Australian Rainfall & Runoff

DISCUSSION PAPER: AN INTERIM GUIDELINE FOR CONSIDERING CLIMATE CHANGE IN RAINFALL AND RUNOFF

FINAL REPORT

AR&R D3

NOVEMBER 2014

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ENGINEERS AUSTRALIA
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AUSTRALIAN RAINFALL AND RUNOFF
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FOREWORD

ARR Revision Process

Since its first publication in 1958, Australian Rainfall and Runoff (ARR) has remained one of the most influential and widely used guidelines published by Engineers Australia (EA). The current edition, published in 1987, retained the same level of national and international acclaim as its predecessors.

With nationwide applicability, balancing the varied climates of Australia, the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:

- Infrastructure such as roads, rail, airports, bridges, dams, stormwater and sewer systems;
- Town planning;
- Mining;
- Developing flood management plans for urban and rural communities;
- Flood warnings and flood emergency management;
- Operation of regulated river systems; and
- Estimation of extreme flood levels.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of ARR. As part of the revision process, there is a need to consult with the profession to provide early advice on likely changes to ARR and to receive feedback on these potential changes.

For this reason, the ARR Revision Team will publish Discussion Papers outlining concepts and methods that are being considered for inclusion in ARR. Feedback from the profession on these concepts and methods will form an essential aspect of the final decision regarding their inclusion or exclusion in ARR.

This draft discussion paper draws on the most recent climate science, particularly the release of the IPCC Fifth Assessment Report on the Physical Science Basis in September 2013 (IPCC, 2013) as well as the new climate change projections for Australia (CSIRO and BoM, 2014), and outlines an approach to address the risks from climate change in projects and decisions that involve estimation of design flood characteristics.

Mark Babister
Chair Technical Committee for
ARR Research Projects

Assoc Prof James Ball
ARR Editor

EXECUTIVE SUMMARY

Heavy rainfall can lead to flooding which is a key risk for many Australian regions and communities. Damage costs from flooding in recent years are in the order of many billions of dollars (RBA, 2011, pp. 38), and there has been loss of life (e.g. van den Honert and McAneney, 2011).

Climate change is expected to have an adverse impact on extreme rainfall intensities which could increase the risk of flood over time at many locations. The IPCC (2013) states that:

- Globally, for short-duration precipitation events, a shift to more intense individual storms and fewer weak storms is likely as temperatures increase.
- Return periods are projected to be reduced by about 10-20% per degree Celsius (°C) over most of the mid-latitude land masses, with larger reduction over wet tropical regions.

Results from the Australian Natural Resources Management (NRM) projections project (CSIRO and BoM, 2014) show simulated increases in the magnitude of the wettest annual daily total rainfall and the 1 in 20 year wettest daily total for all of the NRM clusters and sub-clusters studied. The increases were largest late in the century (2090) and under the highest representative concentration pathway (RCP8.5, Section 2.1), and also occur in the region that had the strongest simulated decrease in mean rainfall (southwest Western Australia).

The Australian Rainfall and Runoff (ARR) guideline is currently being revised to incorporate 25 years of data since its last publication and to take into account the effects of climate change. This revision is expected to be completed by December 2015.
To inform this revision, key research projects are underway to quantify possible changes and uncertainties in design rainfall Intensity-Frequency-Duration (IFD) curves due to anthropogenic climate change for the Greater Sydney region and for south-east Queensland.

This draft discussion paper on an Interim Guideline for Climate Change draws on the most recent climate science, particularly the release of the IPCC Fifth Assessment Report on the Physical Science Basis in September 2013 (IPCC, 2013) as well as the new climate change projections for Australia (CSIRO and BoM, 2014), and outlines an approach to address the risks from climate change in projects and decisions that involve estimation of design flood characteristics. For consistency with the new rainfall IFD estimates for Australia (ARR, Book II – Rainfall Estimation, 2015), the Interim Guideline is intended to be applied to the key system design event (i.e., the design standard for the structure or infrastructure). It is applicable for rainfall intensities under the current climatic regime within the range of probability of one exceedance per year or annual exceedance probabilities (AEPs) from 50% to 1%. Flood generation mechanisms such as antecedent wetness, baseflow, tailwater levels and oceanic processes (e.g. wind, waves and tides) are not considered.

Recommended Procedure for Design Flood Estimation and Planning in Australia

A six-step procedure for the incorporation of climate change in flood designs or planning decisions will be recommended in the Interim Guideline. It has been formulated to respond to the question: "Is climate change a significant issue for the location and project at hand?" If the answer to that question is "No", it is recommended that the determination of the design flood or decision be based on rainfall estimates derived from ARR Book II, using at-site frequency, regional frequency or catchment simulation techniques. If the answer is "Yes", further work is required which may range from a simple to a more complex analysis depending on the purpose of the facility (e.g., asset, process or management strategy), costs of potential changes in flood-related design requirements, consequences of structural failure or failure to meet operating requirements, and costs of retrofitting that may be incurred as a consequence of climate change. The procedure can be summarised as follows:

1. *Set the Service Life or Planning Horizon*. Service life is the total period during which an asset remains in use and a planning horizon is the length of time that a plan looks into the future. If either is less than 20 years from 2015, determine the design flood or make the decision based on ARR Book II and flood estimation approaches. Otherwise, proceed to Step 2.
2. *Set the Design Standard*. If the standard is the Probable Maximum Flood, use the latest available estimate of Probable Maximum Precipitation from the Bureau of Meteorology. Otherwise, proceed to Step 3.
3. *Consider the Purpose and Nature of the Asset or Activity*. Define the purpose of the asset or activity (e.g., flow conveyance, reduced frequency of exposure) and flood-related design requirements (e.g. minimum floor levels), and consider the consequences of failure (e.g., risks to life, property and the environment) and cost of retrofitting. If the consequences of failure and cost of retrofitting are low, determine the design flood using ARR Book II and flood estimation approaches. Otherwise, proceed to Step 4.
4. *Carry out a Screening Analysis*. For example, if the design AEP is 1% consider the impact of the 0.5% and 0.2% AEP events on the facility of interest and the associated consequences. If the impact, consequences of failure and cost of retrofitting are low, determine the design flood using ARR Book II and flood estimation approaches. Otherwise, proceed to Step 5.
5. *Consider Climate Change Projections and their Consequences of Impact*. Carry out a more detailed analysis to assess the cost and other consequences of changes in the flood-related design requirements under projected climate change and the residual risk (i.e., the level of risk remaining after climate change has been factored into the design or planning process). If the cost of the modified design is low relative to the benefits for reduction in residual risk, adopt the changed design. Otherwise, proceed to Step 6.

6. *Consider Statutory Requirements*. If statutory requirements relating to climate change are in place, adopt the changed design. Otherwise, carry out a detailed comparative cost-benefit analysis of the original and potentially changed flood-related design requirements and make an informed decision on how to proceed.

To enable detailed consideration of changing risks of flooding over time, it is proposed that it be assumed that climate change will result in a 5% increase in rainfall intensity (or equivalent depth) per °C of global warming. This assumption is consistent with recent research findings (see, e.g., CSIRO and BoM (2014)), and links potential increases in rainfall intensity with future levels of warming. There are, however, a number of caveats (Section 3.2). The Climate Futures tool (to be released in 2014) is recommended for use in guiding the selection of projections for surface temperatures for a given representative concentration pathway and a user-specified time point (Section 2.1). Further detail is provided in Section 3.2.

Concluding Remarks

This document is provided for the guidance of engineers and decision makers who are expected to take responsibility for any application of the procedure described. A key focus is to provide a structured approach that leads to a reasonable understanding of climatic risk. Climate change science is a dynamic field, and the most up-to-date and localised studies should be drawn on in any decisions.

It is expected that the Interim Guideline will be replaced over time as new research findings are released. Where exposure to climate change and the consequences of failure of the asset are high, more detailed studies including the use of downscaling methods are recommended. At a minimum it is recommended that the Interim Guideline be reviewed following the release of the IPCC Sixth Assessment Report on Climate Change which is scheduled for release in 2020/21.

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1. Introduction

1.1. Context

Flooding events can cause substantial damage to communities and infrastructure, and impact on life as well as regional economies. The highly urbanised regions along Australia's eastern coastline are particularly prone to flooding, and as a result of the 2010-2011 floods the estimated net additional expenditure on public buildings and infrastructure was about $8 billion (RBA, 2011, pp. 38).

There is growing confidence in the science community that in a changing climate flooding events could become more frequent and more intense in densely populated areas of Australia. It is imperative, therefore, that effective approaches to adaptation be identified and progressed.

Australian Rainfall and Runoff (ARR) is a national guideline document for the estimation of design flood characteristics. The ARR is relevant to decisions and projects involving:

- Infrastructure such as roads, rail, airports, bridges, dams and stormwater and sewer systems
- Town planning
- Flood management planning for urban and rural communities
- Flood warnings and emergency management
- Operation of regulated river systems, and
- Estimation of extreme flood levels.

The current version of the ARR was released in 1987, and it is now being revised in a multi-year project to incorporate a further 25 years of hydrologic and weather data and improved knowledge of future risks. There is now a robust body of research globally that indicates that human-induced climate change has the potential to alter the prevalence and severity of rainfall extremes, storm surges and floods. Past trends provide valuable evidence in preparing for future environmental change but, by themselves, are insufficient for assessing the risks associated with an uncertain and changing future. The updated ARR should provide an improved approach for assessing the implications of climate change for projects and decisions involving estimation of flood design characteristics.

In recognition of this the Council of Australian Governments in 2007 identified as a priority the need to revise the ARR to consider climate change in the National Climate Change Adaptation Framework. Revision of the ARR was identified as an important national initiative to facilitate better planning of new infrastructure and to reduce potential damage to existing infrastructure.

However, there continue to be major gaps in our knowledge of how climate change will affect the behaviour of extreme rainfall and flooding events in different areas of Australia. For example there is little confidence in knowledge about how climate change will alter rainfall Intensity-Frequency-Duration (IFD) relationships, or in whether the risks of coincident flood and sea inundation events will change significantly. Further information on the state of science with regard to climate change, flooding and heavy rainfall is given in Section 2.2.

It is important that engineers and other decision-makers continue to access the most up-to-date science and expert local knowledge in making decisions, and to exercise good judgement in response to the possible impacts of climate change. Maintaining and building links between the engineering profession and the climate science community will help build the understanding and skills to enhance the quality of decision making in Australia.

1.2. Framing Climate Change Decisions

In discussions about weather and climate, the terms prediction, forecast, projection and scenario are often used interchangeably, as if they have the same meaning. Important distinctions between these terms should be recognised if analysts and decision makers are to have a clear understanding of the task at hand and to communicate their findings effectively. A useful set of definitions has been provided by MacCracken (2001):

- A *prediction* is a specific statement about the future based on what is known today
- A *forecast* is the most likely picture of the future
- A *projection* is a statement of what could happen if certain assumed boundary conditions prevail in the future, and
- A *scenario* is series of events that could lead from the present to a plausible but not assured future situation.

The focus of an assessment of the impact of climate change on a facility (asset, process or management strategy) should be on preparedness rather than prediction. The approach described below recommends the use of a single projection which should be adequate for many applications. However, when the consequences of failure (i.e. structural failure or failure to meet operational requirements) are assessed to be high an analyst should also specifically consider the implications of plausible events that have a low probability and high impact if the additional expense involved can be justified. The goal should be to reach a robust solution that works well under a range of plausible future conditions. Such an approach reduces sensitivity to climate and hydrologic model inaccuracies, uncontrollable and irreducible uncertainty, and violated planning assumptions (Lempert and Schlesinger, 2000; Pittock et al. 2001; Dessai et al. 2009). Such studies should be limited to a modest number of projections in order to avoid “paralysis by analysis”.

1.3. Use of Interim Guideline

The Interim Guideline document will provide designers and decision makers that utilise ARR with an approach to consider the implications of climate change while further research is undertaken to reduce key uncertainties.

The proposed approach considers regional risks from climate change, the service life (i.e., the total period during which an asset remains in use) or the planning horizon of the decision (i.e., the length of time that a plan looks into the future), the social acceptability and other consequences of failure, and the cost of retrofits. If climate change is found to be a significant issue for the facility of interest through a screening analysis, a more detailed analysis is proposed that draws on the best available knowledge of the likely future climate and allows for changes in the intensity of heavy rainfall events over time.

The document is intended to be used by professional engineers and decision makers with expertise in floodplain management, infrastructure design, and construction or operation under current climate variability. It does not replace the need for informed judgement of likely risks, or the need for detailed local analysis (for example through the use of downscaling approaches and hydrological modelling) where the facilities under consideration are important and the risks potentially large.

It is anticipated that the Interim Guideline will be replaced gradually as new and detailed research findings are released.

2. Science of Rainfall and Runoff in a Changing Climate

2.1. Projections of climate change

The IPCC Fifth Assessment Report (AR5), released in September 2013, introduced a new way of developing emissions scenarios (IPCC, 2013). These scenarios span the range of plausible radiative forcing, and are called representative concentration pathways (RCPs). RCPs are prescribed pathways for greenhouse gas and aerosol concentrations, together with land use change, that are consistent with a set of broad climate outcomes used by the climate modelling community (Figure 1). The four pathways are characterised by the radiative forcing produced by the end of the 21st century relative to pre-industrial values. Radiative forcing is the extra heat (W m^{-2}) the lower atmosphere will retain as a result of additional greenhouse gases (Jubb et al. 2013). These concentration pathways (RCP8.5, RCP6, RCP4.5 or RCP2.6) are then used to simulate how the climate will change around the world using global climate models. Further information can be found on the IPCC website (www.ipcc.ch).

With respect to rainfall the AR5 found that heavy precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely (i.e., with at least 90 percent probability) become more intense and more frequent by the end of this century, as global mean surface temperature increases. Further the IPCC AR5 notes that “return periods of late 20th century twenty-year return values is reduced from 20 years to 14 years for a 1 degree Celsius (℃) local warming. Return periods are projected to be reduced by about 10-20% per ℃ over most of the mid-latitude land masses, with larger reductions over wet tropical regions” (IPCC, 2013, Section 12.4.5.5).

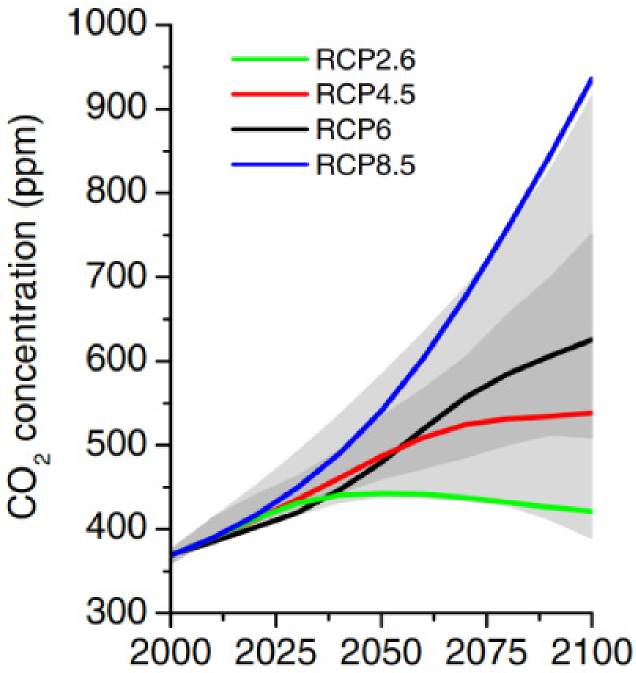

Figure 1. Four representative concentration pathways (RCPs). Grey bands indicate the 98th and 90th percentiles (light/dark grey) of an earlier modelling study. (Source: van Vuuren et al. 2011, Figure 9.)

The AR5 followed the 2012 IPCC Special Report on Extremes which found, in addition to likely increases in heavy precipitation events in the 21st century in many areas, that:

- Projected precipitation and temperature changes imply possible changes in floods, although there is low confidence in projections of changes in fluvial floods. Given the rarity of events of this nature, there are few data with which to make assessments regarding changes in the frequency or intensity of these events.
- There is medium confidence (an assessment based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in local flooding in some catchments.

The AR5 has identified increased frequency and intensity of flood damage to settlements and infrastructure in most parts of Australia as a key risk for the 21st Century. The CSIRO and Bureau of Meteorology are developing a Climate Futures tool that facilitates informed selection of a sub-set of climate model results for use in impact assessments and access to application-ready data sets. It will provide regional information on a range of projected climate variables (Whetton et al. 2012). At present the tool will not include detailed projections of changes to rainfall IFD relationships due to the paucity of available information. Climate Futures is expected to be released in 2014. It utilises the RCPs developed for the AR5 and global climate model simulations. It will be fully integrated into the www.climatechangeinaustralia.com.au website in 2014. Owing to constraints on data availability for some variables, spatial detail will range from national natural resources management (NRM) cluster or sub-cluster averages (Figure 2), to a five km grid-average, to specific cities. Data from up to 48 climate models have been analysed from the Climate Model Intercomparison Project Phase 5 (CMIP5, Taylor et al. 2012). The number of models varies as there are fewer results available for some RCPs and climate variables.

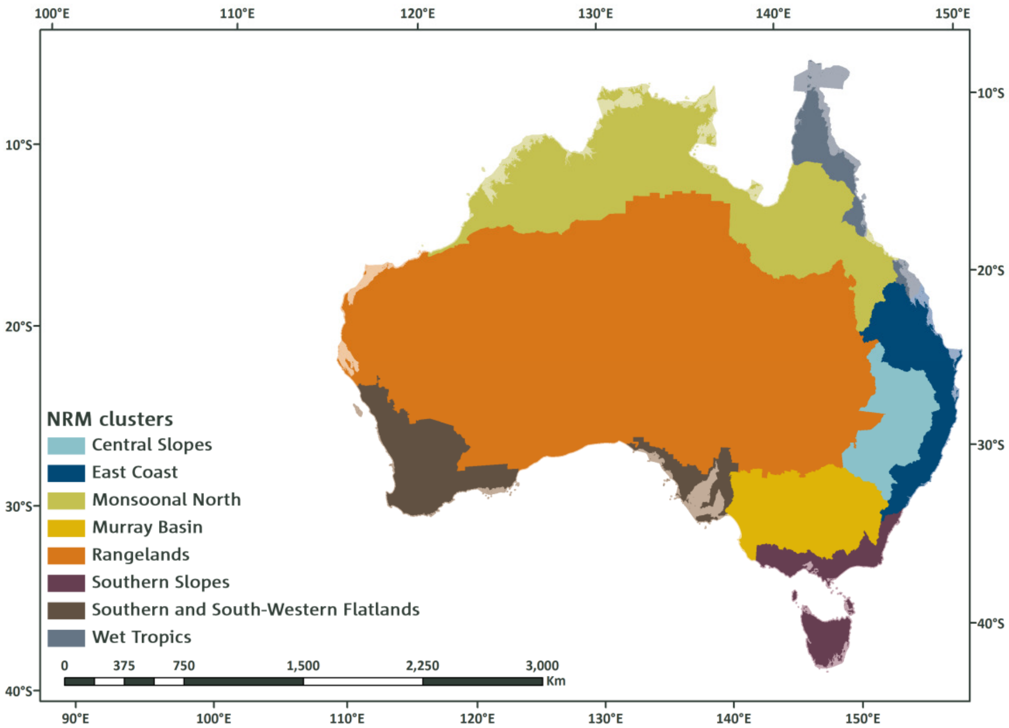

Figure 2. Locations of national NRM clusters.

2.2. Regional Australian studies into heavy rainfall and climate change

A number of studies have examined a wide variety of statistics of ‘extreme’ sub-daily and daily rainfall in Australia. Their findings include:

- Extreme rainfalls (defined in this instance as the 95th or 99th percentile) exhibit changes of sign that are consistent with those for mean rainfall changes, and indices of annual extreme frequency and intensity show decreases in the southwest and eastern coastal regions since 1950 (Gallant et al. 2007).
- Trends in extreme precipitation are correlated with trends in mean precipitation, and the rate of change of extremes show a greater rate of change than for the means (Alexander et al. 2007).
- Extreme rainfall scales with temperature at rates that are consistent with the Clausius-Clapeyron relationship for temperatures up to about 20-26 °C and durations up to 30 minutes. At greater temperatures, negative scaling is observed. Moisture availability was hypothesized to become the dominant control of how precipitation scales at higher temperatures (Hardwick-Jones et al. 2010), and it is not clear how moisture availability will change in a future climate.
- Short-duration (6-minute) rainfall extremes in eastern Australia exhibit a greater rate of change than those for longer duration events. There are limited changes in daily rainfall with the exception of southwest Western Australia where there is a noticeable decline (Westra and Sisson, 2011). A second study has shown that there are considerable seasonal and geographic variations in the frequency and

magnitude of rainfall events, implying different dominating rainfall-producing mechanisms and/or interactions with local topography (Jakob et al. 2011).

- For rainfall data with 6-minute temporal resolution, statistics such as the total wet period duration, storm event duration, and autocorrelation decrease with increasing temperature, while the maximum wet period depth and IFD relationships show an increasing trend with temperature (Gyasi-Agyei, 2013; Westra et al. 2013).
- Changes in rainfall intensity at short durations (< 1 h) positively correlate with changes in mean maximum temperature. Changes in rainfall intensity at longer durations positively correlate with changes in the mean annual rainfall, but not with mean maximum or minimum temperatures (Chen et al. 2013).

Many of the conclusions in the above studies mirror conclusions for other locations globally: namely, that (a) there is a clear historical relationship between extreme precipitation intensity and near-surface atmospheric temperature, with up to a 15% per degree scaling rate for short-duration (e.g. hourly) precipitation but also with possible declines in intensity at very warm temperatures; (b) hourly or sub-hourly rainfall is more sensitive to local atmospheric changes compared to daily-scale rainfall; and (c) there may be significant geographic variations, due to changes in large-scale circulation and dominant precipitation-generating mechanisms (see Westra et al. 2014 for a detailed review of the observational and modelling literature on this topic). Although most climate models have significant difficulties in representing the physical processes that lead to short-duration extremes, the few that are run at convection-permitting scales (e.g. Kendon et al. 2014) suggest that future changes to the behaviour of convective events may be substantial.

In terms of climate change projections, coarse-resolution modelling of the 99th percentile daily precipitation for 2050 suggests a small increase in intensity over most of the country, although projections for southwest Western Australia show a decrease (CSIRO and Bureau of Meteorology, 2007). Using extreme value theory and a fine-resolution downscaling approach, Rafter and Abbs (2009) projected increases in daily rainfall across all regions, and across most global climate models, for 20-year time slices centred in 2055 and 2090. The spatial patterns were consistent with previous studies, with smaller increases in the south and larger increases in the north.

In contrast, analysis of the latest global climate models (CMIP5) ensemble) under the NRM projections project (CSIRO and BoM, 2014) has shown simulated increases in the magnitude of the wettest annual daily total and the 1 in 20 year wettest daily total in all of the NRM clusters and sub-clusters (Figure 2) studied. This increase was most evident late in the century (2090) and under the highest representative concentration pathway (RCP8.5), and was present even in regions that had the strongest simulated decrease in mean rainfall (e.g. southwest Western Australia). The projected changes for these rainfall statistics is 2 to 8% per degree °C of warming.

At more local to regional scales, there have been a small number of analyses of the likely implications of climate change for heavy precipitation events. Abbs et al (2007) investigated the impact of climate change on extreme rainfall over south-east Queensland using dynamical downscaling methods. They found that climate change is likely to result in an increase in the 2-hour, 24-hour and 72-hour rainfall extremes for a large region including the McPherson Range and the Great Dividing Range west of Brisbane and the Gold Coast. By 2030 changes in extreme rainfall intensity for 24-hour and 72-hour events are most likely to be up to an increase of 20%, and by 2070 the region along the Great Dividing Range could experience increases in intensity in these events of 20% or more. The regions of rainfall increase also increase in spatial extent over time. With regard to temporal patterns the study was consistent with previous studies that found that as atmospheric moisture availability is increased, the period of heavy rainfall (rainfall rates > 25 mm/h) begins earlier and is more continuous.

Hennessy et al (2004) found that while much of NSW shows a tendency towards drier seasonal-average conditions under enhanced greenhouse conditions, it does not necessarily follow that daily rainfall events will become less frequent or severe. By 2030 increased 1-day rainfall extremes were projected for much of the south and centre of the state, and also in the north-east, trends which strengthened by 2070. Changes in the seasonality of heavy rainfall events were also identified.

There has been little detailed analysis, including downscaling, of the implications of climate change for the intensity, frequency and duration of heavy rainfall events in other parts of Australia. An exception is the Climate Futures for Tasmania project from which rainfall projections to the end of the 21st century indicate higher mean annual maximum daily rainfall amounts (up to 35% in some coastal regions) and sizable increases in 6-minute rainfall rates (particularly in eastern Tasmania). Further details can be found in White et al. 2010.

2.3. Research directions

A Climate Change Research Plan for ARR has been developed with the aim of enhancing our understanding of how projected climate change may alter the behaviour of weather extremes relevant to ARR and for the incorporation of this knowledge into design guidelines (Engineers Australia, 2013). The Plan identifies six key themes for research:

- Historical rainfall trends – to evaluate the presence of trend in shorter rainfall events throughout the historical record and understand the evidence of such trends in the context of climate variability
- Rainfall IFD relationships – to quantify possible changes and uncertainties in IFD data as a result of climate change in major population centres and regions

- Rainfall temporal patterns – to apply new methods of determining rainfall temporal patterns from historical data to downscaled reanalysis data to identify likely changes in future temporal patterns and the underlying mix of storm types
- Continuous rainfall sequences – to improve approaches for generating continuous daily rainfall sequences at gauged and ungauged sites, suitable for use with rainfall-runoff models, including derivation of rainfall IFDs and pre-storm antecedent conditions
- Antecedent conditions and baseflow regimes – to assess and provide guidance on baseflow and antecedent rainfall and soil conditions preceding extreme daily rainfall events from previous studies, and to consider extension to other parts of Australia in order to understand distributional changes, and
- Simultaneous extremes – to model and describe simultaneous forcings such as extreme rainfall and storm surge that are frequently responsible for flooding.

As a first phase in the implementation of this Research Plan two projects have been funded for the Greater Sydney region (Nowra to Port Stephens and east of the Great Dividing Range) and for south-east Queensland. The objectives of these projects are:

- To quantify possible changes and uncertainties in rainfall IFD curves due to anthropogenic climate change, and
- To provide interim advice to practitioners on how these changes can be included into design and planning decisions.

There is a need to extend this work to other metropolitan and key regional areas in Australia.

3. Interim Guidance for Engineers, Flood Risk Managers and Infrastructure Providers

3.1. Overview of approaches to consider climate change and heavy rainfall

In the absence of robust research results or national guidance, a number of states and organisations have developed approaches to allow for the impacts of climate change on extreme rainfall.

The NSW Government has published guidelines to assist local government authorities to consider climate change impacts as part of floodplain management processes (DECC, 2007). A sensitivity analysis is recommended for flood and floodplain risk studies, with rainfall values for the analysis including increases of 10%, 20% and 30% in peak rainfall and storm volume. Review of these guidelines will be considered following the release of the updated Australian Rainfall and Runoff.

The Queensland Government has released a report on an inland flooding study to help local governments factor in increased rainfall intensity as a result of climate change into flood studies (Queensland Government, 2010). The report proposed a 5% increase in rainfall intensity per °C of global warming. This increase can be incorporated into annual exceedance probability (AEP) flood events to inform the location and design of new development, using scaled temperature increases over time (2 °C by 2050, 3 °C by 2070, and 4 °C by 2100).

Overseas, the Ministry for Environment NZ (2008) has recommended adjustments to rainfall for each 1 °C of warming. Values are given for various average recurrence intervals and for rainfall durations from less than 10 minutes up to 72 hours. Adjustments for 24-hour rainfall are based on simulation by a single regional climate model and one emissions scenario, and those for 10-minute rainfall on the theoretical increase in the amount of water held by the atmosphere for a 1 °C rise in temperature. Adjustments for other durations were obtained by logarithmic (in time) interpolation. In the United Kingdom, PPS25 (2010) lists a set of precautionary sensitivity ranges for peak rainfall intensity and peak river flow for four time slices: 1990 to 2025; 2025 to 2055; 2055 to 2085; and 2085 to 2115.

Practical application of the NSW approach of using 10, 20 and 30% increases for sensitivity checking, particularly around the commonly used 1% AEP design event, has resulted in the use of current design events, such as the existing 0.5% AEP and 0.2% AEP events, as proxies to test sensitivity to this range of change in rainfall intensities. This approach reduces the number of modelling runs required and provides additional information on current flood impacts to support decision making. McLuckie et al (2010) provides a broad scale example of the use of the 0.5% AEP event as a proxy.

3.2. Proposed Interim Guideline for Climate Change in Australian Rainfall and Runoff

For consistency with the new IFD design estimates for Australia (ARR, Book II – Rainfall Estimation, 2015), the Interim Guideline is intended to be applied to the key system design event (i.e., the design standard for the structure or infrastructure). It is applicable for rainfall intensities under the current climatic regime within the range of probability of one exceedance per year or annual exceedance probabilities (AEPs) from 50% to 1%. Flood generation mechanisms such as antecedent wetness, baseflow, tailwater levels and oceanic processes (e.g. wind, waves and tides) are not considered.

A six-step process is proposed for considering climate change risks in decisions involving the estimation of design flood characteristics (Figure 3a-c).

Step 1 – Set the Service Life or Planning Horizon (Figure 3a)
Determine the service life of the asset or planning horizon of the activity. This underpins the design philosophy and may fundamentally control the selection of material, methods and expertise. A broad perspective on service life may be required incorporating engineering, client and community perspectives. Potential climate change considerations may influence these decisions, particularly as the risks from climate change are likely to increase over time. Figure 4 shows the general indicative service life of a number of infrastructure assets.

If the service life or planning horizon is relatively short (less than 20 years from 2015) anthropogenic climate change is likely to have negligible impact on the rainfall IFD characteristics over that period of time. That is, the exposure risk is low and the design process should be based ARR Book II and approaches such as at-site frequency, regional frequency or catchment simulation techniques. Otherwise, proceed to Step 2.

Step 2 – Set the Flood Design Standard (Figure 3a)
If the design standard is the Probable Maximum Flood (PMF), use an up-to-date estimate of Probable Maximum Precipitation (PMP) to determine the PMF. This approach has an appropriate degree of conservatism as PMP estimates are updated from time to time by the Bureau of Meteorology. This will ensure that any future climate change signal is captured, and that unwarranted expenditures based on crude adjustments to the PMF will be avoided. Otherwise, proceed to Step 3.

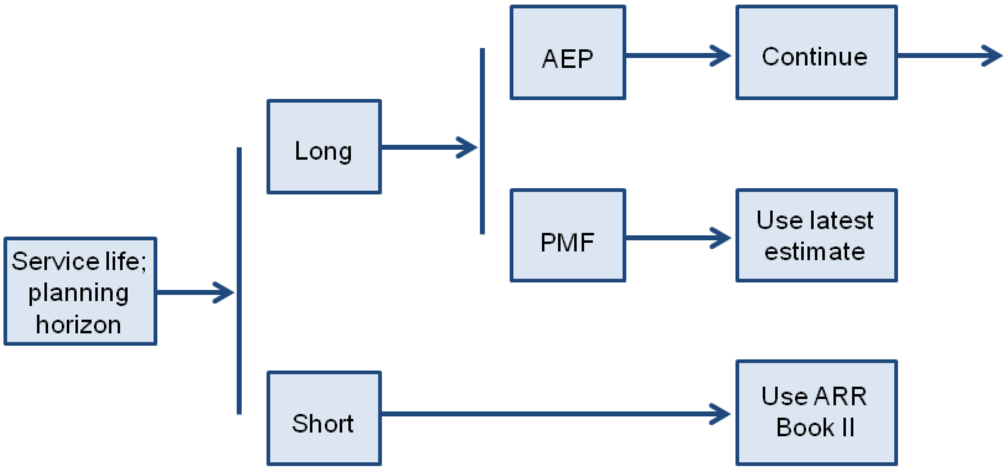

Figure 3a. Decision tree for incorporating climate change in flood design – Part A (AEP = annual exceedance probability; PMF = Probable Maximum Flood)

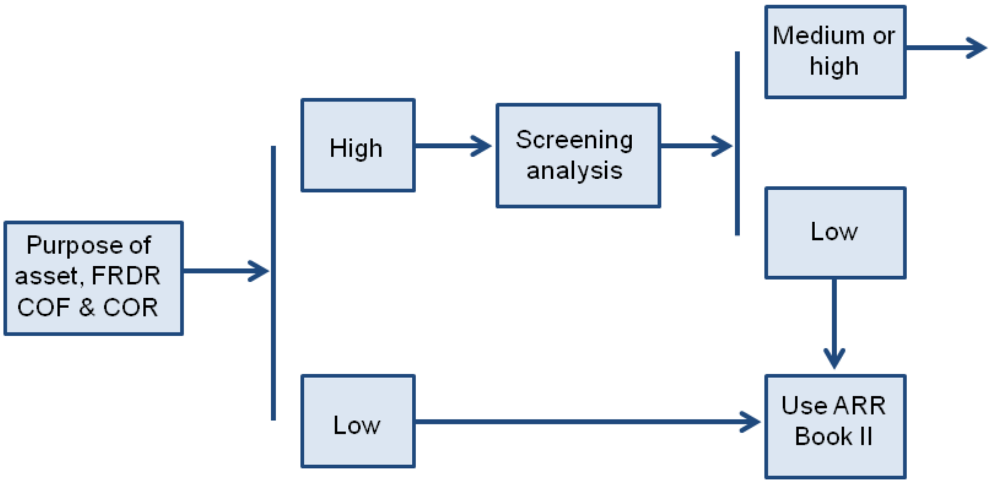

Figure 3b. Decision tree for incorporating climate change in flood design – Part B (FRDR = flood-related design requirements; COF = consequences of failure; COR = cost of retrofits)

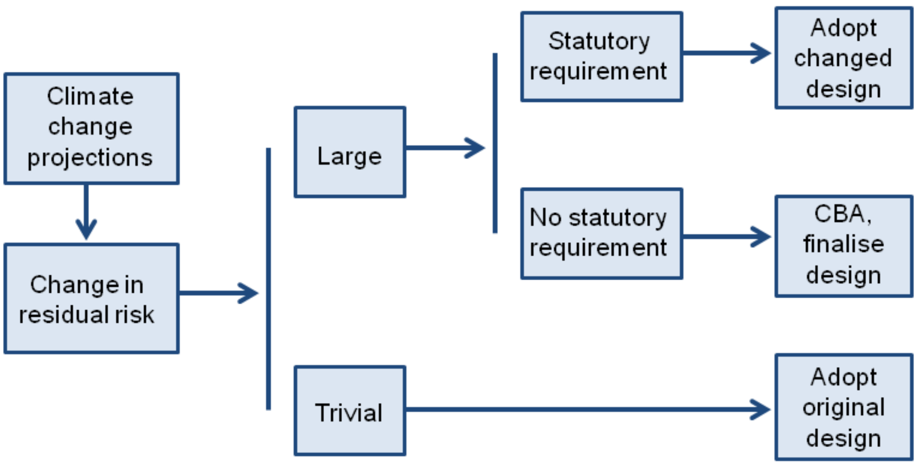

Figure 3c. Decision tree for incorporating climate change in flood design – Part C (FRDR = flood-related design requirements; CBA = cost-benefit analysis)

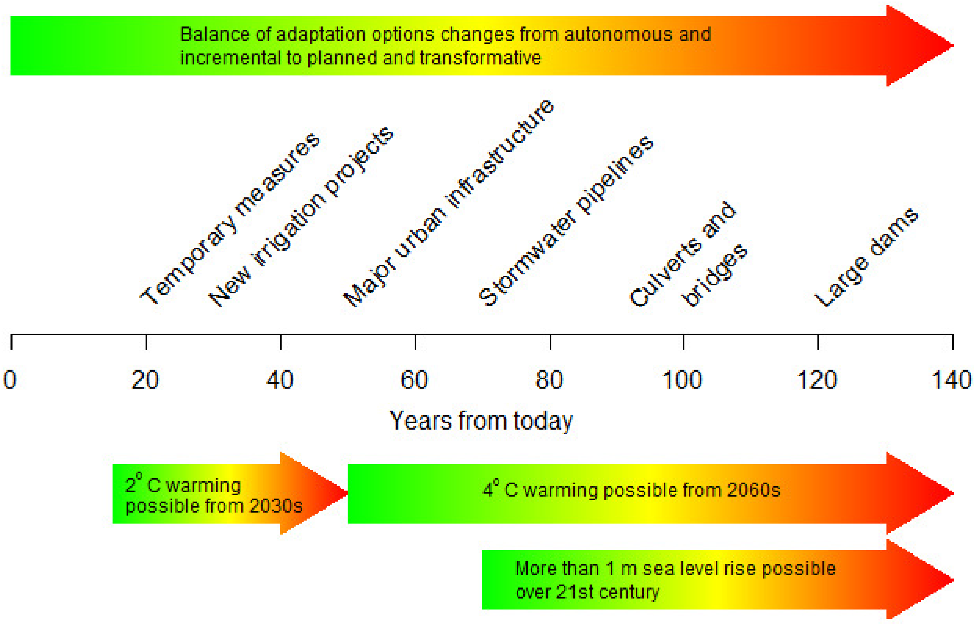

Figure 4. Timeline illustrating the lifetimes (sum of lead time and service life) of different types of decisions, compared with the time scales for some global environmental changes, and the changing implications for adaptation. (Adapted from Stafford-Smith et al. 2011, Figure 1.)

Step 3 – Consider the Purpose and Nature of the facility (Figure 3b)

The purpose of the facility (e.g., asset, process or management strategy) may include flow conveyance, improved safety, or reduced frequency of exposure and damage. Flood-related design requirements (e.g. minimum fill levels and minimum floor levels) need to be considered, as well as consequences of failure (e.g., risks to life, property and the environment) and the cost of retrofitting assets as rainfall IFD characteristics change in the future.

The impact of the possible failure of the facility will have direct and indirect consequences, and should be assessed in terms of primary risk outcomes as issues of cost, safety, social acceptability and environmental impact. Some categorisation of facilities may be useful when determining the consequences of failure. For example, projects or decisions involving assets involved in the delivery of essential services can have very damaging consequences if performance is significantly impaired or if failure occurs.

It is proposed that the consequences of failure be rated as either low, medium or high. A suggested interpretation of this consequence risk rating is:

- Low consequence: there is risk that asset performance will be impacted but delivery of services will be only partially or temporarily compromised, or alternative sources of services (e.g. availability of different power sources) are readily available.

- Medium consequence: significant risk that performance of important but non-critical assets and delivery of services will be impacted or fail for a short period of time.
- High consequence: significant risk that performance will be impacted or fail leading to disruption to delivery of essential services (where alternative sources of services are not readily available). Generally related to high value assets, or assets of significant economic or welfare importance.

Where the consequences of impact on performance or failure and the costs of retrofitting are considered to be low, the project or decision should proceed in accordance with the original design specifications. Otherwise, proceed to Step 4.

Step 4 – Carry out a Screening Analysis (Figure 3b)

This step responds to the question: “Is climate change a significant issue for the facility of interest?” Here the risks of climate change are assessed with regard to their capacity to impair the facility’s ability to perform its intended function. The description of impact or failure involves the use of extreme rainfall events with different AEPs. This task can be facilitated by use of the AEPs listed in Table 1. If the design AEP corresponds to the i^{th} position in Table 1, consider the impact of the AEP events corresponding to the $(i+1)^{th}$ and $(i+2)^{th}$ positions on the facility of interest and the associated consequences. For example, if the design AEP is 1% consider the impact of the 0.5% and 0.2% AEP events.

Table 1: Design flood annual exceedance probabilities.

AEP (%)	AEP (1 in x years)
99.75	1.002
98.17	1.02
95.02	1.05
86.47	1.16
63.21	1.58
50.00	2
39.35	2.54
20.00	5
18.13	5.52
10.00	10
5.00	20
2.00	50
1.00	100
0.50	200
0.20	500
0.10	1000
0.05	2000
0.02	5000

The outputs from this step include an improved understanding of the extent to which the risks of climate change may exceed the coping capacity of the facility to perform its intended function. If the incremental impact and consequences are low (e.g. increases in flood levels are small) then the exposure risk to climate change is low, and the design flood should be determined using historical information and approaches. Otherwise, proceed to Step 5.

Step 5 – Consider Climate Change Projections and their Consequences (Figure 3c)

At this point the exposure to climate change and consequences of impact on performance has been judged to be medium or high. Hence consideration needs to be given to whether the original design specifications of the project or the decision need to be reviewed and adjusted. This will necessitate the use of climate change projections.

The Climate Futures tool (Section 2.1) can be used to place the projected changes from the suite of CMIP5 global climate models into classes defined by two climate variables such as temperature and rainfall. The changes are relative to a 20-year (1986-2005) baseline, and can be tabulated for a given time point corresponding to the end of service life or planning horizon (e.g., 2030, 2050, 2070, or 2090) and one of the four RCPs (RCP8.5, RCP6, RCP4.5 and RCP2.6). *For practical applications of the Interim Guideline, it is proposed that RCP6 be used as the basis for all impact assessments until new information becomes available.*

Figure 5 displays an example output from the tool for a given location (Southern Slopes NRM cluster), season (winter), time point (2060) and RCP6. The 21 global climate models considered are grouped into three class intervals for winter temperature: ‘slightly warmer’ (0 to 0.5℃), ‘warmer’ (0.5 to 1.5 ℃) and ‘hotter’ (1.5 to 3.0 ℃). Perusal of Figure 5 indicates that 17 of the 21 models are in the ‘warmer’ class interval. A pragmatic choice for the projected temperature increase is (0.5+1.5)/2 = 1.0 ℃. (*Note that the projected changes in seasonal rainfall should not be used for design flood estimation purposes.*)

CONSENSUS	PROPORTION OF MODELS
Not projected	No models
Very low	< 10 %
Low	10 to 33 %
Moderate	33 to 66 %
High	66 - 90 %
Very high	> 90 %

		June - Aug temperature (°C)			
		Slightly warmer 0 to +0.5	Warmer +0.5 to 1.5	Hotter +1.5 to +3.0	Much hotter > +3.0
June - Aug rainfall (%)	Much wetter > +15.0				
	Wetter +5.0 to +15.0		1 of 21 models		
	Little change -5.0 to +5.0	1 of 21 models	14 of 21 models	2 of 21 models	
	Drier -15.0 to -5.0		2 of 21 models	1 of 21 models	
	Much drier < -15.0				

Figure 5: An example table from the *Climate Futures* web tool showing results for the Southern Slopes NRM Cluster (Figure 2) when assessing plausible climate futures for 2060 under RCP6, as defined by GCM simulated winter rainfall (% change) and temperature (°C warming).

If there is little tolerance for risk or interest lies in low probability but plausible flood events, a more complete analysis could be undertaken provided the additional expense can be justified. For example, the temperature increase indicated by the midpoint of the ‘Hotter’ class interval could be selected for additional analysis. An additional choice is to consider RCP8.5. *To ensure clarity of advice for decision makers, however, it is important to limit the number of cases considered.*

As noted in Section 2, there is a growing body of evidence that as the atmosphere warms, the atmospheric water vapour also increases, which increases the risk of more intense rainfall events. <u>*It is proposed that the Interim Guideline set a 5% increase in rainfall intensity (or equivalent depth) per °C of global warming until more detailed information becomes available.*</u> Returning to the example above, the scaling factor for the design rainfall intensity obtained from ARR Book II is therefore 1.0*1.05 = 1.05.

While the 5% increase in intensity is at the lower end of that predicted by the Clausius-Clapeyron relationship for daily rainfall (about 5 to 10% per °C) it is consistent with the results obtained from the NRM projections project (Section 2.2). The proposed rate of increase has been tempered because: there is no guarantee that the same scaling will apply across all of the frequencies and durations typically considered in flood design (Section 2.2), and there are other factors that have the potential to affect future rainfall intensity changes over land. These factors include:

- Changes in Southern Hemispheric and regional atmospheric circulation, including changes in storm track position. These changes can lead to decreases in rainfall intensity, as is evident in southwest Western Australia (Li et al. 2005; Frederiksen and Frederiksen, 2007; Westra and Sisson, 2011).
- Changes in the frequency or character of synoptic weather systems (e.g., Bates et al. 2010).
- Changes in soil wetness which may increase or limit the availability of atmospheric moisture, particularly in interior regions (e.g., Boucher et al. 2009).

Given that little information exists on potential simultaneous changes in rainfall IFD relationships, it is recommended that only rainfall intensity be scaled at the present time. Nevertheless, as the science of climate change is continually changing, the latest published sources should always be sought for use in future assessments. Where there is an additional risk of coastal flooding from sea level rise the Engineers Australia Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering (3rd edition, 2012) should be consulted.

Taking all of the above into account, if the cost of the modified design is low relative to the associated benefits in reduction to residual risk (i.e., the level of risk remaining after climate change has been factored into the design or planning process), adopt the changed design. Otherwise, proceed to Step 6.

Step 6 – Consider Statutory Requirements (Figure 3c)

If statutory requirements relating to climate change are in place, adopt the changed design. Otherwise, carry out a detailed comparative cost-benefit analysis of the original and potentially-changed flood-related design requirements and make an informed decision on how to proceed.

4. Concluding Remarks

This document is provided for the guidance of engineers and decision makers who are expected to take responsibility for the incorporation of information about projected climate change in flood design. Although this document provides a preliminary guideline for this task, climate change science is a dynamic field and the most up-to-date and localised studies should be drawn on in any decisions. This will require a continuing dialogue between designers, planners and climate scientists.

It is expected that the Interim Guideline will be replaced over time as new research findings become available. Where exposure risks to climate change and the consequences of failure of the asset are high, more detailed studies including the use of downscaling analysis specific to the location of interest are recommended. At a minimum it is recommended that the Interim Guideline be reviewed following the release of the IPCC Sixth Assessment Report on Climate Change in 2020/21.

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