Accounting for climate change in the management and development of South Australia's stormwater infrastructure

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Executive Summary

This report describes issues relevant to accounting for climate change in stormwater planning and design. The issues raised in this paper are expected to inform an update of the 2003 Metropolitan Adelaide Stormwater Management Study, and help underpin a standard approach to represent the expected future impacts of climate change on stormwater runoff and flood hazard. Key findings are outlined below in terms of projected changes to meteorological driving variables, implications of these projected changes on stormwater runoff and flood hazard, and a description of decision making and design principles that might be adopted in response to climate change.

Projected changes to the meteorological and climatic drivers of stormwater runoff and flood hazard in Metropolitan Adelaide and surrounding regions

- There is medium confidence that extreme rainfall has already increased and will continue to do so, with projected changes within an indicative band of 0%-15%/°C. The magnitude of change is likely to vary depending on storm burst duration, with sub-daily and particularly sub-hourly extremes expected to change more rapidly than daily and multi-day rainfall extremes.
- There is high confidence of an expected drying in average South Australian catchment conditions as a result of decreased average rainfall and increased potential evapotranspiration, with implications on both water quantity and quality. This drying may also potentially partially offset the impacts of an intensification of extreme rainfall on flood hazard.
- There is medium confidence of a change in rainfall seasonality, with heavy rainfall projected to increase particularly in the drier summer months. Furthermore, changes in the averages, extremes and seasonality of rainfall imply changes to other features of rainfall such as the number of wet days and the wet-dry sequencing; these in turn suggest changes to runoff across the flow-duration curve from base flows through to flood flows.
- There is high confidence of an increase in the mean sea level, with reasonable confidence in near-term (e.g. 2030) projections of the magnitude of change, but with high uncertainty regarding the magnitude of change for long-range projections (e.g. 2090).
- There is little information on changes to joint probability considerations between flood drivers, including implications on the interaction between extreme rainfall and storm surge, as well as changes to rainfall spatial and temporal patterns.
- The effect of climate change on extreme rainfall is likely to exhibit similar patterns throughout large parts of South Australia, and the rate of sea level rise is likely to be similar across the coastline. However, the relative roles of flood-producing rainfall and antecedent moisture conditions are likely to vary, especially for drier catchments and large-catchment floods.

Implications of projected changes on stormwater runoff and flood hazard

- The specific combinations of meteorological and climatic drivers that influence stormwater runoff and flood hazard are likely to be case-specific. For example, smaller urban catchments are more likely to be susceptible to increases in flood hazard than larger rural catchments, because of the greater importance of short-duration rainfall and lower infiltration capacities for these smaller catchments.
- Uncertainty bounds of future changes in stormwater runoff and flooding are very wide, and are likely to remain wide for the foreseeable future. Nevertheless, the balance of drivers points to future reductions in stormwater flows on average, but potential increases in flood hazard.

Implications on water quality and other aspects of stormwater system function are poorly understood but may be substantial.

- Despite high levels of uncertainty, there is now substantial evidence at continental and global scales that some of the meteorological drivers of stormwater runoff and floods have already changed as a result of human-induced climate change.

Decision making and design principles to accommodate future changes

- The significant changes to the climatic drivers of stormwater runoff and flooding at the regional, national and global scales suggests that climatic changes to stormwater runoff and flood hazard should be considered for both near-term and long-term planning decisions.
- The high levels of uncertainty associated with future stormwater runoff and flood hazard in the Metropolitan Adelaide region and surrounding districts suggest that approaches to understand and account for uncertainty will be critical in the management and development of South Australia's stormwater infrastructure.
- There are currently no agreed methods for specifying probability distributions of future changes to flood hazard however. However, there is sufficient information available to develop a set of plausible scenarios of future changes to the meteorological drivers of stormwater runoff and flood hazard in the metropolitan Adelaide region. Nevertheless, there will be a high level of subjectivity on the range of future changes to be considered, given that there are no definitive lower and upper bounds on the magnitude of future changes. Furthermore, the development of projections and/or scenarios will likely need to be tailored to specific applications, such as flood estimation or stormwater reuse.
- Guidance should be given on using scenarios in decision making, including robust approaches (e.g. satisficing approaches that articulate minimum standards that should be met regardless of the future climate scenario), flexible approaches (e.g. adaptive pathways and assessments of the extent to which a decision now constrains a decision later), decision timeframes (e.g. whether the decision is based on the climate state at the end of the infrastructure design life, or averaged over the design life) and strengths and limitations of risk-based assessment methods.
- In many cases, mapping between the climate drivers (e.g. intensification of extreme rainfall, reduced annual average rainfall, changes in seasonality and/or intermittency, increases in potential evapotranspiration) and system performance will be complex, and more detailed 'stress testing' may be appropriate to guard against unanticipated system behaviours as the climate changes.

Overall, there are a number of aspects of the design and decision making processes that have potential to be standardised to provide consistency in methodological principles of assessing future stormwater management and flood hazard in Metropolitan Adelaide. Nonetheless, such a methodology needs to retain sufficient flexibility to avoid a one-size-fits-all approach and accommodate differences associated with specific catchment features, design requirements, and influences of relevant climate drivers.

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1. Introduction

1.1 Scope

This discussion paper describes issues relevant to accounting for climate change in stormwater planning and design in the South Australian context. The issues raised in this paper are expected to inform an update of the 2003 Metropolitan Adelaide Stormwater Management Study, and help develop a standard approach for stormwater and flood practitioners to represent the expected future impacts of climate change on stormwater and flood hazard. The discussion paper reviews existing research and policy on the following key topics:

1. A summary of the 'state of the science' regarding expected future changes to flood hazard within the South Australian context, focusing on variables and drivers relevant to the Metropolitan Adelaide region and surrounding districts. These include extreme precipitation, antecedent catchment conditions, sea level rise and 'joint probability' events, and the meteorological drivers of those variables.
2. A discussion on approaches for addressing climate change uncertainty in the context of decision making. This includes alternative approaches for representing the uncertainty associated with climate projections, and decision-making tools to help account for this uncertainty.
3. An international review of state-of-the-art approaches for providing flood guidance, focusing on the UK, North America, Europe and New Zealand.

It is anticipated that the combination of these topics can form the basis for the development of locally relevant guidance.

1.2 Review methodology

The approach taken in this discussion paper is to assess the peer reviewed scientific literature, particularly to support Section 2 (Future changes to South Australian Floods). The literature review has been carefully curated to focus on information relevant to South Australia, and has been assessed by the authors in the context of how much confidence each line of evidence provides on historical and future changes to South Australian flood hazard. This review should be considered in the context of broader integrated assessments such as provided by the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC 2013), the Australian Rainfall and Runoff flood guidance document (Ball et al. 2016), and Climate Change in Australia (CSIRO and Bureau of Meteorology 2015).

The approach taken to Section 3 (Decision Making in an Increasingly Uncertain Future) is again based on a review of the international literature, focusing on recent work on decision making under uncertainty. This review recognises the multiple and sometimes conflicting approaches for how climate change uncertainty should be interpreted and addressed, and seeks to provide options for accounting for this in the context of possible South Australian guidance.

Finally, Section 4 (Australian and International Approaches to Incorporating Climate Change in Flood Guidance) was based on a combination of internet searches and direct approaches to international experts known to the authors. The guidance is classified in the context of decision making process described in Section 3, and is designed to support a discussion about the best approaches to represent uncertainty in the context of South Australian stormwater planning and management.

2. Future changes to South Australian floods

2.1 The meteorological drivers of stormwater runoff and flooding in the metropolitan Adelaide region and surrounding districts

The climate in the metropolitan Adelaide region is classified as Mediterranean, characterised by mild wet winters with rainfall events dominated by mid-latitude storm tracks, hot dry summers and frequent heatwaves due to hot northerly air masses. These meteorological drivers have a significant influence on the runoff regime, with the majority of annual runoff volume typically occurring in winter and spring, but with flood flows having the potential to occur at all times of the year.

Although the large-scale synoptic drivers tend to be relatively homogenous over the greater Adelaide region, local-scale physiographic features can play a critical role in determining how these large-scale processes translate to local-scale meteorology and runoff (Johnson et al. 2016; Merz and Bloschl 2003). Orographic uplift means that rainfall tends to be heavier in the higher elevations of the Adelaide Hills, compared to closer to the coast. Floods in larger catchments tend to be influenced by longer-duration rainfall events compared to in smaller catchments, and low-lying catchments near the coastline may be influenced by both fluvial processes as well as oceanic processes (including both astronomical tides and storm surges). The pervious area and presence of storages (e.g. small and large dams, water sensitive urban design features) can influence the relative roles of the extreme ‘flood-producing’ rainfall, as can the antecedent conditions (catchment wetness) prior to the rainfall event. As a consequence, local catchment features—particularly catchment size, impervious area, storage capacity and elevation relative to sea level—will have a significant bearing on how climate change will influence stormwater characteristics and the runoff regime. Further confounding analyses of expected future changes to flood magnitude and/or frequency is that the relative influence of drivers will depend on the magnitude of the flood event being considered; for example antecedent moisture is generally more important for small ‘nuisance’ flood events compared to extreme events such as the probable maximum flood (e.g. Wasko and Sharma 2017).

This heterogeneity makes it difficult to provide a uniform set of projections on how future changes to the climate will influence runoff in metropolitan Adelaide. As will be discussed below, short-rain phenomena (e.g. convective rainfall events) are affected by different climate drivers than long-rain phenomena (e.g. multi-day rainfall events that might be associated with frontal systems), so that it is possible to have different trends in flood risk within a small urban water catchment that is embedded within a larger headwater catchment (e.g. see Zheng et al. 2015 for the case of the Sydney metropolitan region). Similarly, floods in catchments with limited storages and high fractions of impervious area will likely be determined clearly by heavy rainfall events, whereas antecedent conditions will have a greater role in catchments with highly pervious soils or where storages are important. In estuarine and coastal catchments, the joint probability of extreme rainfall and storm surge is important given that both can be driven by the same meteorological phenomena, and should be considered in conjunction with non-meteorological drivers such as the mean sea level and the astronomical tides (Westra et al. 2016; Zheng et al. 2015; Zheng et al. 2014; Zheng et al. 2013). **This notion that each catchment may exhibit unique features and processes is critical in assessing how climate change will impact on stormwater quality and quantity at individual locations.**

Although the focus of this section is on meteorological drivers in metropolitan Adelaide, a number of the key processes are likely to extend to other parts of South Australia. For example, the effect of climate change on extreme rainfall is likely to exhibit similar patterns throughout large parts of the state, and rate of sea level rise is likely to be similar across the South Australian coastline. However, the relative roles of flood-producing rainfall and antecedent conditions are likely to vary for drier catchments, and large-catchment floods such as can occur in the Murray-Darling Basin are driven by very different meteorological processes to other parts of South Australia.

Box 1: Evaluating the scientific evidence for changes to South Australian runoff

There are multiple 'lines of evidence' for how anthropogenic climate change could influence stormwater runoff and flood hazard, and they need to be interpreted jointly to understand likely future risk.

Heuristic approaches based on physical reasoning: A simple 'rule of thumb' argument for the intensification of rainfall is that extreme rainfall intensity should scale with the maximum capacity of the atmosphere to hold moisture, which in turn scales with the temperature of the atmosphere based on a formula known as the Clausius-Clapeyron equation. This would suggest an increase in rainfall intensity of 6-7% per degree of atmospheric warming. In contrast, the global average annual rainfall is constrained by the global energy balance, and is suggestive of a global average rainfall change of 2% per degree of global warming. The extent to which these 'rules of thumb' can be applied to understand global average changes continues to be actively debated in the scientific literature, and are unlikely to be relevant to any particular region or rainfall 'type' given the range of local features (e.g. synoptic conditions) that are likely to be equally important to the 'large scale' changes. Nevertheless, heuristic arguments give rise to expectations that rainfall extremes are more likely to increase than the averages, and are often used to provide 'first-order' estimates regarding possible changes in extreme rainfall. Analogous approaches for other drivers such as sea level rise and 'compound' events are unavailable.

Approaches based on historical trends: The global climate has warmed approximately 1°C since preindustrial times (IPCC 2013), so that change is already apparent in some drivers such as extreme rainfall intensity and sea level. In the context of extreme rainfall, the large variability of year-to-year extreme rainfall means that it is generally not possible to find a climate change 'signal' at any specific location. However, sophisticated statistical techniques are available to combine data from multiple locations across a large spatial region, in an effort to reduce the degree of variability and thus increase the 'signal-to-noise' ratio. These techniques have found statistically significant trends in multiple regions globally, and form the basis for increased confidence in projections for rainfall intensification as provided by the IPCC (2013) and reviewed in (Westra et al. 2014). However, these methods provide average trends over large spatial domains, and therefore may mask the significant heterogeneity from one location to the next within this domain. In the context of sea level rise, the signal-to-noise ratio is much higher, adding confidence to projections of the direction of change, and to projections of the magnitude of near-term change. Finally, trend studies are typically based on relatively frequent 'extremes' such as the annual maximum event, and thus need to be interpreted with caution when considering extremes relevant to flood estimation (e.g. the 1% annual exceedance probability event).

Projections based on climate models: Global climate models (GCMs) are the primary tool used by climate scientists to develop projections of future change. These models use the equations of fluid motion and energy conservation, and apply these over a discrete set of 'grid boxes' that are currently in the order of 100km x 100km at the global scale. A limitation is that many of the physical processes that influence rainfall occur at much smaller spatial scales, and it is thus common to downscale climate models. This downscaling can be either statistical or dynamical, with a very large literature on the strengths and weaknesses of individual techniques (e.g. Fowler et al. 2007; Maraun et al. 2010). In the context of extreme rainfall, statistical downscaling methods make simplifying assumptions that are unlikely to be valid for most extremes, whereas dynamical downscaling techniques provide an improved physical representation (e.g. higher resolution) but still do not fully capture all the physical processes associated with extreme rainfall events such as convection. Furthermore, with few exceptions, dynamical models are not evaluated in the context of how they represent the physical processes associated with extreme rainfall (see Cortes-Hernandez et al. 2016). An alternative approach to the GCM/downscaling suite of tools is to use highly idealised models at high resolution that can resolve cloud physics; however these are generally not coupled to larger-scale circulation changes, so that although these experiments improve understanding of physical processes, they are not directly interpretable in the context of projections. Finally, like methods based on historical trends, most modelling results are based on relatively frequent 'extreme' events, rather than on the level of extremes commonly relevant to flood estimation.

2.2 Rainfall extremes

Extreme rainfall is expected to be the leading driver of pluvial and fluvial floods in the metropolitan Adelaide region and surrounding districts, and the conclusion from most observational and modelling studies is that the intensity of extreme rainfall is likely to increase. Much of this is based on physical arguments based on thermodynamic considerations (see Box 1) that the moisture-holding capacity of the atmosphere will scale at 6-7% for each degree of warming. Under the assumption that all other factors are unchanged, this would lead to an equivalent change in the intensity of flood-producing rainfall (Trenberth et al. 2003).

There has been significant recent research and debate in the literature, based on both observational and modelling evidence, which suggests that this scaling rate is unlikely to be either a lower or upper bound of what might be possible (Bao et al. 2017; Barbero et al. 2017; Berg and Haerter 2013; Berg et al. 2013; Haerter and Berg 2009; Haerter et al. 2010; Hardwick-Jones et al. 2010; Lenderink et al. 2011; Lenderink and van Meijgaard 2008; Lenderink and van Meijgaard 2009; Lenderink and van Meijgaard 2010; Loriaux et al. 2013; Utsumi et al. 2011). Several studies have suggested that the assumption that actual moisture in the atmosphere may not scale with the capacity of the atmosphere to hold moisture. For example, Hardwick-Jones et al. (2010) found that at higher temperatures, moisture limitations started to constrain extreme rainfall intensity. Projections of future change also found that although the relative humidity (i.e., the moisture in the atmosphere relative to its capacity to hold moisture) is projected to remain unchanged on average globally (IPCC 2013), this may not apply for dry continental regions such as large parts of Australia (CSIRO and Bureau of Meteorology 2015). Therefore, there is the potential for extreme rainfall to scale at a rate well below that indicated by the Clausius-Clapeyron equation. Conversely, other evidence suggests that it is possible for rainfall to scale at rates of at least double the Clausius-Clapeyron rate, particularly for short-duration convective systems (e.g. Lenderink and van Meijgaard 2008). This is partly attributed to the additional buoyancy created by the warmer atmosphere, leading to storms not only drawing in more moist air, but also drawing this air in at a more rapid rate. This phenomenon is known as ‘super Clauisus-Clapeyron scaling’, and rates of 15% per degree of warming or above are commonly cited in the literature.

The above studies explore the relationship between the intensity of extreme rainfall and the atmospheric temperature on the day the rainfall occurred; however this historical association does not provide a direct indication of how extreme rainfall intensity will change as a result of increases in atmospheric moisture content. For example, this type of analysis does not identify changes in the *likelihood* of extreme events occurring (for example due to changes in circulation), and the assumption that the historical temperature-extreme rainfall relationship will stay unchanged in the future is largely untested but unlikely to be valid. Analyses that link temperature scaling arguments to key storm mechanisms (e.g. Dowdy and Catto 2017) are largely absent, although several studies suggest that changes as a result of convective systems are likely to be different (and probably stronger) than those associated with frontal systems (Berg and Haerter 2013; Berg et al. 2013)

An alternative line of evidence is therefore whether extreme rainfall intensity has changed as a result of historical increases in atmospheric temperature. Unfortunately, there is no credible evidence of historical trends in extreme rainfall that directly reflects the local conditions in the metropolitan Adelaide region, as a result of the low signal-to-noise ratio when analysing such a small geographic region (see Box 1). However, there have been numerous studies conducted either over continental Australia or large sub-regions, which may provide a guide as to the likely changes relevant to this region. For example, Westra and Sisson (2011) analysed trends for a region in eastern Australia (encompassing Adelaide) and found limited evidence of change at daily timescales, but statistically significant evidence that surpassed expectations based on thermodynamic considerations at hourly timescales. Zheng et al. (2015) found a similar result for the Greater Sydney region, suggesting that the different rainfall mechanisms could lead to fundamentally different findings for short-duration events (which tended to happen in summer as a result of convective processes) and longer-duration events (which were more evenly distributed throughout the year, and were triggered by different mechanisms).

The main source of information for future climate projections relevant to South Australia is provided in the Climate Change in Australia document for the Southern and South-Western Flatlands – East cluster encompassing metropolitan Adelaide (Hope et al. 2015). This suggests high confidence in the intensification of heavy rainfall events, but there is low confidence in the magnitude of the change. For example, the magnitude of the 20-year return level of daily extreme precipitation is projected to increase by between -2% and +40% for the 2080-2099 time horizon relative to 1986-2005 for representative concentration pathways (RCPs) 4.5 and 8.5[1]. The report has the caveat that the range of changes "do not relate directly to the probability of the real world changing under a given RCP", and that the uncertainty is likely to be wider than indicated.

Some downscaling has been conducted for South Australia; however it is unclear whether these add value to the results provided by Climate Change in Australia in the context of precipitation extremes. In particular, the non-homogenous hidden Markov model (NHMM) approach was not specifically designed to capture the physical processes that lead to extremes, and in evaluating the utility of this dataset for flood flows in the Onkaparinga, Westra et al. (2014) identified concerns with this dataset particularly in the context of multi-day extremes.

Summary: There is medium confidence of an increase in extreme rainfall intensity and/or frequency, with projected changes within an indicative band of 0%-15%/°C. There is likely to be a strong link between projected changes and storm burst duration, with sub-daily and particularly sub-hourly extremes expected to change more rapidly than daily and multi-day rainfall extremes. There is now sufficient evidence at global and continental scales that extreme rainfall, particularly at sub-daily timescales, has already increased as a result of warming over the 20th and early 21st centuries.

2.3 Average moisture conditions

A catchment's moisture conditions prior to an extreme rainfall event can play a significant role in determining whether an extreme rainfall event will lead to a flood (Merz and Bloschl 2003). Within the context of this report, antecedent moisture conditions refer to the moisture held in the catchment immediately prior to a 'flood-producing' extreme rainfall. This can include water stored in the catchment's saturated (i.e. groundwater) and unsaturated (i.e. soil moisture) zones, in lakes and reservoirs, in detention basins and other water storage devices. In this sense, 'antecedent moisture content' is not a measurable quantity, but rather a conceptual term that determines the extent to which moisture that is stored in the various parts of the catchment influence how extreme rainfall is translated to flooding. Empirical estimates of antecedent conditions include the Antecedent Precipitation Index (API), which is an index measuring rainfall prior to a flood event; and loss parameterisations within event-based rainfall-runoff models.

The impact of climate change on antecedent moisture conditions will depend on a range of factors, including changes in annual and seasonal average rainfall, the wet-dry sequencing of rainfall events, and the timing of flood-producing rainfall. In South Australia the latter can be particularly important

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[1] Representative Concentration Pathways (RCPs) are hypothetical future atmospheric greenhouse gas concentrations, with RCP4.5 and RCP8.5 representing a net radiative forcing in 2100 of 4.5 and 8.5 W/m^2 relative to pre-industrial values, respectively. RCP4.5 represents the case of emissions peaking in 2040 and then declining, whereas RCP8.5 represents continual increases in emissions through to 2100.

if there is a change in the seasonality of flood-producing rainfall, given the significant drying of catchments during the warmer months. Furthermore, catchment features will have a strong influence on the role of antecedent moisture conditions: based on mass-balance considerations, extreme rainfall on catchments with large impervious areas and limited reservoirs and other storages are likely to be less influenced by antecedent conditions compared to highly pervious catchments with significant storages.

Based on historical flood data, there is some emerging evidence that antecedent moisture conditions may be important in driving flood risk in rural catchments in southern Australia (including South Australia, Victoria and southwest Western Australia). For example, Ishak et al. (2013) showed a declining trend in annual maximum flood flows in this region, despite not finding evidence of a similar trend in annual maximum rainfall events, suggesting the importance of annual average rainfall in influencing flood magnitude. Similar results were found by Do et al. (2017) and Wasko and Sharma (2017), with the latter study suggesting that "only in the most extreme cases, for smaller catchments, do increases in precipitation… correspond to increases in streamflow". However, due to limited gauging information in urban stormwater catchments, the extent to which such a decrease is occurring in urban catchments in the metropolitan Adelaide region is unclear.

Based on climate projections, there are indications that projected changes in antecedent moisture will act to reduce flood hazard in South Australia. In particular, even as extreme rainfall is projected to increase, annual average rainfall is projected to decline (Hope et al. 2015; Westra et al. 2014), such that extreme rainfall may fall on drier catchments. This is also indicated in a detailed downscaling study applied to runoff in the Onkaparinga catchment, in which Westra et al. (2014) found a median change of 37% by 2071-2100, and worst-case changes of up to an 80% decline in annual average runoff, and with 98% of simulations agreeing that runoff will decline towards the end of the 21st century. Furthermore, possible shifts of seasonality (with declines in rainfall over winter but less obvious trends in summer) suggest the possibility that flood-producing rainfall may occur more frequently over the drier summer months.

Summary: There is high confidence of an expected drying in average South Australian catchment conditions, potentially offsetting the flooding implications of an intensification of extreme rainfall. Furthermore, projected changes to the seasonality of flood-producing rainfall suggest that extreme rainfall events may increasingly occur during the drier summer months. Drier catchment conditions are also anticipated to lead to reductions in annual average flows and the frequency of low flow events.

2.4 Sea level rise and storm surge

Coastal flooding typically occurs through the combination of high astronomical tides and storm surges. Global mean sea levels have increased by about 1.7 mm/yr over the period from 1900-2010, with increases in southern Australia consistent with this global average (CSIRO and Bureau of Meteorology 2015). Near-term projections are for mean sea level to increase in the coastline adjacent to Adelaide by a further 0.07-0.17 m above the 1986-2005 level by 2030 (Hope et al. 2015). The uncertainty in mean sea level projections increases substantially after this time depending on the emissions scenario together with highly uncertain changes to ice shelf dynamics in the Arctic, Greenland and Antarctic. Projections for Port Adelaide provided by CSIRO and Bureau of Meteorology (2015) indicate a change of between 0.23 and 0.84 m by 2090 (integrating across RCPs 2.6 to 8.5). However this report also highlights that these are 'likely' ranges encompassing at least the 66% probability interval, and therefore provide limited information on likely 'worst case' changes particularly as the result of possible feedbacks from the Antarctic ice sheet, which would lead to projections 'several tenths of a metre' above this range.

In addition to changes to mean sea level, changes to storm surge, wave set-up and wave run-up could lead to even higher peak sea levels that could cause flood events. Based on all these factors, CSIRO and Bureau of Meteorology (2015) provide allowances that should be used in order to preserve the same exceedance probability relative to 1986-2005, which for Port Adelaide is approximately 0.13 m for 2030 (approximately the mid-range of the mean sea level rise projections), and between 0.50 and 0.81 cm for 2090. However, limited information about the uncertainty of these estimates is presented. This report suggests, based on climate model analyses, that changes to extreme sea levels as a result of changes to weather systems are likely to be small, with projected changes in mean sea level being the dominant factor affecting changes to extreme sea levels. These numbers are largely consistent with recommendations by the South Australian Coast Protection Board (2004) to consider 0.3 m sea level rise by 2050 and 1 m sea level rise by 2100 for coastal policy.

Finally, it is noted that beyond the direct influence of sea level rise on flood risk, the indirect impacts of changes to estuarine geomorphology could also impact on estuarine flood risk. The importance of geomorphological response to sea level rise and changes to storms is highlighted in Tonmoy et al. (2018), who suggest that this forms an integral component of the uncertainty estimate within a risk assessment. The extent to which longer-term geomorphological changes along the metropolitan Adelaide coastline will affect overall flood hazard in low-lying catchments has not been assessed in this report.

Summary: There is high confidence of increase in mean sea level, with reasonable confidence in near-term (e.g. 2030) projections of the magnitude of change, but with high uncertainty regarding the magnitude of change for long-range projections (e.g. 2090), or of other aspects related to estuarine flood risk such as changes in coastal geomorphology.

2.5 Joint probability considerations

Floods commonly arise because of a complex combination of factors that align in both space and time, and often as the result of multiple separate drivers. Such events are referred to as 'compound events', and are discussed at length in Seneviratne et al. (2012) and Leonard et al. (2014). An example of such an event is the Queensland 2010/11 flood, in which a La Niña event resulted in a wetter-than-average spring, saturating soils and filling up a number of reservoirs. A flash flood occurred in Toowoomba as a result of a very intense short-duration rainfall event, whereas the emergency releases from Wivenhoe Dam that led to the Brisbane floods were the result of two separate heavy rainfall events occurring three days apart. Cyclone Yasi in the north of Queensland was also part of the sequence of events, and was associated with heavy rainfall and storm surges causing widespread flooding across Queensland. This combination of events stretched emergency response services, and placed a heavy burden on state and national government budgets. Examples analogous to the Queensland flood in terms of their complexity have also overwhelmed flood defences in other parts of the world, most recently including Hurricane Harvey in southern USA.

The implications of climate change on compound events has started receiving increased attention, but published research remains scarce. In many cases, limitations are the result of challenges in representing the multitude of spatial and temporal scales pertinent to compound events. Furthermore, major historical events are relatively rare and tend to be unique, so that there is limited empirical data on which to develop future projections. However, the understanding that system failures often result from multi-dimensional phenomena with complex spatial and temporal signatures rather than 'canonical' flood events typically used for risk assessment is posing a significant challenge to traditional approaches to planning and managing of both historical and future flood hazards.

To this end, arguably the main area of research in Australia has been associated with the joint probability of extreme rainfall and storm surge along the coastal zone. This work is included in the Australian Rainfall and Runoff guidance (Westra et al. 2016), and describes methodology for quantifying flood risk in estuarine regions that may be affected by both fluvial and oceanic processes. The method enables incorporation of climate change in the individual driving variables (e.g. an intensification of extreme rainfall, or an increase in sea level), but assumes that the joint probability of extreme rainfall and storm surge is likely to stay constant into the future. This assumption has not been tested using climate models, but it is likely that changes to the dependence between these processes are likely to be second-order relative to changes to the individual driving variables.

Other joint probability considerations are generally rarely considered in practice in the context of flood risk estimation. Changes to the temporal patterns of rainfall events relates to the potentially opposing changes in extreme flood-producing rainfall and antecedent conditions discussed earlier. Although methodology is available to account for continuous sequences of rainfall events in flood estimation (Sharma et al. 2016), these methods are rarely used in practice, and limited information is currently available on how to adapt these methods in a climate change setting. Similarly, although there is emerging evidence that the spatial features of extreme rainfall events are temperature-dependent (Wasko et al. 2016) and thus are likely to change in the future, there is currently no guidance available on the implication of these issues on areal reduction factors or conditional flood risk (i.e. the likelihood that one location is flooded, given a neighbouring location if flooded, as would be required for the design of emergency evacuation routes).

Summary: It is anticipated that changes in the joint probability of extreme rainfall and storm surge as a result of climate change are likely to be second-order relative to changes in the primary variables themselves, although this assumption has not been tested using climate models. Other joint probability considerations, such as the spatial dependence of extreme rainfall events and the temporal sequencing of heavy rainfall, have received little attention in the literature, although increasing evidence suggests the temporal and spatial patterns of extreme rainfall are likely to change in the future.

3. Decision making in an increasingly uncertain future

3.1 Classes of information to support decision making in an uncertain future

As discussed in Section 2, assessments of future changes to stormwater and flood hazard are characterised by high levels of uncertainty. This uncertainty arises because of the complexity of the processes involved, the range of space and time scales (ranging from planetary processes and multi-decadal timescales through to local-scale catchment processes at the sub-hourly timescale), and uncertainty about future technological advances and human actions taken to reduce greenhouse gas emissions (which affects future emissions trajectories). Based on the current rate of scientific advances in the field, uncertainty of future changes to stormwater runoff and/or flood risk in South Australia is unlikely to be reduced substantially over the coming 5 to 10 years.

Managing this large degree of uncertainty is often an overriding factor in the choice of analysis method, and should inform the design framework, the planning horizon and scope, the influence of design parameters such as cost or risk aversion, and potential trade-offs between design decisions. In selecting an appropriate decision-making framework, a key distinction is whether the method assumes that future climate states are represented probabilistically or not, which relates to an on-going debate about the differences between 'risk' and 'uncertainty' (see Box 2).

Box 2: Risk* versus uncertainty

A key distinction between risk* and uncertainty is made by Knight (1921) and has been variously re-expressed by others in literature:

Knightian uncertainty	(Knight 1921) – 'uncertainty' is essentially unmeasurable and therefore cannot be represented probabilistically, whereas 'risk*' can be quantified through a probability distribution.
Deep uncertainty	(Lempert et al. 2003) – 'analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate models to describe the interactions among a system's variables; (2) the probability distribution to represent uncertainty about key variables and parameters in the models; and/or (3) how to value the desirability of alternative outcomes.'
Black swan events	(Taleb 2010) – events that fall outside historical statistical patterns, and thus are difficult to characterise using traditional statistical approaches.

Knightian uncertainty (or its more recent variants) poses a significant challenge to traditional risk-based approaches, which are based on the integration of probability and consequence and thus assume that the probability of a given event can be quantified. Economic approaches for decision making, such as cost-benefit assessments, similarly assume that costs and benefits can be estimated through integration across the set of possible future events.

* *'Risk' in the Knightian context refers to a probability distribution of future states of the world, and is distinct from the risk used elsewhere in this report that combines both probability and consequences.*

The distinction between risk and uncertainty leads to two separate 'classes' of information that are commonly used to inform decision making under climate change:

Projections – probabilistic statements of future climate states, which enable statements of 'most probable' future climate or the development of a complete probability density function. This information is usually obtained from outputs derived from climate models, potentially followed by some form of dynamical and/or statistical downscaling, and are particularly useful for quantitative risk-based analysis approaches.

Scenarios – hypothetical changes detached from any notion of probability, that are designed to enable 'what if' analyses (e.g. 'what if there is a 10% increase in extreme hourly rain'). A common application of scenarios is to explore the potential of cliff-edge effects (significant changes in system function as a result of changes in some variable, and that may alter decision making). There are numerous approaches for scenario generation, with the most suitable approach dependent on the available information and on the application. Examples of approaches include:

- Scenarios based on historical events or perturbed historical events (e.g. a historical event with a higher ocean level, or a historical event in which extreme rainfall and storm surge coincided whereas in reality they did not). These scenarios have the benefit of physical plausibility, and are often easy to relate to for decision makers and the general public.
- Expert elicitation of future climate outcomes can formalise the development of scenarios, whether based on historical events or hypotheticals. Quantitative and semi-quantitative methods are available to interpret and combine qualitative information from experts to determine scenarios that are plausible, relevant, and challenging (Riddell et al. 2018). The process may involve any number of methodologies and experts depending on resourcing and availability. Prominent examples include the Delphi method and fuzzy cognitive mapping. Compared to uncertainties associated with risk exposure and vulnerability, the requirement for physical plausibility of a flood hazard imposes a strong constraint.
- Outputs from climate models may be interpreted as scenarios, particularly when considering multiple future concentration pathways or recognising that not all processes are adequately represented in the climate models.
- Scenarios to inform structured sensitivity analyses (e.g. a 10%, 20% and 30% change in extreme rainfall).

Based on the state-of-the-science review in Section 2, it is not possible to develop precise probabilistic statements of future climate states as relevant to stormwater runoff and/or flood hazard. However sufficient information is likely to be available to generate scenarios and articulate the range of expected future change in the climatic drivers of stormwater runoff and/or flood hazard. Such information will need to be tailored to the approach for decision making as discussed in the following section.

3.2 Methods for decision making under uncertainty

The selection of a method for decision making depends on whether future states of the world are interpreted probabilistically or as scenarios as defined above. Table 1 provides a brief description of four key methods, the type(s) of information required by each method, and the key output that the method provides as the basis for guiding decisions. Further information on each method is provided in the sections that follow. Note that the first three methods identify 'best' decisions whereas the fourth method (sensitivity testing) is qualitatively different and is more suitable for mapping the performance of the system and identifying decision options rather than determining 'best' decisions. In many cases, sensitivity methods are used as a precursor to one of the other decision making approaches.

Table 1 Comparison of methods according to information input and decision output

Method	Information type	Key output(s)
Risk-based methods – where risk is the product of event probability and consequences	**Projections** –represented with an associated probability of occurring (e.g. providing a 'most likely' future change and 5 and 95 percentile bounds)	Often a single 'best' option (e.g. through an economic evaluation of costs and benefits), plus a statement of how to deal with residual risk.
Robust methods – determine the best option from multiple scenarios in a non-probabilistic manner	**Scenarios** – a range of hypothetical cases of plausible future states of the world, often obtained from model outputs and/or expert elicitation	Identification of a best option regardless of future climatic conditions.
Flexible methods – focus on assessing flexibility in sequences of options according to critical timeframes and decision points	**Scenarios and/or Projections** – where combinations of options are considered according to multiple projections and/or scenarios	A dynamic or flexible plan specifying sequences of implementation and review actions as climate changes
Sensitivity methods – (e.g. system 'stress testing') focus on system understanding decoupled from climate projections	**Scenarios (then Projections)** – scenarios are used to identify decision options and understand the system. Optionally, the method can be extended to include information from climate models and other lines of evidence to further guide decision making.	A map of system performance against possible future changes, to identify decision options.

Risk-based methods

Risk estimates are generally derived as the combination of the probability of a given hazard multiplied by the magnitude or consequence of its impact. They align well with conventional design methodologies for urban water infrastructure in Australia, which focus heavily on probabilistic specifications (e.g. 1EY, 5% AEP, 1%AEP, etc) of water levels or related measures of performance such as inundation area, runoff volume, flow velocity x depth, rate of rise, etc.

The intent of risk frameworks is that decisions are made through formal consideration of both the probability of a future event and its expected magnitude or consequences. Risk-based methods align well with common methods for economic decision making such as cost-benefit analyses, whereby the costs of mitigation of an adverse impact (e.g. a levee to mitigate against a flood) can be compared to the cost of the flood losses multiplied by the probability that those losses will occur. A benefit of risk-based design is that it allows for greater levels of risk aversion to be considered according to the magnitude or consequences of impact. Similarly, the precautionary principle can be applied where greater uncertainty in an estimate of risk leads to greater levels of risk aversion.

In the absence of anthropogenic climate change, the historical record has often considered as a good proxy for the probability distribution of future outcomes, and the tractability of risk-based calculations has meant that risk-based approaches are now widely used in stormwater and flood design. However as discussed earlier, the critical challenge of risk-based approaches when considering future climate change over potentially long future time horizons is the role of Knightian uncertainty (Box 2), which prevents precise statements of hazard probability and therefore risk. This is partly addressed through risk-based approaches that rely on qualitative assessments of probabilities (e.g. 'very likely', 'likely', 'unlikely', 'rare') and consequences (e.g. 'minor', 'moderate', 'significant', catastrophic'), although a judgement about qualitative probabilities is nevertheless required.

An alternative approach for addressing the potential for probability misspecification is to ensure that contingencies are available to deal with 'residual risks'. Engineering practice has conventionally used a number of methods of varying sophistication to account for residual risk, e.g.:

- Simple specifications such as explicit overdesign, safety factors, and freeboard (Olsen 2015); or
- Use of operational measures for monitoring, mitigating and emergency response.

As a result of Knightian uncertainty, risk-based approaches are likely to become increasingly difficult to apply for decisions that span a long way into the future or for which uncertainty is already very high. As a result, there has been significant focus on two alternative risk-based approaches; those based on 'robustness' concepts (i.e. the design that is successful regardless of the future climate outcome) and those based on 'flexibility' concepts (i.e. flexibility is built into the design to be able to accommodate changes in climate outcomes as further information comes to light). These two approaches are now discussed.

Robust decision making

Robust decision making is when the performance of a system is evaluated to account for the uncertainty of multiple plausible future scenarios without reference to probabilities (McPhail et al. 2018), and therefore partially offsetting difficulties posed by Knightian uncertainty. Common to all robustness metrics is the requirement to specify future conditions (scenarios), decision alternatives (design options, plans) and the outcome of each decision alternative (cost, reliability). Examples include:

- Maximin and Maximax – the design that works best against the worst-performing and best-performing scenarios, respectively, corresponding to extremely pessimistic and optimistic risk appetites.
- Hurwicz rule – the design that performs best against a weighted average of worst and best cases where the weighting between zero and one parameterizes the degree of risk aversion.
- Principle of insufficient reason – cites ignorance in the scenario likelihood, implying scenarios should be treated equally, i.e. calculate expected performance as a non-weighted average.
- Minimax regret – the design that minimizes the worst-case regret, where regret is the difference between the performance of a selected design relative to the design with the best possible performance.
- Satisficing criteria – leading to all designs satisfying minimum performance thresholds and where risk aversion is parameterized via the performance thresholds.

Robustness metrics codify the problem of 'deciding how to decide' on evaluation of the system performance (McPhail et al. 2018). For example, there is a large difference in the degree of implicit risk aversion associated with the various metrics. Reasons for the differences include whether the performance is based on absolute or relative performance, the subset of climate scenarios considered, and the metric of interest. In other words, the use of robustness metrics does not inherently settle the problem of objectivity, since the decision maker must articulate their appetite for risk in order to appropriately select a robustness metric.

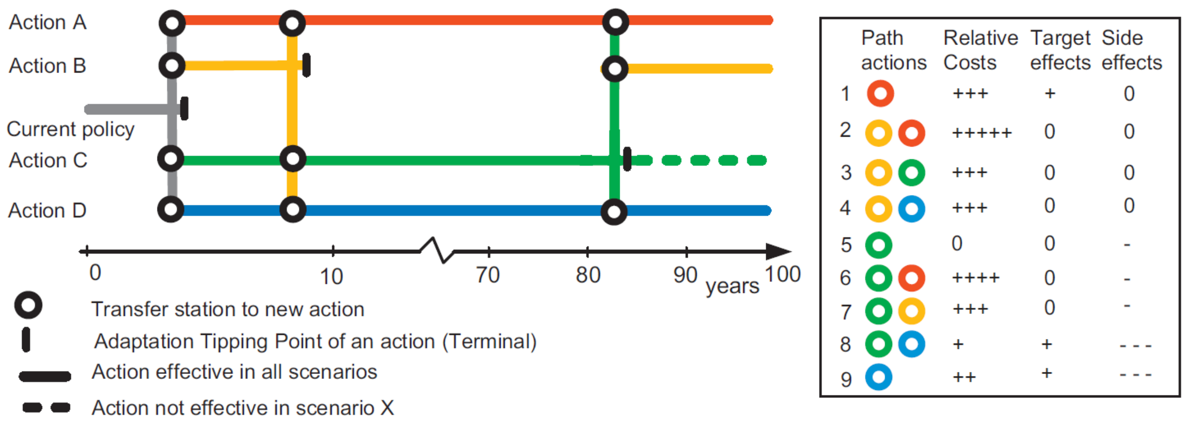
Flexible decision making

Adaptive methods pre-empt and guard against ways a plan might fail, prepare for future actions that might be triggered, and allow for continual monitoring of system performance. They are designed to keep options open by avoiding lock-ins, identifying opportunities, delineating path dependencies, framing plans according to different societal perspectives, developing contingency plans, deferring decisions and allowing for monitoring and corrective actions as the plan progresses (Haasnoot et al. 2013). They also connect short-term actions to long-term goals via possible sequences of implementation options.

Flexible adaptive plans have been applied in numerous countries for water management and implementation of flood risk infrastructure. While there is variation in terminology (e.g. options analysis, decision trees, roadmaps, and iterative risk assessment) there is considerable overlap in concepts. These approaches emphasize the need for flexibility and stand in contrast to conventional methods that express a static 'optimal' plan focussed on a single 'most likely' future or a static 'robust' plan across a set of plausible future scenarios.

One established method for accommodating changes throughout a design life is the ‘Observational Method’ (Olsen 2015). The observational method is a continuous, managed process of design, monitoring and control that enables modifications to be incorporated appropriately, achieving overall economy without compromising safety. For example, a dam might be built having a moderate level of residual risk, but with options to upgrade the dam height down the track. Using this method, infrastructure is based on the most probable conditions rather than the most unfavourable, with uncertainty accounted for in the subsequent monitoring and adjustment process (Olsen 2015). For this reason, the observational method is particularly suitable for gradually varying climatic changes such as those associated with sea level rise, where departures from the ‘most probable conditions’ can be identified early and taken into account in subsequent decisions.

‘Dynamic adaptive policy pathways’ is a method developed in the Netherlands to guide long-term decision making. The pathways represent a sequence of alternative routes to achieve the same desired point in the future. They are presented with a strong analogy to colour-coded transit 'metro' maps, where an overall journey can be completed by switching routes at key stations and where the cost and benefit of each route is accounted for using a scorecard (Figure 1). In this methodology, it is assumed that different climate projections affect the timescale of implementation, but not the identified sequence (e.g. a relatively more severe climate projection leads to the actions being implemented on a shorter timescale).



	Path actions	Relative Costs	Target effects	Side effects
1	🔴	+++	+	0
2	🟡🔴	+++++	0	0
3	🟡🟢	+++	0	0
4	🟡🔵	+++	0	0
5	🟢	0	0	-
6	🟢🔴	++++	0	-
7	🟢🟡	+++	0	-
8	🟢🔵	+	+	- - -
9	🔵	++	+	- - -

Adaptation Pathways Map

Scorecard pathways

Figure 1 Example metro-map from Haasnoot et al. (2013).

Adaptive pathway approaches can be more complex than other methods, as they often involve mapping a large number of options and triggers against a broad set of future climate scenarios. However, the idea of an adaptive strategy is often attractive to planners (Haasnoot et al. 2013), and the framework’s strength is in forming sequences of actions that account for decision trade-offs.

Regardless of method, flexible adaptive plans work best for cases involving gradual changes (as with population change or sea level rise), but can struggle with cases where extreme events are erratic, with timing that is hard to predict (as with the natural variability of droughts or extreme rainfall events). This is because for these cases, it may be difficult to know when a trigger point is surpassed, since this requires a diagnosis of whether any change is a manifestation of natural variability or anthropogenic climate change.

3.3 'Stress-testing' and sensitivity analyses

The above methods assume that a set of design options have already been identified, so that the problem is to select the 'best' option for the case of an unknown future climate. However, in many cases a systematic approach is needed for identifying alternative design options that can be resilient against a range of future climate states. In these cases, climate 'stress testing' of both current system performance and potential alternative design options can help identify design strengths and weaknesses, and thus may facilitate the generation of alternative design options that can address vulnerabilities and respond to a range of plausible future climate states.

'Stress testing' and sensitivity analysis represent a set of formal methods for mapping system behaviour for all conceivable states to which the system might be subjected (Reynard et al. 2017). An advantage of these methods is that they prioritise system understanding across multiple states rather than converging on a pre-conceived future climate. They are particularly useful for analysing complex systems that are subjected to multiple interdependent climate drivers[2], for which climatic changes and/or system modifications can lead to unanticipated modes of behaviour that cannot be identified through more qualitative desktop approaches. Ways of representing the results from stress tests include:

- 'Decision-scaling' (Brown et al. 2012), which seeks to identify the conditions under which a given design option is preferable to another design option;
- 'Operational adaptive capacity' (Culley et al. 2016), which seeks to identify the extent to which modifications in system operation can mitigate the need for infrastructure upgrades

Finally, because stress testing is conducted on a wide range of future changes, the system understanding will remain relevant in the light of new climate projections and/or scenarios, which can be easily overlaid onto existing maps of system performance without needing to repeat analysis of the system (Reynard et al. 2017).

3.4 Comparison of methods and recommendations

Table 2 provides a comparison of methods showing significant differences in emphasis, procedures and key outputs. Appreciating the key requirements of a design or decision process will significantly aid the ability to identify the most relevant method(s) and to standardise specifications for how that method is deployed. Important requirements to consider are the relative importance of the design (and hence effort put into analyses), the design life, the level of risk aversion, the breadth of climate states to be considered, the complexity of the system, likely influence of key climate variables, the number of options to be considered and available mechanisms for accommodating residual risk.

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[2] Examples of complex systems include water supply systems that are dependent on multiple water sources (e.g. surface water, groundwater and inter-basin transfers) that are each affected by different climate drivers (e.g. intensification of extreme rainfall, reduced annual average rainfall, changes in seasonality and/or intermittency, increases in potential evapotranspiration) or coupled water/energy systems.

Table 2 Comparison of assessment techniques for addressing climate uncertainty in decision making

Assessment technique	Advantages	Disadvantages
Risk-based methods	• Established with existing codes of practice • Represents a formal quantitative method for decision making, via methods such as cost-benefit analyses	• The extent to which climate projections can be interpreted probabilistically has recently been questioned.
Robust methods	• Are designed to avoid requirement of probabilistic assessments of future climate change • Suitable for decisions that are difficult to augment or modify later on, or for cases with significant natural variability where identification of 'trigger points' is difficult.	• Potential high level of sensitivity to the scenarios • Different robustness metrics represent different levels of implicit risk aversion • May lead to an unnecessarily 'conservative' decision
Flexible methods	• Able to generate plans for complex systems with optimal sequences of actions and options • Provides a reliable system that enables decisions to be deferred and reviewed until they become necessary. • Provides a pathway for multiple climate scenarios (as with 'adaptive pathways')	• Computationally demanding • Requires careful selection of decision options and parameters • Best suited to gradual change (sea level, land use) and less apt for erratic events (extreme rain).
Sensitivity methods	• Focuses on understanding the system rather than on climate projections • Can be readily updated with new evidence (model runs, observations) • Particularly useful for complex systems where the relationship between future climate changes and system performance can lead to unanticipated behaviours and outcomes.	• Can be computationally demanding when climate sensitivity of many variables is required • Does not directly lead to a design decision or adaptive pathway, but instead may be used as a precursor to these analyses

The above analysis leads to the following recommendations:

- The implications of climate change on stormwater and flood hazard is inherently uncertain, so that a precise probability distribution of future climate change is unlikely to be available in the foreseeable future. Risk-based approaches are nevertheless likely to be appropriate when probabilities are interpreted in a more approximate or qualitative sense, and where analyses of residual risks are undertaken to account for unforseen outcomes.
- Robust and flexible approaches are appropriate in situations where future climate scenarios are available. Robust approaches are particularly useful for decisions that are difficult to modify or augmentation later on; whereas flexible approaches are useful when there is scope for modification or augmentation.
- For complex systems where the relationship between future climate drivers and system performance can lead to unanticipated behaviours and outcomes, sensitivity analyses and system 'stress tests' can assist in identification of key vulnerabilities and possible design options.

3.5 Case study: an integrated framework for decision making under uncertainty

The climate resilience assessment framework and tools (CRAFT) was recently developed for the South Australian Goyder Institute as the basis not only of system stress testing, but also in identifying and selecting between alternative options for improving overall system resilience (Bennett et al. 2018). The framework comprises the following five steps:

1. **Problem definition and identification of system performance measures**. This step requires clear articulation of system boundaries, performance measures (including social, economic and/or environmental measures), and an articulation of how climatic and non-climatic factors can influence system performance.
2. **System stress testing**. In this step, hypothetical future changes of key climate variables and combination of those variables (such as changes in the averages, seasonality, extremes and intermittency of rainfall) are run through a system model, to assess the extent to which the system performance may change in the future. This could include identification of 'failure boundaries' (i.e. the climatic conditions under which the system is no longer acceptable) and an overall assessment of the key drivers of system performance.
3. **Incorporation of climate projections and other lines of evidence**. At this point, outputs from climate models (possibly with statistical and/or dynamic downscaling) and other lines of evidence can be superimposed onto the analysis in Step 2. Importantly, the method does not presuppose an approach for handling uncertainty, and is suitable for both projection-based and scenario-based thinking.
4. **Identification of system management options**. Once key system sensitivities are identified, an exploratory process is proposed for developing possible solutions. These can include planning, engineering, management, economic and other forms of solutions, and importantly depends on how the system boundaries and performance measures are defined. It is possible that revisiting system boundaries and/or performance measures may be needed at this point.
5. **Decision analysis**. Having identified alternative options in Step 4, in this step trade-offs between different options can be considered. Importantly, it is suggested that decisions be considered within an adaptive pathways context, in which the flexibility to make future modifications should be considered as part of the overall analysis.

The framework is accompanied by an open-source software tool (*fore*SIGHT – System Insights from Generation of Hydroclimatic Timeseries), available from https://CRAN.R-project.org/package=foreSIGHT and includes multiple stochastic weather generators, visualisation tools and user documentation.

The framework and software have been tested on the Parafield stormwater capture and managed aquifer recharge system. The results from this case study showed that climate change could lead to a significant change in system performance (based on volumetric reliability), due to a combination of changes to mean annual rainfall, potential evapotranspiration, number of wet days (intermittency) and seasonality. This provides the underpinning information to enable the selection of alternative infrastructure scenarios (e.g. increase number of injection wells, augmentation of holding storage) that can address future climate risk. Further detail on this case study is provided in (Bennett et al. 2018).

4. Australian and international approaches to incorporating climate change in flood guidance

4.1 Australian guidance

National guidance on consideration of climate change in the estimation of flood risk is provided as part of Australian Rainfall and Runoff (Bates et al. 2016). The objective of this guidance is to provide practitioners, designers and decision makers with an approach to address the risks of climate change in projects and decisions that involve estimation of design flood characteristics.

The guidance is available for potential changes in rainfall intensity (or equivalent depth) from an annual exceedance probability ranging from 50% to 1%. In terms of treatment of uncertainty, the guidance takes a scenario-based approach as part of a pre-screening analysis that partially covers the uncertainty space, followed by a risk-based approach that involves a multiplicative factor superimposed onto traditional design flood estimation approaches. Based on a flow chart, this guidance would lead to a recommendation of not incorporating climate change into design flood estimates for a large number of circumstances. Where climate change is incorporated, typical changes for Adelaide would involve an increase between 5% and 12% relative to historical IFD curves[3].

The key steps in the guidance are summarised below.

Step 1: Set the effective service life or planning horizon. If the service life or planning horizon is within 2035, then climate change is considered to have 'negligible' impact on IFD characteristics, and the design process should be based on historical climate data;

Step 2: Set the flood design standard. The guidance only considers annual exceedance probabilities from 50% to 1%, and if the probable maximum precipitation (PMP) is of interest, then up-to-date estimates of the PMP from the Bureau of Meteorology should be obtained. Note that current guidance from the Bureau of Meteorology is that it is not possible to confirm that PMP estimates "will definitely increase under a changing climate" (Jakob et al. 2009).

Step 3: Consider the purpose and nature of the asset or activity, and its consequences of failure. This step involves the following considerations:

- 'Purpose of asset' can refer to flow conveyance, improved safety, and reduced frequency of exposure and damage;
- 'Flood-related design' requirements include examples such as minimum fill levels and minimum floor levels;
- 'Consequences of failure' include risks to life, property and the environment; and
- 'Costs of retrofitting' include considerations in case IFDs change with time.

If the above are designated as 'low', the project or decision should proceed based on historical climate data, otherwise the screening analysis in Step 4 is recommended.

Step 4: Carry out a climate change screening analysis. This step assumes flood risk is calculated for a range of AEPs, and involves an assessment of how the impacts and consequences change by moving to a rarer AEP. For example, if the interest is in the 1% AEP event, then the implications of flooding from the 0.5% and 0.2% events should be considered. If this analysis was conducted for a 24 hour event in Adelaide (34.9285°S, 138.6007°E), this would be equivalent to increasing the 1% AEP by 10% and 26%, respectively. If the incremental impacts and consequences of this increase are low (e.g.

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[3] Only for a single case would an increase of 19% be considered.

the increases in flood levels are slight), then the design rainfall should be estimated based on the historical climate.

Step 5: Consider climate change projections and their consequences. This recommends use of RCP 4.5 as the basis for design, and suggests that 'where the additional expense can be justified on socio-economic and environmental grounds', the maximum consensus case for the high concentration pathway RCP 8.5 should also be considered. Based on the temperature obtained from this, the IFDs should then be estimated based on historical information and multiplied by an additional 5%/°C. Assuming a decision to only consider RCP 4.5, then application of the tool would suggest an increase in heavy rainfall intensity relative to the historical IDF calculations of 5% up to (and including) 2060, and 12% from 2070 to 2090. If RCP 8.5 was to be considered, this would result in changes of 5% up to and including 2040, 12% from 2050 to 2080, and 19% for 2090. Once this analysis is complete, then if the associated cost of the design is low relative to the associated benefits in the residual risk, the changed design should be adopted. Otherwise proceed to Step 6.

Step 6: Consider statutory requirements. If the costs of accounting for climate change in the design are not low, then if statutory requirements relating to climate change are in place, the changed design should be adopted. Otherwise, an economic analysis should be completed as the basis for a decision.

4.2 New Zealand guidance

National guidance on the consideration of climate change in the estimation of flood risk is provided by the Ministry for Environment – '*Preparing for future flooding: A guide for local government in New Zealand'* (New Zealand Ministry of the Environment 2010). This guidance is directed at local government bodies and sets out a two stage approach for estimating the effects of climate change on flood flow as part of a risk-based approach.

To estimate the impact of climate change on flooding, the guidance adopts an approach that comprises an initial screening assessment and then directs further analysis in the form of a detailed study of scenarios. The detailed study occurs whenever the initial assessment indicates the presence of a significant issue or where it is determined that the initial screening analysis yields inadequate information. It is noted that the use of the advanced methods may require the assistance of expert practitioners.

The key elements of each stage are summarised below:

Stage 1: Basic screening methods – consist of simple testing using change factors applied to extreme rainfall and then using this adjusted rainfall to estimate flow. These change factors vary with ARI and duration, with a percentage adjustments ranging from 3.5% to 8% per degree of warming (New Zealand Ministry of the Environment 2010). Basic empirical methods to translate extreme rainfall to flow are recommended for this stage (i.e. the 'rational method', the US Soil Conservation Service method, or the unit hydrograph method).

Stage 2: Advanced methods – draw directly on climate projections and more complex rainfall-runoff modelling approaches. One suggested method is to apply monthly change factors derived from climate projections to the historical rainfall time series then use rainfall-runoff modelling to estimate the change in streamflow. Methods flagged as more complex include the use of weather generators, historical analogues and dynamic or statistical downscaled climate model data to estimate changes in rainfall and the use of fully distributed, physically based hydrological models to translate rainfall to flow.

Following the estimation of climate change impacts on flooding, the guidance sets out a risk assessment procedure that assigns a risk level based on the consequences of a flood event (including social, cultural, economic and environment considerations as a 'quadruple bottom line') and the likelihood of an event occurring (factoring in design-life of any structures/planning decisions). The risk analysis is applied to current and future climate condition(s). The risk analysis results are compared to see if/how the risk profile may change with climate change. Users of the guidelines are referred to the standard *NZS 9401:2008 Managing Flood Risk – A Process Standard for best practice*.

The guidance then directs the user to consider legislated requirements and outlines the principles and options for planning and decision-making for managing flood risk exacerbated by climate change, including use of a precautionary approach, use of flexible or adaptive management options, selecting no- or low-regret options, progressive risk reduction, as well as integrated and sustainable approaches for managing flood risk.

4.3 UK guidance

National guidance on consideration of climate change in the estimation of flood risk is provided by the Environment agency for flood management authorities (Environment Agency 2016) and for flood risk assessments (Environment Agency 2016) that feed into the National Planning Policy Framework. The guidance recommends a 'managed adaptive approach' where possible and a precautionary approach where a managed adaptive approach is not technically feasible. The potential impacts of climate change on flood risk are evaluated using climate change allowances that quantify the potential change of river flow, extreme rainfall, mean relative sea level rise and storm surge to the baseline. For flood flows the climate change allowances represent the change in the 50 year return period flood peak. To allow for spatial variability in the allowances, England is divided into 11 river basin districts. The flow climate change allowances are presented as a set of five scenarios—Lower (10th percentile), Central (50th percentile), Higher Central (70th percentile), Upper (90th percentile) and H++ (upper limit of climate projections considered plausible)—for three time slices (2020, 2050, 2080) across each district. Within flood risk management applications, the Central, Higher Central and Upper allowance have been designed to enable investigations with a 'full appreciation of emission scenario and climate uncertainty'. However, where the consequences of rare events could be very severe the users are directed to use the H++ allowances as a more appropriate measure of the full range of risk (e.g. large tidal barriers). For example, for a time slice of 2020 the Central flow allowances range between 10 and 15% and the H++ allowances set the total potential change between 20% and 30% depending on the basin district. However, for the 2080 time slice the total potential change anticipated ranges from 20% to 35% for the Central limit and from 65% to 120% for the H++ limit depending on the basin district.

The guidance recommends that the Central climate change allowance forms the baseline risk over the lifetime of the decision. The Lower and Upper allowances should then be used to assist users to understand how more or less change could affect the risk and what measures would be required to manage this risk range via sensitivity testing, including the identification of any 'cliff-edge' effects where the Upper climate change allowance consequences shift to become extremely severe. The motivation behind this sensitivity testing is that with a greater appreciation of the risk, users are encouraged to think more broadly and consider what measures can be taken to avoid maladaptation or to encourage the building in of flexibility where appropriate (Reynard et al. 2017).

For small catchments (< 5 km^2) the climate change allowances for rainfall may instead be used. Central and Upper limits are provided for the whole of England for the three time slices for use with daily rainfall for events rarer than 1 in 5 years. The Upper limit sets the total potential anticipated change to 40% at the 2080 time slice. Whereas the Central limit sets it at 20%.

For planning developments, the flood risk assessment guidance (Environment Agency 2016) further sets out which climate allowances should be used depending on the flood zone (zone classifications are based on the probability of river and sea flooding, ignoring defences) and considering the lifetime and vulnerability of the proposed development (e.g. water compatible, less vulnerable, more vulnerable, highly vulnerable or essential infrastructure). For example, a hospital is classified as 'more vulnerable' whereas a basement dwelling is considered 'highly vulnerable'.

4.4 European Guidance

A mixture of state based, regional and national guidance on the incorporation of climate change into flood risk estimation exists (Madsen et al., 2014). Belgium, Denmark, Norway and Sweden have national guidance, and German states Bavaria and Baden-Württemberg have their own guidance on the consideration of climate change in flood risk. Typically, a change factor approach is applied to design rainfall or floods for use with risk-based methods. See (Madsen et al. 2014) for a description of the guidance in English.

4.5 US guidance

No current national guidance on the incorporation of climate change into flood risk estimation was found. The American Society of Civil Engineers (ASCE) has published policy statements on flood risk management (American Society of Civil Engineers 2015) and the impact of climate change (American Society of Civil Engineers 2015), highlighting the currently non-uniform state of flood risk assessment and the lack of consideration of the impact of climate change stating:

> *'Current engineering design standards, codes, regulations and associated laws that govern infrastructure are currently not structured to allow design adaptation to address climate change.'* – ASCE policy statement 360

Although no current national guidance exists, a recent report by the ASCE entitled 'Infrastructure and Civil Engineering Practical Guidance to a Changing Climate' (Committee on Adaptation to a Changing Climate 2015) provides a general discussion of key issues surrounding climate change impacts on flood risk, including discussions on both risk-based approaches and scenario-neutral approaches, and adaptive pathways.

4.6 Canadian guidance

There is no national guidance on incorporation of climate change into flood guidance. Although, a five-year $40m project entitled the "Climate-Resilient Buildings and Core Public Infrastructure Project" was launched in 2016. It includes: (i) investigations into storm sewers, their related drainage systems, and stormwater management systems, and (ii) the development of guidelines for the adaptation of existing stormwater management systems to reflect climate change, to prevent flooding of urban areas and to prevent the discharge of untreated floodwaters.

As part of this project, the National Research Council Canada held an international workshop on floods and climate change in July 2017 (Attar et al. 2017). It was recognised that there are no established criteria for incorporating climate change in flood design in Canada that are developed at the national scale, and a series of presentations provided alternative perspectives for the issues and underpinning research that would be needed to enable the development and implementation of more robust design procedures in codes and standards.

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