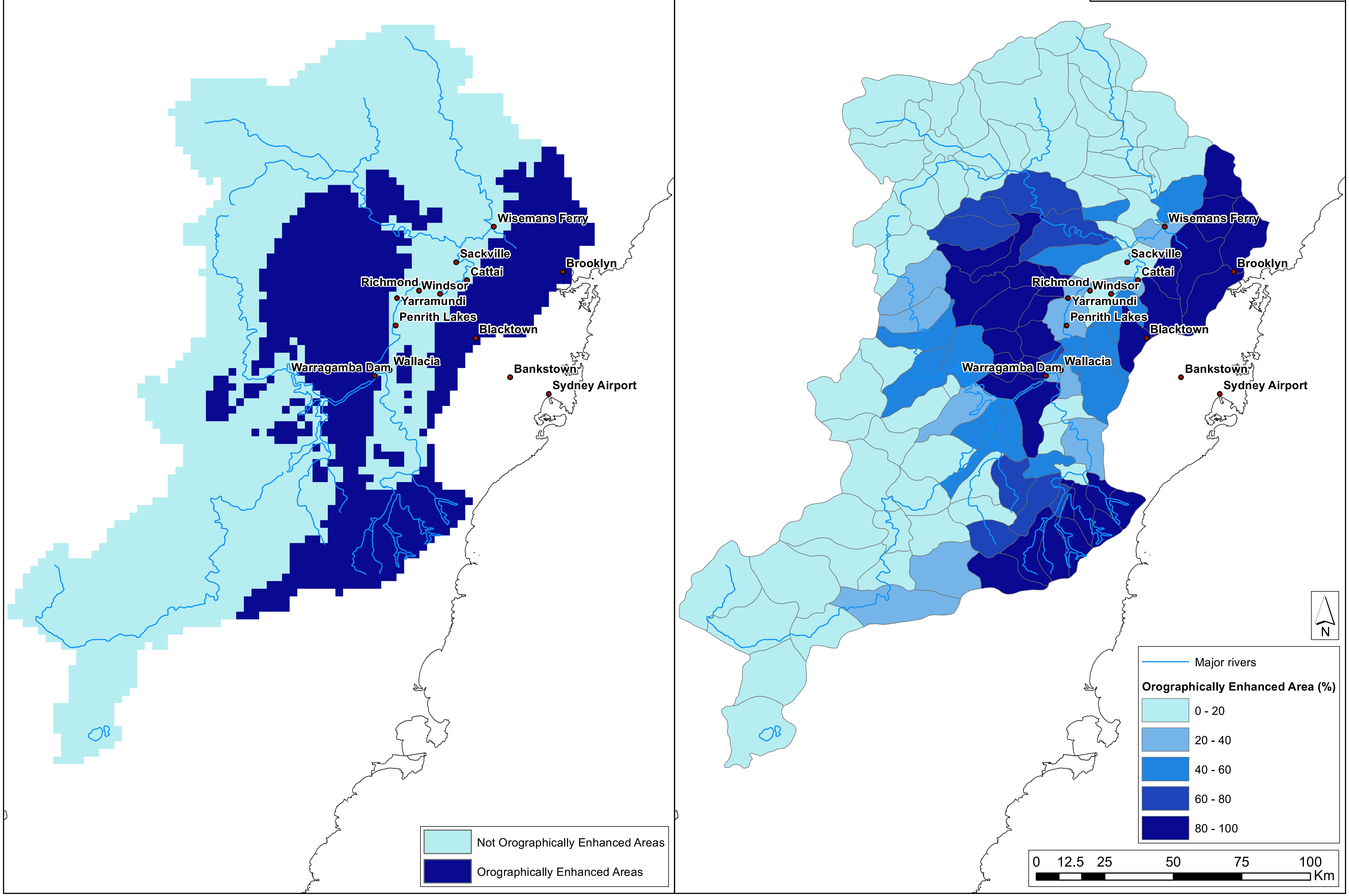


FIGURE 20
CLIMATE CHANGE COMPARISON OROGRAPHICALLY ENHANCED AREAS



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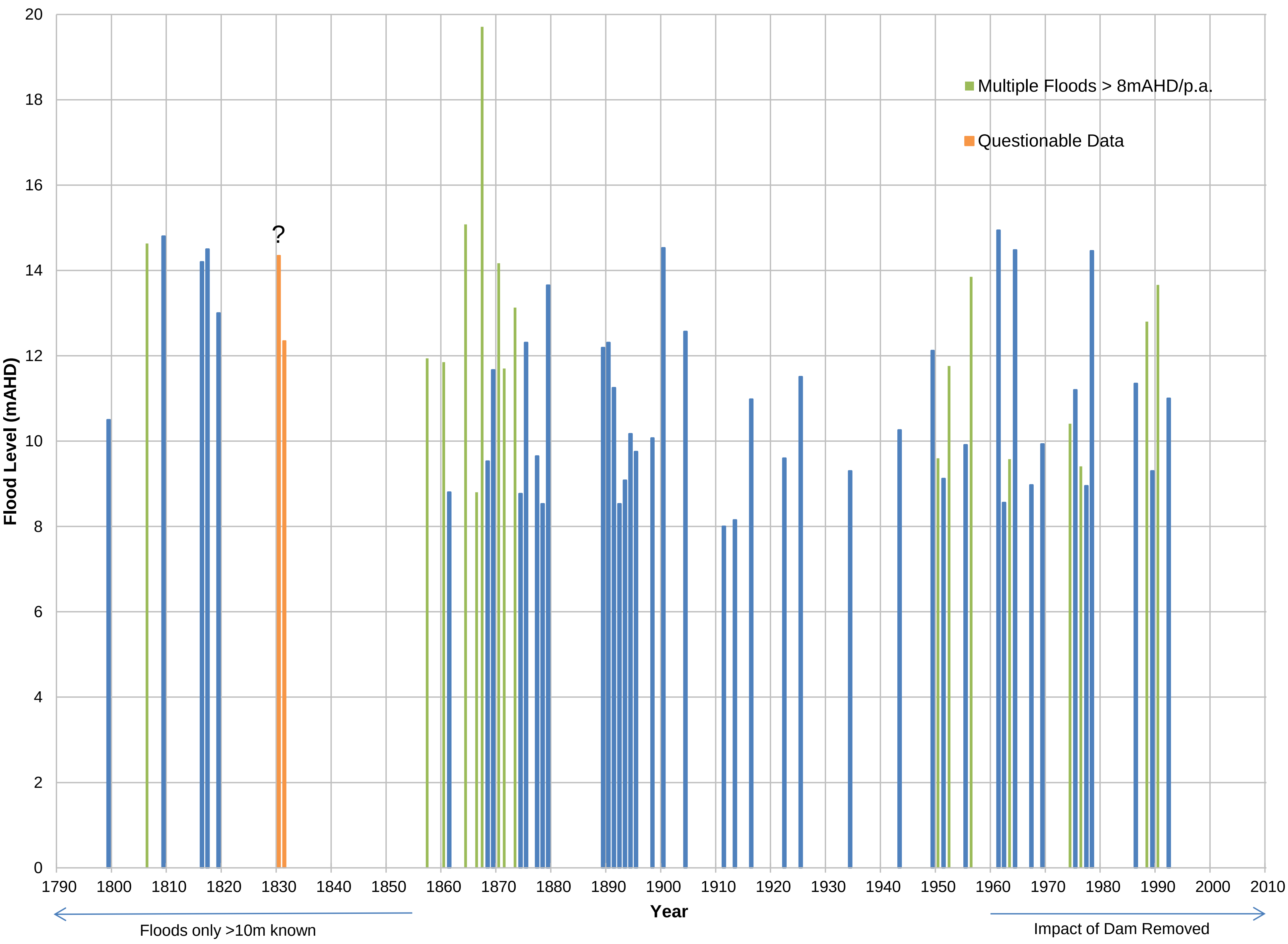

FIGURE 21
WINDSOR FLOOD RECORD

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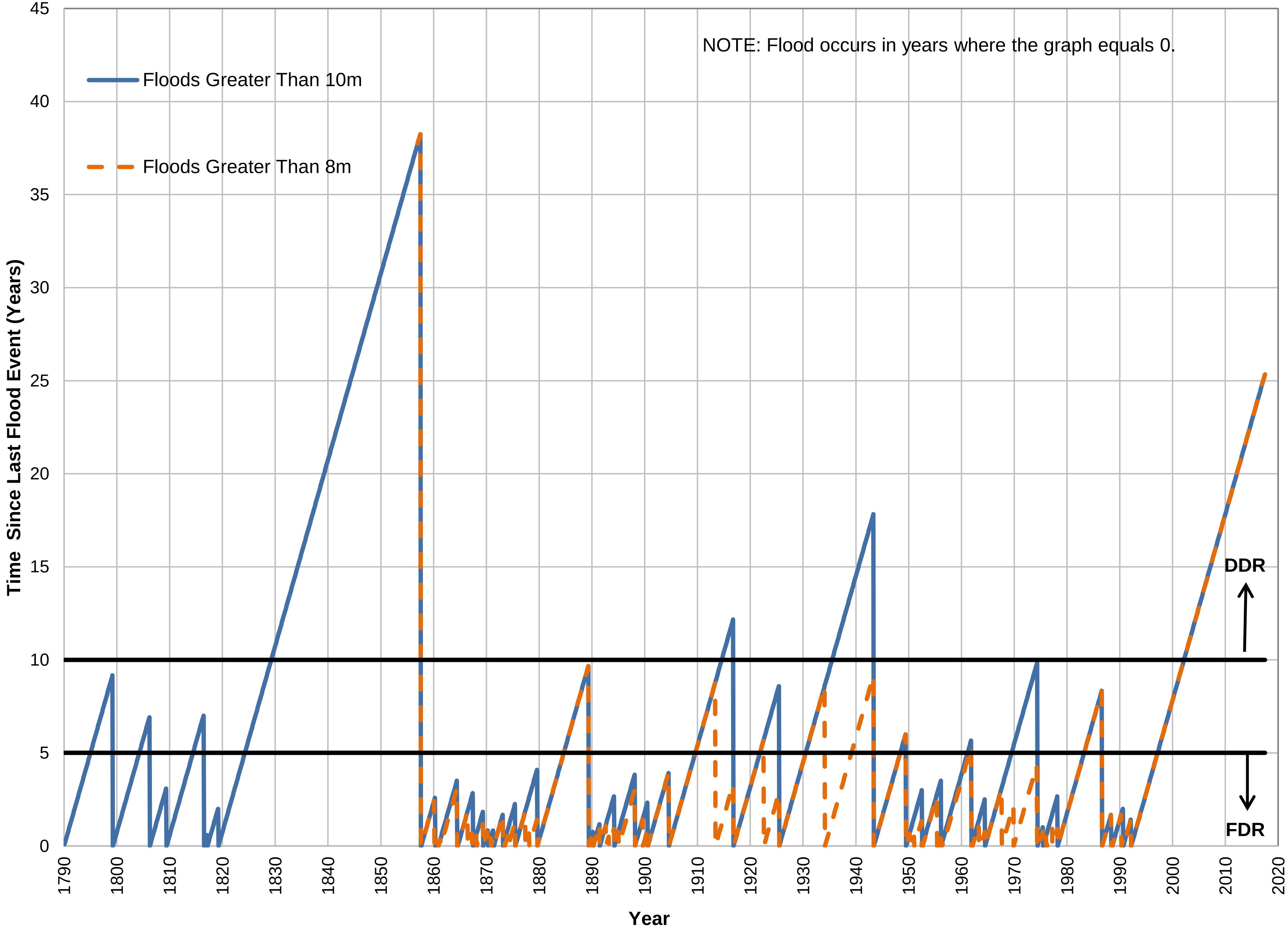

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FIGURE 22
INTERARRIVAL TIME PARTIAL SERIES

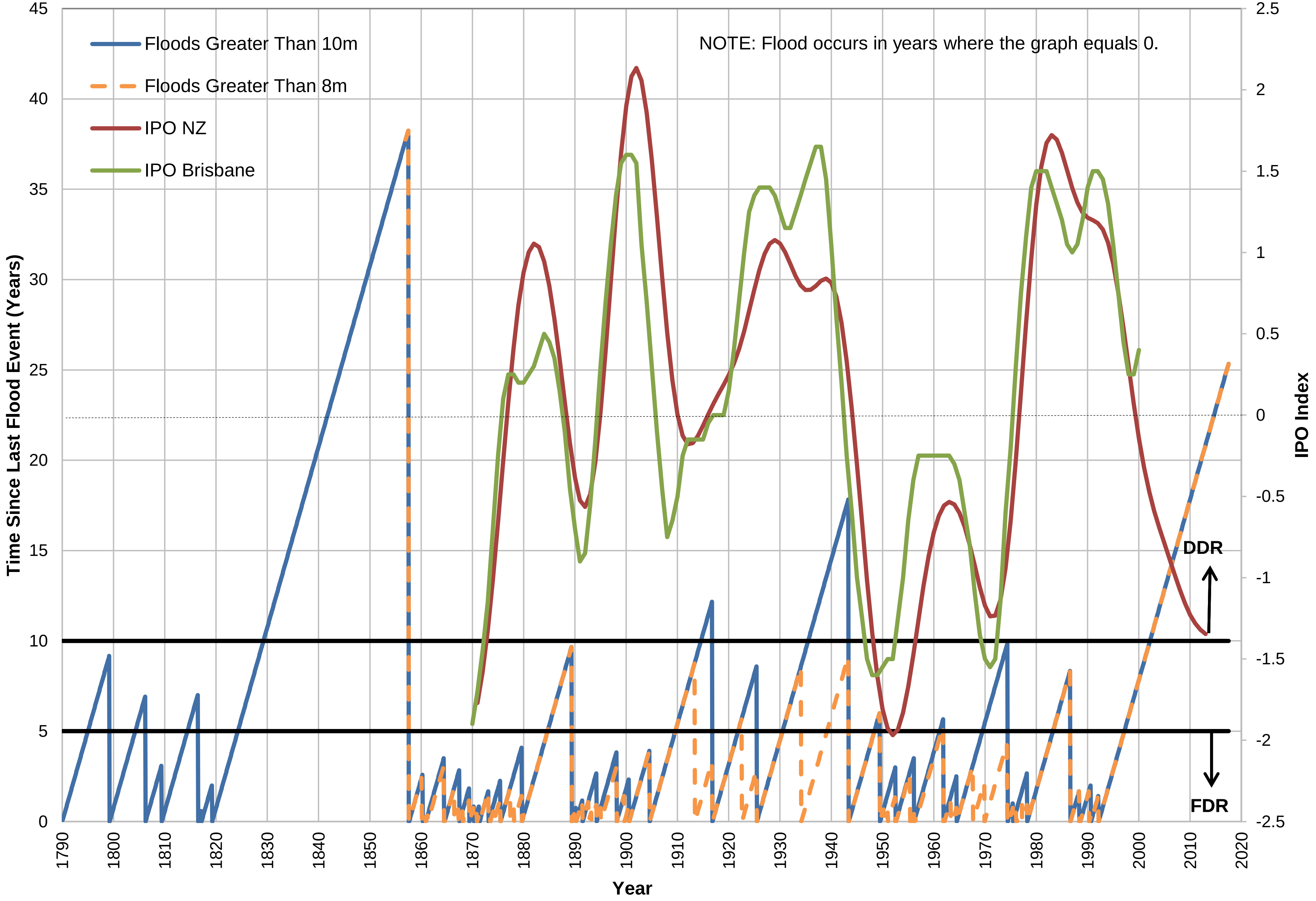

FIGURE 23
INTERARRIVAL TIME PARTIAL SERIES
IPO INDEX

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FIGURE 24

LP3 FITS AT WINDSOR

FLOOD AND DROUGHT DOMINATED REGIMES

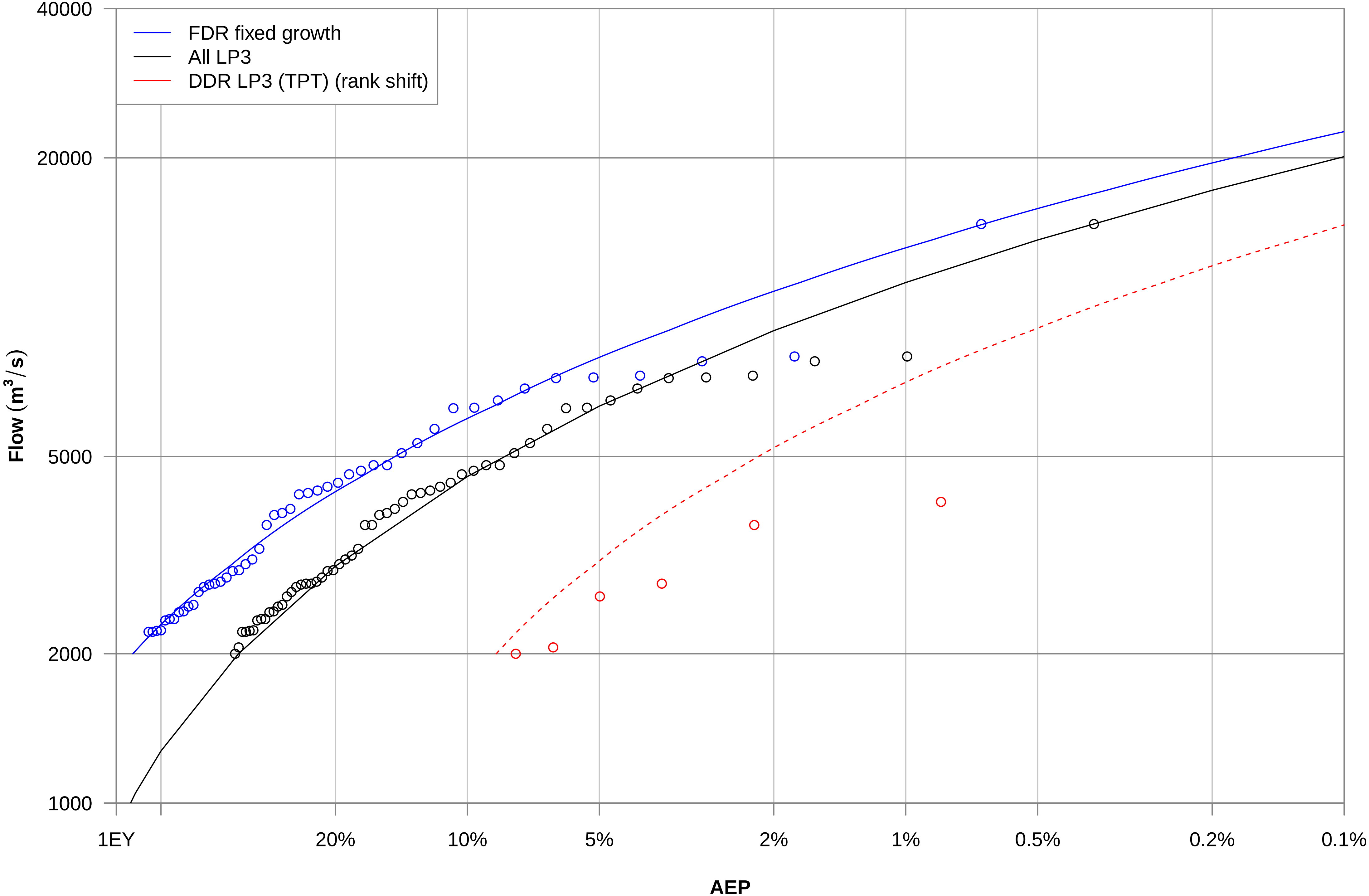


FIGURE 25

LP3 FITS AT WINDSOR

FLOOD AND DROUGHT DOMINATED REGIMES

DDR RANK REDUCED

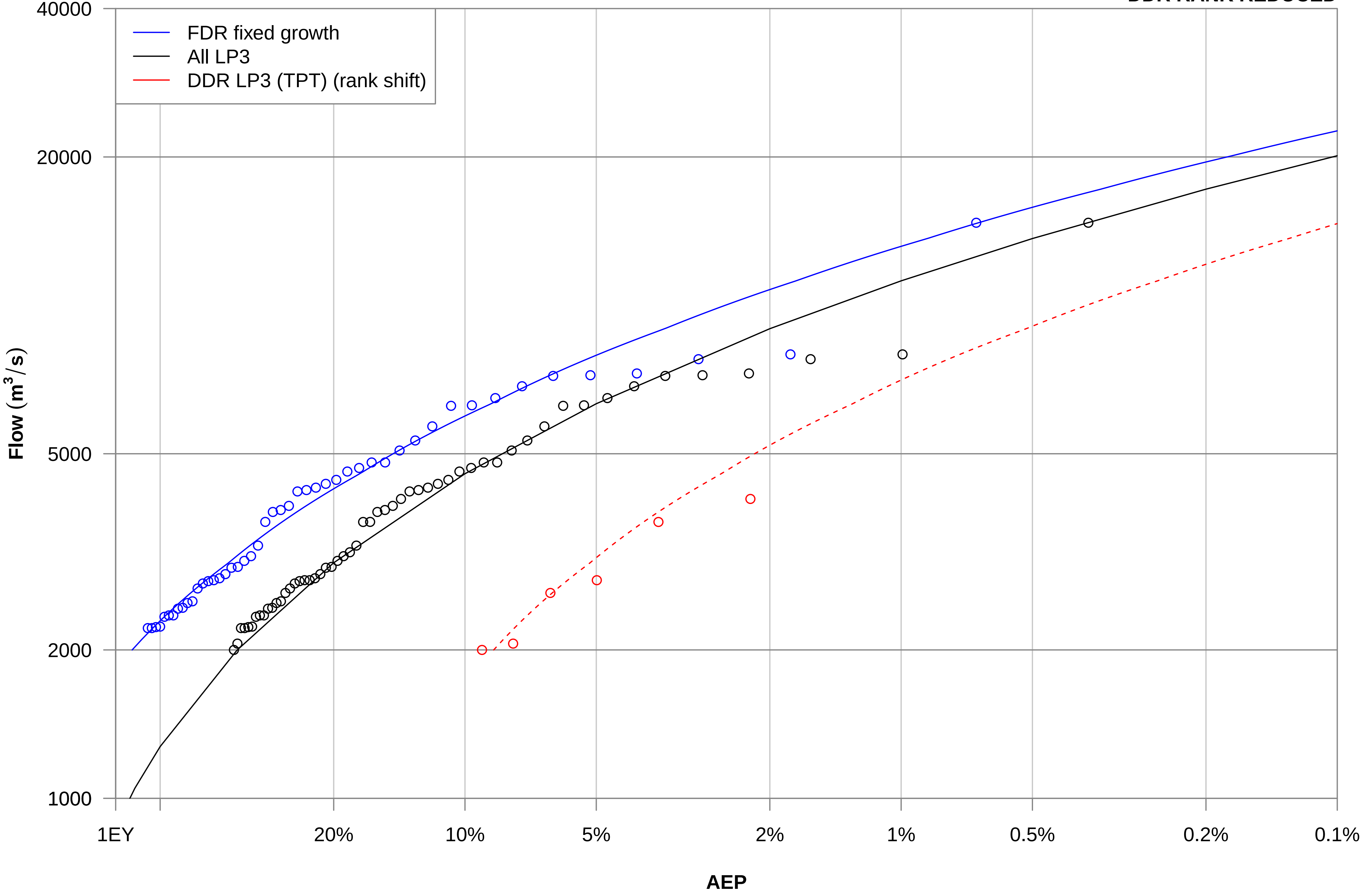
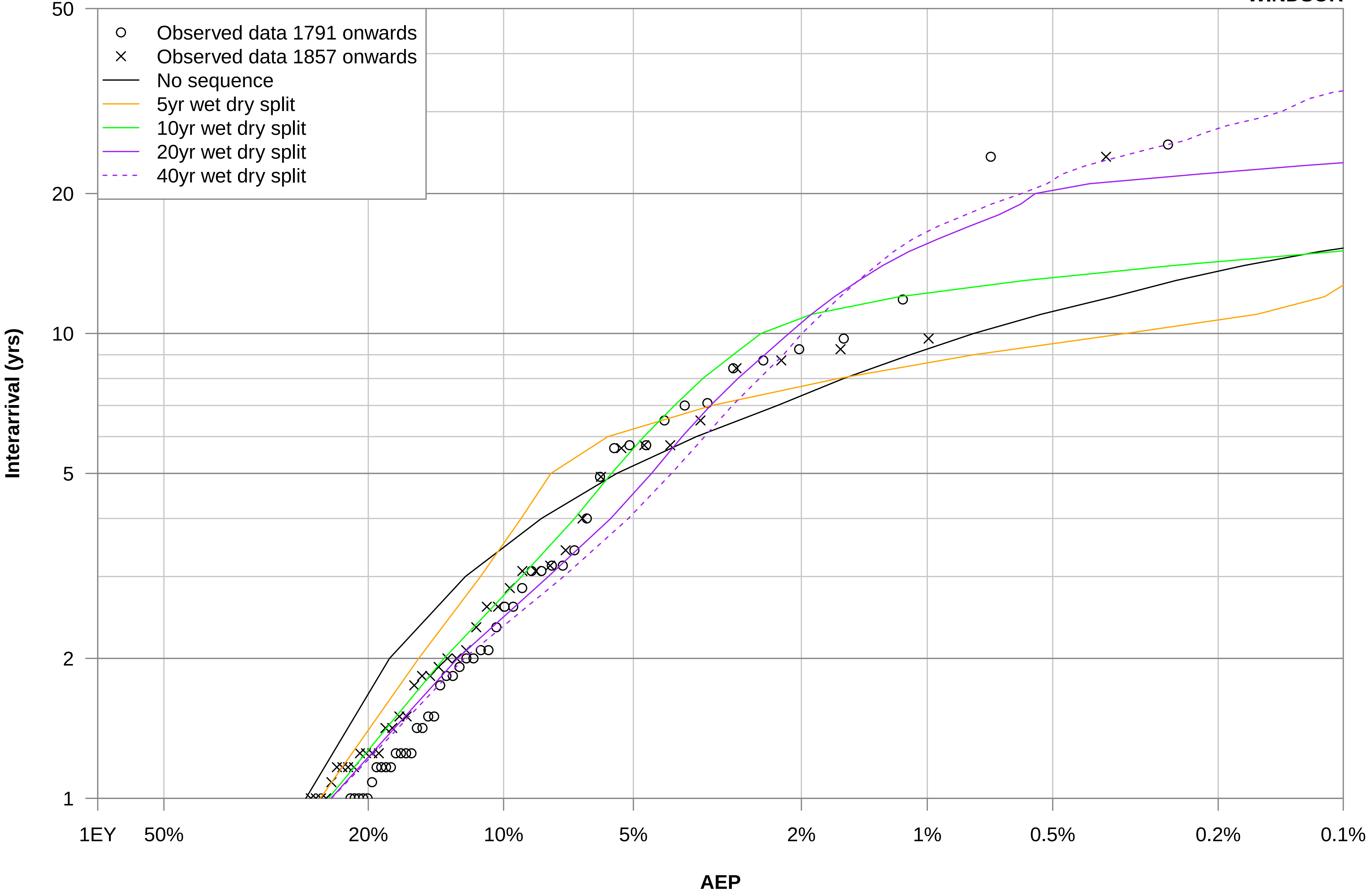


FIGURE 26

INTERARRIVAL TIMES
GENERATED VS OBSERVED
WINDSOR



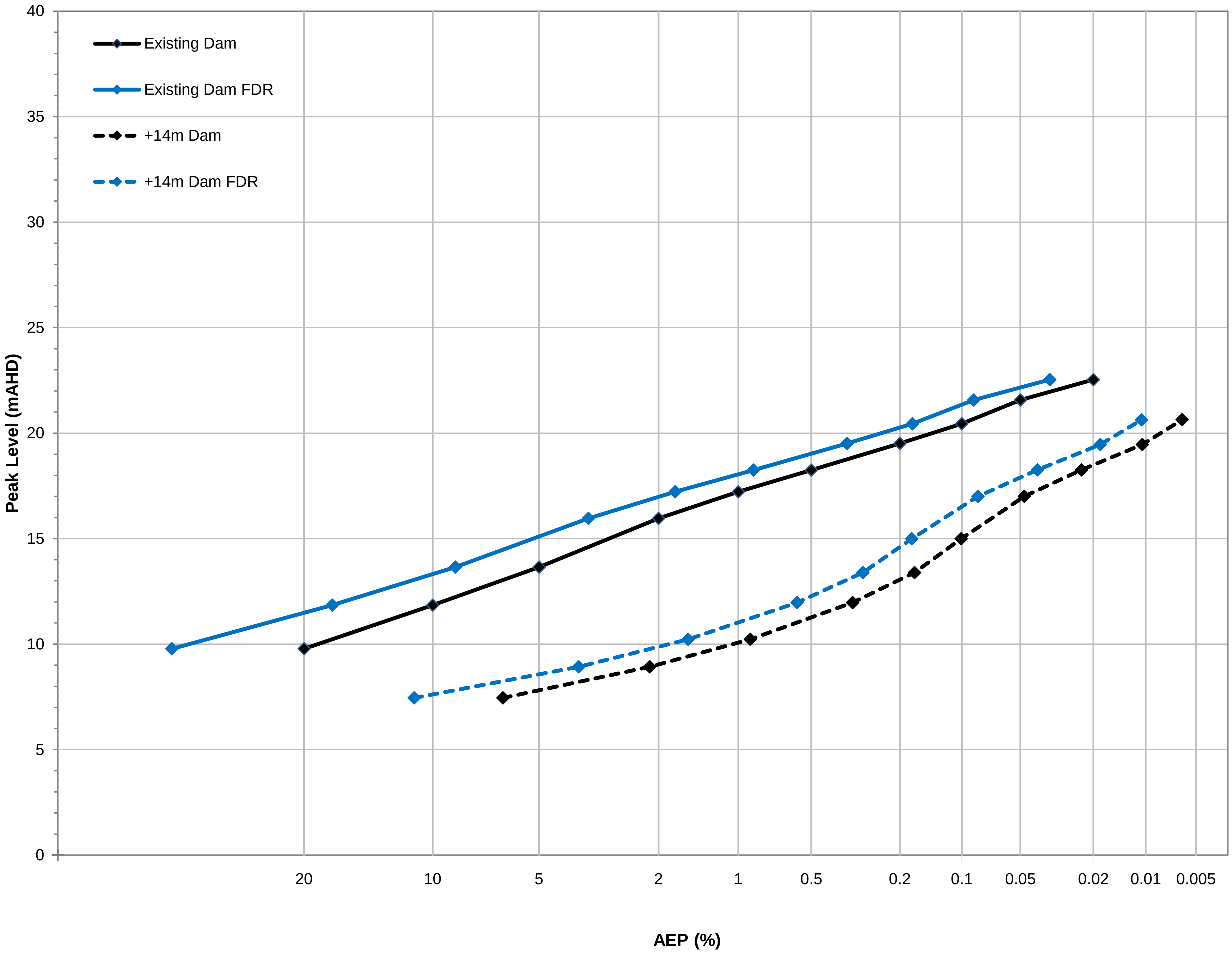


FIGURE 27
COMPARISON OF FULL RECORD AND FDR STAGE FREQUENCY DISTRIBUTIONS WINDSOR

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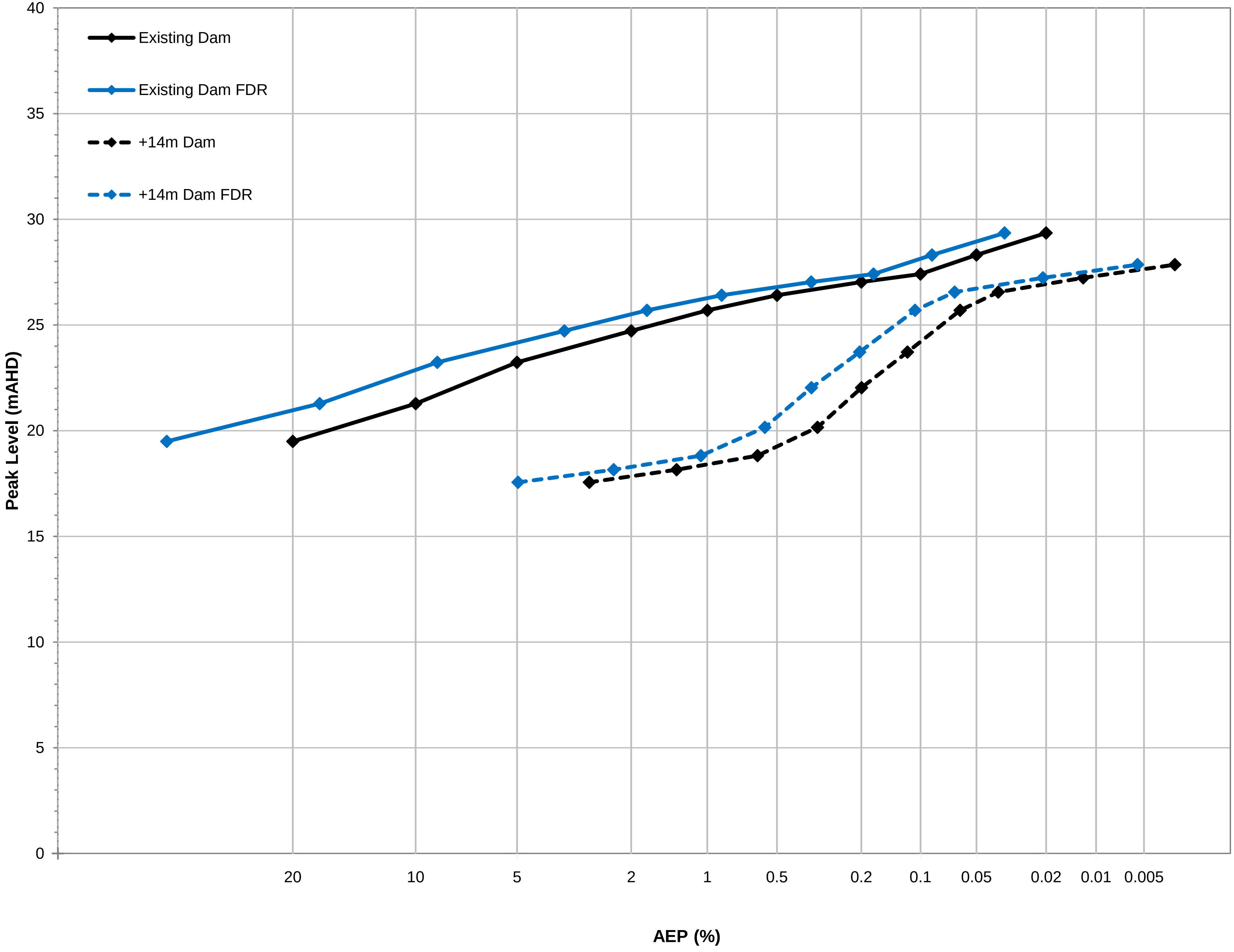

FIGURE 28
COMPARISON OF FULL RECORD AND FDR STAGE FREQUENCY DISTRIBUTIONS PENRITH

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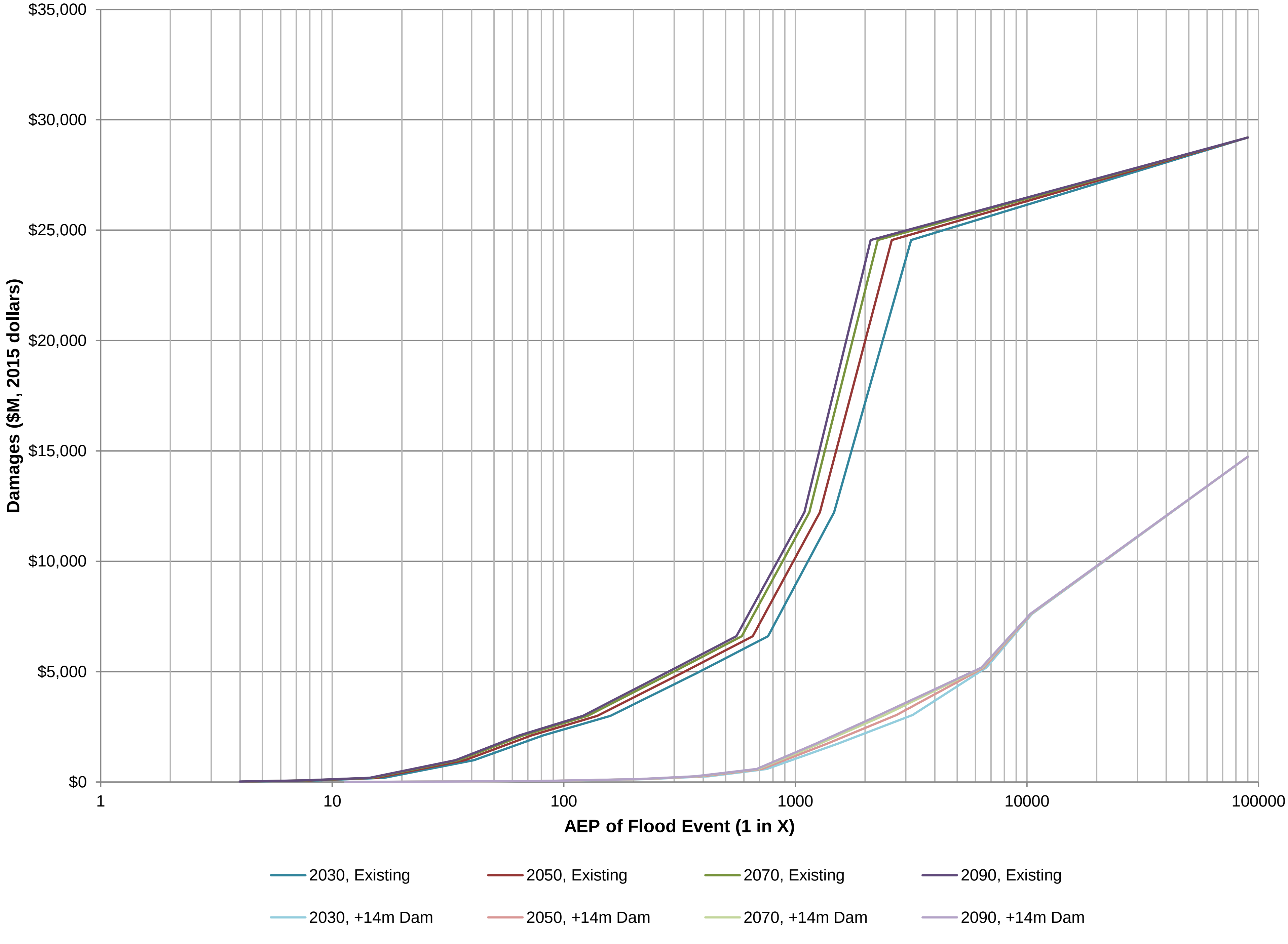

FIGURE 29
CLIMATE CHANGE DAMAGES WITH RAISED DAM - A7 LOW EMISSION

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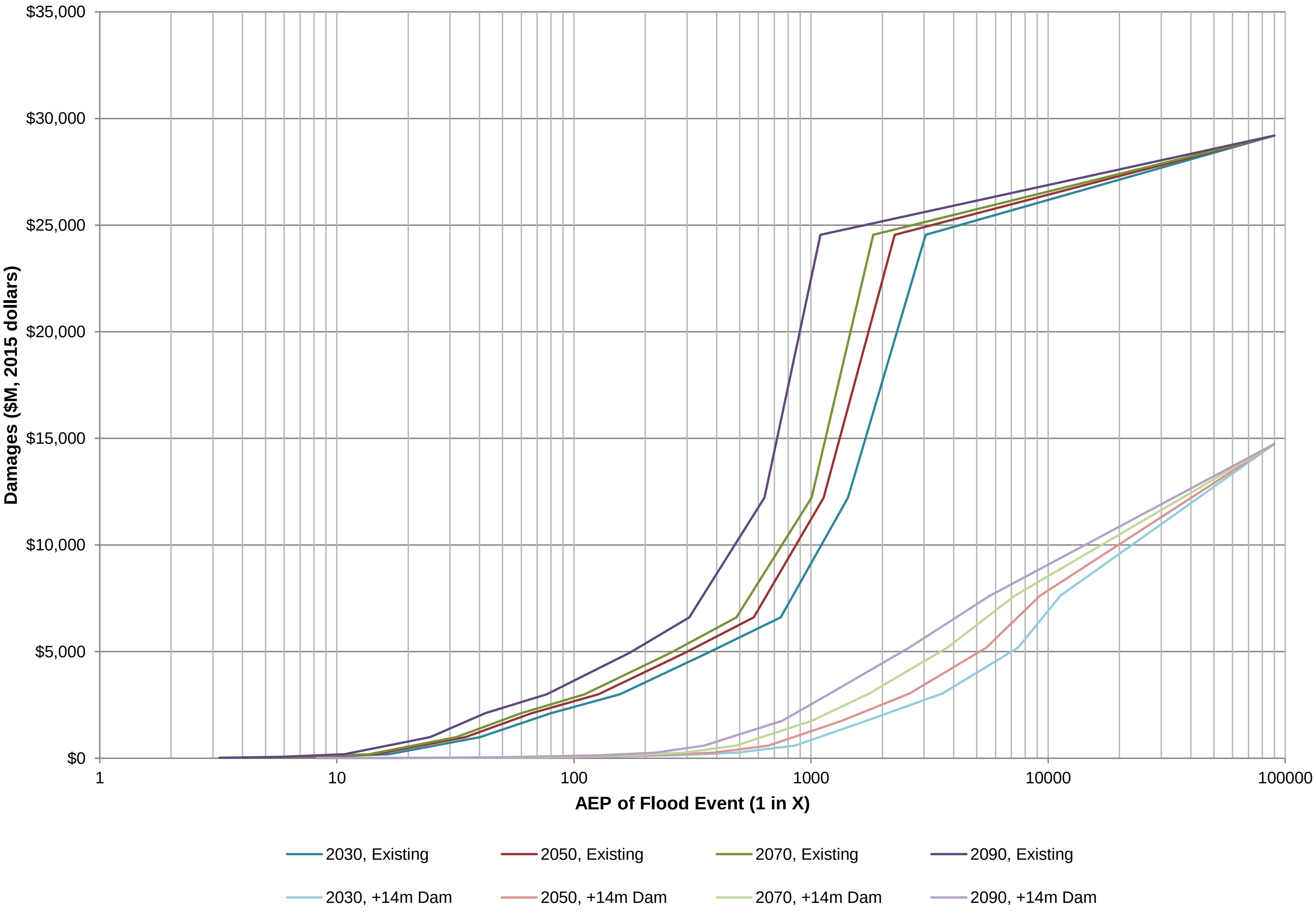

FIGURE 30
CLIMATE CHANGE DAMAGES WITH RAISED DAM - A7 HIGH EMISSION

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Appendix A

APPENDIX A. PREVIOUS ANALYSIS - NOT UPDATED WITH LATEST DAM DESIGN

As the report was undertaken over a long time period the proposed design of the dam changed as did the climate change rainfall increases assessed. Some elements of the report were not updated for the latest version of the report but still inform the assessment and so have been moved from the main report to this appendix.

A.1. Summary

This section investigates dam raising options under historical, current and future climate conditions. The results clearly show that the existing flood risk is set to increase with climate change and that a 17m dam achieves the same benefits in 2090 as a 14m dam under historical conditions. Under a medium climate projection the 1% AEP or 100 year ARI flood levels at Windsor are set to increase from 17.22m to 18.28m in 2090. A 14m dam will reduce this to 13.4m under historical conditions, and this creeps back to 15.04m by 2090.

A.2. Climate Change and a Raised Dam

Table 11 shows that increases in rainfall intensity associated with climate change increases the frequency of floods reaching the flood planning level. This also means that some flood events will rise faster and evacuation roads would be cut earlier.

Different dam raising options ranging from 14 to 20 metres were considered by the Taskforce (2014-16) for determining a preferred mitigation zone that would significantly reduce the regional flood risk in the valley while limiting the temporary upstream inundation impacts. The resultant 2017 Flood Strategy required that WaterNSW complete a detailed concept design and submit environmental and planning approvals for raising Warragamba Dam by around 14 metres. The recommendation “around” 14 metres was in recognition that additional assessment including consideration of spillway heights, release rules and more detailed analysis of climate change impacts would be required to determine the optimal dam raising height and design.

As part of the detailed climate change analysis for the final dam design, different dam heights were examined to determine the relationship between changes in mitigation benefits under the full range of climate scenarios to 2090. This assessment of dam raisings up to 20 metres was for comparative purposes and does not change the Flood Strategy’s commitment to proceeding with design and approvals for a dam raising of around 14 metres.

A.2.1. Spillway Assessment for a Raised Dam

In order to consider the higher dam raising cases on a consistent basis with the 14m dam raising case, spillway configurations and heights were determined to allow the PMF to safely pass the dam. Table A 1 summarises the adopted spillway levels and crest heights from the Taskforce investigations.

Table A 1: Spillway levels and dam crest heights

Dam Raising (m)	Crest Level (m AHD)	Centre Spillway Width (m)	Centre Spillway Weir Coefficient	Centre Spillway Crest (m AHD)	Side Spillway Width (m)	Side Spillway Weir Coefficient	Side Spillway Crest (m AHD)
14	144.4	70	2.17	128.45	183.5	2.12	128.45
15	145.4	70	2.17	129.60	183.5	2.12	129.60
16	146.4	70	2.17	130.75	183.5	2.12	130.75
17	147.4	70	2.17	131.90	183.5	2.12	131.90
18	148.4	70	2.17	133.05	183.5	2.12	133.05
19	149.4	70	2.17	134.20	183.5	2.12	134.20
20	150.4	70	2.17	135.35	183.5	2.12	135.35

A.3. Results of Climate Change Assessment for a Raised Dam

Figure A1 and Figure A2 present the stage frequency curves at Windsor and Penrith for the different dam raising cases compared to existing dam case under current climate conditions. For events up to 5% AEP there is no difference between the dam raising options. At the 1% AEP level there is approximately a 1m difference in flood levels at Windsor between the 14m and 20m dam raising cases.

Figure A3 presents the time to reach 17.3m AHD for the various dam raising heights with climate change compared to the existing dam case and Dam +14m case under current climate conditions. The Dam +17 and +18m cases with 9.1% increase in rainfall under climate change, exhibit similar event characteristics to the Dam +14m case without climate change.

Figure A4 presents the upstream inundation for Dam +17m case and shows that with the revised operating rules the 14 days can just be achieved.

Table A 2 shows the change in probability of the existing 100 year ARI event at Penrith and Windsor for different dam raising cases and climate change scenarios. Under the 14m dam raising case and current climate, the 100 year ARI event becomes a 508 year ARI event. Under a 9.1% climate change rainfall increase scenario, a dam raise of 16 to 17m would be required to maintain the probability of this event at the 14m dam raising case under current climate. Table A 3 the same information as in Table A 2 as a ratio compared to the 14m dam raise case under existing conditions.

Diagram 14 and Diagram 15 present the change in flood level for each dam raising case compared to the existing dam case. The red bar represents the change in flood level due to climate change for each dam raising case. The blue bar represents the residual benefit in reduction in flood level, achieved under current climate. For a 17m or greater dam raising there are diminishing returns in building a larger dam under climate change, when considering the flood level at Windsor for a 1 in 100 AEP*.

Table A 2: Dam raising change in probability of reaching current flood planning level table (AEP

1 in Y)

Location	Dam Case	Current 2016 Average Climate	Climate Change Scenario (Increase in Rainfall by 2090)			
			4.9%	**9.1%**	**13.9%**	**18.6%**
PENRITH	Existing Dam	100	78	65	54	46
	14m	508	377	302	238	184
	15m	622	465	361	283	224
	16m	759	577	443	337	268
	17m	945	708	553	415	320
	18m	1206	-	665	-	-
	19m	1486	-	811	-	-
	20m	1701	-	997	-	-
WINDSOR	Existing Dam	100	80	65	54	44
	14m	589	421	335	256	197
	15m	731	496	388	298	236
	16m	808	607	458	348	277
	17m	954	750	552	404	321
	18m	1100	-	665	-	-
	19m	1311	-	745	-	-
	20m	1486	-	853	-	-

Note – indicates scenario not run

Table A 3: Climate change – Dam raising – change in ratio look up table

Location	Dam Case	Current 2016 Average Climate	Climate Change Scenario (Increase in Rainfall by 2090)			
			4.9%	**9.1%**	**13.9%**	**18.6%**
PENRITH	Existing Dam	5.08	6.52	7.88	9.44	11.17
	14m	1.00	1.35	1.68	2.14	2.76
	15m	0.82	1.09	1.41	1.80	2.27
	16m	0.67	0.88	1.15	1.51	1.89
	17m	0.54	0.72	0.92	1.22	1.59
	18m	0.42	-	0.76	-	-
	19m	0.34	-	0.63	-	-
	20m	0.30	-	0.51	-	-
WINDSOR	Existing Dam	5.88	7.39	9.01	10.97	13.32
	14m	1.00	1.40	1.76	2.30	2.98
	15m	0.81	1.19	1.52	1.97	2.49
	16m	0.73	0.97	1.29	1.69	2.13
	17m	0.62	0.79	1.07	1.46	1.84
	18m	0.54	-	0.89	-	-
	19m	0.45	-	0.79	-	-
	20m	0.40	-	0.69	-	-

Note – indicates scenario not run

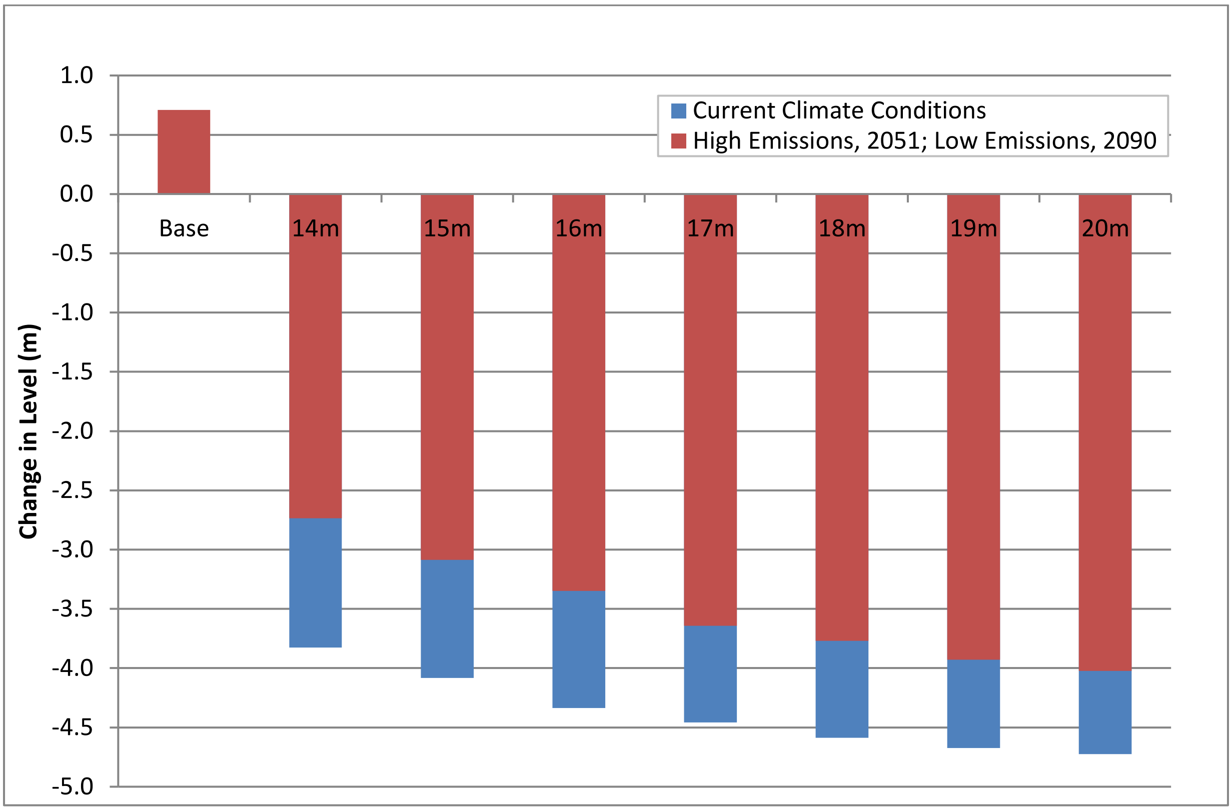

Diagram 14: Change in flood level all dam raise- 1 % AEP level - 9.1% climate change -Windsor

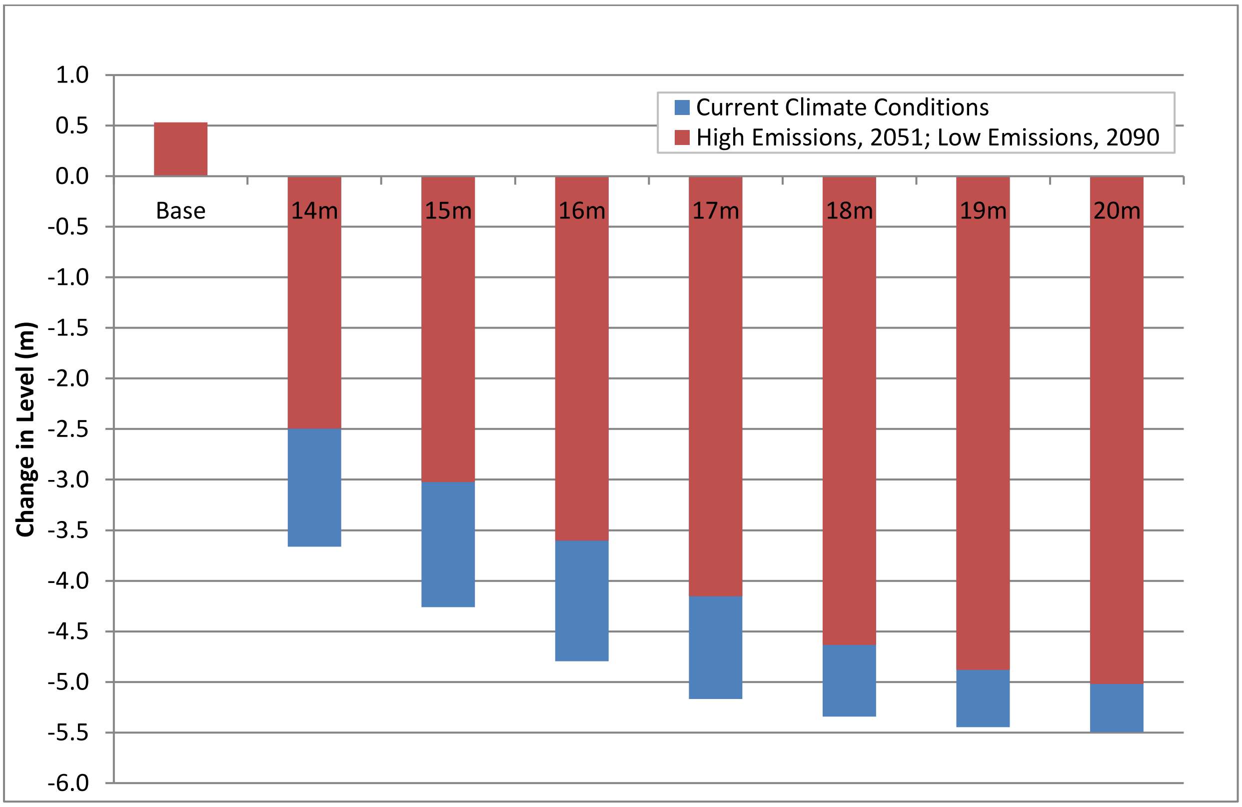

Diagram 15: Change in flood level all dam raise -1% AEP level - 9.1% climate change –Penrith

A.4. Spatially Varying Rainfall Increases Under Climate Change

Dynamic downscaling research suggests areas subject to orographic rainfall enhancement will experience proportionally higher rainfall increases than other areas. While standard practice is to uniformly scale rainfall, it was considered prudent to test the performance of different mitigation dams under a scenario where rainfall increases were higher in these orographically enhanced areas, as many of these areas are not controlled by Warragamba Dam. This is particularly apparent for the Nepean system, where the upper reaches are subject to some of the most orographically enhanced rainfall. While 4 major water supply dams are in the Upper Nepean Catchment, their combined storage is relatively small compared to Warragamba Dam. Figure 20 depicts the relative orographic enhancement. In Figure 20, the areas subject to orographic enhancement (calculated as the top 1/3 of 1% AEP IFD values) are shown in the first panel, whilst the second panel depicts the percentage of area in each subcatchment subject to orographic enhancement. The rainfall was increased in these areas, and proportionally decreased over the remaining catchment so that the overall rainfall increase in the catchment remained the same.

The spatially varying rainfall increase cases were run as a sensitivity analysis. Figure A5 and Figure A6 present the stage frequency curves at Windsor and Penrith for the Existing Dam, Dam +14m and Dam +17m cases for the standard 9.1% rainfall increase and a spatially varying 9.1% rainfall increase. For frequent events there is very little change in flood levels between the two cases. For events from 5% AEP to 0.5% AEP at Windsor, flood levels are slightly higher when a spatially varying rainfall increase is applied. At Penrith, flood levels are slightly higher when a spatially varying rainfall increase is applied for events from around 5% AEP to 2% AEP. For very rare events applying the spatially varying rainfall results in a lower flood level for the same AEP event. Table A4 compares the design event levels at Windsor.

Table A 4: Comparison of flood levels at Windsor bridge for 9.1% climate change between spatially varying rainfall and standard rainfall

AEP (%)	Existing Dam without Climate Change (m AHD)	Dam +14m without Climate Change (m AHD)	Dam +17m without Climate Change (m AHD)	Existing Dam Standard rainfall increase (m AHD)	Dam +14m Standard rainfall increase (m AHD)	Dam +17m Standard rainfall increase (m AHD)	Existing Dam with Spatially Varying Rainfall (m AHD)	Dam +14m with Spatially Varying Rainfall (m AHD)	Dam +17m with Spatially Varying Rainfall (m AHD)
20	9.78	7.45	7.45	10.56	8.00	7.99	10.51	8.25	8.25
10	11.85	8.92	8.90	12.62	9.52	9.49	12.56	9.83	9.81
5	13.65	10.23	10.12	14.47	10.88	10.73	14.55	11.15	11.05
2	15.96	11.97	11.58	16.71	12.90	12.28	16.83	13.09	12.56
1	17.22	13.40	12.77	17.93	14.48	13.58	18.00	14.59	13.78
0.5	18.25	15.00	14.04	18.95	16.11	15.13	18.94	16.02	15.14
0.2	19.51	17.00	15.97	20.27	18.04	17.0	20.16	17.85	16.90
0.1	20.45	18.26	17.32	21.26	19.26	18.40	21.08	19.05	18.20
0.05	21.57	19.47	18.66	22.39	20.42	19.68	22.22	20.30	19.57
0.02	22.54	20.63	19.90	23.41	21.55	20.91	23.12	21.42	20.79

A.5. Different Main and Auxiliary Spillways

The current concept (at the time of undertaking the original investigation study, the design now includes offset spillways) designs have the central and side spillways at identical levels. This means that at any time the spillways are operating, more than two thirds of the flow will be discharged via the side spillway. The existing dam side spillway was designed to operate significantly less frequently than the main spillway, and only when significant flows were already in the river as a result of discharge over the main spillway. Like many auxiliary spillways that are very unlikely to operate, parts of the side spillway are unlined, with the design allowing for some scour where flows enter the main river. While the side spillway has never operated, the main spillway and energy dissipater has experienced flows around 7,000-7,500m^3/s on several occasions, with only minor damage on the last occasion in August 1990.

Two alternative dam configurations were investigated where the side spillway only operates once there is major flow down the main spillway. The first case set the main spillway at the same level used for the 14m dam and the side spillway at the same level used for the 17m dam. This option separated the spillway levels by 3.45m, and the main dam wall would need to be constructed to a level of a 16.2m dam. The second option assumed the dam wall would be raised to the 17m level which allowed the side spillway to be raised an additional 1.5m producing a spillway separation of 4.95m. Table A 5 summarises the spillway levels.

The first option ensures that there is 1,000m^3/s in the river before the side spillway operates and the second option ensures that there is 1,600m^3/s. More importantly, once major flows occur there will be significant flow in the river. Figure A7 and Figure A8 present the stage frequency curves for the spilt spillway tests. The 16.2m dam produces very similar results to the 16m dam at Penrith and Windsor. At Penrith the 17m dam with 4.95m spillway offset results in a similar level to a 16 m dam up to a 100 year ARI and transitions to a 17m dam flood level for a 200 year ARI. At Windsor the results are similar although the transition to the 17m dam flood levels occur at rarer events.

Table A 5: Split Spillway test levels

Dam Raising (m)	Crest Level (m AHD)	Centre Spillway Width (m)	Centre Spillway Weir Coefficient	Centre Spillway Crest (m AHD)	Side Spillway Width (m)	Side Spillway Weir Coefficient	Side Spillway Crest (m AHD)
14	144.4	70	2.17	128.45	183.5	2.12	128.45
17	147.4	70	2.17	131.90	183.5	2.12	131.90
Equiv. 16.2m dam	146.6	70	2.17	128.45	183.5	2.12	131.90
17m dam with 4.95m spillway offset	147.4	70	2.17	128.45	183.5	2.12	133.40

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FIGURE A1

STAGE FREQUENCY CURVE
DAM RAISING - NO CLIMATE CHANGE
WINDSOR

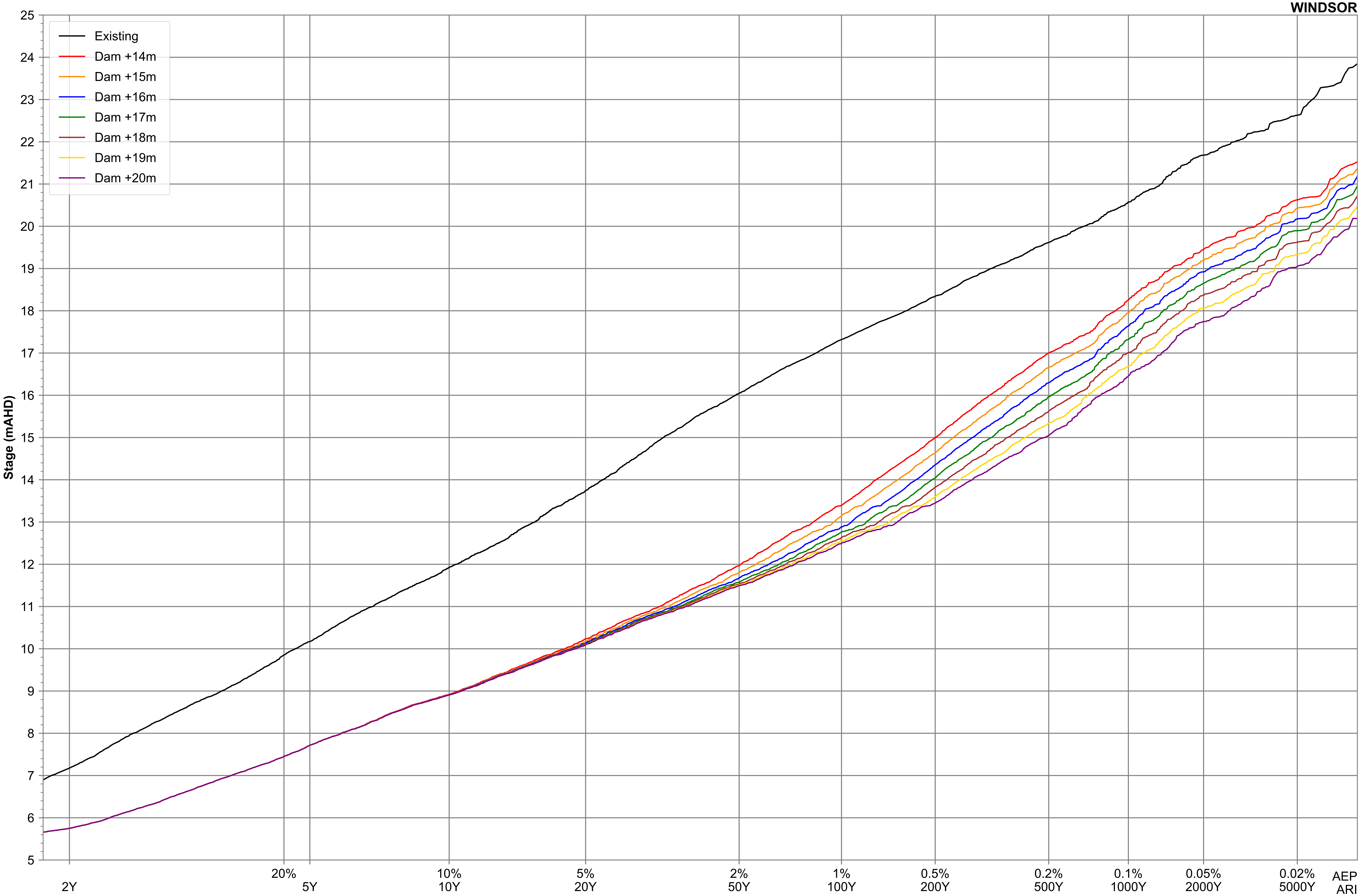
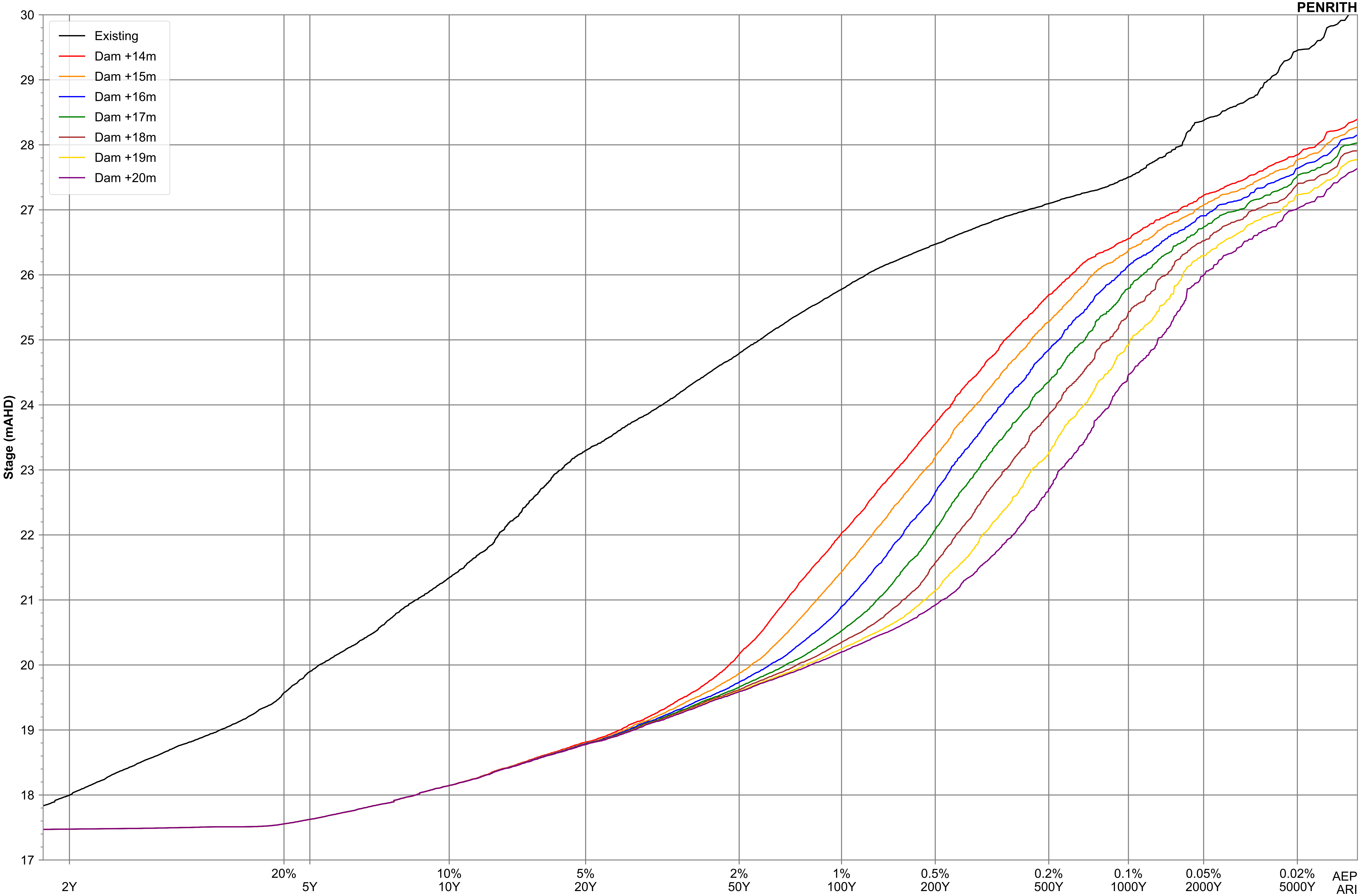
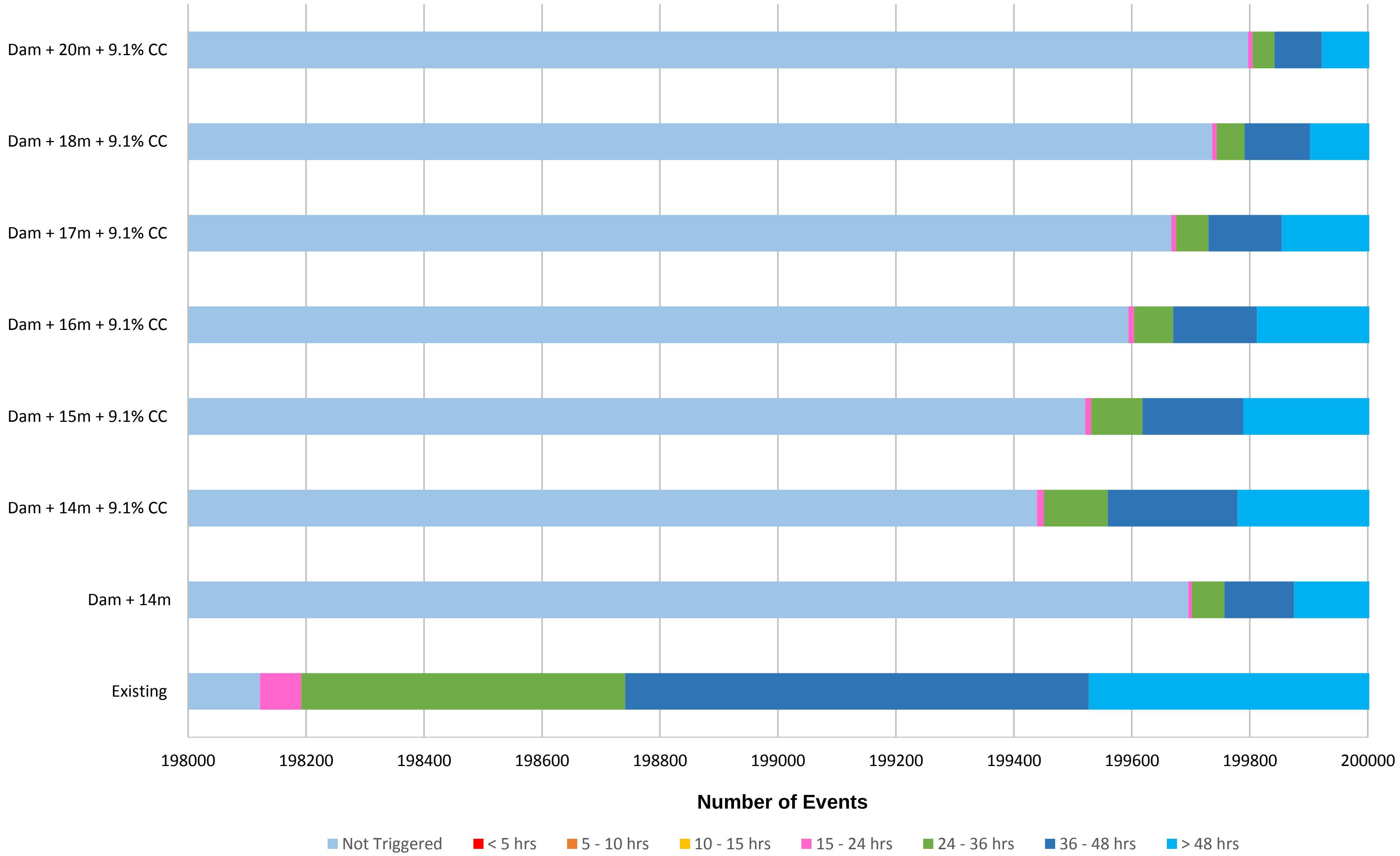


FIGURE A2

STAGE FREQUENCY CURVE
DAM RAISING - NO CLIMATE CHANGE
PENRITH





NOTE: Some events that are not triggered and therefore are not shown for clarity.

FIGURE A3
TIME FROM 4m TO 17.3mAHD
EXISTING AND DAM RAISING WITH AND
WITHOUT CLIMATE CHANGE

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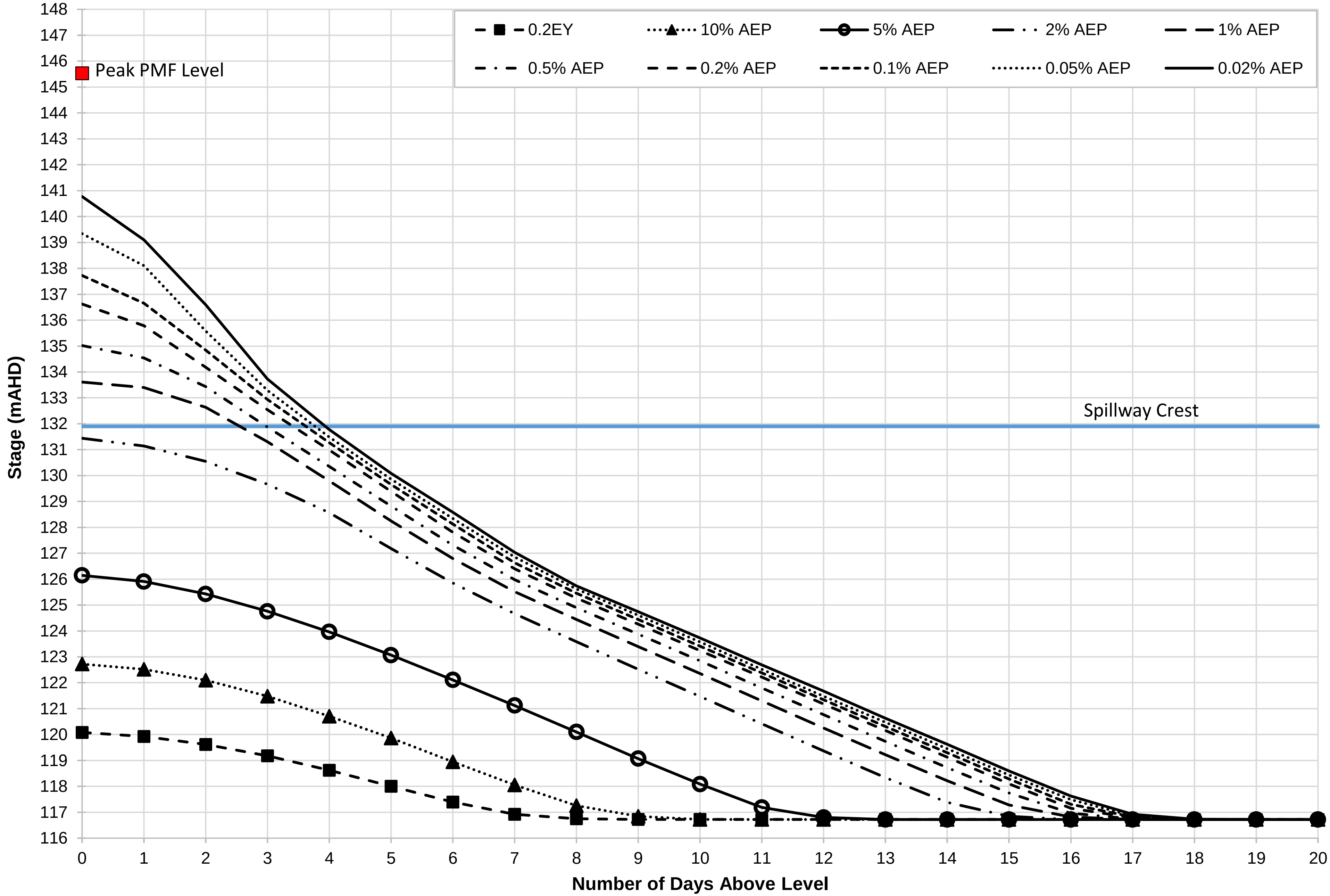

FIGURE A4
UPSTREAM INUNDATION
DAM LEVEL+17M

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FIGURE A5

STAGE FREQUENCY CURVE
SPATIAL SHIFT VS CLIMATE CHANGE
WINDSOR

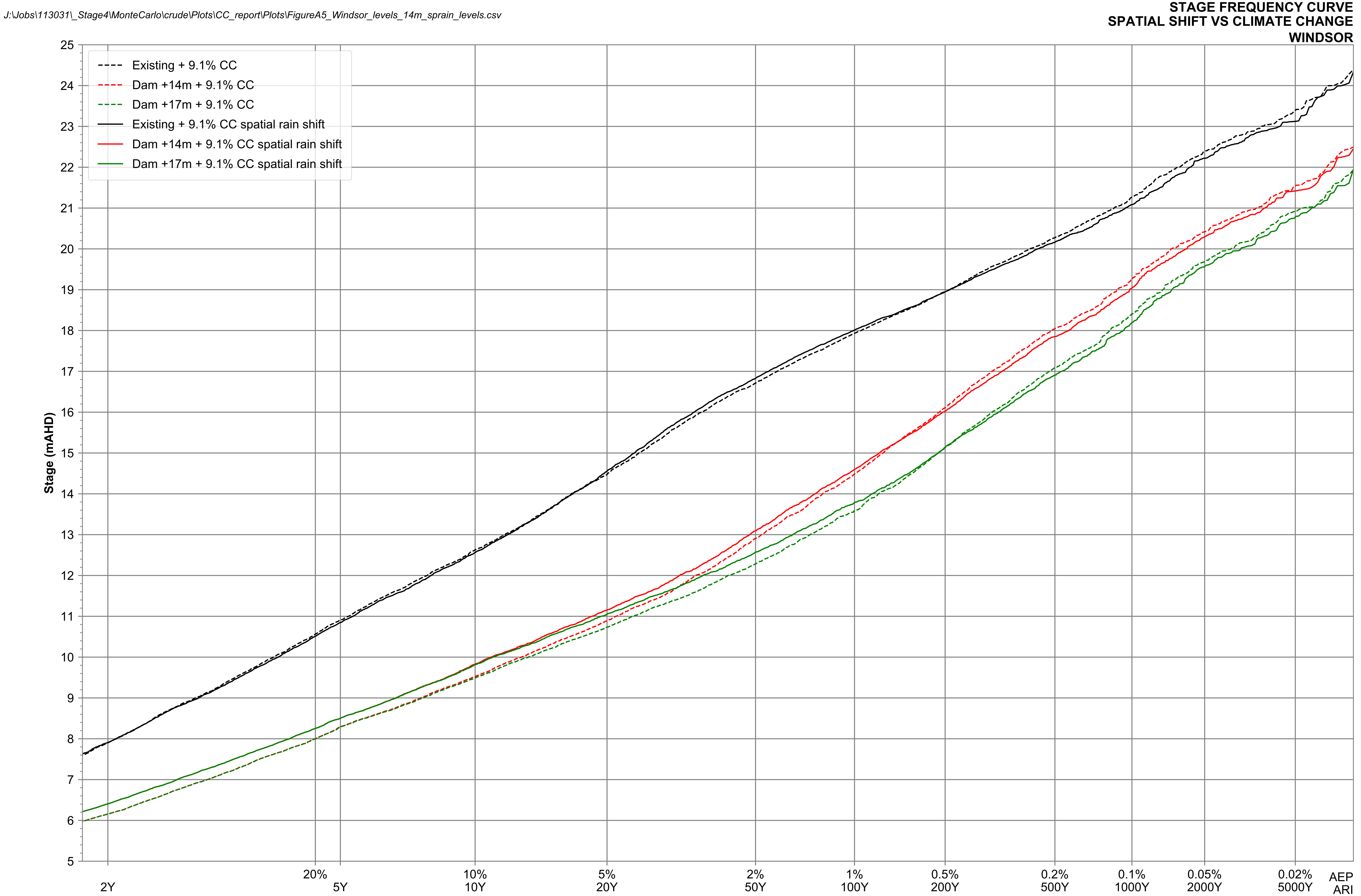

FIGURE A6

STAGE FREQUENCY CURVE
CLIMATE CHANGE VS CLIMATE CHANGE SPATIAL SHIFT
PENRITH

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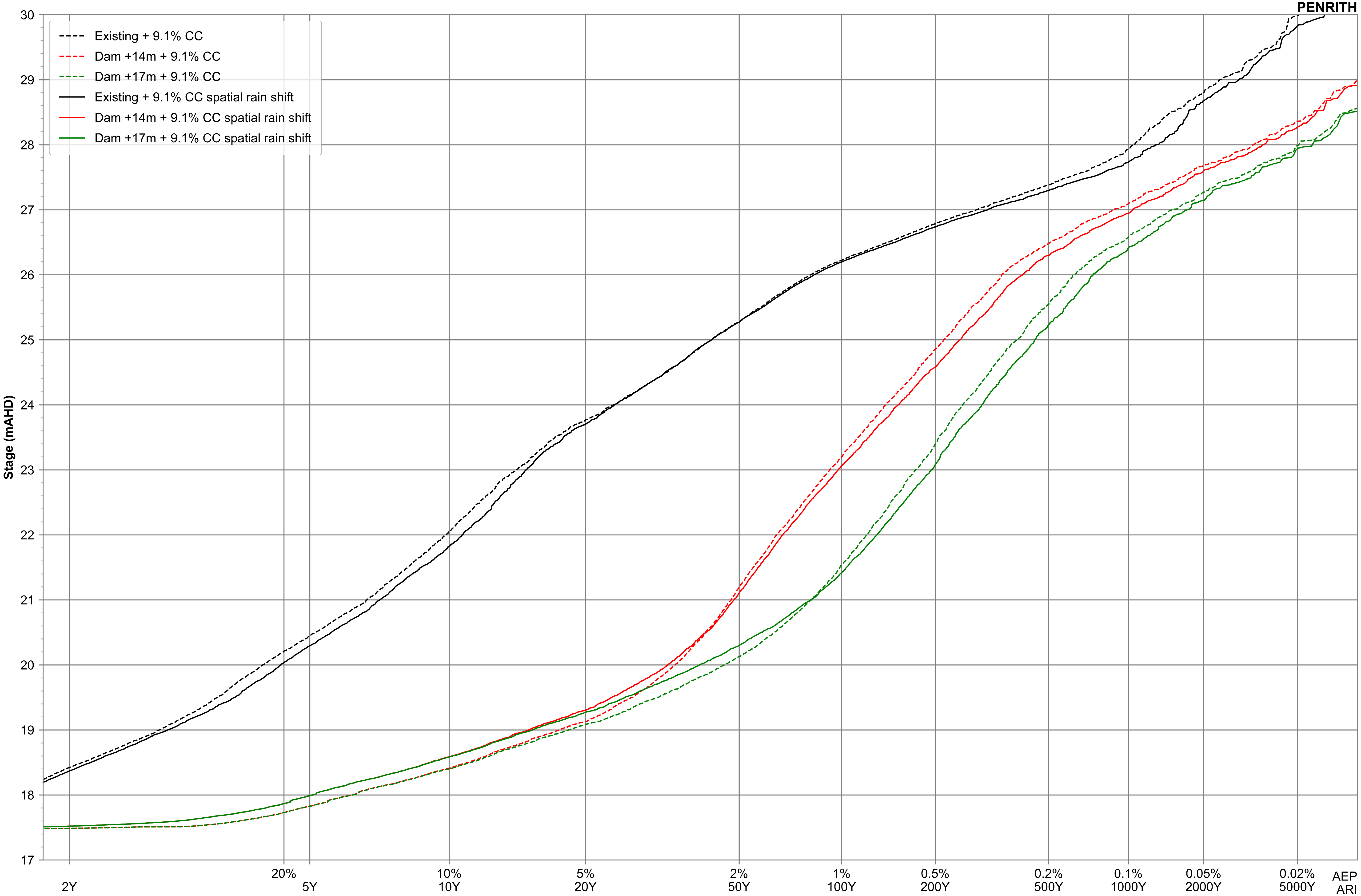

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FIGURE A7

STAGE FREQUENCY CURVE
DIFFERENT SPILLWAYS
WINDSOR

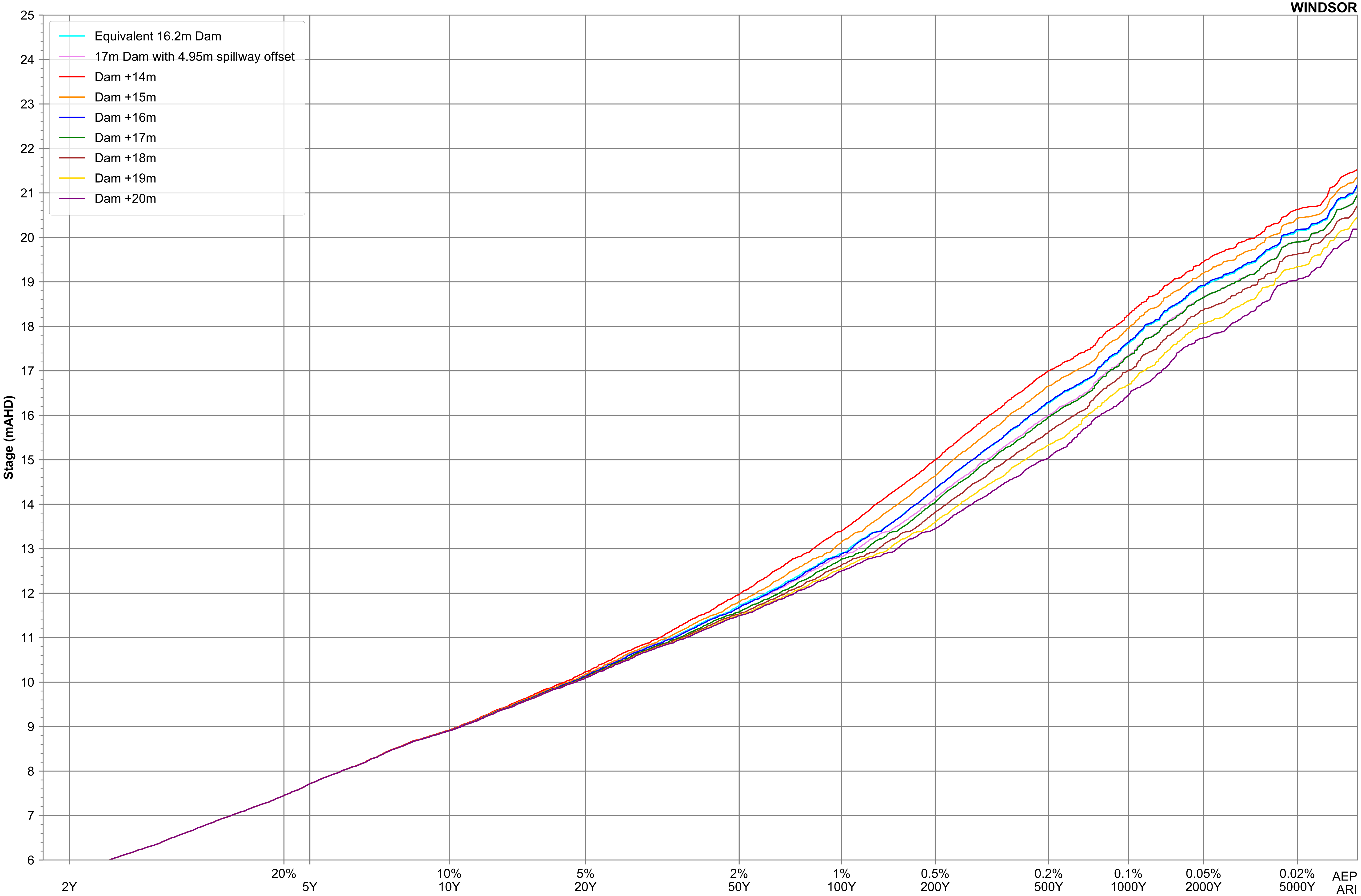
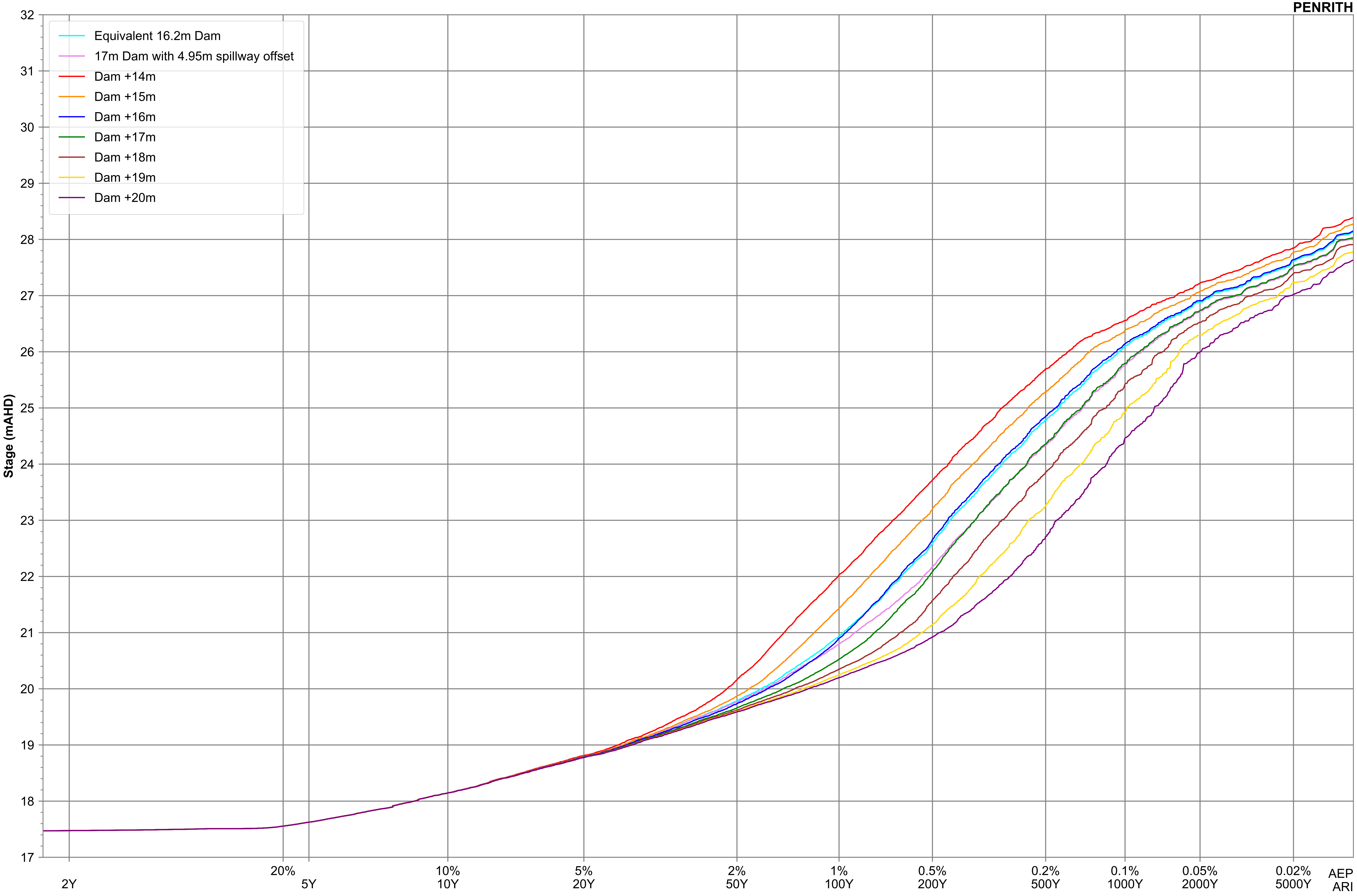


FIGURE A8

STAGE FREQUENCY CURVE
DIFFERENT SPILLWAYS
PENRITH



Appendix B

APPENDIX B. GLOSSARY

Taken from the Floodplain Development Manual (April 2005 edition)

acid sulfate soils	Are sediments which contain sulfidic mineral pyrite which may become extremely acid following disturbance or drainage as sulfur compounds react when exposed to oxygen to form sulfuric acid. More detailed explanation and definition can be found in the NSW Government Acid Sulfate Soil Manual published by Acid Sulfate Soil Management Advisory Committee.
Annual Exceedance Probability (AEP)	The chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a 500 m^3/s or larger event occurring in any one year (see ARI).
Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level.
Average Annual Damage (AAD)	Depending on its size (or severity), each flood will cause a different amount of flood damage to a flood prone area. AAD is the average damage per year that would occur in a nominated development situation from flooding over a very long period of time.
Average Recurrence Interval (ARI)	The average number of years between the occurrence of a flood as big as, or larger than, the selected event. For example, floods with a discharge as great as, or greater than, the 20 year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.
caravan and moveable home parks	Caravans and moveable dwellings are being increasingly used for long-term and permanent accommodation purposes. Standards relating to their siting, design, construction and management can be found in the Regulations under the LG Act.
catchment	The land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.
consent authority	The Council, government agency or person having the function to determine a development application for land use under the EP&A Act. The consent authority is most often the Council, however legislation or an EPI may specify a Minister or public authority (other than a Council), or the Director General of DIPNR, as having the function to determine an application.
development	Is defined in Part 4 of the Environmental Planning and Assessment Act (EP&A Act). **infill development:** refers to the development of vacant blocks of land that are generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development. **new development:** refers to development of a completely different nature to that associated with the former land use. For example, the urban subdivision of an area previously used for rural purposes. New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water

supply, sewerage and electric power.

redevelopment: refers to rebuilding in an area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services.

disaster plan (DISPLAN) A step by step sequence of previously agreed roles, responsibilities, functions, actions and management arrangements for the conduct of a single or series of connected emergency operations, with the object of ensuring the coordinated response by all agencies having responsibilities and functions in emergencies.

discharge The rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second (m^3/s). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s).

East coast low East coast lows are intense low-pressure systems which occur on average several times each year off the eastern coast of Australia, in particular southern Queensland, NSW and eastern Victoria. Although they can occur at any time of the year, they are more common during Autumn and Winter with a maximum frequency in June. East coast lows will often intensify rapidly overnight making them one of the more dangerous weather systems to affect the NSW coast. East coast lows are also observed off the coast of Africa and America and are sometimes known as east coast cyclones. (from “What are East Coast Lows”, Commonwealth Bureau of Meteorology website)

ecologically sustainable development (ESD) Using, conserving and enhancing natural resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be maintained or increased. A more detailed definition is included in the Local Government Act 1993. The use of sustainability and sustainable in this manual relate to ESD.

effective warning time The time available after receiving advice of an impending flood and before the floodwaters prevent appropriate flood response actions being undertaken. The effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions.

emergency management A range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding.

flash flooding Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain.

flood Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flooding associated with major drainage before entering a watercourse, and/or coastal inundation resulting from super-elevated sea levels and/or waves overtopping coastline defences excluding tsunami.

flood awareness Flood awareness is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.

flood education Flood education seeks to provide information to raise awareness of the flood

	problem so as to enable individuals to understand how to manage themselves and their property in response to flood warnings and in a flood event. It invokes a state of flood readiness.
flood fringe areas	The remaining area of flood prone land after floodway and flood storage areas have been defined.
flood liable land	Is synonymous with flood prone land (i.e. land susceptible to flooding by the probable maximum flood (PMF) event). Note that the term flood liable land covers the whole of the floodplain, not just that part below the flood planning level (see flood planning area).
flood mitigation standard	The average recurrence interval of the flood, selected as part of the floodplain risk management process that forms the basis for physical works to modify the impacts of flooding.
floodplain	Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land.
floodplain risk management options	The measures that might be feasible for the management of a particular area of the floodplain. Preparation of a floodplain risk management plan requires a detailed evaluation of floodplain risk management options.
floodplain risk management plan	A management plan developed in accordance with the principles and guidelines in this manual. Usually includes both written and diagrammetic information describing how particular areas of flood prone land are to be used and managed to achieve defined objectives.
flood plan (local)	A sub-plan of a disaster plan that deals specifically with flooding. They can exist at State, Division and local levels. Local flood plans are prepared under the leadership of the State Emergency Service.
flood planning area	The area of land below the flood planning level and thus subject to flood related development controls. The concept of flood planning area generally supersedes the Aflood liable land@ concept in the 1986 Manual.
Flood Planning Levels (FPLs)	FPLs are the combinations of flood levels (derived from significant historical flood events or floods of specific AEPs) and freeboards selected for floodplain risk management purposes, as determined in management studies and incorporated in management plans. FPLs supersede the Astandard flood event@ in the 1986 manual.
flood proofing	A combination of measures incorporated in the design, construction and alteration of individual buildings or structures subject to flooding, to reduce or eliminate flood damages.
flood prone land	Is land susceptible to flooding by the Probable Maximum Flood (PMF) event. Flood prone land is synonymous with flood liable land.
flood readiness	Flood readiness is an ability to react within the effective warning time.
flood risk	Potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances across the full range of floods. Flood risk in this manual is divided into 3 types, existing, future and continuing risks. They are described below. **existing flood risk:** the risk a community is exposed to as a result of its location

	on the floodplain.
	future flood risk: the risk a community may be exposed to as a result of new development on the floodplain.
	continuing flood risk: the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.
flood storage areas	Those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage can increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.
floodway areas	Those areas of the floodplain where a significant discharge of water occurs during floods. They are often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flows, or a significant increase in flood levels.
freeboard	Freeboard provides reasonable certainty that the risk exposure selected in deciding on a particular flood chosen as the basis for the FPL is actually provided. It is a factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. Freeboard is included in the flood planning level.
habitable room	**in a residential situation:** a living or working area, such as a lounge room, dining room, rumpus room, kitchen, bedroom or workroom.
	in an industrial or commercial situation: an area used for offices or to store valuable possessions susceptible to flood damage in the event of a flood.
hazard	A source of potential harm or a situation with a potential to cause loss. In relation to this manual the hazard is flooding which has the potential to cause damage to the community.
hydraulics	Term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity.
hydrograph	A graph which shows how the discharge or stage/flood level at any particular location varies with time during a flood.
hydrology	Term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.
local overland flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.
local drainage	Are smaller scale problems in urban areas. They are outside the definition of major drainage in this glossary.
mainstream flooding	Inundation of normally dry land occurring when water overflows the natural or

artificial banks of a stream, river, estuary, lake or dam.

major drainage

Councils have discretion in determining whether urban drainage problems are associated with major or local drainage. For the purpose of this manual major drainage involves:

- the floodplains of original watercourses (which may now be piped, channelised or diverted), or sloping areas where overland flows develop along alternative paths once system capacity is exceeded; and/or
- water depths generally in excess of 0.3 m (in the major system design storm as defined in the current version of Australian Rainfall and Runoff). These conditions may result in danger to personal safety and property damage to both premises and vehicles; and/or
- major overland flow paths through developed areas outside of defined drainage reserves; and/or
- the potential to affect a number of buildings along the major flow path.

mathematical/computer models

The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.

merit approach

The merit approach weighs social, economic, ecological and cultural impacts of land use options for different flood prone areas together with flood damage, hazard and behaviour implications, and environmental protection and of the States rivers and floodplains.

The merit approach operates at two levels. At the strategic level it allows for the consideration of social, economic, ecological, cultural and flooding issues to determine strategies for the management of future flood risk which are formulated into Council plans, policy and EPIs. It involves consideration of the best way of conditioning development allowable under the floodplain risk management plan, local floodplain risk management policy and EPIs.

minor, moderate and major flooding

Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood:

minor flooding: causes inconvenience such as closing of minor roads and the submergence of bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded.

moderate flooding: low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered.

major flooding: appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.

modification measures

Measures that modify either the flood, the property or the response to flooding. Examples are indicated in Table 2.1 with further discussion in the Manual.

peak discharge	The maximum discharge occurring during a flood event.
Probable Maximum Flood (PMF)	The PMF is the largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with a range of events rarer than the flood used for designing mitigation works and controlling development, up to and including the PMF event should be addressed in a floodplain risk management study. Note that a different definition exists in ARR 2016 (Ball et al, 2016) and particularly refers to dam design.
Probable Maximum Precipitation (PMP)	The PMP is the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to PMF estimation.
probability	A statistical measure of the expected chance of flooding (see AEP).
Representative Climate Pathway (RCP)	Possible future emissions and concentration scenarios adopted by the Fifth IPCC report and based on existing published literature. They focus on the ‘concentrations’ of greenhouse gases that lead directly to a changed include a ‘pathway’ – the trajectory of greenhouse gas concentrations over time to reach a particular radiative forcing at 2100.
runoff	The amount of rainfall which actually ends up as streamflow, also known as rainfall excess.
stage	Equivalent to water level. Both are measured with reference to a specified datum.
stage hydrograph	A graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum.
survey plan	A plan prepared by a registered surveyor.
water surface profile	A graph showing the flood stage at any given location along a watercourse at a particular time.
wind fetch	The horizontal distance in the direction of wind over which wind waves are generated.

Appendix C

Mahes Maheswaran
Water NSW
Level 14/169 Macquarie Street
Parramatta NSW 2150

18th December 2018

Dear Mahes,

Review of Assessment of Climate Change Impacts on Design Floods for Warragamba Dam

I am writing with comments on responses provided by WMAwater to the review I provided of their report in March of this year (*Climate Change and Flooding Effects on the Hawkesbury Nepean; Independent Review of Report by WMAwater*, 24th March, 2018, a review prepared for WaterNSW).

I received an email from WMAwater on the 26th September 2018 summarising their response to my review, and I provided some informal comments to them by email on the 19th October 2018. Subsequently, I have been contacted by David Harper of WaterNSW requesting me to formalise my response so that it can be provided to Infrastructure NSW and the Office of Chief Scientist and Engineer. For completeness, this letter summarises the response provided by WMAwater as well as my comments to their response.

The points provided below need to be read in the context of my original review. For clarity, the text in bold font represent the concluding points from my original review, the text in italics is the verbatim response provided by WMAwater, and the plain text represent my comments on their response. The comments provided below are largely similar (but not identical) to the text provided informally by email on 19th October 2018.

A) Commentary on conclusions made in the original review

1. **The range of temperature increases considered are well suited to assessing the impacts of climate change over decadal time scales under different assumptions of emission scenarios, though it is possible that the results could be presented in a manner better suited to the needs of decision-makers.**

   WMAwater: See below.

   RJN: See response provided in item 9, below.

2. **The climate change impacts are based solely on the expected increases in rainfall associated with warmer temperatures. While it is not entirely clear how the precise change factors were derived, the adopted factors are consistent with the available evidence.**

   WMAwater: Yes, ARR data hub versions of Climate change factors. The data hub used an early version of a paper discussing the proposed ARR method which had a slight mistake in the formula *which causes a slight underestimation of the values. The 2090 values for low medium and high change from 9.1% to 9.3%, 11.4% to 11.7% and 18.6% to 19.9% in Sydney. The ARR team is still waiting to hear back from the chapter authors. Given this is a sensitivity assessment and it really only affects the high scenario it is not considered a major issue.*

RJN: I originally noted in Section 3.1 of my report that "the numbers adopted by WMAwater appear quite reasonable, it is just not clear how they were obtained". The differences are well within the notional uncertainty of such uncertainties and this "slight mistake" is not of material concern. I thus agree with WMAwater's response.

3. **There is insufficient information available to assess the impacts of possible changes in storm type and frequency, or in the possible intensification of spatial and temporal patterns. It is reasonable to assume that such uncertainties are accounted for by the increase in design rainfall depths.**

WMAwater: Yes, the big question is how rainfall producing east coast lows will change. There has been extensive research on this topic but it is not conclusive. As we need to understand how the magnitude and frequency will change. It is likely there will be some intensification of spatial and temporal patterns. Given the extremities of the catchment particularly the Wollondilly often do not contribute to flooding a decrease in the spatial footprints of east coast lows could be expected to increase flooding.

RJN: I originally noted in Section 3.2 of my report that "It would be difficult to know how to accommodate the uncertainty in such changes in an explicit manner, and thus the approach adopted by WMAwater is considered appropriate." Additional commentary on this is provided in Section 3.3. I thus have no concerns with WMAwater's response here.

4. The study does not consider the effects of changed antecedent catchment wetness on flood magnitude. It is difficult to speculate how important his factor is to floods in the Hawkesbury Nepean, but it is likely that such impacts will offset to some degree the influence of increased rainfall depths.

WMAwater: This is true and some sensitivity should be carried out. Most of the Hawkesbury Nepean floods occur on relatively wet catchments in autumn and winter and are unlikely to be as affected by warmer temperatures and higher evaporation as other storm types.

RJN: If temperatures and evaporation are higher in winter and autumn months then it would be expected that the catchments will not be as wet (in absolute terms) as they are now. Thus, it is likely that any such impacts will offset to some degree the influence of increased rainfall depths. While a number of global and continental studies have found that on average rainfall extremes are increasing (eg see Sharma and Wasko, 2019[1]), the evidence for increased flooding is less compelling. Since undertaking my review I have been involved in some research that shows that decreasing trends in soil moisture are correlated with decreasing trends in flood peaks[2]. Our research provides historical evidence for the fact that more sites throughout Australia exhibit decreasing trends in flow peaks as compared to increases. The degree of moderation due to changes in soil moisture is dependent on catchment size (larger catchments are more sensitive to changes in soil moisture) and latitude (northern latitudes are associated with increases and southern with decreases) and event severity (the influence of soil moisture decreases with event severity). We conclude that changes in soil moisture conditions need to be considered when

[1] Sharma, A., Wasko, C., 2019. Trends and Changes in Streamflow With Climate, in: Teegavarapu, R. (Ed.), *Trends and Changes in Hydroclimatic Variables*. Elsevier Inc., pp. 275–304. https://doi.org/10.1016/B978-0-12-810985-4.00005-0

[2] Wasko, C. and Nathan, R. 2019. Influence of changes in rainfall and soil moisture on trends in flooding. Paper under review by Journal of Hydrology.

predicting the flood response of a catchment due to climatic change. Further comment on this is provided in Item 10, below.

5. **WMAwater was not able to access the results of reservoir simulation studies during their investigation and were thus not able to consider the (likely mitigating) influence of changed water levels on outflow floods.**

   WMAwater: The reservoir simulations were used to define current conditions starting water levels. However this was not available for the climate change scenario. This input is dependent on data from Water NSW. It is worth noting that the system response brings forward pumping from the Shoalhaven and desalination plant when levels drop below key triggers so the system partial self compensates for climate effects.

   RJN: Rising temperatures, lower rainfalls, increased drought severity and higher populations, will all serve to reduce expected water levels in Warragamba. It would be expected that alternative sources of supply will mitigate these reductions to some extent. However, the floods of most relevance to the objectives of the study are influenced by changes in initial water level assumptions. At present no quantitative evidence has been presented to help determine whether or not this is a material issue.

6. **It is understood that flows at Windsor are influenced by tide levels, but it is not clear whether higher sea levels associated with warmer temperatures are of significance at the locations of interest.**

   WMAwater: while Windsor is tidal in non flood times flood larger than 1 in 5 AEP are not affected by ocean levels under current or even increase in ocean levels of up to 2m will not affect this type of floods. For example the 1 in 100 AEP is 17.3mAHD which is a significant amount above any significant tidal effects.

   RJN: This additional information makes it clear that this issue need not be given further consideration.

7. **All simulations appear to have been undertaken on an annual not seasonal basis. It is difficult to speculate how important the issue of seasonality is for the Hawkesbury Nepean. From a purely catchment perspective it is noted that seasonal changes in rainfalls and soil moisture may combined to reduce flood risks in autumn/winter, and it is also possible that seasonal changes to initial water levels in Warragamba Dam may be of significance.**

   WMAwater: The large catchment rainfall and flood record for the Hawkesbury Nepean is completely dominated by east coast low events occurring in Autumn and Winter. There is very little difference between an annual and an autumn/winter assessment. Only one of the top 18 events in the last 140 years has occurred in the September/January period (Nov 1961). This event is classified as an east coast low in the east coast low database. The longer flood record shows the same behaviour. There is no real seasonal cycle to Warragamba dam levels. The system has a very long term system memory with time between spills, being as long as a decade. While evaporation and demand is higher in warmer months there is no large scale change in demand as there are no irrigation releases. Minor inflows can occur at any time and are common in summer. Larger inflows tend to occur in Autumn and Winter and can come from either individual events or periods of very high flow.

   RJN: In the GSAM region of Australia it is typically found that dominant rainfall and flood events gradually shift from cool to warmer months as the severity of the event increases. Thus, in many locations the seasonality of the events in the historic record are not representative of the seasonality of the more extreme events that are relevant to dam safety. However, the dominance of east coast lows over such a long record in the Hawkesbury-Nepean (assuming that the top 18 events relate to floods not rainfalls), and the absence of seasonality in drawdown levels, is compelling evidence that justifies the adoption of an annual sampling scheme when deriving the floods of most relevance to this study (i.e. 1% AEP).

8. **Results are provided for a comprehensive range of criteria and most results are clearly presented and easily interpreted. Without understanding the basis of the simulation scheme it is difficult to assess the risk implications of some results related to changes in the frequency of reaching selected trigger levels.**

   WMAwater: Trigger levels relate to the NSW SES evacuation triggers. The report uses 17.3mAHD which is also the 1% AEP level at Windsor. All of these triggers are publically available in the Hawkesbury Nepean flood plan.

   RJN: the original review comment was not directed at the selection of the trigger levels, but rather at the interpretation of the figures which report on the changes to frequency of reaching the frequency levels (Figures 3, 11, and 16). This point is discussed in Section 4 of the original review, and relates to the need to clarify the basis on which the 20,000 simulations were undertaken to allow the reported frequency changes to be interpreted in probabilistic terms.

B) Commentary on key recommendations made in the original review

9. **Present the results in a manner that may be better suited to the business case used to support the recommended dam raising.**

   WMAwater: The results have been presented in a particular way because the project has in principle approval for the about 14m case only. The purpose of the report is 2 fold: to understand performance of different options under climate change and particularly how the benefits of the 1014m case will be reduced with climate change.

   RJN: The discussion regarding Figure 1 in the original review highlights how the period over which expected benefits associated with a 14m raising are directly dependent on the rate of assumed climate warming. This suggestion was provided to address perceived difficulties of interpretation relevant to development of a business case. Whether or not such an alternative presentation is helpful to different stakeholder groups is something that others need to comment on.

10. **Investigate the potential for projected changes in antecedent losses to offset the impacts of increased rainfalls.**

   WMAwater: There is no easy to use research that is available to do this in the timeframe available. We understand that this is scheduled to occur in the longer term.

   RJN: While it is agreed that there is no established procedure for investigating this issue, at least two studies have been undertaken in Australia which have independently used the same approach to adjust event-based losses on the basis of continuous simulation modelling[3,4]. If suitable observed data on concurrent daily rainfall and reservoir inflows is available, then it should not take more than two or three weeks to complete and document the study; if a suitable calibrated continuous simulation model is available, then the time required to complete this work would be reduced.

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[3] Fowler, K., Hill, P., Jordan, P., Nathan, R., and Sih, K. (2010): Application of available climate science to assess the impact of climate change on spillway adequacy. *Proc. ANCOLD 2010 Conference on Dams*. Hobart.

[4] Stephens, C. M., Johnson, F. M., & Marshall, L. A. (2018). Implications of future climate change for event-based hydrologic models. *Advances in Water Resources*, *119*(July), 95–110.

11. **Investigate the potential for projected changes in initial water levels to provide greater airspace to absorb the expected larger inflow volumes.**

    WMAwater: This depends on the WATHNET data from Water NSW however extensive testing on drawdown scenarios and the sensitivity of results to different drawdown assumptions has shown this will have limited effect to larger floods.

    RJN: No information has been provided in the reports made available to this reviewer that details the results of this sensitivity analysis, and thus it is not possible to provide independent comment on this point.

12. **Investigate the impacts of increased rainfalls and antecedent conditions on a seasonal basis to better identify the influence of climate change on conditions relevant to the timing of East Coast Lows.**

    WMAwater: See attached graph in next sheet [appended to this letter]

    RJN: The basis for the original review comment is provided in item 7, above. Given the focus of this study is on 1% AEP floods, the information provided in the graph provided by WMAwater in 26th September 2018) supports the adoption of an annual sampling approach. It thus seems sensible to not invest further effort in investigating the impacts on a seasonal basis.

I trust the above comments are self-explanatory, but please do not hesitate to contact me if anything is unclear.

Sincerely yours,

A/Prof Rory Nathan
Infrastructure Engineering
Melbourne School of Engineering

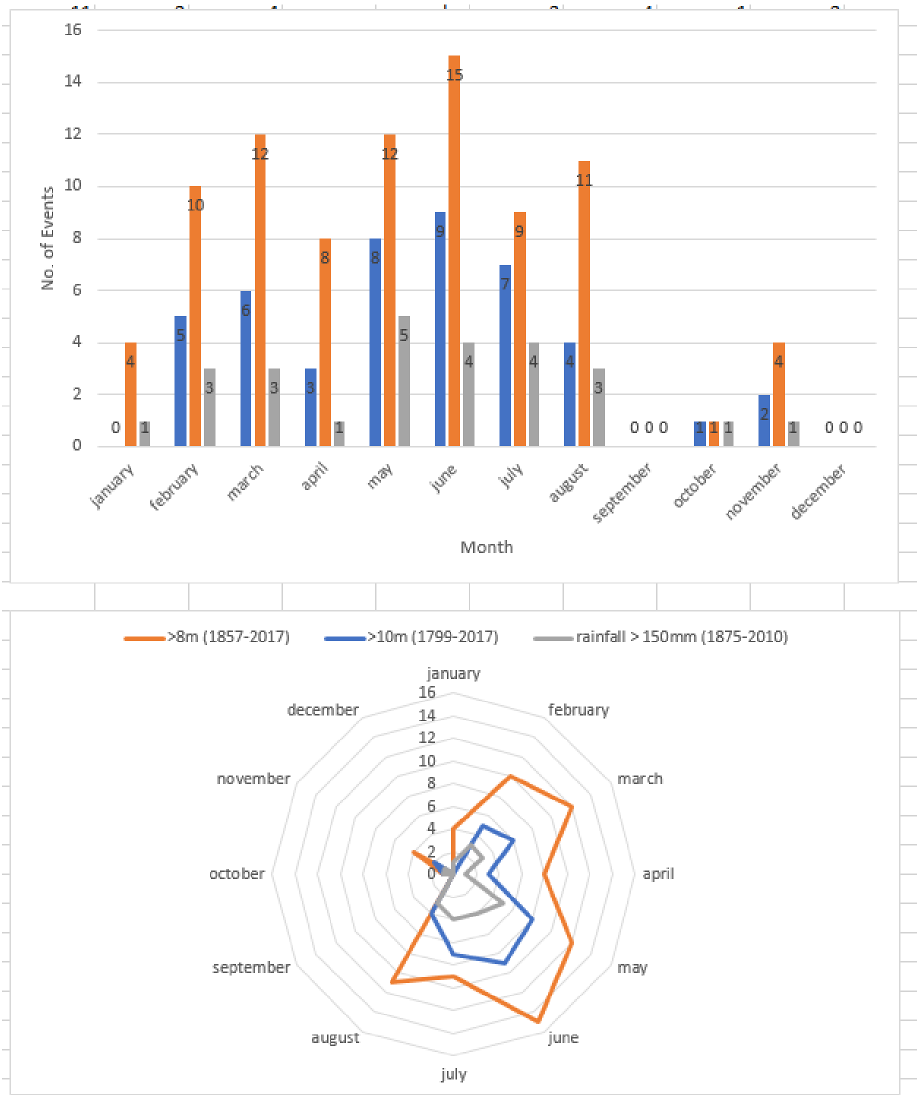

Figure provided by WMAWater in support of the commentary discussed in item 12.