FINAL REPORT

Critical review of climate change and water modelling in Queensland

November 2019

An independent report completed for the
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Summary

Computer-based models are valuable tools to inform water allocation decisions, water quality investments, and objectively assess the impacts of industry development and the implementation of planning initiatives on the availability, movement and quality of water resources. Under the Queensland Water Modelling Network's Research, Development and Innovation (RDI) portfolio, Alluvium Consulting, in partnership with the University of Newcastle and CSIRO, was commissioned to undertake a 'Critical review of climate change in Queensland water models.' The intent of this report is to provide an understanding of the stakeholder needs, state of the science, state of the modelling and future investment needs in order to improve our understanding of existing climate variability and future climate change in Queensland's water models.

Through this report, we refer to existing climate variability as the representation of variability in a range of climate factors that may be present not just in the last 120 years of recorded data, but also from improved understanding of past climate patterns, sequences and influences determined through palaeoclimate research.

We also refer to future climate change in this report as the representation, either at global, regional or local scales, of the impacts of climatic shifts as a result of increased greenhouse gas emissions in the atmosphere. These are likely to cause changes to a range of climate factors in addition to existing climate variability and may further add to that variability (e.g. through increases in frequency and/or intensity of climatic events). Therefore, the reference to future climate change in this report can mean both accounting for trends in climate factors (such as increases in temperature or changes in rainfall) and changes to existing climate variability in future years.

Water modelling in Queensland is undertaken for many reasons and uses a range of tools to evaluate ecological, social and economic impacts of water management. These models are not only used in isolation but can be utilised in combination to answer specific questions. An illustration of this is shown in the figure below.

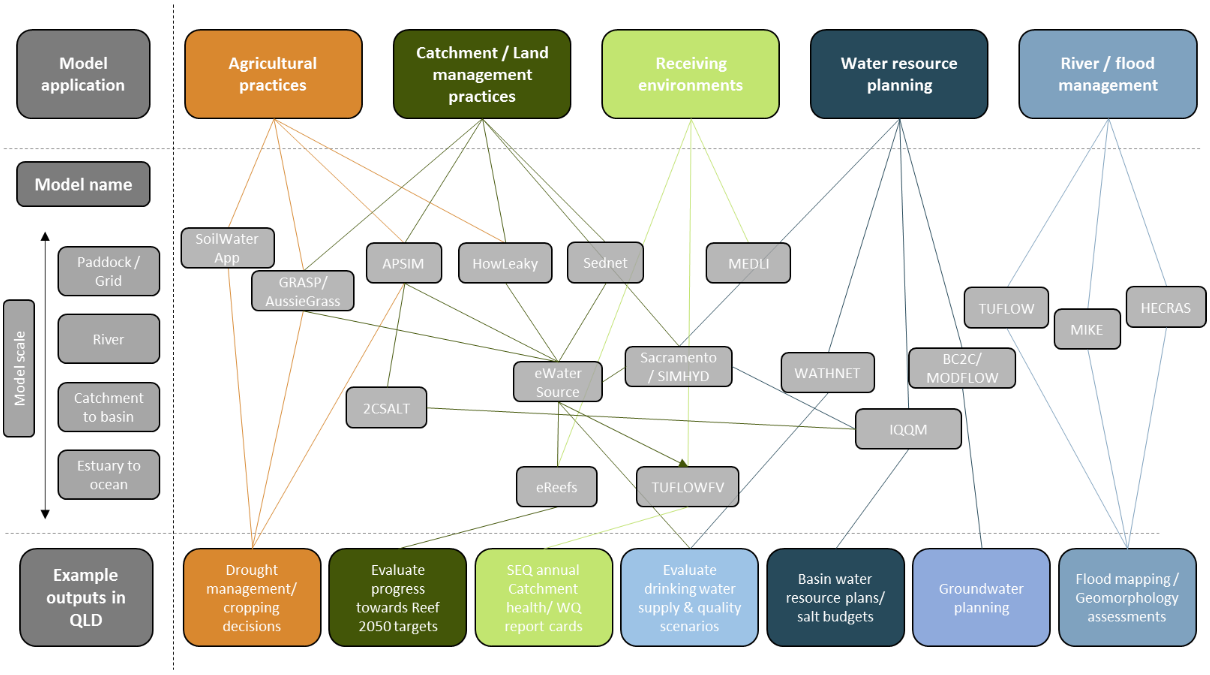

Figure 1. *Models used in Queensland for water modelling and their connections.*

Accounting for existing climate variability and future climate change is going to be a foundational requirement for using these models in future planning and management assessments.

This project has used a 'multiple lines' of evidence approach to evaluate inputs from modellers, decision makers, scientists and practitioners, in addition to evaluations of the science, a review of current modelling approaches, and a synthesis of all of these into the development of a future investment plan to better account for existing climate variability and future climate change. This is illustrated in the figure below.

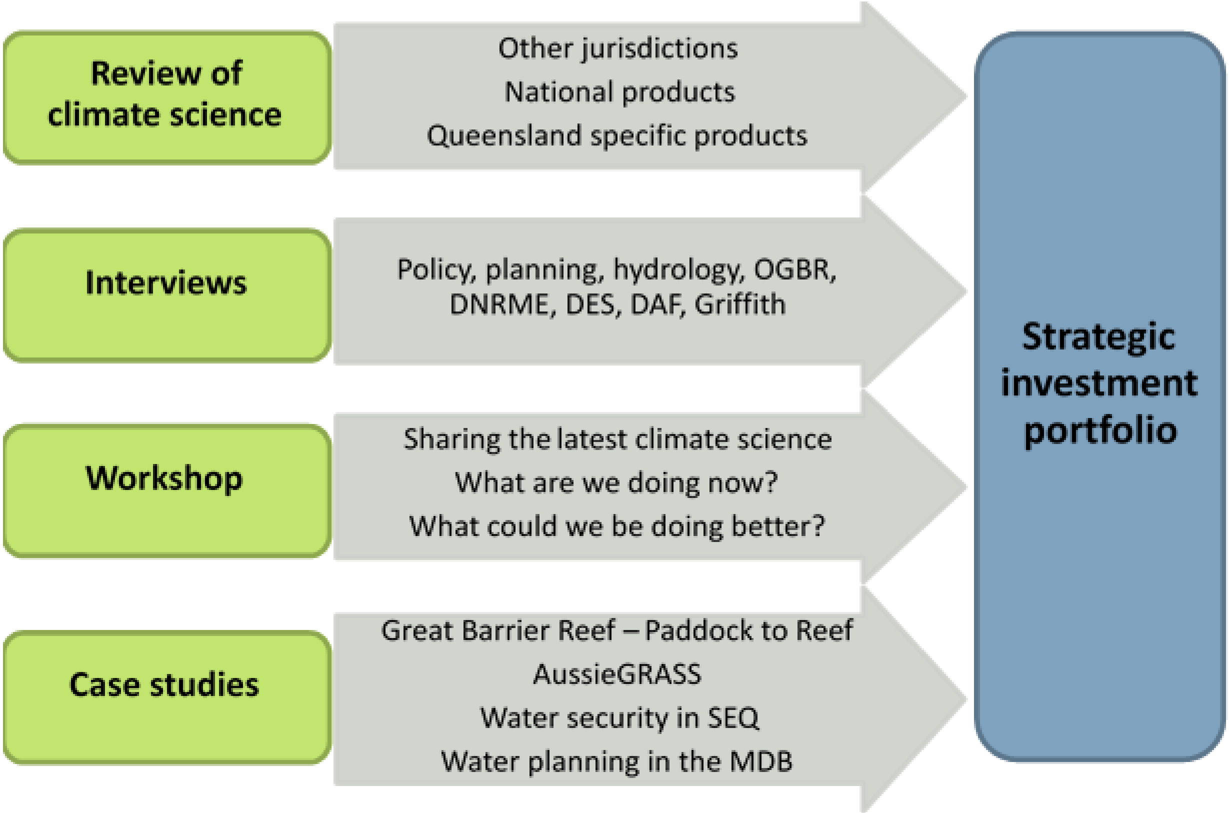

Figure 2. *The multiple lines of evidence approach used in this study*

This report shows that existing models largely rely on recorded data to understand the range in climate extremes, but that may not represent the full range of variability possible as indicated by the palaeoclimate research, and the potential for longer term droughts and more severe wetter periods is greater than what is currently accounted for in the measured data.

With respect to future climate change, there are a number of new datasets and derived data products that can be used to inform models, the choice of which will depend on the modelling question. The current major datasets are tabulated to help users select fit for purpose datasets. There are specific datasets developed for Queensland (see longpaddock.qld.gov.au) at resolutions appropriate for some water models. These are realisations of downscaled data for one future climate pathway and will not fully represent the range of potential future climate extremes.

There are also many sources of climate projection data available in addition to the Queensland downscaled climate change data and there is a need to consider what datasets may best suit different modelling approaches, such as top-down impact modelling, where emissions/warming from global climate models (GCMs) are used for downscaling to regional and local scales. The challenge is that the range of future projections can be large, therefore bottom-up decision scaling can be useful for assessing system resilience to climate change risk.

Overwhelmingly, current approaches to evaluate climate change rely on a “delta change” approach, where adjustments are made to existing climate records to produce estimates of future climate. While useful in establishing initial estimates of climate change impacts, this report highlights that the overall system behaviour under climate change also needs to be evaluated, as climate responses such as changes in vegetation, cropping, water column chemistry and ecology, soil properties, population dynamics and similar processes may all compound changes in temperature, rainfall, evaporation and other climate factors important for water models. There is also a need to adapt, conceptualise, and parameterise water models to enable them to project the future under climate change, (e.g. through accounting for hydrological non-stationarity where future responses of runoff to rainfall may differ from historical records) as there are few models currently available where this is accounted for and this may help better account for changes in system behaviour.

New approaches in decision frameworks for dealing with uncertainty in future climate change are available. Fundamentally, questions around incorporation of climate change into decision processes are based on understanding:

a) The magnitude of climate change (and uncertainty in which of the ranges of future scenarios is most likely)
b) The speed of climate change (and uncertainty as to how quickly policy actions need to be implemented)
c) The impacts on specific areas and regions (downscaling uncertainty)
d) The policies that should be implemented to mitigate or adapt to the consequences of climate change (uncertainty around the efficacy of the policy action)

Decision frameworks need to be able to deal with these compounding uncertainties and consider the trade-off of risk and reward in planning. For some modelling questions, high-level considerations of uncertainty may be sufficient, whereas understanding risk to future water supplies may require a far more detailed consideration of the likely changes in risk profiles under different uncertainties.

Ultimately, improvements in accounting for existing climate variability and future climate change in Queensland water models need to be based around improvements in knowledge, capacity and communication of those involved in using models for decision support. This is not focused solely on modellers, but on planners, policy makers and managers who may be reliant on the model outputs to support future water management.

Model improvements also need to be focused on those which are required to best answer the modelling question, so there will always be a need to answer the question with a flexible and adaptable modelling process that has clear objectives and well communicated modelling outcomes to inform planning and policy. This 'pipeline' process of modelling needs to address a range of questions when considering improved climate change modelling, whether this be from the perspective of the modeller, or those using the results of models in the decision process. This is illustrated in the following figure.

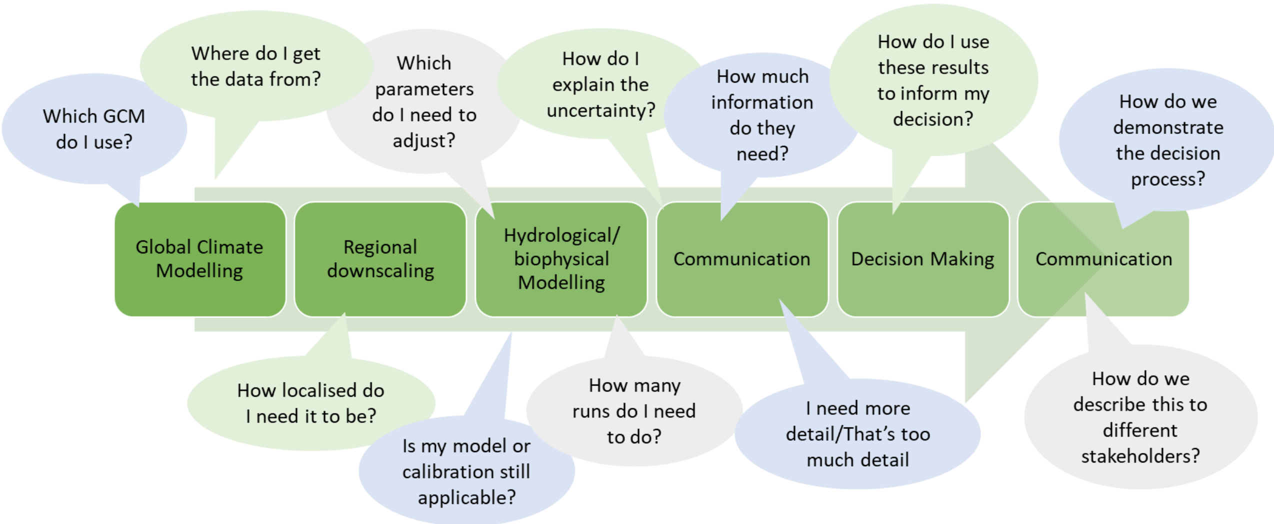

Figure 3. *The modelling process 'pipeline' when accounting for climate change*

This approach has led to the development of the Strategic Investment Portfolio in order to improve the delivery of the modelling 'pipeline' as shown above.

The primary objective of the Strategic Investment Portfolio is to:

Increase Queensland's ability to understand the impact of climate variability and change on water-related systems, to increase economic, social, cultural and environmental resilience

The five key outcomes which will contribute to achieving this objective are:

Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate variability and change

Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland

Outcome 3: Address climate science and water modelling gaps through targeted research initiatives

Outcome 4: Empower individuals and collectives and facilitate collaboration

Outcome 5: Develop training, communication and guidance materials to support Outcomes 1-4

A range of outcomes are proposed in the portfolio and these are presented in terms of short-term (next 12 months), medium-term (2-3-years) and long-term (3-5 years) investment priorities. Also outlined is a suggested timeline of actions, demonstrating that it will not just be delivery of short, then medium and finally long-term, but that some of these will need to be delivered in parallel, and some are dependent on other actions being undertaken.

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Abbreviations and acronyms

AIMS	The Australian Institute of Marine Science
BoM	Australian Bureau of Meteorology
CCAM	Conformal Cubic Atmospheric Model, a dynamic downscaling model
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
DAF	Department of Agriculture and Fisheries, Queensland
DES	Department of Environment and Science, Queensland
DNRME	Department of Natural Resources, Mines and Energy, Queensland
EEP	External Engagement Program
ESCCI	Eastern Seaboard Climate Change Initiative
GBR	Great Barrier Reef
GCM	Global Circulation Model
IOCI	Indian Ocean Climate Initiative
MDBA	Murray Darling Basin Authority
MDBSY	Murray-Darling Basin Sustainable Yields project
NARCliM	NSW and ACT Regional Climate Modelling project
NHMM	Nonhomogeneous Hidden Markov Model, a statistical downscaling model
OGBR	Office of the Great Barrier Reef – Department of Environment and Science, Queensland
QCAS	Queensland Climate Adaptation Strategy
QG	Queensland Government
QWMN	Queensland Water Modelling Network
SEACI	South Eastern Australian Climate Initiative
SEQ	South East Queensland
TASY	Tasmanian Sustainable Yields project
VicCI	Victorian Climate Initiative
VicWaCI	Victorian Water and Climate Initiative
WRF	Weather Research and Forecasting regional climate model

1 Introduction

In February 2017 the Queensland Government launched the interdepartmental Queensland Water Modelling Network (QWMN). The state-wide network is improving the state's capacity to model its surface water and groundwater resources and their quality. The QWMN provides the tools, information and collaborative platforms to support best-practice use of water models, and the uptake of their results by policy makers and natural resource managers. The QWMN delivers this through its research, development and innovation program; as well as focusing effort on building the capability of Queensland's water modelling sector.

Computer-based models are valuable tools to inform water allocation decisions, water quality investments, and objectively assess the impacts of industry development and the implementation of planning initiatives on the availability, movement and quality of water resources.

Alluvium Consulting, in partnership with the University of Newcastle and CSIRO, was commissioned by the QWMN to undertake a 'Critical review of climate change in Queensland water models.' The project provided an assessment of Queensland Government's ability as of May 2019 to incorporate existing climate variability and future climate change projections into the diverse range of water models used across Queensland.

Through this report, we refer to existing climate variability as the representation of variability in a range of climate factors that may be present not just in the last 120 years of recorded data, but also from improved understanding of past climate patterns, sequences and influences determined through palaeoclimate research. This research indicates that existing climate records are poor predictors of what climate variability may be in future years. Water models will therefore need to incorporate better representations of this variability, in addition to trends from future climate change, in order to best understand the impacts of the full range of climate variability that may influence future water modelling outcomes and subsequent decisions based on those models.

Also, throughout this report we refer to future climate change as the representation, either at global, regional or local scales, of the impacts of climatic shifts as a result of increased greenhouse gas emissions in the atmosphere. These are likely to cause changes to a range of climate factors in addition to existing climate variability and may further add to that variability (e.g. through increases in frequency and/or intensity of climatic events). Therefore, the reference to future climate change in this report can mean both accounting for trends in climate factors (such as increases in temperature or decreases in rainfall) and changes to existing climate variability in future years.

2 Context

In the water-modelling realm, implications of existing climate variability and future climate change for water resources and water quality have been discussed in many forums, however consistent approaches incorporating such factors within models are not well established. Australia has been at the forefront of understanding the science and impacts of climate variability and change through several academic institutions and is strongly engaged with leading organisations and initiatives globally including the Intergovernmental Panel on Climate Change (IPCC).

Hydrologic, water resource and water quality modelling are well-developed fields in Australia and there have been a number of examples where future climate change and existing climate variability have been incorporated within water models. This has mostly been through specific projects or through key experts, rather than mainstream adoption of consistent modelling approaches. Australia is also seen as a world leader in water resource management and the adaptation and application of best available science to water-related issues. What is therefore needed is the integration of this science and knowledge with a better understanding of the modelling contexts where climate variability and change need to be evaluated, so that it can move from niche or boutique applications, to consistent application on a regular basis across a range of water models. Through understanding the implications of the modelling contexts and the application of the best available science, we can identify where the potential gains and opportunities for improvement may lie. This therefore provides a clear pathway to consistent, robust approaches for assessing the impacts of climate variability and change in water modelling and incorporation into subsequent decision-making frameworks.

This project is a foundational step in improving water modelling practice in Queensland, providing an opportunity for the science and modelling experts to discuss ways forward that can help build capacity in the water modelling realm, not only for modellers, but also end users of the modelling, such as policy makers, planners and corporate initiatives.

While this project had a focus on Queensland Government modelling groups and end users, we note that there are a range of organisations, and roles within these organisations, which actively use water models, inform water models, or use the outputs of water modelling for decision support. Exploring the needs and capabilities of each of these groups, and the interactions between these groups, was essential for understanding the various end user requirements and developing recommendations for investment which will support the sector in assessing and adapting to current and future risks from climate variability and change.

2.1 Climate change and the water sector

Climate variability and change, and how impacts from these affect water issues, cut across many agencies and sectors. Adaptation approaches in the water resource sector are challenging because of the large uncertainties in the future hydroclimate projections and the different climate change management responses or pathways. Reasons for these large uncertainties include multiple plausible but different future emission scenarios, multiple plausible but different future rainfall projections, and the extrapolation of water models to predict a future under changed landscape and hydrologic conditions. These issues are magnified at the spatial scales where water issues are likely to be realised (i.e. catchment or regional scale).

The complexity of modelling applications to address climate variability and change must be guided by the purpose of the application, for example, the need for climate change consideration, and climate change risk in the context of other drivers. Given the uncertainty in future hydroclimate projections, assistance dealing with uncertainty through a decision scaling or sensitivity approach may be useful to assess catchment and water system resilience and adaptation options to changes in different climate characteristics, prior to a detailed climate change impact assessment.

2.2 Overview of water modelling in Queensland

Management of Queensland's water resource aims to optimise the balance between economic, environmental, social and cultural outcomes. To guide water planning and water resource management across the state, rigorous science is a key input. This is well documented in 'The Water Planning Science Plan 2014-2019' (Department of Environment and Science and Department of Natural Resources, Mines and Energy) and builds on existing knowledge about the hydrology of surface and groundwater systems, ecological assets and their critical water requirements to guide the future analysis, interpretation and collection of fit-for-purpose information for use in water and environmental management.

Responsibilities are shared between several departments and groups across Queensland Government, primarily the Department of Environment and Science (DES), Department of Natural Resources, Mines and Energy (DNRME) and Department of Agriculture and Fisheries (DAF), with resources distributed across the state.

The majority of water modelling for rural and urban water planning is undertaken within DES (using IQQM and more recently eWater Source), with results provided to the policy and planning areas of DNRME. The Office of the Great Barrier Reef (OGBR) in DES, in conjunction with DNRME and DAF, leads the Paddock to Reef (P2R) modelling program as part of the Queensland Reef Water Quality Program. Groups leading marine and freshwater receiving water modelling are more distributed, with high levels of input from research groups such as Griffith University, AIMS and CSIRO, and through major projects such as eReefs. Statutory bodies such as Seqwater and Queensland Urban Utilities (QUU), and other water and wastewater organisations, as well as local government authorities also rely on internal or external water modelling to support their operations.

2.3 Study approach and report outline

This study uses a 'multiple lines of evidence' approach to assess end user needs, understand the current approaches to incorporating climate change and variability into water modelling, and review the latest available science and best practice to identify opportunities to form a strategic investment portfolio (Figure 4). This report summarises the findings of each of these study components.

Section 3 provides an overview of the latest climate science and data products, reviews approaches across other Australian jurisdictions, and describes the availability of climate projection data for Queensland and its applicability for hydrological modelling.

Section 4 outlines a stakeholder analysis and 'end user' requirements.

Section 5 summarises the current approach and future opportunities for the treatment of climate change and variability in water modelling and decision making, based on stakeholder interviews and workshop outcomes.

Section 6 summarises four case studies that explore the treatment of climate change and variability in water modelling programs across Queensland.

Section 7 then brings together the primary findings of earlier Sections to identify the key/priority gaps and recommendations for improvement.

Section 8 presents recommended investment priorities to address the gaps identified in Section 7. These recommendations have also been summarised in a stand-alone Strategic Investment Portfolio.

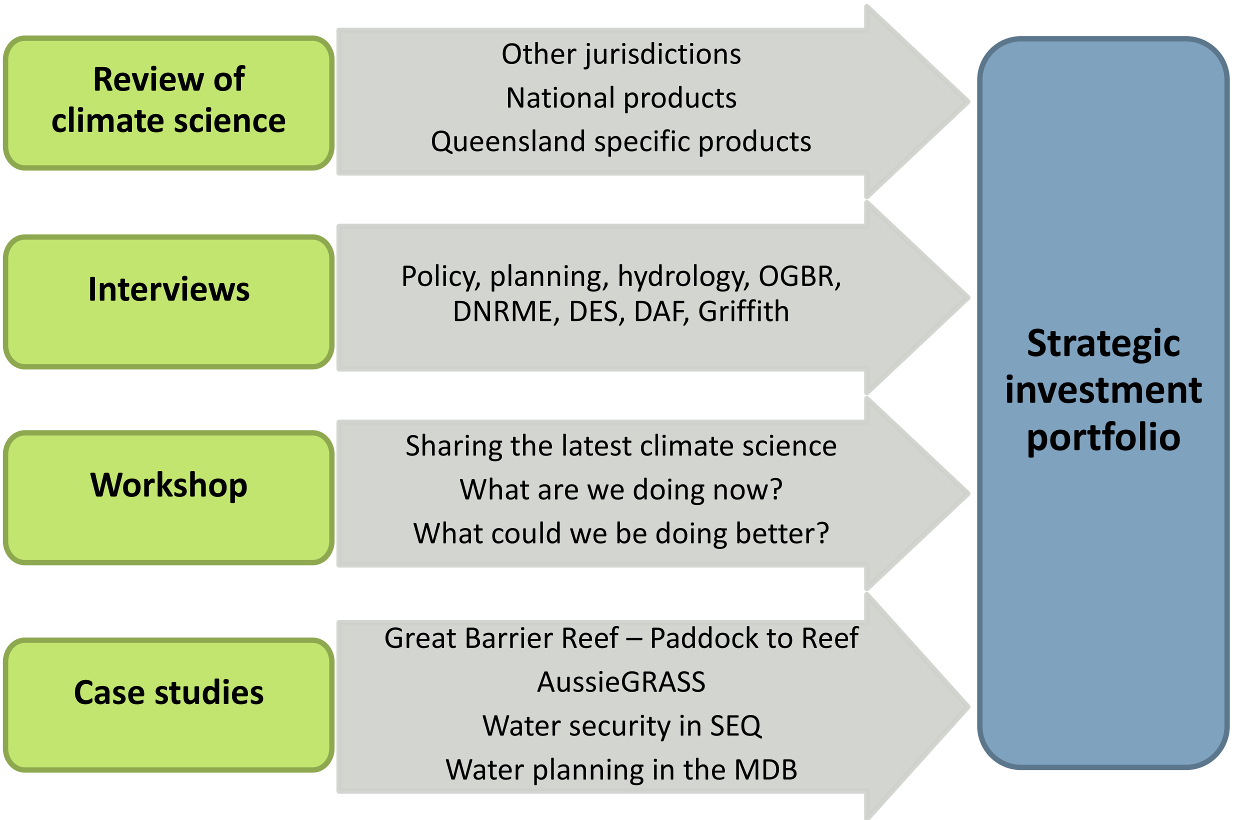


Figure 4. *Multiple lines of evidence approach*

3 Review of climate change and climate variability science and best practice

3.1 Climate change science

Climate change has impacted and will continue to impact natural, managed and human systems over the coming decades. The magnitude of expected change depends on future greenhouse gas emissions and climate feedbacks. The hydrological impact of climate change will affect people, agriculture, industries and ecosystems. These impacts are potentially very significant and therefore the management and planning of water resources systems need to adapt to cope with the projected changes.

Inter-annual to multi-decadal variability in Australian river flows is very high. This high natural hydroclimate variability is expected to dominate in the near term (Mora et al. 2013). Improved management of water resources systems to cope with hydroclimate variability will help buffer the system against long dry spells as well as facilitate adaptation to climate change. The use of palaeoclimate data can help characterise inter-annual to multi-decadal variability beyond that seen in the instrumental record (see Section 3.2). Climate change impacts are projected to become increasingly pronounced further into the future, this “time of emergence” (Mora et al. 2013) is currently under debate (Hawkins et al 2014) but estimated to be in the next 20-50 years. Therefore, climate change needs to be considered in long-term water resources planning in addition to managing the impacts associated with natural climate variability.

Figure 5 shows the modelling components involved with projecting future water availability, catchment hydrology and river flow characteristics which then ultimately result in changes to dependent systems. The following sub-sections describe these components and the associated uncertainties.

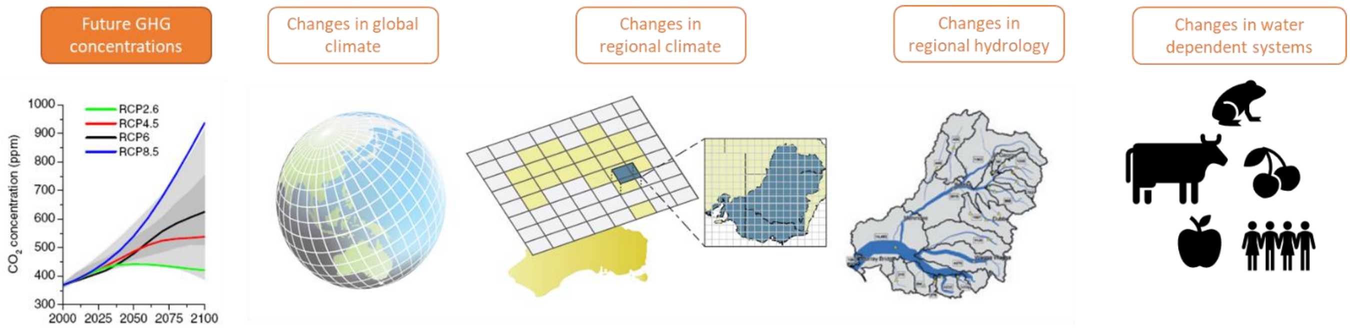


Figure 5 *Modelling components and the sources of uncertainty in predicting future water outcomes. (adapted from* http://www.seaci.org/publications/documents/SEACI-2Reports/SEACI_Phase2_SynthesisReport.pdf)

3.1.1 Future greenhouse gas emissions

The Intergovernmental Panel on Climate Change uses what are known as ‘Representative Concentration Pathways’ (RCPs) to describe four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use (IPCC 2014). The RCPs have been developed using Integrated Assessment Models (IAMs) as input to a wide range of climate model simulations to project their consequences for the climate system. These climate projections, in turn, are used for impacts and adaptation assessment. (Table 1 and Figure 5). The high emission scenario, RCP8.5 (radiative forcing of 8.5 W/m^2 by 2100 relative to pre-industrial value), represents a future with little curbing of greenhouse gas emissions and CO_2 concentrations continuing to rapidly rise. The medium scenario, RCP4.5, represents emissions peaking around 2040, and then stabilising at around 2100. The most ambitious, best-case mitigation scenario is RCP2.6, which sees emissions peaking around 2020 and then rapidly declining. **As of 2019, RCPs 4.5 and 8.5 are recommended as the preferred basis for Queensland Government climate projections to provide a realistic envelope or a realistic range of future emissions. RCP 6.0 is suggested if an additional climate projection is required.**

For the four emission scenarios, the rise in global mean surface temperature in the atmosphere at land and ocean surfaces by the end of the 21st century is more than two-thirds certain to be in the ranges 2.6-4.8°C (RCP8.5), 1.4-3.1°C (RCP6.0), 1.1-2.6°C (RCP4.5) and 0.3-1.7°C (RCP2.6). The difference in climate projections for the different emissions scenarios is relatively small in the near-term (because near-term changes are already locked in due to the lag in the climate system response) but deviate significantly in the latter half of the century. The global average surface temperature by ~2060 (relative to ~1990) will be about 1.5–2.0°C warmer under RCP4.5 and 2.0–2.5°C warmer under RCP8.5. These are illustrated in the tables and figures below.

Table 1. *The four Representative Concentration Pathways (RCPs) used in IPCC AR5 and CMIP5.*

Name	Radiative forcing	Concentration (ppm)	Pathway	Source of RCP*
RCP8.5	>8.5W/m^2 in 2100	>1,370 CO_2-equiv. in 2100	Rising	MESSAGE
RCP6.0	~6W/m^2 at stabilization after 2100	~850 CO_2-equiv. (at stabilization after 2100)	Stabilisation without overshoot	AIM
RCP4.5	~4.5W/m^2 at stabilization after 2100	~650 CO_2-equiv. (at stabilization after 2100)	Stabilisation without overshoot	GCAM
RCP2.6	Peak at 3W/m^2 before 2100 and then declines	Peak at ~490 CO_2-equiv. before 2100 and then declines	Peak and decline	IMAGE

- MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impact, International Institute for Applied Systems Analysis, Austria
- AIM, Asia-Pacific Integrated Model, National Institute for Environmental Studies, Japan;
- GCAM, Global Change Assessment Model, Pacific Northwest National Laboratory, USA (previously referred to as MiniCAM);
- IMAGE, Integrated Model to Assess the Global Environment, Netherlands Environmental Assessment Agency, The Netherlands.

Table 2. *From Moss et al. (2010). Median temperature anomaly over pre-industrial levels and RCP pathway.*

Name	Radiative forcing	CO_2 equiv (p.p.m.)	Temp anomaly (°C)	Pathway
RCP8.5	8.5 Wm^2 in 2100	1370	4.9	Rising
RCP6.0	6 Wm^2 post 2100	850	3.0	Stabilization without overshoot
RCP4.5	4.5 Wm^2 post 2100	650	2.4	Stabilization without overshoot
RCP2.6 (RCP3PD)	3Wm^2 before 2100, declining to 2.6 Wm^2 by 2100	490	1.5	Peak and decline

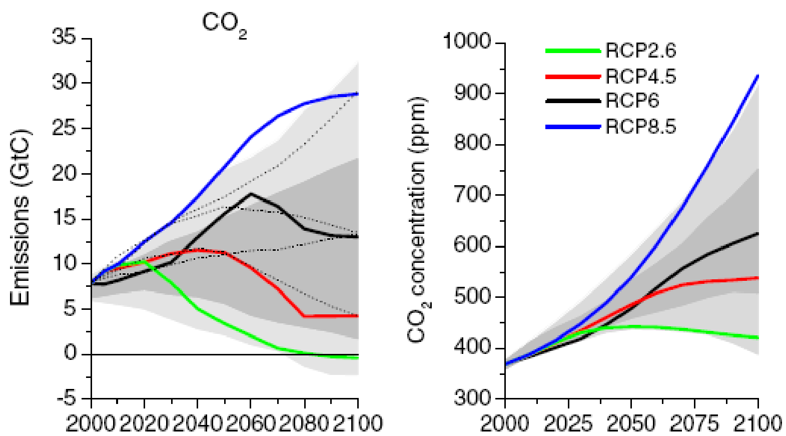


Figure 6. *Relative Concentration Pathways (total emissions and CO2 concentrations) from Climate Change in Australia (www.climatechangeinaustralia.gov.au)*

3.1.2 Global climate modelling

General Circulation Models (GCMs) represent the atmosphere, land and ocean on three-dimensional grids, with a typical horizontal resolution of 200–300 km and 20–50 vertical levels. GCMs are based on fundamental laws of physics including conservation of mass, energy and momentum. GCMs are able to simulate key features of current and past climate and show a substantial and robust warming signal due to increasing greenhouse gas concentrations. GCMs are simplifications of reality and are undergoing significant development and improvement, particularly over the last decade.

Many climate change studies in Australia and globally make use of the climate change projections from the 40+ GCMs archived in the CMIP5 database (Coupled Model Intercomparison Project Phase 5), which complements the IPCC AR5 (IPCC Fifth Assessment Report). Projections from CMIP6, which complements IPCC AR6, will start to become available in 2020, and there are likely to be more than 100 GCMs from over 30 modelling groups participating in CMIP6. This raises challenges on how to interpret and effectively use so many GCM outputs. Further work will be needed to understand the implications of these GCM outputs for Australia and Queensland conditions.

The large number of RCPs and GCMs provide the range of plausible futures used in many climate change impact and adaptation studies. Additionally, the range represents uncertainties in the initial conditions and parameters of the models. Some studies attempt to reduce the range in the future projections by putting more weight on, or using only, the better GCMs, evaluated against their ability to reproduce historical conditions. This is challenging because different considerations can be used to assess the GCMs (e.g. ability to reproduce the observed climate variables (and there are many of them), or the large-scale oceanic and atmospheric variables like ENSO, IOD or SAM, or the correlation between large scale variables/drivers and local/regional scale climate). Many studies have shown that selecting GCMs based on their performance does not necessarily reduce the uncertainty in the projections compared to using all available GCMs(CSIRO and Bureau of Meteorology, 2015; Chiew et al., 2009 ; Smith & Chandler, 2009 ; Ekstrom et al. 2015; Grose et al. 2015).

3.1.3 Downscaling

As noted above, GCMs can provide us with projections of how the climate of the earth may change in the future. These results are the main motivation for the international community to take decisions on climate change mitigation. However, the impacts of a changing climate, and the adaptation strategies required to deal with them, will occur on more regional and national scales. This is where downscaling of GCMs has an important role to play by providing projections with much greater detail and more accurate representation of localised extreme events. Downscaling translates the coarse horizontal (~200km) resolution information from GCMs to finer scale (~10-50km) grids.

Statistical downscaling relates the observed local scale climate to the large-scale atmospheric features simulated by GCMs. Numerous methods for statistical downscaling exist, including analogue methods that identify the most similar weather pattern in the past based on large-scale climate predictors, weather generators, regression or machine learning models, and hybrid approaches. Statistical downscaling is relatively easier to apply, because once the relationship between local scale climate and large scale GCM features has been established, it can be used to downscale projections from the large range of GCMs. Statistical downscaling methods have limitations, for example, potential changes in the statistical relationship under climate change, correlation between different climate variables may not be properly accounted, or a particular large-scale climate feature used as a predictor is not well captured by a GCM or has a strong bias overall or in the region of interest. Continuing method developments attempt to account for these factors.

Dynamical downscaling uses a high resolution (10–50 km) regional climate model (RCM), constrained by the boundary conditions provided by the GCMs. Dynamical downscaling potentially offers more insight as it directly attempts to resolve local scale features, like orography and coastlines, which cannot be captured by the coarse resolution GCMs. Dynamical downscaling also directly simulates the dynamic evolution of weather events, allowing the physical mechanism driving the changes to be studied and interpreted. An additional advantage is that mesoscale processes are resolved, leading to more realistic simulation of extreme events which often play a significant role in Queensland weather/climate/rainfall processes which are to large extent convective, especially in summer. Dynamical downscaling can potentially offer more robust high-resolution projections, but is limited by long computational times yielding a reduced number of runs (often from a single regional climate model) and may underestimate the plausible range in the future projections. In addition, there are challenges in robustly bias-correcting the raw climate data outputs from the RCMs specifically for hydrological applications. The quality of bias correction is conditional on availability of high-quality observational data used to derive transfer functions for bias correction. Spatial and temporal coverage of rainfall data in Queensland is a limiting factor in application of bias correction, including temporal aspects of low frequency variability.

Table 3 in Section 3.3 provides examples of statistical downscaling and dynamical downscaling climate projections data sources available for Australian states, but there are also continental downscaling projections available, including:

- The Coordinated Regional Downscaling Experiment (Cordex) http://www.cordex.org/domains/region-9-australasia/ ;
- The Earth System Grid Federation data portal has access to a number of downscaling products at https://esgf.nci.org.au/projects/esgf-nci/ ; and
- NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP), statistically downscaled global projections at 25km grid cells https://nex.nasa.gov/nex/projects/1356/

3.1.4 Generating future climate series to drive hydrological models

The GCMs and RCMs also simulate hydrology, including rainfall, evapotranspiration and runoff, and sometimes through to river flows. All GCMs have runoff as direct outputs, but GCM runoff simulations at the catchment scale are hampered by the very coarse GCM resolution and the lack of calibration of the land surface models used in GCMs against streamflow data. However, the simulation is a simplification of the real world and has considerable biases compared to detailed hydrological models developed specifically for the catchment or river basin. As such, studies of climate change impacts on hydrology typically rely on offline hydrological models run with future climate variables informed by GCMs and RCMs.

Most studies typically compare a future period (e.g. 2050–2080) to a historical period (e.g. 1970–2018). Many studies use an empirical scaling or ‘delta-change’ method where the historical climate series is scaled by a change factor (or set of factors) to reflect the future climate series. The change factor is informed by the climate change signal from the GCMs and RCMs. The entire historical climate series is scaled by the same factor, which can be applied differently at annual, seasonal or monthly levels, or to the daily rainfall distribution itself (where the different rainfall percentiles are scaled by different factors). The delta-change method is simple, but in using the same historical climate sequence (albeit scaled to reflect climate change), it does not consider potential changes in the future climate sequence. It does reflect some historical variability which may be contained in the forcing data being changed (e.g. using a historic rainfall timeseries and scaling that are not able to be represented by a simple scaling of data), but may not properly account for the likely variability now known through paleo-climate studies. Nevertheless, it is worth noting that the GCMs have some ability in simulating broad-scale changes (e.g. rainfall changes at the seasonal level and changes in high rainfall extremes, which can be captured by the delta-change method), but are very poor in simulating changes in other rainfall features (e.g. multi-year variability).

To overcome the limitations of the delta-change method, statistical downscaling (as described in 3.1.3) and bias-correction methods can be used. In bias-correction, parametric or non-parametric methods are used to directly relate the distribution of the observed historical rainfall (often daily rainfall) and rainfall simulated by the GCMs or RCMs, and then use this relationship to translate the future rainfall simulated by the GCMs or RCMs to the point or catchment rainfall. There may be some added value in this approach, particularly when used with RCMs to capture higher spatial resolution and changes in temporal characteristics beyond long-term averages. However, the bias-correction methods suffer the same limitations as statistical downscaling, the bias correction that needs to be applied is often larger than the climate change signal itself, and it remains challenging to robustly bias correct RCM rainfall for hydrological modelling (particularly in the spatial rainfall characteristic and multi-day rainfall that are important in runoff generation).

Instead of comparing a future period relative to a historical or current period, statistical downscaling and bias-correction can be used with RCMs to provide transient simulations or continuous future trajectories. This potentially allows for consistent interpretations of the spread (or ensemble or uncertainty) of near-term changes (which is likely to be dominated by natural climate variability) and long-term changes (which will be more influenced by climate change). Nevertheless, as noted above, at present there are too few RCM runs available to adequately represent the range of uncertainty. Stochastic methods can help overcome this, where future climate series is generated stochastically, informed by historical characteristics as well as climate change signals or trends that can be realistically simulated by GCMs and RCMs (e.g. increasing/decreasing trend in mean rainfall, increasing trend in high rainfall extremes).

3.1.5 Hydrological modelling

In most applications, future climate inputs are used to drive a hydrological model to simulate future hydrological characteristics. The same model parameters obtained from model calibration against historical observations are generally used to model the future. This assumption of 'hydrologic stationarity' may be flawed, particularly as the models are extrapolated to predict a future that is very different from the past (e.g. changed rainfall patterns, higher temperature, higher CO_2). For example, in catchments and landscapes, the rainfall-runoff relationship may vary under different hydrologic conditions (e.g. surface-groundwater connection in long dry spells) and vegetation responses and feedbacks will change under higher atmospheric CO_2 concentration. Empirical relationships derived from fitting past data, for example loss functions in river system models, might not be the same in the future. Anecdotal information from understanding step changes in hydrologic response in Victoria and Western Australia suggest that this is more likely than not and is the subject of current research. This model limitation will generally lead to an underestimation of the projected range of change, as well as underestimating the predicted decrease in runoff where a runoff decrease is anticipated, and underestimate the modelled increase in runoff where a runoff increase is anticipated. The shape of river beds may also change over time as a consequence of hydrological change, and this too will affect hydrological dynamics.

Hydrologic stationarity is still used as it provides for analysis to be completed in reasonable timeframes to provide indications of change, but this should be balanced against the uncertainty in the stationarity assumption, though this may be similar or less than that for the climate projections themselves as discussed further below. Consideration of how hydrologic processes may change under different climate scenarios still needs further research and modelling to properly represent the likely non-stationarity extent. It should also be recognised that in some cases, the climate responses over the last 20-30 years may include some non-stationarity such as increased temperatures, but then this is not made explicit in the models and may not be resolved above the existing climate variability. Further work on understanding whether recent climate is an indication of future responses may be required, but again, existing climate variability and the short time frames may not produce any meaningful directions.

For most Australian conditions, where the future direction and magnitude of changes to rainfall is highly uncertain, the main source of uncertainty in predicting or projecting water futures comes from the future rainfall projections. The following references (and references therein) provide overviews, appraisals and guidance on selecting and interpreting climate projections data – Chiew et al. (2017), CSIRO and Bureau of Meteorology (2015), Ekstrom et al. (2015, 2016), Grose et al. (2015), Potter et al. (2018) and Teng et al. (2012, 2015). Another source of uncertainty comes from extrapolating hydrological models to predict a future under changed catchment conditions. The following papers provide descriptions and examples of the problem and modelling challenges and potential solutions – Cheng et al. (2017), Chiew et al. (2014), Coron et al. (2012), Hughes et al. (2012), Fowler et al. (2016), Saft et al. (2016), and Vaze et al. (2010).

3.2 Climate variability science

Climate in Australia is driven by a variety of physical processes that operate on a range of spatial and temporal time scales. These include ocean-atmospheric interactions in the Pacific, Indian and Southern Oceans as well as continental scale synoptic processes such as the subtropical ridge (STR), atmospheric blocking, and cut-off lows (refer to Murphy and Timbal (2008) and Gallant et al. (2012) for comprehensive reviews). The important sources of hydroclimatic variability for Queensland are discussed in the following sub-sections.

3.2.1 What causes hydroclimatic variability in Queensland?

Hydroclimate refers to the way climate factors influence the conversion of rainfall to runoff and how those factors may also influence other water related factors (e.g. water column temperature, evaporation etc.). Klingaman et al. 2013 notes that the variability experienced in Queensland is strongly associated with inter-annual and decadal rainfall variability. In winter, spring and summer the leading, state-wide rainfall patterns are highly correlated with the El Niño–Southern Oscillation (ENSO); the Inter-decadal Pacific Oscillation modulates the summer ENSO connections. In addition, the Madden-Julian Oscillation (MJO) influences rainfall patterns in the Northern regions of the state, mostly during monsoonal periods. In autumn, the leading connections between rainfall and broader climate patterns are associated with locally driven, late-season monsoon variations, while ENSO affects only tropical northern Queensland. In the southeast, rainfall anomalies respond to the strength and moisture content of onshore easterlies, controlled by Tasman Sea blocking. The summer rainfall-climate pattern connectivity in the southeast is more associated with onshore flow and blocking, and has been negative since 1970, consistent with the observed decline in rainfall along the heavily populated coast. The south-eastern Queensland hydroclimate shows considerable multi-decadal variability, which is independent of large-scale drivers. Summer rainfall in Cape York is associated with tropical-cyclone activity.

Descriptions of how each of these factors influence hydroclimate variability in Queensland are outlined further below.

3.2.1.1 El Niño/Southern Oscillation (ENSO)

On an inter-annual scale the El Niño/Southern Oscillation (ENSO), and the various different 'flavours' of ENSO including ENSO Modoki, is the key climate driver for, at least, the eastern half of Australia. As a result of intensive research over the last 20 years, a good understanding of the basic physical features and processes involved in the ENSO cycle and how it evolves once it has begun has been developed.

ENSO is an ocean-atmospheric climate pattern that occurs across the tropical Pacific Ocean. It is characterized by quasi-periodic (i.e. every 3-5 years) variations in the sea surface temperature (SST) of the tropical eastern Pacific Ocean. Under normal or ENSO neutral conditions, air rises in the west Pacific, flows eastward in the upper atmosphere, descends in the eastern Pacific and flows westward along the surface of the tropical Pacific (i.e. the easterly trade-winds). This is known as the Walker circulation. Under neutral ENSO conditions the typical easterly equatorial trade-winds result in warm surface water pooling in the west Pacific and cold water upwelling along the South American coast. El Niño conditions are associated with a relaxing (or reversal) of the equatorial trade-winds (weakening or reversal of the Walker circulation) which, in turn, results in warm surface water migrating towards the South American coast and reduced cold water upwelling in the east Pacific. La Niña conditions are essentially the opposite of El Niño with a strengthened Walker circulation and stronger equatorial trade-winds resulting in an enhancement of both the warm pool in the west Pacific and also the cold water upwelling in the east Pacific.

The impacts of ENSO on Australian climate are well documented (e.g. Murphy and Timbal, 2008; Gallant et al., 2012). Seasonally, winter, spring and summer rainfall variations are most strongly associated with ENSO events and the effects of ENSO include magnified fluctuations in streamflow volumes compared to rainfall (Chiew et al., 1998; Wooldridge et al., 2001; Verdon et al., 2004b), elevated flood risk during La Niña events (Kiem et al., 2003), and increased risk of drought (Kiem and Franks, 2004) and bushfire (Verdon et al., 2004a) during El Niño events.

3.2.1.2 Interdecadal ENSO

ENSO is an irregular, inter-annual oscillation of equatorial Pacific SST and the overlying atmospheric circulation. However, the characteristics of ENSO is modulated on longer, inter-decadal timescales, by a mode of variability that affects the wider Pacific Basin which is known as either the Pacific Decadal Oscillation (PDO; Mantua et al., 1997), if referring to northern Pacific Ocean variability, or the Inter-decadal Pacific Oscillation (IPO; Power et al., 1999a), if referring to basin-wide Pacific Ocean variability. Links between the IPO phenomena and climate variability in Australia include decadal and annual-scale fluctuations in rainfall, maximum temperature, streamflow, bushfire and wheat crop yield (Power et al., 1999a; Kiem et al., 2003; Kiem and Franks, 2004; Verdon et al., 2004a, 2004b) – see Figure 7 and Figure 8 for further details. The IPO primarily influences the eastern Australian climate during the austral spring, summer and autumn by inducing variations in the South Pacific Convergence Zone, which tends to be active during these months (Folland et al., 2002). The IPO regulates the eastern Australian climate indirectly by modulating both the magnitude and frequency of ENSO impacts (Power et al., 1999b; Kiem et al., 2003; Verdon et al., 2004b; Cai and Cowan, 2009). This dual modulation manifests in the historical record as periods of two to three decades during which either El Niño (if IPO is positive) or La Niña (if IPO is negative) events tend to dominate. In addition, when the IPO is in a warm (i.e. positive) phase, the relationship between ENSO and Australian rainfall is weakened, while it is strengthened during the cool (negative) phase (Power et al., 1999a). The greatest effect of this dual modulation is significantly above average rainfall and streamflow during La Niña events that occur within the negative IPO phase. In other words, during the cool IPO phase, wet events are likely to be wetter and more frequent than during a neutral or warm IPO phase, elevating flood risk across eastern Australia (Kiem et al., 2003; Verdon et al., 2004b). Conversely, during the warm IPO phase wet events are less frequent and not as wet as they are during the IPO cool phase, which results in an increased risk of drought across most of eastern Australian (Kiem and Franks, 2004; Verdon-Kidd and Kiem, 2009a). This can also have a significant effect on flooding and water security assessments as shown in Figure 9.

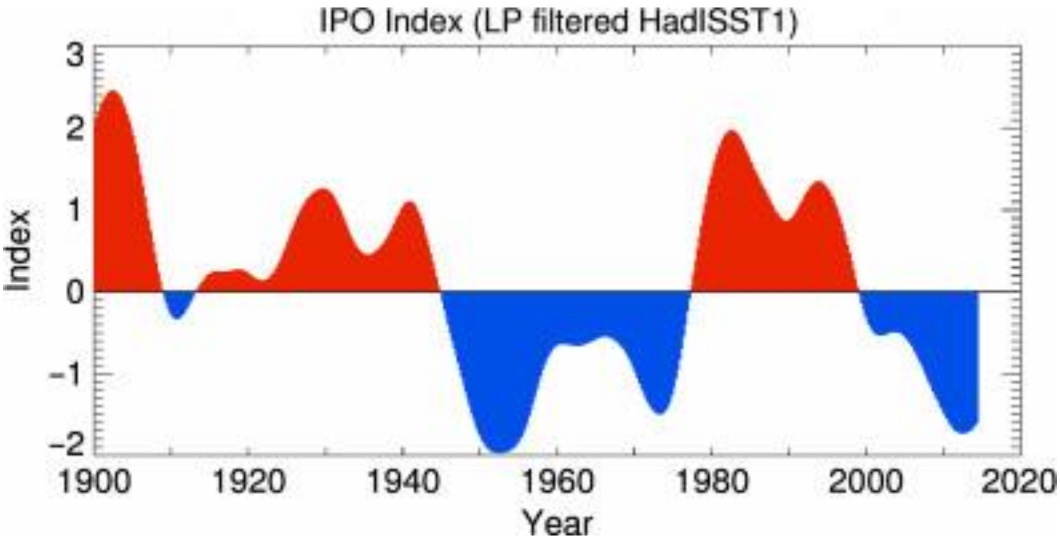


Figure 7. *IPO phases from 1900-2014*

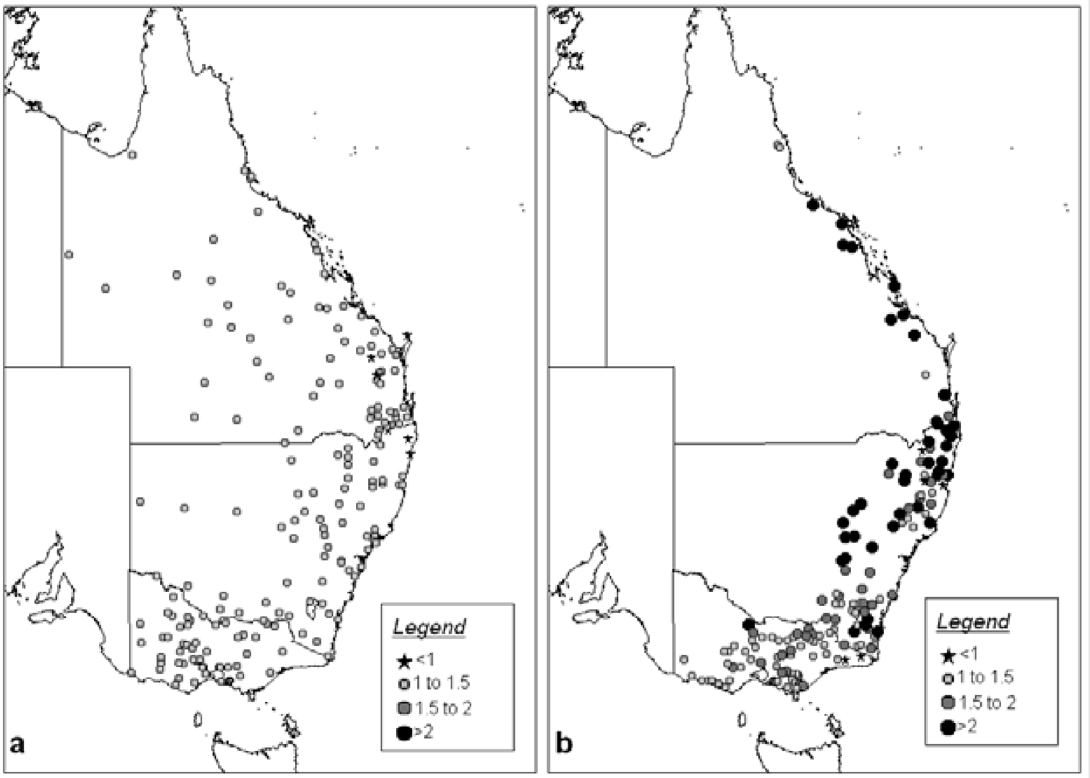
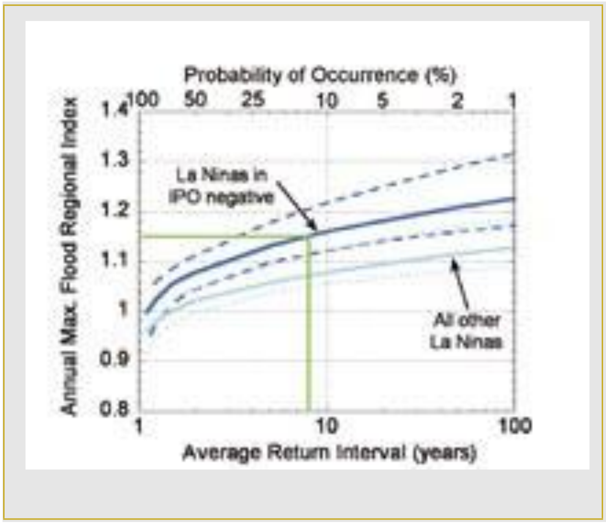


Figure 8 *Increase in (a) rainfall and (b) streamflow during IPO negative years compared to IPO positive years (from Verdon et al., 2004b)*



Dashed lines indicate 90 per cent confidence intervals. Horizontal green line indicates the magnitude of the ‘1 in 100 year flood’ calculated using ALL years (i.e. under the traditional assumption that flood risk is the same from year to year). Vertical green line indicates that the probability (~12.5%) of the ‘1 in 100 year flood’ occurring during a La Niña event is more than twelve times greater than traditionally estimated (see Kiem et al. (2003) for further details).

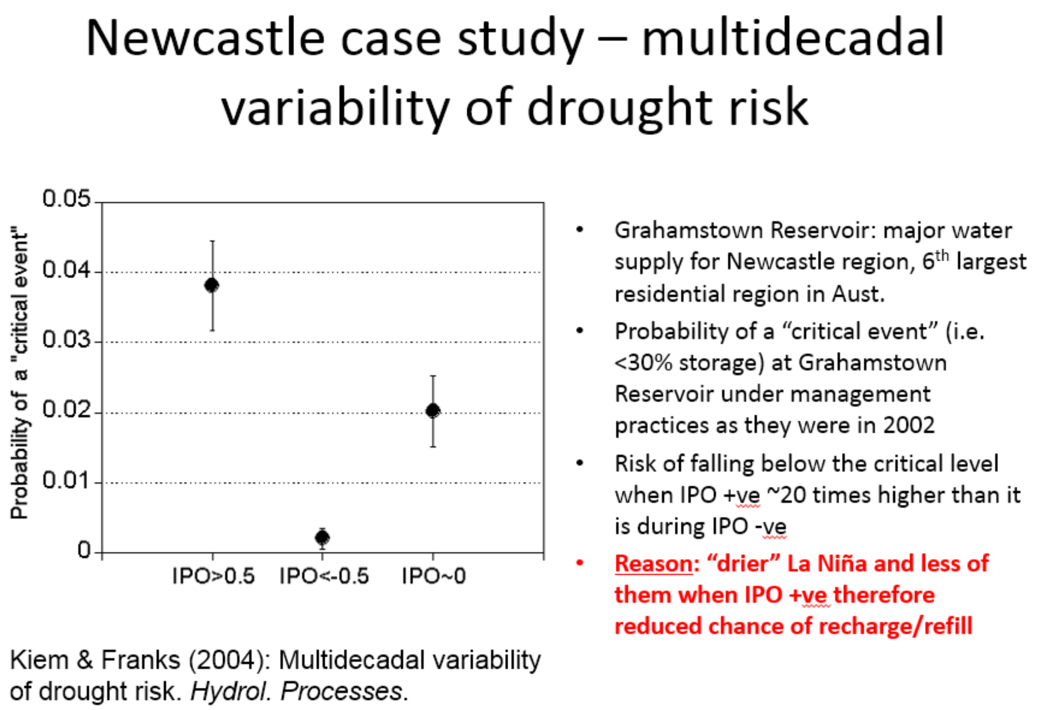


Figure 9 *(top) Regional flood frequency curves for La Nina events under IPO negative (dark blue) and IPO non- negative (light blue) conditions. (bottom) Average probability of a ‘critical event’ during each of the three IPO phases using current water/reservoir management practices for a case study in Newcastle, New South Wales (bars represent the 90% confidence intervals in each case).*

3.2.1.3 Indian Ocean influences on Australian climate variability

Inter-annual variations in eastern Australian rainfall have been linked to Indian Ocean SST anomalies, particularly in winter (JJA) and spring (SON) (e.g. Nicholls, 1989; Ashok et al., 2000; Verdon and Franks, 2005) and the Indian Ocean Dipole (IOD) (e.g. Saji et al., 1999; Ashok et al., 2003; Meyers et al., 2007; Ummenhofer et al., 2009). The IOD is characterized by SST anomalies of the opposite sign in the east and west of the Indian Ocean Basin, which are coincident with large-scale anomalous circulation patterns.

During the phase of the IOD associated with cool east and warm west Indian Ocean SST anomalies, low winter rainfall over eastern Australia is likely, and vice versa for the opposite phase of the IOD (e.g. Saji et al., 1999; Ashok et al., 2003; Meyers et al., 2007; Ummenhofer et al., 2009). However, several studies show a similar modulation of rainfall with eastern Indian Ocean SSTs only (e.g. Nicholls, 1989; Verdon and Franks, 2005;

Nicholls, 2009), suggesting that the influence of the SST gradient (combined western/central and east Indian Ocean SSTs) on southeast Australian rainfall is perhaps not as important as the state of eastern Indian Ocean SSTs alone (Nicholls, 1989; Verdon and Franks, 2005).

3.2.1.4 Southern Ocean influences on Australian climate variability

The Southern Annular Mode (SAM) is the leading mode of atmospheric variability over the southern extratropics. Also known as the Antarctic Oscillation and the High Latitude mode, the SAM represents an exchange of mass (sea-level pressure see-saw) between the mid latitudes (~45°S) and the polar region (> 60°S) (Thompson and Wallace, 2000; Thompson et al., 2000).

The SAM modulates westerly winds over the southern extratropics and embedded frontal weather systems. The SAM also has links to Australian rainfall that vary regionally and seasonally. With a poleward contraction of the mid-latitude storm track (positive SAM), the southern third of Australia is more likely to experience lower rainfall during winter (Hendon et al., 2007) due to southward displacement of rain-bearing cold fronts and cyclones. However, during the spring and summer months, anomalously poleward storm tracks (positive SAM) induce changes to the local circulation that draw moist easterly winds inland and increase the likelihood of rainfall across much of the southern third of Australia, particularly eastern sections. Kiem and Verdon-Kidd (2009, 2010) reported that dry conditions during autumn are more likely if an El Niño event occurs in combination with a positive SAM.

3.2.1.5 Madden-Julian Oscillation (MJO)

Across Northern Queensland, rainfall patterns during October to April have been shown to be strongly correlated with the Madden-Julian Oscillation (BOM 2019). This process is based around equatorial latitudes and results in a pulse of wind, enhanced cloud and rainfall that cycles eastwards around the equator. It is a very short-term cycle (30-60 days) and can drive increased likelihood of cyclones and bursts and breaks in monsoon rainfall. During initial emergence over the Indian Ocean, rainfall is lower over Northern Australia, but as the cycle moves eastwards and enters Australian longitudes, more rainfall is likely. This pattern has been well studied and has led to improved rainfall predictions in Northern Queensland (see Wheeler and Hendon 2009), however changes in MJO due to future climate change are currently an area of research and less well resolved, especially because the process operates over small temporal and spatial scales (Chang et al 2015).

3.2.1.6 The subtropical ridge (STR) and atmospheric blocking

High-pressure systems primarily inhibit rainfall. Over much of Australia, these high-pressure systems typically constitute part of the climatological belt of high-pressure in the mid-latitudes that is associated with the descending arm of the Hadley Cell, which is known as the sub-tropical ridge (STR).

Persistent and stationary high-pressure systems that are removed from the STR are responsible for the phenomenon of atmospheric blocking, where rain-bearing weather systems are diverted around the immobile high-pressure system. In eastern Australia, atmospheric blocking and the high pressure systems associated with the STR are the primary systems responsible for rainfall suppression (Pook et al., 2006; Risbey et al., 2008, 2009; Verdon-Kidd and Kiem, 2009). Much of the cool-season drying in far south-eastern Australia has been partly attributed to the expansion in the Hadley cell and strengthening of the STR associated with warmer global temperature.

It should be noted that for north-east Australia (i.e. Queensland), ENSO and IPO are most important, followed by the Indian Ocean Dipole influences and finally SAM/STR. The latter are likely to have more effect in Southern Queensland.

3.2.2 What do we know about the range of climate variability that has occurred (or is plausible)?

In order to properly manage water resources, it is essential that the risk of droughts and floods is realistically quantified so that appropriate policy, planning and infrastructure can be implemented. This was highlighted in a 2016 Special Issue on "The effect of historical and future climate changes on natural hazards in Australia" (see here for further details: https://theconversation.com/au/topics/australian-natural-hazards-series-32987) where Kiem et al. (2016) argued that even though droughts and floods are a recurrent and natural part of Australia's hydroclimate our ability to manage drought and floods is exposed as insufficient whenever they occur. To improve understanding and management of drought, flood, water security and hydroclimatic risk the long-term history of drought and flooding needs to be better documented and understood.

To date, hydroclimatic risk in Australia has typically been assessed using primarily historical instrumental records of rain, evaporation and streamflow. These instrumental records typically only exist for about the last 100 years at best. Recent studies (e.g. Ho et al., 2015a, 2015b; Vance et al., 2013, 2015; Tozer et al., 2016, 2018) have demonstrated how such an approach underestimates the range of hydroclimatic variability that has occurred and also misrepresents the true risks of drought and flood that need to be managed (which can be higher or lower that what is estimated from only the instrumental records).

The uncertainties associated with using short instrumental records are compounded because eastern Australia is subject to decadal epochs of enhanced/reduced drought frequency that is strongly related to large-scale ocean-atmosphere circulation patterns such as the El Niño/Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (see Section 3.2.1). Despite these insights into physical mechanisms that deliver hydroclimatic extremes to eastern Australia, the practical implications of time-varying risks of extreme climate events (including drought and water supply shortage), and how best to deal with them, are presently unclear (Kiem et al., 2016; Johnson et al., 2016). This is at least partially due to the fact that existing instrumental records do not capture enough cycles of multidecadal variability to give accurate insights into what is plausible.

A recent project ("Learning from the past – incorporating palaeoclimate data into water security planning and decision-making" completed in June 2017 for the then Queensland Department of Science, Information Technology and Innovation and Seqwater) investigated pre-1900 (i.e. pre-instrumental record) climate variability using palaeoclimate records from sources such as corals, tree-rings, freshwater and marine sediments. Despite being remote from Queensland, a high-resolution and correlated (with Queensland rainfall) palaeoclimate record from the Law Dome ice cores in Antarctica exists (Vance et al. 2015). This record has identified eight mega-droughts (lasting from 5-39 years) during 1000-2009 AD. Most importantly, the palaeoclimate information confirms that the post-1900 instrumental period (i.e. the period on which all water resources infrastructure, policy, operation rules and strategies is based) does not capture the full range of variability that has occurred.

Other key findings from the project include:

1. The instrumental period is not representative of the full range of past climate variability in Queensland.
2. Some centuries are drier than others (e.g. there are fewer dry periods in the 1400s, 1500s and 1800s relative to the 1000s, 1100s, 1200s and 1700s).
3. Although long dry periods are evident in the instrumental period, they are not unprecedented and the longest dry period in the instrumental record (8 years from 2000-2007) has actually been matched or exceeded several times prior to 1900.
4. Irrespective of the way we define drought the instrumental record only includes three of the worst 10 droughts in the last 1000 years and the worst drought that has occurred in the instrumental record is not in the worst five from the last 1000 years.
5. Palaeoclimate data can be used in conjunction with analogue maps developed using gridded data from climatically similar periods in the instrumental record to infer the location and spatial extent of pre-instrumental dry/wet periods.
6. Relying on the statistics from one century worth of data (or less) for drought management planning, as is currently common practice, is problematic given that all centuries have a different frequency and duration of dry (and wet) epochs and there is no reason why this will not continue to be the case in the future.
7. Irrespective of the multi-year period or drought magnitude being investigated, the probability of drought is always higher when the reconstruction record is used than it is when the instrumental record is used. This demonstrates again that the instrumental record does not properly capture the

full range of variability that has occurred or is possible. Also important to note is that, according to the instrumental record certain rare but high impact drought events are not possible (e.g. 5- and 10-year periods associated with 30% less rainfall overall, 3- and 5-year periods associated with 40% less rainfall overall). However, there is evidence in the palaeoclimate records that strongly suggests that these types of events have occurred before and while they are rare the likelihood of them occurring should not be considered to be zero.

Notwithstanding the above, the application of palaeodata to hydrological problems can be complicated and contains high levels of uncertainty. It can only realistically be completed in a statistical/probabilistic framework when the uncertainties are incorporated and addressed. This is an area that requires further research and testing with current operational modelling approaches, which is currently being investigated by the Queensland Government.

3.3 Approaches across Australia

In Australia, most examples of water resources planning that considers climate change come from south-west Western Australia, Victoria, and the Murray-Darling Basin (see Table 3). These have been largely driven by addressing issues surrounding the Millennium drought that occurred from ~1997-2010 in south-east Australia and the decline in water availability in southern Australia. Nevertheless, the extent to which climate change risk is taken into account is debatable. Water resources adaptation to climate change is challenging because of the large uncertainty in future hydroclimate projections. Therefore, adaptation will need to consider the risk versus rewards of adaptation options, that is, the cost of adaptation versus the consequences of not adapting sufficiently and early enough.

Table 3. *Examples of climate change research programs and datasets, hydrological modelling and water resources adaptation*

State and region	Climate change research program and dataset	Hydrological modelling and water resources adaptation
Queensland	CCAM dynamically downscaled climate projections dataset. Plus statistically downscaled biophysical model-ready data sets. Queensland Future Climate on the Long Paddock website https://www.longpaddock.qld.gov.au/qld-future-climate/ QLD projections also provide bias corrected daily data for hydrological modelling for RCP4.5 & 8.5 with high frequency 3 – hrs rainfall projection data available. Global 50 km resolution data is also available from 11 CMIP5 models from RCP4.5 and RCP8.5. (http://qgsp.maps.arcgis.com/apps/MapJournal/index.html?appid=1f3c05235c6a44dcb1a6faebad4683fc)	
New South Wales	WRF dynamically downscaled climate projections dataset from NARCliM. NARCliM and ESCCI climate change programs. https://climatechange.environment.nsw.gov.au/	Runoff projections dataset across NSW. https://climatechange.environment.nsw.gov.au/

State and region	Climate change research program and dataset	Hydrological modelling and water resources adaptation
Victoria	Empirically scaled climate projections dataset. https://publications.csiro.au/rpr/download?pid=csiro:EP161427&dsid=DS2 CCAM dynamically downscaled climate projections dataset for the Victorian Climate Projection 2019 (VCP19) project. SEACI, VicCi and VicWaCI initiatives. http://www.seaci.org/ https://www.water.vic.gov.au/climate-change/climate-and-water-resources-research/victorian-climate-initiative https://www.water.vic.gov.au/climate-change/climate-and-water-resources-research/the-victorian-water-and-climate-initiative	Runoff projections dataset across Victoria. https://www.water.vic.gov.au/climate-change/climate-and-water-resources-research/victorian-climate-initiative Development of water sector adaptation plans across Victoria using the above projections and guidelines. https://www.water.vic.gov.au/__data/assets/pdf_file/0019/410851/WSAAP-Web-version-FINAL_v2.pdf
South Australia	NHMM statistically downscaled climate projections dataset (SA Climate Ready). https://data.environment.sa.gov.au/Climate/SA-Climate-Ready/Pages/default.aspx Goyder climate action research program. http://www.goyderinstitute.org/research/climate-action/	
Murray-Darling Basin	Climate and runoff projections from SEACI and MDBSY.	Basin Plan, climate change risk, and climate change research program. https://www.mdba.gov.au/sites/default/files/pubs/Climate-change-discussion-paper-Feb-19.pdf
Tasmania	CCAM dynamically downscaled climate projections dataset. Climate Futures For Tasmania research program. http://acecrc.org.au/climate-futures-for-tasmania/	Hydrological modelling from TASY project used to guide development of irrigation infrastructure. https://www.csiro.au/en/Research/LWF/Areas/Water-resources/Assessing-water-resources/Sustainable-yields/Tasmania
Western Australia	NHMM statistically downscaled climate projections dataset. IOCI initiative. http://www.ioci.org.au/	Significant adaptation driven by shift in climate. Only 10% of urban water supply in far south-west WA now comes from surface water compared to 50% two decades ago.

CCAM Conformal Cubic Atmospheric Model, a dynamic downscaling model
ESCCI Eastern Seaboard Climate Change Initiative
IOCI Indian Ocean Climate Initiative
MDBSY Murray-Darling Basin Sustainable Yields project
NARCliM NSW and ACT Regional Climate Modelling project
NHMM Nonhomogeneous Hidden Markov Model, a statistical downscaling model
SEACI South Eastern Australian Climate Initiative
TASY Tasmanian Sustainable Yields project
VicCI Victorian Climate Initiative
VicWaCI Victorian Water and Climate Initiative
WRF Weather Research and Forecasting regional climate model

3.4 Evaluation of available data sets in Queensland

Projections of climate and water futures for Queensland are summarised in Box 1. The main sources of future climate projections data are Queensland Future Climate (dynamically downscaled 10km-resolution projections for Queensland https://www.longpaddock.qld.gov.au/qld-future-climate/) and CCIA (Climate Change in Australia, for whole of Australia https://www.climatechangeinaustralia.gov.au/en/). These projections can be used together with hydrological modelling to assess the potential impact of climate change on water availability and catchment hydrological and river flow characteristics.

Box 1 Future climate and water projections for Queensland

Temperature

– Temperature will increase by 1.5–2.0°C by 2060 under RCP4.5 (medium emissions scenario) and by 2.0–2.5°C under RCP8.5 (high emissions scenario).

– This will result in increases in hot days, potential evapotranspiration, water demand, and other climate-water metrics related to temperature.

Extreme rainfall and flood risk

– Extreme high rainfall is projected to become more intense in the future.

– Design rainfall intensity is projected to increase by 5% to more than 10% for shorter duration and longer return period storms.

– More intense extreme rainfall is projected to result in greater flood risk in north-east Australia.

Rainfall

– Projections of future rainfall span a large range. Under RCP8.5, mean annual rainfall is projected to change by -25% to +10% in south-east Queensland and by -20% to +15% in north-east Queensland.

– Winter rainfall is likely to decrease.

– Natural climate variability will remain the major driver of variability/change in rainfall in the near term (next 20 years).

– High resolution climate modelling indicates that rainfall is likely to decline in the coastal parts of Queensland.

Runoff (and water availability)

– The percentage change in rainfall will be amplified in the percentage change in runoff, by a factor of 2 in wet regions to more than 3 in dry regions.

– Projected changes in mean annual runoff for ~2060 under RCP8.5 range from -40% to +20%.

The Queensland Future Climate Dashboard on Long Paddock (the Dashboard) is developed specifically for Queensland and provides projection datasets from dynamical downscaling with CCAM (Conformal Cubic Atmospheric Model) constrained by boundary conditions from 11 CMIP5 GCMs. In addition, more datasets are available on the AWS servers including gridded changes in rainfall and temperature. Figure 10 shows an example of rainfall projections from the Dashboard. The Dashboard provides projections of rainfall, temperature and other climate variables, as well as 30 climate-related metrics. The Dashboard provides much higher spatial resolution datasets (10 km) compared to CCIA which is largely based on the coarse-scale CMIP5 GCMs. The Dashboard's dynamically downscaled projections therefore offer the prospect of improved representation of regional climate features (e.g. orographic effect showing significant drying in the coast and convective rainfall generation). Further research is needed to fully evaluate the added robustness and value for these projections.

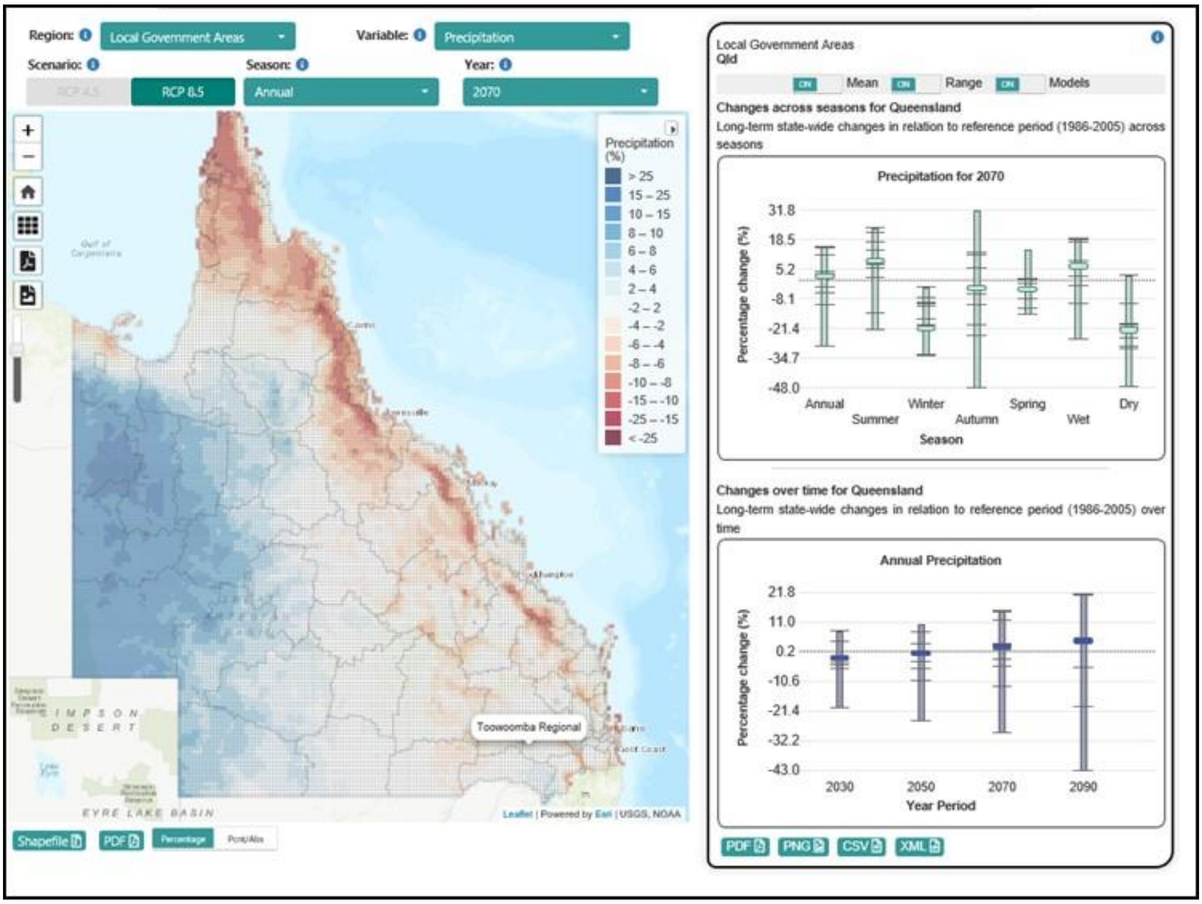


Figure 10 *Projected changes in future mean annual rainfall from Long Paddock under RCP8.5.*

[Screenshot from Queensland Future Climate Dashboard, Long Paddock, https://app.longpaddock.qld.gov.au/dashboard/]

To provide a whole-of-Australia context, Figure 11 shows projections of rainfall, potential evapotranspiration (PET) and runoff across Australia, for 2046–2075 relative to 1976–2005 under RCP8.5. The rainfall projections come from the CMIP5 GCMs (same as CCIA), and the runoff is modelled using a hydrological model informed by the future projections from the GCMs (Chiew et al., 2017). To provide further perspective, Figure 12 summarises the projected changes to average rainfall and extreme high rainfall from CCIA. Table 3 further summarises approaches used across Australia, to provide comparative examples.

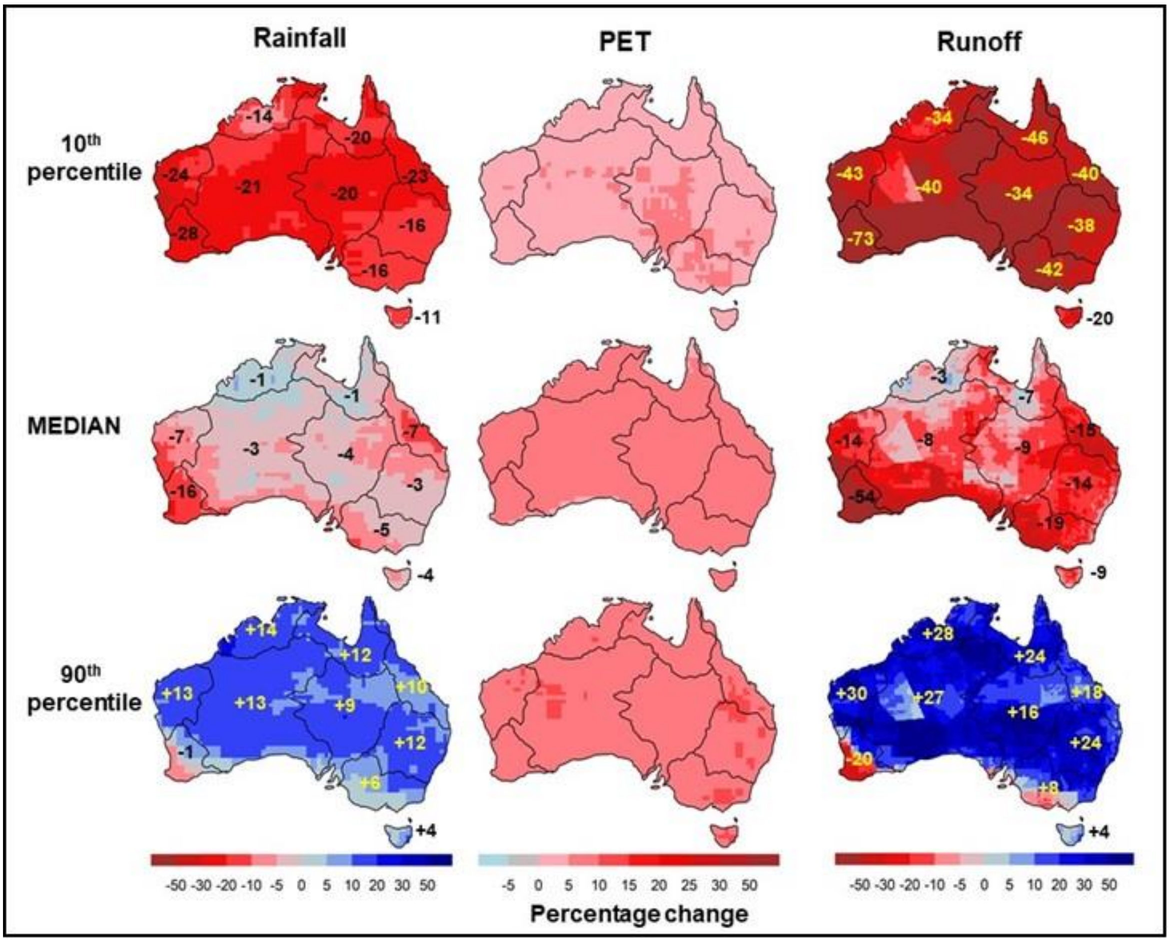


Figure 11 *Range of projected changes in future rainfall, PET and runoff for Australia for 2046–2075 relative to 1976–2005 under RCP8.5 (modelling following Chiew et al., 2017).*

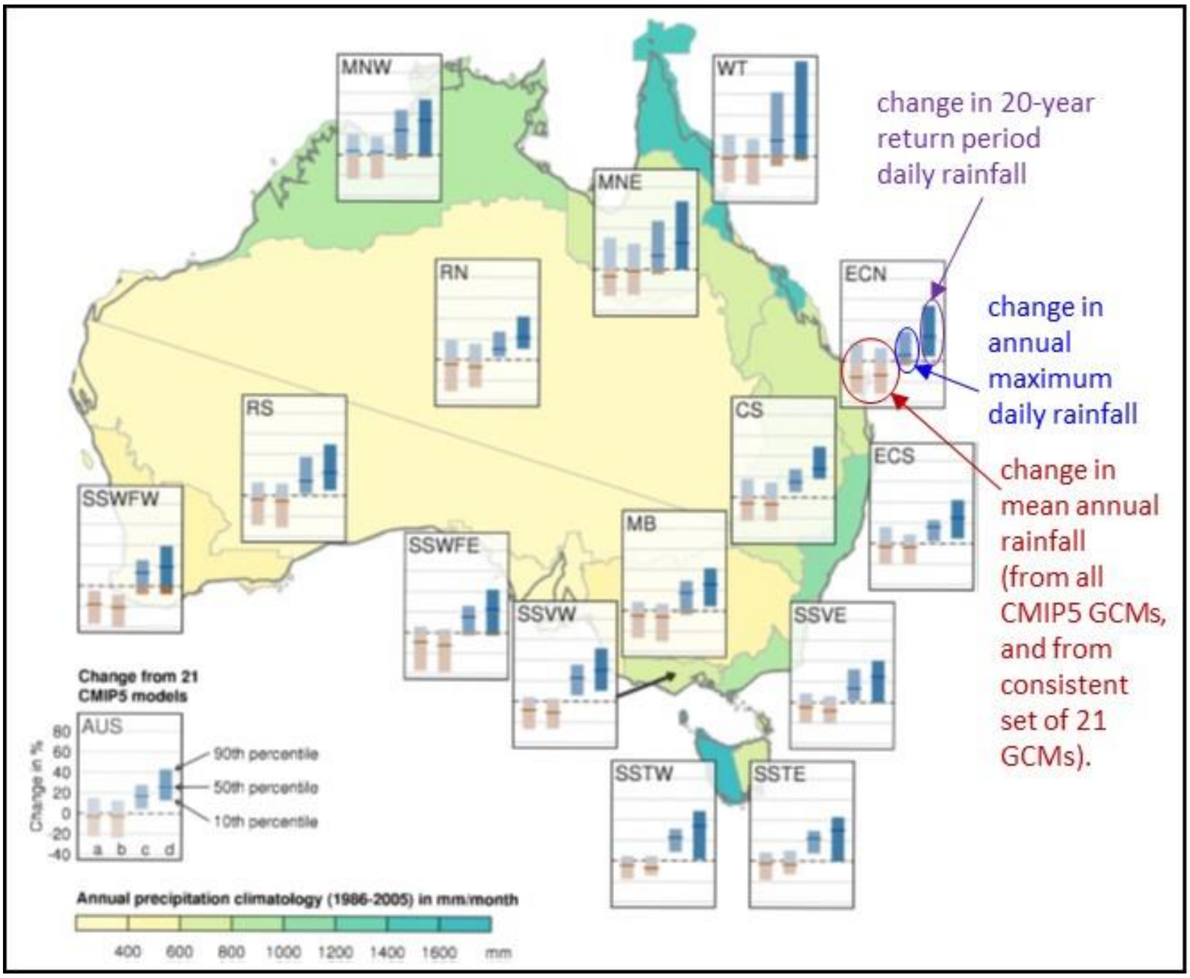


Figure 12 *Range of projected relative change in mean annual rainfall and extreme high rainfall from Climate Change in Australia (CCIA) from 1986–2005 to 2080–2099 under RCP8.5.*

[Adapted from CSIRO and BoM (2015), https://www.climatechangeinaustralia.gov.au/en/]

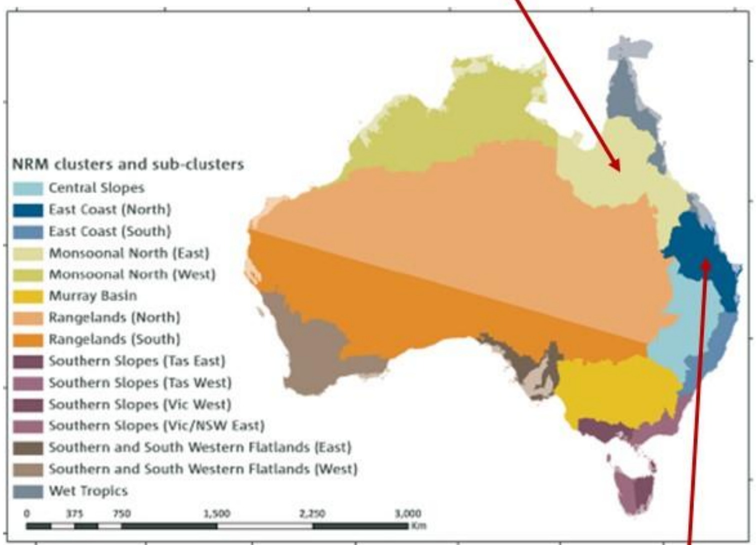
The CCIA product (CSIRO and Bureau of Meteorology, 2015) is a climate change projection data source that covers the whole of Australia. The product compiles, analyses and interprets projections data from the CMIP5 GCMs (and several downscaling data sources), and presents the range of plausible futures for rainfall, temperature and other climate variables. The CCIA provides summary projections for 8 NRM (Natural Resources Management) regions or clusters, and 15 sub-clusters. Figure 13 shows summary projections for rainfall and temperature for two of the sub-clusters that cover large parts of Queensland. The CCIA also provides more detailed projections datasets and future climate time series for inputs into sector models, as well as scientific and practical guidance on the interpretation and application of the datasets.

Both the downscaled Queensland dataset on Long Paddock and the CCIA product for the whole of Australia provide indications of future climate outcomes for Queensland. The Long Paddock site has a range of datasets at finer resolution than the CCIA datasets, but is only realised for one Representative Concentration Pathway, RCP 8.5. The Queensland dataset therefore provides a finer scale resolution, but the CCIA datasets include a greater range of projected climate outcomes. The choice of which one to use will then be dependent on the modelling question.

These datasets are also largely based on Assessment Report 5 (AR5) from the IPCC which was produced in 2014. AR6 is currently under development with updated modelling, data and synthesis now becoming available with the report itself due in 2022. As such, it is likely that as new GCM results become available, this will provide a good opportunity to consider the products, and how they may be updated and supplemented.

North-east Queensland
[Monsoonal North (East) sub-cluster region]

Annual Rainfall (%)		Annual Mean Surface Temperature (C): Slightly Warmer < 0.50	Warmer 0.50 to 1.50	Hotter 1.50 to 3.00	Much Hotter > 3.00
	Much Wetter > 15.00		2 of 48 (4%)	2 of 48 (4%)	
	Wetter 5.00 to 15.00		1 of 48 (2%)	9 of 48 (19%)	
	Little Change -5.00 to 5.00			10 of 48 (21%)	1 of 48 (2%)
	Drier -15.00 to -5.00		1 of 48 (2%)	12 of 48 (25%)	2 of 48 (4%)
	Much Drier < -15.00		1 of 48 (2%)	4 of 48 (8%)	3 of 48 (6%)



South-east Queensland
[East Coast (North)sub- cluster region]

Annual Rainfall (%)		Annual Mean Surface Temperature (C): Slightly Warmer < 0.50	Warmer 0.50 to 1.50	Hotter 1.50 to 3.00	Much Hotter > 3.00
	Much Wetter > 15.00			2 of 48 (4%)	
	Wetter 5.00 to 15.00		2 of 48 (4%)	4 of 48 (8%)	
	Little Change -5.00 to 5.00		1 of 48 (2%)	11 of 48 (23%)	
	Drier -15.00 to -5.00		1 of 48 (2%)	10 of 48 (21%)	
	Much Drier < -15.00			14 of 48 (29%)	3 of 48 (6%)

Figure 13 *Range of projected changes in future temperature and mean annual rainfall from Climate Change in Australia (CCIA) for ~2060 under RCP8.5.*

[Compilation of screenshots from CCIA, https://www.climatechangeinaustralia.gov.au/en/]

Table 4 below presents a summary of available climate change data sets for use in water models. There is a wide spread of spatial extents, GCMs, RCPs and data creation approaches. Some of this spread can be attributed to the time, computation and funds available for their creation and that they have been tailored to specific regions and applications. However, the spread demonstrates the potential for inconsistencies across climate change assessments.

Table 4. *Summary of climate change data sets for Australia*

Name	Extent	Spatial scale	Temporal scale	No. GCMs	RCPs	Downscaling	Initial conditions	Projection Periods	Strengths	Weaknesses
CMIP5	Global	~200km	6-hrs to annual	~40 (no of GCM vary for different RCPs)	2.6,4.5, 6.0, 8.5	None	Yes from pre-industrial control run	2006-2100	Many GCMs, regional and global extent, representing a fuller range of uncertainty	Coarse grid
Consistent Climate Scenarios	Australia	5 km	Daily for rainfall, evaporation minimum and maximum temperature, solar radiation and vapour pressure deficit	CMIP3&CMIP5 7 10 km downscaled for QLD	A1FI, A2, A1B, B2 A1T B1, 550ppm stabilisation by 2150 and 450ppm stabilisation by 2100. RCP2.6RCP4.5RCP6.0 and RCP8.5	Statistical transformation of SILO 5 km observed data	No	2030 & 2050	Statistically downscaled to provide data at higher spatial resolution	Only for 2030 & 2050 Extrapolation of statistical relationship

Name	Extent	Spatial scale	Temporal scale	No. GCMs	RCPs	Downscaling	Initial conditions	Projection Periods	Strengths	Weaknesses
Qld Climate Change Dashboard and TERN	QLD region (9.5-32S, 132-158E)	10km	3hr to annual	11 CMIP5 models downscaled for each RCP	CMIP5 RCPs4.5&8.5	Dynamic	Yes/NCEP Reanalysis	2005-2100	High resolution downscaled data for whole of Queensland Model coverage and testing focussed on Queensland Better representation of convective rainfall generation and orographic effects	Single dynamic downscaling model

Name	Extent	Spatial scale	Temporal scale	No. GCMs	RCPs	Downscaling	Initial conditions	Projection Periods	Strengths	Weaknesses
NARCliM	NSW & ACT	10km		4 CMIP3 models downscaled for one SRES scenario (best for NSW)	CMIP3 single scenario SRES A2	Dynamic	Yes/host GCM model	2 periods 2020-2039 & 2060-2079	High resolution dynamic downscaling potentially providing better representation of rainfall features Significant research and development, with many published results and scientific discussion	Single regional climate model, low number of host GCMs, CMIP3, no continuous simulations
Goyder	SA only	Station level downscaling for rainfall, Tmin, Tmax, solar radiation and vapour pressure	Daily	15 CMIP5 models RCP45 & RCP8.5	CMIP5	Statistical	No	2006-2100	Statistically downscaled to provide data at higher spatial resolution	Extrapolation of statistical relationship

Name	Extent	Spatial scale	Temporal scale	No. GCMs	RCPs	Downscaling	Initial conditions	Projection Periods	Strengths	Weaknesses
IOCI	WA (South West, Central West)	Daily rainfall & temperature for selected stations in SW WA & NW WA	Daily	CMIP3 SRES B1 A1B A2	Several CMIP3 GCMs	Statistical	No	2047-2064 & 2082-2099	Statistically downscaled to provide data at higher spatial resolution	Extrapolation of statistical relationship
Tas Futures	TAS	10km	6-hrs to annual	6 CMIP3 models for SRES A2 & B1	CMIP3 SRES A2 and B1	Dynamic	No	2000-2100	High resolution dynamic downscaling potentially providing better representation of rainfall features	Single dynamic downscaling model, limited number of host GCMs
Victorian CCAM projections	Victoria	5km	6-hrs to annual	6 CMIP5 models	RCP4.5&8.5	Dynamic	Yes Reanalysis	2006-2100?	High resolution dynamic downscaling potentially providing better representation of rainfall features	Single dynamic downscaling model, limited number of host GCMs
NASA	Global	25km Rainfall, tmax & tmin only	Daily	21 CMIP5 models for RCP4.5 & RCP8.5	RCP4.5 & RCP8.5	Statistical	No	2006-2100	Global	Statistical interpolation

Name	Extent	Spatial scale	Temporal scale	No. GCMs	RCPs	Downscaling	Initial conditions	Projection Periods	Strengths	Weaknesses
ESGF	Global	Global models varying resolution	1-hr to anuual	SSP Scenarios CMIP6	Several SSPs (1.9,2.6,4.5,7.0, 8.5)	None Global GCMs	Yes from pre-industrial control run	~2010-2100	Global	Progressively generated
Cordex	Regional	50km	9-hrs to annual	CMIP3/ CMIP5		Regional models	Yes	2006-2100	Higher spatial resolution than GCMs	Resolution is still relatively coarse. Few models available for Australian region

Consideration: Table 4 can inform the practitioner as to the appropriate climate change data set to use for their application. Additionally, the table can point towards future investment to address gaps in data

3.5 Establishing evaluation criteria for treatment of climate science in water modelling

In Section 6 four different case studies are evaluated to see how existing climate variability and future climate change can be applied to current modelling projects. This provides an overview of the models and how they may need to be changed to incorporate alternative climatic conditions. In doing so, several criteria were considered in evaluating each modelling application. For evaluating other models, it is recommended that the following criteria be applied. These criteria are further expanded in Table 5.

The modelling question

- Evaluate where and when improved representation of climate change or variability is needed to better answer the modelling question. For example, understanding changes in water infrastructure operations, changes in human systems which use water, changes in processes that rely on water.

Data inputs and forcing data

- Consider how the inputs, or forcing data, for the model may change. This may be as straight forward as climate variables such rainfall, evapotranspiration, temperature, humidity, solar radiation, wind, seasonality, intensity, duration, but it also may need to evaluate whether other inputs may be affected by change or variability, such as streamflow data, agricultural cropping requirements, economic data or even social information (e.g. how will land use representation change under different climate outcomes). Also consider the availability and representativeness of the forcing data that accounts for climate change or variability. Do the data sets have the same indicators or parameters, does there need to be further verification or derivation to make it suitable for use and if so, what are the implications in doing so.

Conceptual process representation

- This should include evaluating how the conceptual processes can account for different climatic sequences. Models may account for broadscale systems such as water supply system yield simulation, or fine scale processes such as changes in water column ecological response under altered temperature or flow conditions. Primarily this is about focusing on the system process or processes that the model is simulating, such as rainfall-runoff, water consumption, ecological response, crop water use, overland flow pathways. Consider whether the system processes will be affected as initial responses to climate change or variability such as changes in runoff from changes in rainfall, or “downstream” processes, such as how should a crop model change if there is less runoff to harvest.

Component models

- Examine each of the component models within the broader model to identify where climate inputs or representation may alter under different climatic sequences. This can include rainfall-runoff, vegetation growth, water demands (both human and industry), ecological response and sociology-economic models. It is important to understand the sensitivity of these component models and whether they will be significantly affected by alternative climate sequences, or even if they may no longer be representative of the process under climate variability or change.

Model outputs

- Can a model be used in an exploratory mode, such that multiple scenarios can be run to evaluate different climate sequences, with large amounts of data output, or is it more that the model is run to evaluate the “most likely” scenario? The latter will have implications for how well the forcing data and system processes are able to represent the overall system response, whereas the former approach allows for “stress testing” to see where the model is best and worst suited to evaluating the model question under change or variability.

Decision frameworks

- Consider how models that account for future climate change will be used in decision making. What decision frameworks will be best suited to considering multiple realisations of future climate, how is risk and uncertainty able to be accounted for, what alternative decisions may be possible or what future forcing conditions may have implications for the results.

Table 5. *Evaluation criteria – expanded*

Criteria	Questions to consider	Responses
The modelling question	1. Direct consideration - does the modelling question specifically refer to future climate change or long-term climate variability (e.g. predicting the change in ecosystem health of river X under climate change)?	Models will need to account for climate variability or climate change directly, in data inputs and forcing data, conceptual process representation, and component models, and be able to represent these appropriately in model outputs.
	2. Indirect consideration - will resolving the question require consideration of existing climate variability or future climate change effects on system behaviours (e.g. understanding water supply infrastructure requirements under future urbanisation)?	Models may need to incorporate improved understanding of system behavioural responses under climate change. May also need to directly account for change and variability as per 1 or may only need broadscale response understanding (e.g. water availability decreases by 10%)
	3. Timeframes - Is the question likely to need resolution of short-term or long-term responses?	For short term responses (5-20 years), improved understanding of existing climate variability is likely to be more important than future climate change. For longer term (20 years +), future climate change in addition to better representation of existing climate variability will need to be accounted for.
	4. Temporal patterns - Does the modelling question require an understanding of changing temporal patterns in the future (e.g. evaluating frequency of extreme rainfall events)?	Need to evaluate the suitability of forcing data to represent the changes, or that the component models are able to resolve changing temporal dynamics (e.g. some models will have static parameters over an entire modelling period and may not be suitable).
Data inputs and forcing data	1. Does the model require climatic forcing data e.g.: - temperature - rainfall - evaporation/evapotranspiration - solar radiation - wind - humidity?	Determine if the forcing data accounts for existing climate variability or future climate change: - Understand which GCMs have been used to derive the data, what RCPs they represent and whether these may be relevant to the question - Are the data available at an appropriate scale (both temporal and spatial)? - Will the data need to be derived from other indicators or is it directly available? Not all climate indicators may be available and some might require calculation using available inputs.

Criteria	Questions to consider	Responses
	2. Will other data inputs be influenced by existing climate change or future climate variability?	Data that relates to system behaviours may be influenced by climate factors and may need to be updated to reflect how this may alter the inputs. These could include: - Potable water demands - Crop water demands - Crop types - Harvesting regimes - Vegetative cover - Soil properties - Stream flows - Economic activity (e.g. farming intensity, coal production) - Social responses (e.g. population growth, tourism activity) - Ecological responses (e.g. algal blooms, changes in groundwater dependent ecosystems, blackwater event frequencies)
	3. Will spatial and/or temporal patterns of data inputs change?	Do the data inputs account for changes in frequency, seasonality, intensity, multi-year variability (ENSO, IPO etc.), orographic effects?
Conceptual process representation	1. Does the conceptual models that underpin the numerical model properly present or allow for climate variability?	Specific aspects that may change under different climate regimes, such as increased temperatures or changes in rainfall, are typically well accounted for in most water related models, however other aspects, such as changes in soil infiltration, increased moisture uptake by plants or improved productivity due to increased CO2 concentrations may not be catered for. When assessing models for suitability to incorporate climate change or variability, evaluating these conceptual models may be needed to understand whether the modelling question can even be represented due to the conceptual model being used.
Component models	1. Do the component models have sufficient parameters to account for changes in climate inputs?	Typically, water models can be made up of a number of different component models (e.g. a rainfall runoff model, an ecosystem response model, a pollutant generation model). Examining these will be needed to understand if and how they may represent different forcing conditions under altered climates.
Model outputs	1. Temporal variability - Does the model show results that can address long-term changes in climate?	Models can be run over different time steps (hours, days, months) and for different periods (1 year, 30 years, 100 years). Do the model outputs cover the period where altered climate patterns will show an influence. For example, a model that is calibrated and validated over a

Criteria	Questions to consider	Responses
		short time period may not be able to represent the changes of an altered climate regime easily without significant work to update the model calibration under the likely future conditions.
	2. Spatial variability – Does the model have sufficient spatial scale or in locations where different climate realisations can be used?	Model outputs that represent single points or land parcels may not show the full range of variability that may be possible due to different climate outputs. Current datasets are available at larger spatial scales and consideration of whether the input data sets will match the scale of the outputs will need to be made.
	3. Scenario testing - Can the model evaluate multiple scenarios or operate in a stochastic fashion?	Exploratory modelling may require hundreds or thousands of scenarios to be evaluated, maybe coupled to stochastic variation of parameters. As such the model will need to provide outputs that can be used in statistical analyses or be able to be run in "batch modes" through scripting or other methods to generate the outputs required.
Decision frameworks	1. Model flexibility – is the model able to be altered easily to account for different actions, inputs or parameters.	Run times, ability to be rerun or changed quickly will provide more flexibility in assessing multiple options or be used in different decision frameworks more easily. For example, having a large model that takes weeks to run may not be conducive to short-term decision making, or it may not provide enough understanding of how different inputs can affect model results. Considering how the model may be used in the decision-making process will improve its usefulness and function in the decision process
	2. Trajectories – does the model represent not just the result of different climates, but also the process of change?	Often it is important to understand not only the "book ends" (e.g. best case/worst case), but also the transition process (i.e. what happens during change), to best understand whether the decisions that address the book ends do not result in undesirable outcomes during the trajectory of change.
	3. Visualisation – can the model present results in ways that are easily communicated, or can the model outputs be easily incorporated into communication tools.	Many models simply generate data or information. Once run, the user (modeller/decision maker/stakeholder) needs to contextualise that information to allow the implications of the model results to be understood in the decision process. Models that produce results that can be visualised easily (e.g. graphs, maps etc) may provide better inputs into decision frameworks than those which require significant post processing.

3.6 Incorporating climate change and climate variability in decision frameworks

Climate change research and assessments are plagued by imperfect and incomplete understanding of how environmental conditions and process will alter related to important climate variables, in addition to the economic and social implications of climate changes (Marchau et al. 2019). Fundamentally, questions around incorporation of climate change into decision processes are based on:

a) The magnitude of climate change (uncertainty in which of the ranges of future scenarios is most likely)
b) The speed of climate change (uncertainty as to how quickly policy actions need to be implemented)
c) The impacts on specific areas and regions (downscaling uncertainty)
d) The policies that should be implemented to mitigate or adapt to the consequences of climate change (uncertainty around the efficacy of the policy action)

From the perspective of water modelling, to fully account for these questions requires that the models are run across multiple climate realisations, multiple scenarios focusing on specific areas and multiple scenarios focusing on different policy outcomes. All of these generate different outputs and a wealth of data, so better methods are required to deal with the multiple (and often compounding) uncertainties and how models are used to help address them. Further details around this are provided in Appendix A.

The key to considering better decision support frameworks for dealing with uncertainties from modelling that accounts for existing climate variability and future climate change means understanding:

a) The way in which information is brought into decision making processes is probably just as important as the information itself (how is the information contextualised?)
b) Collaborative approaches which involves the understanding of multiple contexts from multiple stakeholders on which to evaluate the information
c) The need to design decision processes to enhance understanding of the information and the context in which it applies.

A generic framework for decision making under deep uncertainty is outlined in Figure 14 below. This follows the classic "Plan, Do, Check, Act" process but is nuanced around how to better complete each of these components.

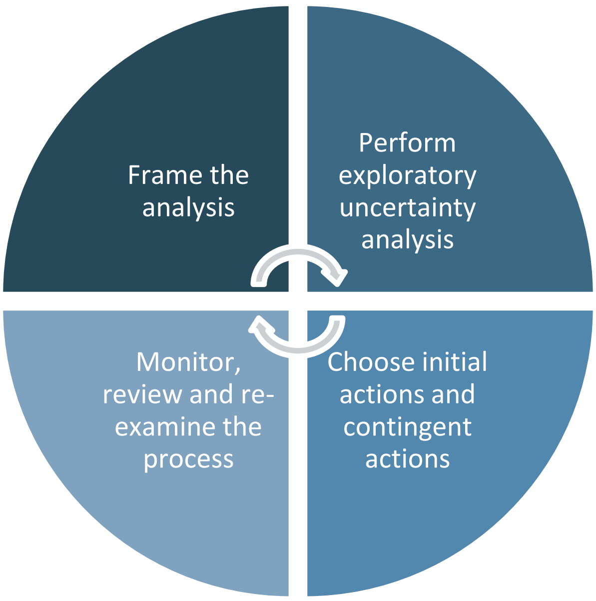


Figure 14. *Generic framework for Decision Making under Deep Uncertainty (DMDU)*

This can be explained through the following generic process:

1. Frame the analysis
    a. Document the key issue, problem or opportunity
    b. Conceptualise the system structure and boundaries (e.g. a conceptual model)
    c. Specify the objectives, goals and outcomes, including key indicators
    d. Specify the likely policies or actions that may be possible
2. Perform exploratory uncertainty analysis
    a. Document the uncertainties or disagreements about external forces, conceptual representation, outcome indicators and how the outcomes may be valued
    b. Explore the outcomes of policy implementation, including testing for vulnerabilities and opportunities, given the uncertainties (this is where models or expert opinions are best used)
3. Choose initial actions and contingent actions
    a. Understand the trade-offs and how to make future adjustments as events occur and knowledge on responses and trade-offs is improved
    b. Develop plans for how to make adjustments in response to the changing trade-offs (when to respond to "tipping points")
    c. Select and plan for adoption of the initial policy and set up mechanisms to adjust it when approaching tipping points
    d. Plan communication, monitoring and adaptation processes
4. Monitor, review and re-examine the process.

There are a number of frameworks available which build on and provide methods for better implementing the above process and these are further discussed in Appendix A.

What is very clear from these frameworks and examples of their application is that better methods to incorporate the increased uncertainties from assessing future climate change are available, but these are likely to be quite different from current approaches and their application will need further capacity building efforts to mainstream them into decision processes in Queensland water modelling.

4 Review of end user requirements and current approaches to treatment of climate change and climate variability

4.1 Stakeholder analysis and model inventory

While this project has a focus on Queensland Government modelling groups and end-users, it must be acknowledged that there are a range of organisations, and roles within these organisations, which actively use water models, inform water models, or use the inputs to or outputs of water modelling for decision support. Exploring the needs and capabilities of each of these groups, and their interactions , is essential for understanding the various end user requirements and developing recommendations for investment which will support the sector in understanding and responding to future risks from climate change and climate variability.

4.1.1 Stakeholder analysis

Table 6 provides a list of key sector roles and organisations, as well as other potential interested groups who may be interested in the outcomes of this project.

Table 6. *Stakeholder identification according to individual roles and organisation*

Sector roles	Key organisations	Other interested players
Modellers	Queensland Government: DES, DNRME, DAF, Emergency services, Transport and Main Roads	Insurance
Planners	Local government	Developers
Operators	Consultants	Landholders
Policy-makers	Federal government: CEWH, BoM, GBRMPA, DEE, MDBA	Primary producers
Media and communication	Research: CSIRO, AIMS, Universities	Tourism
Scientists	NGOs: NRM groups, GBRF, HLW	Industrial use
Politicians	Utilities: Seqwater, Sunwater Unitywater, QUU	Mining and resources
Data providers	Regulator: QCC	Other jurisdictional bodies
Software developers		Community groups
Investors		The community
Students		
Regulators		

4.1.2 Model inventory

In 2018, the QWMN commissioned Griffith University to produce a catalogue of water models used by the Queensland Government (State of Queensland, 2018) which provides a concise overview and collation of the major water models currently used by the Queensland Government. 18 water models were identified through consultation with Queensland Government modelling, planning and policy representatives, and have also been used as a basis for this review. The water models have a wide and diverse range of uses within government and provide support for: land-holder decision making; agricultural systems assessments; water planning decision making; framing catchment and groundwater policy making and reporting; and for receiving waters and coastal water quality reporting.

The Water Model Catalogue organises the models based on their uses as shown in Table 7.

Table 7. *Organisation of water models according to use as per the Water Model Catalogue (State of Queensland, 2018)*

Model use	Model name
Farmer decision support	SoilWater App
Agricultural systems assessments	Howleaky, APSIM, Grasp – AussieGrass
Planning support	MEDLI, 2CSalt
Catchment policy	Sacramento, SIMHYD, IQQM, eWater Source - Quantity, eWater Source - Quality, MIKE 11, HEC-RAS, WATHNET
Groundwater policy	MODFLOW, BC2C
Receiving water and coastal water quality reporting	eReefs, TUFLOW

On the following page is a diagrammatic illustration of how these water models link together in the water modelling environment, the types of outputs they provide and an indication of the sectors they apply to. There is no hard boundary in the component models, and many models have interconnections and linkages, both to other models and to provision of key outputs in the Queensland water modelling space.

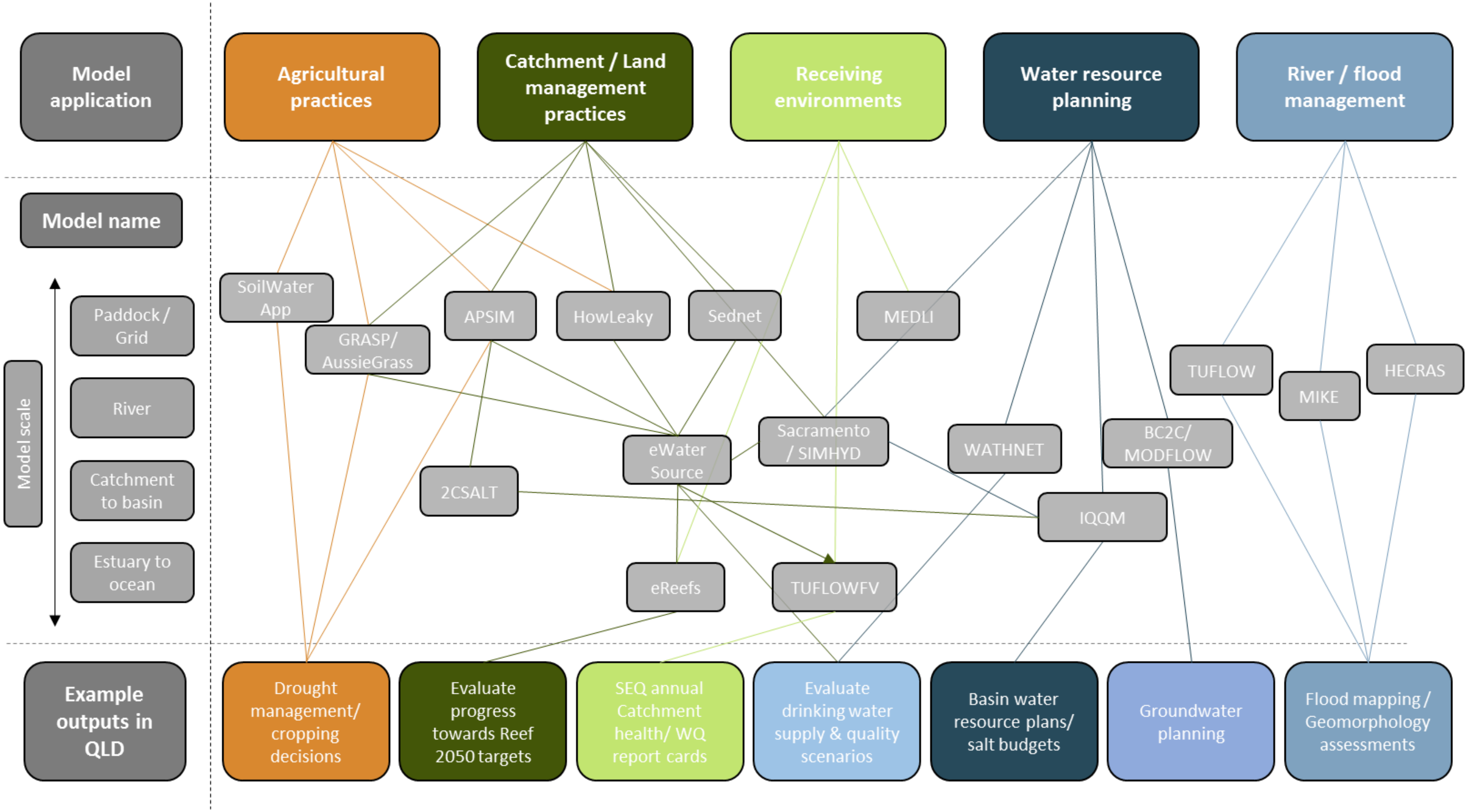


Figure 15 *Interactions between various water models and their applications at various model scales*

4.2 End user requirements

Figure 15 shows the complexity of model interactions and modelling tools available to assist end users in their roles as policy makers, planners, advisors, operators and regulators. The use of water models in supporting these functions is not new, but there is additional complexity in information demands when considering climate variability and change. Water modelling usually considers climate variability by using available, multi-decadal climatic records. This is one of the key reasons for modelling with long time series data, and to manage the system for a given reliability or risk from (mainly) climate variability. But 100 years of instrumental record may be too short to characterise longer-term variability over future 10–20 year periods. We also need to be aware that with just 100 years of data, we could be overestimating or underestimating the probability of extreme droughts and floods (and therefore over-designing or under-designing systems). The use of palaeodata allows us to better characterise (and manage) long-term climate variability and to understand the suitability (or not) of those recorded datasets in predicting extremes.

Climate change is in addition to the above. But managing the large range of climate variability (although different, and not sufficient) better will not only help systems cope with variability, but also help buffer systems against climate change.

End users are now seeking additional information and analysis to support evidence-based decision-making and risk-management, such as:

- Does the historic record provide adequate variability to account for potential climate-based risks?
- Is climate change likely to change our risk profile?
- What is the uncertainty around modelling results?

One of the complexities with end user expectations, is that that the request asked of water modellers is often along the lines of ‘could you just do an extra “climate change” run?’. While the consideration of climate variability and change in strategic planning is becoming more widespread, climate change still often remains an after-thought in project design, which can be a challenge for water modellers. There is a responsibility on the part of the end users and the modellers to consider the vulnerability to climate variability and change from the outset of project and model design.

Understandably, there is wide variability in the technical understanding of end users when it comes to water modelling and climate science. For many, they may simply want best practice approaches to be applied to provide a range of potential future scenarios, others may prefer to discuss the advantages and disadvantages of different approaches and interpretations to the treatment of climate change and variability. There is a need for effective communication of the modelling questions from the end users, and then the model results, assumptions and uncertainty from the modellers, as summarised in Figure 16.

For decision-makers in particular, the end user requirement is not an accurate prediction of the future climate (which is an impossible task), but increased confidence for which of a set of options is more likely to result in a more resilient outcome.

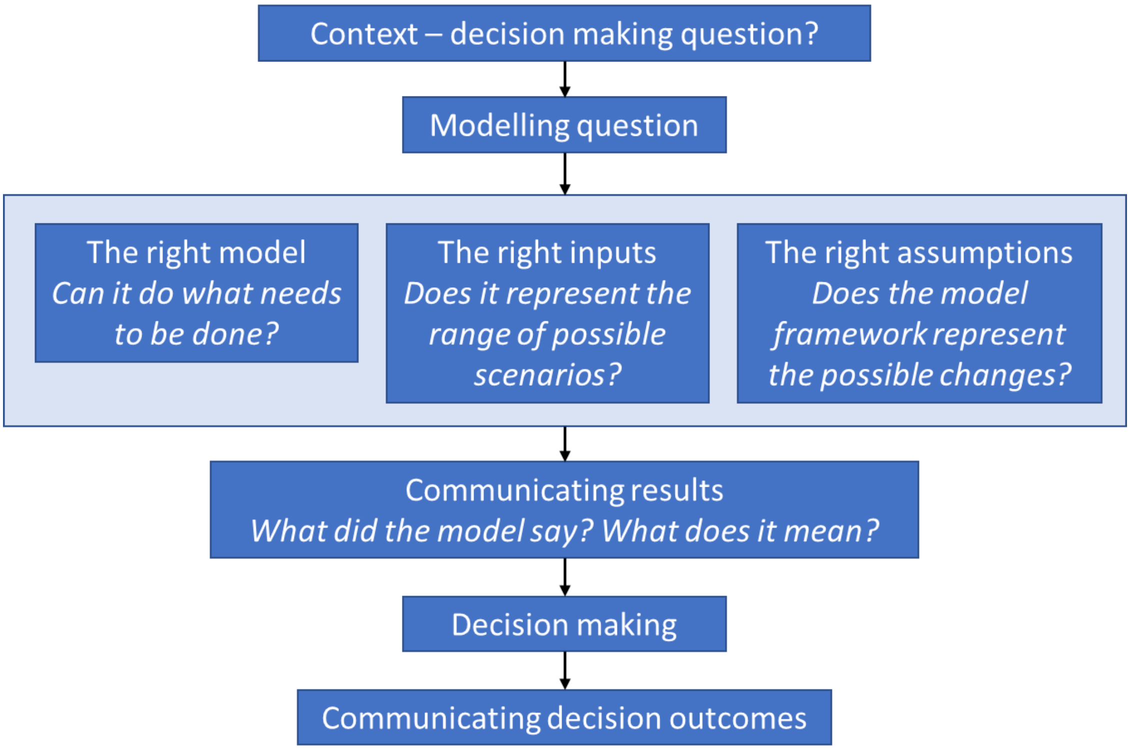


Figure 16 *Modelling and decision making*

5 Distilling the issues

As discussed in Section 2.3, this review used a ‘multiple lines of evidence’ approach to gain an understanding of the current approach to the treatment of climate variability and change in water modelling and decision-making, and the subsequent identification of opportunities for improvement. Section 5.2 provides an overview of the current approach, based on a series of interviews with Queensland Government staff, the outcomes of a project specific workshop held in April, information gathered at QWMN community of practice events, and a literature review of supporting documents that were provided to the project team.

The workshop, held in April 2019, focussed primarily on the government sector, and had 32 participants from the Departments of Environment and Science (Science and Technology, Office of the Great Barrier Reef, Environmental Policy and Programs) and Natural Resources, Mines and Energy, as well as the Queensland Reconstruction Authority and Seqwater. Other organisations represented included the Bureau of Meteorology, CSIRO, the Great Barrier Reef Foundation and the International Water Centre. The workshop generated positive and constructive discussion around the key challenges and opportunities in reflecting climate change and variability appropriately in the State’s water models to support decision-making and inform action.

5.1 The pipeline concept

Through the conversations held as part of this review, it became clear that the concept of the ‘modelling pipeline’ was a useful tool for discussing strengths, weaknesses, gaps and opportunities at all stages of the modelling process.

This is consistent with Jakeman’s ‘10 iterative steps of best practice modelling’ Figure 17) which also informed the QWMN Good Modelling Practice Principles, developed by Australian National University in 2018, see Figure 18.

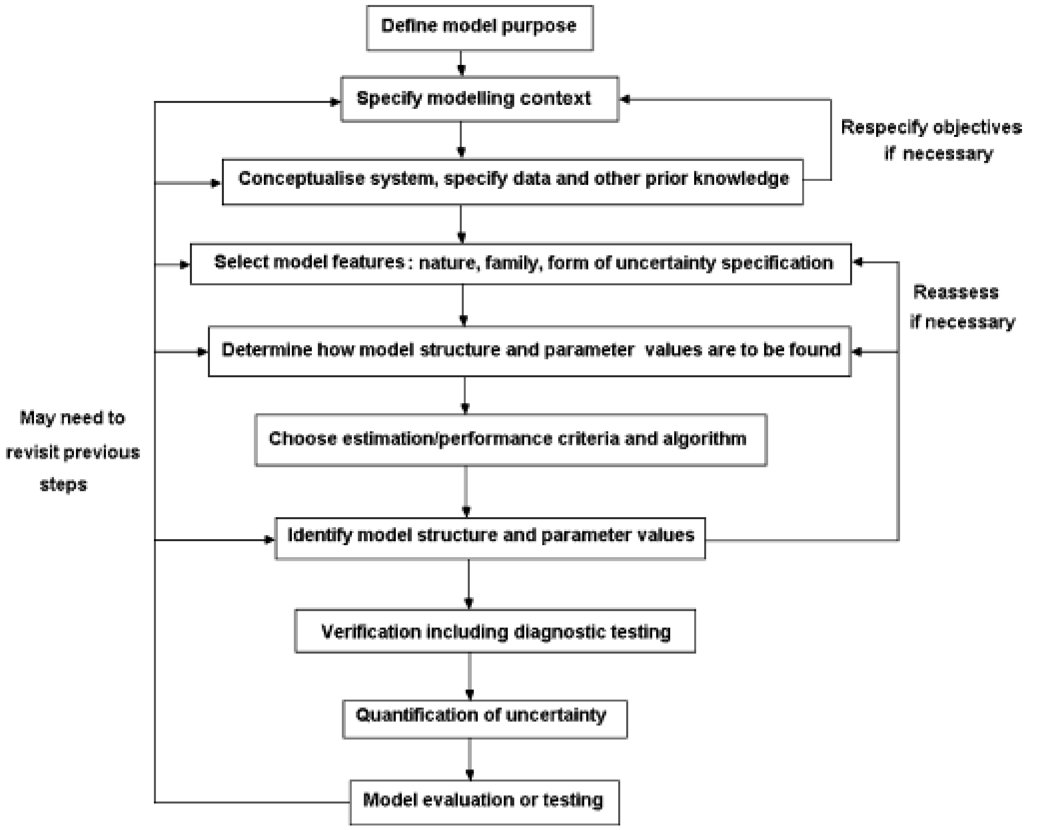


Figure 17 *Iterative relationship between model building steps (Jakeman et al 2006)*

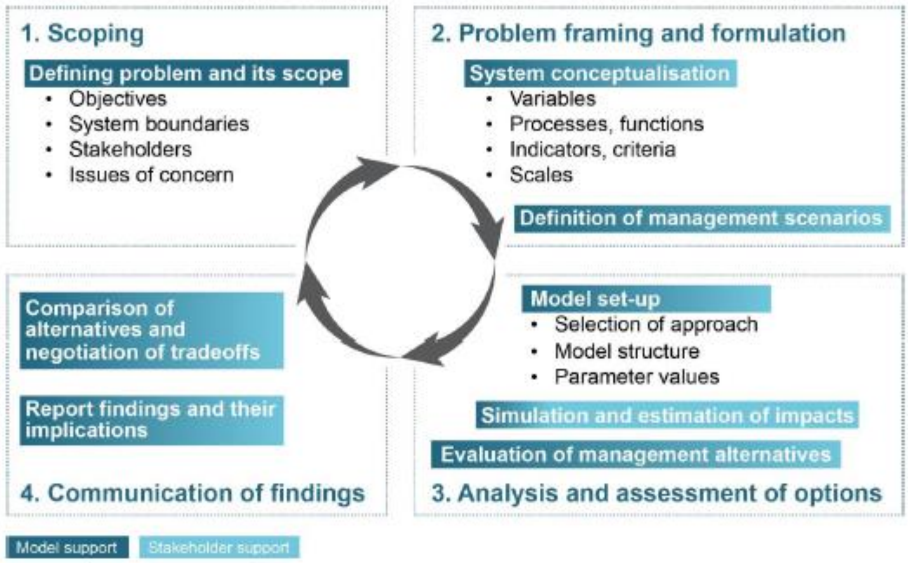


Figure 18 *Phases and steps in the integrated modelling and assessment process (Jakeman et al 2018)*

When compared with the 10 iterative steps (2006), the integrated modelling and assessment process (2018), has a much clearer emphasis on stakeholders and communication. The SEACI (2012) conceptualisation of the steps from greenhouse gas emission concentrations to hydrological modelling (Figure 19) also provides a valuable visual representation of the steps applied to model changes in regional hydrology.

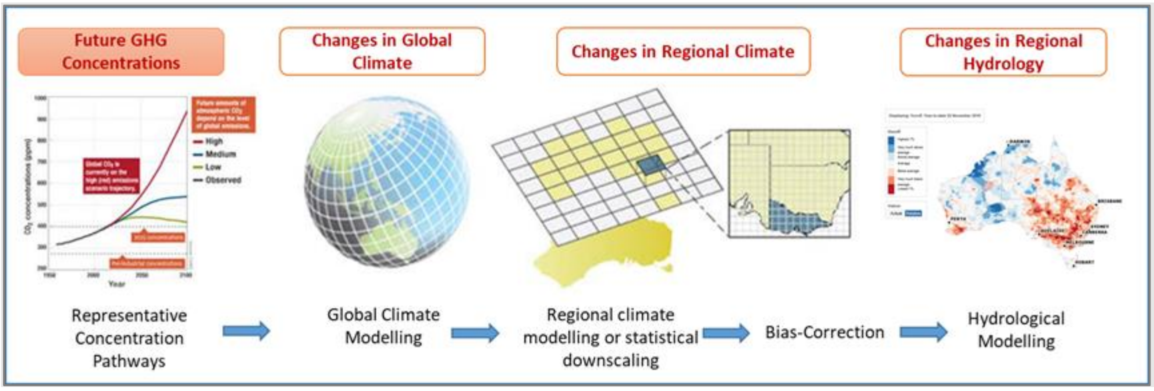


Figure 19 *Pathway from greenhouse gas concentration predictions to hydrological modelling (adapted from SEACI 2012)*

In Section 4.2, the flow chart shown in Figure 16 highlighted the importance of communication between modellers and end users in defining the modelling question, and using modelling results to effectively inform decision making. For the purposes of this review, the concepts raised in each of these process diagrams have been simplified to the 6-step 'modelling pipeline' shown in Figure 20. This aligns with the idea of 'projections to policy' which has previously been raised within QWMN.

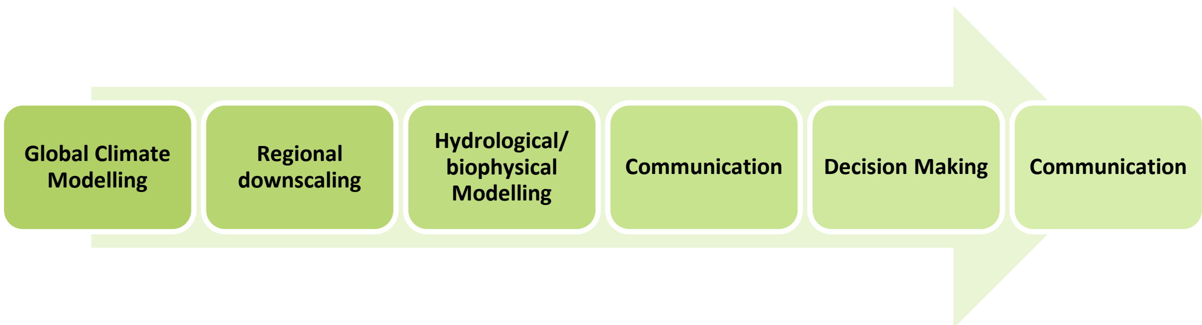


Figure 20 *The 'modelling pipeline'*

5.2 Exploring the current state

As part of the review, the project team reviewed current approaches to incorporating climate variability and change into water modelling and decision making. As part of the workshop, participants explored the following six key questions, which were used to understand the variation in approaches, potential strengths and weakness, and ultimately inform the gap analysis.

1. Do we understand drivers and impacts?
2. How do models help?
3. Do we have the right data?
4. How well do we communicate results?
5. What is our capacity and capability?
6. What drivers, legislation, guidelines and frameworks guide our approaches?

5.2.1 Drivers and impacts

In the discussion of climate drivers and impacts, the workshop group identified five key drivers: extended droughts, heat, increased flood intensity, sea level rise and changes to variability and extremes. Participants discussed the resilience of systems to withstand compound events and/or changed sequencing of events (e.g. loss of recovery time). It was discussed that there was little analysis of historical observed data sets to support understanding of the correlation of events to allow long-term forecasting and sector-specific risk assessment.

5.2.2 Modelling approaches

Various uses and benefits of water models were identified through the review, specifically the role of models in supporting decision making at diverse spatial and temporal scales, helping shift from a reactive to a proactive approach, which is increasingly important with changing climate conditions.

Limitations of current modelling practices with regard to the treatment of climate variability and change that were identified through the review included:

IQQM and Source for water resource management (water planning and urban water security)

- Limited understanding of climate variability impact on rainfall runoff relationships
- Physical catchment processes not well represented
- Data limitations
- Misunderstanding basic assumptions leading to misinterpretation of results
- Uncertainty on how climate change might affect variability
- Reliance on historical (instrumental) record for simulation period
- Lack of sensitivity modelling impacts on low flows (an ecologically important part of the flow regime)

Great Barrier Reef

- Physical processes related to temperature not well accounted for (e.g. nitrogen)
- Explicit/fixed climate signatures assumed in some aspects of models
- Lack of integration/interoperability with water planning models

Flood modelling

- High consequence of modelling error and high community expectations
- Feasibility of action to mitigate modelled scenarios is sometimes limited
- Probability distributions are based on stationary climate and independent and identically distributed assumptions

General

- Understanding of statistics and probability in the general population is low, particularly around the issues of likelihood and probability[1].
- Subjectivity in social values (and tipping points)
- Hard to predict possible extreme events using current methods (e.g. the severity of the recent monsoonal event in Townsville was outside of existing predictive estimates)
- Models are sometimes used out of context just because they exist and without good understanding of the benefits and limitations of their application.

5.2.3 Data availability

There has been some consideration of climate change in Queensland water models to date. Where climate change was considered, there were inconsistencies in input datasets and methods of application. It was identified that practitioners often found it difficult to find 'the right data at the right scale'. While there was a general appetite for consistent datasets to be used, there was a strong desire for any data products to represent a range of scenarios. It was also mentioned that there is limited knowledge on what data is available, and often significant waiting times on receiving data. For datasets that are available, it was reported that there was insufficient documentation and independent evaluation of datasets. It was also discussed that there is a high level of trust in observed/monitored data, with a perceived distrust in 'synthetic' datasets, with similar implications for models and their perceived value when using synthetic data.

5.2.4 Communication

Effective communication of modelling results is essential to supporting robust decision making and building trust within the sector and with the broader community. Through interviews, the workshop and particularly the QWMN forum on 'Accommodating climate change and climate variability in water modelling and decision making', there was a large focus on communication. One of the biggest challenges raised was communicating uncertainty, with participants suggesting that there should be a differentiation between 'policy uncertainty' (do we know enough to make a decision now or to not do anything yet?) versus 'scientific uncertainty' (do we need to invest in further research?). A barrier to including climate change in water planning modelling to date is the high uncertainty and lack of a clear trend or signal e.g. could be wetter or drier in any given year and the need to assess short-term vs long-term outcomes (variability is likely to dominate in short-term assessments, with change likely to be more prevalent in long-term assessments).

It was also highlighted that communications must be tailored to different audiences, with a strong need for key messages, and creative methods such as visualisation and story-telling being valuable in some contexts. In a number of forums, communication of climate predictions and their influence on derived information from models has been raised and this is a significant need in the industry. Suggestions were made that there could be a standard for a simplified overview supported by details allowing the reader to choose the level of detail appropriate for their level of scientific understanding and need for detail based on the level of risk. It was suggested that there could be a 'ski run' approach, with easy, medium and difficult explanations marked like ski runs so that the user could identify which one was best suited to their skills or the audience.

Participants mentioned that the focus of communication is often around the limitations and areas of uncertainty, which can lead to a mistrust of science or projections. There is still a need for a base level of awareness within Queensland Government and the general public to increase the acceptance of modelling approaches and outcomes. The Queensland Future Climate Dashboard and the supporting information at 'Queensland Future Climate: Understanding the data'[2] is helping to raise general awareness and understanding of climate science and data, with a series of videos developed by CSIRO and the Australian Government.

[1] This has been recognised previously and has promoted awareness videos such as:
https://www.longpaddock.qld.gov.au/forage/videos/understanding-percentiles-in-climate-data/
[2] https://app.longpaddock.qld.gov.au/climateFacts/

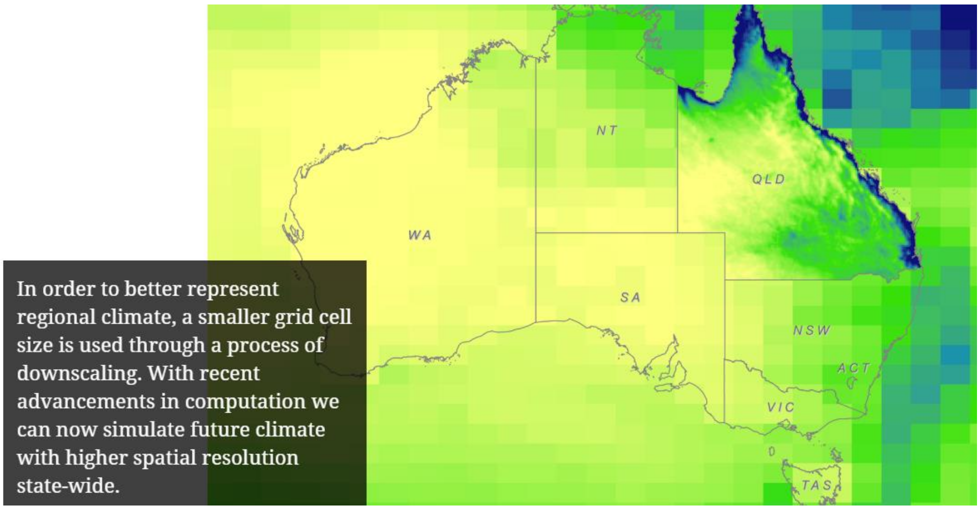


Figure 21. *Example climate data explanation from Long Paddock website*

5.2.5 Capacity and capability

While it was recognised that there is an abundance of intelligent, experienced and committed personnel in the Queensland Government water modelling space, it was also recognised that there were opportunities to increase understanding and application of climate science and to improve communication between groups to improve consistency in approaches. There is therefore an opportunity to improve the links between science, policy and communication to inform internal and external users of the information, including methods to address a range of audiences, from professionals and policy makers through to the general community.

5.2.6 Drivers for change

Following amendments to the Queensland Water Act in 2018, water related climate change effects on water availability, water use practices and the risk to land or water resources arising from use of water on land must be considered in the preparation of water plans. Climate change considerations have already been included in twelve statutory Minister's five yearly performance assessment reports for water plans in 2018/19 with the remaining reports to be prepared over time. The Act also requires best practice science to be used. The reality of changing frequency, duration and intensity of extreme climate events such as flood, drought, bushfire, cyclones and heat waves is perhaps the primary driver for improving the ability to understand water-related systems under future climate conditions with some sense of urgency.

For urban water security, there are legislated Levels of Service for South East Queensland but not for other parts of the state where local government is responsible for water security. For regional urban water security planning, there are no specific guidelines for accounting for climate change, however stochastic modelling is being used by DES as part of the modelling used to inform regional urban water security plans.

In the Great Barrier Reef space, the Reef 2050 Plan highlights climate change as the greatest risk, however climate change is not currently incorporated into Paddock to Reef modelling. It is acknowledged that changes in climatic conditions will impact progress towards the Water Quality Improvement Plan targets, but there is no formal process for quantifying this as yet.

As part of the Queensland Climate Adaptation Strategy (QCAS), an Emergency Management Sector Adaptation Plan for climate change was published in 2018. The strategy highlights that the changes in the frequency, intensity, distribution and duration of climate extremes resulting from climate change, coupled with the intensification of population growth and urban development in hazard-prone areas are likely to increase exposure and risks to Queensland communities and infrastructure. The plan sets out priorities to further engrain climate change into sector strategic investment and disaster management planning at all levels, positioning the sector to remain a trusted broker of climate related risk data and information for communities. How this relates to modelling directly is yet to be explored.

5.3 Exploring future opportunities

Building on the analysis of different aspects of the current state and the main concerns and challenges of the interviewees and workshop participants, future opportunities were discussed. This section aims to present all of the suggested opportunities that were raised throughout the review, and discusses the main trends and contradictions. These are then used to inform the recommendations in Section 0 which considers how these opportunities may best respond to the needs and challenges across Queensland Government and for other water modellers, end users and sectors.

A Strengths, Weaknesses, Opportunities and Threats (SWOT) approach was used to explore the future opportunities, focussed on four main focus areas:

1. Strengthening climate science knowledge and data inputs for water models
2. Improving the ability of water models to incorporate climate science
3. Developing a framework and/or guidelines to support bridging the gap from climate science to decision-making
4. Building Queensland's capacity and capability to understand and apply climate science to inform better decisions and outcomes

5.3.1 Theme 1: Strengthening climate science knowledge and data inputs for water models

There are many examples of innovative and advancing use of climate science within Queensland Government. Stochastic methods are being used effectively for testing system reliability, and the Long Paddock data portal and Queensland climate dashboard are increasing the ability of practitioners to access and understand climate data products.

Challenges, weaknesses and threats identified through the review included:

- CMIP6 is currently being developed and will become available while downscaling of CMIP5 is still being used so there may be issues around ensuring that the best available science is being applied at any given point in time
- Version control, data control, modules, metadata will be essential to ensure traceability to specific projections or datasets
- Computing capacity may restrict complex ensemble modelling but also need better guidance on when this may be required
- Budgets do not always allow for the appropriate level of modelling to reflect the climate science
- Downscaling climate models is expensive and resource intensive so decisions around when this may need updating will be required, in addition to understanding whether this will necessarily improve predictive capability (i.e. if the same limitations apply to the GCMs being used, then it may not provide any greater certainty).
- Assumptions in model inputs (which do not hold under future climate conditions) need to be better understood
- Static inputs (e.g. land use, rainfall-runoff parameters) may not reflect future conditions
- Short modelling periods (based on historic records) may not adequately account for climatic variability over long time periods
- Water quality/biogeochemical process changes under different climate regimes are not accounted for in most models, including higher-level ecological outcomes.
- Integrated socio-biophysical modelling is even less common in accounting for different climate regimes.
- No clear stocktake of what data is currently available for Queensland

- Issues with large data sizes (storage) and tools to process the data (both in size and spatially)
- Groups currently working in silos and using different decision criteria to choose datasets (lack of consistency in data chosen and approach used)
- Using input data without sufficient understanding of underlying assumptions
- Using input data without adequate independent review or validation
- One method at high resolution may not provide sufficient confidence or provide false confidence
- High resolution not always better
- Election and budget cycles

In response, the following opportunities were identified:

- Detailed stocktake, evaluation and user guides for datasets
- Framework for developing metadata and document control
- Framework/guidelines for how to use palaeoclimate and downscaled GCM hydro-climate data
- Script and data sharing portal
- Model evaluation and peer review processes
- Enhanced computing power and data sharing capability (within QG and beyond), could co-invest
- Update aged models
- Enabling change over time to be represented in models using new technologies (e.g. satellite data for land use and vegetation cover change)

With more climate data products becoming available, there is a risk of inconsistent assumptions being made, as well as products not being used appropriately or effectively, despite best intentions.

5.3.2 Theme 2: Improving water modelling tools and approaches for incorporating climate science

One of the primary strengths identified relating to the improvement of water modelling tools and approaches for the treatment of climate variability and change was that there is generally strong awareness, commitment and enthusiasm for improving modelling techniques. Models are continuously becoming more sophisticated, increasing the ability to represent different scenarios, but also making it more challenging to find experienced modellers that fully understand model functionality, **and** are able to communicate the model outcomes effectively.

This review found that there was an appetite for independent assessment of models and climate change projection data (similar to the Prosser review for sediment modelling), as well as for more prescriptive guidelines for approaches to incorporating climate variability and change. There were contrasting perspectives when it came to guidelines, with some viewing the variation in contexts and information needs being too broad for one set of guidelines, and that guidelines can stifle innovation. After considering the various perspectives presented throughout the review, the project team determined that the development of recommended approaches, applicable to the identified level of risk, would provide valuable support to many practitioners full of enthusiasm, but unsure of where to start when it comes to incorporating climate risk into water modelling. These guidelines could be part of an online tool, providing flexibility to be updated easily as new climate science and data products become available. Guidelines could also include recommendations for data-model-run management, allowing better records to be kept of model setup and results. This is explored further in Section 5.3.3.

Regarding the modelling tools themselves, interviewees and workshop participants also raised the need to adapt model structures and parameters to account for future climate conditions, rather than assuming that projected climate data alone will be sufficient. It was also raised that expectations (particularly for end users) need to managed in terms of the additional resources, time and funding to incorporate climate variability and change compared with a more simple or deterministic approaches.

Opportunities suggested throughout the review by interviewees and workshop participants included:

- Validate past model simulations to increase confidence
- Develop consistent methods for input data development
- Establish maintenance funding for storage and access to data
- Develop guidelines for incorporating new datasets into models
- University courses – training the next cohort of water modellers
- Improved quality assurance processes
- Develop library of datasets
- Examine suitability of models to incorporate climate change
- Ongoing funding to explore gaps in scientific knowledge required to further develop models to robustly predict the future
- Specific training for modellers in the value of uncertainty/confidence and how best to communicate
- Align all datasets with changed climate data -> e.g. demand, patterns, agricultural usage, water usage
- Develop and fund long term workforce development

5.3.3 Theme 3: Developing a pathway to bridge the gap from climate science to decision-making

As discussed in Section 5.3.3, there were contrasting views regarding the development of guidelines. It was deemed that rigid, overly-prescriptive guidelines may not cater for the full range of contexts, might stifle innovation, and may create additional burden without necessarily leading to better outcomes. These concerns should be considered in the development of any such guidelines.

The idea of guidelines is not new, with examples of guidelines used elsewhere in the water sector including:

- Operational guidelines for dam-break event response
- Australian institute for disaster resilience guidance for flood risk management
- Victorian guidelines for assessing the impact of climate change on water supply
- NWI guidelines (2017) – Considering climate change and extreme events in water planning and measurement

Some of the benefits of guidelines that were raised as part of the review included:

- Give clarity to decision making or infrastructure development
- Clarifies priorities
- Provides consistency across agencies and organisations

Recognising the advantages and disadvantages mentioned above, the suggestions raised by workshop participants and interviewees included:

- Hosting guidelines online to allow flexibility to update easily with new science and climate data products
- Building on existing products (e.g. the climate risk matrix)
- Guidelines being 'suggested' approaches rather than mandatory
- Different approaches for different contexts and risk profiles

- Integrated monitoring and modelling platform that can provide a responsive decision support system (potential learnings from Reef and SEQ)
- Accessible expert pool (no written guidelines)
- One set of broad guidelines – e.g. flowchart, not overly prescriptive

It was also discussed that there may need to be some additional interpretation or guidance on what it means to 'consider climate change' in the Water Act

With regard to decision making and level of service, it was also discussed that there is often a discrepancy between the desirable level of service, preferred level of service, and affordable level of service. Climate scenario modelling might show the potential for extreme drought periods, this does not necessarily mean that water security planning and infrastructure can or should be able to manage for this as this will necessarily need to account for the risk of providing (or not providing) for these extremes. The discussion indicated that some support for decision makers in how to use water model outputs to make robust and defensible decisions.

5.3.4 Theme 4: Building Queensland's capacity and capability to understand and apply climate science to inform better decisions and outcomes

As mentioned earlier in this report, there is a clear and strong willingness to improve modelling and decision-making practices. In addition, there is general agreement that climate science and products have reached sufficient maturity to be implemented. There is an opportunity to enhance the individual capability and collective capacity to more effectively apply the available scientific knowledge and products in both water modelling and subsequent decision making. Some of the challenges raised during the review related to capacity and capability include:

- Silos existing at some levels (i.e. a lack of communication or perhaps a lack of sharing of information)
- Lack of coordination
- Uneven level of knowledge and understanding
- Under resourcing
- Inadequate training at all levels (graduate, professional, practitioner, political)
- Short term funding availability and insufficient core funding

The QWMN Research, Development and Innovation initiatives, as well as the External Engagement Program (EEP) are already playing a key role in strengthening knowledge and collaboration within Queensland Government, and with the broad range of modellers and 'end users' of modelling.

Some opportunities for increasing capacity and capability with regard to climate science and water modelling identified during the review included:

- Strategic seeding of RDI funding
- Dedicated centre with science and policy working together (e.g. SEACI, IOCI, ESCCI, VicWaCI)
- Establish team of experts both for long term planning and emergency response
- Secondments between groups and organisations
- Incorporating traditional knowledge and citizen science

6 Case studies

A series of modelling projects have been evaluated as part of this project to examine how existing climate variability and future climate change may be better accounted for in either the models or the projects in which the modelling is being conducted.

6.1 Case Study 1 – Paddock to Reef (P2R) Source Modelling

6.1.1 Introduction

This case study reviews the current application of the eWater Source Model in the P2R Catchment Loads Modelling program with a view to understanding how this modelling could incorporate (if required) the impacts of future climate change and existing climate variability on the modelling process and the results obtained. It is not intended to be an in-depth review of the modelling but to identify where the models may need additional considerations if the models were required to address climate change and variability in more depth.

6.1.2 Modelling Question

The application of the Source Modelling Framework (Welsh et al 2013) to the Great Barrier Reef catchments has been ongoing for a decade. The primary modelling question to be answered is evaluating and reporting progress towards the Reef 2050 Water Quality Improvement Plan (see https://www.reefplan.qld.gov.au/) through the ongoing analysis of baseline condition and application of improved management practices in a range of agricultural industries included targeted treatment options and investment prioritisation relative to a baseline year.

6.1.3 Role

Models have been developed for each of 6 NRM regions (Cape York, Wet Tropics, Burdekin Dry Tropics, Mackay Whitsundays, Fitzroy and Burnett Mary) as shown below. The models are used to compare changes in management practice implementation against a baseline scenario (nominally 2013) by simulating different agricultural industries and their associated management at the paddock and landscape scales. These are completed in component models such as APSIM (Holzworth et al 2014), HowLeaky (Shaw et al 2011) outside of Source and in a dynamic SedNet model within Source at the landscape scale through changes in cover.

This coupling of component models approach (Waters et al 2014) means that there are a wide range of model inputs and parameters that may be influenced by the need to better account for future climate change and existing climate variability. A screenshot of the Wet Tropics P2R model is shown in the figure below.

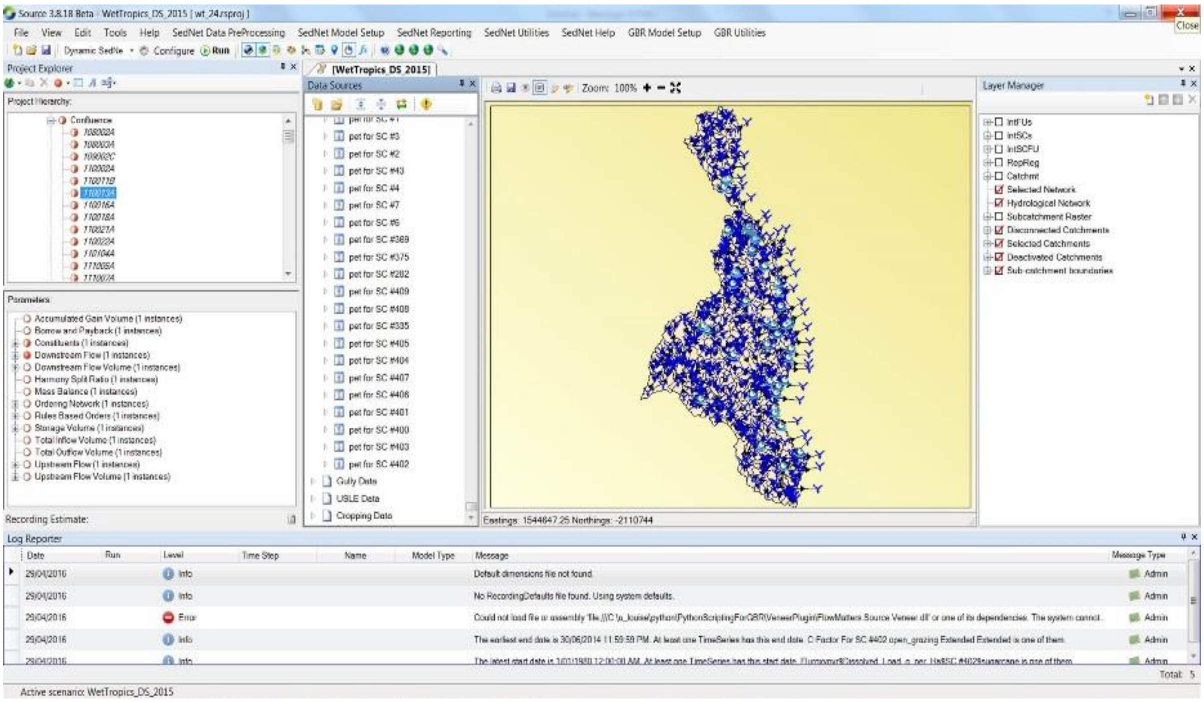


Figure 22 *Wet Tropics P2R Source Model*

The Source model is run every year incorporating the new practice adoption layer, with major updates to the model and input data sets every 5 years (last update 2018). The model development process is outlined below.

There are a number of key points in this process (highlighted by red circles) where the accounting of climate variability and climate change may influence the model outcomes, including initial input data sets such as climate, but also methods of calibration, soil properties (e.g. soil moisture stores, soil erodibility, infiltration rates), storage operation, vegetation cover, in addition to component model (APSIM and HowLeaky) inputs and parameters. These are discussed further below.

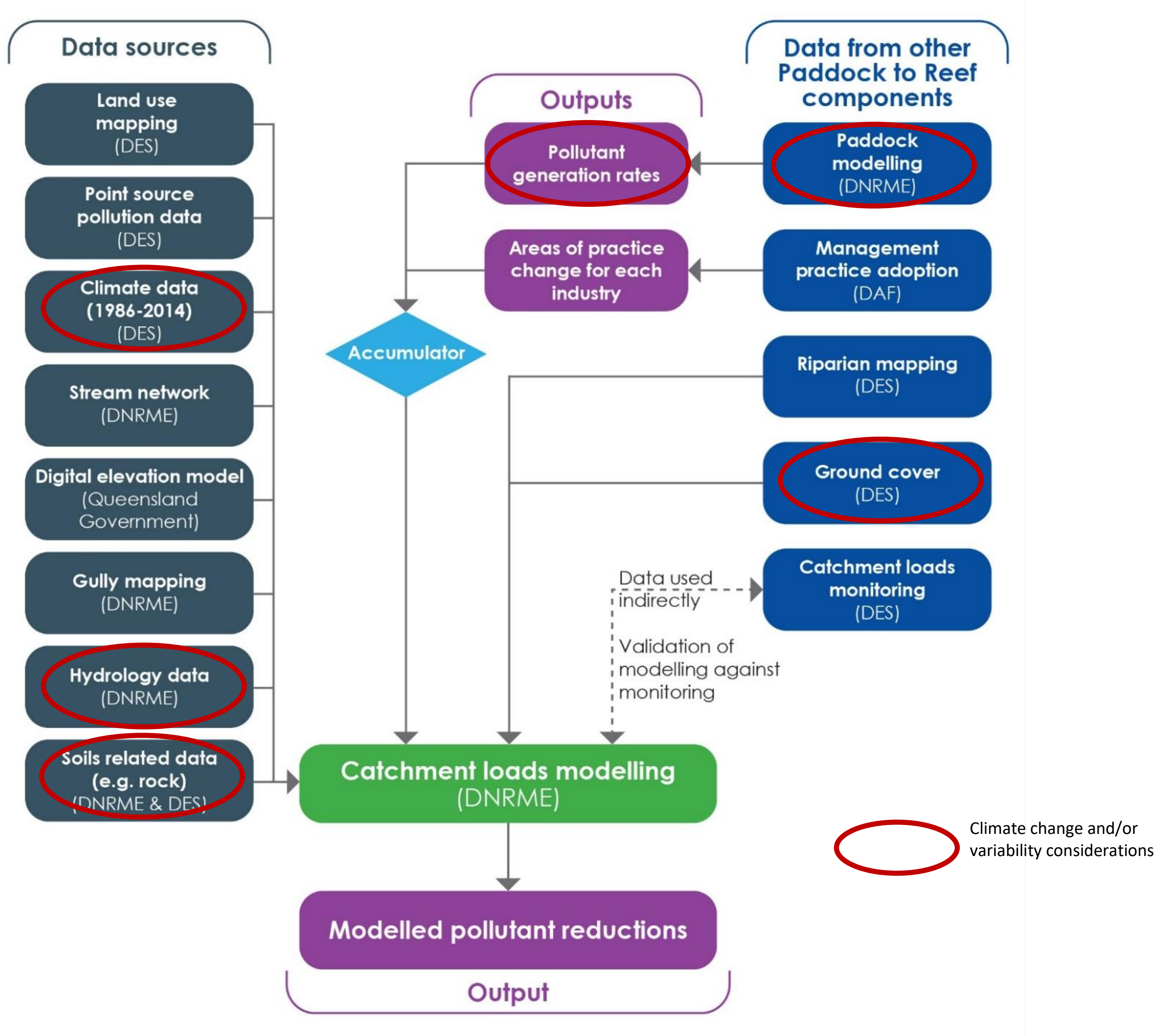


Figure 23 *P2R Model development process*

6.1.4 Structure

The P2R Source models are not a single model, but an ensemble of component models brought together within the Source modelling framework. Separate models exist for runoff generation, pollutant generation, stream routing and constituent/pollutant transport, transformation and delivery. It is not intended to go into depth of all these models within this case study, but rather to highlight where climate change and climate variability may need to be incorporated or have influence on key model inputs, parameterisation and model processes.

The conceptual structure of Source (and many other lumped conceptual hydrologic models) is shown below. Basically, a series of landscape characteristics such as land use, topography and surface/soil characteristics are used to spatially discretise the hydrologic response of a catchment (i.e. different parts of the catchment can be configured to respond differently). These landscape characteristics are used to then parameterise a rainfall-runoff model which uses climate input data (typically rainfall and evapotranspiration) to derive a specific flow response according to both the input data and the landscape characteristics. These flows are then accumulated or “lumped” to a subcatchment and then moved down through a flow path network where further transformations can occur.

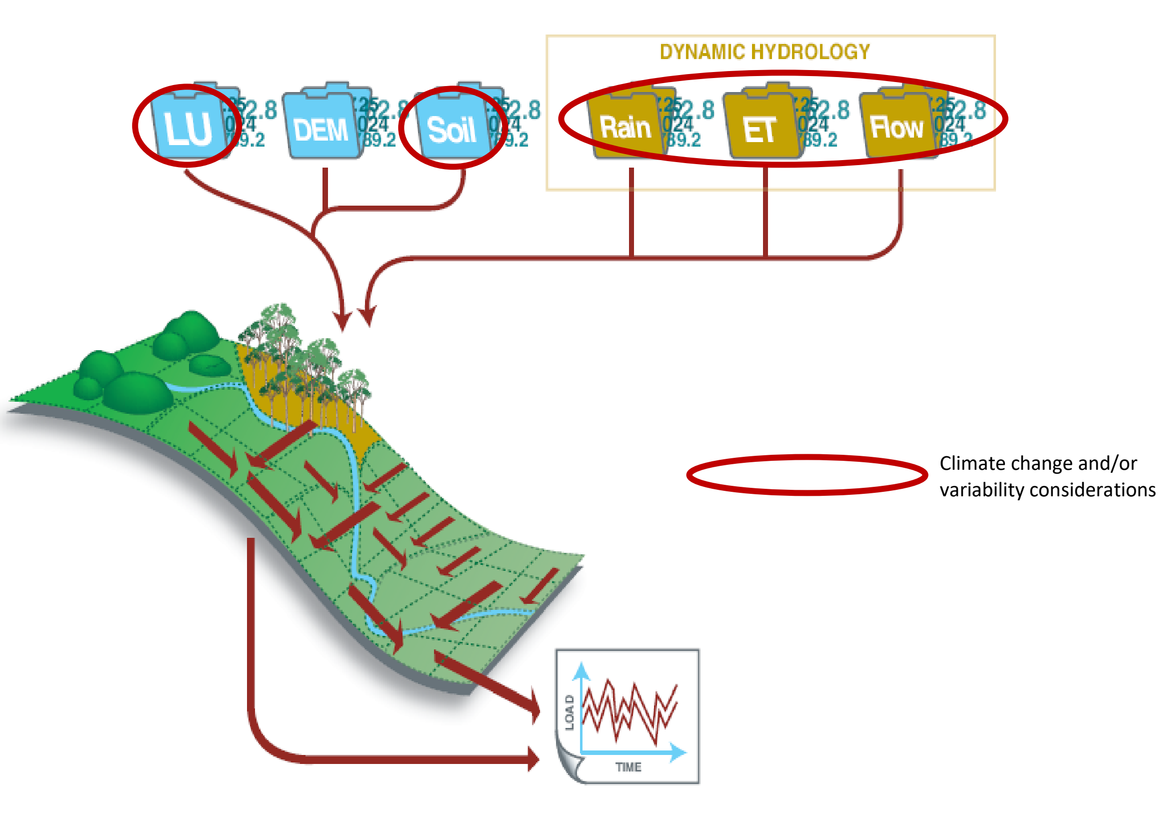


Figure 24 *Conceptual representation of a hydrologic model in Source (2010)*

In these types of models, the rainfall-runoff component is generated through either a single model or series of models that transform climate data into a runoff response through a series of different flow pathways and stores. In the Paddock to Reef model, the runoff model Sacramento is used as the primary model for runoff generation. Loads are also generated through agricultural systems models s namely APSIM (cane) and HowLeaky (grains and bananas), largely based on the PERFECT runoff and cropping model (Littleboy et al 1992).

Rather than examine all the rainfall-runoff models, this case study focuses on the Sacramento model as an indication of where climate variability and change may influence inputs, parameters and outputs.

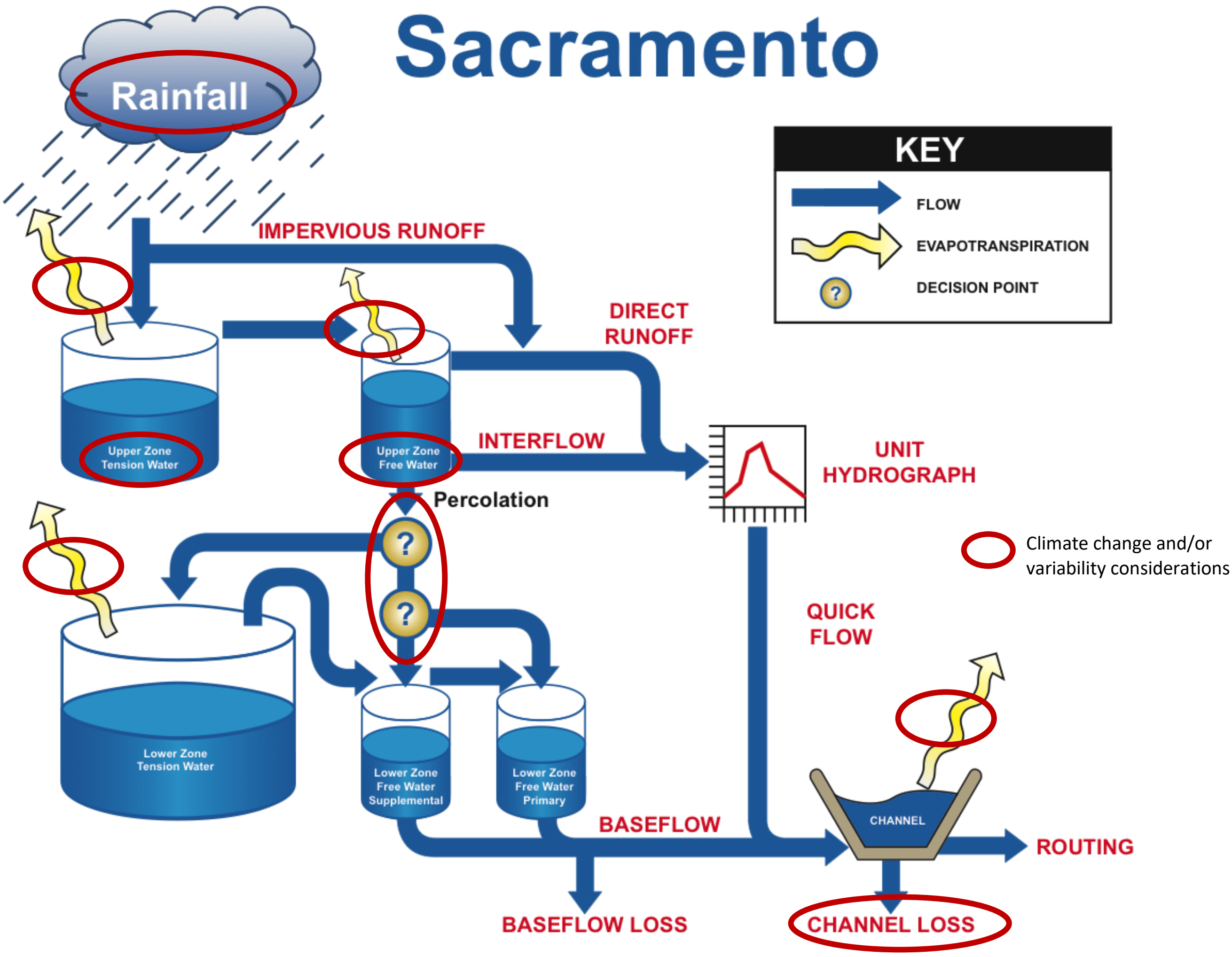


Figure 25 *Conceptual model for Sacramento Rainfall Runoff model (eWater 2019)*

In addition to the rainfall-runoff model, constituents and therefore catchment loads and water quality are represented in Source as outlined in the conceptual diagram in Figure 24. The figure shows a number of the component models such as the Revised Universal Soil Loss Equation (RUSLE), APSIM and HowLeaky, in addition to other input data components such as storages and extractions. Again, red circles have been used to identify key areas where climate change and climate variability may have an influence on model use and outputs. Some aspects, e.g. gully erosion, are not circled as these are based on disaggregation of long-term sediment discharges, rather than simulations based on climate data inputs.

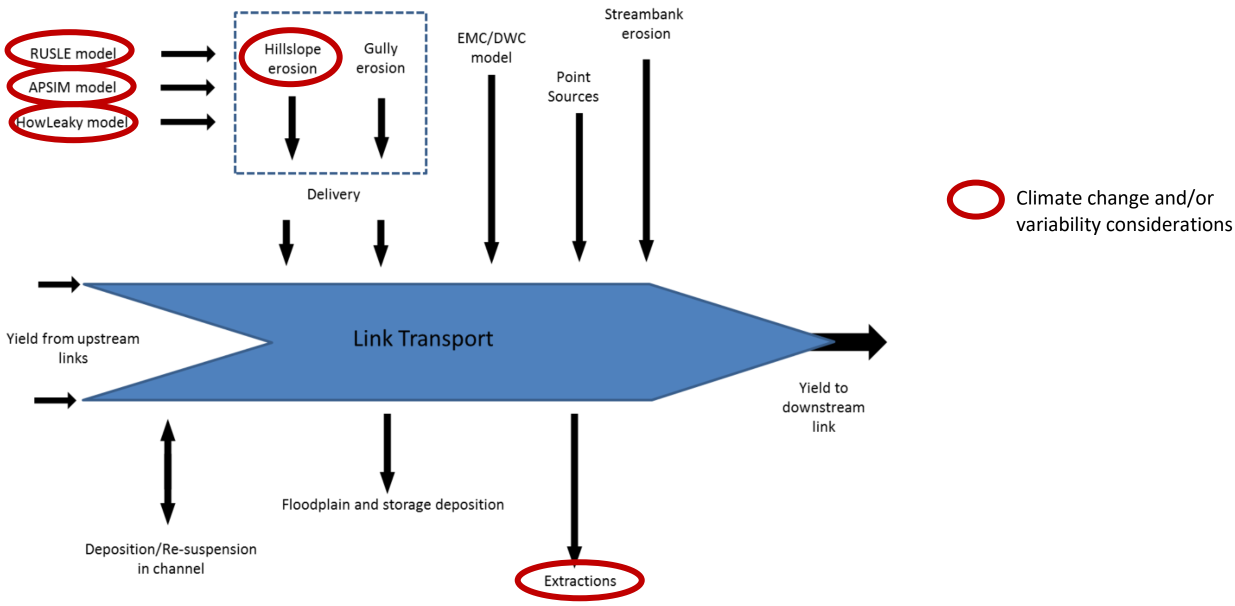


Figure 26 *Constituent conceptual model*

6.1.5 Inputs

6.1.5.1 Rainfall and Evapotranspiration

Currently, the Source models use SILO gridded data for a specific climatic period (1986-2014). Similar daily gridded data products are now available at the same regional scale that incorporate downscaled climate data that could be incorporated into the Source models if required (see Section 3.4). ***Consideration – suitability of climate change data products in terms of resolution and climate sequences.*** Greater variability could be considered by assessing longer time periods or using different time periods as indications of wetter or drier periods.

The key challenge in utilising a different data set is the need to ensure consistency with the existing climate period used in order to demonstrate the effects of climate change only, rather than complicating this with the effects of a different climatic sequence. This is important where the models are being used to deliver a report card result, as it is a comparison of scenarios where there is a like vs like assessment (e.g. management practices under existing and future climates). This may mean that simply adopting existing data products may not be appropriate, as it may be difficult to resolve whether any changes assessed are because of a different climatic period having altered frequencies of events etc., not just the changes in rainfall, evapotranspiration and temperature that may occur on a climate period consistent with the baseline 1986-2014 period assessed under the existing case. ***Consideration – is it possible to assess future climate changes over a consistent climatic sequence to that currently used in P2R models? Also, is the current baseline the best representation of existing climate variability (wet and dry periods) that are likely to be experienced in the GBR regions?***

The component agricultural models APSIM and HowLeaky may also have similar issues around the use of different climate inputs, but also may not account for changes in other climate factors such as temperature, wind, solar radiation etc. ***Consideration – further assessment of the impacts of changes in climate factors of component models, especially APSIM and HowLeaky, is required if climate change is to be incorporated into P2R modelling.***

In the current application of the P2R Source model, consideration of extreme events is confined to those which occur in the 1986-2014 period, so further inclusion of additional climate variability is not required for use of these models in assessing the Reef Report Card. We have noted that there is an ongoing need to assess the impacts of extreme events outside of this period e.g. Cyclone Debbie, 2019 Monsoonal Trough and the likely frequency and magnitude of these based on the existing climate variability and future climate change. Whilst this is not currently in the remit of the P2R modelling work, there may be a future need to investigate this and therefore a more detailed consideration of the incorporation of improved climate variability may be required.

Consideration – Improvements in climate variability within the P2R models are not likely to be required as part of the P2R program, but there is an ongoing need to evaluate extreme events. This may require further analysis of the suitability of existing climate sequences to adequately represent the frequency and magnitude of those extremes.

6.1.5.2 Land cover

Within the existing models, hillslope erosion is driven by the RUSLE model. A key component to that model is the cover factor "C" which is currently informed through analysis of remote sensing information for seasonal timesteps over the climate period of interest. Given that this is a recorded data input, neither the representativeness nor significance of this cover under a future climate regime is understood. ***Consideration – If assessment of future climate change was to be required as part of the P2R program or using the P2R models, some evaluation of the likely impact on vegetation cover under future climate sequences.***

6.1.5.3 Storages, Losses and Extractions

There are a number of water storages, losses and extractions within the P2R models that have been derived from water resource models across the state to simulate their response under the conditions of the existing climate period. With different climatic sequences representing future climate change, it is highly likely that the responses of those will need to alter to be consistent with the future climate sequence. Whether this has implications for water resource models in the same locations has not been explored, as the modelling questions for P2R are focused more around constituent/pollutant loads rather than explicitly around water quantity. ***Consideration – Further understanding on how existing inputs around storage operations, system losses (such as channel loss), and water demands/extractions be modified to represent their response under a future climate change sequence.***

6.1.6 Key Parameters

A number of model parameters associated with the rainfall-runoff model, agriculture component models and the hillslope erosion model, as well as the conceptualisation of the processes, are likely to be influenced if representing future climate change. These are largely focused on the following key areas:

- From a landscape process perspective, changes in surface-groundwater interaction and subsurface evapotranspiration may be significant.
- Land uses may alter (e.g. cropping areas, types of crops, changes to agriculture activities such as moving from cane to grazing) if particular crops or enterprises are not adaptable to future climates
- Crop growth/vegetation responses, irrigation demand or harvesting regimes may alter under different climate sequences which may influence soil exposure, fertiliser applications, pesticide applications, nutrient uptake and nutrient and pesticide export.
- Alterations in erodibility of soils through different vegetation and soil moisture conditions may result from different rainfall erosivity conditions (different rainfall energy and frequency of exceedance rainfall thresholds that cause erosion)
- Current use of static estimates for gully erosion may need to be revised if different erosion regimes (rainfall intensity, frequency or duration) are likely in the future

During stakeholder interviews and workshop interactions it was obvious that these issues are in the "front of mind" of modellers and decision makers and there are a number of articles on these issues in the broader climate change literature, however there are no focused projects on understanding how these model parameters may need to alter in the component models in the P2R Source modelling. ***Consideration – greater understanding of how model parameters or conceptual model structures may need to be altered to better represent future climate change is required as there is no current guidance on how to account for different hydrologic responses due to climate influences on land use, landscape processes, surface-groundwater interaction, soil conditions, crop growth, agricultural activities (irrigation, fertiliser and pesticide use) and changes in rainfall erosivity and soil erodibility under future climate change.***

6.1.7 Results and Outputs

The results of the P2R models currently inform ongoing assessment of the progress towards the Reef 2050 Water Quality Improvement Plan. As such, the model outputs are used to make comparisons of a baseline scenario with an assessment of the implementation of improved practices and treatments across the Great Barrier Reef catchments. If future climate change needs to be considered in these assessments, and given the 2050 timeframe of the Reef 2050 WQIP, this is well within the timeframes where climate change is likely to have an impact, then the results and outputs of the P2R models will need to be compared against a baseline consistent with that currently used. With the large spatial extent of all of the P2R models, presentation of results and outputs for different regions may need to be considered independently depending on the suitability of model inputs and parameters to be resolved at the regional and sub-regional level i.e. the spatial extent may be too large to evaluate climate change influences properly within the existing P2R Source framework.

Consideration – An assessment of how best to represent a comparison of the existing baseline with a future climate change model output needs to be considered if climate change is to be evaluated. In addition, the ability to consider climate change across the large spatial scale of the GBR catchments, including the adequacy of inputs and parameters at those scales, is not well understood. This is likely to be a need across all modelling programs within the Queensland Government, so may need broader scale assessment than just a focus on P2R.

6.1.8 Recommendations

From the above information, the following key recommendations are proposed if climate change is to be further considered in P2R models:

1. *Assess the suitability of current climate change data products in terms of resolution and climate sequences and their applicability to the P2R models, including the need to develop a comparable climatic change sequence to that currently used in P2R models*
2. *Evaluate if the current baseline best represents existing climate variability (wet and dry periods) likely to be experienced in the GBR regions.*
3. *Undertake further assessment of the impacts of changes in climate factors of component models, especially APSIM and HowLeaky.*
4. *Undertake further analysis of the suitability of existing climate sequences to adequately represent the frequency and magnitude of extreme events, especially with reference to paleoclimate studies.*
5. *Evaluate the likely impact of climate change on vegetation cover under future climate sequences.*
6. *Investigate the impacts of climate change on land use change, especially around agricultural activities (crop types, changes in farm types).*
7. *Investigate how existing inputs around storage operations, system losses (such as channel loss), and water demands/extractions can be modified to represent their response under a future climate change sequence.*
8. *Examine how model parameters and conceptual model structures can be altered to better represent future climate change.*
9. *Assess how best to represent a comparison of the existing baseline with a future climate change model output needs to be considered.*

These recommendations have been incorporated within the overall recommendations listed in Section 7.5. Not all have been listed specifically, but have been incorporated into others where required.

6.1.9 An example application of the modelling criteria

Evaluation criteria for considering how existing climate variability and future climate change is incorporated in models are outlined in Section 3.5. As an example of their application, this case study has been reviewed against these criteria and is presented in the results below. It should be noted that this is done to consider if the P2R model was required to undertake climate change assessments as part of its annual reporting and evaluation of the implementation of improved practices across the GBR. If so, the following assessments against the evaluation criteria may be of use.

Criteria	Questions to consider	P2R modelling assessment
The modelling question	1. Direct consideration - does the modelling question specifically refer to future climate change or long-term climate variability (e.g. predicting the change in ecosystem health of river X under climate change)?	No - Currently this is not required under the P2R program, but may be a future need.
	2. Indirect consideration - will resolving the question require consideration of existing climate variability or future climate change effects on system behaviours (e.g. understanding water supply infrastructure requirements under future urbanisation)?	Yes - The majority of focus would be on future climate change representation to understand changes in pollutant loads to the reef.
	3. Timeframes - Is the question likely to need resolution of short-term or long-term responses?	Long Term - The models will be required to evaluate the changes over longer time frames (e.g. 20-50 years)
	4. Temporal patterns - Does the modelling question require an understanding of changing temporal patterns in the future (e.g. evaluating frequency of extreme rainfall events)?	Yes - changes in events such as cyclones, monsoonal patterns etc will need to be accounted for in future climate change assessments. This is currently not occurring but may be a future requirement.
Data inputs and forcing data	1. Does the model require climatic forcing data e.g.: - temperature - rainfall - evaporation/evapotranspiration - solar radiation - wind - humidity?	Yes - In the existing P2R models, rainfall and evapotranspiration are the primary climate forcing data.
	2. Will other data inputs be influenced by existing climate change or future climate variability?	Yes - Other components such as vegetation cover and land use may need to be changed to account for issues such as increased temperature, sea level rise, changed agricultural practices.
	3. Will spatial and/or temporal patterns of data inputs change?	Yes - Changes in extreme event frequency are not a current focus of the program, but are likely to be needed in the future and this will require better assessment of changes in temporal patterns.

Criteria	Questions to consider	P2R modelling assessment
Conceptual process representation	1. Does the conceptual models that underpin the numerical model properly present or allow for climate variability?	Possibly - The conceptual processes of rainfall runoff and constituent generation do allow for climate influences to be represented, however some elements such as changed vegetation cover etc are not explicitly represented (nor are they in many other similar models)
Component models	1. Do the component models have sufficient parameters to account for changes in climate inputs?	Yes - In most cases the current Sacramento rainfall runoff model, HowLeaky and APSIM agricultural models, and the dSedNet constituent generation models can account for changes in climatic conditions on the direct processes they are simulating.
Model outputs	1. Temporal variability - Does the model show results that can address long-term changes in climate?	Possibly - The models are run over a 28-year consistent climate period to allow for comparison against baseline scenarios. Altering the climate of this 28 year period may have implications for assessing changes against a baseline condition with a different 28 year climatic period. This period may also not represent the full variability likely to be experienced across the GBR region if accounting for the extent of variability possible from the palaeo and recorded climate regimes.
	2. Spatial variability – Does the model have sufficient spatial scale or in locations where different climate realisations can be used?	Yes - The models run at a scale that uses broad scale climatic inputs such as SILO gridded rainfall and therefore are at the optimal scale to use climate change data products currently available.
	3. Scenario testing - Can the model evaluate multiple scenarios or operated in a stochastic fashion?	Yes – the models can run multiple scenarios but run times may prevent use in stochastic assessments.
Decision frameworks	1. Model flexibility – is the model able to be altered easily to account for different actions, inputs or parameters.	Yes – the models are quite flexible to adjust parameters and run different scenarios and are commonly used in this form.

Criteria	Questions to consider	P2R modelling assessment
	2. Trajectories – does the model represent not just the result of different climates, but also the process of change?	No – currently this is not easily represented without some adjustment to input data sets (e.g. running models over shorter time frames) as some of the input data is static (e.g. land use). The use of dynamic cover in the models does allow for some representation of one component of trajectory to be simulated.
	3. Visualisation – can the model present results in ways that are easily communicated, or can the model outputs be easily incorporated into communication tools.	Possibly – The current outputs are typically post-processed to provide for different visualisations, though some work is occurring to improve this process.

The above evaluation indicates that the P2R models are likely to be able to incorporate components of existing climate variability or future climate change, though additional effort may be needed for input data, accounting for different climatic periods, fully accounting for the range of likely influences of climate change (because of potential limitations in conceptual processes), and in the representation of trajectories and visualisation of results. This is further discussed in the Case Study section.

What this shows is the potential of the evaluation criteria to assist in identifying the suitability of models but also where gaps and improvements may exist. It relies on knowledge of the models and how they are used and is not intended as scoring system, but a way of understanding the potential of models to account for existing climate variability and/or future climate change.

6.1.10 References

Waters, DK, Carroll, C, Ellis, R, Hateley, LR, McCloskey, GL, Packett, R, Dougall, C and Fentie, B, (2014). Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef Catchments: Whole of GBR, Technical Report, Volume 1. Brisbane, Queensland Department of Natural Resources and Mines.

6.2 Case Study 2 – AussieGRASS – Pasture/Forage simulation

6.2.1 Introduction

Across Australia more than 43% of the land area is devoted to grazing. There have been a number of “degradation episodes” over the last 120 years related to both climate and land management which have affected the productivity of those grazing lands (McKeon et al 2004). To understand this and provide information to landholders, the AussieGRASS Environmental Calculator is used to simulate how pasture growth changes under different climatic conditions across Australia’s grasslands and rangelands and has become a valuable tool for graziers and land managers. While not strictly a water model (as it does not do any detailed water movement across the landscape), understanding pasture growth is important for relating to changes in land cover and therefore likely hydrologic and water quality responses.

6.2.2 Modelling Question

AussieGRASS is a modelling framework developed to provide information on the effects of rainfall deficits and climate variability on pasture growth and associated variables such as soil moisture, runoff, erosion and animal production. It is intended to provide continental scale information on the current status of forage cover for the whole of Australia. In addition the current state is compared to historical conditions to express current conditions as percentiles. The system also runs seasonal forecast of future conditions based on the SOI phase system.

6.2.3 Role

Running the modelling engine GRASP (Rickert et al 2000) on a daily timestep across a 5km by 5km grid, AussieGRASS is used to provide mapping products and property scale information on a continental scale and has been operational for 20 years. The information is provided through the Long Paddock website which has been providing climate and pasture information since 1995 and was the primary driver behind provision of SILO climate data on a gridded scale for the whole of Australia.

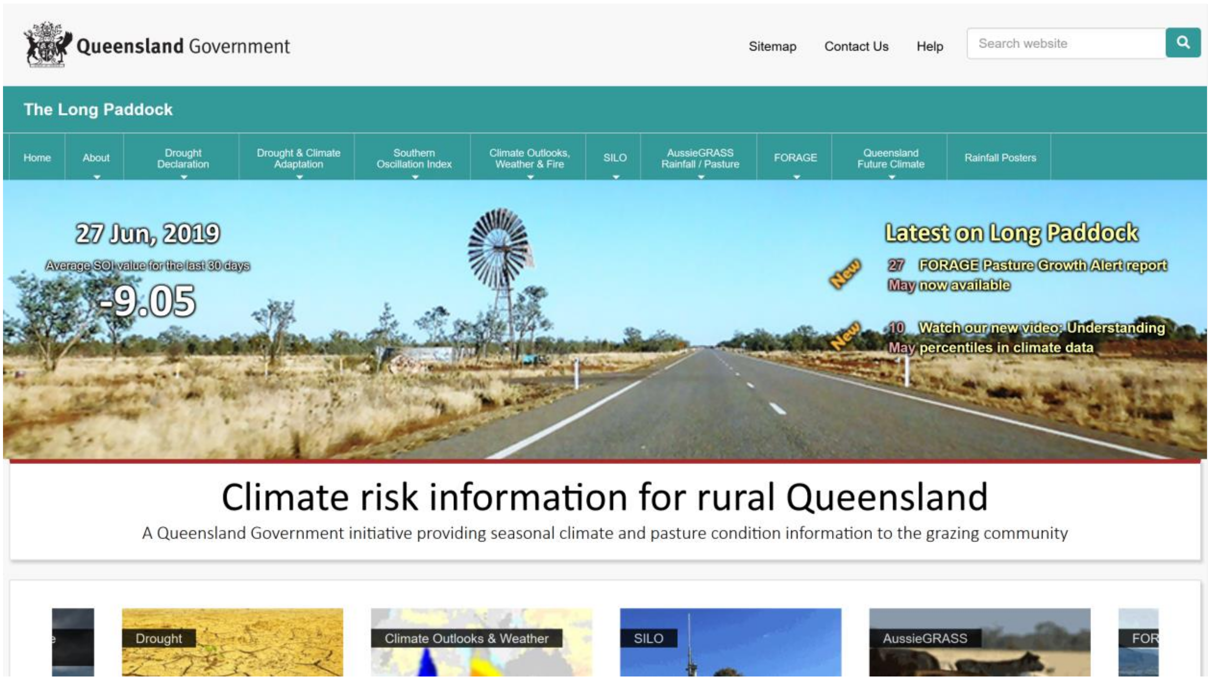


Figure 27 *The Long Paddock Website (featuring SILO and AussieGRASS)*

AussieGRASS uses the GRASP model spatially on a daily basis utilising the 5km x 5km gridded climate information and maps the results for the whole of Australia. The GRASP model is a one dimensional soil, water, pasture and livestock model that is represented conceptually as shown in Figure 28 below. We have highlighted in this diagram where key existing climate variability and future climate change may influence the model.

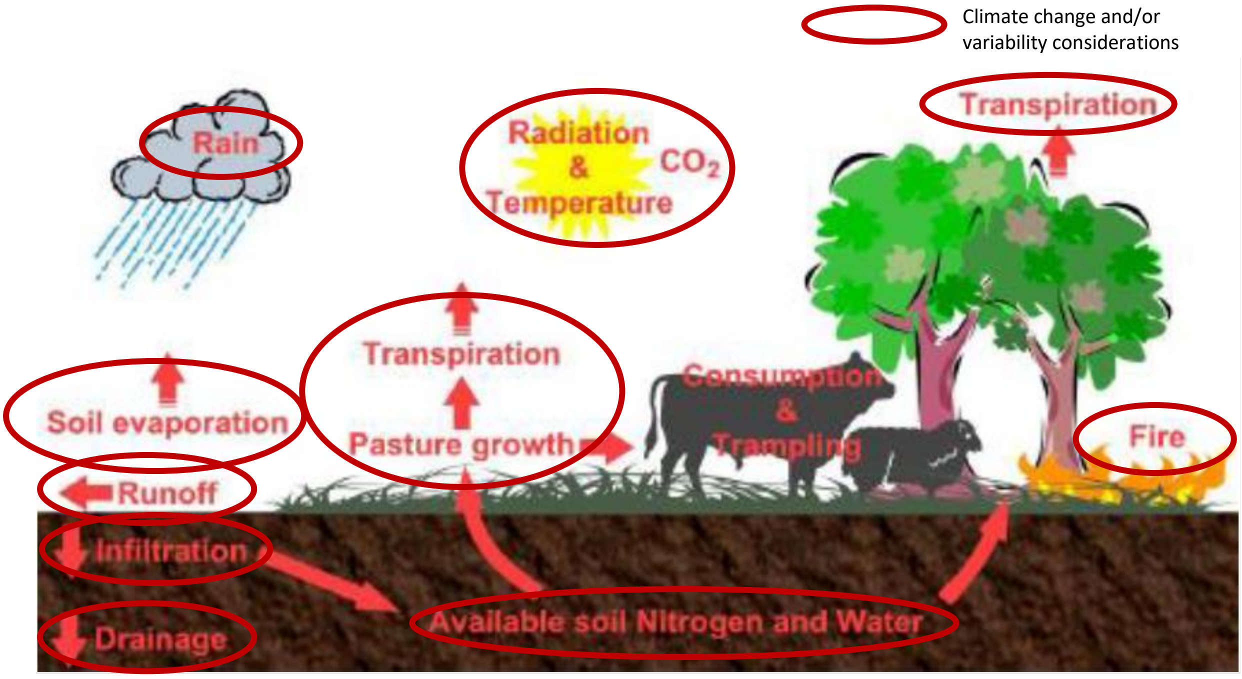


Figure 28 *GRASP model conceptualisation (from Carroll and Yu 2017)*

What is interesting in the above conceptual diagram is that climate change and climate variability may have an impact on nearly all components and processes indicated, with key forcing data such as rain, evaporation and transpiration, radiation, temperature and CO_2 all likely to require modifications for future climate or increased climate variability considerations, and the likely reactive processes such as infiltration, runoff, drainage, available soil water and nutrients, and fire needing to be also assessed as to how they may alter if considering future climate change. Consumption and trampling are not likely to be directly affected by climate change and climate variability as a process, but may respond through other feedback mechanisms (e.g. as a result of lower stock numbers).

6.2.4 Structure

AussieGRASS provides parameters to the GRASP model on a spatial basis from data around climate, soil attributes, tree cover and stock numbers and represents 185 discrete plant communities in the simulation. The combination of real time data around climate and remote sensing information provides outputs around rainfall percentiles, soil moisture, biomass and others that are then represented spatially or through individual reports (forage system often running point versions of the model) through the Long Paddock website (Stone et al. 2019). This is shown diagrammatically below.

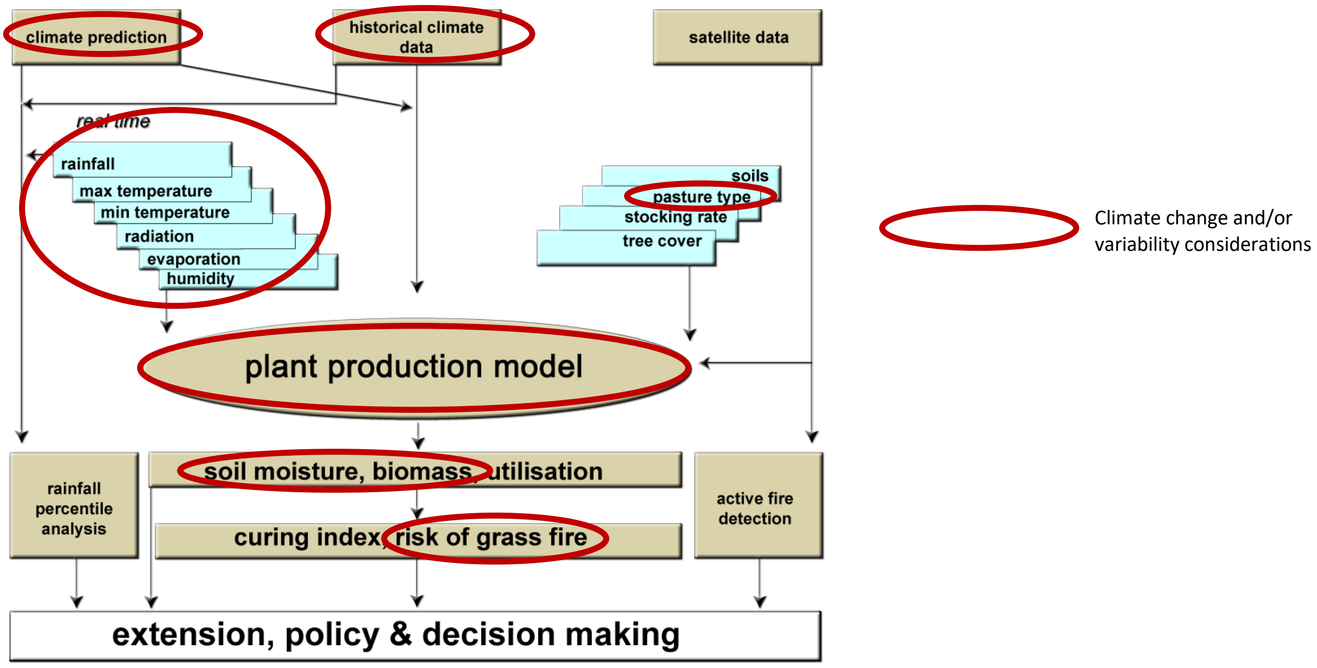


Figure 29 *AussieGRASS conceptual framework (from AussieGRASS Product Description)*

6.2.5 Inputs

6.2.5.1 Climate

The AussieGRASS model utilises the SILO gridded climate data for the following key parameters:

- Rainfall
- Temperature (max/min)
- Solar radiation
- Potential Evapotranspiration
- Humidity (vapour pressure)

As noted in the conceptual models above, many of these climate input variables may be influenced by climate change and variability. In the case of the climate inputs, new downscaled datasets of climate change provided through the Terrestrial Ecosystem Research Network (TERN), as derived by the Queensland Department of Environment and Science, may be able to be utilised either directly or with some minor pre-processing to supplement the existing SILO gridded data (note that the same team producing the downscaled datasets also produce the existing SILO data). We note there are some slight differences in parameters and also in grid resolution that may influence the direct application of that data set, but it would be worth further consideration. Discussions with AussieGRASS researchers also indicated a need to produce bias corrected SILO like climate grids at 5km from downscaled GCM outputs (note that bias correction has been done for Tmax, Tmin and rain, but not for vapour pressure, solar radiation or evapotranspiration. Some of this data is already available for modelling at the point scale from Long Paddock, but not at the gridded, continental scale.

Consideration – suitability of high-resolution downscaled products to inform future climate change assessment and the production of bias corrected SILO type climate grids. Palaeoclimate data sets may also be needed if the full range of variation is not included in the historical dataset.

In terms of historical climate, the existing SILO gridded dataset is derived from measured rainfall data from the late 1890s onward, so is a reflection of measured climate record variability and potential recent (last 10-20 year) climate changes, but would not account for the variability noted in longer term climate sequences derived through palaeoclimate assessments. The ability to utilise these longer records may be precluded because of the number of climate parameters needed in AussieGRASS which would require significant effort in reconstruction if longer sequences were to be utilised. It may be possible to reconstruct synthetic climate sequences reflecting the variability noted in some palaeoclimate assessments using existing climate records as proxies, but this would be considered a research project rather than necessarily adding value to existing AussieGRASS modelling questions. Some palaeoclimate research is currently being undertaken within the Queensland Government modelling teams, and this may provide further insights.

Consideration – ability to utilise palaeoclimate data for further drought impact assessment.

6.2.5.2 Other inputs

In addition to climate forcing data, the following land type attributes are used in the GRASP model engine that lies within AussieGRASS.

- Hydrology (predominant runoff type)
- Depth of pasture soil moisture zone
- Texture (available water range within the soil, 3 layers for pasture, 4 for trees)
- Texture (wilting point, maximum soil evaporation rate)
- Soil fertility (nutrient uptake rate)
- Pasture species
- Tree density
- Flooding (where available from Landsat)

Obviously, a range of these will also be influenced by existing climate variability or future climate change but the responses of these are less well understood. That being said, a number of papers have examined these issues (Hall et al 1998, McKeon et al 2009, Whish et al 2014) and it is obvious from these that the configuration of AussieGRASS and the underlying GRASP model are well suited to investigating climate variability and climate change assessments. It was noted in some of these articles that further work on the likely response of pasture species under the ranges of climate forcing characteristics needs to be further examined. ***Consideration – further research on the response of vegetative species under different climate forcing conditions is required both for predictive modelling and adaptation considerations.***

6.2.6 Results and Outputs

The primary outputs of AussieGRASS are to provide indications of pasture growth and a range of other variables (as absolute, historical and forecast) over the near term on a continental scale, as indicated in the figure below. Many other system components (e.g. Nitrogen in runoff, Methane fluxes soil moisture can be output for diagnostic or special purposes).

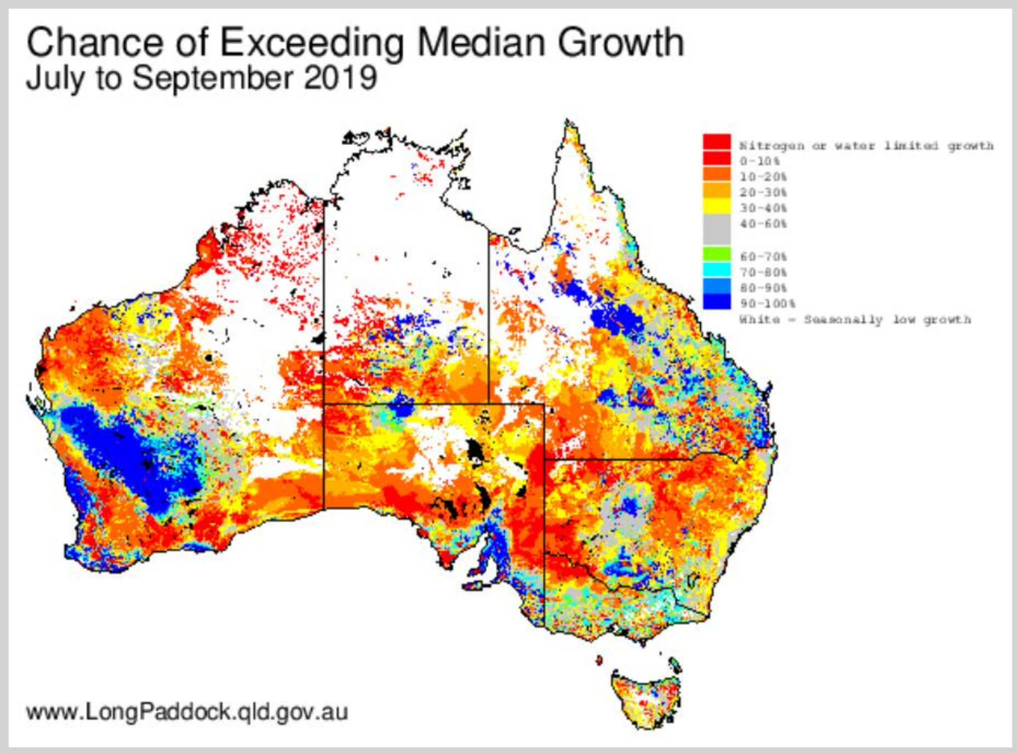


Figure 30 *AussieGRASS output (longpaddock.qld.gov.au)*

In addition to spatial outputs, point scale predictions on a property scale are also available on a cadastral parcel basis from a point-based version of the underlying GRASP model.

With regards to these typical outputs, it is unlikely that future climate change or existing climate variability will be a significant need, so further assessments of these in AussieGRASS are likely to be part of research or focus projects. Given the previous studies looking at long-term pasture changes under different climatic regimes, it is unlikely that significant further adaptation of AussieGRASS and the underlying GRASP model would be needed in order to better account for climate change or variability, though further revisions may be required if long-term future pasture growth assessments are required. It is also obvious that the model is well suited to these assessments given the number of studies looking at change in pasture response under climate change and it would be useful to evaluate whether better connections of the AussieGRASS outputs could be used in other hydrologic and biophysical models being used to understand climate change impacts on Queensland landscapes. ***Consideration – Using AussieGRASS outputs as forcing data for other hydrologic or biophysical models exploring climate change, especially where vegetative (grass and litter) cover changes are a primary consideration.***

A paddock to property scale version of the underlying GRASP model which powers AussieGRASS also exists in the FORAGE subsystem of Long Paddock enabling modelling to serve from continental to paddock scale applications. A prototype example from FORAGE is shown below where safe carrying capacity is estimated for the current climate (modelled) and for 2070. Estimates from other data sources and heuristics such as runoff, erosion, ground cover, and live weight gain could be additional outputs in the future for climate change scenarios.

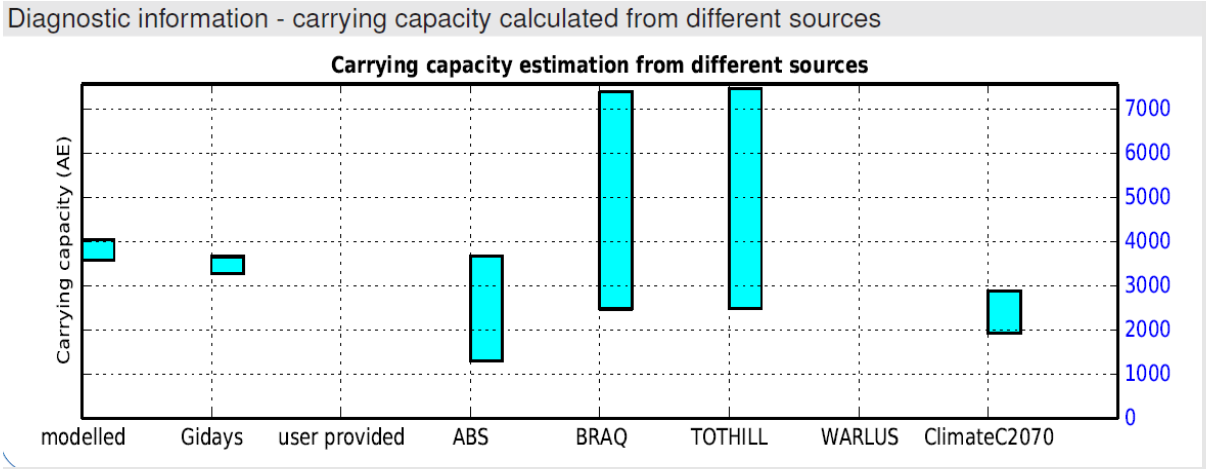
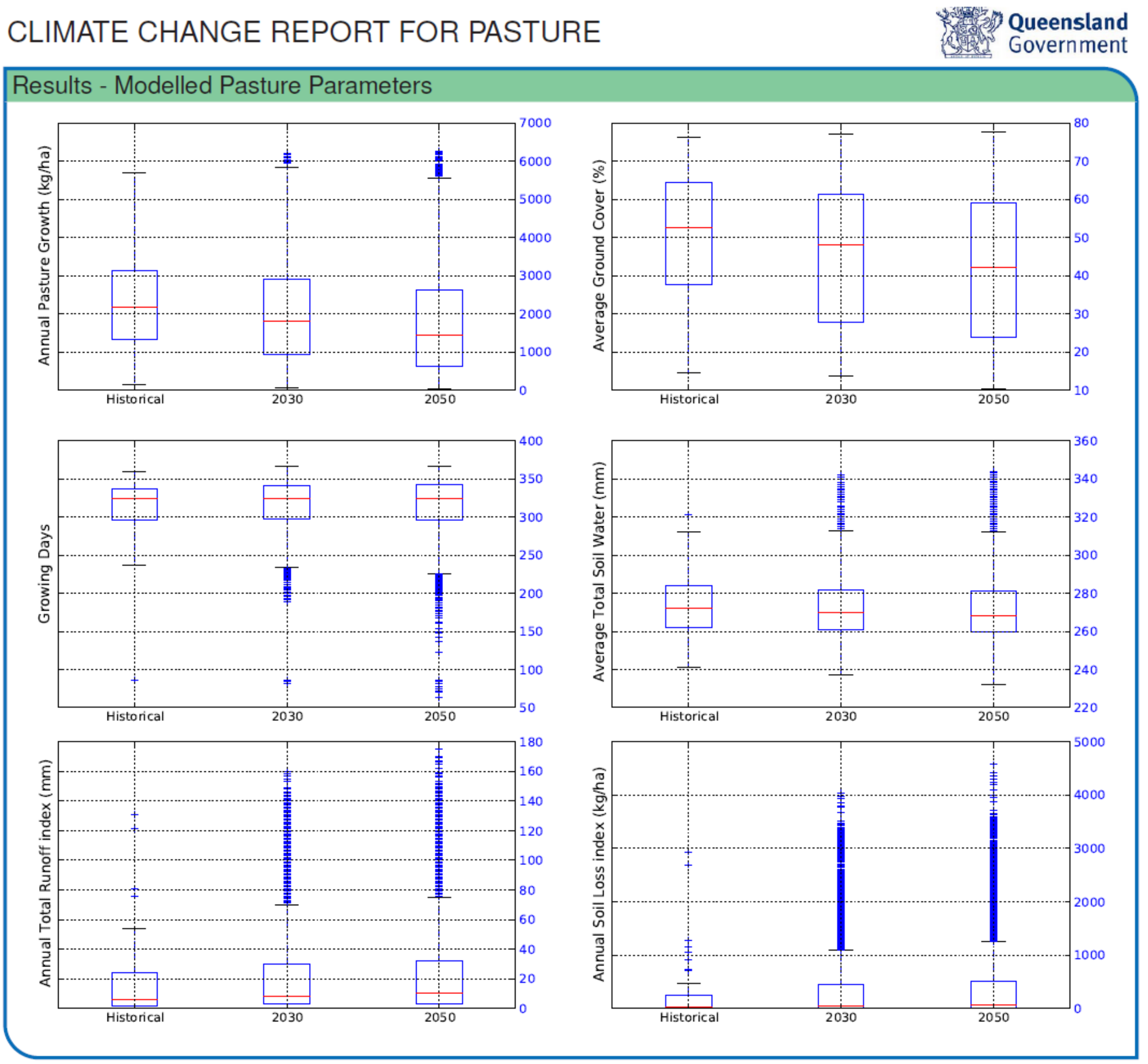


Figure 31. *Outputs from prototype FORAGE model for evaluating climate change impacts*

An older prototype has also been used to consider climate change, once again using change factor approach and not dynamically downscaled data (noting that no consideration of future changes in stock numbers or tree density, pasture type, fire were made). With dynamically down scaled data it would be possible run the 11 models *2RCPs as a continuous time series into the future so trend is not influenced by selection of particular decades. This is illustrated in the results below.



To account for climate change, these point-scale model parameters have been changed in regards to:

- transpiration rate /per unit green cover (representing decreases in stomatal density under higher CO_2)
- Radiation use efficiency
- Transpiration use efficiency
- Nitrogen dilution in grasses
- Frost effects (more severe under increased CO_2)
- Climate is modified in terms of changing sub daily rainfall intensity as a function of daily rainfall amount and daily temperature.

Climate change could therefore not only be implemented by changes in climate forcing inputs in these models but also via CO_2 response.

This highlights significant potential in AussieGRASS to better account for system behavioural responses to climate change, including the incorporation of temperature responses of grasses, modified on the basis of long term average temperature changes (e.g. prior 30 years) to account for natural selection and adaption of the complex species mixes that make up grass swards to higher temperatures. Given this potential***, further investment in AussieGRASS is likely to result in widescale improvements in representing climate change impacts on pasture cover and the inclusion of this would be also advantageous to other landscape models where pasture cover is a concern (e.g. Paddock to Reef modelling).***

6.2.7 Recommendations

From the above information, the following key recommendations are proposed:

1. *Target investment in the AussieGRASS model to improve representation of climate change impacts on pasture cover, the inclusion of which would be advantageous to other landscape models where pasture cover is a concern (e.g. Paddock to Reef modelling).*
2. *Examine the suitability of high-resolution downscaled products to inform future climate change assessments directly within AussieGRASS.*
3. *Evaluate the need and ability to utilise palaeoclimate data for further drought impact and likelihood assessments.*
4. *Undertake further research on the response of vegetative species under different climate forcing conditions. [This is consistent with other case studies where biophysical responses to future climate characteristics need further investigation].*
5. *Investigate the potential to use AussieGRASS outputs as forcing data for other hydrologic or biophysical models exploring climate change, especially where vegetative cover changes are a primary consideration.*

These recommendations have been incorporated within the overall recommendations listed in Section 7.5. Not all have been listed specifically, but have been incorporated into others where required.

6.2.8 References

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6.3 Case Study 3 – Water resource and hydro-ecological modelling in the Queensland Murray Darling Basin

6.3.1 Introduction

Management of Queensland's water resources aims to ensure that water allocation optimises the balance between economic, environmental, social and cultural outcomes. To guide the sustainable allocation of water and understand the associated threats to the environment from water development, rigorous science and modelling is a key input into the water planning process. The management of water resources within the Murray Darling Basin (MDB) catchments in Queensland also has implications for downstream water users and the environment. As such, water models need to evaluate the range of water uses (e.g. irrigation, stock and domestic supplies, town water supplies, environmental water etc.) and how these are equitably allocated across the relevant water basins they are simulating. The river basins within the Murray Darling Basin are shown in Figure 32.

Figure 32 *The Murray Darling Basin (www.mdba.gov.au accessed 2019)*

6.3.2 Modelling Question

The underlying modelling question for water resource modelling in the Queensland area of the MDB is to evaluate and account for water sources, water allocation and water use in the Paroo, Warrego, Moonie, Border Rivers and Condamine-Balonne basins.

6.3.3 Role

The roles of the MDB water resource models are to assist in evaluating the water balance across a river basin to inform the development of water plans, volumetric entitlements and licensing, scenario analysis and ongoing monitoring of water allocation. Measuring, modelling and estimating the different components in the water balance is a complex space as indicated in the figure below.

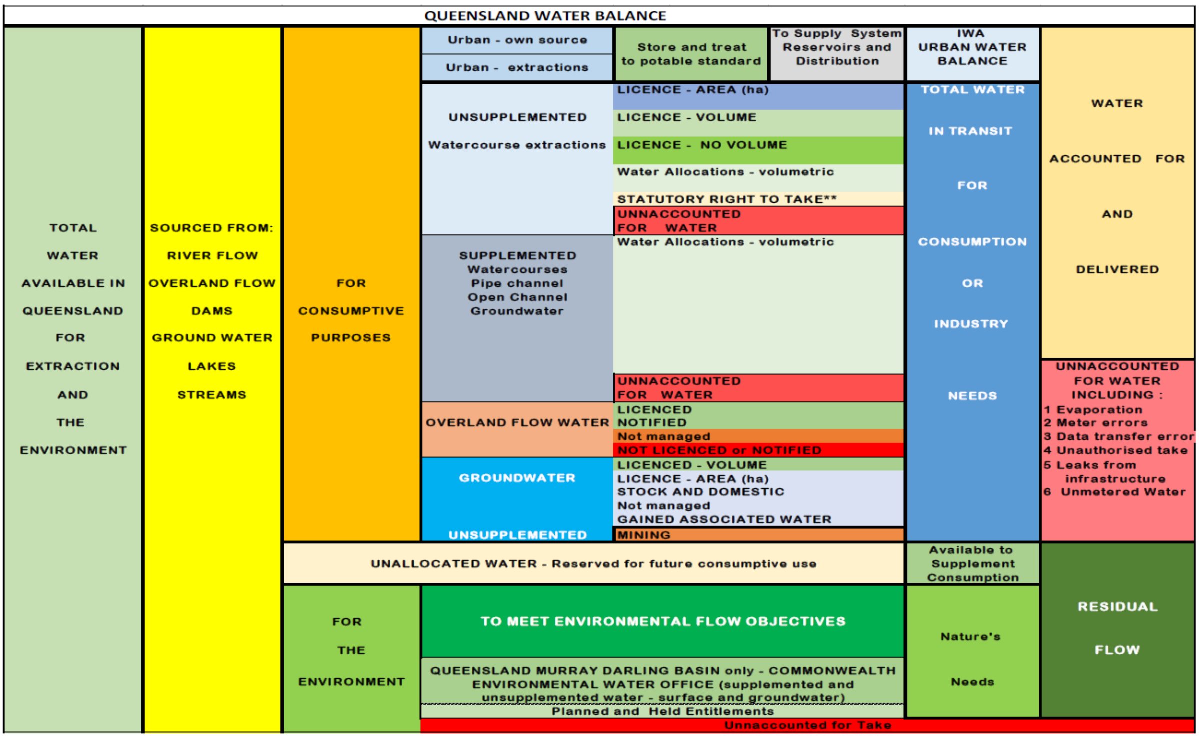

Figure 33 *The Queensland Water Balance (from Independent Audit of Queensland Non-Urban Water Measurement and Compliance Final Report)*

In the Murray Darling system in Queensland, water models are primarily used to quantify surface water and groundwater resources and how these resources are then used (e.g. through irrigation, town water supplies, stock and domestic uses and the environment), to ensure equitable allocation of these resources across a basin. They are run over long climatic time periods (>110 years) to provide long-term guidance on water supply and water uses while accounting for recorded climate variability.

6.3.4 Structure

Two modelling suites have been used in the Queensland part of the MDB, the Integrated Quantity and Quality Model (IQQM) and the Source model, with the latter model adopted as Australia's National Hydrologic Modelling Platform for water resource assessments. Source models have been developed for the Border Rivers and Moonie systems, with the IQQM model in use for the Paroo, Warrego and Nebine. A bespoke model has been created for the St George Irrigation Area as neither Source nor IQQM were able to properly account for water resource behaviour in that system.

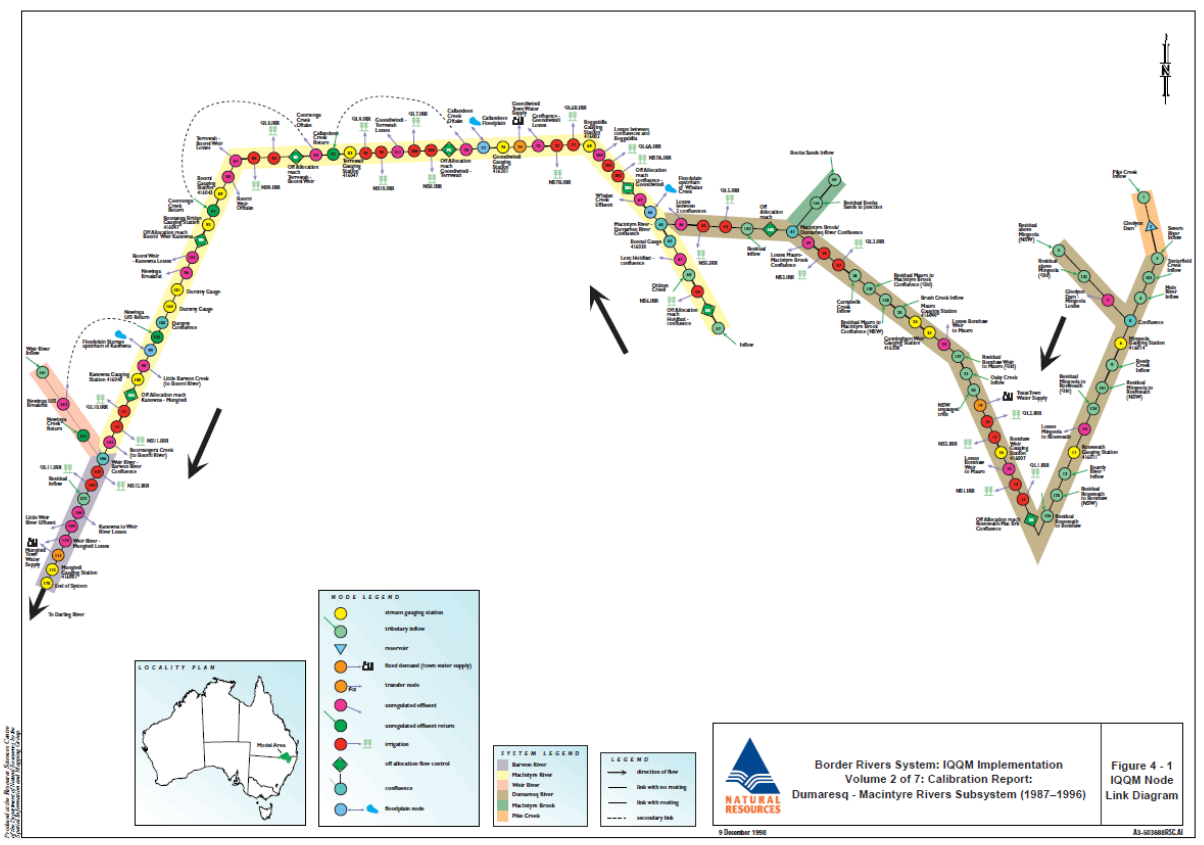

Figure 34 *IQQM model schematic (portion of Border Rivers system)*

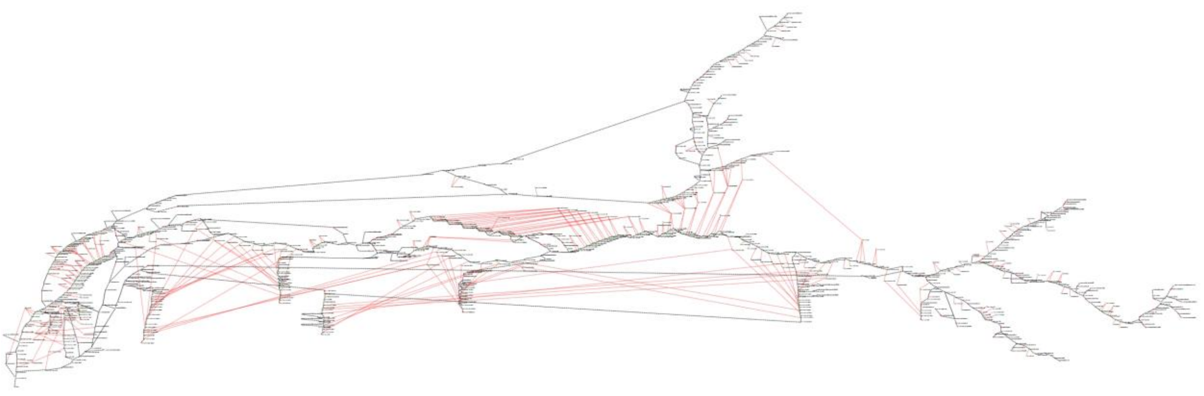

Figure 35 *Source model schematic (entire Border Rivers system)*

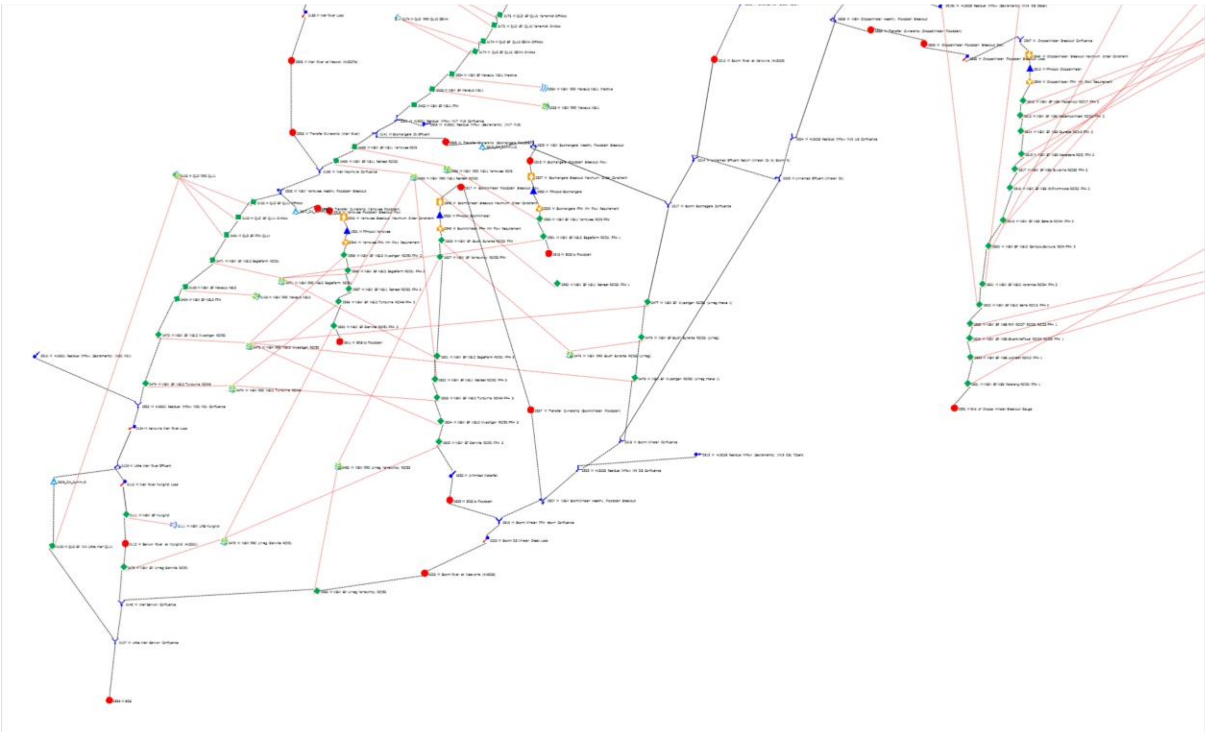

Figure 36. *Source model schematic (portion of the Border Rivers system)*

Both the IQQM and Source models are hydrologic "node-link" models and represent various components of the water system through assigning component models within nodes and links. Nodes are used to represent water diversions, water uses (including irrigation/crop models, stock and domestic demands, direct extractions etc.), wetlands, storages, weirs, accounting tools (e.g. minimum order constraints) and custom-built functions and timeseries. Links are used to represent transmission of water from one node to the next and nominally represent river reaches, such as those between flow gauges, or between different offtake points. Links can be set up to model groundwater/surface water interactions, transmission losses, time lags and flow routing (changes in flow rate moving through a reach).

The model structures are established to represent a series of scenarios, one of which features a "baseline" scenario (which in Queensland models represent users attempting to make full use of their water allocation) or a particular time period (e.g. the Cap scenario representing uses at the time of the Murray Darling Cap on water use in 1993/1994).

To determine runoff from some areas of the basin being represented, the Sacramento rainfall-runoff model is used. This supplement gauging station data in areas where either there are insufficient recorded gauges, or smaller parts of the system that may have unregulated runoff. Additionally, storage behaviour (water levels combined with releases) are used to provide derived inflow data. For baseline scenarios, a model is developed to represent the gauging station information from reach to reach, and account for differences between reaches according to water allocation and use, but also transmission and other losses as water moves from the top of a basin to the downstream outlet. The final model is therefore one which combines significant sections of recorded data, derived data from storage behaviour and rainfall-runoff modelling to best represent the scenario being modelled, after significant efforts in calibration and validation. When the models are used in climate change assessments, differences between "no climate change" and "climate change affected" Sacramento runoffs are used to modify the existing model-input flows. An illustration of the Sacramento model is shown in Fig 37 below.

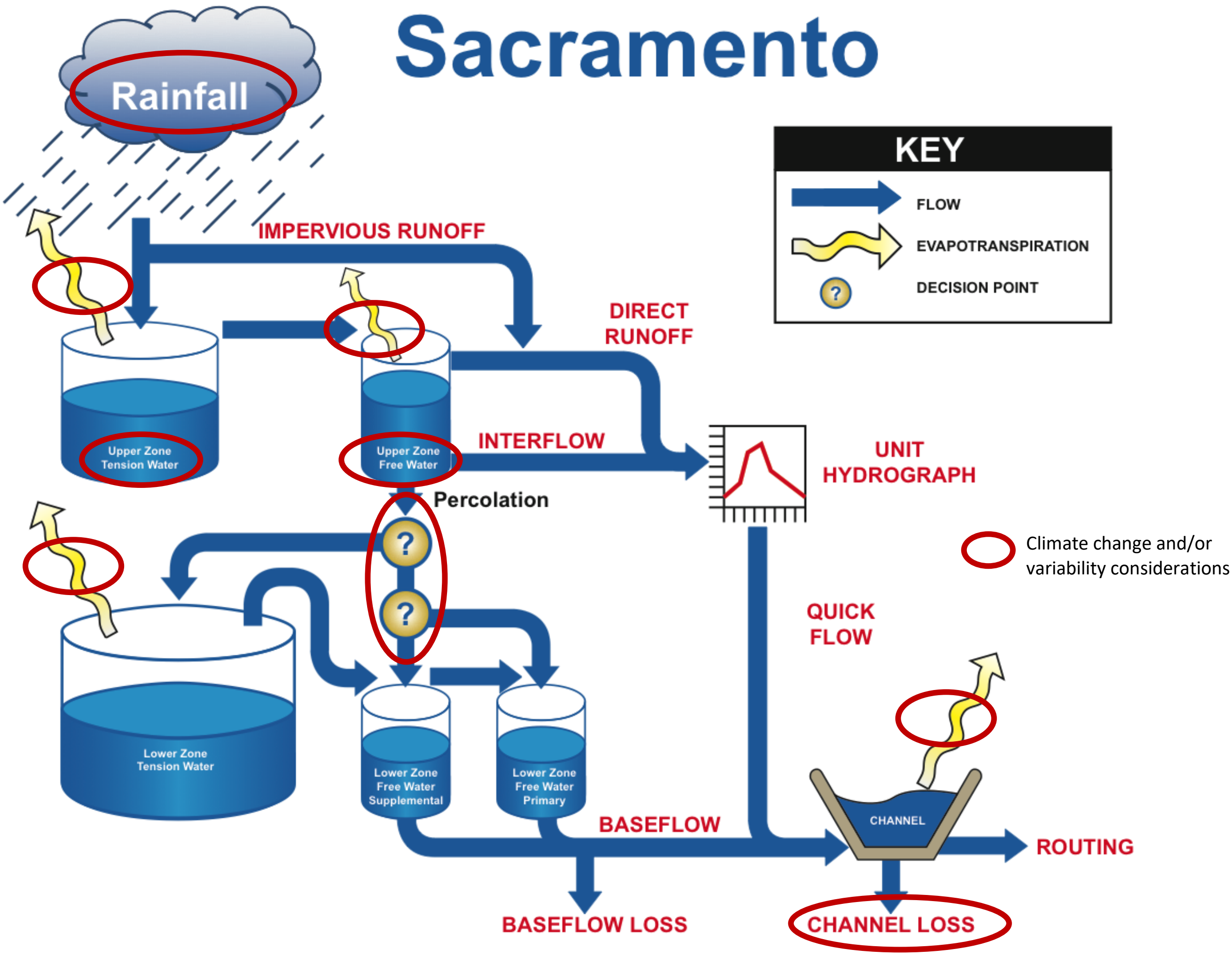

Figure 37. *Sacramento rainfall-runoff model used in MDB Water Resource models in Queensland*

6.3.5 Incorporation of Climate Variability and Climate Change in MDB Water Models

Between 114 and 123 years of climate data are used in the models with the 114-year period used to model the Baseline Diversion Limit and Sustainable Diversion Limit, and 123 years (from July 1890 to June 2013) used to model draft Water Plans (Bewsher 2019). The use of climate data over this period is consistent with the requirements of models to be accredited by the MDBA so variations of this climate sequence are not currently required for assessing existing water resource requirements. These models are established as, in effect, accounting tools to evaluate water availability and permitted water take across the Queensland sections of the Murray Darling Basin. They are therefore highly refined to simulate conditions as they currently exist or through scenarios that emulate different time periods such as the water resource conditions as at the time of the Murray Darling Cap.

To evaluate climate change, existing conditions, such as river flows, need to be altered to represent how they would occur in different climatic sequences, in addition to changing input data such as rainfall and evapotranspiration. A process for doing this has been developed by the Queensland Hydrology group in DES and is shown below.

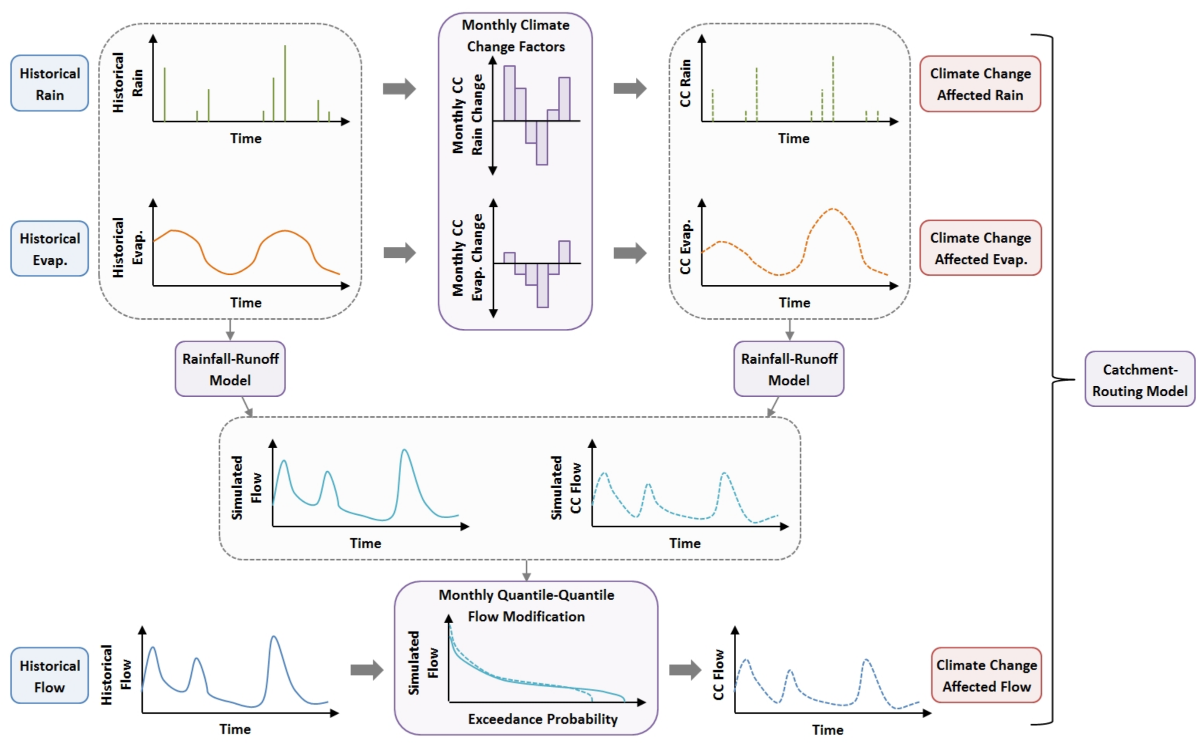

Figure 38. *Current process for accounting for climate change impacts on rainfall, evaporation and streamflow*

DES modify the historical data sets based on the projected changes in evaporation and rainfall for a particular emission scenario at a particular projection year. The process (shown in the figure above) is as follows:

- The catchment is broken into smaller subcatchments.
- For a particular projection year and emission scenario the monthly changes in evaporation and rainfall are extracted from each of the GCMs based on a 20 year period centred on the target project year. The shape of the subcatchment is used to “cut” the data from the grids.
- The monthly changes are applied to the historical evaporation and rainfall data for each subcatchment. Then rainfall-runoff programs are run for each subcatchment – both “no climate change” and “climate change affected” runs – to produce synthetic streamflow.
- The historical streamflow is modified using a quantile-quantile transformation of the “climate change affected” synthetic streamflow to the “no climate change” synthetic streamflow on a daily basis. Additional modifications are made when the particular GCM is wetter than the historical record and produces additional anomalous flow events.

This creates a set of climate-change-affected evaporation, rainfall and streamflow data for each GCM. Water resource simulation models are run with each set of data producing an ensemble of outputs. The final climate-change-affected simulation outputs are reported using the median and percentile statistics calculated of the ensemble. Doing this produces a “best estimate” (the median) and an “uncertainty range” (the percentiles).

Climate change projections are available for 2030, 2040, 2050, 2060, 2070, 2080 and 2090. The projections used for water planning assessments are dependent on the plan requirements.

The challenge with the above “delta-change” approach is that it assumes that the existing climate patterns are a suitable surrogate for representing change in precipitation and evaporation/evapotranspiration into the future. It does not account for changes in seasonality or periodicity (i.e. whether the time between events changes, or the timing of rainfall changes), nor is it able to accurately account for changes in rainfall intensity.

Consideration: Further work is needed to evaluate whether other climate sequences that may account for changes in climate patterns are required, including changes in frequency, intensity and duration of climate

indicators. This is a significant piece of work as it will need to assess whether this will provide better estimates than current approaches or is more useful to understand variability and extremes.

Improvements in incorporation of better representations of existing climate variability and improved representation of climate change will need to consider the following issues:

- 100+ years of data is a long data set and provides a reasonable baseline for water resources assessment and planning.
- Longer data sets (guided by palaeoclimate data) will provide an improved ability to characterise longer-term decadal variability (e.g. very long droughts or wet periods).
- Representation of future climate and extremes. Are the drier periods getting longer? Are the wetter periods getting wetter?
- Representation of the current baseline is difficult to define. For example, the past 40-years in Perth have been significantly drier than the past 100-years, and water resources management and planning in far south-west WA simply considers post-1975 as the baseline.

The challenge is then to understand whether the climate has shifted to a different baseline (see also "time of emergence" discussed in Section 3.1). There are therefore questions regarding how representative the existing historic climate record is of the "current baseline" and whether this needs to be re-evaluated. From the assessment of the palaeoclimate literature as presented in this report, it now recognised that the existing climate record is a poor indication of future climate variability. ***Consideration: An assessment of the robustness of the existing long-term climatic record in accounting for likely future climate variability in representing the current baseline is required.***

For longer term planning, beyond the life of most existing and proposed Water Plans, suitable representations of future climate under climate change are being considered as discussed above, however there is little information about how system behaviours may change under different climate sequences. In this case, system behaviours such as changes to irrigation requirements, may alter demands. From a water allocation and entitlements sense, changes in these system behaviours may not be required, as the modelling is to inform the way the reliability or availability of water to satisfy the entitlements may change, not on-farm decisions related to adapting to changing reliability or availability. For ecohydrological response though, system behaviour changes may need significant further consideration in order to evaluate whether particular components of the flow sequence (e.g. base flows, low flow, periods of no flow) change significantly. This will include how cropping systems (and therefore patterns of water use) may change (are the existing cropping systems suitable under an altered climate sequence), does the structure of water use alter significantly, such as the shift from rice to cotton in the southern MDB to improve water use efficiency, will the water availability and timing alter considerably and how may this affect existing water users? Ultimately, the consideration of how climate change may influence water availability, allocation and use has not been studied in depth within the basin and it was only in February 2019 that the MDBA CEO Phillip Glyde stated "The overwhelming scientific consensus is that climate change is currently affecting the Basin so more work is needed to inform future management strategies." This is not an isolated issue for Queensland only, it is a much larger, Basin wide series of studies required to examine the way future climate change will impact on all water use activities across the MDB. As such, a collaborative approach to modelling will be required to evaluate this. ***Consideration: The assessment of future climate change on water availability, allocation and use across the MDB will require a collaborative approach across all Basin states. Current guidance on approaches to consider system behavioural changes in the basin are not well resolved and a concerted effort to understand the range of system responses to future climate change is strongly needed. A coordinated approach, perhaps in the nature of a multi-jurisdictional collaborative network with contributions from Basin states, academia and industry is required to deal with the complexity of the social, environmental and economic systems and how they respond to climate extremes and climate change. Without a collaborative approach, ad hoc projects will continue to slowly build knowledge, but in an uncoordinated manner with duplication of effort and missed opportunities for co-developed approaches to shared problems likely to be common.***

6.3.6 Ecohydrologic modelling

Within the Queensland region of the MDB, work has been continuing using a risk-based approach to assessing environmental flow regimes and requirements (McGregor et al 2018). This approach uses a 6-step process based on the principles of Ecological Risk Assessment through ecohydrologic assessment. These steps are:

1. Identifying the ecological assets - indicators and representation of a broader set of ecological values of an area
2. Defining the ecohydrological rules – understanding the ecological asset's system requirements (associated with life history or process) and related to flow dependency (e.g. location, timing, frequency, magnitude, duration)
3. Defining the assessment end points – representing the environmental values of concern (e.g. a level of abundance, productivity etc.)
4. Defining consequence or "Thresholds of Concern" – these represent the frequency of flow-based events that are required to sustain an ecological assets, so if they are not achieved, it may lead to failure of that asset.
5. Defining likelihood through ecological modelling – based on the outputs of the hydrologic water resource models outlined above, determining the flow related opportunities from the current or proposed water resource operations or scenario.
6. Assessment of risk – this combines the assessment of likelihood in Step 5 and consequence in Step 4 and evaluating this across spatial and temporal scales to understand the patterns of risk across a catchment.

This process is reliant on good conceptual understanding of the flow dependencies of ecological assets, but also detailed process knowledge. Monitoring, local research, literature and expert elicitation are all used to inform this. A visualisation of the process is shown below, in addition to areas where future climate change or existing climate variability may have an influence.

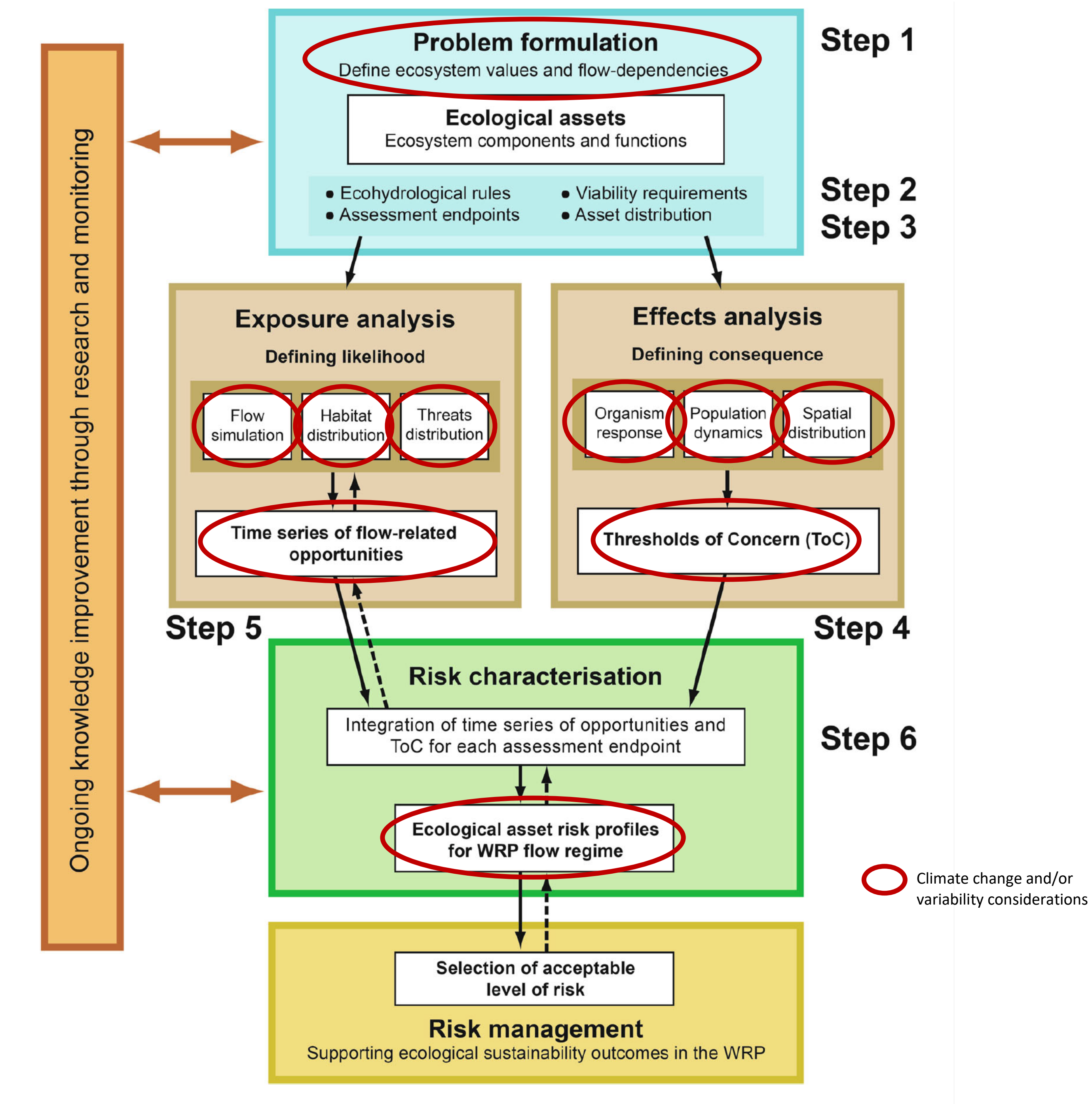

Figure 39. *Process for ecohydrological risk assessment (McGregor et al 2018)*

As can be seen from this diagram, the potential for existing climate variability and future climate change to impact on this process is likely to occur at many points throughout it, including determining whether accounting for these is actually required in the initial problem formulation.

Ultimately, the incorporation of improved understanding of existing climate variability and future climate change will be reliant on how well these are incorporated into the hydrologic models, but also how the aspects of climate change that are not directly water related, such as increased overall temperatures, increased frequency of extreme heat events, changes in wilting points, vegetation cover or types, may impact upon the ecological assets of interest also need to be evaluated. Reviewing recent literature suggests that while there are some papers on evaluating the impacts of prolonged recent drought events, there are few specific papers examining the longer-term ecohydrologic impacts of climate change at the same scales as current ecohydrological assessments. This is obviously related to uncertainties in which climate trajectory is likely to be most dominant, but it may be that existing research on system responses under surrogates for climate change (e.g. drought conditions, extreme heat events etc.) may be applicable. Still, it is obvious that further work is needed in this area. ***Consideration – Further research into ecohydrologic responses under climate change is needed. Current approaches where altered hydrology is simulated in river system models may be a useful starting point, but further work on understanding system behavioural responses is required, especially those around specific hydrological and/or ecological tipping points.***

6.3.7 Recommendations

From the above information, the following key recommendations are proposed:

1. *Assess the robustness of the existing long-term climatic record (including the suitability of estimates based on palaeoclimate research) in accounting for likely future climate variability over the life of the Queensland Government water plans.*
2. *Develop projections of climate change metrics that influence key hydrologic and water metrics and adapt existing landscape models to improve assessment of climate change risk on water availability, water allocation and water use to underpin robust and connected Basin-wide hydrological models for scenario modelling.*
3. *Scope mechanisms for establishing a coordinated, multi-jurisdictional collaborative network to research interactions between social, environmental and economic systems, climate extremes and climate change supported by contributions from Basin states, academia and industry.*
4. *Undertake targeted research and detailed modelling of impact and adaptation options and scenarios, building on past research e.g. plausible climate change impact on runoff in Queensland catchments.*
5. *Scope the need for other climate sequences to account for changed climate patterns, including changes in frequency, intensity and duration of climate indicators. [This is a significant piece of work as it will need to assess whether this will provide better estimates than current approaches or is more useful to understand variability and extremes].*
6. *Undertake further research into ecohydrologic responses under climate change to improve understanding of system behavioural responses in addition to changes in hydrology.*
7. *Investigate how to best represent and model social, economic and ecological tipping points related to climate extremes in hydrological models.*

6.3.8 References

Bewsher Consulting, (2019). Independent Review of Generation 2 Hydrological Models for: Border Rivers, Condamine-Balonne and Moonie Valleys, completed for Queensland Hydrology, Department of Environment and Science, Queensland.

Mcgregor, G, Marshall, J, Lobegeiger, J, Holloway, D, Menke, N., Coysh, J, (2018). A Risk-Based Ecohydrological Approach to Assessing Environmental Flow Regimes. Environ Manage 61, 358–374.

6.4 Case Study 4 – South East Queensland Water Supply Assessments

Note - this case study isn't a comprehensive review of all Seqwater activities in relation to climate change and water modelling. Please contact Seqwater for up to date information

The supply of raw water for drinking water supply is critical to the sustainability of the South East Queensland (SEQ). The region experienced a period of water scarcity during the Millennium Drought where the main storage reservoir at Wivenhoe Dam fell below 15%. In addition, the region has experienced significant flood events where extreme turbidity caused water treatment plants to fail for a significant period, threatening continuity of drinking water supply to the region.

Modelling of the yields of the raw water system and the delivery network, including water demands, is an ongoing process within Seqwater and current approaches rely heavily on the existing water resource models for the region developed by Queensland Hydrology. The water supply system in SEQ has been developed over more than 100 years and recent investments have focused on building resilience to climate extremes such as prolonged droughts and extreme runoff events. A "water grid" has been created which provides a unique ability to move water around the water supply system to deal with short-term issues, but also has some capacity constraints that, without augmentation, may limit the ability to deal with longer term climate impacts. The water grid is shown in Figure 40.

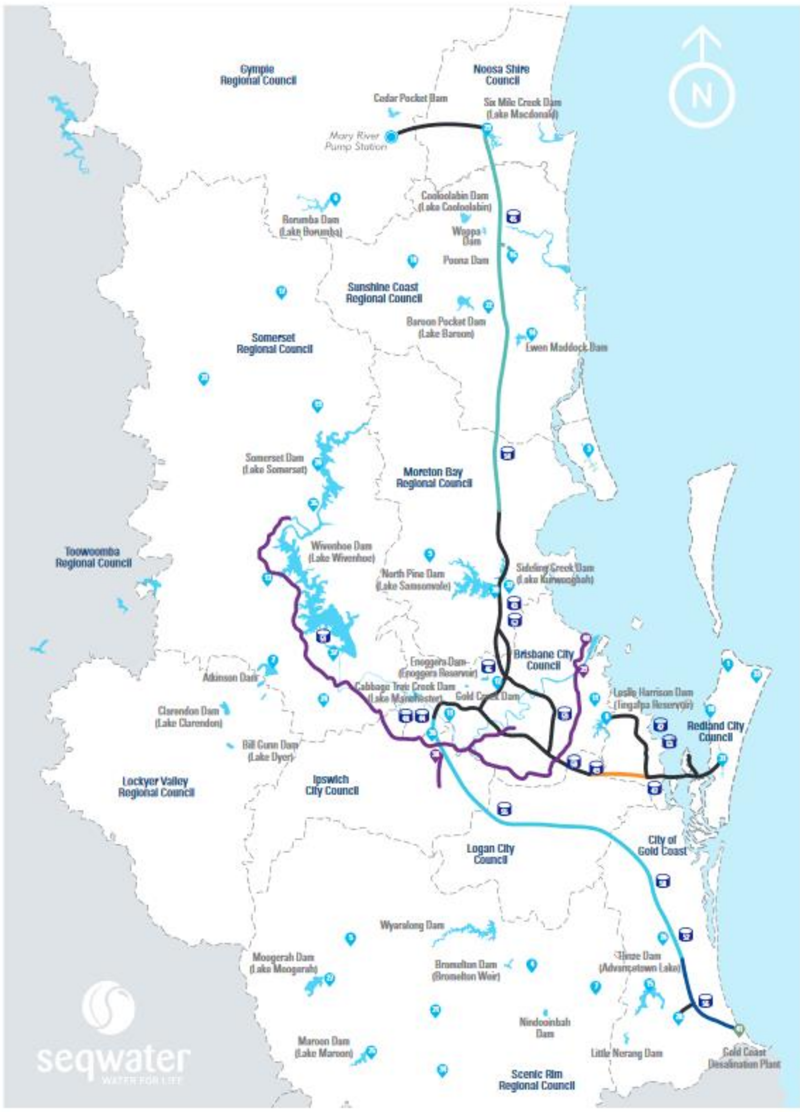

Figure 40. *The SEQ Water Grid (www.seqwater.com.au)*

As noted in the previous case study, understanding water supply availability is dependent on the evaluation of catchment yields and climate resilient water sources (e.g. desalination) in providing sufficient high quality raw water to allow the achievement of levels of service (LOS) that Seqwater have adopted in consultation with its customers. To understand how these yields may change and impact on the LOS, modelling is conducted which links the outputs of water resource models such as those noted in the previous case study, with a WATHNET water simulation model (Kuczera, 1997). WATHNET is a generalised simulation model that is able to simulate the operation of the water supply system using information about the current state of the system at each model timestep. To determine water availability, the model determines water allocation for a given streamflow and system demand in accordance with the following hierarchy:

a) Satisfy the demands at all demand zones
b) Satisfy all the instream flow requirements
c) Ensure that all reservoirs are at target volumes at the end of a season
d) Minimise delivery costs, and
e) Avoid unnecessary spills from the system.

This SEQ specific model is called the SEQ Regional Water Balance Model and assessment of water supply system yields using multiple stochastic climate replicates (using random variations built from existing climate sequences that mimic the same patterns and variability but may be scaled according to particular climate factors). A summary of the modelling tools used by Seqwater is shown below, in addition to where future climate change may impact on these elements.

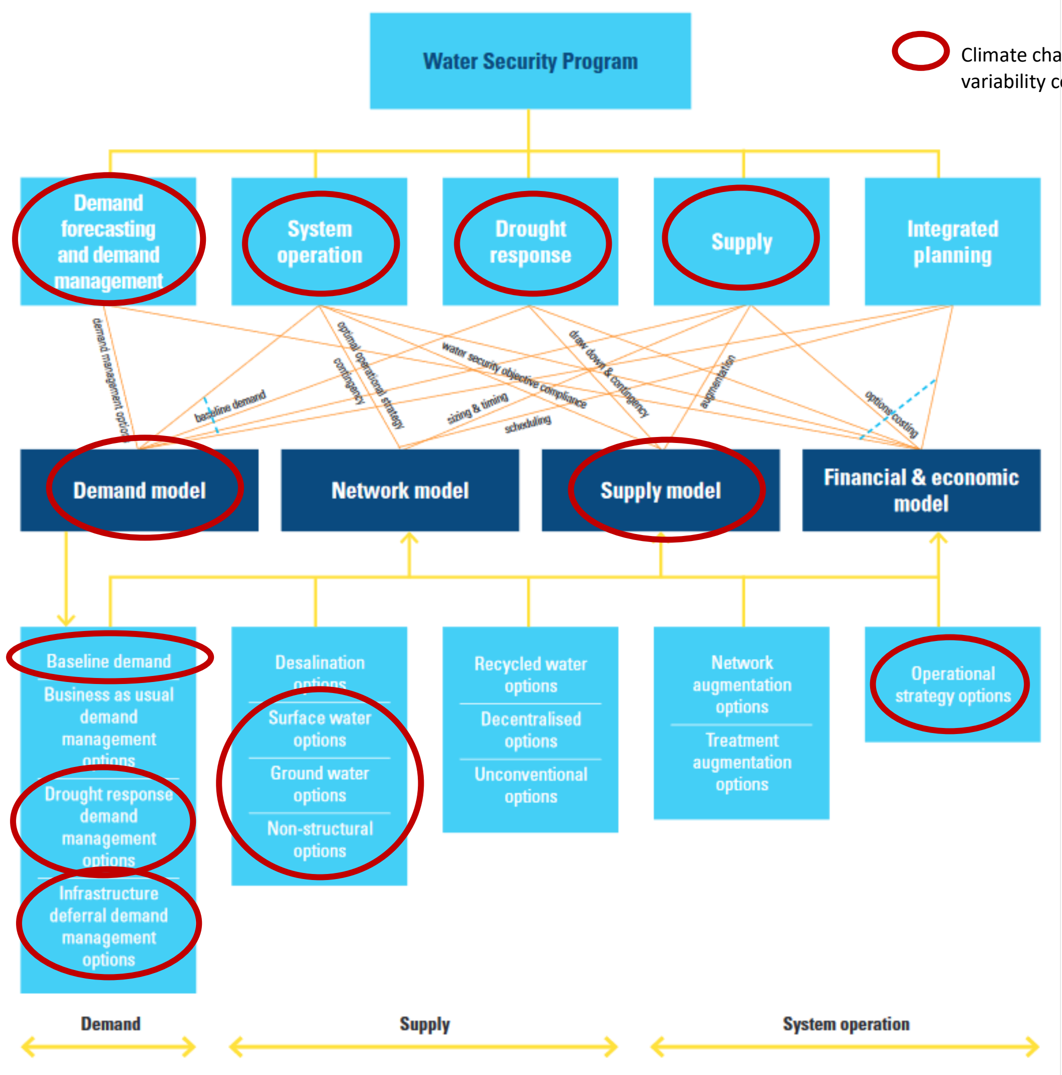

Figure 41. *Modelling frameworks used by Seqwater (Water for Life 2017)*

Hamilton and Burford (2019) have been developing a research plan for Seqwater focusing on climate change impacts on catchments and landscapes and how this may impact on future research and modelling requirements for Seqwater. They note that there has been information developed on managing water supplies associated with extreme events such as flooding and prolonged drought, but there are a number of gaps in assessing climate change impacts in the current SEQ water supply system modelling. These gaps include:

- The use of multiple years to generate stochastic replicates does not adequately address climate change and may inflate the level of confidence in assessments of how the current system is able to achieve LOS. (from discussions with DES Hydrology modellers, climate change affected stochastic datasets have been made available to Seqwater and may have subsequently been included in grid modelling)
- The modelling doesn't account for how water quality impacts (e.g. increased frequency of high turbidity events, increased cyanobacterial blooms) may increase the potential for parts of the water grid to be offline.
- It doesn't consider synergistic effects of climate change such as both increased evaporation, reduced rainfall and increased air temperature interacting to limit system yield while also increasing demand, though some initial assessments have been completed in other models (Gibbes et al 2014)

Consideration: Current approaches used to estimate climate variability impacts on the water supply system appear to be based on stochastic generation of climate replicates with existing recorded climate data. From the findings in this report, an assessment of the appropriateness of that variability with that being estimated by palaeoclimate studies is needed as it is likely that the stochastic methods are not representing the full range of variability possible.

Consideration: System behavioural responses are not being adequately accounted for in current Queensland water modelling (i.e. not just in this case study). Further research and knowledge are needed to improve our understanding of how these may impact water modelling efforts, such as responses in water quality, biogeochemistry and landscape scale processes.

Consideration: Synergistic effects of future climate change are currently not being fully evaluated and this, combined with system behavioural responses, may yield far greater variability in water model outputs than are currently being predicted.

As noted in previous sections in this report, they also note that the issue of hydrologic non-stationarity may be prevalent but current work indicates that there is no fundamental shift indicated in SEQ rainfall-runoff relationships as yet, but given the wealth of recorded flow gauging data, examination of long-term trends in runoff would be beneficial, in addition to the relationships of surface and groundwater contributions to stream baseflows. ***Consideration: Undertake assessment of long-term hydrologic records to evaluate likely climate changes over time to assess the impacts of hydrologic non-stationarity.***

They note also that the changes in evaporation in future climate are likely to be the most significant impact on water supply system yield, and as yet only a limited assessment of the impacts of evaporation ranges and methods of deriving future evaporation have been completed. ***Consideration: Evaluate the impacts of changes in evaporation as part of future climate change on reservoirs and subsequent impacts on system yields.***

The report also notes that future climate change may impact on biogeochemical responses of the landscape, including increased soil erosion from increased rainfall intensity, larger build up and wash off of organic matter and increased frequency of bushfires. This relates to understanding the system behavioural responses under alternative climate sequences and therefore understanding not only the impacts on hydrology, but processes that may be related to them such as changes in vegetation, land cover, erosion and organic matter, with subsequent related impacts on in-stream and in-reservoir water quality.

This case study has been informed by the work completed by Griffith University on behalf of Seqwater. Discussions with researchers and Queensland Hydrology staff were also very helpful in drafting this document.

6.4.1 Recommendations

From the above information, the following key recommendations are proposed:

1. *Evaluate the approach of stochastic generation of climate replicates with existing recorded climate data against that being estimated by palaeoclimate studies.*
2. *Research and apply a systems approach to the impact of climate change on Queensland water modelling e.g. responses in water quality, biogeochemistry and landscape scale processes.*
3. *Research the synergistic effects of future climate change on the variability of water model outputs.*
4. *Assess the long-term hydrologic records to evaluate likely climate changes over time to understand the impacts of hydrologic non-stationarity.*
5. *Evaluate the impacts of changes in evaporation as part of future climate change on reservoirs and subsequent impacts on system yields.*

6.4.2 References

Carroll C, Yu B, (2018), The QWMN Water Model Catalogue, prepared for the Department of Environment and Science by the Australian Rivers Institute, Griffith University, Queensland.

Hamilton DP, Burford MA, (2019). Climate and Catchments Research Plan, ARI Report No. 2009/006 to Seqwater. Australian Rivers Institute, Griffith University, Queensland.

Kuczera, G, (1997), WATHNET-Generalized water supply headworks simulation using network linear programming, version 3, software, School of Engineering, University of Newcastle, Newcastle, New South Wales, Australia

Seqwater (2017), Water for life - South East Queensland's Water Security Program 2016-2046 – Version 2, accessed at https://www.seqwater.com.au, August 2019.

7 Prioritising investment

When it came to identifying investment opportunities, it was found that many of the recommended actions would result in improvements and benefits under several of the themes and focus areas, and that some actions in combination would be considerably more beneficial than individually. For example, (A) guidelines combined with (B) training, would be more beneficial than either A or B being undertaken in isolation. This would lead to building capability, bridging the gap from climate science to water modelling to decision making, and improving the uptake (and effective use) of available datasets. In developing these priorities, we considered the gaps and responses in addressing different elements of the modelling pipeline, as highlighted in the figure below.

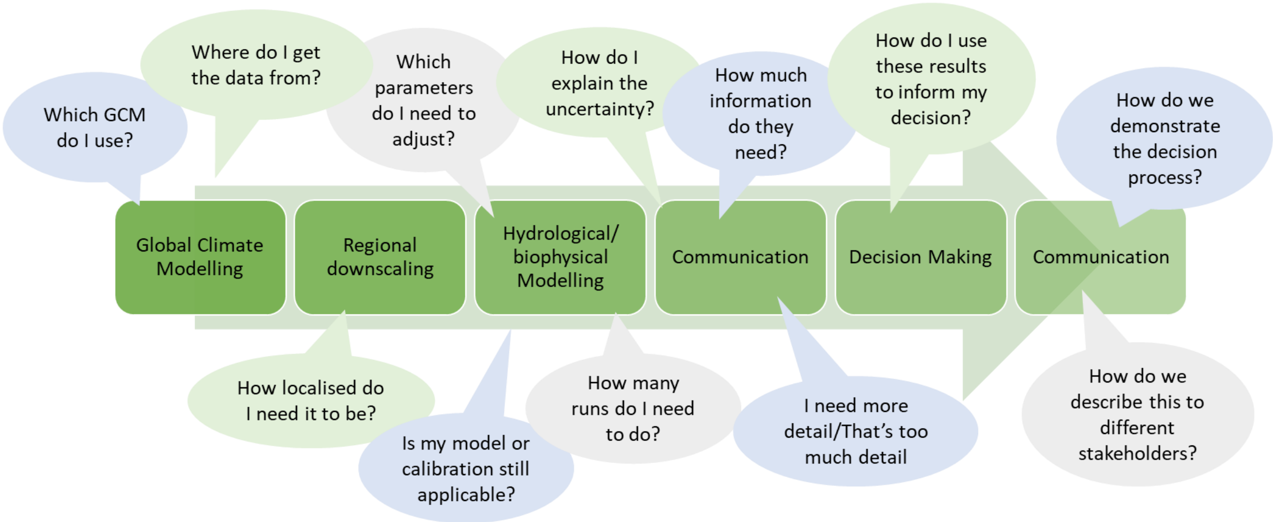

Figure 42 *Climate change water modelling pipeline and gaps*

7.1 Strengthening climate science knowledge and data

Water models can help shift from a reactive to proactive approach to natural resource management. Ensuring that models best represent current and future conditions and pressures (climate, land use, infrastructure, system operation, biophysical processes) relies on the availability and accessibility of appropriate, substantiated and relevant data, software, hardware, resourcing and capability. The Department of Environment and Science's Climate Change and Sustainable Futures group is leading the development of high-resolution downscaled climate projection data and information on how it can and should be used in a variety of contexts, accessible via the Queensland Future Climate Dashboard. Concurrently, the Earth Systems Climate Change Hub is leading discussions and coordination to produce the next generation climate projections for Australia after the release of IPCC AR6, and the Bureau of Meteorology will soon release national hydrological projections.

7.2 Improving the ability of water models to incorporate climate science

From the case studies in the previous section, there are some broad needs around how models could be improved with the advances in climate science covered in this report. These include understanding how existing data sets can best be incorporated into the models, improved understanding of process responses to alternative climate sequences, collaboration in how best to adapt models to incorporate climate change and variability, especially at large, multi-jurisdictional scales, and consideration of how the modelling questions need to be considered in evaluating existing climate variability and future climate change. We have summarised these into the recommendations outlined below, but also consider there is a broader research need to explore these issues in the level of detail needed to improve knowledge and understanding.

7.3 Bridging the gap from climate science to decision-making

Until very recently, there was no legislative imperative for climate change to be considered in water management. Following amendments to the Queensland Water Act in 2018, water plan preparation must now explicitly consider the water-related climate change effects on water availability, water use practices and the risk to land or water resources arising from use of water on land. In addition to ensuring water plans are adaptive to prevailing climate conditions, this approach helps promotes community awareness of the implications of climate change on water resources. Climate change considerations have already been included in twelve statutory Minister's five yearly performance assessment reports for water plans in 2018/19 with the remaining reports to be prepared over time. The reality of changing frequency, duration and intensity of extreme climate events such as flood, drought, bushfire, cyclones and heat waves are perhaps the primary driver for improving the ability to understand water-related systems under future climate conditions. For better informed and more consistent risk-based decision making, the opportunity to formalise drivers and standards for the treatment of climate change is strongly supported.

The benefits of water modelling can only be realised when the information produced is used effectively to support decision making. This relies on the effective communication of results from those undertaking the modelling, the ability of decision makers to understand this information, and the communication skills and methods to share the outcomes, and related uncertainty, with the broader stakeholders, particularly the communities that are directly impacted by such decisions. There is opportunity to improve our ability, and consistency, in communicating modelling outcomes, and creating communication materials which account for the background knowledge and information needs of different audiences.

Given the levels of uncertainty and changes in risk, consideration needs to be given to supporting improved decision-making processes. The information provided in Appendix A would support this.

7.4 Building Queensland's capacity and capability

While there is strong general awareness of the increasing need to consider climate change in planning and decision making with regard to Queensland's water-based systems, the ability of individuals and groups to obtain and apply existing climate science effectively, and understand and communicate results, uncertainty and trends remains somewhat limited. There is an opportunity to focus the existing knowledge, experience and commitment through targeted training, to more effectively use existing climate science, data products and modelling solutions. There is scope and opportunity for alignment and sharing of course content across state and local government training packages that are currently in development. There are potential constraints that will also need to be considered, with regard to human resource capacity, and supporting computer processing power, and data management systems, in addition to communication methods and processes that better translate improved predictions to a wide range of audiences.

7.5 Recommendations

The outcomes of this review, based on the 'multiple lines of evidence' approach, have been used to form a Strategic Investment Portfolio for consideration by a range of actors including the QWMN, Queensland Government departments, and other interested parties. The Strategic Investment Portfolio is designed to address critical gaps over a five-year period, including short, medium and long-term outcomes.

One of the main themes emerging from this review is that there is strong willingness and commitment to improve treatment of climate variability and change in water modelling and subsequent decision making, but that there is a lack of clarity or shared visions for how to best make this happen.

As such, the primary objective of the Strategic Investment Portfolio is to:

Increase Queensland's ability to understand the impact of climate variability and change on water-related systems, to increase economic, social, cultural and environmental resilience

The five key outcomes which will contribute to achieving this objective are:

Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate variability and change

Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland

Outcome 3: Address climate science and water modelling gaps through targeted research initiatives

Outcome 4: Empower individuals and collectives, and facilitate collaboration

Outcome 5: Develop training, communication and guidance materials to support Outcomes 1-4

The recommended short-term (next 12 months), medium-term (2-3-years) and long-term (3-5 years) investment priorities are summarised in Table 8. This table includes the *opportunity* for how this action will respond to the gaps identified in this review, as well as the *lead agency*, primary *audience* benefit from the recommended action. An indication of budget is also provided, as well as which of the strategic outcomes the action is designed to target.

The intent is to list out all actions/recommendations identified in this report, but they have not been ranked or sorted in this table as these choices are relatively arbitrary and may change according to issues and priorities at any time. Within Appendix B, a condensed list of actions is presented ranked in order by priority, impact and then budget, however these choices are based on those of the author and may change if viewed under different contexts. They are therefore presented for information only.

Table 8. *Recommended actions for the Strategic Investment Portfolio to 'increase Queensland's ability to understand the impact of climate variability and change on water-related systems, to increase economic, social and ecological resilience'*

Green highlight with ✓ indicates which outcome/s the recommendation addresses

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate change	Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland	Outcome 3: Address climate science and water modelling gaps through targeted research initiatives	Outcome 4: Empower individuals and collectives, and facilitate collaboration	Outcome 5: Develop communication and guidance materials to support outcomes 1-4
Short-term (within next 12 months)	M	Knowledge, capacity	A.1 Develop an online climate risk assessment framework and guidelines with corresponding approaches for quantifying response to climate variability and change.	Building on previous risk management matrix, provide recommended approaches for various levels of vulnerability to climate drivers. Identify and enhance links to Queensland based models and supporting information.	Led by DES with potential application to the Queensland water sector (hosted on Long Paddock website)	Policy makers, project planners, modellers	H	$$	✓	✓		✓	✓
	H	Data	A.2. Continue to support downscaling work by DES. Finalise and document peer review of climate projection data for Queensland	Provide independent assurance that QG endorsed product is fit for purpose	Independent review sponsored by DES and DNRME	DES climate change staff.	M	$	✓	✓	✓		
	M	Capacity, capability	A.3 Conduct awareness training of climate variability and climate change implications for modelling, policy and decision making in collaboration with Climate Change and Sustainable Futures group	Responding to need to increase capability and capacity of individuals and organisations.	Coordinated by DES and DNRME	Policy makers, project planners, modellers	M	Self-funded or delivered through existing frameworks (e.g. EEP)	✓			✓	✓

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate change	Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland	Outcome 3: Address climate science and water modelling gaps through targeted research initiatives	Outcome 4: Empower individuals and collectives, and facilitate collaboration	Outcome 5: Develop communication and guidance materials to support outcomes 1-4
	M	Capacity, capability	A.4 Create opportunity for forums and networking for practitioners e.g. through Community of Practice for climate change and climate variability in water modelling	Provide collaboration opportunities for practitioners to discuss approaches, issues and advances.	QWMN through EEP	Scientists, modellers, practitioners	H	Part of existing EEP	✓	✓	✓	✓	
	H	Data	A.5. Review priority gaps in order to establish a process to identify data improvements required to support future assessments and research, including system behavioural responses, streamflow, and climate data.	Many of the current approaches for incorporating climate change use existing data. This would ensure there is an assessment of critical data to support continued investment in collection activities	Coordinated by DES and DNRME	Scientists, modellers	M	$	✓	✓	✓		

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate change	Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland	Outcome 3: Address climate science and water modelling gaps through targeted research initiatives	Outcome 4: Empower individuals and collectives, and facilitate collaboration	Outcome 5: Develop communication and guidance materials to support outcomes 1-4
	H	Models	A6. Enhance AussieGRASS as potential tool for assessing landscape change under climate change assessments.	Of all the models assessed in the case studies, AussieGRASS had the most potential to assess climate change impacts using the existing model configurations, and this would provide increased understanding of landscape behaviour under climate change	Coordinated by DES and DNRME	Scientists, policy makers, project planners, modellers, farmers, agricultural groups	M	$$	✓	✓	✓		
	H		A7. Continue existing project evaluating palaeoclimate data in water models.	A current project is evaluating the use of palaeoclimate data can inform variability in existing water models.	DES	Scientists, modellers	H	$		✓	✓		
Medium-term (next 2-3 years)	H	Knowledge	B.1 Enhance collaborations to underpin research coordination for water and climate risk modelling in Queensland, with other states and nationally.	Address lack of coordinated approaches across groups, agencies and modellers and increase collaboration	Collaboration with DES, DNRME, CSIRO, BoM, MDBA, water utilities, other state agencies, academia, industry	Scientists, policy makers, project planners, modellers, practitioners	H	$$$	✓	✓	✓	✓	

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate change	Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland	Outcome 3: Address climate science and water modelling gaps through targeted research initiatives	Outcome 4: Empower individuals and collectives, and facilitate collaboration	Outcome 5: Develop communication and guidance materials to support outcomes 1-4
	M	Capacity, capability	B.2 Establish a centralised guidance, models, data access and sharing portal, building on existing information and data	Enable centralised provision of consistent and easily accessible climate data	Led by DES and DNRME for Queensland water sector (hosted on Long Paddock website)	Scientists, modellers, practitioners	H	$$$	✓	✓		✓	✓
	L	Capacity, capability	B.3 Provide input to the LGAQ Cert IV-level course on climate risk management for local government	Increasing consistency across all levels of government (modelling, policy and action)	Led by DES	Practitioners	L	From existing CCS budget	✓			✓	✓
	H	Capacity, capability	B.4 Create guidance and case studies to demonstrate effective communication of climate, water, and ecological modelling results for decision makers and broader community engagement	Critical need for improved communication and decision support for climate change and variability	Led by QWMN, with inputs from experts	Policy makers, project planners, modellers	H	$	✓			✓	✓

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate change	Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland	Outcome 3: Address climate science and water modelling gaps through targeted research initiatives	Outcome 4: Empower individuals and collectives, and facilitate collaboration	Outcome 5: Develop communication and guidance materials to support outcomes 1-4
	H	Knowledge	B.5 Leverage research programs and activities that improve understanding of changing dominant landscape processes (e.g. land use, water use, surface-groundwater interaction, vegetation under enhanced CO2, evapotranspiration and soil erosion) under different climate realisations and how this is incorporated into water models.	This is required for a number of water models across Queensland and would build on similar work interstate. Ideally this would be developed by the collaborative network	Led by the collaborative network, or collaboration with DES, DNRME, CSIRO, BoM, MDBA, other state agencies, academia, industry	Scientists, policy makers, project planners, modellers, practitioners	H	$$$$			✓		
	M	Knowledge	B.6 Improve understanding of how extreme event frequency, duration and intensity may change in a future climate, and implications on hydrology, water infrastructure, and water management.	Build on existing information and work through the Emergency Management Sector Adaptation Plan for Climate Change, and other research on climate extremes	Led by QFES with support from DES and DNRME, could also be done through the collaborative network	Scientists, policy makers, project planners, modellers, practitioners, insurers, emergency services	M	$$$		✓	✓		

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome				
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	H	Knowledge	B.7 Review/collate existing studies on impacts of climate variability and change on water storages in terms of yield, water quality and water demand, including synergistic effects and address research and knowledge gaps.	A broadscale project to consider how water demands and water availability will alter under different climate realisations, building on existing work	Led by the collaborative network or collaboration with DES and DNRME in partnership with water utilities (Seqwater, Sunwater), with inputs from experts	Scientists, policy makers, project planners, modellers, water utilities, local government	M	$$$		✓	✓		
	M	Knowledge, data	B.8 Review existing work and identify priority areas for development and incorporation of palaeoclimate information to improve assessments of the impacts of climate variability, especially in consideration of drought and flood frequencies	A research project to evaluate how best to incorporate climate variability more frequently in modelling projects	Led by collaborative network or by QWMN, with inputs from experts	Scientists, modellers, practitioners	M	$$$		✓	✓		
	L	Models	B.9 Evaluate the potential to link or integrate model outputs (e.g. AussieGRASS with P2R) when evaluating climate change responses	With different modelling programs considering climate change, there may be opportunities to look at integration and linkages from different modelling suites	Coordinated by DES and DNRME	Scientists, modellers	L	$	✓	✓	✓	✓	

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate change	Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland	Outcome 3: Address climate science and water modelling gaps through targeted research initiatives	Outcome 4: Empower individuals and collectives, and facilitate collaboration	Outcome 5: Develop communication and guidance materials to support outcomes 1-4
	M	Models	B.10 Improve integration between Paddock to Reef models and Source water planning models and consistent consideration of climate change.	With different modelling programs considering climate change, there is a need to ensure integrated models use similar approaches to climate change	Coordinated by DES and DNRME	Modellers	L	Within existing funding	✓	✓	✓		
	L	Models	B.11 Improve modelling the impacts of climate change on surface-groundwater interactions for areas where groundwater use is significant	Groundwater modelling may deserve increased attention in areas of groundwater importance (e.g. wetlands, floodplains, GDEs, shallow aquifers) to ensure climate change is considered in these models.	Coordinated by DES in partnership with DNRME	Scientists, policy makers, project planners, modellers	M	$$$		✓	✓		
	M	Data	B.12 Develop new data products to support climate sequences that may account for changed climate patterns, including changes in frequency, intensity and duration of climate indicators	Existing approaches to incorporating climate change largely rely on replicating existing climate patterns. Supplementing these with datasets that also consider changes in patterns is needed.	Led by the collaborative network or coordinated by DES	Scientists, modellers	H	$$$	✓		✓		

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate change	Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland	Outcome 3: Address climate science and water modelling gaps through targeted research initiatives	Outcome 4: Empower individuals and collectives, and facilitate collaboration	Outcome 5: Develop communication and guidance materials to support outcomes 1-4
	H	Data	B.13 Evaluate the robustness of the existing long-term climatic records in accounting for likely climate variability in water resource assessments.	It is highly likely that existing climate records do not account for the likely variability in climate based on paleoclimate research.	Led by the collaborative network or existing work coordinated by QG.	Scientists, policy makers, project planners, modellers	L	$$$	✓	✓	✓		
	M	Data, models	B.14 Assess the implications of CMIP6 GCM outputs for Australia and Queensland conditions when they become available.	As part of the release of the next round of GCM outputs, the implications need to be considered for Australian and Queensland conditions	Coordinated by DES	Scientists, policy makers, project planners, modellers	H	Within existing funding	✓	✓	✓		
	H	Capacity, capability	B.15 Provide training and guidance on the use of improved decision frameworks, including decision making under deep uncertainty (DMDU) approaches.	Climate change assessments require consideration of a range of uncertainties. New decision frameworks are available to assist this, but they require paradigm shifts in current approaches. This needs to be supported through training and guidance	Led by QWMN (perhaps through EEP or in partnership with ANU)	Scientists, policy makers, project planners, modellers, practitioners	H	$	✓			✓	✓

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate change	Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland	Outcome 3: Address climate science and water modelling gaps through targeted research initiatives	Outcome 4: Empower individuals and collectives, and facilitate collaboration	Outcome 5: Develop communication and guidance materials to support outcomes 1-4
Long-term (next 3-5 years)	M	Capacity, capability, knowledge, models, data	C.1 Collaborate with proposed climate science working group to influence future investment in climate science and training packages	There is an ongoing need to coordinate climate science approaches and training across Queensland – noting that this could also be a role of a collaborative network	Coordinated by DES and DNRME or the collaborative network	Scientists, policy makers, project planners, modellers, practitioners	M	$	✓	✓	✓	✓	✓
	H	Knowledge	C.2 Understand the biophysical processes in catchments and receiving waters under changing climate conditions	A key outcome of this project is the need to understand the impacts of changing climate on water related system responses, especially in ecological systems in receiving waters such as lakes, storages, estuaries and the GBR lagoon	Led by the collaborative network or QWMN in collaboration with other agencies (AIMS, CSIRO, Universities)	Scientists, policy makers, project planners, modellers	H	$$$$			✓		
	H	Knowledge	C.3 Contribute to the consideration of the implications of changing climate on water availability, allocation and use across the Murray Darling Basin	A collaborative approach is needed in considering climate change impacts across the MDB	Led by the collaborative network or MDBA with collaboration from DES, DNRME and other agencies	Scientists, policy makers, project planners, modellers	H	$$$$	✓	✓	✓	✓	

Timeline	Priority High=H Med=M Low=L	Focus	Actions	Opportunity	Lead agency	Target audience	Impact factor High=H Med=M Low=L	Estimated budget >$200k = $$$$ $100-200k = $$$ $50-100k = $$ <$50k = $	Outcome Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate change	Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland	Outcome 3: Address climate science and water modelling gaps through targeted research initiatives	Outcome 4: Empower individuals and collectives, and facilitate collaboration	Outcome 5: Develop communication and guidance materials to support outcomes 1-4
	M	Knowledge, models	C.4 Consider consistent approaches to modelling climate impacts of changed water availability on environmental, social and cultural outcomes	This relates to earlier recommendations about understanding system behavioural responses, but is more related to water resource uses	Led by the collaborative network or MDBA with collaboration from DES, DNRME and other agencies	Scientists, policy makers, project planners, modellers, practitioners	M	$$$	✓	✓	✓		

8 Conclusions

This critical review has evaluated how existing climate variability and future climate change could be better incorporated into water modelling and subsequent decision making within Queensland. We have examined the issue using a 'multiple lines' of evidence approach based on stakeholder interviews, workshops, review of literature and case study evaluations in order to prepare an investment strategy for consideration by Queensland Government.

The project has highlighted a considerable amount of existing work that has been undertaken in Queensland, changes in understanding around climate science and the need for more consistency, improved capabilities and further research into how improved climate science can best be incorporated into water modelling programs.

The recommendations provided for the investment priorities are based on a primary objective and five key outcomes.

Objective
Increase Queensland's ability to understand the impact of climate variability and change on water-related systems, to increase economic, social and ecological resilience

The five key outcomes which will contribute to achieving this objective are:

> ***Outcome 1: Increase consistency and defensibility of approaches for assessing risks from climate variability and change***
>
> ***Outcome 2: Interpret and summarise the applicability of existing climate science and datasets for Queensland***
>
> ***Outcome 3: Address climate science and water modelling gaps through targeted research initiatives***
>
> ***Outcome 4: Empower individuals and collectives, and facilitate collaboration***
>
> ***Outcome 5: Develop training, communication and guidance materials to support Outcomes 1-4.***

Overall, this project has highlighted that there already exists a number of innovative approaches, initiatives and outputs relating to climate variability and change across Queensland and commends the Queensland Government for continuing to expand on these efforts to improve water modelling across the state. Further investment, coordination and collaboration across government is required to ensure climate change effects are considered in all water models, and this is done in a consistent way.

Key investments are recommended in areas around knowledge generation, capacity and capability development, model improvements and improved datasets. There is also a strong need for coordinated and collaborative approaches to facilitating these investments, and this would be best delivered by the establishment of an inter-jurisdictional collaborative research network to share learnings and build common approaches to shared problems.

Overall, the incorporation of existing climate variability and future climate change in Queensland water models is an area worthy of significant investment if we are better able to understand how we manage the State's water assets now and into the future.

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Appendix A – Decision Making Under Deep Uncertainty (DMDU)

INCORPORATION OF UNCERTAINTY INTO DECISION MAKING

Incorporation of existing climate variability and future climate change into water models is associated with increased uncertainty in the modelled outcomes. This introduces a challenge, namely expansion of the requirement to deal with this uncertainty, including how to evaluate changes in risk under multiple, equally likely, scenarios. The consideration of uncertainty in decision support is an expanding topic and it is beyond the scope of this review to outline all of these, but, with support from Joseph Guillaume of the Australian National University, we have outlined below some key aspects of decision making under deep uncertainty (DMDU).

In this context, deep uncertainty describes where experts or decision makers cannot resolve or agree on:

(i) The external context of a system (i.e. the elements that influence how a system behaves),
(ii) How the system works or its boundaries (i.e. the system behaviour), and/or
(iii) The outcomes of interest from the system (i.e. outputs from the system).

A good example might be how water quality parameters in a stream might change under climate change. We have significant uncertainty around the climate drivers that might influence conditions in the water column that affect a range of water quality parameters, there is resultant uncertainty then around the water column might respond to those drivers and so we may find it very hard to resolve what the values of the future water quality parameters might be.

It is worth considering that the approaches we have outlined to dealing with DMDU are a pragmatic way to incorporate decision frameworks and to provide flexible tools for use in decision support, but they still represent a substantial change to the status quo decision making processes. Many of the cases where these techniques are used have involved cultural change in how decisions are made, rebuilding decision making processes around these frameworks and ideas (e.g. robustness, adaptive pathways, bottom-up approaches). As one major example, it's often easier to think about alternative futures in terms of simple delta-changes (e.g. how could we react if rainfall increased by 5%), with heavy duty climate scenario modelling only playing a relatively minor role as a sanity check on which delta-changes are plausible (e.g. we don't need to think about how to react to 200% changes). This goes against the general preference to predict-and-control.

Whenever possible, model-based impact assessments that are intended to account for uncertainty in future climate should be formulated within an explicit decision framework. This places impact assessments immediately into a decision context, recognising that the climate uncertainties are substantial enough that this is primarily a management rather than science communication problem. Whether runoff will change by 5% or 20% is less important than discussion of the possible reactions to each case – and to the observation that both might be possible.

Investment is needed in courses, knowledge sharing, capability development and other capacity building exercises to increase understanding of available methods for robust decision making, contingency planning, and development of adaptive policy capable of handling the substantial uncertainty that is inevitable in a climate change context. Modellers can use tools for decision making under deep uncertainty to help understand model results for different hypothetical or forecast climate scenarios, but users of model results also need to adjust their approaches to incorporate these tools.

The book "Decision Making Under Deep Uncertainty – From Theory to Practice" Marchau (2019) provides the following examples of decision frameworks:

- Robust Decision Making (RDM) – uses a "deliberation with analysis" process to stress test strategies over myriad plausible paths into the future, and then to identify policy-relevant scenarios and robust adaptive strategies (see Figure 43)

- Dynamic Adaptive Planning (DAP) – analysis approach for designing a plan that explicitly includes provisions for adaptation as conditions change and knowledge is gained, including specification of a monitoring system (see Figure 44)
- Dynamic Adaptive Policy Pathways (DAPP) – explores alternative sequences of decisions (adaptation pathways) for multiple futures and illuminates the path dependency of alternative strategies. (see Figure 45)
- Info-Gap Decision Theory (IG) - a method for prioritizing alternatives and making choices based on concepts of "robustness" and "opportuneness" defined in terms of horizons of uncertainty satisfying specific outcomes
- Engineering Options Analysis (EOA) – process for assessing the value of including flexibility in the design and management of technical systems

Each of these frameworks includes a number of tools for working through a decision-making process and includes different methods on how to adapt and change policies and decisions in the light of future knowledge and understanding. Some examples are shown below.

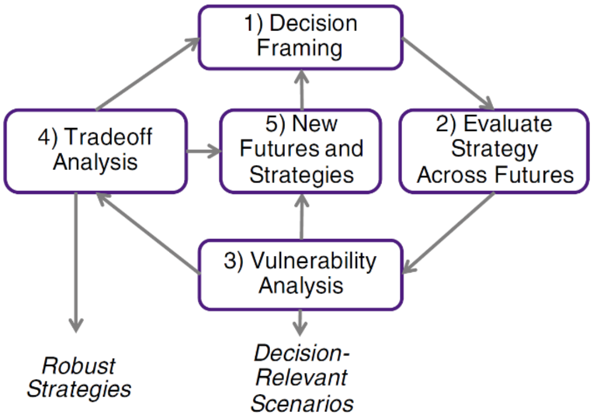

Figure 43 *Steps in a Robust Decision Making analysis (Lempert et al 2013a in Marchau et al 2019)*

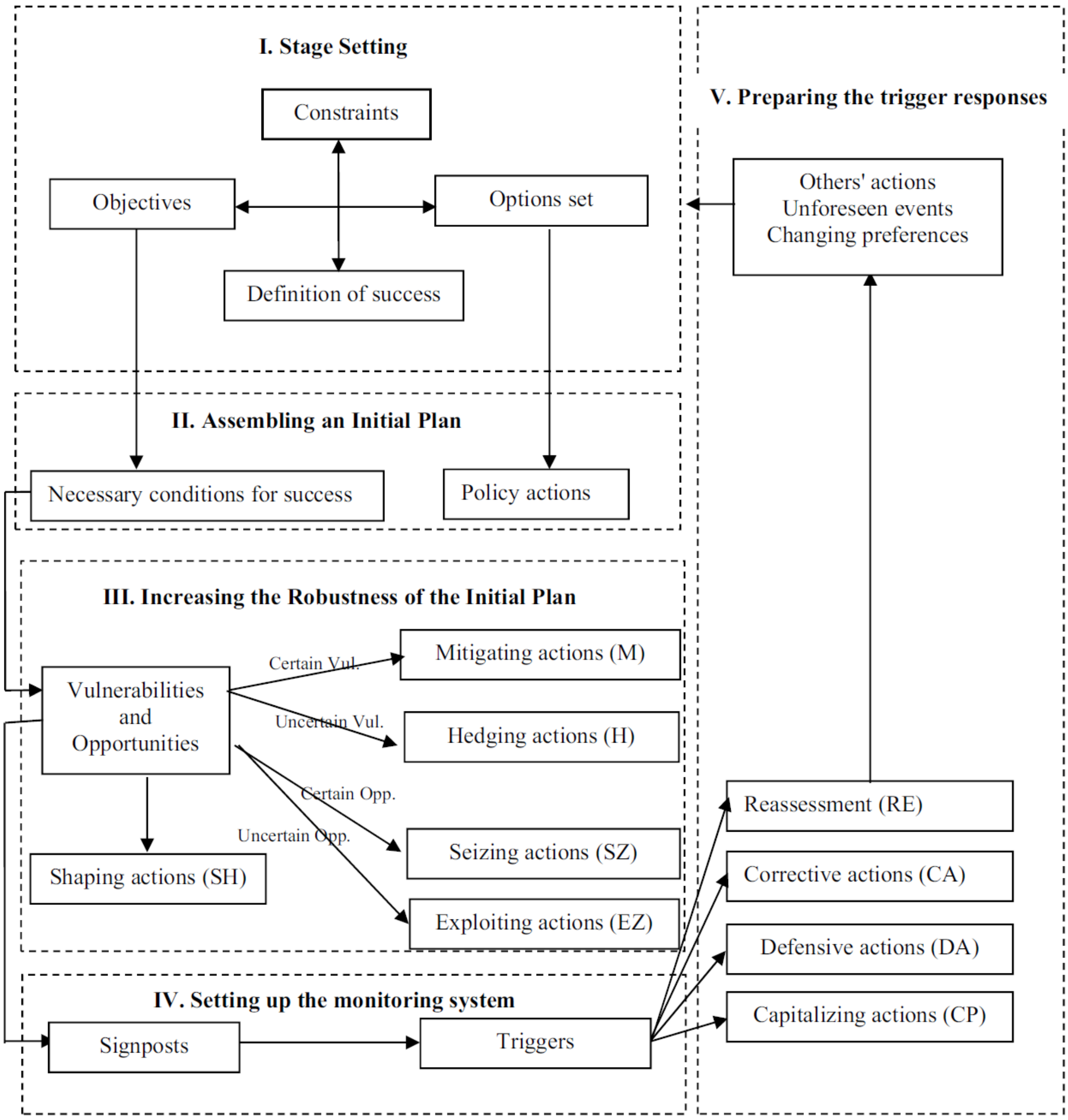

Figure 44 *Steps for Dynamic Adaptive Planning*

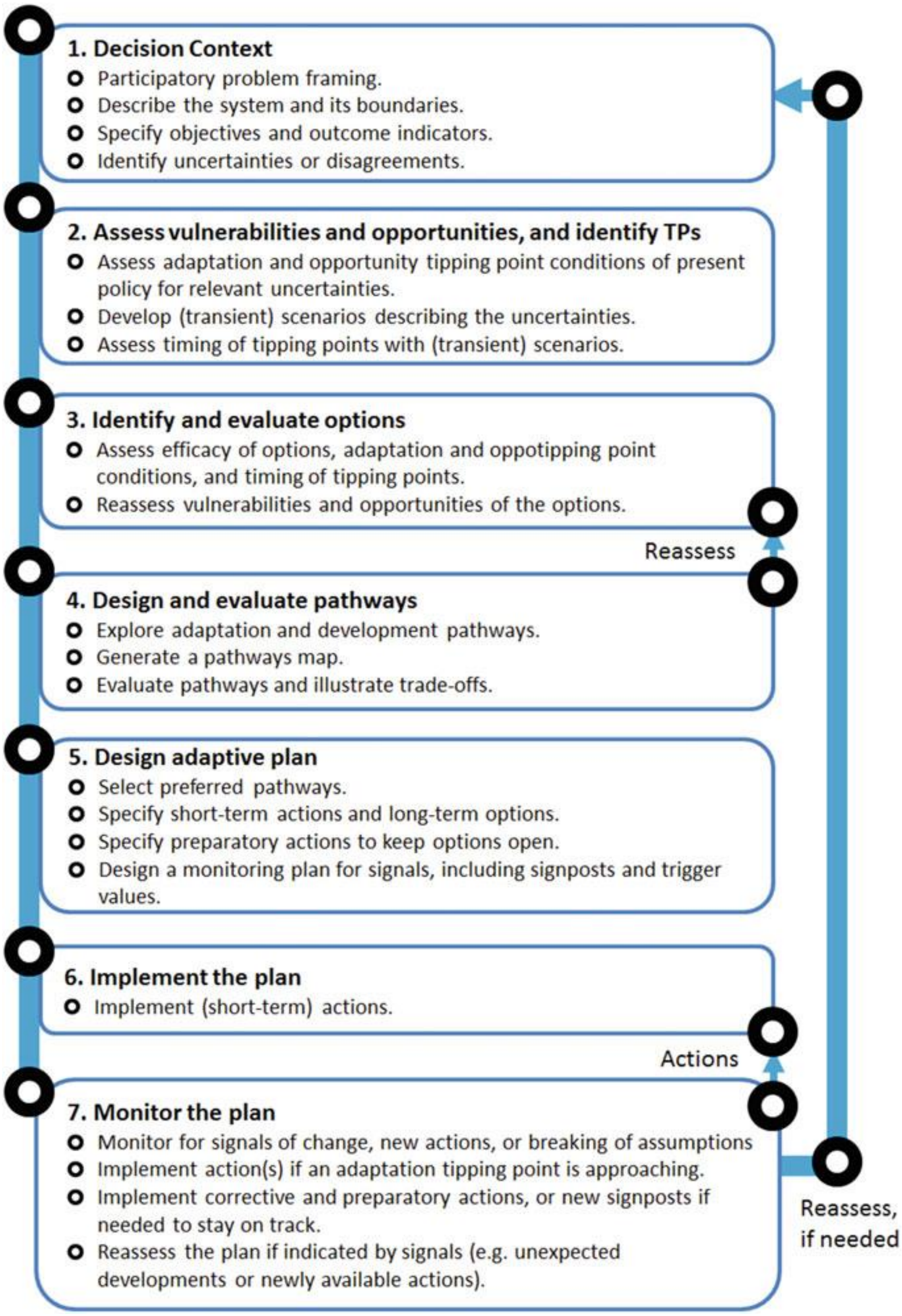

Figure 45 *Steps for Dynamic Adaptive Policy Pathways*

The intent with these is to simply highlight some of the potential frameworks that are available and that further work is needed on how best to adapt these to evaluating the uncertainty and changes in risk when considering existing climate variability and future climate change in water modelling.

Appendix B – Actions ranked by Priority, Impact and Budget

This table ranks the actions in order of priority, impact and then budget. Actions list with an Ax number are short term actions, those with Bx are medium term and those with Cx are long term actions.

Table 9. *Ranked order of actions*

Priority High=H Med=M Low=L	**Actions**	**Impact factor** High=H Med=M Low=L	**Estimated budget**
H	A7. Continue existing project evaluating palaeoclimate data in water models.	H	$
H	B.4 Create guidance and case studies to demonstrate effective communication of climate, water, and ecological modelling results for decision makers and broader community engagement	H	$
H	B.15 Provide training and guidance on the use of improved decision frameworks, including decision making under deep uncertainty (DMDU) approaches.	H	$
H	B.1 Enhance collaborations to underpin research coordination for water and climate risk modelling in Queensland, with other states and nationally.	H	$$$
H	B.5 Leverage research programs and activities that improve understanding of changing dominant landscape processes (e.g. land use, water use, surface-groundwater interaction, vegetation under enhanced CO2, evapotranspiration and soil erosion) under different climate realisations and how this is incorporated into water models.	H	$$$$
H	C.2 Understand the biophysical processes in catchments and receiving waters under changing climate conditions	H	$$$$
H	C.3 Contribute to the consideration of the implications of changing climate on water availability, allocation and use across the Murray Darling Basin	H	$$$$
H	A.2. Continue to support downscaling work by DES. Finalise and document peer review of climate projection data for Queensland	M	$
H	A.5. Review priority gaps in order to establish a process to identify data improvements required to support future assessments and research, including system behavioural responses, streamflow, and climate data.	M	$
H	A6. Enhance AussieGRASS as potential tool for assessing landscape change under climate change assessments.	M	$$
H	B.7 Review/collate existing studies on impacts of climate variability and change on water storages in terms of yield, water quality and water demand, including synergistic effects and address research and knowledge gaps.	M	$$$
H	B.13 Evaluate the robustness of the existing long-term climatic records in accounting for likely climate variability in water resource assessments.	L	$$$

Priority High=H Med=M Low=L	Actions	Impact factor High=H Med=M Low=L	Estimated budget
M	A.4 Create opportunity for forums and networking for practitioners e.g. through Community of Practice for climate change and climate variability in water modelling	H	Part of existing EEP
M	B.14 Assess the implications of CMIP6 GCM outputs for Australia and Queensland conditions when they become available.	H	Within existing funding
M	A.1 Develop an online climate risk assessment framework and guidelines with corresponding approaches for quantifying response to climate variability and change.	H	$$
M	B.2 Establish a centralised guidance, models, data access and sharing portal, building on existing information and data	H	$$$
M	B.12 Develop new data products to support climate sequences that may account for changed climate patterns, including changes in frequency, intensity and duration of climate indicators	H	$$$
M	A.3 Conduct awareness training of climate variability and climate change implications for modelling, policy and decision making in collaboration with Climate Change and Sustainable Futures group	M	Self-funded or delivered through existing frameworks (e.g. EEP)
M	C.1 Collaborate with proposed climate science working group to influence future investment in climate science and training packages	M	$
M	B.6 Improve understanding of how extreme event frequency, duration and intensity may change in a future climate, and implications on hydrology, water infrastructure, and water management.	M	$$$
M	B.8 Review existing work and identify priority areas for development and incorporation of palaeoclimate information to improve assessments of the impacts of climate variability, especially in consideration of drought and flood frequencies	M	$$$
M	C.4 Consider consistent approaches to modelling climate impacts of changed water availability on environmental, social and cultural outcomes	M	$$$
M	B.10 Improve integration between Paddock to Reef models and Source water planning models and consistent consideration of climate change.	L	Within existing funding
L	B.11 Improve modelling the impacts of climate change on surface-groundwater interactions for areas where groundwater use is significant	M	$$$
L	B.3 Provide input to the LGAQ Cert IV-level course on climate risk management for local government	L	From existing CCS budget

Priority High=H Med=M Low=L	Actions	Impact factor High=H Med=M Low=L	Estimated budget
L	B.9 Evaluate the potential to link or integrate model outputs (e.g. AussieGRASS with P2R) when evaluating climate change responses	L	$