Brisbane River Catchment Flood Study: Comprehensive Hydrologic Assessment

Assessment of the Implications of Climate Change on Flood Estimation Discussion Paper

Prepared for the State of Queensland (acting through): Department of State Development, Infrastructure and Planning/Department of Natural Resources and Mines

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Aurecon team

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1 Introduction

The Brisbane River Catchment Flood Study (BRCFS) is being undertaken as the Queensland Government's response to the Recommendation 2.2 of the *Queensland Floods Commission of Inquiry* (QFCI) Final Report. The purpose of the current stage of the flood study, the hydrological assessment, is to provide an up-to-date, consistent, robust and agreed set of methodologies and flood estimation for the Brisbane River catchment.

The Flood Study is based on current and past climate variability. However, given the onset of climate change, it is important that the potential implications of climate change for the flood modelling are understood and that users of the model outputs are aware of the limitations of the model for understanding flooding effects into the future and what key variables might be used if models were to be used to test various climate change affected scenarios. This need was recognised in section 3.6.7.10 of the Invitation to Offer (July 2013) which requested an *'Assessment of Implications of Climate Change on Flood Estimation'.*

This paper has been prepared as part of the BRCFS hydrological assessment and provides discussion on what the relevant climatic variables are, projected climatic changes for South-East Queensland, and a practical means of incorporating the predicted change into the BRCFS. Importantly, the paper includes a review of what constitutes best practise in accounting for climate change in flood modelling for a range of interstate and international organisations.

2 Aims and objectives

This paper is focused on the Brisbane River Catchment, and provides:

- A summary literature review of the latest climate change science
- A summary literature review of best practice incorporation of climate change predictions into flood studies from within and outside of Australia
- Information on the key climatic variables that may affect the development of robust flood estimation in the Brisbane River catchment (covering a range of planning horizons up to 2100) and
- Discussion on practical means of incorporating the predicted climatic variations into flood estimation methodology for the Brisbane River catchment

3 Literature and science review

3.1 Review of climate change science

This section reviews the current understanding of changes in the hydrological cycle. It does not exhaustively review the observed changes in climate variables, as the overall purpose of this paper is to provide guidance and recommendations for including projected future climate change into flood risk studies. However, in some cases these observed changes are relevant for understanding projected future changes in relevant climatic variables and therefore these are discussed.

Flooding in the Brisbane River can be affected by high rainfall, high sea-levels or by storm surge, or by a combination of these factors. Climatic variables that are likely to directly affect rainfall driven flood occurrence are rainfall, the antecedent condition of the catchment prior to rainfall, and the preceding river water-levels. Storm surge or high sea-levels can also have a direct influence on flooding at the tail end of the basin. Therefore these must be taken into account in the modelling efforts. Note however, that flooding due to high sea levels (coastal flooding) is not of direct interest here, only the extent to which high sea-levels affect flood occurrence in the river basin.

All of these above factors are potentially affected by climate change and are discussed below.

3.1.1 Rainfall

Rainfall is probably the single most important climate variable for flood risk estimation. The Intergovernmental Panel on Climate Change (IPCC) in its latest assessment report concludes that globally other than for the mid-latitude northern hemisphere, there is low confidence[1] that there have been long term changes (positive or negative) in annual precipitation (IPCC 2013). With regard to heavy precipitation events however, there are more land areas where heavy precipitation events have increased in frequency than areas where these have decreased (IPCC 2013).

Several modelling studies are available to estimate changes in rainfall based on simulations from climate models. In mid-latitude and subtropical dry regions, mean precipitation is likely to decrease (IPCC 2013). Extreme precipitation events on the other hand will very likely become more intense and more frequent over mid-latitude land areas by the year 2100 (IPCC 2013).

Climate in Australia has a high natural variability, owing largely to the strong influence of the El Niño Southern Oscillation (ENSO), and especially rainfall is highly variable over Australia (Reisinger et al. 2014). Increases in precipitation have been found in north-western Australia since the 1950s, and declines in autumn/winter precipitation in south-west Australia since the 1970s and in south-east

[1] The IPCC uses the following confidence and likelihood language: A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high; the assessed likelihood of an outcome or a result is expressed as: virtually certain 99-100% probability, very likely 90-100%, likely 66-100%, about as likely as not 33-66%, unlikely 0-33%, very unlikely 0-10%, exceptionally unlikely 0-1%, and additional terms are extremely likely 95-100%, more likely than not >50-100%, and extremely unlikely 0-5% (IPCC, 2013).

Australia since the 1990s (Reisinger et al. 2014). Apart from overall rainfall changes, the frequency of conditions suitable for thunderstorm occurrence has not been increasing in Australia, according to one study (Allen and Karoly 2013). For Australia, the evidence for past changes in extreme rainfall events (95th and 99th percentile) is mixed or insignificant (Reisinger et al. 2014), with for the east coast region significant declines in total rainfall and extremes over the period 1950-2005 (Gallant et al., 2007).

It is important to note however that changes in rainfall extremes in Australia have been observed for very small time intervals; ie sub-daily (Westra 2011; Westra and Sisson 2011; Jakob et al. 2011). This suggests that with further increasing temperatures, changes in rainfall may also occur at sub-daily time steps. Westra (2011) further notes that the spatial scale at which changes in rainfall occur, have not really been well addressed yet by research, and that while mean rainfall changes are related to circulation changes over larger areas, changes in intense rainfall may be occurring at smaller spatial scales. The same holds true for rainfall type (Westra, 2011); where mid-latitude storm types may move pole ward and become more important for Australia, while tropical cyclone become less frequent and tracks move southward.

Figure 3-1 illustrates according to two different ensemble simulation datasets the extent to which rainfall in December-February may change across Australia by the end of the century, albeit with considerable uncertainties for the Australian east coast. Future patterns of precipitation change according to a high climate change scenario (the RCP8.5 scenario; see left panel in Figure 3-1 below) indicate that south-east Queensland may see a slight decline in total annual rainfall of -4.8% (+/-22.1% variation between different climate models), while precipitation during December-February is expected to increase by around 6.8% (+/-22.2%) (Irving et al 2012).

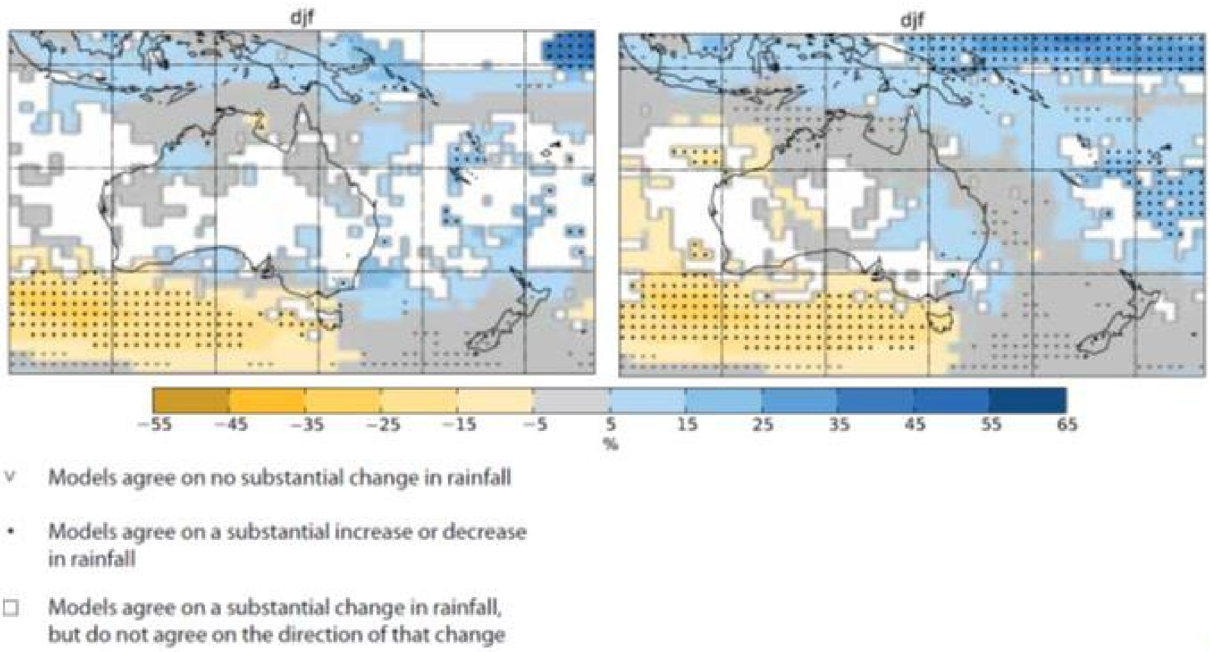

Figure 3-1 Projected mean change in rainfall for the period 2080-2099 relative to 1980-1999, according to climate simulations (RCP 8.5 scenario; left, and SRES A2 scenario; right) (Source: Irving et al 2012)

The finding that sub-daily rainfall amounts have increased alongside mixed trends in total rainfall (see above), leads to the implication that despite uncertainties in the change of annual and seasonal mean rainfall, intense rainfall events may occur more frequently in the future. Projections of future extreme rainfall for Australia show possible increases in heavy rainfall events, substantially contributing to 5-day rainfall total and to annual rainfall totals (Alexander and Arblaster, 2009). Overall, the IPCC concludes that there is medium confidence in changes in current 20 year return period events and in short duration (sub-daily) extremes in most regions of Australia (Reisinger et al., 2014: Table 25-1).

Scenarios for Southeast Queensland derived from downscaled projections developed by the Queensland Climate Change Centre of Excellence (2010) are summarised below. These projections are based on simulations for the IPCC fourth assessment report, dating from 2007.

Table 3-1 Projected future changes of selected climate variables, by the year 2050 (Source: Queensland Climate Change Centre of Excellence (2010))

Annual mean temperature	Rainfall	Evaporation	Extreme weather events
Increase by 1.1°C to 1.8°C	Decrease by 3-5% Increase in rainfall intensity could result in more flooding Increased numbers of severe thunderstorms	Increase by 3-6%	Slight (9%) decrease in frequency of cyclones, but slight increase in intensity (Category 3-5). Number of severe cyclones increases Cyclone belt shifts southwards, with greater impact projected for Southeast Queensland 1 in 100 year storm tide event in Wellington Point, Moreton Bay projected to increase by 42 cm

It is important to note that two projects are currently carried out under the Australian Rainfall and Runoff (ARR) programme building on the recommendations by Westra (2011).The first study will provide a set of national interim guidance, scheduled for release in November 2014. The second project will provide benchmark methods for estimating changes in IFD with climate change using a consistent data set covering greater Sydney. However, these research projects will not be completed in time to incorporate the findings into the Brisbane River Flood Study.

3.1.2 Antecedent conditions

There is little research on how climate change may affect antecedent conditions (principally soil moisture and evapotranspiration) that are important for the occurrence of flooding. In southern Australia there are indications that large scale circulation variability related to the Pacific-Decadal Oscillation (IPO) modulates soil moisture, thereby influencing flood occurrence (generally declining) through antecedent conditions, rather than through rainfall (Westra, 2011). For instance, Micevski et al. (2003) demonstrate that during IPO negative phases, flood risk is substantially increased (up to a factor 2.0 higher discharge). Flood conditions are expected to increase in the north of Australia, whereas in the south of Australia increasingly drier soil moisture conditions compensate for changes in rainfall (Reisinger et al., 2014: Box 25-8). There is no research related specifically to south-east Queensland on this topic.

Other processes that are less frequently considered include increased evaporation that could result in drier soil moisture conditions. A rapid change from a dry situation to a highly intense rainfall situation could influence runoff. Equally, drought conditions followed by extreme rainfall can exacerbate the amount of sediment discharged from the catchment. It could be recommended to monitor and assess both processes into the future, to inform modelling.

3.1.3 Sea-level rise and storm surge

The global mean sea-level increased by some 0.19 m between 1901 and 2010. For Australia, the rate of sea-level rise was 1.4 mm per year over the period 1900-2011 (Reisinger et al., 2014; Burgette et al., in press), slightly below the global average rate. Extreme sea-levels in Australia have risen at the same rate as the average sea level rise (Reisinger et al., 2014; Menendez and Woodworth, 2010).

Depending on the assumed emission scenario, global mean sea level is projected to rise by 0.53 to 0.97 m by 2100 (high emissions, RCP8.5) relative to the average of 1986-2005, or between 0.28 and 0.6 m (low emissions, RCP2.6) (IPCC, 2013). Projected future sea-level rise along the Australian coast is expected to exceed the average historic rate, contributing to the trend in higher extreme sea-levels (Reisinger et al., 2014 IPCC, 2013). Studies suggest that with sea-level rise, the frequency of extreme sea-levels, as well as the number of exposed properties, may increase disproportionally along the Australian south-east coast (Reisinger et al., 2014; McInnes et al., 2011; McInnes et al., 2012), although other studies assume a proportionate increase (Wang et al., 2010).

Compared to the Fourth Assessment report, there is more caution about the relation between climate change and changes in tropical cyclone activity. The Fifth Assessment report states that there is low confidence in past increases in tropical cyclone activity, except for the North Atlantic basin (IPCC 2013). Also confidence in changes in future projected cyclone activity is low, except for the North Atlantic and Western North Pacific basins, where changes are “more likely than not” (IPCC, 2013).

The number of tropical cyclones and their intensity in Australia have not significantly changed over the period 1981-2007 (IPCC, 2014), but the number of severe cyclones making landfall in north-east Australia (between Cairns, Queensland, and Ballina, New South Wales) has declined significantly since the mid-19th century (Reisinger et al., 2014; Callaghan and Powers, 2011).

For Australia, changes in future storms and cyclones are expected to play a minor role in changes in the occurrence of extreme sea-levels, compared to sea-level rise. A study using the CSIRO CCAM model found that the number of tropical cyclones may decrease strongly (by about 50%) by the end of the century (period 2051-2090 compared to 1971-2000), and a southward movement of genesis and decay regions (Abbs, 2012).

The following changes in storm tides are estimated for Moreton Bay in Brisbane, depending on the scenario for sea-level rise used Using current upper and lower end estimates for the “likely” range of sea-level change from the Fifth Assessment report (see above), would result in the following estimates for storm tides for Moreton Bay: storm tides could increase up to between 2.76 and 3.32 m by the year 2100, relative to the current 2.5 m (Wang et al., 2010)[2].

Finally, combinations of storm surge levels at the tail-end of the basin, combined with intense rainfall from the cyclone could potentially lead to peak water levels. It could be useful to assess the joint probabilities and intensities of these two processes, as a low-probability and high-impact event in a model.

[2] We note that the Brisbane City Council adopted 100-year storm tide level is 2.2 m. We have requested the associated reports and will review the documents underlying this adopted level, and may adjust the proposed storm tide projections included here, and in Table 5.

3.2 Review of best practice incorporation of climate change predictions into flood studies

There are several jurisdictions within and outside of Australia which incorporate climate change into their flood modelling. This section provides a brief summary of existing guidance and policy from select interstate and international government bodies on how they incorporate climate change into flood risk management projects. Note that the guidance provided by each government body relates to their geographical jurisdiction and is not necessarily applicable elsewhere ie in South-East Queensland. However the review is useful in identifying the physical parameters that have been amended and the mechanism by which hydrologic and / or hydraulic models have been changed to take account of climate change projections.

3.2.1 Australia – QLD

In 2010 the then Minister for Climate Change and Sustainability and the Minister for Infrastructure and Planning in partnership with Local Government Association of Queensland (LGAQ) commissioned a report which included the aim of delivering an improved methodology for assessing inland flooding risk while accounting for climate change.

The report drew upon the best available science (in 2010) and recommended an allowance for projected increased rainfall intensity be incorporated into flood studies. It proposed a 5% increase in rainfall intensity per degree of global warming when considering the 1%, 0.5% and 0.2% Annual Exceedance Probability (AEP) flood events. The report recommended that local governments use the following temperature increases and planning horizons when implementing the above advice: 2°C by 2050, 3°C by 2070 and 4°C by 2100.

The report was specific to inland areas and advice was not provided for coastal rivers and estuaries where sea-level rise and storm surge are important factors.

A number of significant flood studies have been undertaken in South-East Queensland in recent years. One example is the Fitzroy Flood Study (Aurecon 2011) undertaken for Rockhampton Regional Council. This flood study report contained its own summary literature review of climate change science (best available at the time) and subsequently implemented the two following climate change scenarios:

- Climate Change Scenario 1 (+20%) – represents a 20% increase in rainfall intensity
- Climate Change Scenario 2 (+30%) – represents a 30% increase in rainfall intensity

For these two scenarios, the increased rainfall was represented in the hydrological URBS model as an increase in the rainfall intensity. This was carried out for the 2, 5, 10, 20, 50 and 100 year ARI events. For the 100 year ARI event the URBS model output hydrograph was then used as input to the TUFLOW model.

For the Fitzroy River at Rockhampton, no assessment of sea level rise was undertaken. The sensitivity analysis undertaken during the design event modelling showed that changes to the ocean levels only impacted upon the 2 year ARI event and had no affect under the 100 year ARI event.

3.2.2 Australia – NSW

In NSW the 'Floodplain Development Manual: the management of flood liable land' (April 2005). Department of Infrastructure, Planning and Natural Resources, NSW Government, states that a flood study should address the possible implications of climate change on flood behaviour, including sea level rise, altered storm patterns and intensity and increased intensity and frequency of extreme events. The manual states the consequences of climate change on flood levels and behaviour should be analysed as part of a flood study either:

- Qualitatively based upon the broad range of floods being examined up to and including the PMF
- Sensitivity analysis in relation to rainfall intensity or downstream water level conditions for key flood events

In 2007, more specific guidance was provided by the NSW Department of Environment and Climate Change (DECC, now Office of Environment and Heritage, OEH): 'Practical Consideration of Climate Change in Flood Investigations'. The guidelines recommend sensitivity analysis is considered for:

- Sea level rise – for low (0.18 m), medium (0.55 m) and high level impacts (up to 0.91 m)
- Rainfall Intensities – for 10%, 20% and 30% increase in peak rainfall and storm volume

The NSW Sea Level Rise Policy Statement (2009) provided by NSW DECC, now OEH, updated the best projections of sea level rise along the NSW coast to be, relative to 1990 mean sea levels, to be 0.4 m by 2050 and 0.9 m by 2100. It was acknowledged that higher rates were possible. The policy statement recommended these sea level rise benchmarks for use in flood risk assessments.

In 2012 the above sea level rise benchmarks were withdrawn by the NSW Statement Government, following widespread concern that the coastal zone implications of their implementation were too onerous. The State Government instructed each Council to determine and implement its own benchmarks. In reality, and without any better science or guidance to follow, most NSW Councils have continued to adopt the 0.4 and 0.9 m benchmarks.

Until relatively recently the table below provided the range of climate change scenarios typically modelled in NSW flood studies for each AEP event. Whilst being a comprehensive approach, this led to a significant number of events being run and subsequent modelling effort.

Table 3-2 Typical scenarios adopted for NSW for sea-level rise and rainfall intensity changes

Scenario	Sea level rise (m)	Rainfall intensity increase
1	0.4	-
2	0.9	-
3	-	10%
4	-	20%
5	-	30%
6	0.4	10%
7	0.4	20%
8	0.4	30%
9	0.9	10%
10	0.9	20%
11	0.9	30%

More recently NSW practice has moved away from running all design events for all climate change cases. Instead it is now usual practice to only run a couple of events, the 1% AEP and a bigger and a smaller event. Consideration is currently being given in NSW and in the interim climate guidelines to putting more emphasis on how the probabilities of different events change rather than running extra climate change IFD runs. In most cases the relatively simple exercise of determining the percentage rainfall increase that would turn a 1% AEP event into a 0.5% (200 year) and 0.2% (500 year) will give a good picture of how changes in rainfall will affect risk management.

3.2.3 England and Wales

In England and Wales the Environment Agency, the primary body responsible for flood risk management, provides detailed and comprehensive advice on how to incorporate climate change projections into flood risk management projects. The advice is summarised in *"Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities"* (2013), a copy of which can be provided on request. This report summarises the findings of the UK Climate Impact Programme 2009 (UKCIP09). The full report is "UK Climate Projections science report: Climate change projections" Department of Environment Food and Rural Affairs (DEFRA) (2009) which can be found at http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87851&filetype=pdf.

Advice is provided on factors (either mm or %) to be incorporated for rainfall, river flow, sea level rise, storm surge and wave climate to take account of the potential impacts of climate change. Depending on the confidence in the underpinning climate science, the advice given for each physical parameter (rainfall, river flow etc) is further refined for UK sub-regions and different future timeframes. Upper and lower end factors are also provided to allow for analysis of scenarios either side of the median climate change scenario.

The advice is too extensive to document here in full. However for the purposes of illustration and discussion a snapshot of the type of advice provided is given in the table below. The table shows, for example, that the recommended increase in river flow in 2080 under the predicted climate change scenario ('change factor') is either 20 or 25% depending upon the UK sub-region. Under an 'Upper end' climate change scenario this increases to either 50 or 70%.

Table 3-3 Changes to river flood flows by river basin district compared to a 1961-1990 baseline total potential change anticipated for the 2020s

UK region	Total potential change anticipated for the 2020s	Total potential change anticipated for the 2050s	Total potential change anticipated for the 2080s
Northumbria			
Upper end estimate	25%	30%	50%
Change factor	10%	15%	20%
Lower end estimate	0%	0%	5%
Humber			
Upper end estimate	25%	30%	50%
Change factor	10%	15%	20%
Lower end estimate	-5%	0%	5%
Anglian			
Upper end estimate	30%	40%	70%
Change factor	10%	15%	25%
Lower end estimate	-15%	-10%	-5%

UK region	Total potential change anticipated for the 2020s	Total potential change anticipated for the 2050s	Total potential change anticipated for the 2080s
Thames			
Upper end estimate	30%	40%	70%
Change factor	10%	15%	25%
Lower end estimate	-15%	-10%	-5%

3.2.4 Scotland

In Scotland the Scottish Environment Protection Agency (SEPA) are the regulatory body responsible for managing flood risk and have a statutory consultation role in assessing development applications. SEPA provide Technical Guidance on preparing a flood risk assessment, via their document *"Technical Flood Risk Guidance for Stakeholders"*.v7 (2013). Which can be found at http://www.sepa.org.uk/planning/flood_risk/developers.aspx. The guidance states that; "best estimates, based on the most up-to date findings, should be made of climate change impacts on probabilities, flood depths and extents for both fluvial and coastal situations". For fluvial flow design estimation, SEPA recommends that a climate change allowance of +20% on the estimated 200 year peak flow be made. For projected increases in sea level rise, SEPA refer to UKCIP09.

3.2.5 The Netherlands

In the Netherlands the KNMI (Dutch meteorological office) has developed 4 future climate scenarios: 2 scenarios representing global temperature increases of +2 degrees (moderate) and 2 scenarios representing +4 degrees (warm). Both the moderate and the warm scenario have 2 air circulation scenarios. Each scenario has its own suite of predicted climatic parameters set for 2 future timelines: 2050 and 2100.

In 2006 when the 4 scenarios were first developed all 4 scenarios deemed equally likely to occur (Hurk, B.J.J.M. van den, A.M.G. Klein Tank, G. Lenderink, A.P. van Ulden, G.J. van Oldenborgh, C.A. Katsman, H.W. van den Brink, F. Keller, J.J.F. Bessembinder, G. Burgers, G.J. Komen, W. Hazeleger en S.S. Drijfhout). However, in 2010, it was officially released that based on measured rising temperature the warmer scenarios were most likely (Klein Tank, A.M.G. and G. Lenderink). How is this taken into account in practise? In 2011 a Governance Agreement on Water was signed (http://english.uvw.nl/), which describe the scenario's that should be used to get insight in the problem in 2050/2100. In practise often two or more scenarios are taken as input for hydrological models so it results in a range of outcomes.

For many engineering questions the scenario values need to be associated with representative information about possible future weather conditions. As part of the KNMI'06 scenarios, software has been developed which transforms observed daily records of temperature and precipitation into time series representative for the future climate, ie a statistical transformation of historical records that brings the seasonal averages and (moderate) extremes in agreement with the scenarios. See http://climexp.knmi.nl.

The KNMI is working on a new set of scenario's which will be released in 2014. The KNMI '14 scenarios are now called the KNMI next scenarios. More info can be found on the website of KNMI: http://www.knmi.nl/climatescenarios/. These scenarios will be spatially distributed (per region a parameter can differ for one scenario). The scenario's themselves won't be much different from the 2006 scenarios. However the time horizon will be 2030, 2050 and 2085.

3.2.6 USA

The USA situation is similar to Australia in that no overarching national/federal guidance exists and that individual states or regions are left to develop policies and take decisions locally.

A good example of this is New York State which has a city specific climate panel. Following Hurricane Sandy the panel revised its ‘Climate Risk Information 2013: Observations, Climate Change Projections and Maps’ Report. The report presents 3 future climate scenarios: Low Estimate (10^{th} percentile); Middle Range (25^{th} -75^{th} percentile) and High Estimate (90^{th} percentile). Developers and planning regulators are encouraged (rather than forced) to adopt the High Estimate (90^{th} percentile) for decision making. This scenario for a 2050 timeline predicts a 15% increase in annual rainfall and a sea level rise of 31 inches. In New Orleans, for development of their urban water plan a 5% increase in precipitation by 2025 was assumed.

California is a US State that has a climate and range of water resource issues not dissimilar to South-East Queensland. The California Coastal Commission have recently completed a public consultation period on draft Sea Level Rise Policy Guidance. The draft guidance presents the following table of projected sea level rise along the Californian coast as being the best available science and then provide clear guidance to decision makers that it should be adopted.

Table 3-4 NRC sea level rise projections for California

Time period	North of Cape Mendocino	South of Cape Mendocino
2000-2030	-4 – +23cm	4 – 30cm
2000-2050	-3 – +48cm	12 – 61cm
2000-2100	10 – 143cm	42 – 167cm

1. Acknowledge and address sea-level rise as necessary in planning and permitting decisions
2. Use the best available science to determine locally relevant (context-specific) sea-level rise projections for all stages of planning, project design, and permitting reviews
3. Recognize scientific uncertainty by using scenario planning and adaptive management techniques

4 Discussion on practical implementation for Brisbane River catchment flood study

Most organisations focus on rainfall depth and sea levels as the two physical parameters with the clearest climate change signals and those most practically altered to take account of future projections. It is important to stress however, that there is considerable uncertainty involved in estimating potential changes in parameters related to rainfall, antecedent conditions, sea-level, and storm surges. Changes in sea-level have a level relatively straightforward relationship with global temperature change, as a result of expansion of sea-water. As is proposed in IPCC (2012 and 2013), we assume a simple scaling of storm tide levels with projected sea-level rise.

Changes in rainfall and antecedent conditions are more difficult to estimate. The related processes of rainfall and their rates are poorly captured by low-resolution global circulation models. Although regional climate models have a higher resolution and can simulate rainfall patterns in greater detail, there is no reason to assume that these can provide accurate predictions of possible changes in rainfall either. Also choices between different downscaling techniques are rather a matter of assumption (see eg Merz et al. 2014).

However, assuming ranges for changes in rainfall patterns, based on the best currently available knowledge, part of this uncertainty can be captured. When new recommendations become available (eg from the ARR programme), the parameters suggested in this paper can be updated.

There is little information on the potential impacts of climate change on antecedent conditions in Australia and none that could be found for South-East Queensland. Given the potential importance of antecedent conditions on catchment flood conditions it may be sensible for the flood study to undertake a sensitivity analysis, through varying initial loss parameters in hydrological modelling, for example, initial loss parameters could be reduced to simulate a wetter catchment (wetter antecedent conditions) at the start of a rainfall/flood event.

Climate change would also potentially influence initial reservoir levels as the long term runoff from the catchment would be impacted in terms of the quantity of runoff and also the temporal distribution of the runoff. This in turn would impact the probability distribution used to describe the initial reservoir relationships for the various dams. However, the impact of possible climate change would most likely be a secondary effect compared to the assumed reservoir operation rules and change in usage and therefore its impact would be difficult to quantify.

Future patterns of precipitation change from the latest CMIP5 experiments using the RCP8.5 (high climate change) scenario indicate that South-East Queensland may see a slight decline in total annual rainfall of -4.8% (+/-22.1% variation between different climate models), while precipitation during December-February is expected to increase by around 6.8% (+/-22.2%) (Irving et al 2012). The Brisbane River catchment flood season correlates strongly with the December to February period, with the majority of the major historical events (including 2013, 2011, 1974, and 1893) occurring in this period, and therefore it might be a reasonable conclusion that rainfall and wetter antecedent conditions during the historically catchment flood prone period will increase.

Continuing sea-level rise will lead to increasing water levels at the tail end of the river basin, especially during storm surge. As the range of projections for sea-level rise is very wide, it is advisable to test the effects of several estimated projections. While offshore sea-level rise may be some 10% higher along the Australian coast (see Reisinger et al., 2014), we assume that IPCC (2013) global sea-level rise estimates are valid for the coast of Eastern Australia.

5 Recommendations

Table 5-1 below provides recommendations for the Brisbane River catchment flood study on the parameters that should be considered for adoption to investigate the potential influence of climate change.

In line with the original brief we have provided clear and practical advice for a range of time horizons.

It is important to keep in mind that considerable uncertainties are involved in these estimates, and in the future these parameters may be (considerably) different from those indicated. Furthermore these estimates are based on scenarios that carry considerable uncertainty and the impacts of these uncertainties on decisions relating to floodplain management will need to be assessed.

However, as these recommendations for climate change parameters should be as practical and clear as possible, four future periods were selected: 2030, 2050, 2070 and 2100. The range of uncertainties is included in the different estimates. For changes in sea-level and storm tide levels, these are depending on the projected rate of global average warming, and response of glaciers and ice caps.

Table 5-1 Proposed climate parameters for inclusion in flood risk studies

Parameter	2030	2050	2070	2100
Design rainfall depth *	+5%	+10%	+15%	+20%
Average sea-level **	+0.09 – 0.21m	+0.17 – 0.38m	+0.19 – 0.60m	+0.26 – 0.82m
Storm tide level ***	2.59 – 2.71m	2.67 – 2.88m	2.69 – 3.10m	2.76 – 3.32m

** Design rainfall depth for flood risk studies, such as described in the AR&R method (see also "Increasing Queensland's resilience to inland flooding in a changing climate: Final report on the Inland Flooding Study", 2010).Proposed percentage increases are relative to the benchmark year of 2014.*
*** Estimates for 2050 and 2100 based on the "likely range" of sea-level rise for the periods 2046-2065 and 2081-2100, as reported in the Summary for Policymakers of IPCC 2013. Estimates for 2030 and 2070 were linearly interpolated between the baseline and 2100, as no scenario information is readily available for these time periods from the IPCC AR5 WG1 report. Changes are relative to the benchmark period of 1986-2005.*
**** The 100-year storm surge level (currently 2.5m) at Moreton Bay, superimposed on the projected sea-level rise from IPCC.*

Further to the advice above, it is recommended initial loss parameters in the hydrological model are altered by +/- 10% to investigate the influence of changes in antecedent conditions of catchment flood risk.

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7 Glossary

7.1 Hydrologic terms

AEP: Annual Exceedance Probability – is a measure of the likelihood (expressed as a probability) of a flood event reaching or exceeding a particular magnitude in any one year. A 1% (AEP) flood has a 1% (or 1 in 100) chance of occurring or being exceeded at a location in any year

AHD: Australian Height Datum (m), the standard reference level in Australia

AR&R: Australian Rainfall and Runoff (AR&R) is a national guideline document for the estimation of design flood characteristics in Australia. It is published by Engineers Australia. The current 2003 edition is now being revised. The revision process includes 21 research projects, which have been designed to fill knowledge gaps that have arisen since the 1987 edition

CHA: Comprehensive Hydrologic Assessment

CL: Continuing Loss (mm/hour). The amount of rainfall during the later stages of the event that infiltrates into the soil and is not converted to surface runoff in the hydrologic model

CRC-CH: Cooperative Research Centre – Catchment Hydrology. In this report, CRCH-CH usually refers to a Monte Carlo sampling method that was developed by the CRC-CH

CSS: Complete Storm Simulation. This is one of the proposed Monte Carlo sampling methods

Cumulative probability: The probability of an event occurring over a period of time, any time in that period. This probability increases over time

DEA: Design Event Approach. A semi-probabilistic approach to establish flood levels, which only accounts for the variability of the rainfall intensity

Design flood event: Hypothetical flood events based on a design rainfall event of a given probability of occurrence (ie AEP). The probability of occurrence for a design flood event is assumed to be the same as the probability of rainfall event upon which it is based (EA, 2003)

DMT: Disaster Management Tool. Work completed by BCC in 2014 for Queensland Government as part of the development of an interim disaster management tool until the completion of the BRCFS

DTM: Digital Terrain Model

EL (m AHD): Elevation (in metres) above the Australian Height Datum

FFA: Flood Frequency Analysis – a direct statistical assessment of flood characteristics

Flood mitigation manual (Flood Manual): A flood mitigation manual approved under section 371E(1)(a) or 372(3) of the Water Supply (Safety and Reliability) Act 2008 (QLD)

FOSM: Flood Operations Simulation Model (refer Seqwater 2014)

Floodplain: Area of land adjacent to a creek, river, estuary, lake, dam or artificial channel, which is subject to inundation by the PMF (CSIRO, 2000)

FSL: Full Supply Level – maximum normal water supply storage level of a reservoir behind a dam

FSV: Full Supply Volume – volume of the reservoir at FSL

GEV: Generalised Extreme Value statistical distribution

GIS: Geographic Information System

GL: Gigalitres This is a unit of volume used in reservoir studies. A Gigalitre = 1,000,000,000 litres or equivalently 1,000,000 m^3

GSDM: Generalised Short Duration Method of extreme precipitation estimation for storms of less than 6 hour duration and catchments of less than 1,000 km^2. Refer BoM, 2003

GTSMR: Revised Generalised Tropical Storm Method of extreme precipitation estimation for storms of tropical origin. Applicable to storm durations of up to 168 hours and catchments up to 150,000 km^2. Refer BoM, 2003

IFD-curves: Intensity-Frequency-Duration curves, describing the point- or area-rainfall statistics. In the current report rainfall depth is generally used as an alternative to rainfall intensity. Rainfall depth is the product of duration and intensity. It was decided to maintain the term "IFD" as this is the terminology that the reader is most likely to be familiar with

IL: Initial Loss (mm). The amount of rainfall that is intercepted by vegetation or absorbed by the ground and is therefore not converted to runoff during the initial stages of the rainfall event

LOC: Loss of Communications dam operating procedure, refer Flood Manual (Seqwater 2013)

LPIII: Log-Pearson Type III statistical distribution

IQQM: Integrated Quantity and Quality Model for water resources planning

JPA: Joint Probability Approach. A general term for probabilistic methods to establish design flood levels

MCS: Monte Carlo Simulation

MHWS: Mean High Water Spring Tide level

ML: Megalitre. This is a unit of volume used in reservoir studies. A megalitre is equal to 1,000,000 litres or, equivalently, 1,000 m^3

m^3/s: Cubic metre per second – unit of measurement for instantaneous flow or discharge

PMF: Probable Maximum Flood – the largest flood that could conceivably occur at a particular location, resulting from the PMP (CSIRO, 2000) and Australia Rainfall and Runoff, 2003 (EA, 2003)

PMP: Probable Maximum Precipitation – the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends (CSIRO, 2000; EA 2003)

PMP DF: Probable Maximum Precipitation Design Flood – the flood event that results from the PMP event

Quantiles: Values taken at regular intervals from the inverse of the cumulative distribution function (CDF) of a random variable.

Stochastic flood event: Statistically generated synthetic flood event. Stochastic flood events include variability in flood input parameters (eg temporal and spatial rainfall patterns) compared to design flood events. Stochastic flood events by their method of generation exhibit a greater degree of variability and randomness compared to design flood events (See also Design flood event)

Synthetic flood event: See Stochastic flood event

TPT: Total Probability Theorem. This is one of the fundamental theorems in statistics. In this report, TPT refers to a Monte Carlo sampling method that is based on stratified sampling and, hence, makes use of the total probability theorem

URBS: Unified River Basin Simulator. A rainfall runoff routing hydrologic model (Carroll, 2012)

7.2 Study related terms

BCC: Brisbane City Council

BoM: Australian Bureau of Meteorology

BRCFS: Brisbane River Catchment Flood Study

BRCFM: Brisbane River Catchment Floodplain Management Study

BRCFMP: Brisbane River Catchment Floodplain Management Plan

Delft-FEWS: Flood Early Warning Systems, a software package developed by Deltares, initially for the purpose of real-time flood forecasting. Delft-FEWS is used all over the world, including by the Environment Agency (UK) and the National Weather Service (US). Currently, it is also being implemented by Deltares and BoM for flood forecasting in Australia. The Monte Carlo framework for the BRCFS-Hydrology Phase will be implemented in Delft-FEWS

DEWS: Department of Energy and Water Supply

DIG: Dams Implementation Group

DNRM: Department of Natural Resources and Mines

DSITIA: Department of Science Information Technology, Innovation and the Arts

DSDIP: Department of State Development and Infrastructure Planning

EA: Engineers Australia formally known as The Institute of Engineers, Australia

GA: General Adapter, an interface between the Delft-FEWS environment and an external module

IC: Implementation Committee of the BRCFS

ICC: Ipswich City Council

IPE: Independent panel of experts to the BRCFS

LVRC: Lockyer Valley Regional Council

ND: No-dams condition. This scenario represents the catchment condition without the influence of the dams and reservoirs. The reservoir reaches have effectively been returned to their natural condition

NPDOS: North Pine Dam Optimisation Study conducted in response to the QFCOI Final Report

PIG: Planning Implementation Group

QFCOI: Queensland Floods Commission of Inquiry

RTC: Real-Time Control. A software package for simulations of reservoir operation. RTC tools is used for the simulation of Wivenhoe and Somerset reservoirs

SC: Steering Committee of the BRCFS

SRC: Somerset Regional Council

TWG: Technical Working Group

WD: With-dams condition. This scenario represents the catchment condition with the influence of the dams and reservoirs represented in their current (2013) configuration

WSDOS: Wivenhoe and Somerset Dam Optimisation Study conducted in response to the QFCOI Final report

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