NCCARF
National
Climate Change Adaptation
Research Facility

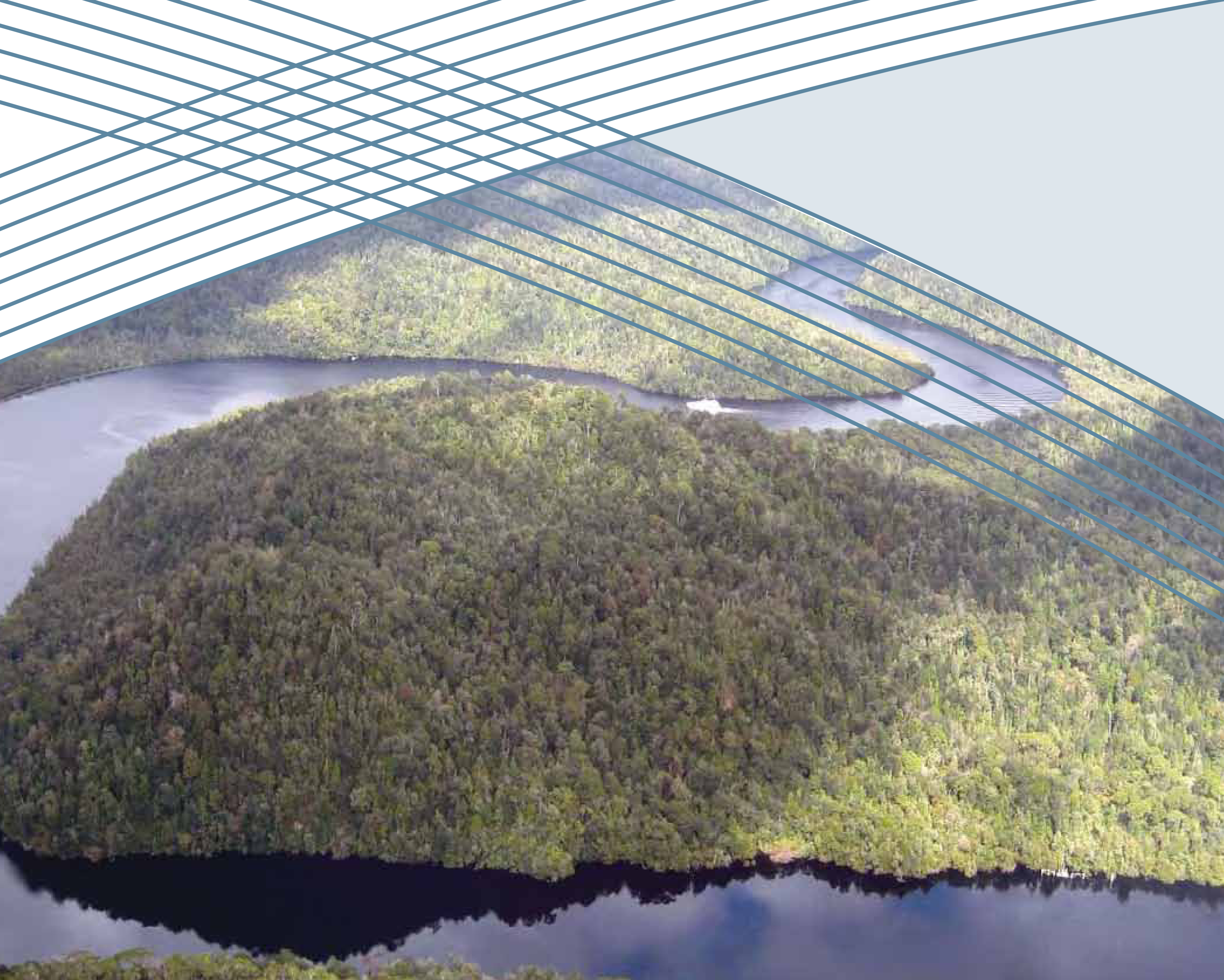
Australian Government
National Water Commission

UTAS

Joining the dots: Hydrology, freshwater ecosystem values and adaptation options

Final Report

Leon Barmuta, Peter Davies, Anne Watson, Michael Lacey,
Bryce Graham, Martin Read, Steven Carter
and Danielle Warfe



Joining the dots: Hydrology, freshwater ecosystem values and adaptation options

Joining the dots: Integrating climate and hydrological projections with freshwater ecosystem values to develop adaptation options for conserving freshwater biodiversity

University of Tasmania

Authors

Leon Barmuta, University of Tasmania
Peter Davies, University of Tasmania
Anne Watson, University of Tasmania
Michael Lacey, University of Tasmania
Bryce Graham, Department of Primary Industries, Parks, Water and Environment
Martin Read, Department of Primary Industries, Parks, Water and Environment
Steven Carter, Environmental Dynamics
Danielle Warfe, University of Western Australia

Published by the National Climate Change Adaptation Research Facility 2013

ISBN: 978-1-925039-10-8 NCCARF Publication 39/13

Please cite this report as:

Barmuta, L, Davies, P, Watson, A, Lacey, M, Graham, B, Read, M, Carter, S & Warfe, D 2013, *Joining the dots: Integrating climate and hydrological projections with freshwater ecosystem values to develop adaptation options for conserving freshwater* biodiversity. *Joining the dots: Integrating climate and hydrological projections with freshwater ecosystem values to develop adaptation options for conserving freshwater biodiversity*, National Climate Change Adaptation Research Facility, Gold Coast, 190 pp.

Acknowledgements

This work was carried out with financial support from the Australian Government (through the Department of Climate Change and Energy Efficiency and the National Water Commission) and the National Climate Change Adaptation Research Facility (NCCARF). The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

We are grateful to the many people who have provided feedback and advice to our research over the past fifteen months. From DPIPWE Tasmania we are indebted to Dr Louise Gilfedder, Dr Jennie Whinam, Mr Mike Askey-Doran, Dr Scott Hardie and Mr Chris Bobbi. Staff from the Centre for Enivironment, University of Tasmania and Climate Futures Tasmania were generous with their expertise, in particular Dr Michael Grose and Dr Regina Magierowski. Our support staff in the School of Zoology Dr Jennifer Sprent, Ms Dydee Mann and Ms Shannon Troy helped bring this project to completion. Ms Alison Howman and Dr Carolyn Maxwell from Hydro Tasmania provided both valuable feedback and access to data sets from Hydro Tasmania and Entura. Dr Nick Bond, Senior Research Fellow, The Australian Rivers Institute, Griffith University, assisted DPIPWE in contributing to the preparation and determination of flow statistics relating to ecological function. We are also indebted to the many people who have contributed to our workshops, interviews and consultations including Mr Daniel Sprod (Tasmanian Wildlife Conservancy), Mr Michael Driessen, Dr Steve Mallick (DPIPWE) and Dr Kathleen Broderick (NRM South). Dr Alistair Hobday (CSIRO Climate Adaptation National Research Flagship) generously shared his perspectives on prioritising adaptation actions. Dr Alice Percy (University of Tasmania) and Mr Frank Stadler (NCCARF, Griffith University) deserve praise for their administrative support and advice throughout, while Dr Samantha Capon and Brendan Edgar of the Water Resources and Freshwater Biodiversity Adaptation Research Network facilitated our final communications activities and participation in the Freshwater Biodiversity Adaptation Research Showcases in Brisbane and Canberra respectively.

Disclaimer

Cover image © 2009 Stephan Ridgway

Table of contents

List of figures

List of tables

ABSTRACT

The objective of this research was to investigate and test the necessary steps in developing an adaptation planning framework for freshwater biodiversity. We used Tasmania as a test case to demonstrate how downscaled climate model outputs could be integrated with spatially resolved hydrological models and freshwater biodiversity data. This enabled us to scope adaptation actions at local, regional and state scales for Tasmania, and to explore how priorities might be set.

To achieve this integration we quantified how different climate change scenarios could affect the risks to biodiversity and ecosystem values ('biodiversity assets') in freshwaters, the scope and types of adaptation actions, and assessed the strengths and weaknesses of the policy and planning instruments in responding to climate change.

We concluded that downscaled climate modelling, linked with modelling of catchment and hydrological processes, refines projections for climate-driven risks to aquatic environments. Spatial and temporal hazards and risks can now be compared at a variety of scales, as well as comparisons between biodiversity assets (e.g. relative risk to riparian vegetation v. in-stream biota). Uncertainties can be identified and built into adaptation processes. Notwithstanding this progress, we identified a number of issues that need to be addressed in order to increase confidence in this process.

The main issues for improved and timely modelling are: frameworks for using and downscaling outputs from improved global climate models as they become available; better data on thermal tolerances of freshwater biota; and, improved methods for predicting key water temperature variables from air temperature and other biophysical predictors. Improvements are also needed in updating and maintaining high quality biodiversity data sets, and better spatially explicit information on the contributions of groundwater to surface waters and rates of recharge.

The list of adaptation options available is extensive, but the key challenge is to organise these options so that stakeholders are not overwhelmed. Scenario modelling that incorporates explicit tools for comparing costs, benefits, feasibility and social acceptability should help with setting priorities but require further development.

A review of current Australian policies revealed a variety of responses driven by both water reform and climate change agendas. Many agencies are actively revising their policies to accommodate adaptation. However, we note that much of the reform of the water sector in the last 10–15 years has aimed to improve certainty for non-environmental water uses. Under the National Water Initiative, governments have agreed that entitlement holders should bear the risks of reduced volumes or reliability of their water allocations as a result of changes in climate. The key opportunity for adaptive uptake of climate adaptations is by developing and periodically reviewing water management planning tools. Pathways need to be developed for integrating the traditional evolution of planning and policy with the needs for climate change adaptation for aquatic ecosystems. Formal mechanisms for the uptake of knowledge about identified risks into policy and legislative instruments remain under-developed. An even bigger challenge is to integrate multiple adaptation strategies (sometimes at different scales) to achieve specific adaptation objectives within regions or catchments—especially where a mix of water management and non-water management is required.

EXECUTIVE SUMMARY

Much climate modelling available in Australia is spatially too coarse to be useful for adaptation planning for freshwater biodiversity. Downscaling of global climate change models will become more common and will be essential for finer-scale planning and management of adaptation responses to climate change. As this happens, states and territories around Australia have several resources available to assist in planning adaptations to conserve freshwater biodiversity: data on climate change, rainfall-runoff models to predict how water moves through the landscape, and various data bases recording the occurrence of freshwater plants, animals and other ecosystem values. These resources vary in their spatial resolution and completeness, and the data sets and models have often been developed in isolation.

These, then, are the 'dots' that need to be joined up so that we can understand how different climate futures will impact our freshwater biodiversity. Tasmania is uniquely placed to do this joining up because it is the first state to have the combination of finely resolved, downscaled climate models (from Climate Futures Tasmania), hydrological models—to convert runoff data into flows in rivers and inflows into wetlands—and a comprehensive planning tool for aquatic ecosystems (CFEV: Conservation of Freshwater Ecosystem Values) which maps biodiversity assets and ecosystem values consistently across the state. These resources, combined with the existing, healthy networks between researchers, managers and stakeholders enabled Tasmania to provide a test case for the integration of risk assessment and management actions at catchment and regional scales.

The aim of this research was to investigate and test the steps necessary in developing a planning framework for adaptation options to conserve freshwater biodiversity in the face of climate change. We used Tasmania as a test case to demonstrate how downscaled climate model outputs could be integrated with spatially resolved hydrological models and freshwater biodiversity data. This enabled us to scope adaptation actions at local, regional and state scales for Tasmania, and to explore how priorities might be set, and what implications this process had for policy.

Of the six downscaled climate models available, we used the driest, the wettest and a model closest to the 'average' of the six models. We did this because we wanted to explore how uncertainties in the modelling process affected prioritisation and policy development. Water temperature variables were computed from projected air temperatures across the state. Hydrological modelling was straightforward in those areas of Tasmania for which rainfall-runoff models were well-developed for natural catchments, and a number of hydrological variables relevant to different biodiversity assets was selected. The changes relative to the reference period (1961–1990) in these variables was computed for each model for different time periods into the future, with most of the focus on 2010–2039. Data from the literature and expert opinion was then used, via Bayesian Belief Networks, to link probabilistically the sizes of these changes (hazards) to their consequences on each biodiversity asset to provide a probability-based assessment of the risk to that asset for the given time period. These risks were then mapped for each river segment and wetland for each climate change model.

We concluded that downscaled climate modelling, linked with modelling of catchment and hydrological processes, refines projections for climate-driven risks to aquatic environments. Spatial and temporal hazards and risks can now be compared at a variety of scales, as well as comparisons between biodiversity assets (e.g. relative risk to riparian vegetation v. in-stream biota). Uncertainties can be identified and built into adaptation processes. Notwithstanding this progress, we identified a number of issues that need to be addressed in order to increase confidence in this process.

The main issues for improved and timely modelling are: frameworks for using and downscaling outputs from improved global climate models as they become available; better data on thermal tolerances of freshwater biota; and improved methods for predicting key water temperature variables from air temperature and other biophysical predictors. Improvements are also needed in updating and maintaining high quality biodiversity data sets, and better spatially explicit information on the contributions of groundwater to surface waters and rates of recharge.

The list of adaptation options available to planners is extensive, but workshops and consultations showed that the key challenge is to organise these options so that stakeholders are not overwhelmed. Scenario modelling that incorporates explicit tools for comparing costs, benefits, feasibility and social acceptability should help with setting priorities but require further development.

A review of current Australian policies revealed a variety of responses driven by both water reform and climate change agendas. Many agencies are actively revising their policies to accommodate adaptation. However, we note that much of the reform of the water sector in the last 10–15 years has aimed to improve certainty for non-environmental water uses. Under the National Water Initiative, governments have agreed that entitlement holders should bear the risks of reduced volumes or reliability of their water allocations as a result of changes in climate. The key opportunity for uptake of human adaptions to climate change is by developing and periodically reviewing water management planning tools. Flexibility in the planning process will be crucial, especially given the divergent projections yielded by different climate models in some regions.

Pathways need to be developed for integrating the traditional evolution of planning and policy with the needs for climate change adaptation in aquatic ecosystems. Formal mechanisms for the uptake of knowledge about identified risks into policy and legislative instruments remain under-developed in most jurisdictions, although there is considerable activity and continuing negotiations within this space. An even bigger challenge is to integrate multiple adaptation strategies (sometimes at different scales) to achieve specific adaptation objectives within regions or catchments—especially where a mix of water management and terrestrial management is required.

1. OBJECTIVES OF THE RESEARCH

1.1 Context

States and territories around Australia have several resources available to assist in planning adaptations to conserve freshwater biodiversity: data on climate change, rainfall-runoff models to predict how water moves through the landscape, and various data bases recording the occurrence of freshwater plants, animals and other ecosystem values. These resources vary in their spatial resolution and completeness, and the data sets and models have often been developed in isolation.

These, then, are the ‘dots’ that need to be joined up so that we can understand how different climate futures will impact our freshwater biodiversity. Tasmania is uniquely placed to do this joining up because it is the first state to have the combination of finely resolved, downscaled climate models, hydrological models—to convert runoff data into flows in rivers and inflows into wetlands—and a consistent state-wide database mapping biodiversity assets and ecosystem values. These resources, combined with the existing, healthy networks between researchers, managers and stakeholders enabled Tasmania to provide a test case for the integration of risk assessment and management actions at catchment and regional scales.

1.2 Objective

The objective of this research was to investigate and test the steps necessary in developing a planning framework for adaptation options to conserve freshwater biodiversity in the face of climate change. We used Tasmania as a test case to demonstrate how downscaled climate model outputs could be integrated with spatially resolved hydrological models and freshwater biodiversity data. This enabled us to scope adaptation actions at local, regional and state scales for Tasmania, and to explore how priorities might be set.

To achieve this integration we quantified how different climate change scenarios could affect the risks to biodiversity and ecosystem values (‘biodiversity assets’) in freshwaters We then scoped and classified the types of adaptation actions, and assessed the strengths and weaknesses of the policy and planning instruments in responding to climate change.

2. RESEARCH ACTIVITIES AND METHODS

2.1 Overview

Figure 1 summarises the research activities and tasks used in this project. There were five main activities, some of which had a number of steps involved as follows.

1. We used the existing hydrological time series derived from three down-scaled Climate Futures Tasmania (CFT) climate projections for Tasmania to derive hydrological measures of ecological relevance for streams and wetlands.
2. Water temperature variables relevant to biota were modelled using gridded CFT air temperature data as the input.
3. Hydrological and temperature changes were attributed to the wetland and stream geographic information system (GIS) layers of the Tasmanian Conservation of Freshwater Ecosystem Values (CFEV) database for each of the three climate change projections.
4. We then assessed the risks posed by each projection to selected, representative biodiversity assets using Bayesian Belief Networks (BBNs) by:
    a) Developing risk criteria (thresholds) for each biodiversity asset (e.g. native fish condition, platypus, riparian or wetland vegetation condition) against the relevant hydrological and temperature indicators ('hazards'). This involved using existing south-eastern Australian data on temperature thresholds and flow-habitat requirements of aquatic biota, and identifying thresholds for key hydrological and temperature variables which would pose significant risk to the biota;
    b) Using this information to relate the likely consequences and probabilities of each hazard for the aquatic biota in the nodes of a BBN. This was based on data mining from the CFEV database combined with expert elicitation from local aquatic ecologists where necessary;
    c) These thresholds and rules were applied to the CFEV ecological data sets for streams and wetlands across the entire CFT data set for each of the three projections;
    d) The risk levels were then attributed to the CFEV wetland and stream GIS layers for each climate change projection, and mapped for each biodiversity asset.
5. Adaptation management options or actions were explored by:
    a) Reviewing the literature and scoping potential adaptation management responses with planning and management staff of the Department of Primary Industries, Parks, Water and Environment (DPIPWE), NRM groups, terrestrial conservation planners and other stakeholder groups in a series of workshops and focussed consultations;
    b) Classifying and organising the adaptation options after consultations with stakeholders;
    c) Exploring methods of prioritising adaptation options using a series of case studies in a workshop and soliciting further inputs from focussed discussions with other key management stakeholders.
6. Identify policy and planning needs for effective adaptation at regional, state and national level. Using the outcomes from step 5, we explored the requirements for existing and possible future policy and planning instruments will be identified. This also involved focussed consultations with policy and planning staff from the relevant Tasmanian and similar consultations are planned with selected interstate agencies.
7. The project findings, the risk framework, and the policy and planning implications were communicated via dedicated NCCARF meetings/workshops, and by seeking feedback from a range of state jurisdictional planners and policy staff.

The hydrological and temperature time series were divided into three time periods: Reference Period (1961–1990), Recent (1991–2009), Period 1 (2010–2039), Period 2 (2040–2069) and Period 3 (2070–2099). These time periods are consistent with those used in the CSIRO sustainable yields projects (CSIRO 2009b, CSIRO 2009a), and hydrological and temperature variables entered the risk analysis in terms of the change of a given period relative to the Reference Period. We generally focussed on changes between the Reference Period and Period 1, although full data analyses were also produced for Period 2. Stakeholder consultation suggested there was limited value to exploring Period 3 since the uncertainties inherent in projections beyond 2070 were too great to warrant further investigation in this project.

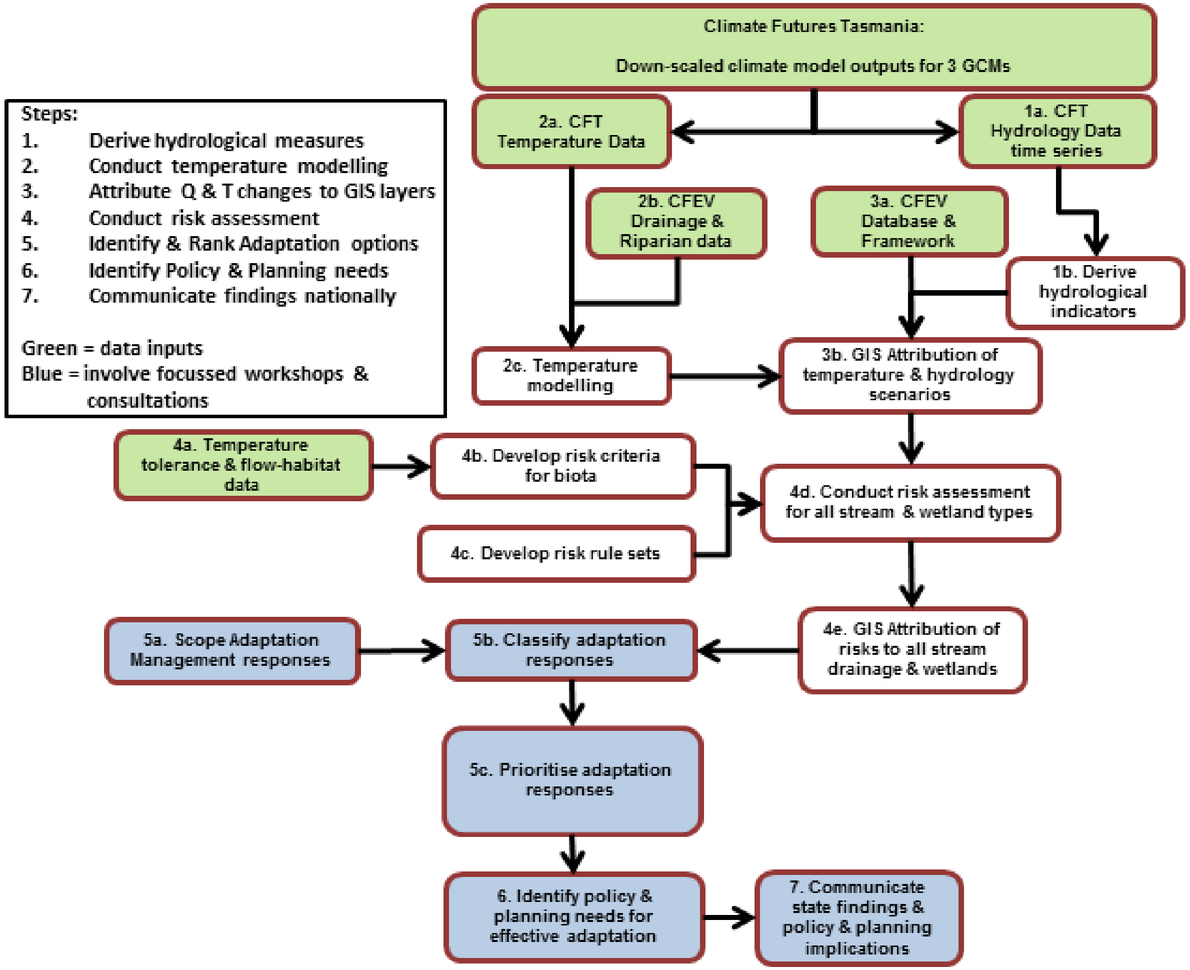


Figure 1 Flow chart of project tasks

Green boxes identify data inputs; blue boxes identify tasks involving stakeholder consultation.

CFT = Climate Futures Tasmania; GCM = global climate model; CFEV = Conservation of Freshwater Ecosystem Values data base.

2.2 Biophysical modelling

The relative level of risk to aquatic ecosystem components across Tasmania, resulting from climate change impacts on key hydrological and temperature variables, was modelled in a number of key steps, using a variety of data sources.

The analysis was possible across the majority of Tasmania due to the availability of:

1. A systematic conservation value framework and database (CFEV) which contained data on:
    a) Base attributes of mapped rivers and wetlands (e.g. elevation, area, slope);
    b) Biological classes of all major ecosystem components for all mapped rivers and wetlands;
    c) Biological condition of all mapped rivers and wetlands, as well as of their key ecological components (e.g. fish, riparian vegetation), as of the mid to late 1990's;
    d) Relative conservation value of all mapped rivers and wetlands, based on CAR (Comprehensive, Adequate and Representative) principles and data on rarity, condition, size and representativeness of ecosystem components;

    which were all mapped and attributed consistently at 1: 25 000 map scale across all Tasmanian catchments.
2. Model-based downscaled climate projections for Tasmania, derived from the CSIRO-Mk 3.5, GFDL-CM2.1 and UKMO-Had CM3 global climate model projections, for the time periods 1961–1990, 1991–2009, 2010–2039, 2040–2069 and 2070–2099, attributed to 10 km grid squares across Tasmania.
3. Modelled hydrological regimes based on the down-scaled climate model projects as inputs for all 'rural' hydrological catchments (all Tasmanian catchments except those of the central highlands, west and south).

2.2.1 Hydrology

Climate Futures Tasmania (CFT) generated dynamically downscaled Global Climate Model (GCM) projections for 721 x 10 km^2 grid cells (0.1°) across Tasmania under the CFT Antarctic and Climate Ecosystems Cooperative Research Centre project (Corney et al. 2010). These data covered the low (B1) and high (A2) carbon emission scenarios for six climate models, for the time period extending from 1960 to 2099.

The hydrology data sets were generated under the CFT Water and Catchments component (Bennett et al. 2010). These provide daily time step series, for six runoff projections, for 78 river catchments. The river runoff models were based on the CSIRO Tasmanian Sustainable Yields Project (TasSY), which assessed ground and surface water, the impact of likely future climate change, and predicted land use changes on water yields (Table 1). *Runoff* models calculate daily runoff in millimetres, while *river* models aggregate runoff at a catchment scale to predict river flow in megalitres per day (ML/d), after water extraction, and diversions to storages (Bennett et al. 2010).

Table 1 Models used to produce runoff projections

From Bennett et al. (2010), with the GCMs used in our modelling indicated by bold type

Global climate model	Downscaling model	Runoff models	Hydro-electric system model	River models
CSIRO-Mk 3.5	CSIRO-CCAM	AWBM	TEMSIM	CSIRO/Entura-TasSY
ECHAMS/MPI-OM		IHACRES		
GFDL-CM2.0		Sacramento		
GFDL-CM2.1		Simhyd		
MIROC3.2(medres)		SMAR-G		
UKMO-Had CM3				

The stretched-grid downscaling model, CSIRO-CCAM (Conformal Cubic Atmospheric Model) was used to dynamically downscale each GCM projection, based on daily rainfall and areal potential evapotranspiration inputs. The only forcings were sea surface temperatures and the concentration of sea ice (Corney et al. 2010). The downscaled climate projections were bias-adjusted (using a simple additive bias-adjustment) and converted to runoff, which was further aggregated to river sub-catchments, and then combined with the modelled outflow of the state hydro-electric system to model river flows (Bennett et al. 2010). The runoff models were calibrated to 90 high-quality stream flow records with the SILO dataset (Jeffrey et al. 2001), interpolated from Bureau of Meteorology weather stations. Although Hydro Tasmania's Tasmanian electricity market simulation model (TEMSIM) was used for CFT hydrological modelling, at the time of data delivery to DPIPWE for analysis, the modelling only included aggregated inflows to power stations and flows were not aggregated nor routed to catchments downstream of power stations. Subsequent downstream catchment flows were highly variable given the complex diversions and interbasin transfers in highly regulated catchments such as the Great Lake and upper Derwent River. Consequently, hydrological modelling was restricted to catchments modelled under the TasSY project (CSIRO 2009b, CSIRO 2009a).

From these data, we selected the CSIRO Mk 3.5 model as the driest scenario, the UK Hadley Meteorological Centre UKMO-Had CM3 model as the wettest scenario, and the median future climate was represented by the US Geophysical Fluid Dynamics Laboratory GFDL-CM2.1 model. Hereafter these models will be referred to by the shortened acronyms CSIRO, UKMO and GFDL respectively. Modelling was restricted to the A2 scenario because global carbon emissions are exceeding the predictions of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Allison et al. 2009).

Eleven hydrology variables were selected from the original set of 433, using a combination of assessing variables for redundancy, with Principal Components Analysis, variable clustering (Harrell 2001), and input from ecological experts. Statistical analyses were undertaken with R (R Core Development Team 2012). The choice of hydrological variables reflected our conceptual understanding of their relative importance in driving the condition of ecosystem components (Table 2).

- The magnitude of dry season low flows and summer-season freshes;
- The strength and timing of the seasonal pattern of catchment yield;
- The magnitude and frequency of high flows (floods and spates);
- The interval between large flood events.

Table 2 Biologically important hydrological variables used in BBN modelling (The name in parentheses is the shortened name used in the BBN models.)

Hydrology variable	Variable definition
Change in the percentage of cease to flow events (% Cease to Flow Change)	Difference in the average percentage of time classified as 'cease to flow' (< 0.1 ML/d) between reference period and test period. An increase or decrease of ≈ 10 cease to flow days per year is assumed to pose a significant risk or benefit to fish survival or condition
Mean annual maximum flow (Mean Annual Max Q Change)	Average annual maximum flow (ML/d) as a ratio of reference period to test period. A large change in maximum flow is considered an erosional risk to the channel and habitats for biota.
Mean duration of very high flow events (Length Q spells> 95%ile Change)	Average duration (days) of spells above the 95th percentile of flow (ML/d), as ratio of median of reference period to teat period. Proportional change > 0.5 increase in duration is likely to represent a substantial change in channel morphology in sensitive channels and to availability of spawning gravels in less sensitive channels
Spring minimum daily flow (Mean Min Spring Q Change)	Ratio between test period and reference period value in spring minimum daily flow where spring minimum > 0, OR ratio between test period and reference period value in spring average daily flow
Seasonality Change	Change in flow, as a percentage of total annual flow, between the medians of the reference and test periods. Changes > 20% from reference are considered very large because dry season flows are a small percentage of total annual flows
Summer maximum daily flow (Summer Max Q)	Change in summer maximum daily flow between reference period and test period. A large reduction indicates a decreased likelihood of flushing flows and potential for impact on bed habitat quality through benthic algal cover and fine sediment accumulation
Coefficient of flow variation (CV of Mean Annual Flow)	Ratio between test period and reference period of Coefficient of Variation in annual flows
Maximum high spell interval (OFS Max Interval)	Ratio between test period and reference period of maximum interval (days) between spells exceeding the 1 in 2 year ARI spell threshold (7 day spell independence)
Minimum high spell interval (OFS Min Interval)	Ratio between test period and reference period of minimum interval (days) between spells exceeding the 1 in 2 year ARI spell threshold (7 day spell independence)
Summer Median Flow	Ratio between test period and reference period of summer median daily flow

Hydrology variable	Variable definition
Maximum high spell duration (Median Q Max Spell Interval)	Ratio of test period to reference period of median value of maximum high spell duration

2.2.2 Water temperature and thermal tolerances

Our aim was to predict water temperatures from air temperatures generated by the Tasmanian downscaled climate models. Predictive models for maximum and minimum water temperatures were built using historical empirical data for catchments with high quality water and air temperature records, using non-linear mixed models. These models were used to generate temperature records for running waters using air temperatures predicted by each of the three contrasting climate models. The resulting predictions were used to:

1. Identify rivers with the greatest and least changes over the time span of the climate models. Those rivers with least changes are likely to remain cooler and provide thermal refugia for biota, or remain warmer and have biota already adapted to warmer conditions, while those with the greatest changes are likely to be rivers where the biota are stressed and most vulnerable to climate change.
2. Generate thermal tolerance limits of in-stream biota, by combining water temperature predictions from the reference period (1961-1990) and existing data on the distribution of in-stream biota from Tasmania. These were combined with existing data on thermal limits from Victoria and New South Wales to avoid potential underestimates of upper thermal limits for taxa common to both Tasmania and south east Australia.

Continuous long-term water temperature records for 23 gauged Tasmanian rivers were provided by the Tasmanian Department of Primary Industries, Parks, Water and Environment (DPIPWE). Water temperature data for a further eight rivers monitored by Hydro Tasmania were provided by their consulting arm, Entura. After filtering to remove low quality records, and sites subjected to thermal effects from upstream reservoirs, data for eighteen rivers were used in the final analyses.

Continuous water temperature records for six lakes were provided by Entura and a further two lakes monitored by the Inland Fisheries Service (IFS). We also attempted to estimate the risk of drying using modelled pan evaporation data and Linacre’s (1993) modified Penman equation.

Species distribution records for freshwater macroinvertebrates, crustaceans, frogs, platypus and fish were collated from data supplied by the Tasmanian Conservation of Freshwater Values database (CFEV database v1.0. 2005), the Tasmanian Natural Values Atlas (NVA), AuSRivAS surveys (DPIPWE), Freshwater Systems Pty Ltd, and the Atlas of Living Australia (ALA).

The relationship between air and water temperatures is sigmoidal (Figure 2), with the lower and upper asymptotes of water temperature restricted by the high thermal inertia of water and evaporative cooling respectively (Caissie 2006, Mohseni and Stefan 1999, Mohseni, Stefan and Erickson 1998).

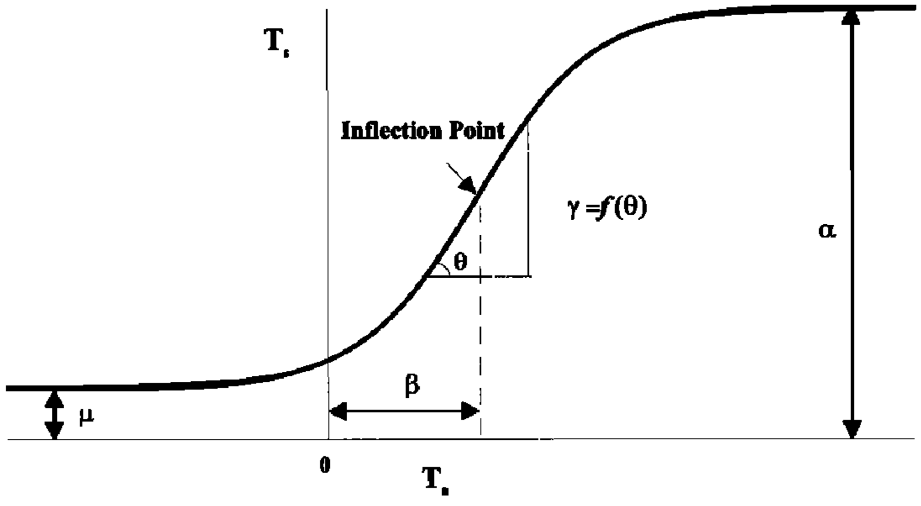


Figure 2 The four-parameter logistic function

From Figure 3 of Mohseni et al. (1998)

The mechanistic model linking water and air temperatures is a four-parameter logistic model, and we followed the parameterisation of Morrill et al.(2005) after Mohseni et al. (1999), implemented with R software (R Core Development Team 2012):

$$T_W = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}}$$

where T_w = estimated water temperature, T_a = measured air temperature, α = measured maximum water temperature, μ = measured minimum water temperature, γ = inflection point (steepest slope) of the T_w function (when plotted against T_a), β = air temperature at inflection point (see Figure 1).

Non-linear mixed modelling (Pinheiro and Bates 2000) was used to perform the regressions to allow for the random effects of between-site variation. Predicted values for each site were plotted with predictions for the population-level (i.e. state-wide) model to determine if any systematic deviations from a state-wide model could be detected. Goodness-of-fit for the population-level model was assessed using both the Nash-Sutcliffe coefficient (NSC, an analogue of the R^2 used in linear regression: range of values 0 to 1, with larger values indicating better fit) and the root mean squared error (RMSE, in units of degrees Celsius).

From these regressions, the minimum and maximum water temperatures were generated from modelled maximum and mean air temperatures respectively for each grid cell for each of the five time periods: Reference Period (1961–1990), Recent Period (1991–2009), Period 1 (2010–2039), Period 2 (2040–2069) and Period 3 (2070–2099).

To derive minimum and maximum temperature bounds for each taxon, distribution records were snapped to the water temperature data derived for each grid cell from the regression model, and the upper and lower bounds for each taxon in Tasmania were compared with those for the same taxa in south-eastern Australia documented by Walsh et al. (2007). For Tasmanian endemics the bounds were taken simply from the Tasmanian data.

Temperature variables for BBN modelling were selected to reflect the change in temperature at the most critical time of the year in Tasmania – the warmest 4 months of the year (December to March). Exceedance of maximum temperatures during this period are likely to include the prime limiting temperature events for in-stream biota (e.g. fish, macroinvertebrates, crayfish) in a warming climate. These events are likely to be most associated with direct thermal stress, sometimes coupled with reduced oxygen availability and raised oxygen demand.

A single temperature statistic was chosen for the majority of risk analyses – the 75th percentile of all maximum daily water temperatures for the four warmest months of the year (December–March). This variable was chosen instead of a direct measure of maximum temperature, due to:

- the absence of reliable water– air temperature relationships at higher temperatures (over 20° C);
- the relatively poor representation of absolute daily maximum temperature values in the climate models;
- the belief that extended periods of temperatures at or just below the thermal threshold is a more appropriate hazard and a substantially greater hazard than brief single day events;
- the likelihood that the absolute value of upper temperature thresholds for aquatic biota defined from the available data is underestimated.

2.2.3 GIS attribution

Water temperature and hydrological variables were attributed to biological variables derived from the Conservation of Freshwater Ecosystem Values (CFEV) database (CFEV database v1.0. 2005). The CFT grid tiles and DPIPWE hydrology polygons were combined spatially with overlapping CFEV rivers and CFEV wetlands spatial layers to link their associated attribute data tables. This produced three datasets with key attributes, covering rivers, floodplain wetlands and non-floodplain wetlands. Although CFEV rivers and wetland data covered the entire state, only those river sections and floodplain wetlands which intersected the DPIPWE hydrology catchments were used. Coverage of the land by the CFT tiles was also incomplete (generally around the coastal margins) so Thiessen polygons were used to extend some tiles to overlap the whole land surface and to ensure that CFT attributes were sourced from the nearest tile.

Floodplain wetlands, with gauged hydrological variables available, were distinguished from non-floodplain wetlands, which used CFT gridded hydrological variables. River sections which had Strahler stream order equal to or greater than three, reach slope of less than 0.02 %, altitude below 400 m AHD and annual runoff greater than 2000 mm were selected from the CFEV database and identified to the intersecting CFEV river catchment polygons. Wetlands which intersected the selected river catchment polygons were then identified as floodplain wetlands. Remaining wetlands were designated non-floodplain. Some wetlands in mountainous areas of western Tasmania that were incorrectly classified as floodplain wetlands in CFEV were reclassified as non-floodplain wetlands.

A single data table was assembled, which combined key attributes from overlapping CFEV river sections with stream order two or greater, DPIPWE hydrology polygons and CFT tiled climate model data. The CFT and hydrology layers were first separately combined with the CFEV river section layer using spatial joins in ArcMap (ESRI). Combined attribute data were then exported to Microsoft Access where queries were used to further combine and sort the data. Where river sections intersected two or more CFT tiles or hydrology polygons, the longest river section was selected.

A similar approach was followed to combine the wetland attributes, keeping floodplain and non-floodplain wetlands in separate tables. The most downstream catchment was selected for floodplain wetlands with an area greater than 20 hectares and extending over two or more hydrology catchments. The majority of remaining wetlands were contained within single hydrology catchments. The catchment with the greatest area was selected where there was an overlap.

2.3 Identifying and assessing risks to biodiversity assets

In this report the term ‘biodiversity asset’ refers to an ecosystem component of interest, be it a taxon, community or ecosystem process. The CFEV data base currently records two main types of asset: individual taxa (e.g. platypus, *Astacopsis gouldi*), or communities of taxa recorded as condition or ‘health’ indices (e.g. macroinvertebrate communities are represented by AusRivAS O/E index values).

2.3.1 Selection of biodiversity assets

Biodiversity assets for Bayesian Belief Network (BBN) modelling were selected on the basis of an extensive literature search, expert advice and consultations with stakeholders. For both rivers and wetlands of Tasmania, the risk assessment was conducted for a number of key ecosystem components, plus one priority species, listed under state and national threatened species legislation. The components we evaluated are listed in Table 3. Those which are single taxa are in bold face type; the others are recorded as ‘condition’ indices. A description and justification for each asset is presented after this table together with a description of the main variables likely to drive changes in these assets.

Table 3 Biodiversity assets selected for river and wetland BBNs

Rivers	Wetlands
Riparian vegetation	Floodplain wetland condition
Platypus	Non-floodplain wetland condition
Giant Freshwater Crayfish (*Astacopsis gouldi*)	Frogs
Native fish	**Dwarf galaxias (*Galaxiella pusilla*)**
Macroinvertebrates (bugs)	
Brown trout (*Salmo trutta*)	

Riparian vegetation was identified as a key asset. Healthy riparian vegetation shades the stream, which reduces water temperature fluctuations; filters overland flows to reduce sediment and nutrient inputs; assists in bank stabilisation and erosion control; and contributes woody debris and organic material to the stream (Gregory et al. 1991). Woody debris reduces the water velocity, increases habitat complexity and provides a substrate for biofilm colonisation (Bilby 1981). Particulate organic material, in the form of leaves and fruit from riparian vegetation, provides the basal resource for the in-stream food chain, from invertebrates to fish (Gregory et al. 1991).

The riparian vegetation communities of Tasmanian rivers are attributed in the CFEV database to all stream sections in the stream drainage. A single community classification is used based on a list of the dominant plant species associated with each class. Riparian vegetation communities are also attributed a condition score in CFEV for all stream sections, based on a rating of the percentage of native vegetation cover within the riparian zone, derived in turn from the Tasmanian TASVEG mapping layer. This information attribute was used as the input to the initial condition rating for the Reference Period in the riparian vegetation BBN

Platypus (Ornithorhynchus anatinus Shaw*)* are semi-aquatic animals that require access to river banks for burrows, and to freshwater habitats where they feed on aquatic invertebrates. They are vulnerable to land use changes, and are known to be susceptible to a waterborne fungal disease, *Mucor amphiborum.* They are also vulnerable to the temperature and hydrological impacts of climate change due to their highly specialised feeding requirements and their limited ability to disperse overland between water bodies (Klamt, Thompson and Davis 2011, Grant and Dawson 1978).

Platypus distributions and population condition ratings for Tasmanian rivers are attributed in the CFEV database for all river sections in the stream drainage. Platypus population condition is derived from integration of information on habitat suitability and disease status. This information attribute was used as the input to the initial condition rating for the Reference Period in the platypus BBN. A second input to the initial condition node in the BBN, a rating of relative macroinvertebrate abundance (derived from CFEV data), was also included, in order to reflect the status of food supply for platypus as an influence on condition of the population at reach scale.

Freshwater crayfish are prominent in Tasmania. The group includes *Astacopsis gouldi* Clark (Decapoda: Parastacidae), the world's largest freshwater crustacean (Gooderham and Tsyrlin 2002). The species is endemic to Tasmania, where it is listed as 'Vulnerable' under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act 1999). It is vulnerable to land use change and poaching, with its limited distribution confined to rivers draining north into Bass Strait (DSEWPC 2012a). This species was selected for BBN modelling as the priority species for riverine biota.

Freshwater crayfish distributions for Tasmanian rivers are attributed in the CFEV database to all river sections in the stream drainage. The condition of *A. gouldi* populations have not been assessed and are not attributed in CFEV, so instead we identified two key condition 'drivers' for *A. gouldi* populations during the Reference Period:

1. *The relative amount of fine sediment in stream substrate*. High levels of fine sediment in stream substrates have been shown to be associated with reduced abundances of *A. gouldi* (Walsh and Walsh 2011). As direct measures of this attribute are not available, data on three key drivers of in-stream sediment loads were used as inputs to a fine sediment load node in the BBN. These were stream section slope, geomorphic sensitivity (a measure in CFEV of erosional responsiveness of river channels to altered hydrology) and a rating of fine sediment delivery to the stream section (a CFEV attribute derived from a set of inputs relating to upstream catchment and land use characteristics).
2. *Water quality during the warmer low flow months*. Low dissolved oxygen (DO) and high water temperatures during low flows are also known to be associated with streams in which *A. gouldi* populations are at low levels (Lynch and Blühdorn 1997). Data on direct measures of these variables are not available. Data on three key drivers of reach scale water quality were used as inputs to a summer-autumn water quality node in the BBN. These were the level of current water abstraction (as a proportion of mean annual runoff), the level of light availability to the stream surface (as a driver of benthic algal production and respiration and stream temperature), and the slope of the stream section (as a driver of re-aeration). Each of these was derived directly or indirectly from the CFEV database.

These information attributes were used as the inputs to the initial condition rating for the Reference Period in the *A. gouldi* BBN. The influences of other drivers, such as illegal fishing or point source pollution, were not included due to the uncertainty surrounding their current influence on *A. gouldi* population status.

Native fish distributions can be directly influenced by temperature and rainfall changes, which can also impact on food resources, habitat availability or reproductive success. These factors may interact with and exacerbate other stressors, such as pollution, increased salinity, disease, competition, overharvesting or land use change (Booth, Bond and Macreadie 2011).

Many Tasmanian native fish have restricted distributions (e.g. Swan galaxias, Clarence galaxias). There are 15 species of Galaxiidae (14 of which are endemic), including 11 which have threatened status under the *Tasmanian Threatened Species Act 1995*. Six of these species have been nominated for listing under the EPBC Act 1999, with the remaining 5 listed as endangered or vulnerable. The Pedder galaxiid (*Galaxias pedderensis*) is considered extinct in its natural range and now only occurs as a translocated population (Jackson 2004). Competition from introduced predatory fish is a major threat to most galaxiid populations, and many survive as fragmented populations in trout-free streams, or are confined to headwaters or Central Plateau lakes. Most galaxiids feed on aquatic insect larvae or crustaceans (Jackson 2004). Other native fish are also vulnerable to climate change. For example, the range of the river black fish (*Gadopsis marmoratus*), has contracted in south-eastern Australia with warming stream temperatures (Booth et al. 2011, Bond et al. 2011). This species is also vulnerable to reduced connectivity between pools (Balcombe et al. 2011).

Native fish communities of Tasmanian rivers are attributed in the CFEV database to all river sections in the stream drainage. A single community classification is used based on a list of the dominant species associated with each class. The condition of fish communities is based on two primary inputs: a rating of relative biomass of exotic versus native fish, and an assessment of the likely level of other impacts on native fish relative to ‘reference condition’ (e.g. dams and acid drainage). These information attributes were both used as the inputs to the initial condition rating for the Reference Period in the native fish BBN.

The exotic brown trout (*Salmo trutta*) fishery is an important local recreation-based industry in Tasmania, with over 30,000 participants and an associated expenditure of up to $5 million annually. It represents one of the major direct socioeconomic values of aquatic ecosystems in the state. Trout populations are found in nearly all the Tasmanian river catchments examined in this study (Tasmanian Inland Fisheries Service unpub. data). Many rivers and lakes are stocked with brown trout by the Inland Fisheries Service (IFS). Brown trout have a narrow temperature tolerance, preferring water temperatures lower than 18^o C (Moloney 2001), and are predicted to contract to higher altitudes with climate change (Bond et al. 2011).

There were no data on the status of the brown trout fishery available in a form that was suitable or readily available for this analysis either within CFEV or from the IFS. However, CFEV data on relative brown trout biomass in the fish community was available. This attribute was used as the input attribute on brown trout fishery condition for the Reference Period. Riverine brown trout catch rates are strongly dependent, among other factors, on the total biomass of fish present. While the CFEV attribute describes only relative biomass, it allows differentiation of locations which would support poor fisheries due to low levels of biomass relative to native fish.

Wetlands were selected for modelling because they can have a highly diverse flora and fauna, due to their hydrological variability. The Tasmanian Wilderness World Heritage Area (WHA) includes much of the Central Plateau of Tasmania, a subalpine periglaciated landscape with numerous shallow tarns and wetlands (Scanlon, Fish and Yaxley 1990). Tasmania's wetlands support a range of threatened and endangered species, and many are listed under the Ramsar Convention for wetlands of high conservation value. Many are important sites for waterbird breeding or feeding. Wetlands are highly vulnerable to land use changes (Kingsford and Norman 2002).

Data on individual ecological components of Tasmanian wetlands are limited, including the thermal tolerances of most wetland biota, with the exception of frogs. This risk assessment therefore focused on assessing:

1. the overall biophysical condition of wetlands as a habitat, from the point of view of climate change driven hydrological hazard.
2. the risk to frog communities from both hydrologically induced habitat change and changes in temperature.

Here, wetlands are defined as 'all mapped standing water permanent or ephemeral water-dependent ecosystems, excluding mapped lakes, ponds and river channels'. CFEV contains an integrated inventory of all Tasmanian wetlands, including open water, ephemeral and saltpan mapped wetlands but also including certain water dependent vegetation communities such as sphagnum bogs, blackwood swamps and sedgelands (DPIW 2008a).

Attribution of environmental variables of wetlands in CFEV is limited to:

1. base data (e.g. elevation, area);
2. data on frog and riparian vegetation communities and burrowing crayfish;
3. ratings for land use intensity, and sediment and nutrient loadings;
4. ratings for local catchment hydrological alteration; and
5. a rating of biophysical condition.

Floodplain wetlands were selected from the CFEV wetlands database in relation to mapped connection to or immediate adjacency to river drainage lines (sections) and their elevation. *Non-floodplain wetlands* were identified in the CFEV spatial wetlands asset data set. The CFEV wetland condition rating attribute WL_NSCORE was used as the initial condition rating for the Reference Period in the floodplain and non-floodplain wetland BBNs.

The Dwarf Galaxiid, a small freshwater native fish, *Galaxiella pusilla* (Galaxiidae) was selected as the priority wetlands species. It is found predominantly in shallow ephemeral and permanent wetlands in Victoria and Tasmania and is listed as vulnerable under the *EPBC Act 1999*, and as rare under the Tasmanian *Threatened Species Protection Act 1995* (DSEWPC 2012b). This species only occurs in wetlands (not rivers), at elevations below 50m AHD, within the distribution of *A. gouldi*, and including the Flinders island group. It is absent on King Island and other NW Bass Strait islands, except Hunter and Three Hummock Islands (Jackson 2004).

Its habitats in northern Tasmania are often degraded or at risk from land use, wetland drainage and declines in the hydrological and water quality status of wetland habitats. It currently has a highly dispersed distribution comprising small vulnerable populations, often in rural landscapes (Figure 3).

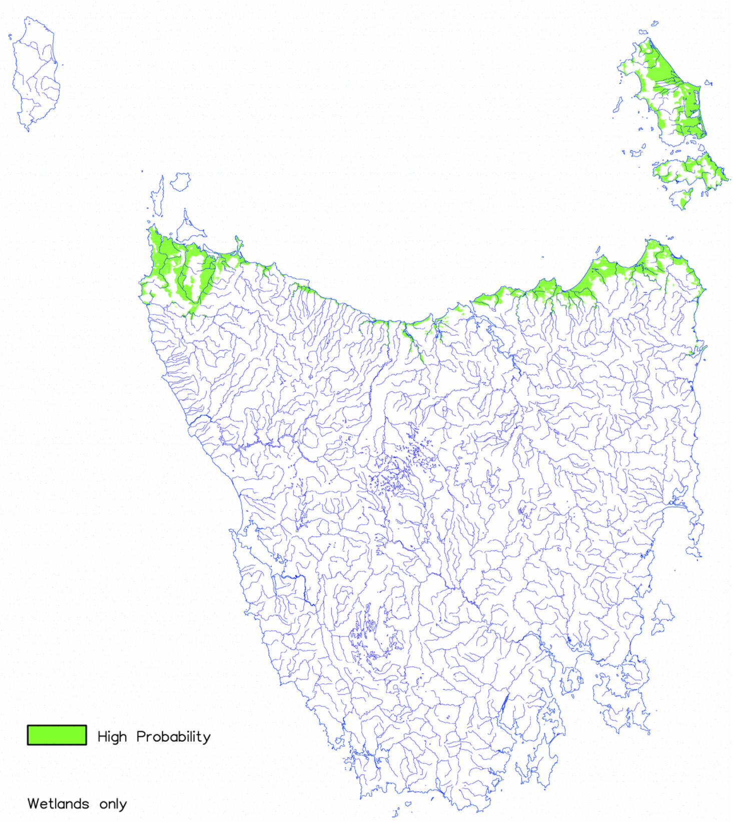


Figure 3 Range map for the Dwarf Galaxias (*Galaxiella pusilla*) in Tasmania

The map shows areas of high probability of occurrence (within wetlands).
Source: DPIW (2008b)

The condition of *G. pusilla* populations have not been assessed and are not attributed in CFEV. We identified two key condition 'drivers' for *G. pusilla* populations during the Reference Period:

1. *Condition of wetland habitats*. The CFEV wetland condition rating attribute WL_NSCORE was used as the measure of habitat condition for *G. pusilla* for the Reference Period.
2. *Maximum temperatures*. Temperature is likely to have been a limiting constraint on *G. pusilla* populations in shallow wetland habitats during the Reference Period due to the potential for summer/autumn thermal stress events and associated declines in water quality (dissolved oxygen). The maximum summer/autumn temperature variable, Max Warm Temp, was used as an input to the Reference Period condition node for *G. pusilla*. The hazard profile for this variable was encoded as for the native fish BBN.

Frogs, and their aquatic juvenile stages, are found in both wetland habitats and in riverine pools. Many frog populations are in decline, due to land use pressures, climate warming and the Chytrid fungus (*Batrachochytrium dendrobatidis*). Tasmania has 11 frog species, of which 3 are endemic: the Tasmanian tree frog, *Litoria burrowsae*; the moss froglet, *Bryobatrachus nimbus;* and the Tasmanian froglet, *Crinia tasmaniensis*. The green and gold frog, *Litoria raniformis*, is listed as vulnerable under the EPBC Act 1999. The striped marsh frog, *Limnodynastes peroni* is listed as endangered. Frogs are vulnerable to warmer water temperatures and evaporating pools in the juvenile stage and warmer air temperatures in the adult stage (and in the egg and juvenile stages for the terrestrial breeding moss froglet).

The Tasmanian wetland frog communities are attributed in the CFEV database to all wetland polygons across Tasmania. A single community classification is used based on a list of species associated with each class. There are 15 frog communities identified for Tasmania in the CFEV database, with their distributions defined by geographic region (e.g. Midlands, South, Eastern Highlands— see Appendix 5: Input node details for wetlands).

The condition of frog communities have however not been assessed and are not attributed in CFEV. Two key condition 'drivers' for frog communities during the Reference Period were identified by us as follows:

1. *Condition of wetland habitats*. The CFEV wetland condition rating attribute WL_NSCORE was used as the measure of habitat condition for frog communities for the Reference Period. This variable is based on an expert rules system weighting of hydrology, catchment disturbance, riparian vegetation condition and water quality input variables.
2. *Maximum temperatures*. Temperature is likely to have been a limiting constraint on frog populations in wetland habitats during the Reference Period due to the potential for summer/autumn thermal stress events. The maximum summer/autumn temperature variable, Max Warm Temp, was used as an input to the Reference Period condition node for frogs, with its relative influence on condition varied by frog community type. Max Warm Temp is the absolute value of the 75th percentile of reference period maximum daily temperatures for the warmest four months (December–March).

One BBN was developed for each ecological component described above. The BBNs had a slightly varying, but fundamentally similar, structure with:

1. a set of input nodes representing hydrological or temperature hazards;
2. input nodes representing inputs to the reference period condition node for the component;
3. intermediate daughter nodes representing key integration steps for hazard variables and/or condition variables;
4. one intermediate daughter node representing the projected condition of the component for the test period;
5. one intermediate daughter node representing the change in condition of the component – equivalent to the consequence; and
6. two output nodes representing the conditional or conditional risk to the component.

The input variables describing the hazards posed by climate-change driven hydrological changes are listed in Table 4.

2.3.2 Overview of Bayesian Belief Networks

A risk analysis was conducted in order to assess the relative level of risk to aquatic ecosystem components across Tasmania resulting from climate change influences on key hydrological and temperature variables. The risk analysis followed the AS/NZS ISO 31000:2009 standards for risk management for Australia and New Zealand (SA/SNZ 2009) by identifying *hazards* – those factors which are believed to drive or potentially drive substantive change in the components of interest, and *consequences* – an assessment of the magnitude of change in the component. The combination of hazards and consequences were used to derive a rating of *risk*.

The risk analysis was conducted using Bayesian Belief Networks which allowed measures of the magnitude of multiple hydrological and temperature variables (hazards) to be linked probabilistically to one or more measures of the biological condition of the component (consequence) and thence to a probability-based assessment of risk. With the rapid development of computational power, Bayesian Belief Networks (BBNs) have emerged as a valuable tool in ecological modelling, and have been successfully used in a number of recent impact assessments (e.g. Chan et al. 2012, Shenton, Hart and Chan 2011, Stewart-Koster et al. 2010, Newton et al. 2007). Webb et al. (2010) have demonstrated that the hierarchical modelling approach of BBNs is more effective in assessing the efficacy of environmental flow releases than standard statistical models, particularly when ecological monitoring data are sparse. BBNs are able to model complex interactions and incorporate the uncertainty inherent in sparse data sets or in highly variable landscapes (Clark 2005).

Bayesian Belief Networks are acyclic graphical representations of multiple links between sets of '*parent*' or input variables and '*daughter*' or output variables (see Figure 27 for an example). Each variable is represented as a *node* and each node contains information on the variable's *states*, as well as the dependencies of that variable's states on the states of its parent nodes. These dependencies are presented as *conditional probability* tables (CPTs) which define the probabilities of each daughter variable state occurring given the occurrence of the parent variable states.

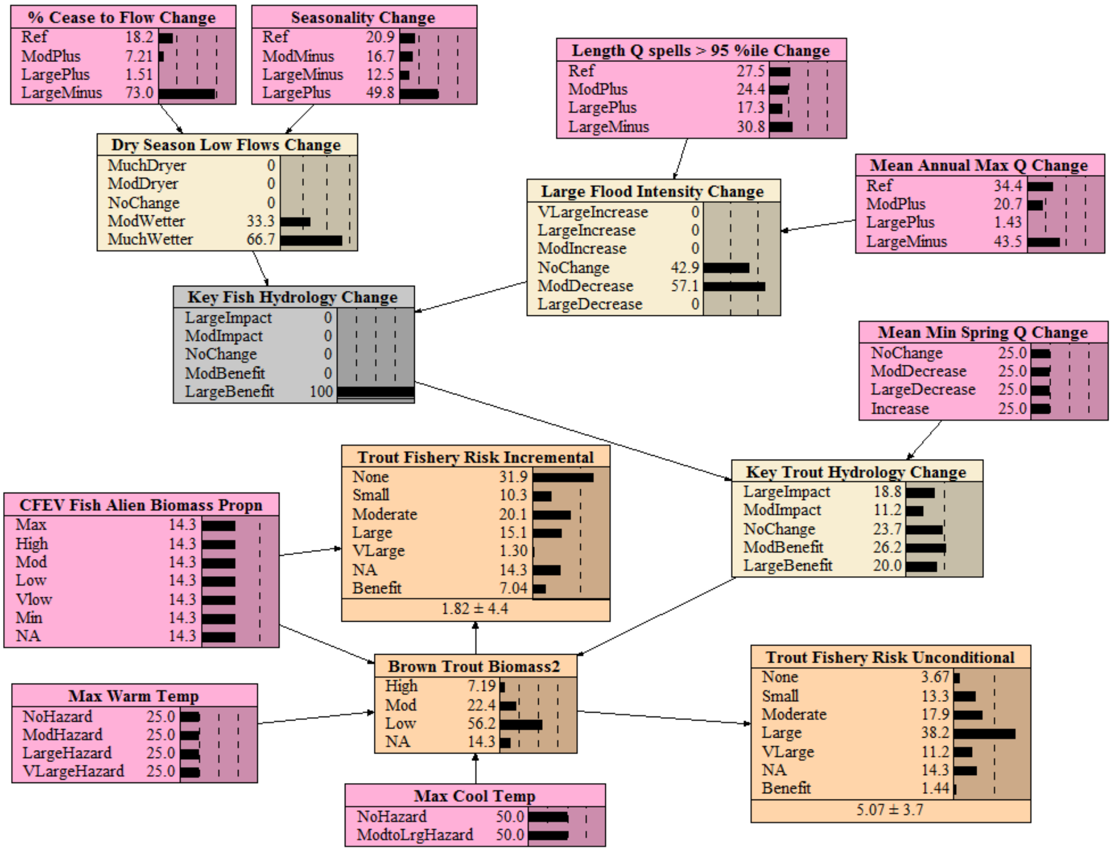


Figure 4 Brown trout BBN model nodes and connections

Pink denotes a 'parent' input variable, which incorporates data from either hydrological modelling or CFEV, grey and cream indicate derived 'daughter' input variables, beige denotes an output condition score. Arrows show the direction of connection between nodes.

The structure of the 'network' of linked parent and daughter nodes, the choice of states within nodes and the probabilities of states given the parent (input) states are all matters for careful conceptual design. All major drivers (hazard variables) and links should be included, and care must be taken in the exclusion of less important variables and links. Network structure is thus highly important to the outcome in a BBN analysis. Similarly the choice and definition of states within nodes requires careful thought. The magnitude of individual probabilities within the node CPTs is also critical. The CPTs in any BBN may be based on actual data, on expert opinion, or a combination of the two.

Once a network structure is established containing all parent-daughter nodes and links of interest, the compiled network can then generate probabilities for all daughter variable states for any given set of input variable states. This property is ideally suited to risk assessment as it allows all hazards to be represented as input variables;

1. All possible consequences which depend on the hazards (and any other contextual variables) to be represented as 'daughter' nodes and states,
2. Risk, which depends on both hazards and consequences to be defined based on change in the magnitude of consequences;
3. The probabilities of possible consequence and risk states to be assigned given known hazards.

This also captures the essence of risk assessment, along with the ability to define uncertainty – either as a set of probabilities (chances of occurrence) for risk states or as a quantified level of variation around the most likely risk state. For this study the overall risk associated with a set of hazard inputs to a BBN was initially identified as a set of probabilities for each of a number of risk states (ranging from 'very high risk' to 'no risk'). An additional risk level was also assigned for those cases in which a potentially beneficial outcome might be anticipated ('benefit').

All ecosystem components were assigned an initial condition rating, based directly on, or calculated from condition ratings provided in the CFEV database for that component. This rating was deemed as representing the condition of the ecosystem component during the 1960 – 1990 reference period, since the CFEV data represented the condition of Tasmanian aquatic ecosystems during the early- to mid- 1990s.
Data on hazard variables were prepared by direct comparison of variable values for three projected *Test* time periods (2010 - 2039, 2040 - 2069, 2070 - 2099) with the value for the *Reference* period (1961 – 1990).

Most hazard variables were entered into the risk analysis as ratios:

$$\frac{Test\ \ Period\ value}{Reference\ Period\ value}$$

with the exception of a small number of variables with values in units of percentage of time. In these cases, the hazard variables were prepared as differences in percentages between the time periods:

$$Test\ \ Period\ value - Reference\ Period\ value$$

The hazard ratings and rationales for each of the hydrology and temperature variables are detailed below:

2.3.3 Hydrology hazard ratings

In the following, the name of each of the hydrological variables used (in italics) is followed by the abbreviated name used in figures, tables and appendices (in parentheses). The hazard ratings for all hydrological variables, which are expressed as the ratio of test to reference period values, are shown in 'Appendix 3: Hydrology and temperature node states'. The biota to which they were applied are shown in Table 4.

Proportion of Cease to Flow Change (p.ctf). Increases in the proportion of time at which flows cease is seen as a substantial stressor for all aquatic biota, due to its effects on temperature, dissolved oxygen and loss of connectivity and ultimately on habitat loss due to dewatering.

- For riparian vegetation, enhanced cease to flow conditions are believed to be tied to the hazard of sustained drying impacts in the root zone. For the non-floodplain wetlands, cease to flow conditions pose a hazard of enhanced evaporative habitat loss during the warmer months, especially for smaller isolated wetlands (Poff, Brinson and Day 2002).
- The hazard ratings for this variable were based on a scientific expert belief that an increase or decrease of > 10 cease to flow days per year poses a significant risk or benefit to native fish survival and the community. This also assumes that not all cease to flow days need to be consecutive. 10 days per year = 2.7% of the time.

Change in seasonality (Seasonality). Substantial shifts in seasonality of river flows, especially in base flows, are believed to pose a hazard via loss of seasonal flow cues (e.g. Chessman 2009), aseasonal dewatering of wetted habitats during key life cycle events, such as fish spawning and egg development (e.g. Hardie, White and Barmuta 2007) and other changes in seasonal timing of key inundation events for wetlands and riparian vegetation, for example (e.g. Casanova and Brock 2000).

- 'Seasonality' represents the proportional change in the percentage of total annual flow occurring in the 6 driest months of the year for the 30 yr time period in question. The overall state-wide median value of this variable for the reference period (1961-1990) was 32% and the minimum value was 14%.
- Changes of 20% from the reference period value were considered to be major. This variable is the percentage of total *annual* yield, of which dry season flows are a small proportion. Hence a small change represents a much larger change in dry season flows – the season in which the bulk of the hazard posed by change is associated.

Duration of high flow spells (Spellsgt95ile) Changes in the length (total duration) of high flow events poses a hazard associated with: geomorphological changes in channel morphology in responsive stream channels (Bendix and Hupp 2000), and availability of spawning gravels in less sensitive channels (e.g. Kondolf et al. 1991); changes in the duration of high flow events are important for plant and fish recruitment; changes in the level of connectivity (river to floodplain); and changes in the level of channel and riparian disturbance (Bendix and Hupp 2000).

- Spellsgt95ile represents the proportional change in the duration of flows greater than the 95th percentile of reference period flows. The overall state-wide median value of this variable for the reference period (1961-1990) was 4 days and the minimum and maximum values were 1 and 22 days respectively. A proportional change from reference period values of more than 0.5, i.e. a 50% increase in duration, was deemed likely to represent a substantial change in the level of hazard associated with this variable.

Maximum flow change (avgmaxann). A large change in the annual maximum flow is considered an erosional and disturbance hazard to the state of the channel and habitats for all in-stream biota (e.g. Walker and Thoms 1993).
A large increase is considered to be when the ratio of test to reference period values of avgmaxann is equal to or greater than 2, with moderate to large changes occurring when greater than 1.5.

Summer maximum flow (Summermax). Changes in the magnitude of larger freshes ('flushing flows') during the low flow summer season are considered to pose a hazard for the quality of bed habitat (build-up of algae and fines), food resources, and to low flow water quality conditions for benthic macroinvertebrates (e.g. Boulton and Lake 2008) and *Astacopis gouldi* (Threatened Species Section 2006).

- Values of summermax below 50% of the reference period value are considered to pose a high level of hazard, whereas values greater than 150% represent a potential benefit.

Mean minimum spring flow (springQmin). Reductions in the average flows during spring (September to November) in Tasmania are known to represent a substantial hazard to spawning success for brown trout in rivers. Dewatering during egg development in stream gravel patches and riffle bars is a major cause of mortality and driver of recruitment decline in brown trout populations, especially when occurring over several consecutive years (Davies 1989, Davies and Sloane 1987).

- Values of springQmin below 50% of the reference period value are considered to pose a high level of hazard, whereas values greater than 125% represent a significant benefit.

Summer median flow (SummerMedQ). Changes in summer median flows represent a hazard to survival, recruitment success and condition of riparian and floodplain vegetation (e.g. Nilsson and Svedmark 2002, Poff et al. 1997), as well as to the potential for wetland drying (Pittock, Finlayson and Howitt 2012). In essence SummerMedQ represents a surrogate for wetter or drier summers.

- Values of SummerMedQ below 50% of the reference period value are considered to pose a high level of hazard, whereas values greater than 150% represent a potentially significant benefit.

CV of Annual flow (AnnCV). Changes in the variability of annual flow yields across a multi-decadal time periods are considered to pose a hazard to the diversity of riparian and wetland vegetation and vegetation communities at catchment scales (Poff et al. 1997, Richter et al. 1997, Ward 1998). Major disturbance events are known to 'reset' seral vegetation assemblages (Bendix and Hupp 2000), often in patches, and assist in maintaining vegetation mosaics in the landscape (e.g. Auble and Scott 1998) (Pringle et al. 1988), both within and among riparian and wetland habitats.

- Values of AnnCV below 50% or above 150% of the Reference Period value are considered to pose a high level of hazard.

OFS Max (OFSMax) *and OFS Min* (OFSMin). These two variables measure the maximum and minimum interval between overbank flow spells respectively. Changes in the interval between overbank flow spells are considered to pose a hazard to vegetation in the riparian zone and in floodplain wetlands through extending the drying period between major overbank wetting events (e.g. Wen et al. 2009). These two variables were selected to represent this, acting in concert

- Values of OFSMax and OFSMin below 50% of the reference period value are considered to pose a high level of hazard, whereas values equal to or above 150% were considered to provide potential benefits.

Median interval between maximum flows (MaxMedSpells). This variable was applied to the non-floodplain wetlands based on the same rationale as for overbank flows above (and with the same hazard ratings). MaxMedSpells was the variable applicable to the hydrology record from the climate model outputs. Non-floodplain wetlands did not have direct hydrology models applicable to them and hence overbank flow measures could not be derived for them.

2.3.4 Temperature hazard ratings

Thermal stress is known to be a major limiting autecological factor for many frog, fish and invertebrate species in both rivers and wetlands (see reviews by Dallas 2008, Ward 1985, Caissie 2006). An extensive literature search was conducted to source the thermal tolerance data for the dominant native fish species, common frog species, *Astacopsis gouldi* and many benthic macroinvertebrate families known from Tasmanian rivers (see section 2.2.2 and Appendix 2: Thermal tolerance references) and used to set the hazard ratings for each taxon, as shown in 'Appendix 3: Hydrology and temperature node states'.

The focus of the hazard ratings was on increases in the upper temperature threshold (using the (MaxWarmTTest variable), as no climate model used in this study showed any substantive temperature declines in any of their projections. In addition thermal variable and associated hazard ratings were based on temperatures during the warmest months (December to March), because Tasmania's upper temperatures during this period are also associated with declines in other synergistic factors such as flow and dissolved oxygen.

Cooler month upper temperatures were considered but only used as a hazard input (using the MaxCoolT variable) for the brown trout fishery BBN, since spawning success and egg development are known to be temperature-limited during the relevant season (May–August) (e.g. Pankhurst et al. 1996).

Table 4 Hazard variables selected as inputs to the BBN risk analysis for each ecological component

Variables included in each river or wetland ecosystem component are indicated with the symbol **x.**

Hazard variables			**Rivers**						**Wetlands**			
Hydrological variable	**Form**	**Description**	**Native fish**	**Benthic macro-invertebrates**	**Platypus**	**Riparian vegetation**	**Brown trout fishery**	***A. gouldi***	**Floodplain wetlands**	**Non-floodplain wetlands**	**Frogs**	***G. pusilla***
Change in Cease to Flow Proportion (pctf)	difference between time periods	difference in proportion of flow falling in the driest 6 months	**x**	**x**	**x**	**x**	**x**	**x**		**x**		
Change in seasonality (Seasonality)	ratio of test to reference period	the proportional change in % of total annual flow from the 6 driest months	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**		
Duration of high flow spells (Spellsgt95ile)	ratio of test to reference period	the mean duration of all flows > 95th percentile	**x**	**x**	**x**	**x**	**x**		**x**	**x**		
Maximum flow change (avgmaxann)	ratio of test to reference period	value of average annual maximum flow	**x**	**x**	**x**	**x**	**x**		**x**	**x**		
Summer maximum flow (Summermax)	ratio of test to reference period	maximum value of summer daily flows		**x**				**x**				
Mean minimum spring flow (springQmin)	ratio of test to reference period	mean daily flow for spring season					**x**					
Summer median flow (SummerMedQ)	ratio of test to reference period	median value of summer daily flows				**x**			**x**	**x**		
CV of Annual flow (AnnCV)	ratio of test to reference period	coefficient of variation of mean annual flow				**x**			**x**	**x**		
OFS Max Interval (OFSMax)	ratio of test to reference period	maximum value for overbank flow spell duration				**x**			**x**			

Hazard variables				**Rivers**							**Wetlands**			
Hydrological variable	**Form**	**Description**		**Native fish**	**Benthic macro-invertebrates**	**Platypus**	**Riparian vegetation**	**Brown trout fishery**	***A. gouldi***		**Floodplain wetlands**	**Non-floodplain wetlands**	**Frogs**	***G. pusilla***
OFS Min Interval (OFSMin)	ratio of test to reference period	minimum value for overbank flow spell duration					**x**				**x**			
Median interval between max flows (MaxMedSpells)	ratio of test to reference period	median of maximum flow duration										**x**		
Temperature variable		**Description**												
Maximum warm temperature (MaxWarmTTest)	absolute value for test period	75%ile of max daily temps for 4 warmest months (Dec - Mar)		**x**	**x**			**x**	**x**				**x**	**x**
Maximum coolest temperature (MaxCoolT)	absolute value for test period	75%ile of max daily temps for 4 coolest months (May - Aug)						**x**						
Habitat condition variable		**Description**												
Test period wetland condition	absolute value for test period	absolute value of BBN-derived condition score for wetland condition											**x**	**x**

A set of conditional probability tables (CPTs) was developed for each BBN, with the probability state break-points based on the expert opinion of Tasmanian scientists. A CPT was developed for every daughter node (a node receiving inputs) in each BBN, taking into account the conceptual basis for the links between the input and output states, and the interactions among input variables. Each CPT has a unique combination of input states associated with probabilities for each output state. An example of a CPT is shown in Table 5 and illustrates the requirement for each CPT in a network model to contain:

- All possible combinations of input variable states;
- For each combination, a full set of probabilities for all outputs states which sums to 100%.

A complete listing of the input nodes for each BBN, including tabulations of the score values and their justifications is provided in ‘Appendix 4: Input node details for rivers’ and ‘Appendix 5: Input node details for wetlands’.

The key measure of consequence in these risk assessment BBNs is the *change in condition* for the ecological component. The change in condition was rated as being in one of five states: an increase; no change; a small decline; a moderate decline; a large decline (Table 5 is an example for macroinvertebrate community condition). The magnitude of change depended on the difference between the states of the two input variables – condition in the Reference Period and condition in relevant test period.

Table 5 Example of a Conditional Probability Table (CPT) for a node in the risk assessment BBNs

The left hand columns contain the two input variables and their states. Right hand columns show the probabilities for each output variable state that are associated with each combination of input states. All rows sum to 100%. Ext = Extremely.

Macroinvertebrate Community Condition input variables and states		Output variable states and probabilities				
Condition at Reference Period	**Condition at Test Period**	**Change in Macroinvertebrate Community Condition (DELBUGCO)**				
		Increase	**No change**	**Small decline**	**Moderate decline**	**Large decline**
Reference	Reference	10	80	10	0	0
	Moderate	0	10	20	50	20
	Low	0	0	0	40	60
	Very Low	0	0	0	10	90
	Ext Low	0	0	0	0	100
Moderate	Reference	60	40	0	0	0
	Moderate	10	80	10	0	0
	Low	0	10	20	30	40
	Very Low	0	0	0	30	70
	Ext Low	0	0	0	10	90
Low	Reference	80	20	0	0	0
	Moderate	60	40	0	0	0
	Low	10	80	10	0	0
	Very Low	0	10	20	30	40
	Ext Low	0	0	0	30	70
Very Low	Reference	90	10	0	0	0
	Moderate	80	20	0	0	0
	Low	60	40	0	0	0
	Very Low	0	80	20	0	0
	Ext Low	0	0	10	30	60
Ext Low	Reference	100	0	0	0	0
	Moderate	100	0	0	0	0
	Low	80	20	0	0	0
	Very Low	60	40	0	0	0
	Ext Low	0	20	20	30	30

Risk was derived in the BBNs from the magnitude of the change in condition of the component. The largest decline in condition was considered the greatest risk, and the smaller the decline the smaller the risk. If the condition increased, risk was deemed to be minimal and was rated as beneficial.

Two forms of risk were derived: unconditional risk and conditional risk. Unconditional risk was based solely on the magnitude of change in condition. Conditional risk was based on both the magnitude of change in condition but also the initial condition in the Reference Period as quantified in the CFEV database. Conditional risk was used in the final assessment, as it was believed to more appropriately reflect the level of risk experienced by ecosystem components due to climate change when starting from an already established level of condition. Risk was rated as being in one of six states, each of which was assigned a score (Table 6):

Table 6 Conditional risk states and assigned risk scores

Risk state	Risk score
Very high risk	10
High risk	7.5
Moderate risk	5
Low risk	2.5
No risk	0
Benefit	- 10

Risk scores were then derived by calculating a probability weighted mean of individual state scores. Overall BBN risk scores, $\bar{s}$, were mapped as the mean value of that variable for all river reaches or wetlands, weighted according to the formula:

$$\bar{s} = \frac{[(I_l \times 5) + (I_m \times 5) + (B_m \times -5) + (B_l \times -10)]}{100}$$

Where I denotes impact, B denotes benefit, and the subscripts l and m denote large and moderate respectively.

The standard deviation for the mean, *sd*, was also derived from the probability weighted scores, according to the formula:

$$sd = \sqrt{}[\sum(x - \mu)^2 \text{ x } p(x)]$$

where μ is the mean $\bar{s}$, $p\,(x)$ is the probability of state x, and x denotes the individual state score.

2.3.5 Risk scores and mapping

BBN output tables were combined with CFEV wetlands and CFEV rivers spatial layers prior to mapping. Geodatabase versions of the CFEV wetlands or CFEV rivers spatial layers were created for each BBN output using ArcCatalog (ESRI).

The relevant BBN output table (river, floodplain or non-floodplain wetland) was imported into the each geodatabase with Microsoft Access. A query was created to combine the BBN table and spatial layer attribute table. This generated a new attribute table which was renamed to match the original. A series of map templates were developed to map the BBN outputs with ArcMap.

Mapping of some of the BBN outputs were constrained to particular geographic regions or features. Native fish BBN outputs were mapped for CFEV river sections of stream order three or greater for clarity. *Astacopsis gouldi* mapping was constrained to rivers where they were known to be distributed and *Galaxiella pusilla* mapping was constrained to the wetlands where CFEV indicated their likely presence. Floodplain wetlands were mapped with gauged hydrology for the part of the state covered by DPIPWE hydrology, and CFT gridded hydrology for the balance of the state (generally the west and southwest). Non-floodplain wetland mapping used the CFT gridded hydrology.

2.4 Adaptation responses

2.4.1 Scoping and classification of adaptation responses

Scoping adaptation responses (step 5a of Figure 1) aimed to capture the full range of responses for freshwater ecosystems. We conducted an extensive literature review, using Scopus, Web of Science and Google Scholar as databases, and the main search terms “climate change”, “adaptation”, “freshwater” and “wetland”, to identify published freshwater adaptation responses from Australia and overseas.

A workshop entitled “Implementing Adaptation to Climate Change in Terrestrial and Freshwater Environments in Tasmania” was held in November 2011 (Gilfedder et al. 2012). We participated in and helped co-ordinate the freshwater sections of this workshop, and gathered additional responses and suggestions from the staff of DPIPWE and IFS. In addition we made presentations to and held discussions with stakeholder groups, including Hydro Tasmania, the Australian Society for Limnology (ASL), Natural Resource Management (NRM South), the NCCARF Future of Environmental Flows workshop in Canberra, and the team from the Centre for Environment Landcare Assistance Project (LAP)).

Then we classified the adaptation options according to four dimensions: the biodiversity asset that it could potentially apply to, the class of the adaptation option, the spatial scope of the option and the jurisdictions likely to be involved with that option. These dimensions corresponded to spatial and operational factors that were used by stakeholders in considering how to organise and implement adaptation options. Each of the last three dimensions is now explained in more detail.

There were four classes of adaptation options (Figure 5):

1. On-ground options encompassed direct interventions with in-stream, riparian or wetland habitats, such as fencing to exclude farm stock, monitoring for weeds or riparian zone management.
2. Water management refers to those options that intervene in the water or flow regime of a wetland or river. These include such diverse actions as dam management strategies or trading in water licenses.
3. Catchment management options refer to terrestrial or riparian interventions such as incentives for changes to farm management or incentives for riparian management. This could include covenants to protect riparian vegetation, or prescriptions for forestry activity.
4. Policy options include a variety of tools that impact water or biodiversity management in freshwater environments. Typical adaptation options could be management of freshwater fisheries or Ramsar listing of wetlands.

Spatial scope was classified to reach/wetland, property, catchment, region or basin/state levels. Reach/wetland actions are those that need to be implemented along an entire reach of a river or a whole wetland, and these may lie entirely within one property or span several adjacent properties. The ‘basin/state’ category describes very broad-scale actions that apply across several regions, such as some major basins in Australia (e.g. Murray-Darling or Lake Eyre basins), or state-wide actions such as policy reform.

Jurisdictional levels were identified as property owner, community group, NRM/CMA (i.e. Natural Resource Management agency or Catchment Management Authority), local government, water utility or agency, state government or federal government.

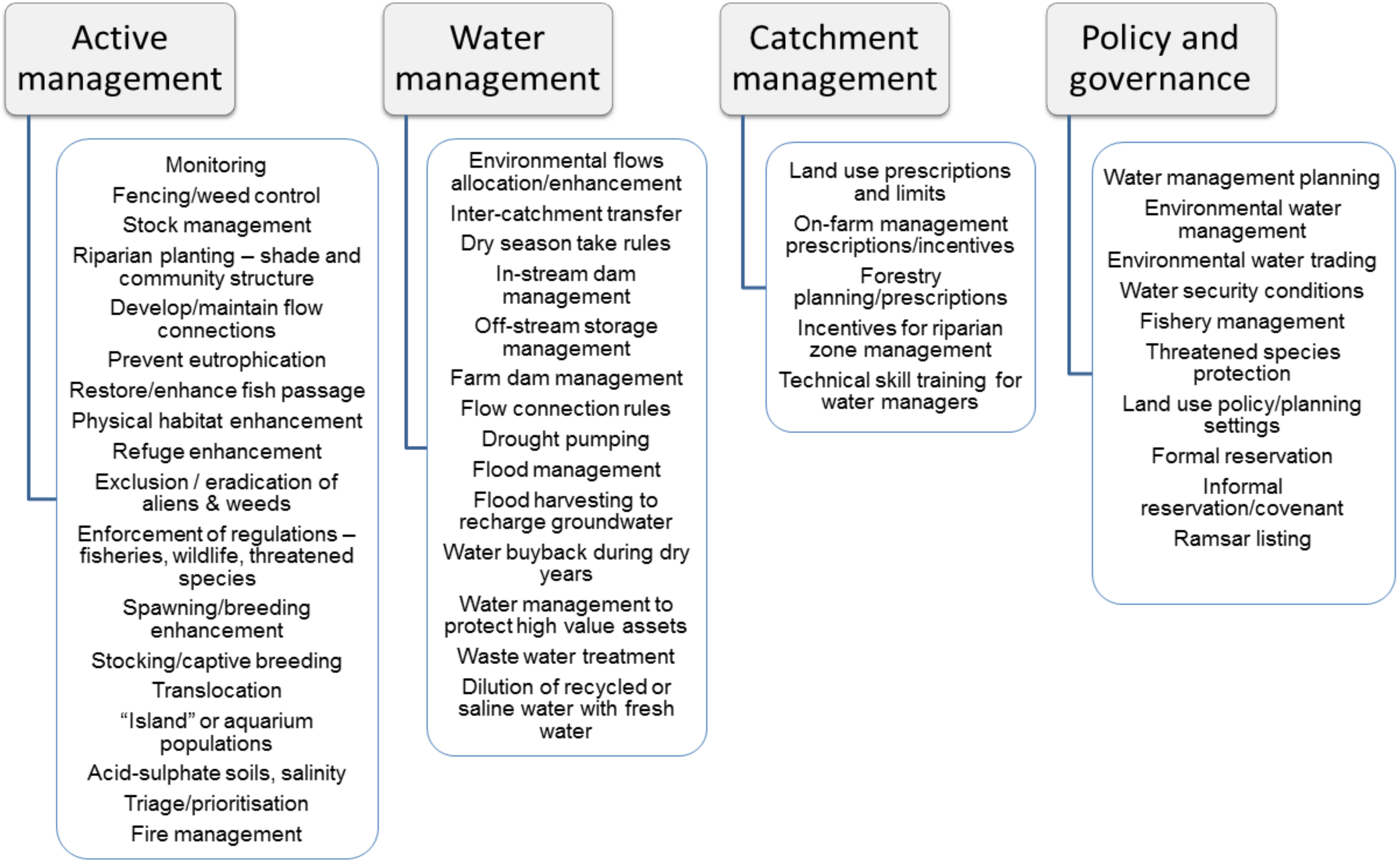
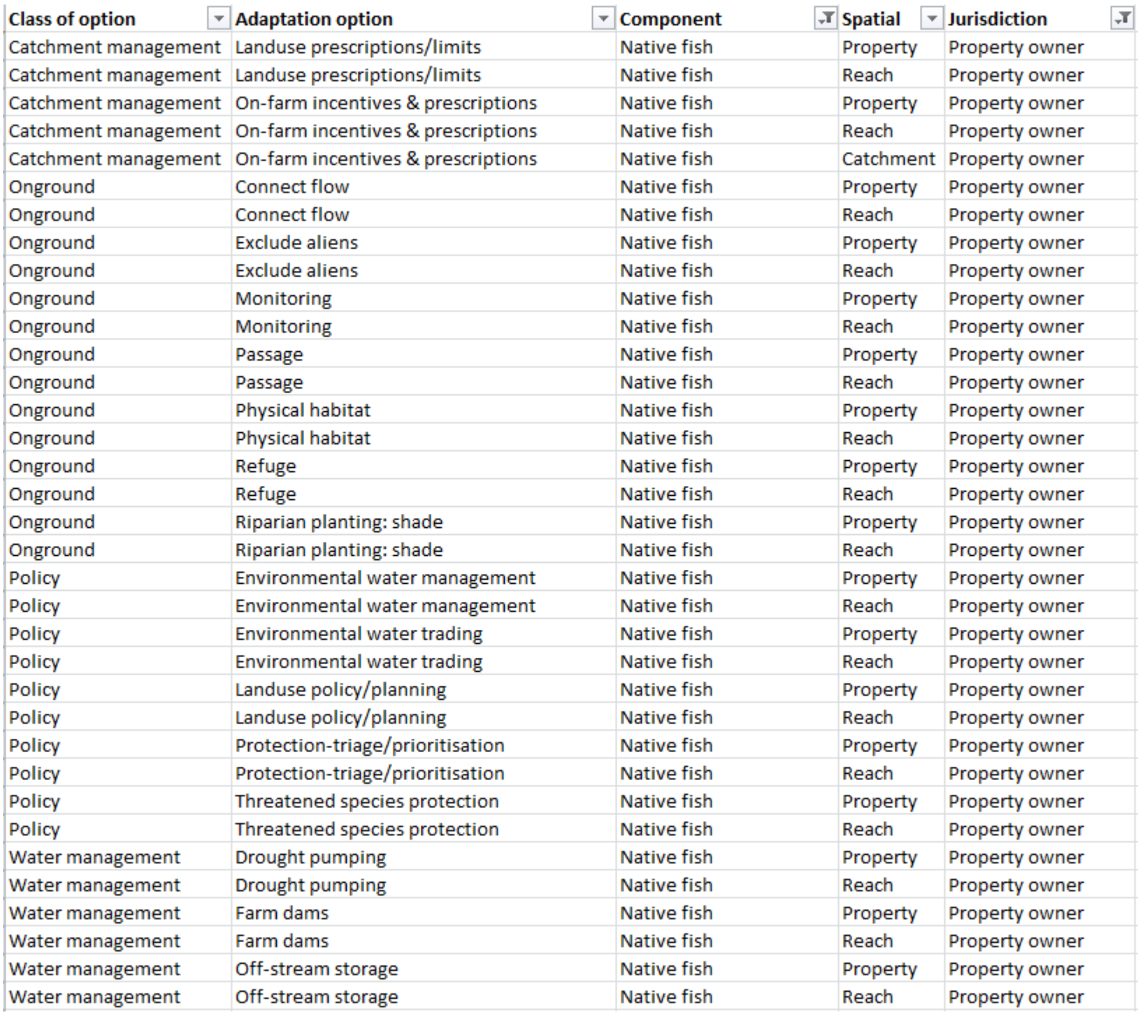


Figure 5 Classes of adaptation actions

These dimensions recognise the inherent complexity of adaptation options for fresh waters. A seemingly discrete option, such as increasing the number of farm dams, has ramifications for several jurisdictions (property owner, NRM/CMA, water utility or agency and state government) and over several spatial scales (property, reach, catchment and state/basin).

To manage this complexity, we organised the adaptation options into a filterable list in Microsoft Excel so that end-users could select the particular categories of each dimension in the order that was most useful to them. The example screen shot in Figure 6 shows the list of adaptation options for native fish conservation relevant to a property owner.



Class of option	Adaptation option	Component	Spatial	Jurisdiction
Catchment management	Landuse prescriptions/limits	Native fish	Property	Property owner
Catchment management	Landuse prescriptions/limits	Native fish	Reach	Property owner
Catchment management	On-farm incentives & prescriptions	Native fish	Property	Property owner
Catchment management	On-farm incentives & prescriptions	Native fish	Reach	Property owner
Catchment management	On-farm incentives & prescriptions	Native fish	Catchment	Property owner
Onground	Connect flow	Native fish	Property	Property owner
Onground	Connect flow	Native fish	Reach	Property owner
Onground	Exclude aliens	Native fish	Property	Property owner
Onground	Exclude aliens	Native fish	Reach	Property owner
Onground	Monitoring	Native fish	Property	Property owner
Onground	Monitoring	Native fish	Reach	Property owner
Onground	Passage	Native fish	Property	Property owner
Onground	Passage	Native fish	Reach	Property owner
Onground	Physical habitat	Native fish	Property	Property owner
Onground	Physical habitat	Native fish	Reach	Property owner
Onground	Refuge	Native fish	Property	Property owner
Onground	Refuge	Native fish	Reach	Property owner
Onground	Riparian planting: shade	Native fish	Property	Property owner
Onground	Riparian planting: shade	Native fish	Reach	Property owner
Policy	Environmental water management	Native fish	Property	Property owner
Policy	Environmental water management	Native fish	Reach	Property owner
Policy	Environmental water trading	Native fish	Property	Property owner
Policy	Environmental water trading	Native fish	Reach	Property owner
Policy	Landuse policy/planning	Native fish	Property	Property owner
Policy	Landuse policy/planning	Native fish	Reach	Property owner
Policy	Protection-triage/prioritisation	Native fish	Property	Property owner
Policy	Protection-triage/prioritisation	Native fish	Reach	Property owner
Policy	Threatened species protection	Native fish	Property	Property owner
Policy	Threatened species protection	Native fish	Reach	Property owner
Water management	Drought pumping	Native fish	Property	Property owner
Water management	Drought pumping	Native fish	Reach	Property owner
Water management	Farm dams	Native fish	Property	Property owner
Water management	Farm dams	Native fish	Reach	Property owner
Water management	Off-stream storage	Native fish	Property	Property owner
Water management	Off-stream storage	Native fish	Reach	Property owner

Figure 6 Screen shot of filtered list of adaptation options

2.4.2 Prioritisation and identifying planning and policy needs

We conducted an extensive review of state and territory planning and policy procedures relating to adaptation to climate change. Members of our team participated in planning and policy workshops, such as the CSIRO facilitated workshop in August 2012, which focussed on setting objectives for climate change adaptions for the Tasmanian Central Plateau World Heritage Area and the December 2012 state-wide NCCARF Project workshop: “Supporting evidence-based adaptation decision-making in Tasmania - the state of adaptation research”.

In addition, we held a workshop in November 2012, attended by twelve experts from the Nature Conservation Branch and the Water Assessment Branch of DPIPWE, Hydro Tasmania, and the Tasmanian Land Conservancy. We presented examples of the maps generated from the BBN predictions, to focus discussion on the regions and biological assets most at risk from climate change. The workshop then considered the adaptation options and limitations for three detailed Tasmanian case studies (Figure 7), with varying land tenures and water supply pressures. Adaptation strategies for a fourth intensive farming area in the northwest of Tasmania, with reliable rainfall and conflicting land uses, were briefly considered. We also held focussed interviews with Tasmanian stakeholders, where the detailed case studies were discussed.

The aim of presenting case studies to the workshop was to elicit specific responses to how adaptation to climate change might be implemented and to determine what policy and planning tools were currently in use. We also sought to actively source advice on deficiencies in planning tools and procedures.

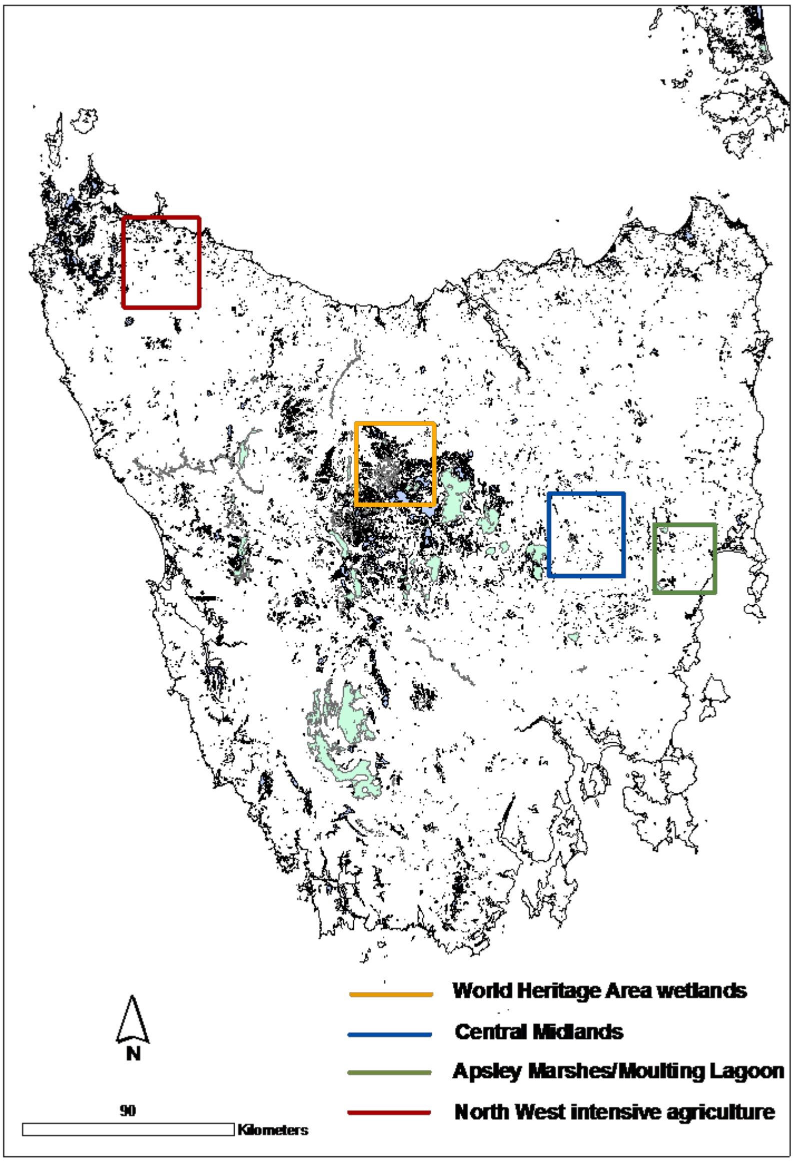


Figure 7 Map of Tasmania showing the four case study areas selected for the adaptation workshop and consultations

The site name is indicated by the rectangle colour shown in the key. Large lakes are shown in pale green, wetlands in light blue/black.

The case studies were considered in order of complexity of land tenure and land use, and water supply and demand issues:

1. *World Heritage Area wetlands*. The WHA wetlands were selected as a case study because they are conserved in an international reserve system, without any major land tenure or land use issues. This area was identified in our temperature modelling as having the highest predicted water temperatures in the state. The wetlands are of high conservation value, with extensive freshwater lakes and tarns, karst systems, many narrow range endemic taxa, and primitive flora and fauna species, such as the 'living fossil' *Anaspides* sp. (Syncaridae).
2. *Apsley Marshes-Moulting Lagoon*. Moulting Lagoon is a Ramsar-listed coastal wetland, with Crown Land tenure, although adjacent land is privately owned and comprised of residential, tourism and agricultural properties (Mowling et al. 2010). The lagoon is the estuary of the Swan and Apsley rivers. The adjacent Apsley Marshes are a privately owned Ramsar-listed freshwater wetland. The two wetlands are important breeding and feeding sites for waterbirds, and provide habitat for several threatened species, such as the Swan galaxiid (*Galaxias fontanus*), the endangered Australasian bittern (*Botaurus poiciloptilus*), and the green and gold frog (*Litoria raniformis*).
3. *The Central Midlands* is a low rainfall area, but has intensive agricultural development, with significant irrigation infrastructure. It provides important habitat for a number of threatened species, including the green and gold frog, southern toadlet (*Pseudophrynne semimarmorata*), the swan galaxiid and the South Esk freshwater mussel (*Velesunio moretonicus*: Hyriidae). The Macquarie and South Esk Rivers have several large, deep (up to 30 m) riverine pools, locally known as 'broadwaters', which contain a diversity of plant and animal species, some listed as threatened or endangered (DPIPWE 2009). Although some broadwaters are Ramsar listed, they are under pressure from water extraction. The area also includes naturally saline wetlands, six of which are listed in the Directory of Important Wetlands Australia (DIWA). The rivers and lakes of the midlands are considered important to the recreational fishing industry.
4. *The North West intensive agriculture area* has fertile soils and is highly valued for horticulture, dairy farming and forestry. It is the centre for milk and vegetable processing and has high demand for irrigation supply, although this area has some of the highest rainfall in Tasmania. On the edge of the Tarkine wilderness area, with pristine rainforest, the region has historical values and aboriginal heritage sites. However, there is strong pressure to increase irrigation supply by inter-basin transfer from the Arthur River, a major source of water for the Tarkine area, and to develop forestry and mining leases in the headwaters of the main rivers. The north coast is also an important region for endemic freshwater crayfish, including the 'Vulnerable' *Astacopsis gouldi*, which is declining in abundance in the northwest rivers (Threatened Species Section 2006). Populations of narrow-range endemic burrowing crayfish, such as the 'Vulnerable' *Engaeus* spp. are also at threat from land use change and altered hydrology (Doran 1999, Richardson, Doran and Hansen 2006).

2.4.3 Communication

Because Tasmania was the first state to access properly downscaled climate change data, this project's initial focus was on Tasmania so as to work through and model how these resources can be combined and integrated for adaptation planning at state-wide and regional scales. During the project development we examined how the steps in Figure 1 could be articulated with water management planning instruments, by working with state agencies and stakeholders to identify policy and planning needs. The final phase of this project was to communicate our understanding of aquatic ecological risk assessment, adaptation options, and the policy and planning needs nationally.

State water management and conservation agencies are the primary user groups since their staff are concerned with policy, planning and management. In the initial phases of our project we were most closely engaged with Tasmanian end-users: Water Planning and Water Management branches of the Water and Marine Resources Division of the Department of Primary Industries, Parks, Water, and Environment (DPIPWE), and conservation planners from the Land Conservation Branch of DPIPWE, the Inland Fisheries Service (IFS), the Parks and Wildlife Service, water managers in the three NRM regions, Hydro Tasmania, Irrigation Tasmania and the Tasmanian Climate Change Office (TCCO) in the Department of Premier and Cabinet.

We broadened our consultation base later in the project as we generated risk maps. Stakeholders from NRM and private conservation NGOs that are active on conservation planning and land management were included in our workshops and targeted interviews. We also collaborated with other projects dealing with adaptation in terrestrial systems including a 2-day workshop entitled “Implementing adaptation in nature conservation and natural environments in Tasmania” on 28-29th November 2011 (Gilfedder et al. 2012).

In addition, we conducted targeted, structured interviews with senior water policy-makers in each State and Territory in early 2013. These interviews were conducted in lieu of workshops as they required less time and encouraged more detailed responses than joint workshops. The interviews were conducted by phone or in person over a 30 minute period and were designed to follow on from our review of national policy and adaptation frameworks for conserving freshwater biodiversity under climate change. This was in recognition that our review only covered publicly-available policies, whereas in most jurisdictions, policy development is an ongoing process (see example questions and people contacted in Box 1).

Our findings were shared and discussed with participants in the two Freshwater Biodiversity Adaptation Research Showcases (Canberra, 21 March 2013, presented by Dr Anne Watson and Brisbane, 22 March 2013, presented by Associate Professor Leon Barmuta). These workshops provided opportunities to share common findings across the NCCARF Freshwater Biodiversity research projects and provided a valuable consolidation of project findings, especially in policy and the organisational logistics of adaptation options. The project findings will be communicated at the the NCCARF National Conference in Sydney in June 2013, and at scientific conferences later in 2013. Papers for submission to international peer-reviewed publications will also be prepared later in 2013. The final report and relevant background materials will be hosted on the DPIPWE web site later in 2013.

Box 1. Targeted interviews were conducted with senior water policy-makers in each State and Territory, as listed below, to provide follow-up on the national review of policies and adaptation frameworks for conserving freshwater biodiversity under climate change, in recognition that policy and adaptation options are commonly in continual development and/or waiting on research outputs.

State or Territory	Contact	Organisation
Tasmania	Dr Martin Read	DPIPWE
Victoria	Dr Jane Doolan	DSE
South Australia	Mr Ben Bruce	DEWNR
Western Australia	Mr Iqbal Samanakay	DOW
Northern Territory	Dr Simon Townsend	NRETAS
Queensland	Dr John Marshall	DNRM
New South Wales	Mr Richard Beecham	DPI

Interview question template:

- Is there recognition in your agency that risks of climate change should be incorporated into water policy?
- If yes, has climate change been explicitly incorporated into water policy and/or legislation, and how?
- Is there an explicit acknowledgement of risks to freshwater biodiversity in this policy?
- Is there flexibility in the policy to adapt to climate change events, or to mitigate climate change risks to i) water availability, ii) freshwater biodiversity?
- Has there been specific research conducted, or used, to underpin this policy? (e.g. Sustainable Yield Assessment)
- If no, are there barriers preventing an explicit acknowledgement of climate change risks to water policy at the current time? (For example, knowledge of freshwater biodiversity may be insufficient, climate data are at unsuitable scales or outdated, down-scaling data requires too many simplifying assumptions, water policy and climate change are treated separately in legislation, etc.)
- What are the main issues that would need to be addressed to better manage water resources and freshwater biodiversity under climate change?
- Are there policies currently in development, or proposed, that may see climate change incorporated into water policy?
- What measures (adaptation options) would you take to address water shortages or environmental water allocations, or which options would be most suitable for your jurisdiction? (For example, reduce summer allocations, water buy-backs, build water storages, set more stringent water allocation rules, incorporate climate change assessments of future water availability into hydrological models, etc.)
- Do you see any State or Territory as having notable water policy that incorporates climate change risks to freshwater biodiversity? If so, how is it notable?

3. RESULTS AND OUTPUTS

3.1 Biophysical modelling

3.1.1 Hydrology

Tasmania has a strong west to east rainfall gradient, with high flow rivers in the west and intermittent streams in the east (Bennett et al. 2010). There is considerable variation in runoff predictions between the six GCMs used in the CFT downscaling, which translates to smaller differences between the hydrological models. However, there is strong agreement between models that runoff is likely to decline significantly across the Central Highlands in most seasons. These are important catchments for hydro-electric power generation, and a major source of irrigation supply. Summer rainfall is projected to decrease by more than 20% in the west and northwest. In contrast, parts of the east coast and Derwent Valley are projected to have up to 100% more runoff in summer and autumn (Bennett et al. 2010) (Figure 8).

Variation between the driest model (CSIRO) and the wettest model (UKMO) is particularly strong for some hydrological variables. For example, many rivers in the state are predicted to have decreased mean base flow under the CSIRO model, but increased mean base flow under UKMO (Figure 9). The Derwent River in the southeast is the only river which is predicted to have increased base flow under both models, although the proportional change varies between them.

Summer maximum daily flows also showed strong differences between the two models. Areas that the CSIRO model predicts to have decreased summer high flows are shown as having increased summer high flows by the UKMO model (Figure 10). However, both models predicted either no change or higher summer maximum flows for the northeast of the state.

In contrast, the duration of flushing flows, shown here as the mean duration of flows greater than the 95th percentile, is predicted to increase by both models in some time periods and in most areas, although the wettest model, UKMO, predicts a greater increase than the dry CSIRO model (Figure 10). The full set of hydrology maps is given in Appendix 6: Hydrology maps.

Risk ratings for hydrology were generated in the Bayesian Belief Network (BBN) outputs for the biodiversity assets (see ‘Appendix 1: BBN listings’), and maps of these risks reflect the same broad patterns, albeit with variations depending on the hydrological variables involved in a given BBN. For example, the hydrology risks for native fish were higher under the CSIRO model, particularly in the central midlands and east coast. As with the hydrological models, some areas identified as at risk (orange or red) in the CSIRO model, were identified as having benefit (blue) to macroinvertebrates in the UKMO model BBN (Figure 12). Both models predicted moderately high or high hydrological risk in the upper Derwent Valley, in the southeast.

The hydrological risk to native fish is similar to the risk to macroinvertebrate communities, mainly because similar variables are shared between the two BBNs (see ‘Appendix 1: BBN listings’). The upper Derwent Valley is predicted to have high native fish risk in both models (Figure 13; note that, for clarity, only streams greater than 3rd order were mapped for native fish in this figure).

Both the CSIRO and UKMO BBNs predict moderate to high hydrological risks for brown trout, but in different areas of the state, with few overlaps. The upper Derwent

Valley is identified as a risk area in both models, but the CSIRO BBN predicts more high risk areas in the north of the state (Figure 14).

Finally, the mean change in low flow conditions was calculated for *Astacopsis gouldi,* because low dissolved oxygen (DO) and high water temperatures during low flows are known to be associated with streams in which *A. gouldi* populations are at low levels (Walsh and Walsh 2011, Lynch and Blühdorn 1997). Figure 15 shows the expected differences between the two models, with overall higher risks from the drier CSIRO model than the wetter UKMO model.

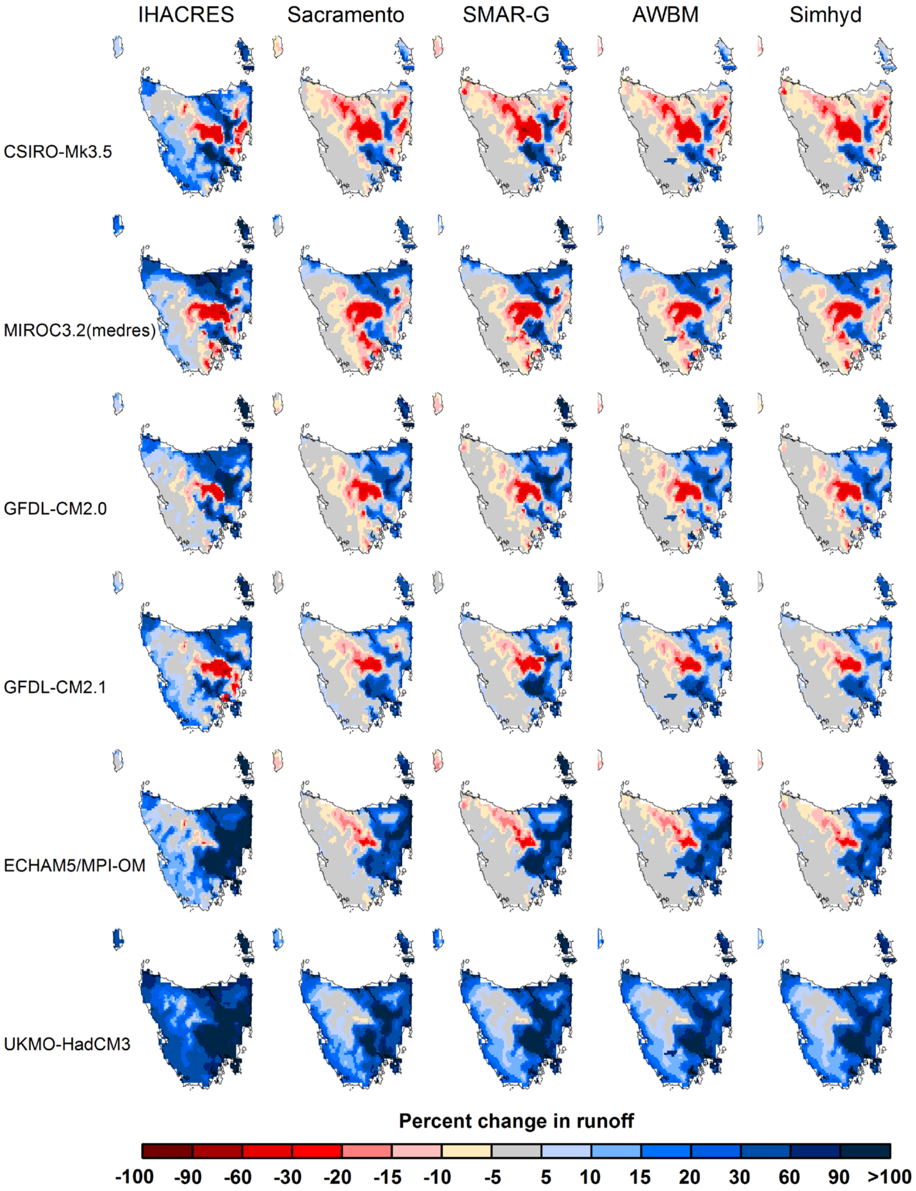


Figure 8 Percentage change in mean annual runoff

This figure compares the 2070–2099 period to the 1961–1990 reference period for all six downscaled GCMs and all runoff models, ordered from top to bottom from driest to wettest statewide projection (from Bennett et al. 2010). Blue denotes an increase in mean annual runoff and red indicates a decrease in runoff.

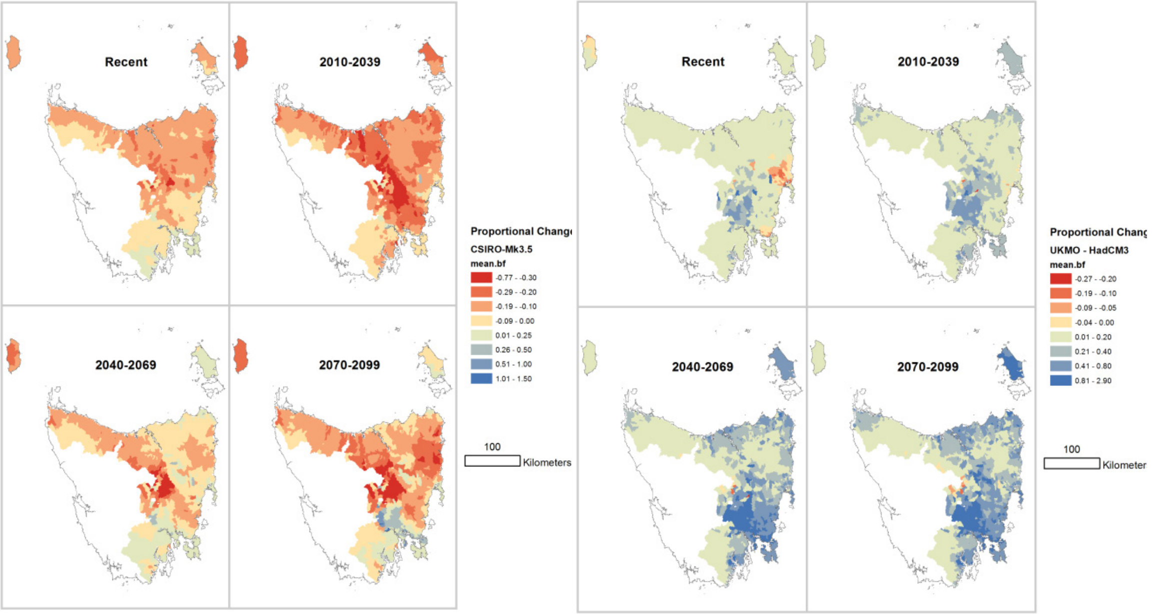


Figure 9 Predicted change in mean base flow

The left panel shows the CSIRO model, the right panel shows the UKMO model.

Each map shows the difference in the flow variable between the Reference Period (1961–1990) and either the Recent Period (1991–2009), or Period 1 (2010–2039), Period 2 (2040–2069) or Period 3 (2070–2099). A *decrease* in a variable is shown in red, and an *increase* in blue.

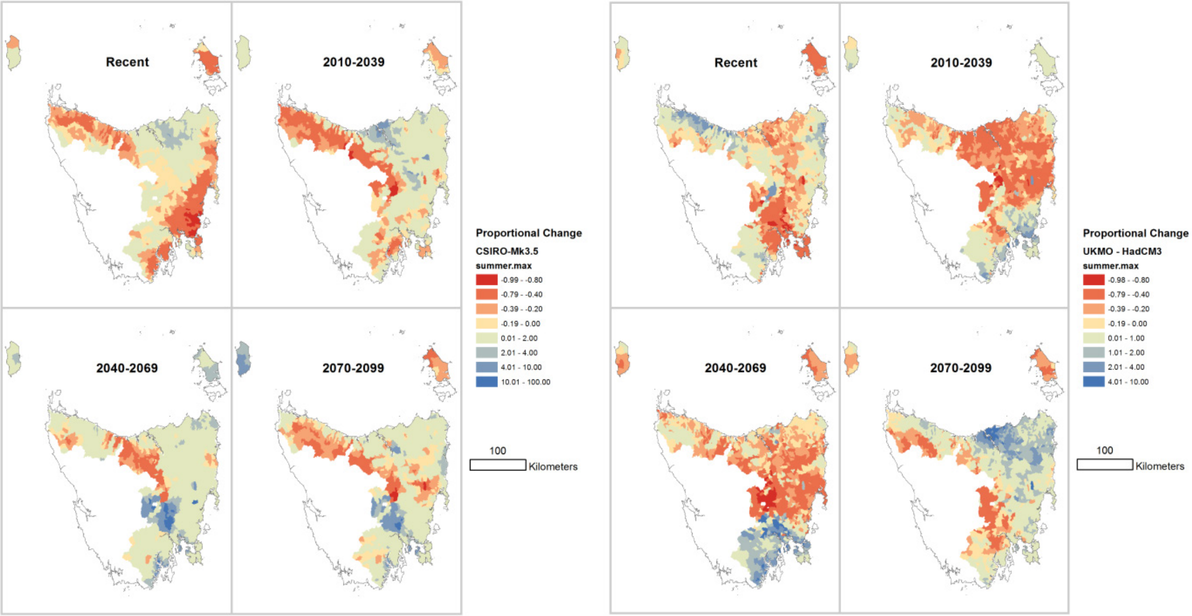


Figure 10 Predicted change in summer maximum flow

The left panel shows the CSIRO model, the right panel shows the UKMO model.

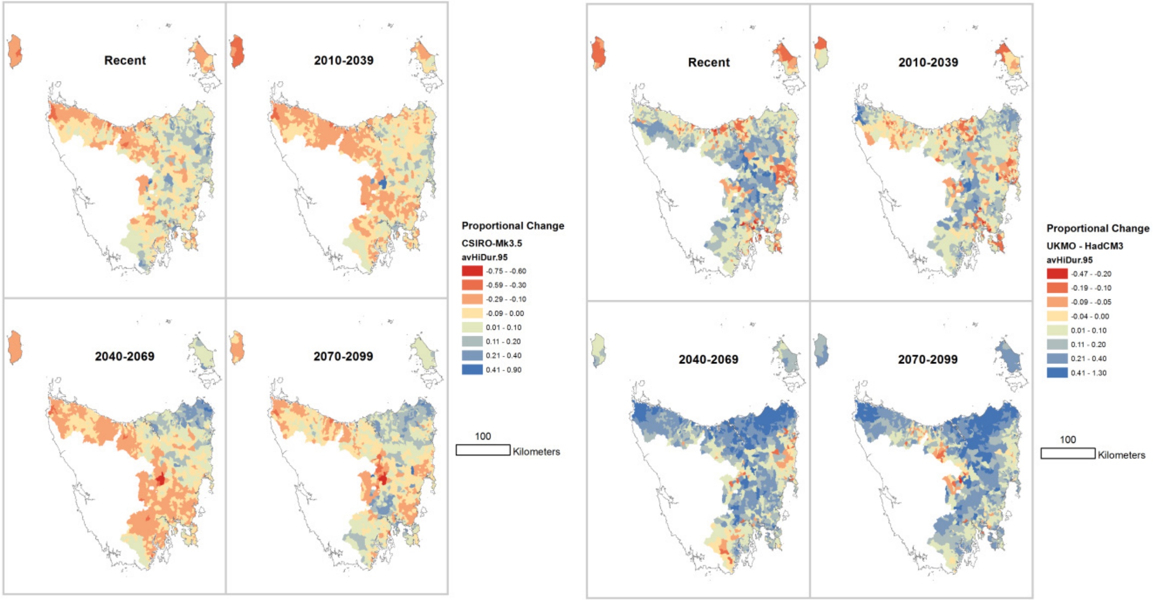


Figure 11 Predicted change in the duration of very high flows

The left panel shows the CSIRO model, the right panel shows the UKMO model.

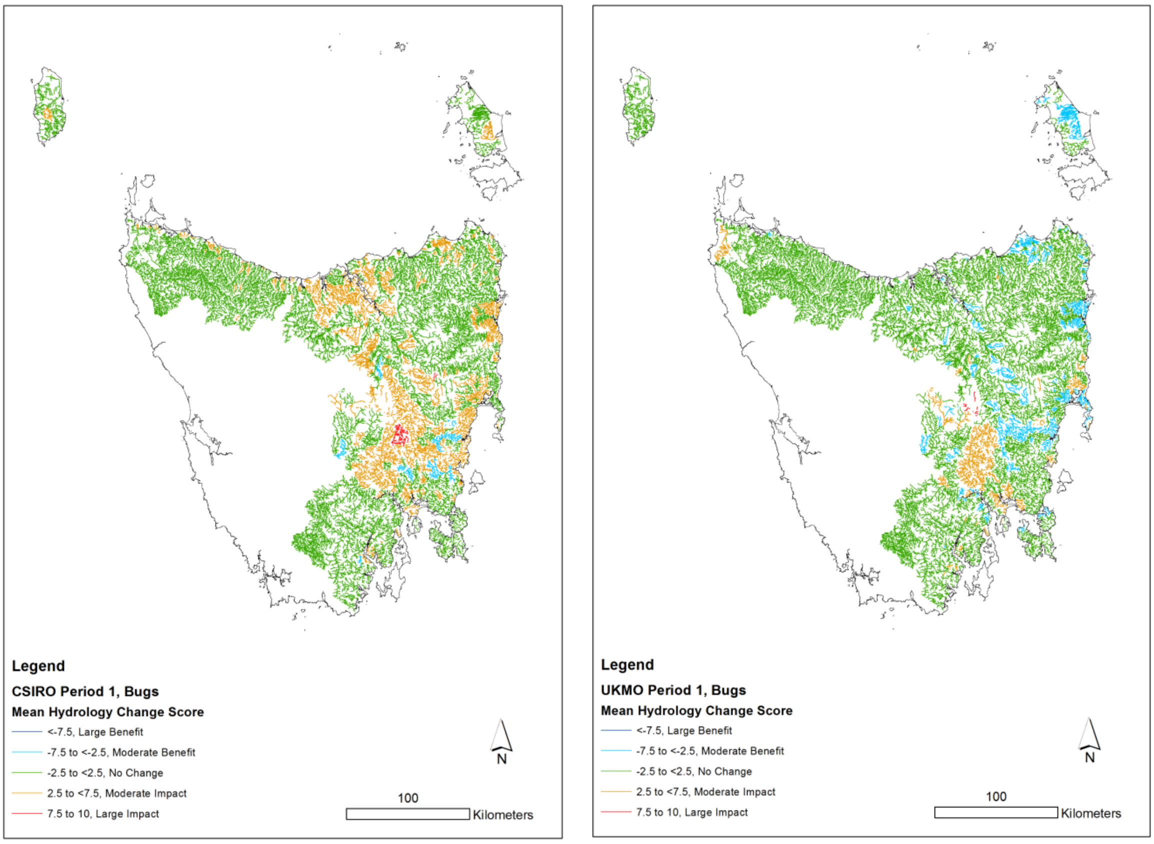


Figure 12 Hydrological risks to macroinvertebrate communities

The left panel shows the CSIRO BBN model, the right panel shows the UKMO BBN model.

In all maps of BBN hydrological risks, benefits to biota are in blue; green indicates no change; and orange and red denote increasing hydrological risks.

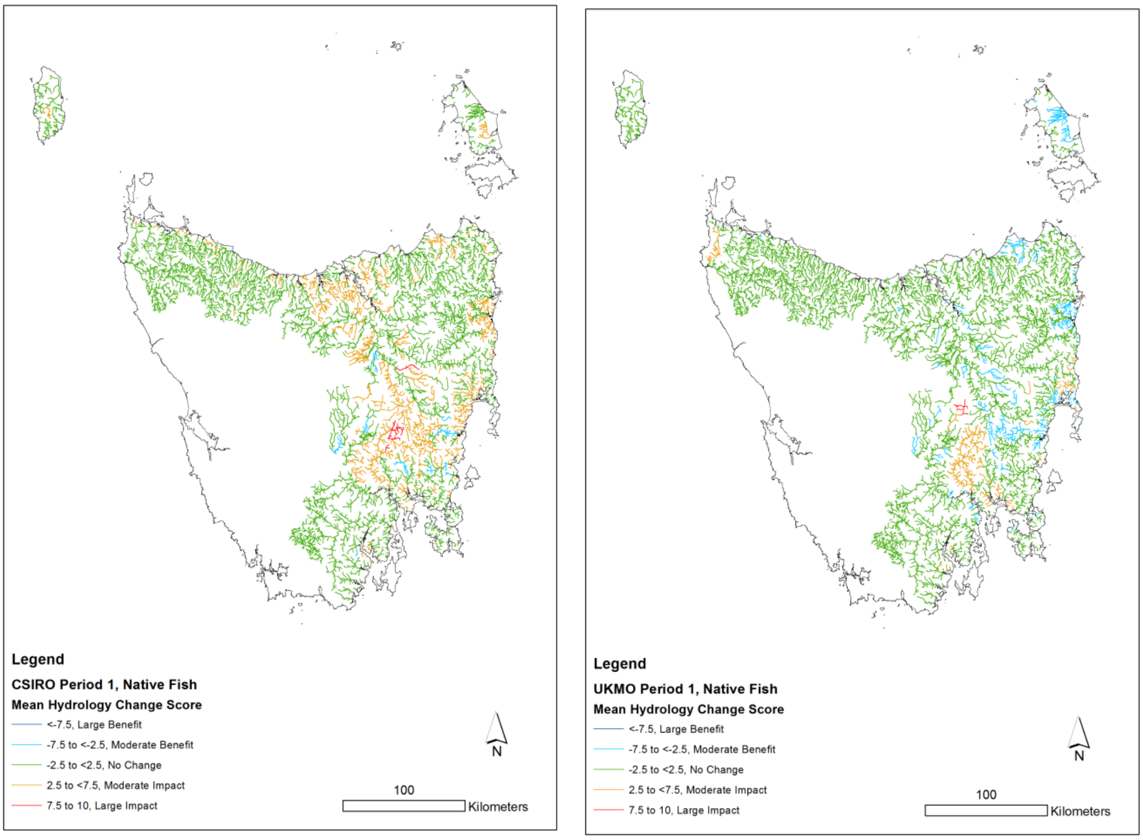


Figure 13 Hydrological risks to native fish condition

The left panel shows the CSIRO BBN model, the right panel shows the UKMO BBN model.

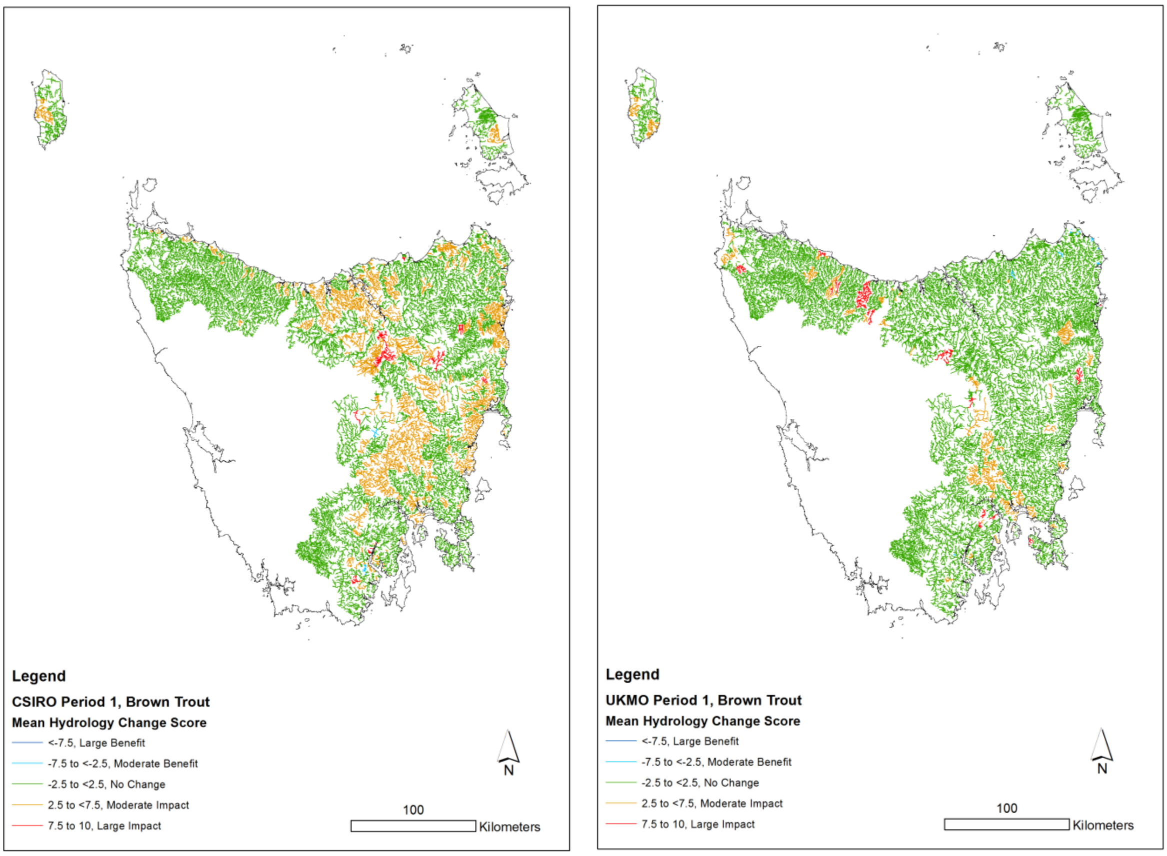


Figure 14 Hydrological risk to brown trout

The left panel shows the CSIRO BBN model, the right panel shows the UKMO BBN model.

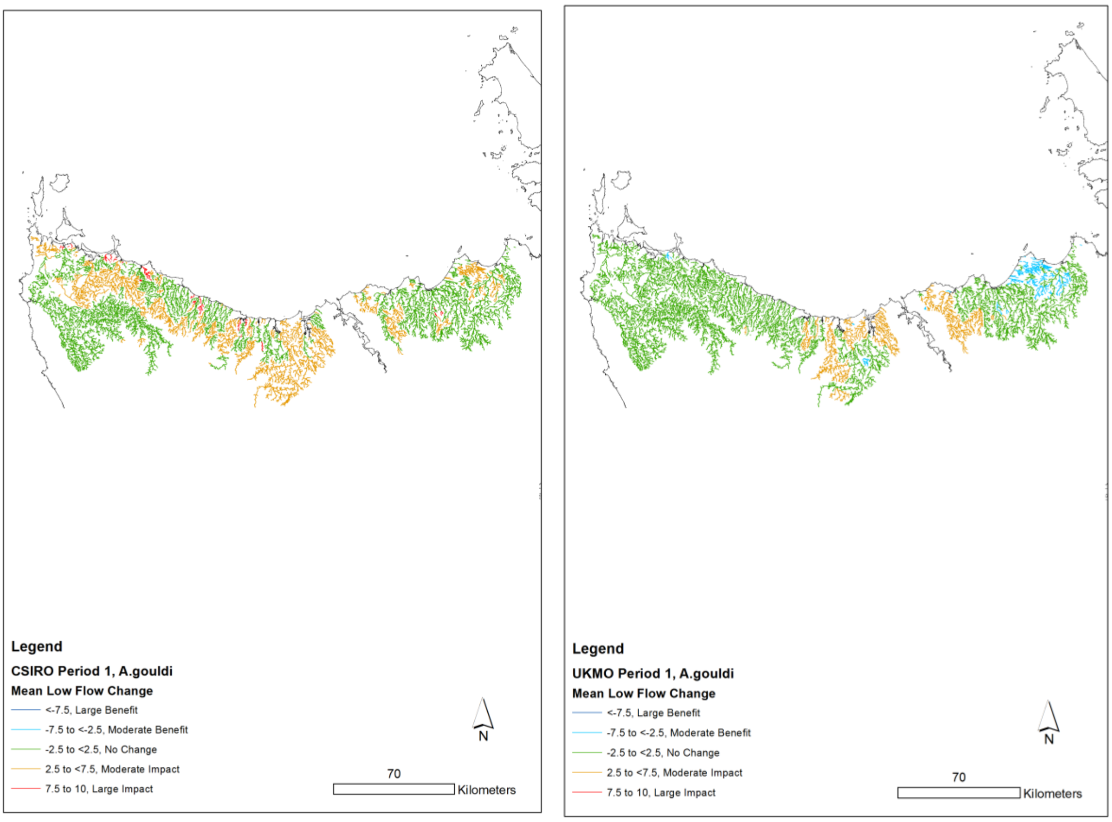


Figure 15 Mean low flow change generating hydrological risk for *Astacopsis gouldi*

The left panel shows the CSIRO BBN model, the right panel shows the UKMO BBN model.

3.1.2 Water temperature and thermal tolerances

State-wide regressions were good fits to the data for the majority of sites (for maximum monthly water temperature, NSC = 0.87, RMSE = 1.6°C). The rivers that showed the greatest deviation from the state-wide regression were those known to have strong inputs from groundwater. The state-wide regression overestimated the maximum water temperatures for stations on the Tyenna River and Jackeys Creek (Figure 16), both of which have substantial karst in their catchments and large inputs from cool groundwater. Conversely, the Ringarooma River at Moorina was the only station where the regression underestimated maximum water temperatures. This is likely to be due to local, site-specific characteristics of this station (shallow, broad, sandy channel with little riparian shading). Similar patterns were found for minimum water temperatures.

While the regression fits were good, we need to emphasize one feature of the Tasmanian data set. Few of the rivers were exposed to sufficiently hot conditions to show a marked upper asymptote. Consequently, the regression relationships that we have developed should not be uncritically extrapolated to mainland Australia, and there is a possibility that these relationships could underestimate maximum water temperatures.

Modelling of wetland water temperatures from air temperatures was not as successful. The smaller sample size (only eight lakes), lack of clearly defined asymptotes combined with the thermal effects of manipulations of water levels meant that the regressions failed to converge to a solution for some lakes, while the fit was unacceptably poor for the remainder. Because water temperature is a key input to the modified Penman equation, we were unable to pursue Linacre's (1993) method to estimate evaporation. Moreover, this and similar methods are only applicable to lakes and wetlands that are mostly open water, whereas many wetlands have substantial vegetative cover. For these reasons, wetland area was used as the surrogate variable for water temperature and potential for drying in the BBNs on the grounds that smaller wetlands tend to be shallower and are therefore more likely to be warmer and have a greater susceptibility to drying under warm conditions.

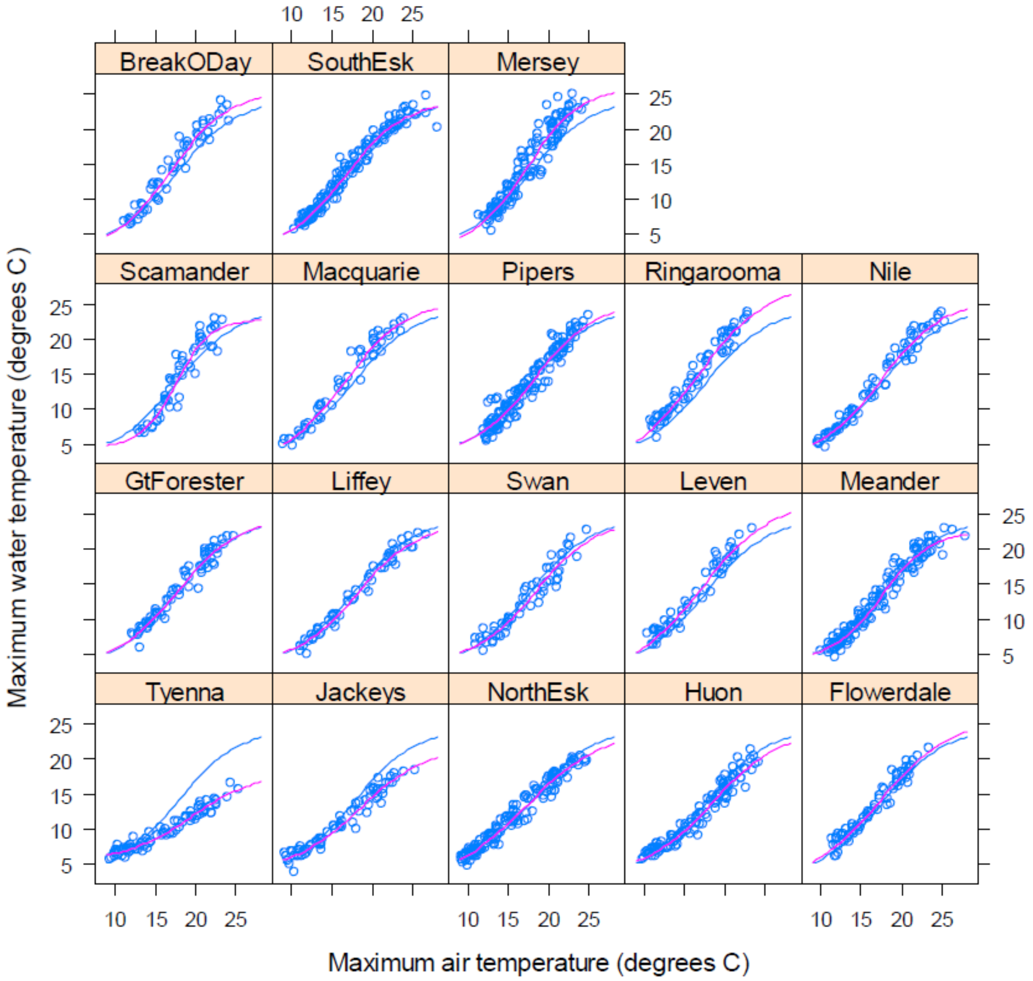


Figure 16 Regressions of maximum water temperature for each site

Estimated relationship for each site is plotted with the magenta line, the state-wide relationship plotted with the blue line. Blue symbols are the observed water temperature data

For those taxa found in both south-eastern Australia and Tasmania, the majority had higher upper bounds documented by Walsh et al. (2007) than in Tasmania, and so the upper tolerance bound was defined as the maximum from the two data sets. The lower temperature bounds found by Walsh et al. (2007) for these taxa were all lower than recorded in Tasmanian rivers, and so Walsh et al.'s lower bounds were adopted. The Tasmanian records are far less extensive than those of Walsh et al. which would explain why the temperature bounds they documented were generally wider than for the Tasmanian data set. This also suggests that the thermal tolerances for the Tasmanian endemics could be underestimated owing to the smaller data base and the paucity of high temperatures in the recent historical record (Figure 16).

Upper and lower thermal tolerance limits derived for taxa were attributed to risk bands for BBN modelling (Table 7). Brown trout were also attributed a maximum low temperature threshold (MaxCoolT) of 13° C, which is the critical limit for egg survival (Pankhurst et al. 1996).

Table 7 Risk bands for maximum water temperature for each taxon

Taxon	No risk (° C)	Small risk (° C)	Moderate risk (° C)	Large risk (° C)	Very large risk (° C)
Native fish	< 20	20 – 25	25 – 30	30 – 35	> 35
Invertebrates	< 22.5		22.5 – 25		25 – 28
Frogs	< 22	22 – 24	24 – 25	25 – 27	> 27
Astacopsis gouldi	< 18		18 – 22		> 22
Brown trout	< 15		15 – 20	20 – 28	> 28

3.2 Risks to biodiversity assets

In this section we present a subset of the maps of risks to illustrate the major conclusions that bear on adaptation planning and policy. Each subsection summarises a key finding, with cross-references to other examples in the appendices. Here we also focus on the results for Period 1 (2010 – 2039), since stakeholders generally felt that projections were likely too uncertain for later periods. The remaining maps are presented in Appendix 7 and are cross-referenced by figure number in this section where necessary. A uniform colour scheme is used in the maps throughout: blues represent benefits, greens represent no change, and yellows through reds depict increasingly large risks.

Outputs from the Bayesian Belief Networks reflected the differences in predicted temperature and hydrology from the three climate models. Similarly, the outputs for specific biodiversity assets were strongly influenced by the input variables.

3.2.1 Assets with strong hydrological effects

Riparian vegetation lacked any temperature inputs in its BBN, with all effects driven by changes to hydrology. The importance of overbank flows for sediment and nutrient fluxes and the dispersal of propagules, combined with changes in seasonality and the intensity and timing of high- and low-flow events combined to present fairly consistent patterns of moderate to high risks to riparian condition across all models. All three models showed largest risks in the Midlands (Figure 17), with the predictions from the GFDL being most similar to the CSIRO model.

For both wetland condition indices, hydrological changes dominated the inputs, with water temperature only entering the BBNs via wetland area as a surrogate. The risk patterns were broadly similar across the state (Figure 18 and Figure 19), albeit with some notable differences in some specific areas where the GCMs differed in their predictions of precipitation (see subsection 3.2.4). Overall the higher risks were in the Bass Strait Islands, north, east and midland areas of the state.

The risk maps for wetlands need to be treated with caution for three reasons. First, the limitations of using wetland area as a surrogate for water temperature has some serious shortcomings: groundwater inputs, water depth, littoral exposure, effects of shading and differences in evapotranspiration between vegetation types may all have substantial impacts on the ability of a wetland to respond to increased temperature. Second, non-linear responses and hysteresis in wetland state are not captured by the BBNs, so the risks mapped may be underestimates. As an example, sphagnum that dried during the recent supraseasonal drought resisted rewetting with the onset of wetter conditions and was more susceptible to fire than conventional soil moisture indicators suggested (J. Whinam, pers. comm.). Third, the BBNs do not capture catchment-scale changes in terrestrial vegetation which will likely have effects both on local hydrology and the conditions of the wetlands themselves (e.g. changes in fire frequency and intensity).

These other effects are likely to be strongly felt in non-floodplain wetlands because of their generally limited, localised catchment areas. Some regions in Tasmania are predicted to evolve into ‘novel ecosystems’ as fire regimes change and new species either disperse or invade, some of which may have the potential to alter ecosystem functions (e.g. ‘ecological engineers’, ‘keystone species’) (Gilfedder et al. 2012). These catchment-scale changes are, obviously, difficult to predict, much less map consistently on a state-wide basis. Nevertheless the potential for such interactions with the terrestrial components of ecosystems need to be kept live during adaptation planning and policy development.

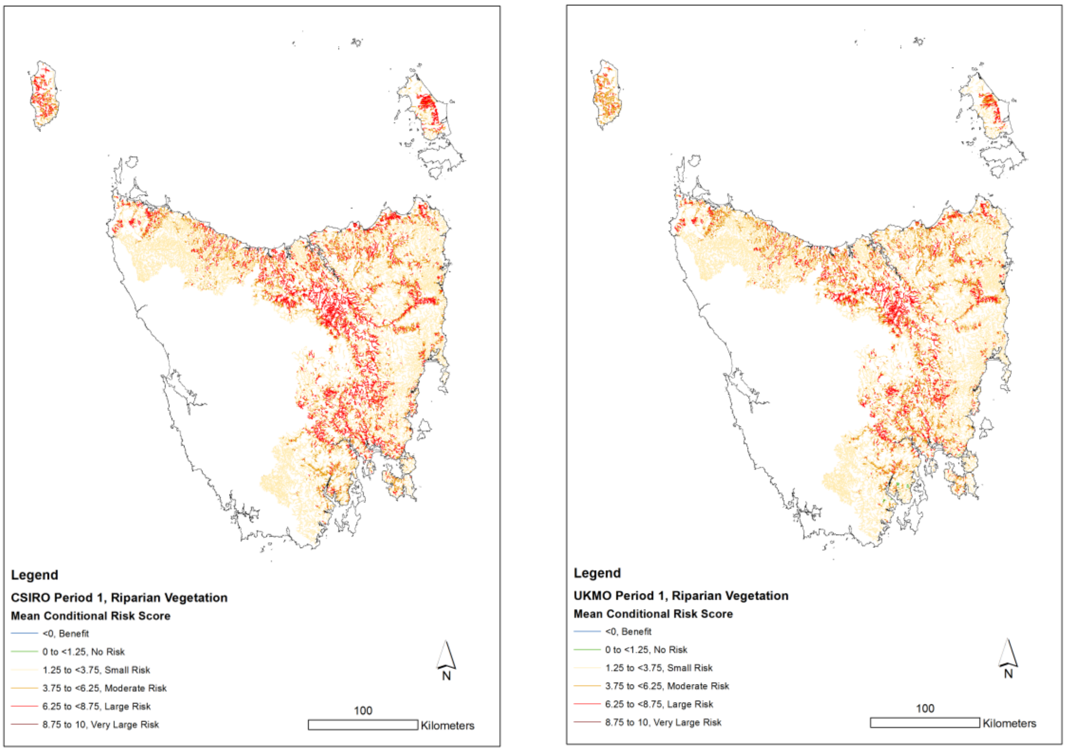


Figure 17 Riparian vegetation conditional risk scores for Period 1

The CSIRO (left panel) and UKMO (right panel) BBN model predictions for Period 1.

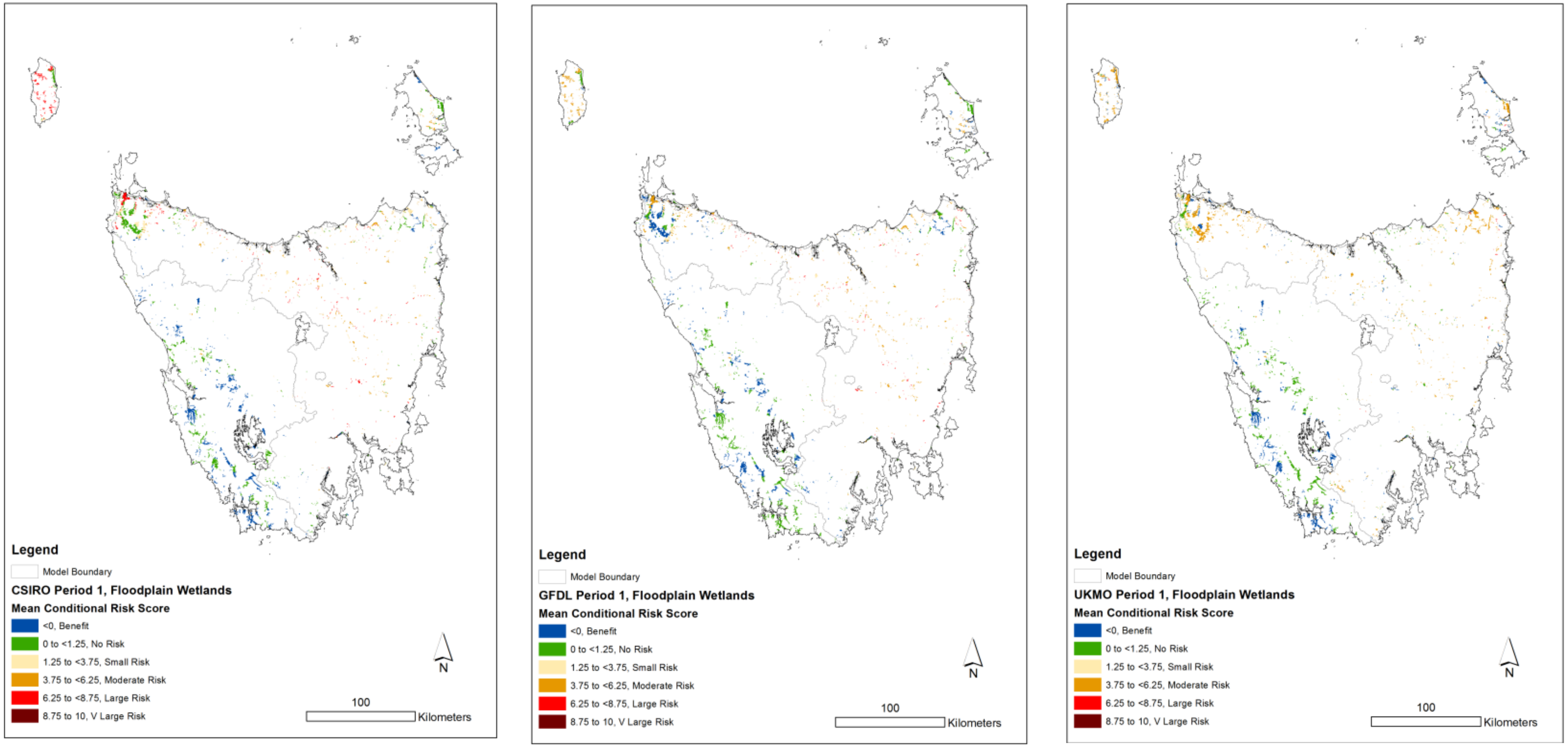


Figure 18 Floodplain wetland conditional risk scores for Period 1

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 1

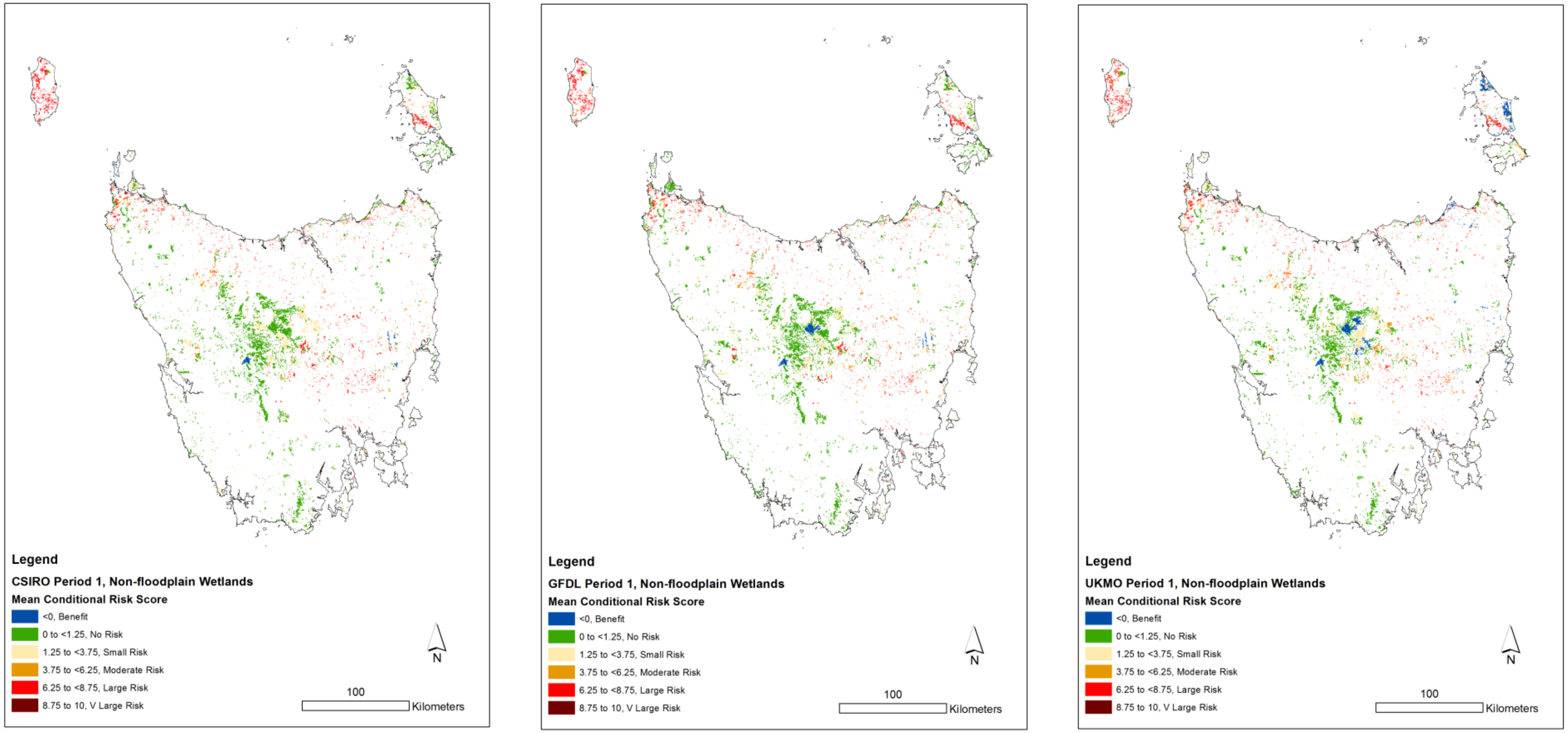


Figure 19 Non-floodplain wetland conditional risk scores for Period 1

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 1

3.2.2 *Temperature-sensitive assets*

Macroinvertebrate conditional risk scores were large to very large in all models, with macroinvertebrate community condition in most of Tasmania predicted to be at large risk under both the driest (CSIRO) and wettest (UKMO) projections for Period 1 (Figure 20). The reason for this was that maximum water temperature was an important input variable to the macroinvertebrate BBN (see Figure 27 of 'Appendix 1: BBN listings'). The condition index for frog communities is similarly strongly influenced by maximum temperatures (Figure 29 of 'Appendix 1: BBN listings'). While the condition of non-floodplain wetlands appears only moderately impacted (Figure 19), the sensitivity of frogs to increasing temperatures means that this group of taxa are at risk, even in upland areas in Period 1 (Figure 48 of 'Appendix 6: Hydrology maps)
The following maps are the full set of maps of predicted changes to river hydrology variables. Each panel gives the proportional change to that hydrology variable between the Reference Period (1961–1990) and each of the Recent Period (1991–2009), Period 1 (2010–2039), Period 2 (2040–2069) and Period 3 (2070–2099). A *decrease* in a variable is shown in red, and an *increase* in blue.

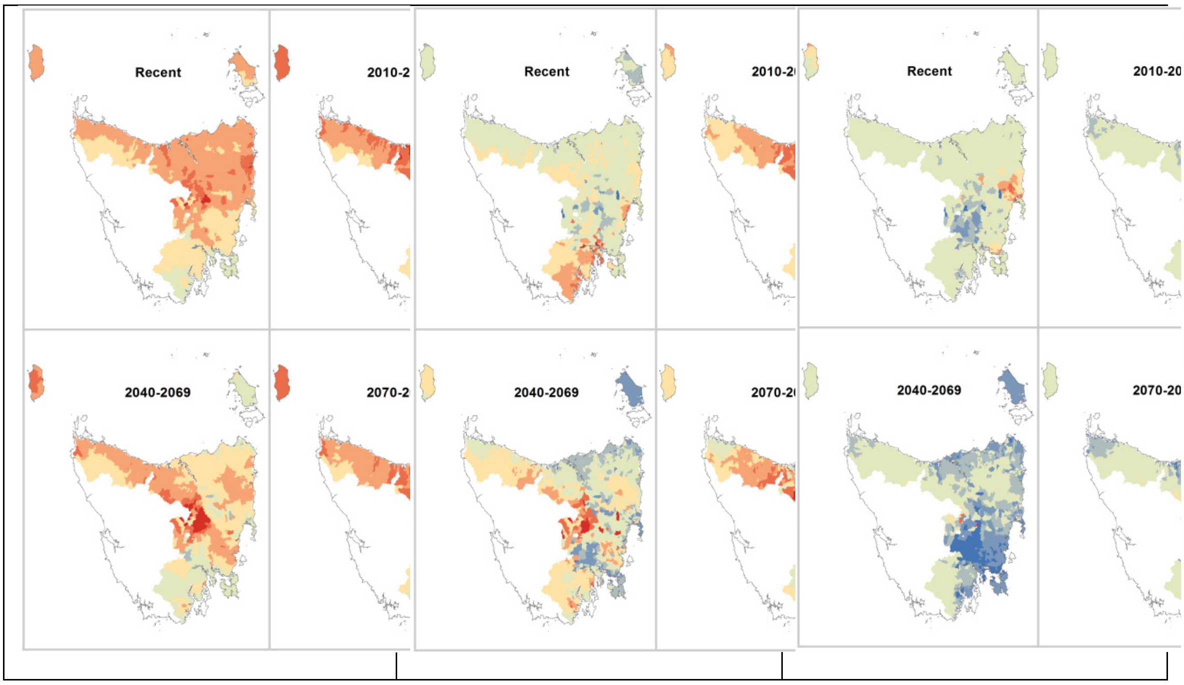


Figure 37 The proportional change in mean base flow from the Reference Period

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

Figure 38 The proportional change from the Reference Period in the number of cease to flow days

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

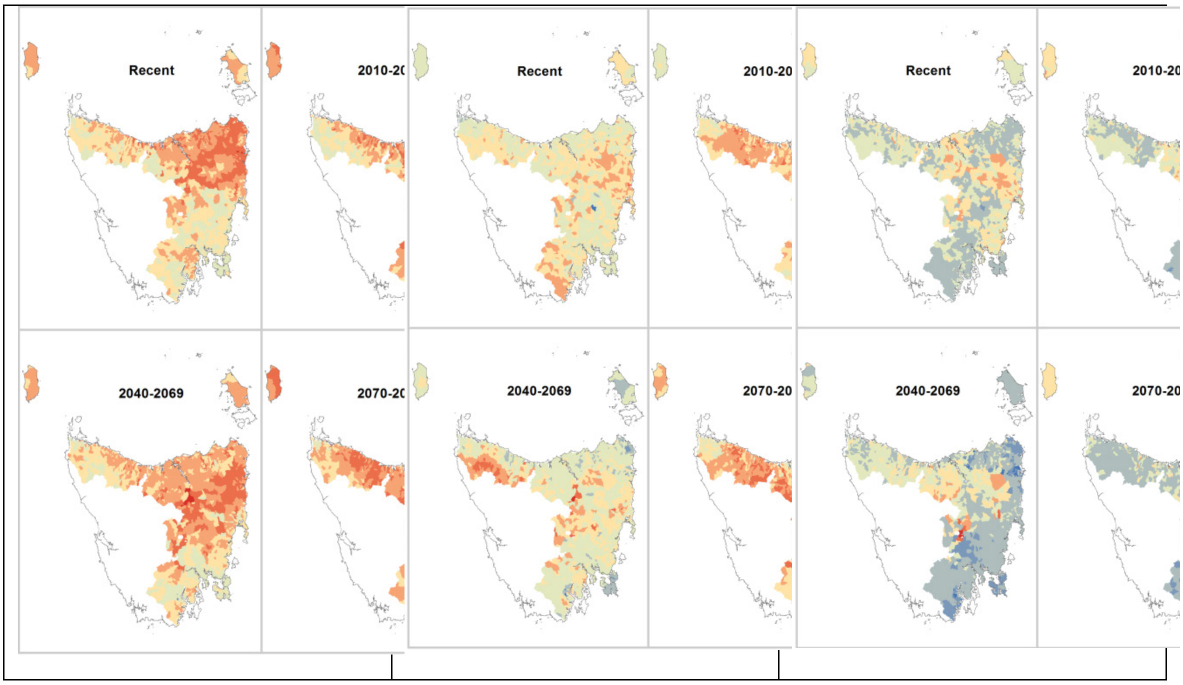


Figure 39 The proportional change from the Reference Period in the average duration of spells above the 25th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

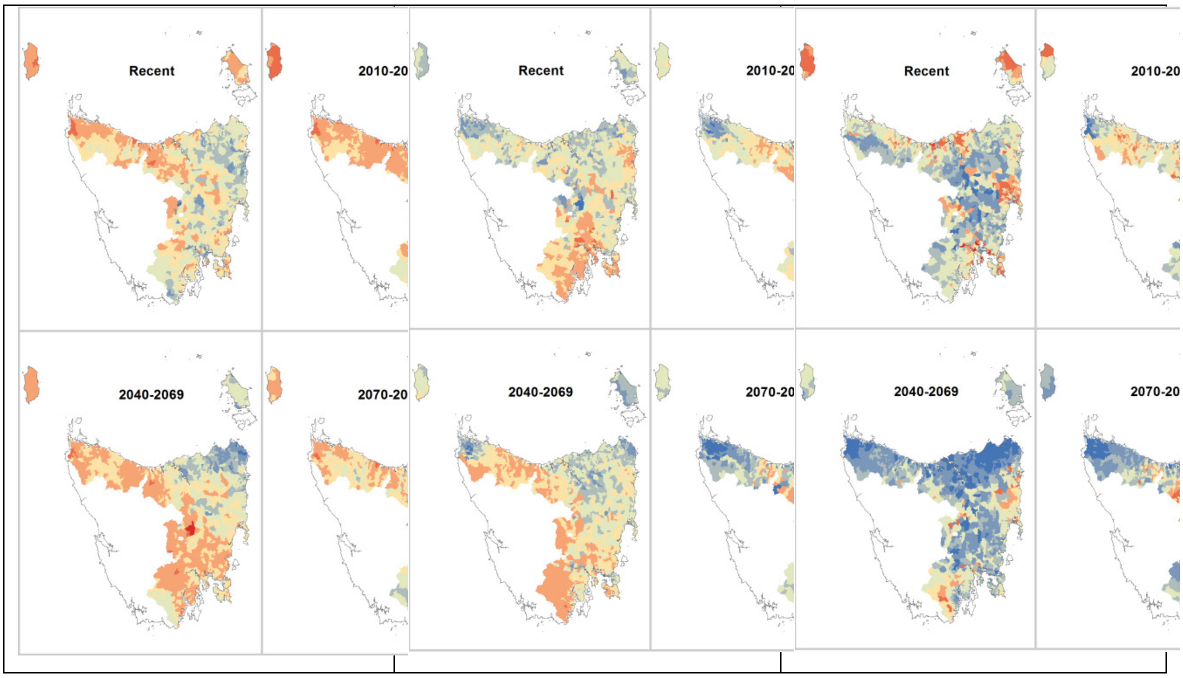


Figure 40 The proportional change from the Reference Period in the average duration of spells above the 95th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

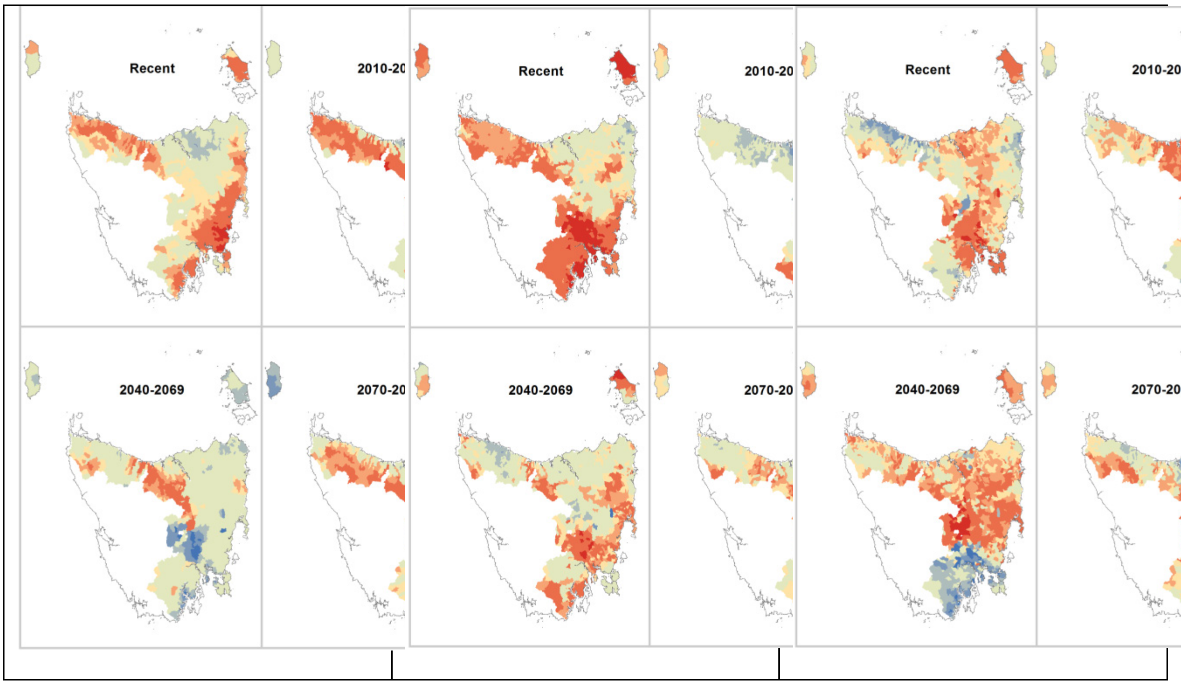


Figure 41 The proportional change from the Reference Period in the summer maximum daily flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

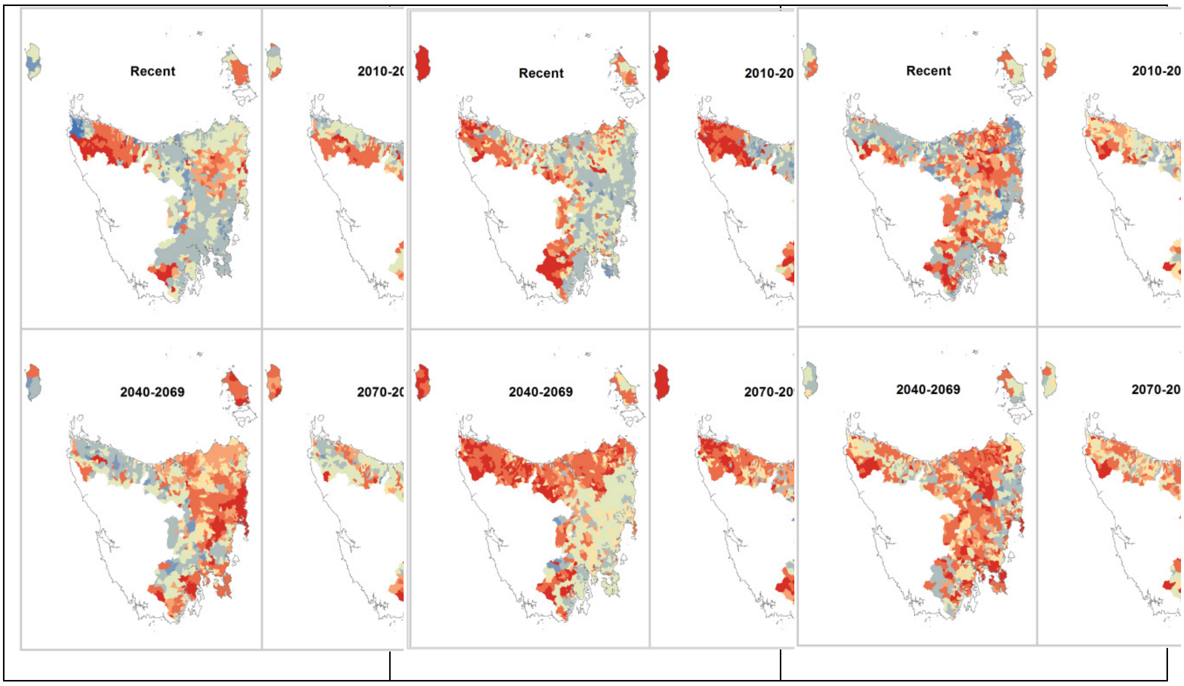


Figure 42 The proportional change from the Reference Period in the minimum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

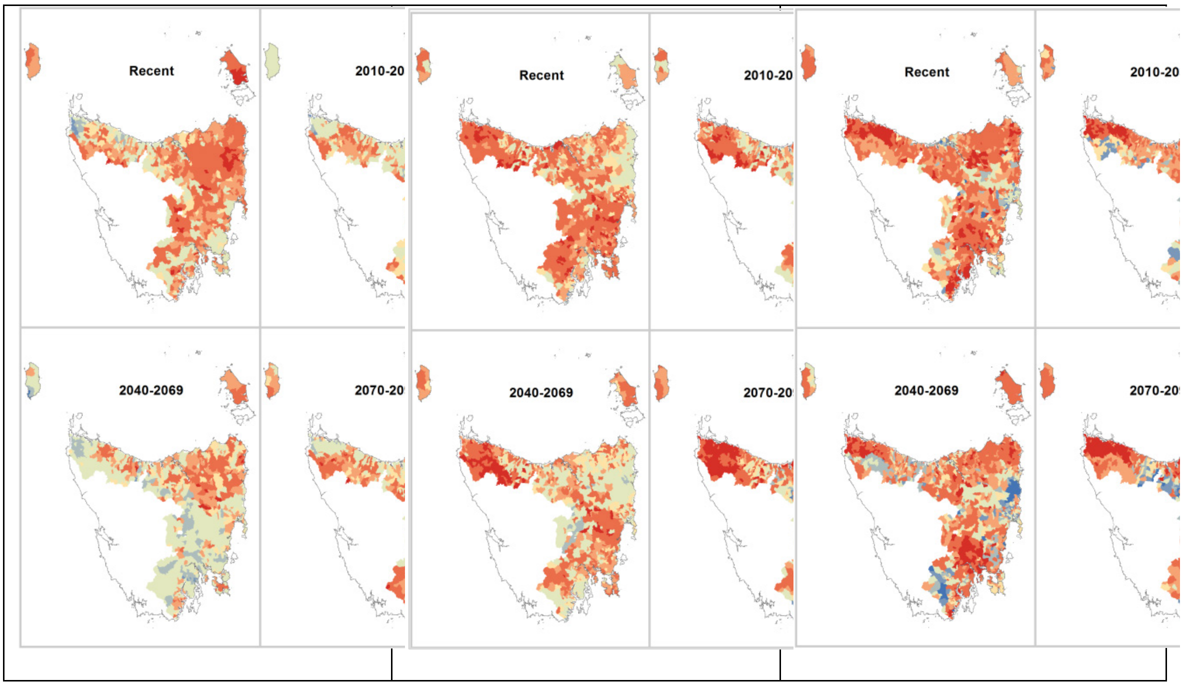


Figure 43 The proportional change from the Reference Period in the maximum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions (Appendix 7: BBN maps') with the risks intensifying in Period 2 (Figure 49 of 'Appendix 6: Hydrology maps)
The following maps are the full set of maps of predicted changes to river hydrology variables. Each panel gives the proportional change to that hydrology variable between the Reference Period (1961–1990) and each of the Recent Period (1991–2009), Period 1 (2010–2039), Period 2 (2040–2069) and Period 3 (2070–2099). A decrease in a variable is shown in red, and an increase in blue.

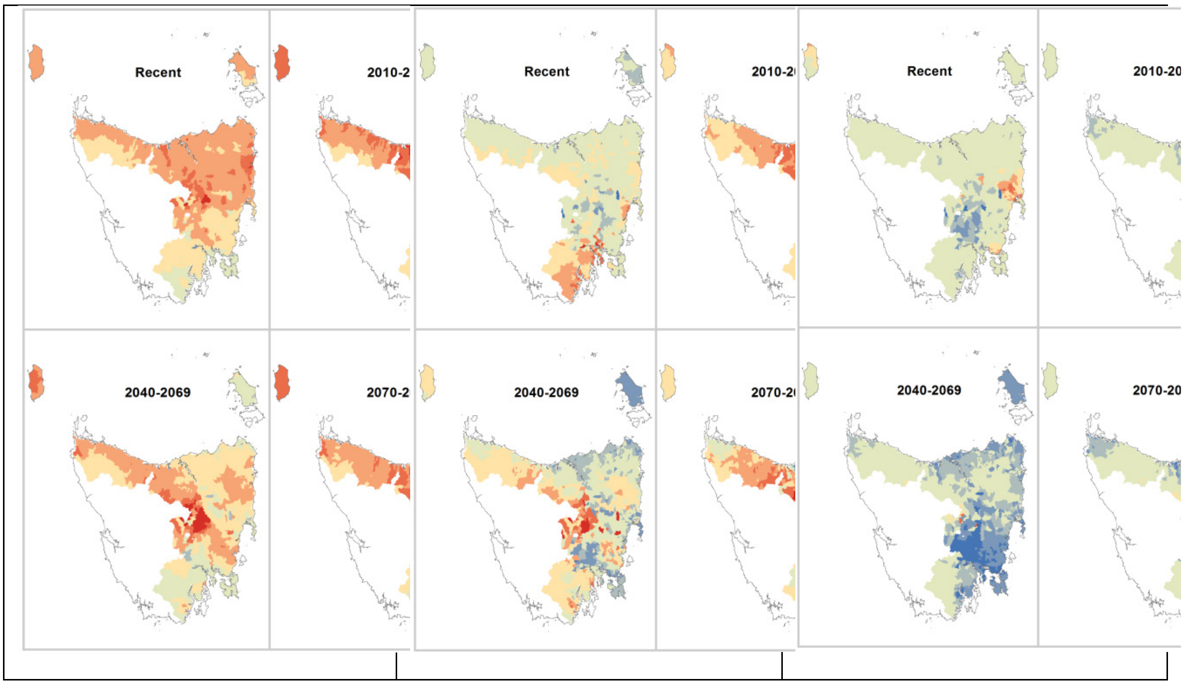


Figure 37 The proportional change in mean base flow from the Reference Period

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

Figure 38 The proportional change from the Reference Period in the number of cease to flow days

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

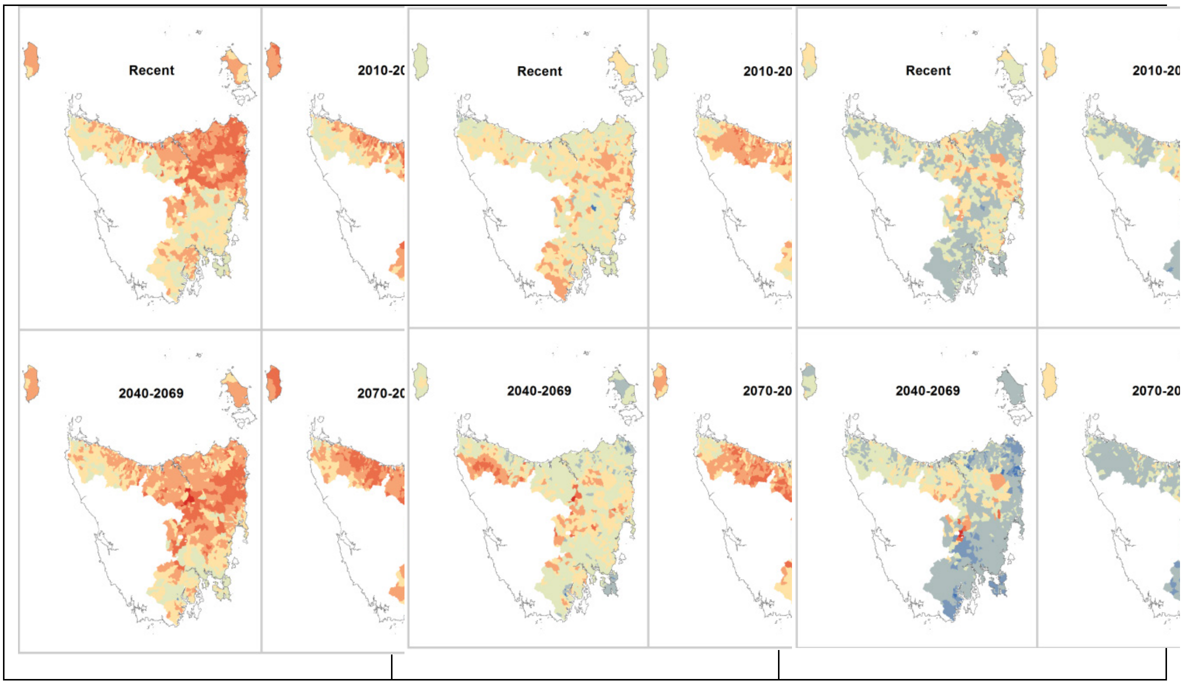


Figure 39 The proportional change from the Reference Period in the average duration of spells above the 25th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

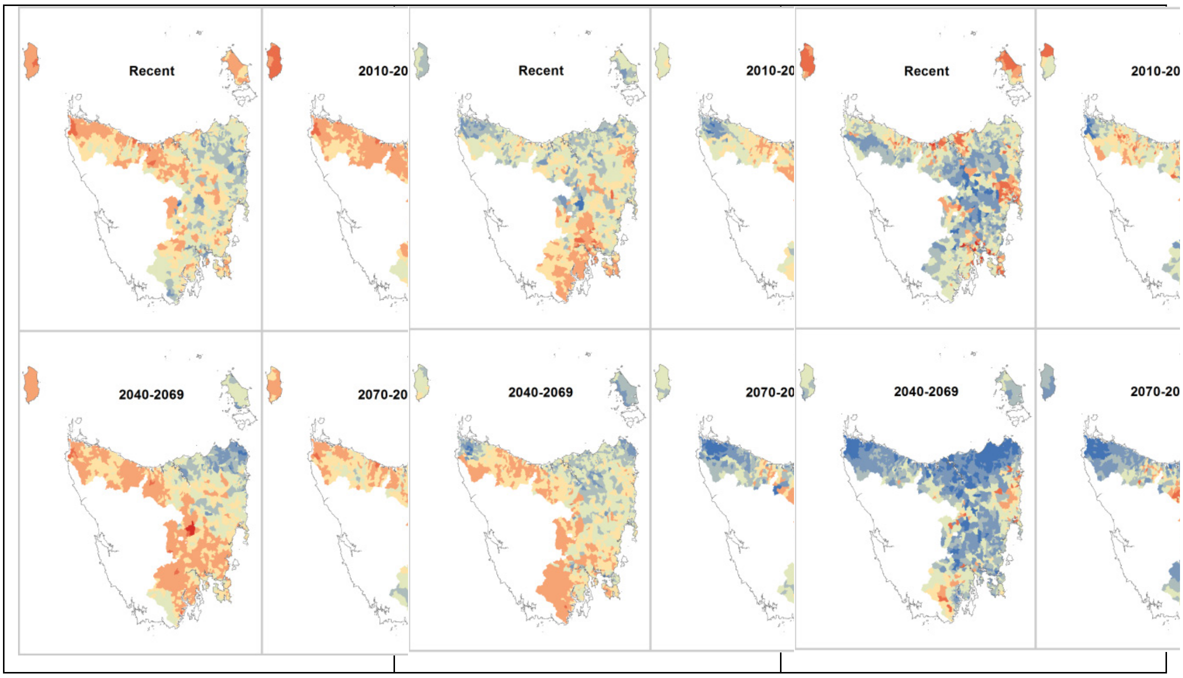


Figure 40 The proportional change from the Reference Period in the average duration of spells above the 95th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

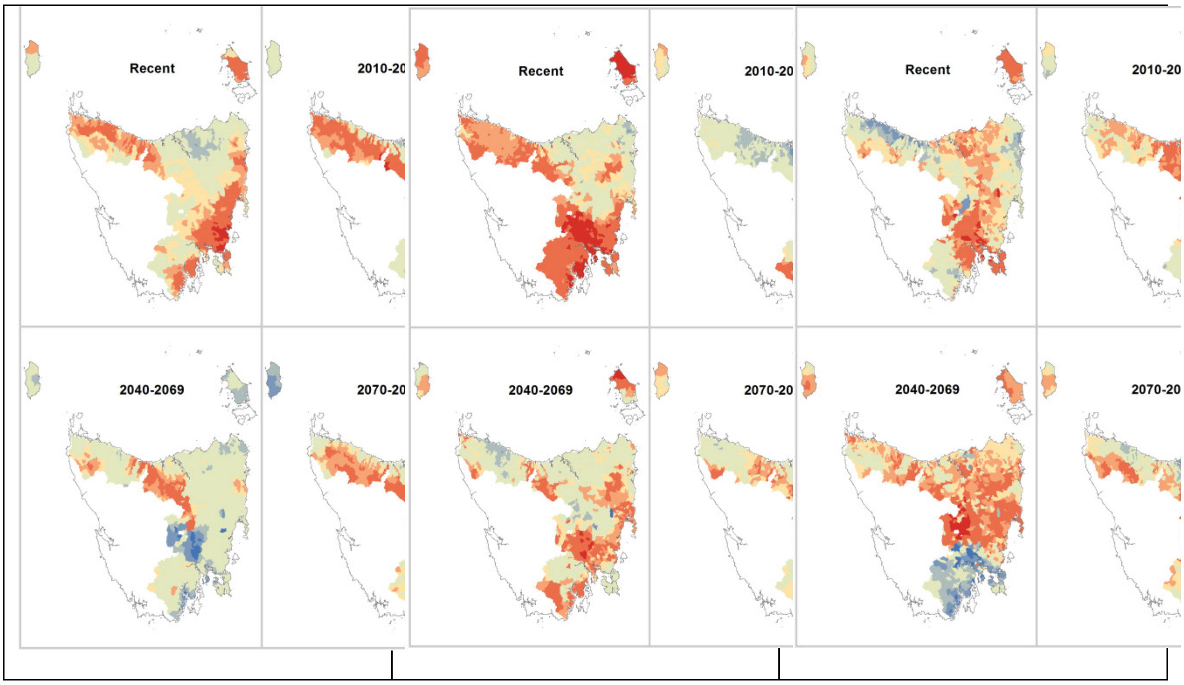


Figure 41 The proportional change from the Reference Period in the summer maximum daily flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

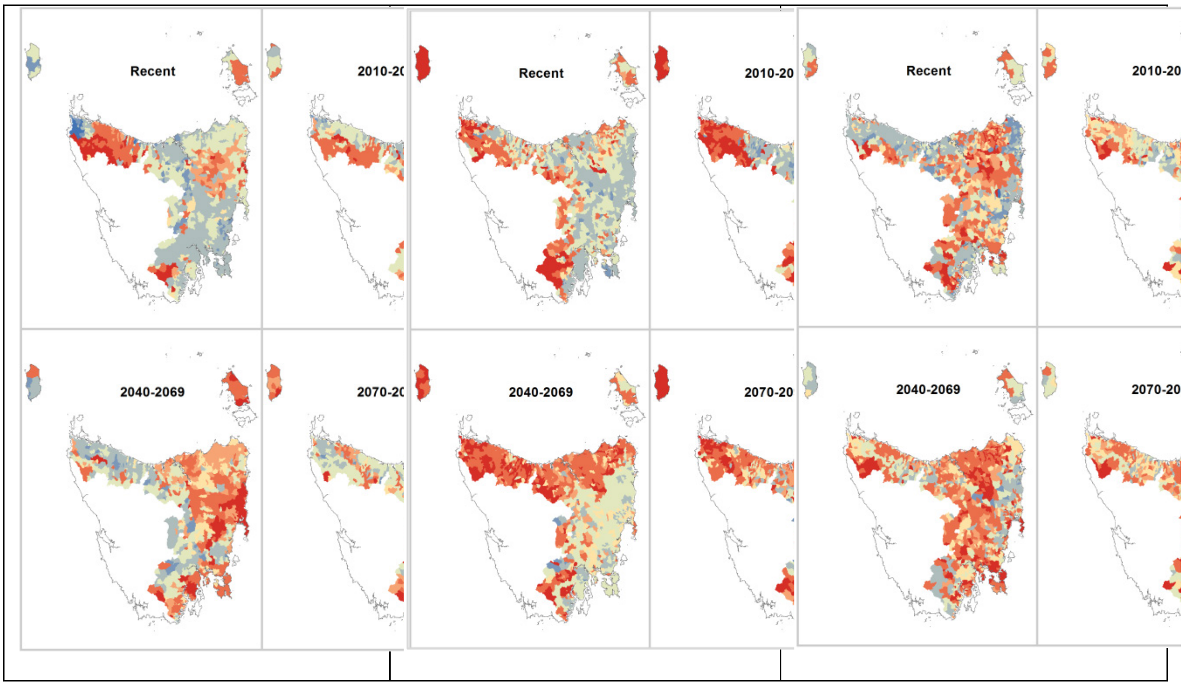


Figure 42 The proportional change from the Reference Period in the minimum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

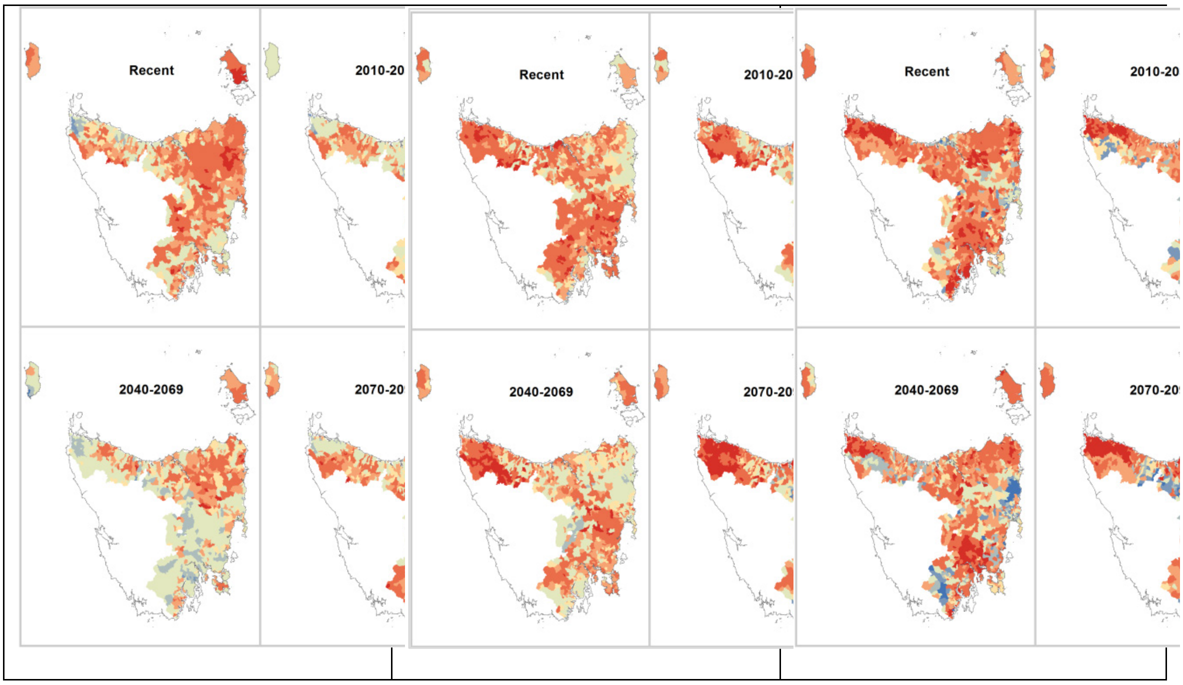


Figure 43 The proportional change from the Reference Period in the maximum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions
Appendix 7: BBN maps'). The other wetland-dependent taxon, Galaxiella pusilla showed similar sensitivity to temperature, with the additional problem of its limited distribution meaning that its survival is in jeopardy (Figure 51 of 'Appendix 6: Hydrology maps
The following maps are the full set of maps of predicted changes to river hydrology variables. Each panel gives the proportional change to that hydrology variable between the Reference Period (1961–1990) and each of the Recent Period (1991–2009), Period 1 (2010–2039), Period 2 (2040–2069) and Period 3 (2070–2099). A decrease in a variable is shown in red, and an increase in blue.

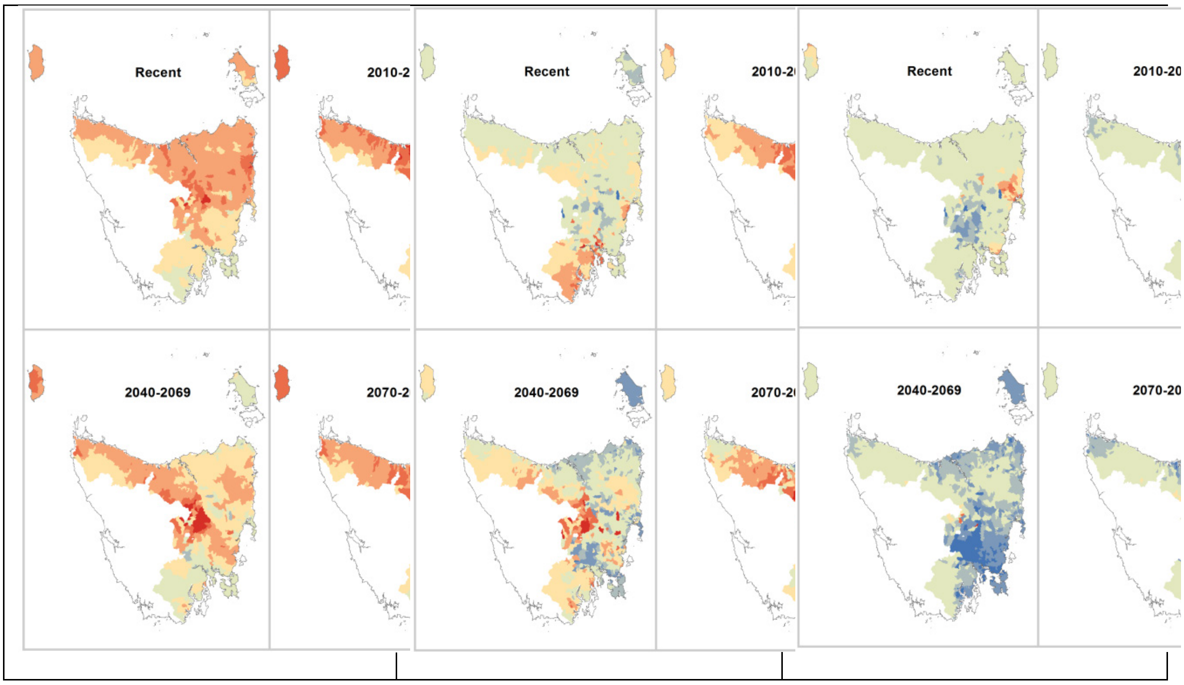


Figure 37 The proportional change in mean base flow from the Reference Period

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

Figure 38 The proportional change from the Reference Period in the number of cease to flow days

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

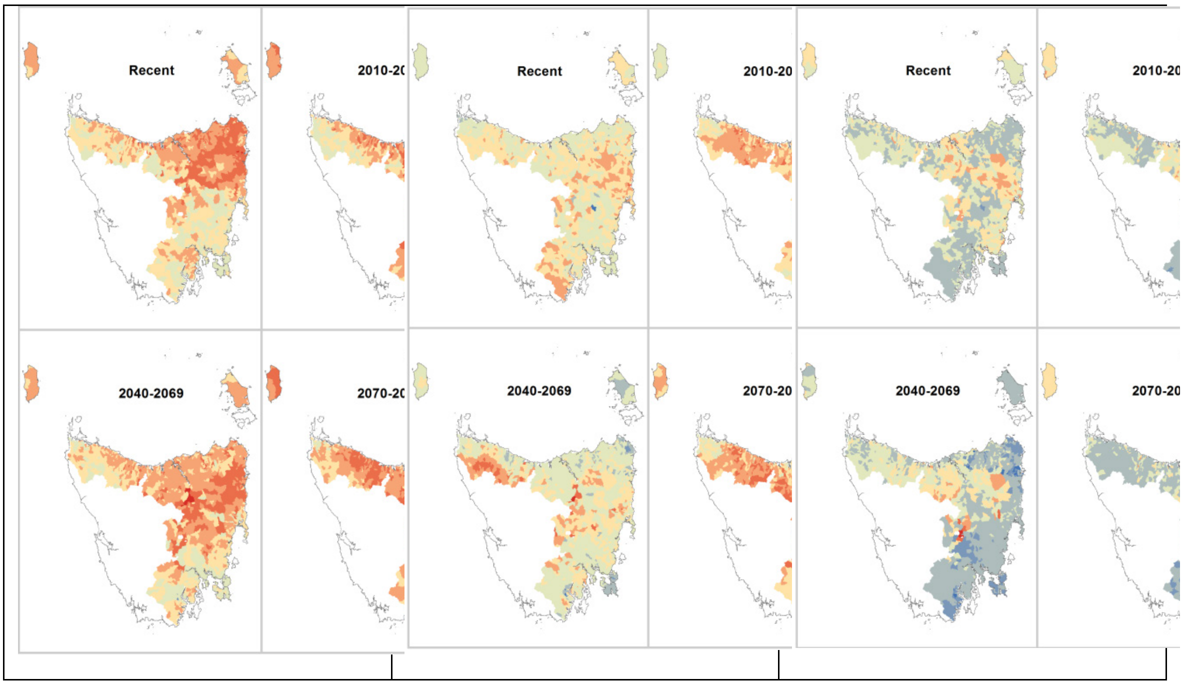


Figure 39 The proportional change from the Reference Period in the average duration of spells above the 25th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

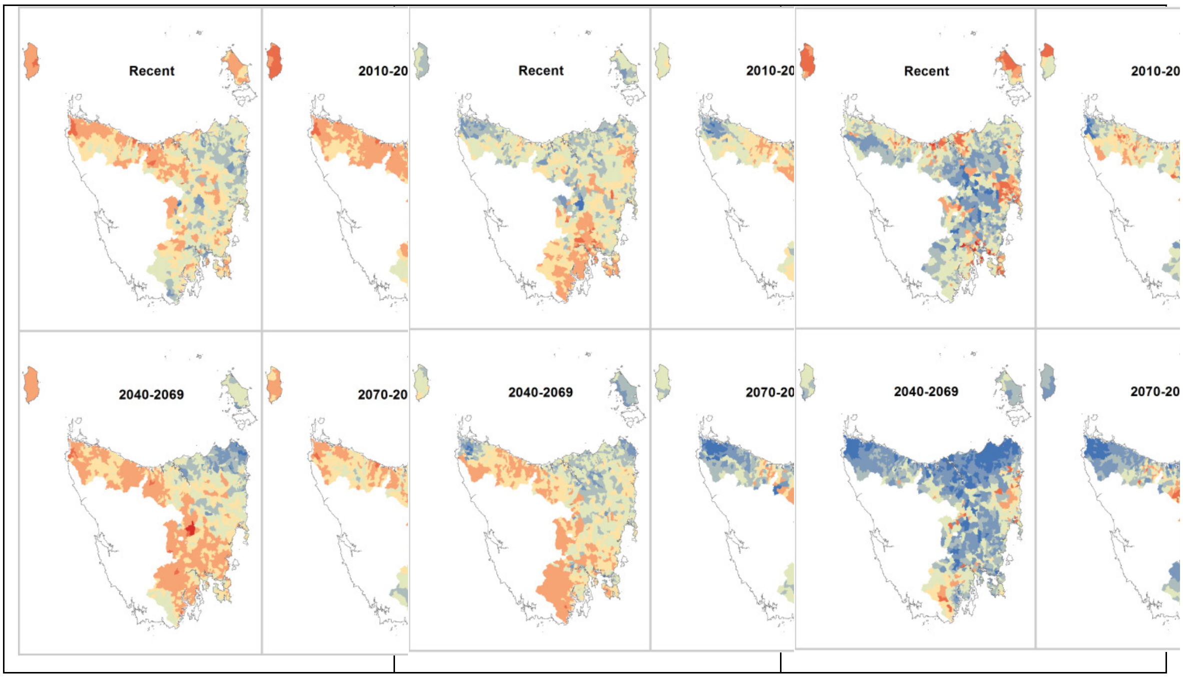


Figure 40 The proportional change from the Reference Period in the average duration of spells above the 95th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

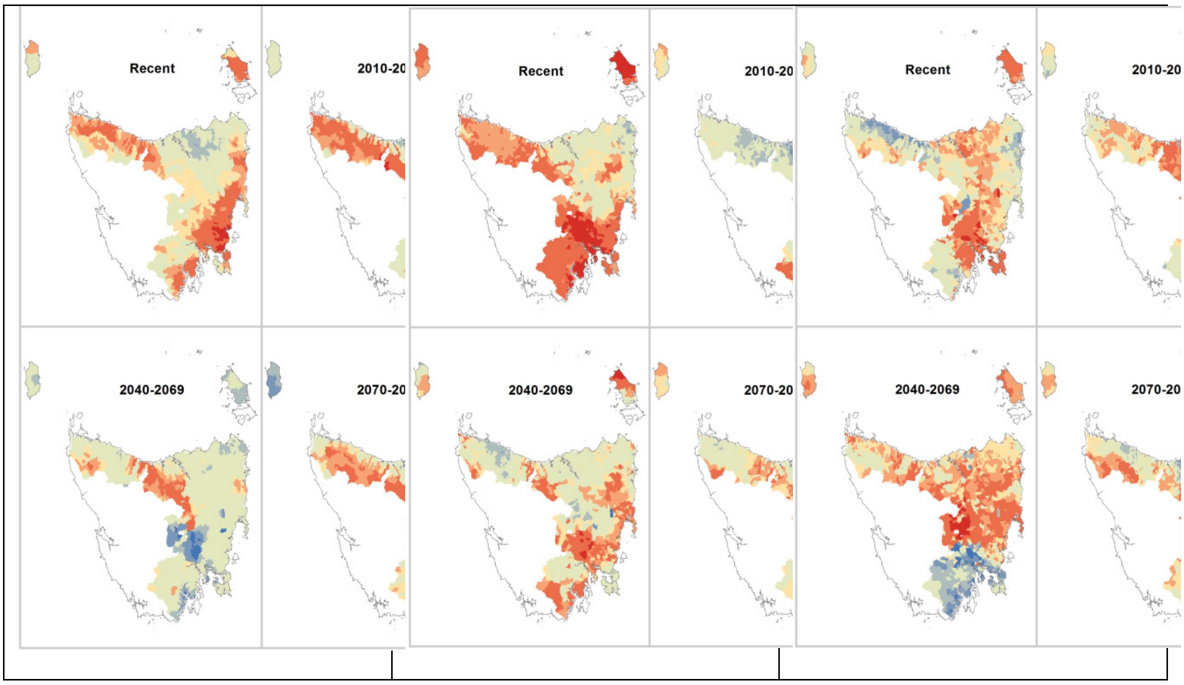


Figure 41 The proportional change from the Reference Period in the summer maximum daily flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

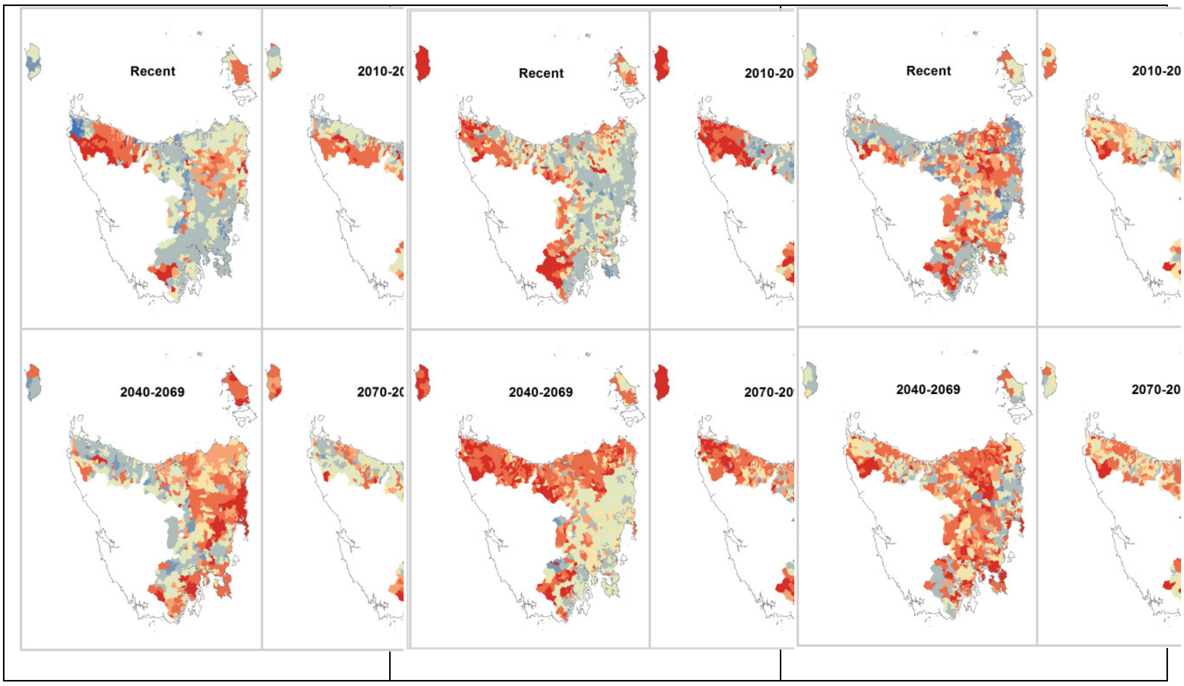


Figure 42 The proportional change from the Reference Period in the minimum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

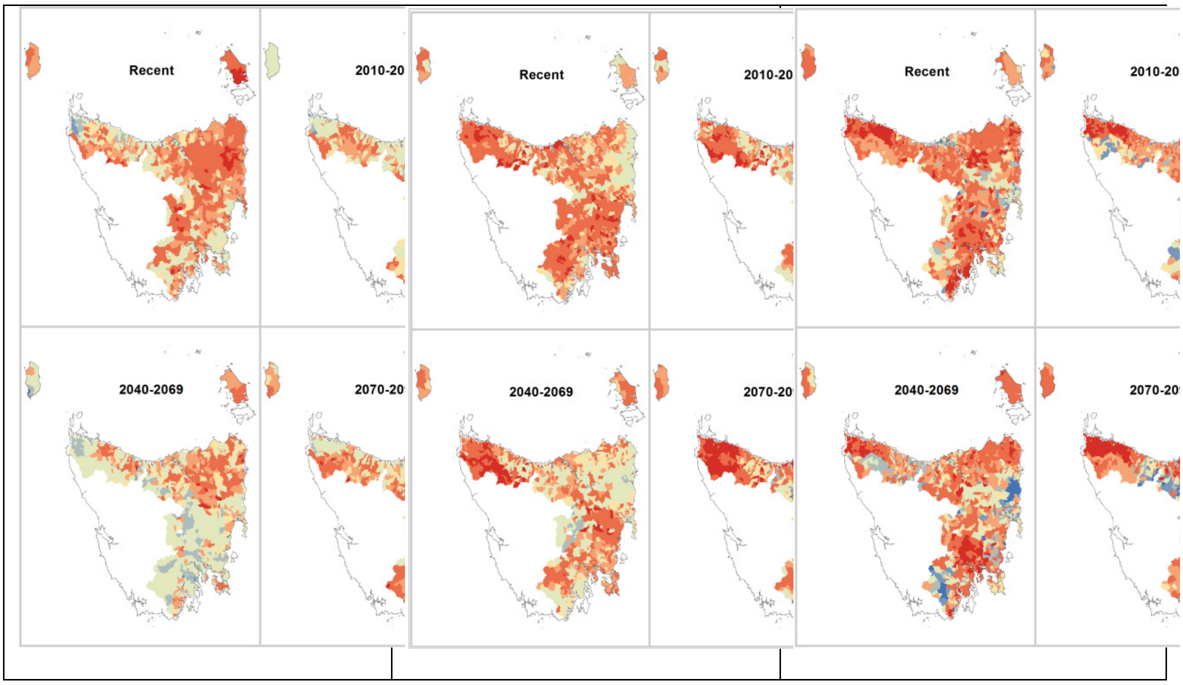


Figure 43 The proportional change from the Reference Period in the maximum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions (Appendix 7: BBN maps’), while the decline in dissolved oxygen from elevated temperatures combined with lower flows (Figure 15) elevated the risks to *Astacopsis gouldi* (Figure 53 of ‘Appendix 6: Hydrology maps The following maps are the full set of maps of predicted changes to river hydrology variables. Each panel gives the proportional change to that hydrology variable between the Reference Period (1961–1990) and each of the Recent Period (1991–2009), Period 1 (2010–2039), Period 2 (2040–2069) and Period 3 (2070–2099). A *decrease* in a variable is shown in red, and an *increase* in blue.

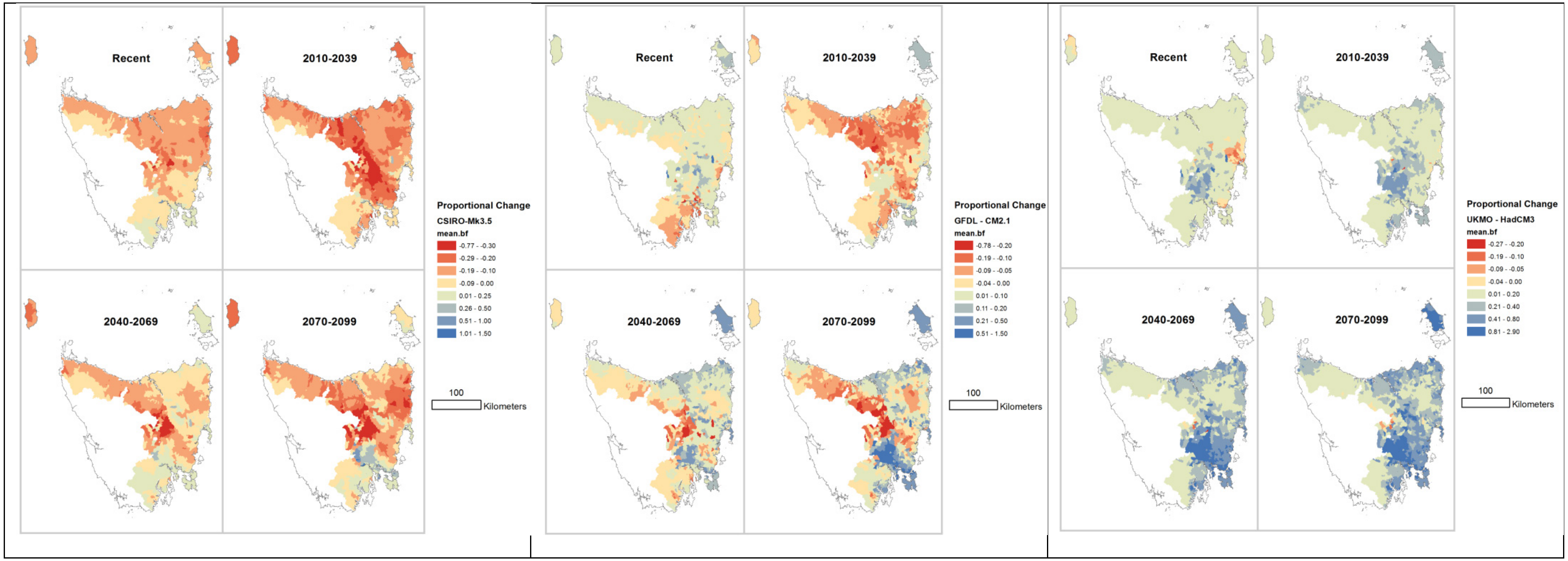


Figure 37 The proportional change in mean base flow from the Reference Period

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

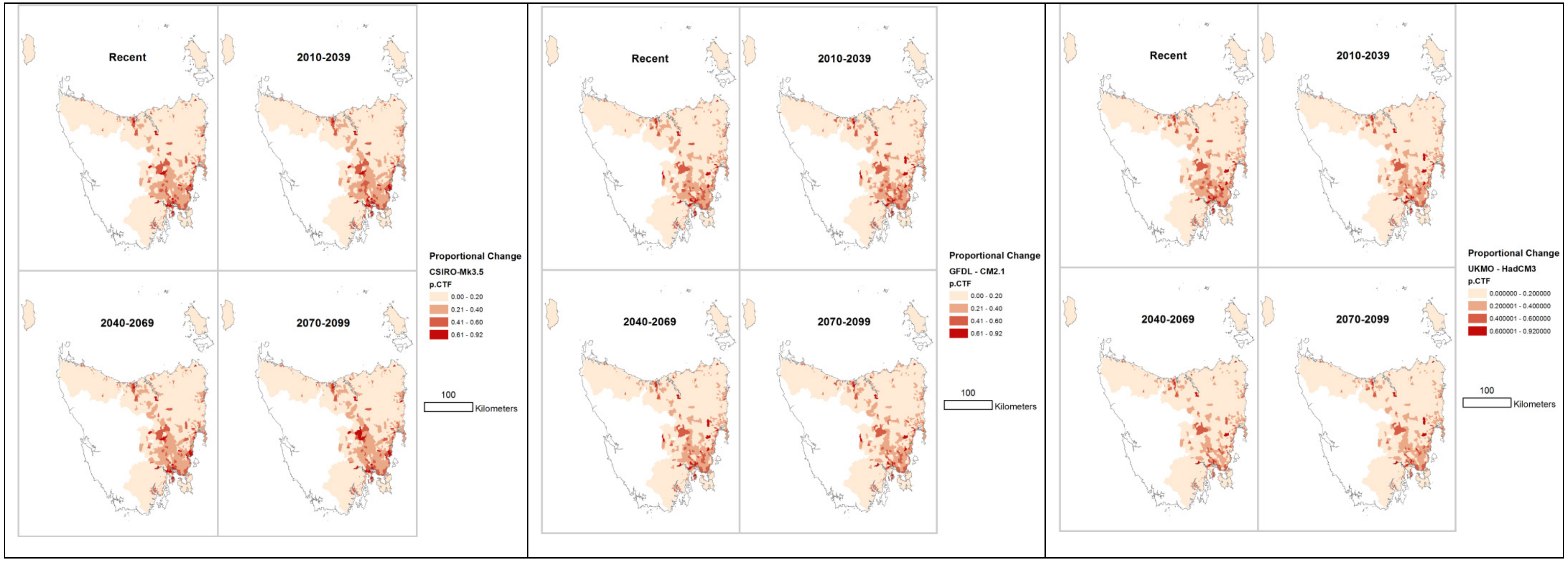


Figure 38 The proportional change from the Reference Period in the number of cease to flow days

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

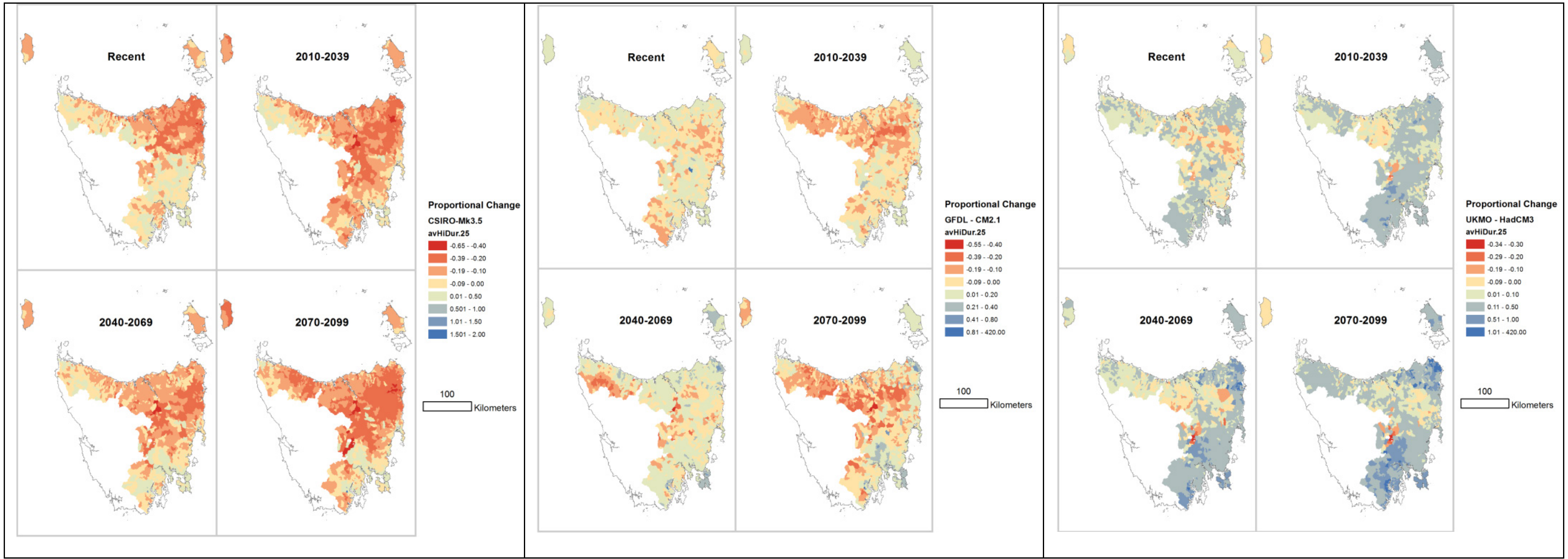


Figure 39 The proportional change from the Reference Period in the average duration of spells above the 25th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

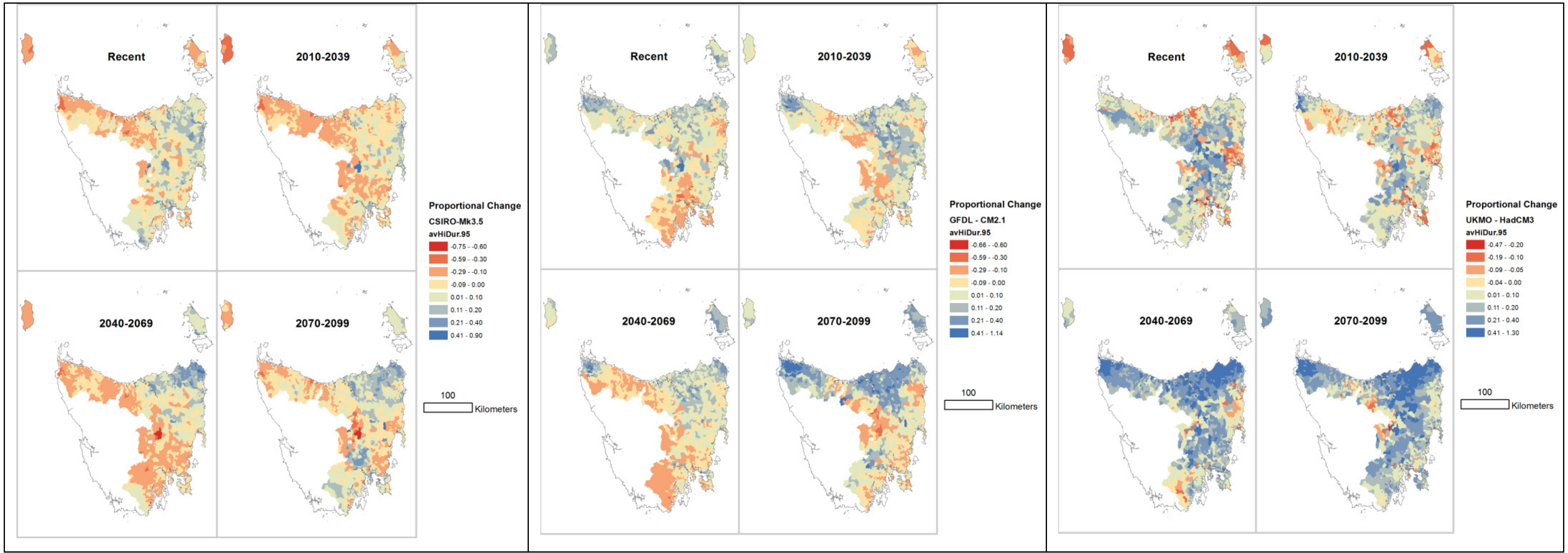


Figure 40 The proportional change from the Reference Period in the average duration of spells above the 95th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

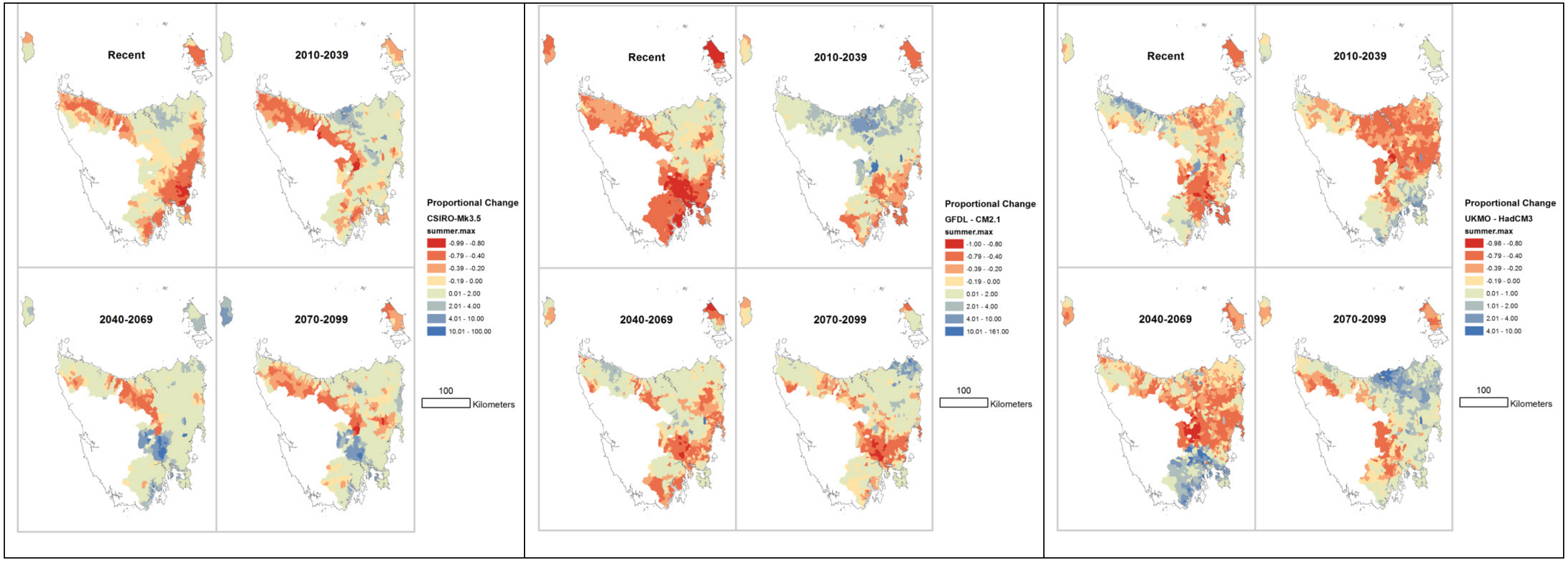


Figure 41 The proportional change from the Reference Period in the summer maximum daily flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

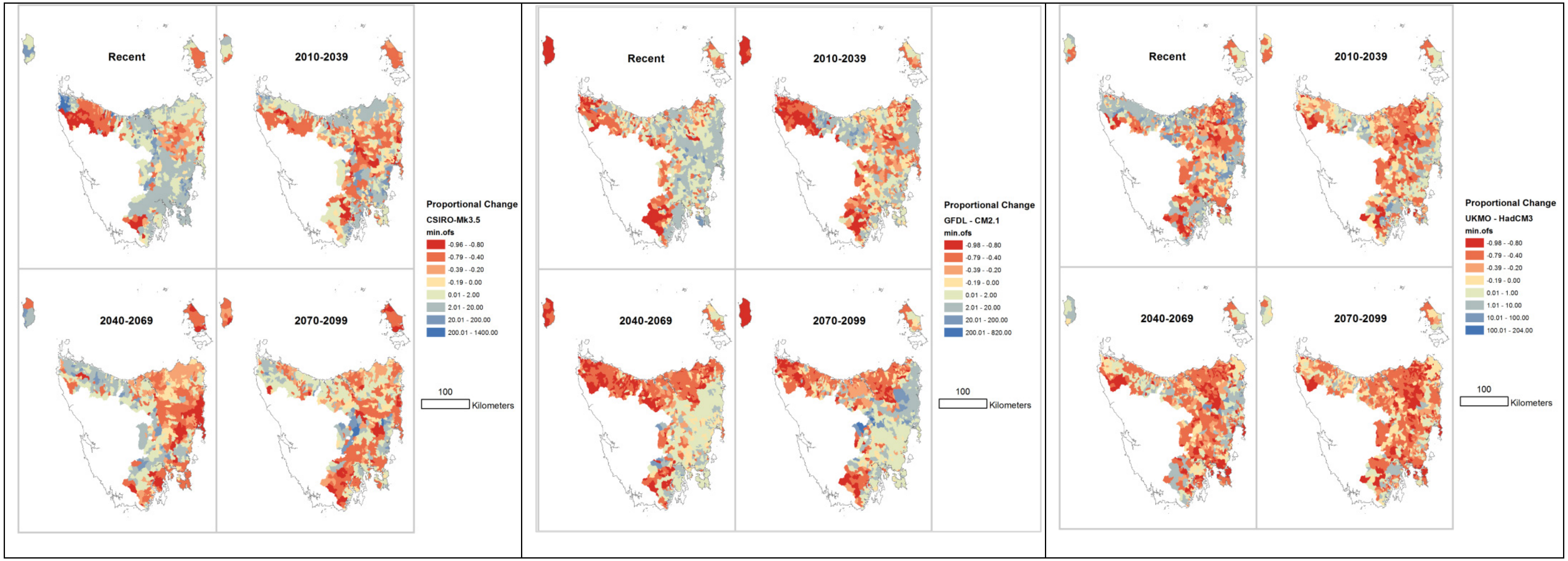


Figure 42 The proportional change from the Reference Period in the minimum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

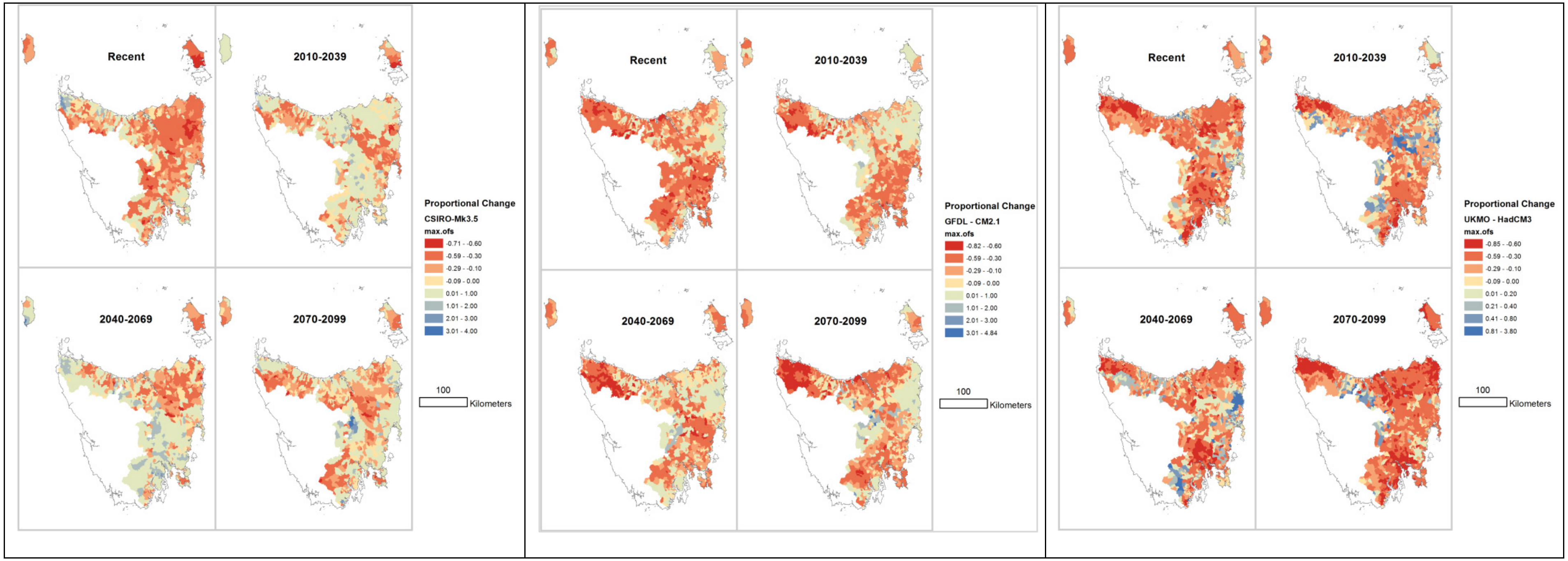


Figure 43 The proportional change from the Reference Period in the maximum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

Appendix 7: BBN maps') and to native fish condition in coastal lowland rivers (Figure 22).

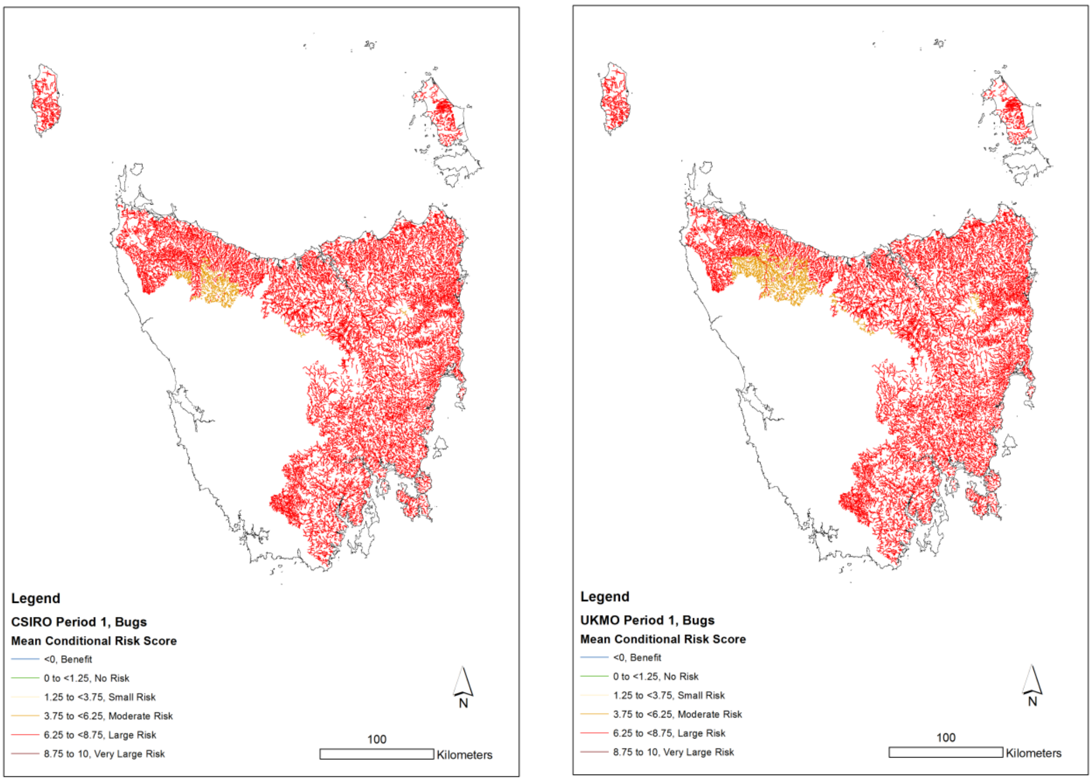


Figure 20 Macroinvertebrate conditional risk scores for Period 1

The CSIRO (left panel) and UKMO (right panel) BBN model predictions for Period 1.

Because macroinvertebrate condition and abundance were inputs to the BBN for brown trout, and because this species itself is sensitive to warmer water, it also showed high risk scores across most of Tasmania (Figure 21). Presumably, the temperature sensitivity of this species overwhelmed the hydrological differences between the models (Figure 14) with only minor differences between the wettest and driest models in Period 1 (Figure 21; the GFDL model was most similar to the UKMO model). However, as maximum water temperatures increase across all models in Period 2, they converge in showing greatly increased risks for brown trout across most of the modelled catchments (Figure 50 of 'Appendix 6: Hydrology maps
The following maps are the full set of maps of predicted changes to river hydrology variables. Each panel gives the proportional change to that hydrology variable between the Reference Period (1961–1990) and each of the Recent Period (1991–2009), Period 1 (2010–2039), Period 2 (2040–2069) and Period 3 (2070–2099). A decrease in a variable is shown in red, and an increase in blue.

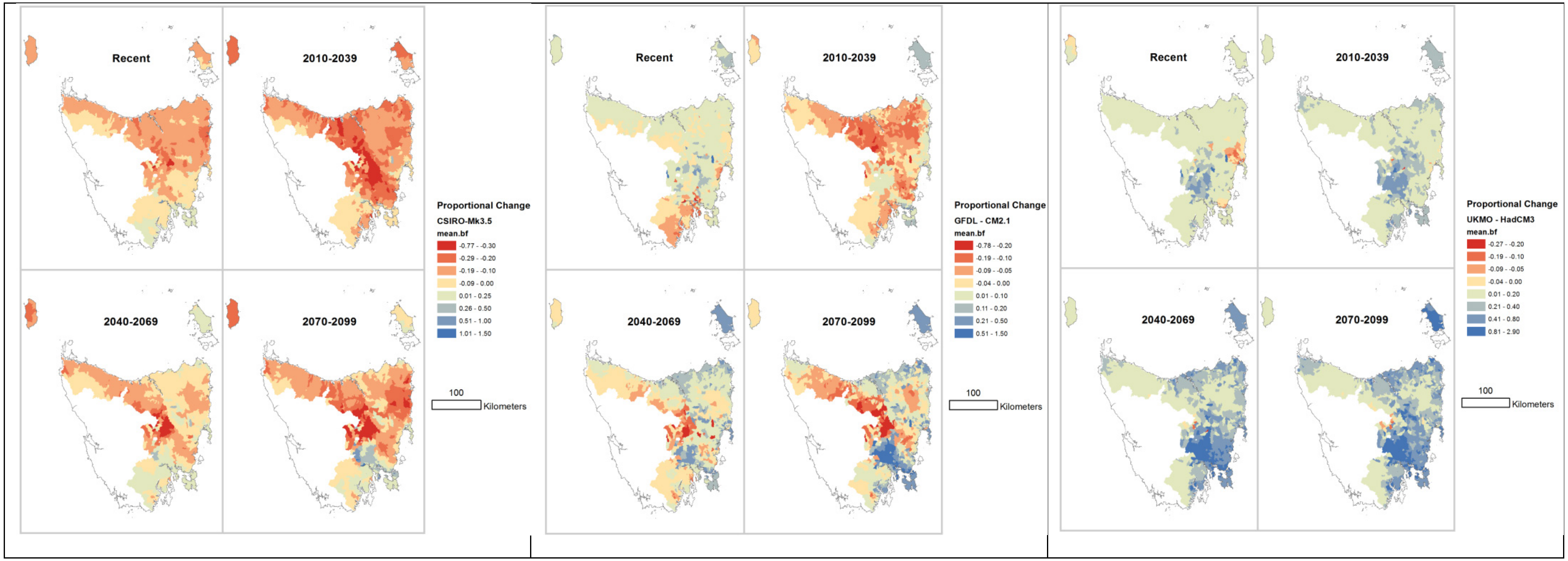


Figure 37 The proportional change in mean base flow from the Reference Period

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

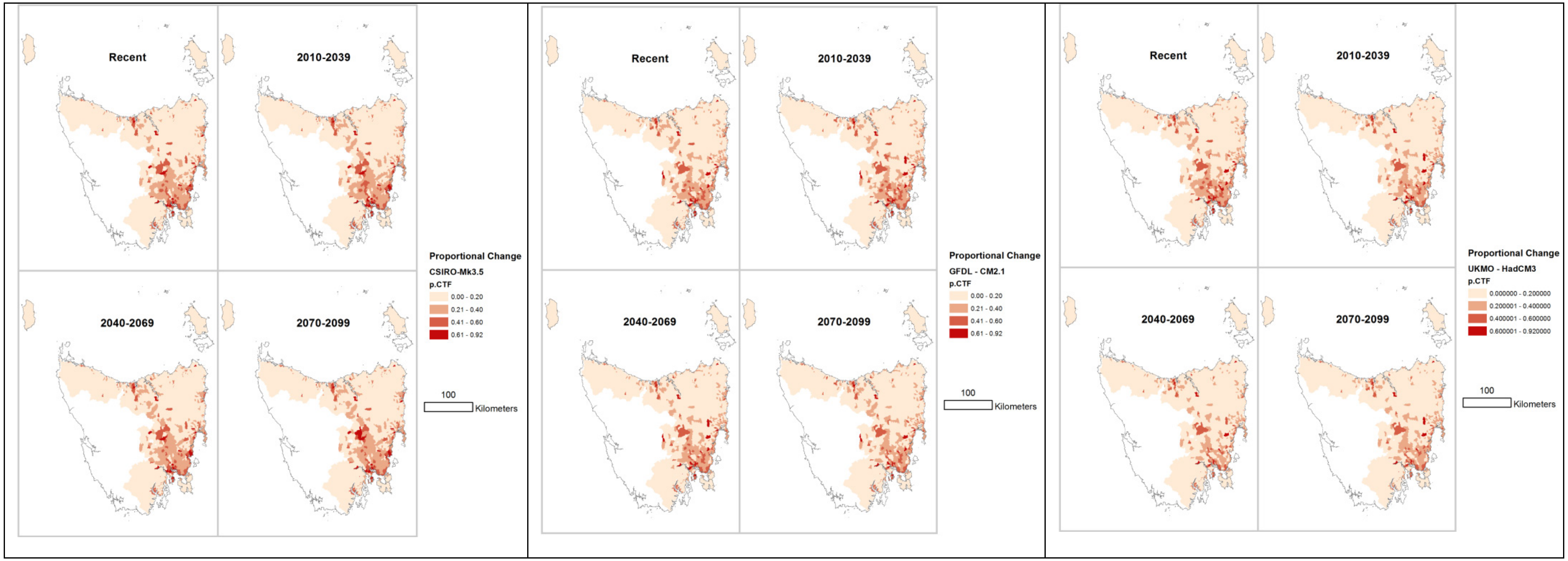


Figure 38 The proportional change from the Reference Period in the number of cease to flow days

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

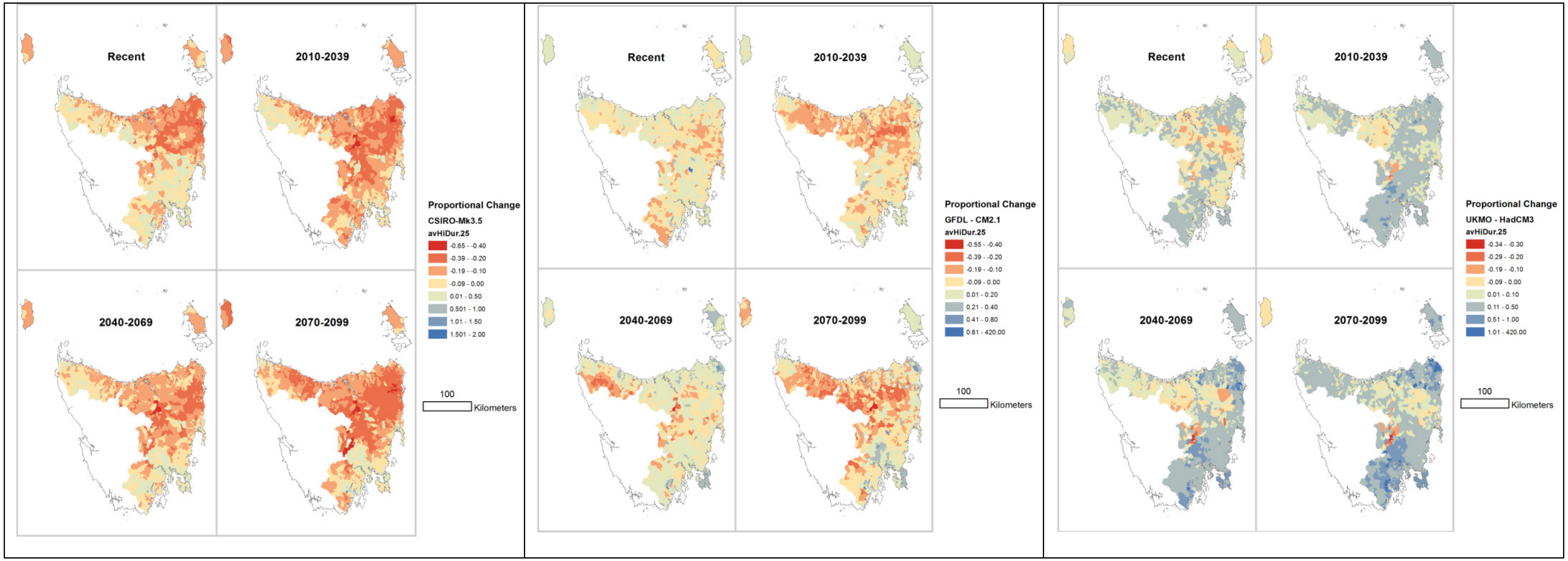


Figure 39 The proportional change from the Reference Period in the average duration of spells above the 25th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

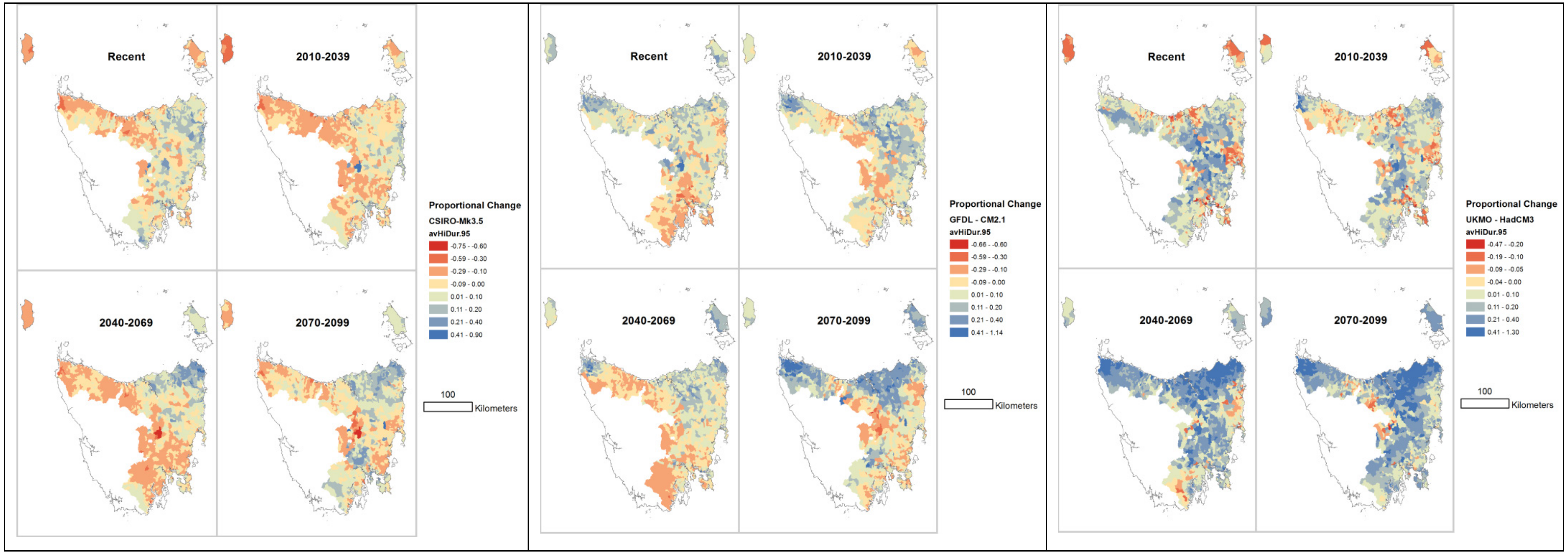


Figure 40 The proportional change from the Reference Period in the average duration of spells above the 95th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

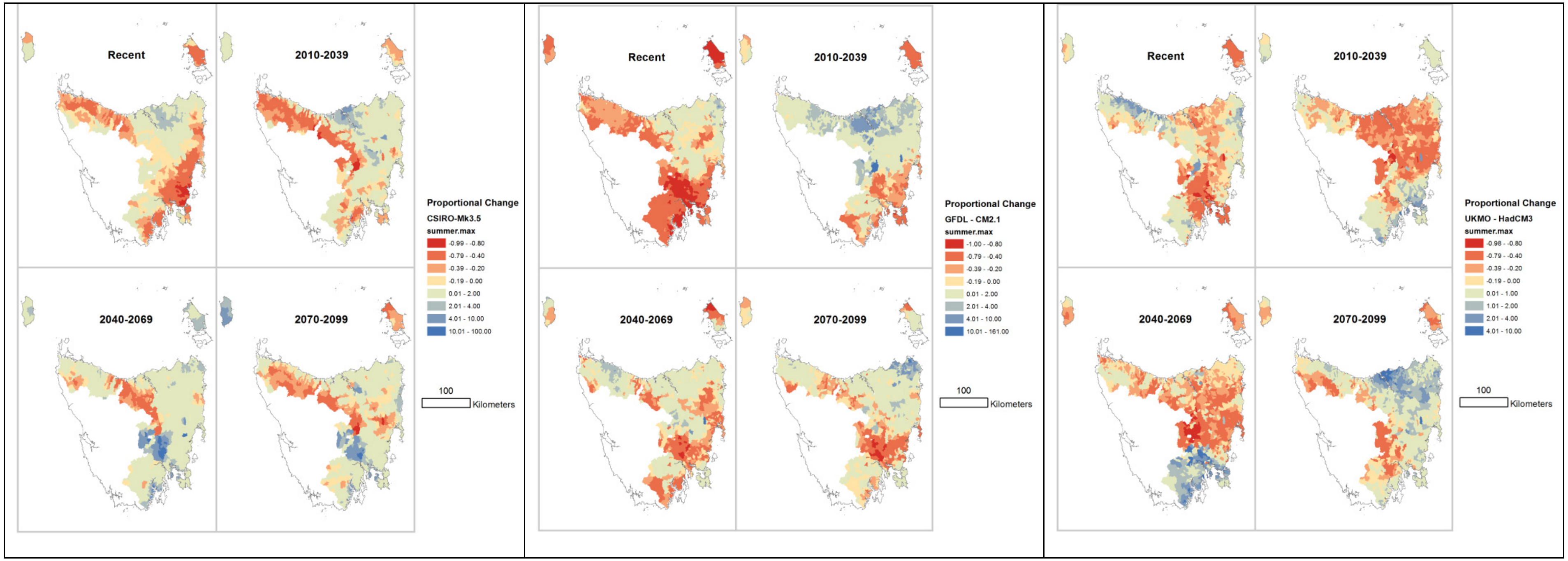


Figure 41 The proportional change from the Reference Period in the summer maximum daily flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

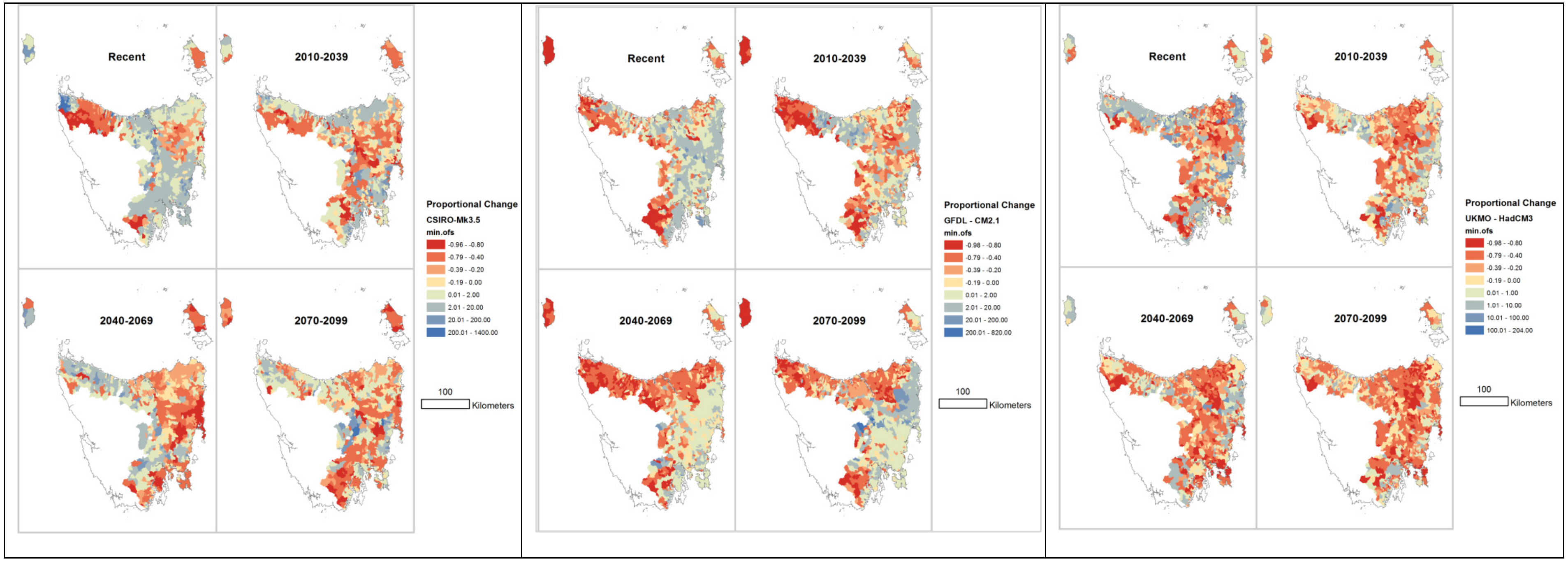


Figure 42 The proportional change from the Reference Period in the minimum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

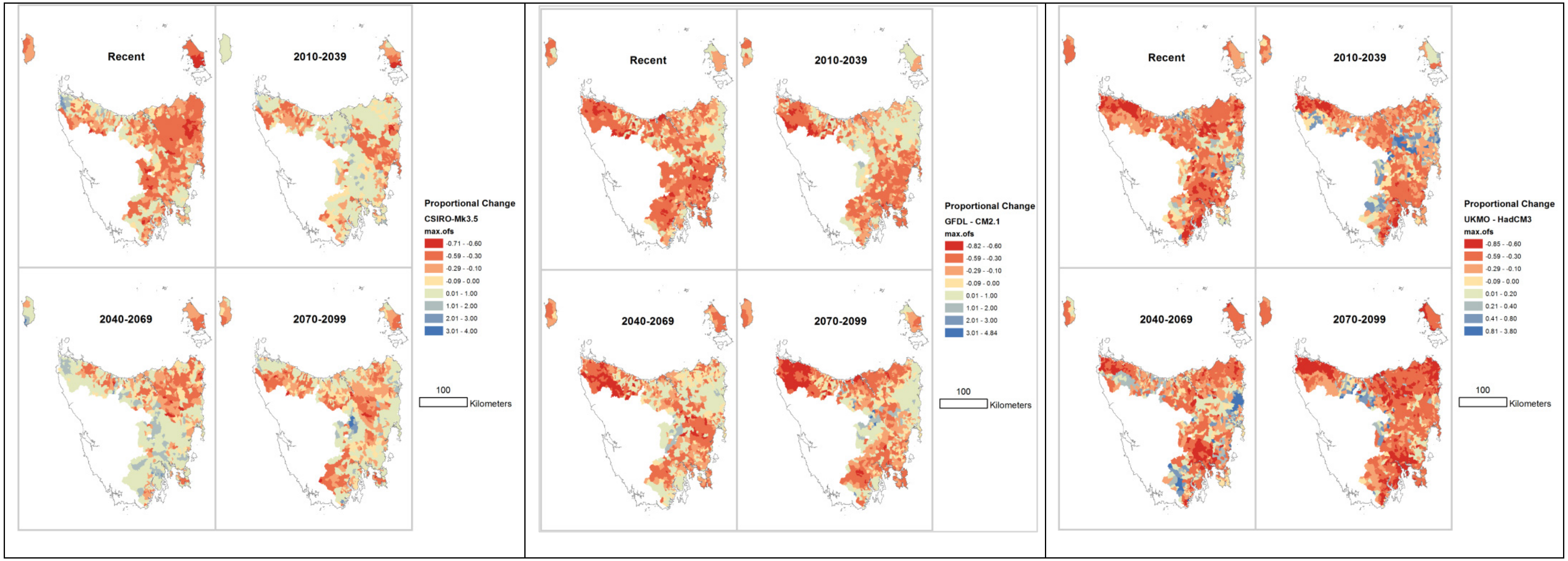


Figure 43 The proportional change from the Reference Period in the maximum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

Appendix 7: BBN maps'), with only a few catchments in the north-east showing some benefits, presumably accruing from the increased summer rainfall events predicted for this region.

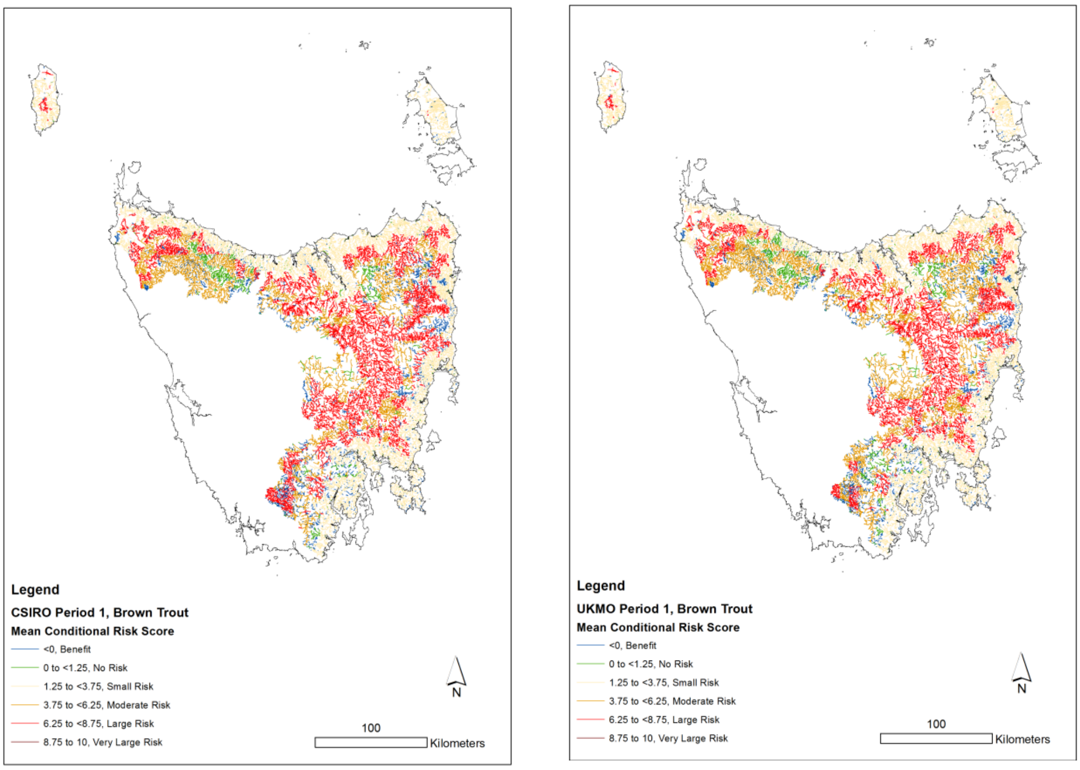


Figure 21 Brown trout conditional risk scores for Period 1

The CSIRO (left panel) and UKMO (right panel) BBN model predictions for Period 1.

3.2.3 Interactions may ameliorate some effects

Native fish community condition has more inputs relating to hydrology than brown trout or macroinvertebrates (Figure 34 of 'Appendix 1: BBN listings'), and the more benign hydrological risks from the UKMO model in the Midlands (Figure 13) appear to have attenuated or compensated for temperature effects resulting in lower risks for native fish in this model than for the CSIRO model (Figure 22). In addition, the demise of brown trout improves the condition of native fish communities (Balcombe et al. 2011), and so the interaction between these factors results in lower overall risks than for brown trout or macroinvertebrates for many mid-order streams (Figure 22). There are also some notable differences between the models, which are described in subsection 3.2.4.

Platypus showed the most varied patterns in risk within each model (Figure 23), which probably reflected the complex interplay of hydrology with feeding and breeding habitats (Figure 31 of 'Appendix 1: BBN listings'). This taxon also showed the most extensive areas of extreme risks (Figure 23), which probably reflects effects of temperature and hydrology on macroinvertebrate condition. Because platypus are unlikely to benefit from the decline of trout in lowland areas, this species shows markedly higher risks in the Midlands and central northern catchments than do native fish communities (cf. Figure 22, Figure 23).

3.2.4 Divergent risks patterns from different models

Perhaps the most difficult issue for prioritising and planning adaptation actions is the divergent predictions of risks that emerge from different GCMs. For native fish condition, for example, differences between the models were most pronounced in the Midlands where moderate to large risks were identified by CSIRO and GFDL models, whereas UKMO showed only moderate risks for Period 1 (Figure 22). Focussing on the upper right portion of Tasmania in Figure 22 shows considerable differences between the CSIRO and GFDL models for some of the major catchments in this region.

Zooming in on north-western Tasmania and King Island produces some striking contrasts (Figure 24) which emphasise the relative differences in hydrology between the models. For those wetlands predicted to benefit in the ‘median’ GFDL model, the ‘drier’ CSIRO model predicts ‘no change’, whereas the ‘wetter’ UKMO model predicts moderate increases in risk. Clearly, over-simplified generalisations of which model is ‘driest’ and adoption of that as a ‘worst case’ scenario will be inadequate. There is considerable fine scale variation between the models in their predictions which will need to be captured and communicated when planning at those scales.

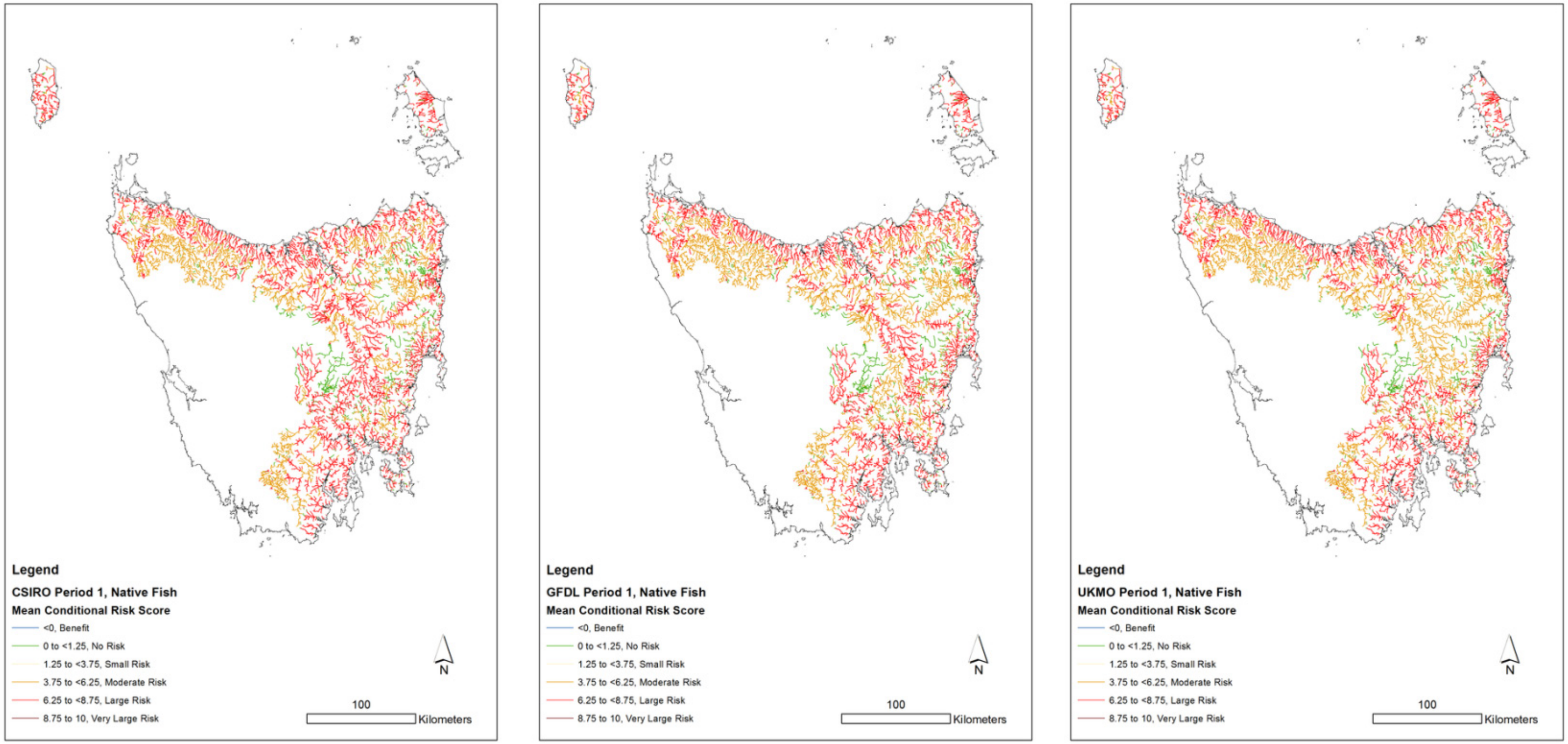


Figure 22 Native fish community conditional risk for Period 1

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 1

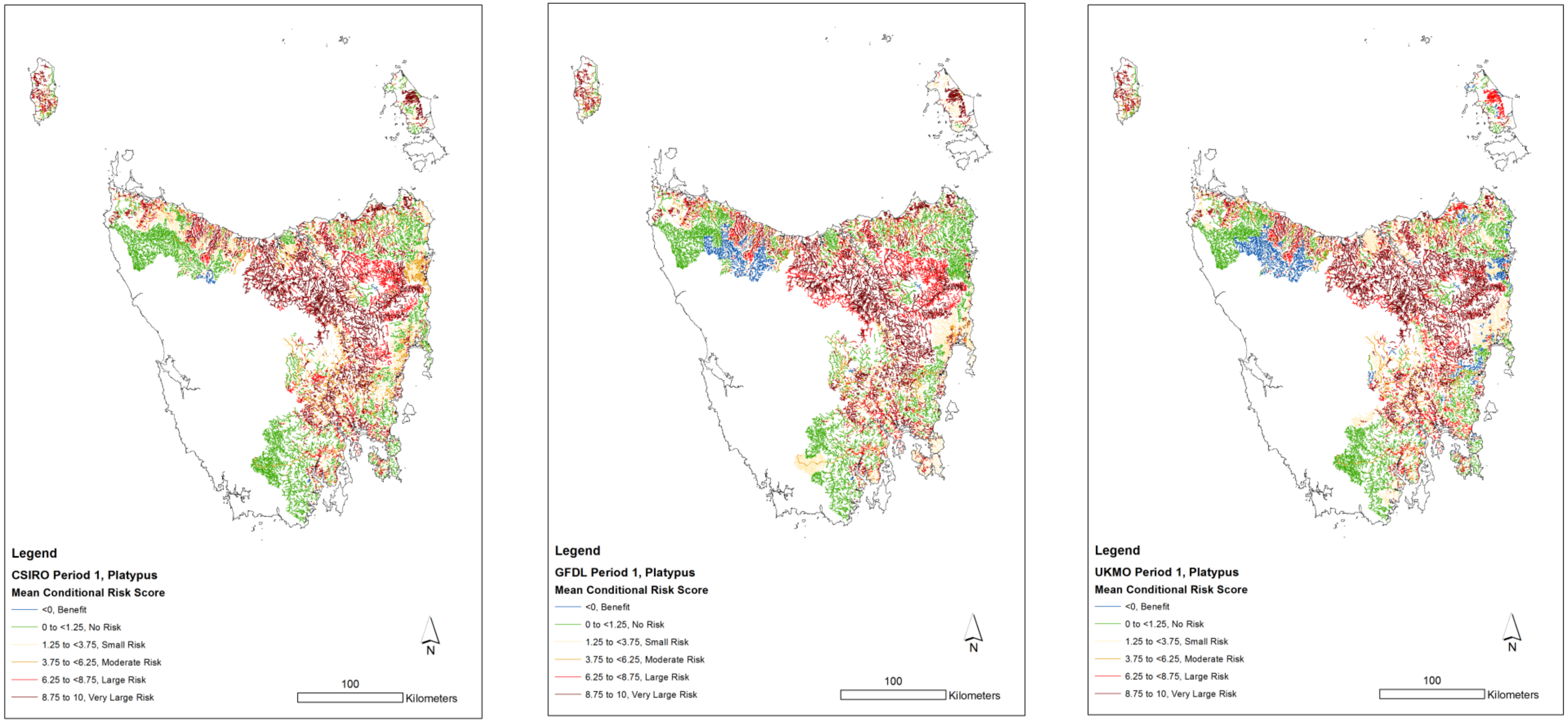


Figure 23 Platypus population conditional risk scores for Period 1

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 1

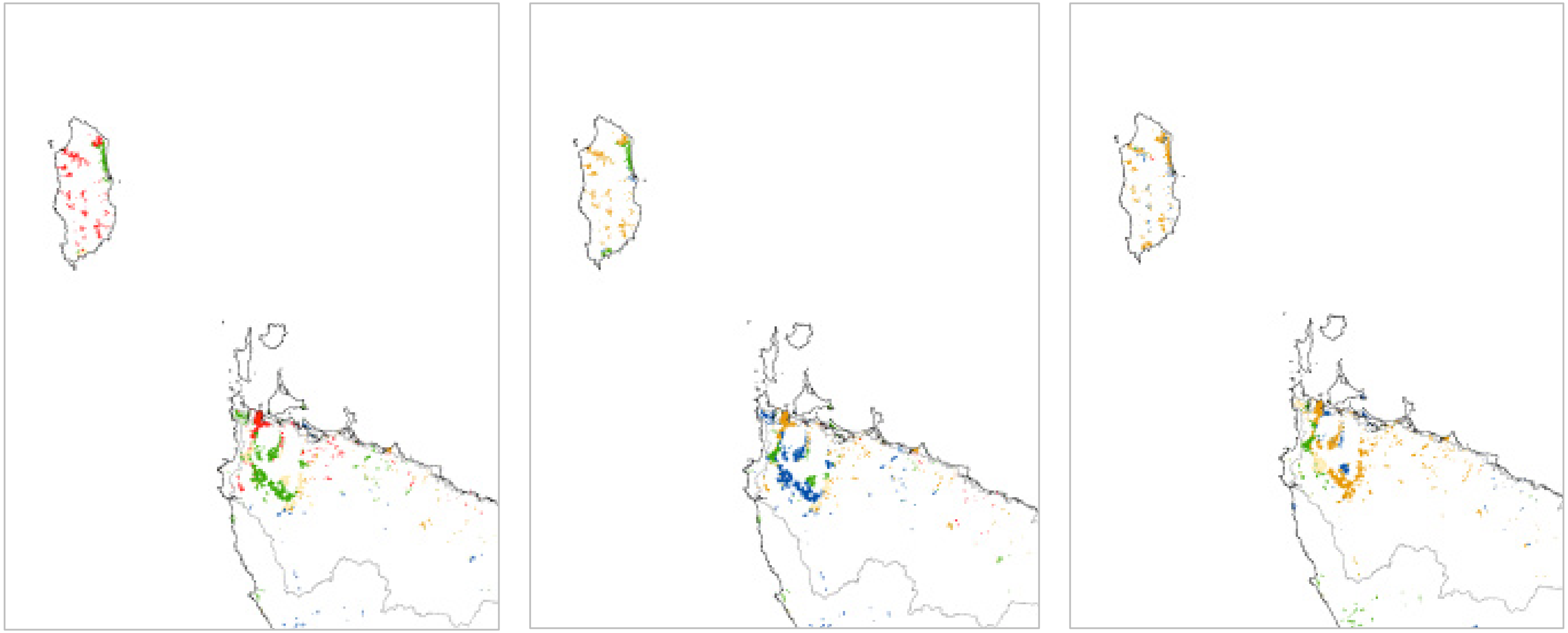


Figure 24 Floodplain wetland conditional risk scores for northwest Tasmania and King Island for Period 1

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 1

3.3 Scoping and classification of adaptation options

Our reviews, workshops and consultations identified over 45 options for climate change adaption in freshwater ecosystems. These adaptation strategies can be broken down into components, depending on the level of jurisdictional control. The prioritisation of activities will depend on the pressures on freshwater assets and available resources of each area. Active or on-ground management activities for a river reach or wetland can be undertaken at a local level by the landowner, community group, land or catchment management or state authority and will frequently be based on state or federal funding for specific projects (Table 8).

Table 8 On-ground, active management activities

Active management activity	Activity definition and aims
Monitoring	Plant and animal populations serve as a barometer of ecosystem integrity (Feenstra et al. 1998). Monitoring is an important component of any adaptation strategy, to assess the effectiveness or otherwise of remedial action, and allow adaptive management of unexpected consequences. It involves ongoing quantitative assessment of the condition of the river or riparian zone. Effective monitoring involves repeated field-based measurements, collected continuously over an extended time period (Lindenmayer and Likens 2010). Identify indicators that can be monitored by community groups, and that are relevant to land managers and adjacent land owners (Parks and Wildlife Service 2007).
Fencing, weed control, management of riparian zone	Fencing to exclude stock from the riparian zone and water course prevents fouling of the water and sedimentation, destabilisation of banks and erosion. Riparian vegetation stabilises the banks, reduces the water temperature by shading the reach, limits the growth of filamentous algae, and provides woody debris to reduce the impact of scouring flows, increases habitat diversity and the input of coarse organic material to sustain riverine productivity (Gregory et al. 1991). Retain mature trees in preference to establishing seedlings - mature trees have greater adaptive capacity and tolerance of climate extremes than seedlings (Franklin et al. 1992).
Riparian zone community structure	Blackberries, hawthorns, willows and gorse are deciduous plants which lose their leaves in autumn, depositing high loads of organic material into the river channel and potentially fouling the water. Willows grow into the channel, and have a dense root structure which clogs the channel and impedes flow, increasing flood damage to the riparian zone (Lester, Mitchell and Scott 1994). Broken branches can resprout and produce new trees downstream, so that removal of willows needs to be carefully undertaken to prevent the spread of new trees and destabilisation of the river banks. Blackberries and gorse are invasive weeds and should be removed to limit spread into adjacent land and along the channel. Conversion of wetlands to agricultural land should be prevented during drought periods to limit damage and weed invasion (Bond, Lake and Arthington 2008).

Active management activity	Activity definition and aims
Exclusion or eradication of alien species and weeds	Many pest and weed species will be advantaged by a higher CO_2 environment and warmer temperatures, requiring active management in agricultural areas, and climate change will increase the prevalence and virulence of many disease vectors (McGlone and Walker 2011). Monitor for new invasive species and prevent spread. Weed management may require a whole-of-landscape approach to avoid ineffective control (McGlone and Walker 2011). Minimise ecosystem disturbance to limit invasion. Exclusion of alien species may involve construction of selective barriers, such as fish ladders and traps, barriers to prevent upstream movement of exotic fish, control of weed populations, control of spread of chytrid fungus (*Batrachochytrium dendrobatidis*) in frogs; mucormycosis in platypus; *Phytophthora cinnamomi* fungus in riparian vegetation. Implement and enforce standardised hygiene guidelines to prevent spread of weed or disease propagules.
Physical habitat or refuge enhancement	Increase the population size or improve the chance of survival by modifying the immediate environment or increase the ability of a habitat to protect a particular species, or increase the resilience of the population or ecosystem (Franklin et al. 1992). Construct dams/weirs to increase depth of pools or maintain riffle sections, or to provide water for overbank flows to maintain riparian vegetation. Water level manipulation in regulated systems, flow regime management to allow overbank flows in winter, summer cease to flows in high variability systems, diversion of flows in unregulated systems, establishment of algae/macrophyte populations (Palmer et al. 2009). Modify thermal regimes with selective level off-takes in regulated systems, to protect ovulation and spawning conditions (Olden and Naiman 2010). Increase habitat heterogeneity with coarse woody debris and snag replacement (Nicol et al. 2002), channel engineering, bank stabilisation. Protect headwaters of streams to preserve low temperature refugia (Lawler 2009). Refuge quality and size are important. Abiotic and biotic stressors, such as predation, are magnified in small low-flow refugia (Jenkins et al. 2011).
Passage restoration or enhancement	Increase the ability of fish or invertebrates to move between habitats. Maintain breeding populations by promoting upstream movement of migratory species. Removal of barriers to passage, such as addition of bypasses for Hydro turbines, or complete removal of redundant dams. Install fish ladders to allow access to feeding or spawning areas upstream of dams or weirs (MDBC 2004).
Develop flow connections	Maintain/enhance connectivity between river sections, or between the channel and the riparian zone. This may require removal or modification of redundant in-stream barriers, such as weirs and small dams, or reduce direct abstraction from the stream (Jenkins et al. 2011). Small overbank flows can be delivered by strategic placement of weirs. Maintain ecological connectivity - transport sediments, nutrients, biota and plant propagules between river and wetlands (VEAC 2008). Increase the capacity of the catchment to capture, store and release water to buffer declines in flow (Aldous et al. 2011),

Active management activity	Activity definition and aims
	including development and maintenance of side channels and floodplain inundation. Increase dispersal ability of desirable species while limiting dispersal of exotic species (Ormerod 2009).
Prevent eutrophication and sedimentation, particularly in wetlands	Dissolved oxygen concentrations may decrease with warmer water. Higher temperatures may alter reaction rates with nitrogen and phosphorus and influence phytoplankton productivity (Woodward, Perkins and Brown 2010). There may be increased sedimentation and nutrient influx after high flow events, with more frequent flash flooding. Identify and control sources of nutrient and leachate contamination, limit upstream erosion, allow flushing flows in dry periods. Plant aquatic macrophytes to manage water quality in wetlands (Qiu et al. 2001), and enhance habitat suitability for biota.
Enforcement of regulations: fishery; wildlife; threatened species	Protection of threatened species by enforcement of anti-poaching laws (e.g. *Astacopsis gouldi*). Maintenance of sustainable populations of native and commercially valuable species (e.g. salmonids) by enforcing hunting season and catch limits, particularly in times of low flow.
Spawning enhancement	Management of lake or river levels and water temperatures to increase breeding success of birds or fish. Some native fish have specific habitat or water temperature requirements for spawning. Water levels may need to be manipulated to expose or inundate spawning gravels (e.g. Hardie et al. 2007). Water temperature can be manipulated by release of water from the appropriate depths of reservoirs - deeper water is colder, but may need oxygenation.
Captive breeding and stocking	Establishment and maintenance of laboratory/nursery breeding facilities. Release of juvenile or adult fish or eels into lakes or rivers. Wild populations may be unsustainable due to low abundance, or local conditions which do not allow survival of eggs or juveniles. Individuals can be reared to viable size and released to increase population abundance. Triploid salmonids are produced by treating eggs to modify the chromosome number. These fish are sterile and continue to grow past sexual maturity, potentially producing larger fish, which are unable to breed in the wild.
Species translocations	Remove species from unsuitable habitat and relocate in areas to which natural migration would be difficult (Feenstra et al. 1998). Movement of threatened species to areas identified as refugia under climate change; or movement of species upstream of barriers which prevent access to spawning or feeding grounds; or transport of species with limited ability to move across catchments (e.g. Crustacea, molluscs) (Turak et al. 2011). The impact of translocation on existing biota needs to be considered and the long-term viability of the new habitat.

Water management activities are more likely to be carried out at a catchment or river level, and be based on water management plans and licensing arrangements under state and federal regulations (Table 9). Implementation of water management adaptation strategies is likely to be by water utilities, hydro-electric power companies, or catchment management authorities. Landowners and community groups can strongly influence decisions and outcomes and landowners have a role in implementation at all levels. The prioritisation of any activity will depend on the resources available, and will generally be driven by the economic cost of the activity to the community.

Table 9 Water management adaptation options

Water management activity	Activity definition and aims
Farm dam management	Regulation of the amount of water that can be abstracted from a river and stored in farm dams, to prevent degradation of the river ecosystem. Farm dams may intercept most of the drainage in some catchments (McMurray. D. 2006). Water stored in shallow dams is warmer than river water and subject to increased evaporation levels. Manage macrophyte communities, limit stock access to prevent bank erosion and fouling of the water. Use riparian plantings to increase shade, reduce wind impacts and limit evaporation. Use hardier varieties of crops with lower water needs, use stubble management to increase soil moisture retention.
Off-stream storage management	Typically, 40% of storage capacity is lost to evaporation (Schmidt 2007). Reduce evaporation by riparian shading. Small deep storages rather than broad shallow storages; development of commercial applications of ultra-thin polymer films (amphiphilic chemicals), which are currently easily disrupted by wind and require frequent reapplication (DNRM 2002, Schmidt 2009). Reduce the need for open channels by situating irrigated agriculture closer to main storage (Hassall and Associates 2007). Use hardier varieties of crops with lower water needs, use stubble management to increase soil moisture retention (Hassall and Associates 2007). Transfers between cascading series of dams may return seasonality and variability without changing the volume of flow (Watts et al. 2011).
In-stream dam management	Maintain dam infrastructure (Palmer et al. 2009, Palmer et al. 2008); dam reoperation to mimic natural flows can involve storage of water in downstream aquifers (Watts et al. 2011), managing water quality with multi-level off-takes (Pittock and Hartmann 2011), changing delivery arrangements with landholders; environmental water releases piggybacked on consumptive water releases, which requires flexible and rapid decision making for release to coincide with high rainfall events (Pittock and Hartmann 2011, Watts et al. 2011). Dam design constraints can seriously limit the ability to release variable flows (Richter and Thomas 2007).
Environmental flow allocation or enhancement (*e*Flows)	The provision of a defined share of water resources to maintain healthy river systems or to restore degraded systems. This includes setting abstraction limits in unregulated streams and specific environmental flow regimes in regulated systems. Ideally, environmental flows would mimic the seasonal timing and volume of natural flows. Adjustment of reservoir release schedules to optimise beneficial flows, which may require collaborative arrangements with dam managers (Pittock and Finlayson 2011). Base flows are the minimal amount of water needed to support in-stream biota and water quality. Loss of flooding flows has been identified as the greatest risk to

Water management activity	Activity definition and aims
	floodplain wetlands (e.g.Jenkins et al. 2011). Small floods also maintain the health of riffle zones, removing sediment and biofilms. Larger floods clean out deeper pools and maintain the channel form and floodplain productivity. Special purpose flows may be needed to protect habitat or encourage breeding of particular species. May need modification of infrastructure to increase outlet size, flood mitigation strategies or easements downstream (Aldous et al. 2011, Watts et al. 2011). Control water releases from storages with multi-level off-takes to avoid release of cold anoxic bottom water to reduce disruption of spawning and migratory cues for biota (Sherman 2000).
Inter-catchment transfer	Transfer of water between river catchments to augment low flows. Pumping of water between storages to provide for future supplies in high use catchments. May need significant investment in infrastructure, including the use of pipes or canals to reduce impact on connecting river systems. May need strategies to prevent transfer of pest species or diseases between catchments (Davies, Thoms and Meador 1992, Snaddon, Wishart and Davies 1998). Can include trade of environmental water from catchments with large license allocations, with short term water sale or leasing, or long term sale of water entitlements to other catchments
Dry season take rules	Regulation of abstraction limits, predetermined and adaptive/staged cease-to-take flow rules, where extractions from the river or reservoir must cease when flow falls below minimum threshold levels. Enforcement of regulations.
Connection flow rules	Regulation of the amount of water that can be allocated to alternative river sections; or the provision of overbank flows to maintain riparian vegetation or spawning of biota; or migratory or dispersal corridors for biota. Maintain connectivity between rivers and wetlands, channel and riparian zone, rivers and tributaries (Bond et al. 2008). May require high level of flow regulation, and significant investment in infrastructure.
Drought pumping	Pumping of water to increase irrigation supply to customers upstream of gravity fed storages, or to return drainage water back into storage; or pumping between downstream and upstream Hydro storages to reuse water during periods of peak demand. This reduces flow downstream of the dam and may require pump stations and significant infrastructure. Water transfers between successive dams may allow some variability in the flow regime, without increasing the volume of water. Costs of pumping and water quality issues may need to be addressed (Watts et al. 2011). Prohibit drought pumping from potential drought refugia (Bond et al. 2008).
Pumping or flood harvesting to recharge groundwater	Groundwater as an alternative water source to direct river abstraction. Floodwater pumping to groundwater to provide baseflows in dry periods and reduce evaporation (Palmer et al. 2008).
Water management to protect assets with	Releases of water to prevent wetlands drying out in peak bird breeding season (Jenkins et al. 2011), or maintain pools in

Water management activity	Activity definition and aims
high biological value	river systems, or to maintain connectivity to allow passage of key biota. Can be coupled with on-ground engineering works to improve flooding efficiency (e.g. The Koondrook-Perricoota Forest Icon site MDBA 2010)
Water buyback during dry years	Purchase of water entitlements to enable flow releases in dry years or seasons (Palmer et al. 2009), or trading (sale or lease) of water entitlements from high resource catchments as priorities change
Shandying (dilution flows)	Increasing water availability by diluting recycled water/saline bore water with fresh water (Aravinthan 2005). Off-stream storages may be required to maintain supply of recycled water. Licensing and approvals may be needed to use recycled water on crops or parklands. Reduced inflows to catchments may reduce the ability to dilute recycled water with consequent reduction on water quality (Shanahan and Boland 2008).
Flood management	Increased flow variability will increase the frequency and intensity of flash flooding to floodplain wetlands. This can add significant sediment loads to wetlands and inundate the nests of breeding birds (Mowling et al. 2010).

Adaptation strategies at the catchment scale are likely to be driven by regulations and incentives for land and water management, but may involve all levels of land management (Table 10). Individual farmers can modify production methods to reduce water requirements or limit runoff into waterways; local governments manage land use planning laws. Non-government organisations such as Natural Resource Managers (NRMs) or catchment management authorities (CMAs) are frequently at the forefront of land management under federal or state funding schemes for remedial action.

Table 10 Catchment management adaptation options

Catchment management activity	Activity definition and aims
Land use prescriptions and limits	Limits to land clearance to protect waterways, conversion of pasture to forest or *vice versa*, regulation of conversion of native vegetation to urban development. Regulation of farm dam abundance to reduce interception of overland flows which would otherwise runoff to rivers or wetlands. Control of effluent drainage from dairy or pig farms, limitation of nutrient and herbicide or pesticide input from irrigation and wastewater return flows, dilution of saline wastewater or bore water. Licensing of farm dams for stock watering. Specification of minimum lot sizes for residential development, covenants to protect native vegetation. Encouragement of efficient water use in urban catchments, reuse and recycling of urban water, storm water capture and storage, encourage urban planting to increase groundwater infiltration. Management of human impacts, particularly on wetlands – hunting, fishing, camping, 4WD activity.
On-farm management prescriptions or incentives	Individual farm actions to reduce impact on water quality or quantity, government incentives to increase water use efficiency or take remedial action. Promotion of efficient

Catchment management activity	Activity definition and aims
	irrigation schemes, monitoring of soil moisture to optimise water use, recycling of waste water from dairies etc., selection of crops by water use efficiency, irrigate at night to reduce evaporative loss, avoiding open channel distribution of water and flood irrigation. Government grants/tax incentives to reduce water use, investment in water-efficient irrigation equipment, financial incentives to preserve or enhance native vegetation. Develop information technology tools to help irrigators calculate water requirements for specific crops; development of water efficiency plans. Incentives for carbon sequestration in riparian zones or soil (Jenkins et al. 2011). Exit grants for unviable farmers to leave the industry (Kiern and Austin 2012).
Forestry planning or prescriptions	Management of water consumption by forestry activity to protect waterways. Preservation of effective riparian buffer strips around water ways; control of regeneration burns to protect the riparian buffer and prevent wildfires; long rotation forestry to limit high water uptake and increased evapotranspiration in new forestry plantations; control of sedimentation and damage to stream crossings from roadworks; limitation of clear fell and burn forestry near waterways or in low rainfall catchments.
Incentives for riparian zone management	Income based or tax-rebate compensation to land holders to manage riparian zones. Carbon credits to preserve riparian zone.
Management of acid-sulphate soils, sodic soils	Acid sulphate soils form when wetlands dry out in previously water logged soils, where iron pyrites (FeS_2) build up. These react with oxygen to form sulphuric acid as the soils dry out (Gurung 2006). Sodic soils are naturally saline, due to the laying down of previous ocean floor sediments. Irrigation can flush salt from the sediments and deposit them in the upper soil horizons or into water ways. Tunnel erosion and failure of dams are additional problems (Doyle and Habraken 1993).
Training of water managers	Managers need to be able to clearly demonstrate issues to the general community - the reasoning behind zoning restrictions, land use regulations. This may require technical assistance to local water managers - training of staff and support for affordable resources (GIS mapping, modelling, e.g.) for communication with community groups (Palmer et al. 2008, Chatterjee, Phillips and Stroud 2008).
Public education	Educating the local community on the value of freshwater assets can have a strong influence on outcomes. A few local ‘champions’ can change community attitudes

3.4 Prioritisation, planning and policy

The consensus from the workshops and stakeholder meetings was that the lists of adaptation options for conserving freshwater biodiversity were comprehensive, at least for Tasmania. Setting priorities to actions proved more difficult, even within individual case studies. Different stakeholders had different approaches, some formalised, and some implicit in their current practices. Accordingly, perceptions about planning tools and policy settings varied amongst participants and reflected the considerable changes in policy settings occurring elsewhere in Australia, with few of these changes finalised at the time of our consultations (section 3.4.2). Nevertheless, the case studies provided important contextual information (summarised in section 3.4.1), which informed our planning and policy needs (described in section 3.5).

3.4.1 Results from case studies

Although each of the case studies had different land use issues and different threats to freshwater biodiversity, there were some common themes. First, was the difficulty in predicting future changes in socio-economic drivers (e.g. land use) or demographic factors (e.g. structural changes in human populations). These anthropogenic changes, including adaptations by other sectors (e.g. agriculture), may foreclose or sometimes facilitate adaptation options for freshwater biodiversity *per se*.

Second, participants found it difficult to envisage long-term (e.g. beyond 2050), transformational changes to systems (Figure 25) because of the uncertainties that accrue from both natural and anthropogenic adaptations to climate change. Consequently, most of the adaptation actions and prioritisation discussions centred around Moser and Ekstrom's (2010) categories of 'coping' and 'more substantial adjustments' (Figure 25). However, a consistent theme at the workshop was the difficulty of translating projected changes, using outputs such as the maps generated from the BBNs, to the general community, particularly when the results from each climate model could differ widely. The 'worst case' model did not always predict the most perverse outcomes for a particular region (e.g. Fig. 24: wetland condition).

The main anthropogenic and natural threats common to all the case studies are summarised in Table 11. Even in protected areas, such as the WHA wetlands, changes in fire regime may profoundly alter surface hydrology and water yields, and it is difficult to envisage what this ecosystem will look like and how it will function a century or more from now (Gilfedder et al. 2012).

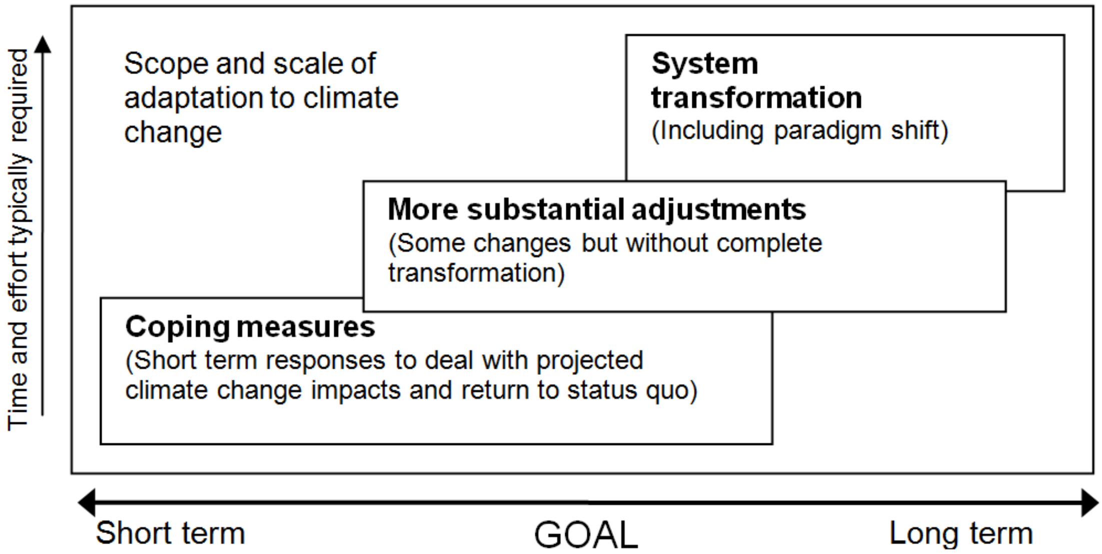


Figure 25 Scope and scale of adaptation options to climate change

Modified from Moser and Ekstrom (2010)

Table 11 Threats to freshwater biodiversity common to all case studies

Threats to freshwater biodiversity	Influential factors identified by case studies
Wildfire	Warmer, dryer climate, more lightning strikes, more peat fires with soils becoming hydrophobic in long dry periods
Future human impacts	Tourism, weed or disease introduction or spread, intensified agriculture and irrigation demand, retirees and “sea changers” – more intense coastal development
Water demand	Water shortage is not seen as an issue with climate change. “Tasmania has plenty of water, just not in the right place - irrigation is the answer”
Community education	The general public has a poor knowledge of climate change and likely future impacts, which influences policy decisions at all levels
Policy direction	Current legislative framework is inadequate. Top-down policy change is needed to alter community attitudes
Agricultural change	Change in crops, climate refugees, crops in new areas, at higher altitudes, higher value crops needing more irrigation
Groundwater abstraction	Groundwater is seen as a sustainable resource, but there is poor knowledge of the extent or distribution of groundwater aquifers in Tasmania
Environmental water allocation	Delivery of water at specific times and in suitable volumes to stimulate or support fish spawning or waterbird breeding

In addition to the broad scale threats in Table 11, specific issues were identified for each case study area. For example, increased demand for irrigation supply was identified as a major threat for both the Apsley Marshes and the Central Midlands, where agriculture is likely to intensify (e.g. shifts to water-intensive viticulture and stone fruits) and demographic changes (e.g. climate-change ‘refugees’ increasing the number of small farms with attendant increases in demand for water). Anthropogenic responses to changes in rainfall patterns will likely increase demand for small-scale on- and off-stream storages and farm dams, and the cumulative effects of these changes may alter the hydrology even further (e.g. Schreider et al. 2002). These changes can have adverse effects on salinity in areas with sodic soils (Doyle and Habraken 1993).

It was recognised that some of the adaptation responses were either extensions of current ‘best practice’ or potentially positive (Table 12). In the WHA, for example, current management practices for fire and exotic species just need to be consolidated and, where necessary, improved and made more strategic as better tools become available for site-specific predictions of changes likely under climate change (Table 12). This case study also yielded one of the few longer-term perspectives in that novel habitats and communities were likely to develop and that the reserved status of most of the land-tenure would likely facilitate adaptation by the biota and maximise the evolutionary potential of this area. Conversely, strong concerns were expressed about the potential for upland Tasmania to be perceived as a refuge for translocating non-endemic, cool-climate species, and there was further recognition that the boundaries and status of reserved areas may change in response to public pressures and changes in biotic composition as climate change intensifies.

In other case studies, some of the demographic and land-use changes may increase the options for adaptive responses. For example, poor summer water quality combined with demographic changes can catalyse better water use and waste water management (e.g. increased installation of rainwater tanks for domestic supplies, Table 12). Farm dams and other small storages may benefit some freshwater species (e.g. Hazell et al. 2001), although the evidence for the suitability of human-made farm dams as habitat remains mixed, at least for frogs (Hazell et al. 2004, Mazerolle, Desrochers and Rochefort 2005). There may be functional benefits to such storages as well: farm dams have been shown to retard or store sediment mobilised by land use changes in the Murrumbidgee basin (Verstraeten and Prosser 2008), for example. Quantifying all the costs and benefits of these options is further complicated by the multiple spatial scales and jurisdictions involved, and the possibility of perverse outcomes for freshwater biodiversity emerged as one of the key issues that needed to be captured in planning (see section 3.5.3).

Table 12 Positive adaptation responses identified for each case study

Case study area	Adaptation response
Tasmanian Wilderness World Heritage Area	Accept that conditions will change, and continue to employ current management of fire, feral animals and weeds
	Accept novel habitats or species that develop in response to climate change as valuable and worth protecting
Moulting Lagoon/ Apsley Marshes	Increase in viticulture and fruit farming introduces a new generation of farmers with better education and different values, which may lead to more water-efficient farms
	Family farms replaced by corporate owners using Tasmania as climate change refuge – potential industry champions with 'green' philosophies and sustainability ethics.
	Larger, more profitable farms are more likely to run field days, open days, which are opportunities for community education
	Holiday shacks replaced with permanent homes with larger footprint, but owners have a greater stake in the local environment
	Poor summer water quality in catchment – catalyst for better water management and waste water treatment
Central Midlands	Encourage riparian planting for carbon credits which will replace cropping in economically low value land, while improving riparian and in-stream values.
	Dual purpose riparian planting – cooler water temperature to encourage recreational fish, more shade to encourage fishers
	Identify local 'champions' or iconic threatened species to increase community engagement and promote freshwater values
North West intensive agriculture	Pressure from tourism industry to limit development
	"Clean green" export image may reduce pressure to clear land for agriculture and limit mining development

The 'filtered list' (Figure 6) of adaptation options met with limited success, with the complexity of the issues and time scales involved proving problematic even for such focussed case studies. Attempts to work through prioritisation exercises were deemed too ambitious within the time frame of the workshop, with some participants suggesting that each case study would require multi-day workshops, while others noted 'consultation fatigue' which would likely be even more of a barrier to community groups and other smaller stakeholders and individual landholders (cf. Byron, Curtis and Lockwood 2001).

Nevertheless, there was wide-ranging and important discussion about generic issues and problems with adaptation, and these issues conformed with the framework for diagnosing barriers to climate change adaptation proposed by Ekstrom, Moser and co-workers (Moser and Ekstrom 2010, Ekstrom, Moser and Torn 2011). The framework is summarised In Figure 26, the red boxes denote the 'understanding' phase, the blue boxes the 'planning' phase and the green boxes the 'managing' phase. The potential barriers to adaptation for each box in the 'understanding', 'planning' and 'managing' phases are listed in Table 13, and Table 15 respectively.

A clear outcome of these discussions was an acknowledgement that more use could be made of participatory processes for in all phases of adaptation, and the agency of different 'actors' in the process is emphasised by Ekstrom et al. (2011). Scenario planning was suggested as a means of improving engagement and managing adaptation overall and there was strong support for integration of adaptation to climate change with other planning and management initiatives.

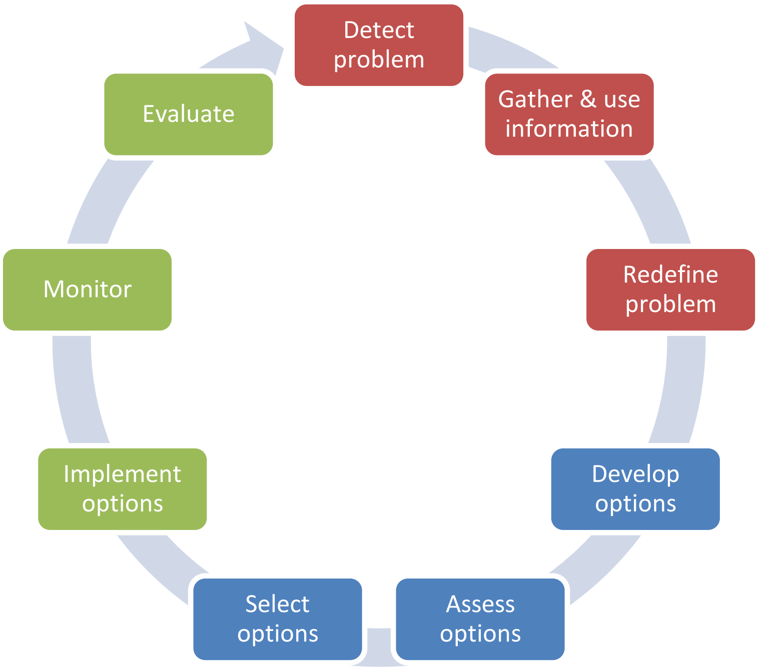


Figure 26 Stages of adaptation phases

Modified from Figure 2 of Moser and Ekstrom (2010)

Table 13 Common barriers between the stages of the ‘understanding’ phase From Moser and Ekstrom (2010)

Stage	Barriers
Detect problem	Existence of a signal
	Detection (and perception) of a signal
	Threshold of concern (initial framing as problem)
	Threshold of response need and feasibility (initial framing of response)
Gather/use of information	Interest and focus (and consensus, if needed) Availability Accessibility Salience/relevance Credibility and trust Legitimacy Receptivity to information Willingness and ability to use
(Re)define problem	Threshold of concern (reframing of the problem)
	Threshold of response need
	Threshold of response feasibility
	Level of agreement or consensus, if needed

Table 14 Common barriers between the stages of the 'planning' phase

From Moser and Ekstrom (2010)

Stage	Barriers
Develop options	Leadership (authority and skill) in leading process
	Ability to identify and agree on goals
	Ability to identify and agree on a range of criteria
	Ability to develop and agree on a range of options that meet identified goals and criteria
	Control over process
Assess options	Control over options Availability of data/information to assess options Accessibility/usability of data Availability of methods to assess and compare options Perceived credibility, salience, and legitimacy of information and methods for option assessment Agreement on assessment approach, if needed
Select option(s)	Level of agreement on goals, criteria, and options
	Agreement on selecting option(s), if needed
	Sphere of responsibility/influence/control over option
	Threshold of concern over potential negative consequences
	Threshold of perceived option feasibility
	Clarity of authority and responsibility

Table 15 Common barriers between the stages of the ‘managing’ phase

From Moser and Ekstrom (2010)

Stage	Barriers
Implement option(s)	Threshold of intent
	Authorization
	Sufficient resources (fiscal, technical, etc.)
	Accountability
	Clarity/specificity of option
	Legality and procedural feasibility
	Sufficient momentum to overcome institutional stickiness, path dependency, and behavioural obstacles
Monitor outcomes & environment	Existence of a monitoring plan
	Agreement, if needed, and clarity on monitoring targets and goals
	Availability and acceptability of established methods and variables
	Availability of technology
	Availability and sustainability of economic resources
	Availability and sustainability of human capital
	Ability to store, organize, analyse, and retrieve data
Evaluate effectiveness of option	Threshold of need and feasibility of evaluation
	Availability of needed expertise, data, and evaluation methodology
	Willingness to learn
	Willingness to revisit previous decisions
	Legal limitations on reopening prior decisions
	Social or political feasibility of revisiting previous decisions

3.4.2 Review of Australian policies

Water management is a crucial—albeit not the sole tool—for managing freshwater biodiversity. In 2007, the Council of Australian Governments (COAG) endorsed a *National Climate Change Adaptation Framework* to guide action by jurisdictions over the next five to seven years. The long-term goal of the Framework is to “position Australia to reduce the risks of climate change impacts and realise any opportunities” and emphasises the leadership roles of governments which include:

- developing, implementing and reviewing policies and strategies, including integrating climate change considerations into existing policies and strategies,
- establishing and maintaining community and essential services to deal with climate change impacts, including emergency management and health services,

- building adaptive capacity, including providing tools and information, raising awareness, education, and investing in climate change science as well as related social, ecological and economic research, and
- managing risks from climate change to their own programmes, activities and assets, including infrastructure and natural ecosystems for which governments have management responsibility.

The Framework recognises that risks should be managed by those best equipped to understand the context and likely consequences of actions, so there is a clear need to build capacity at local and regional scales. The Framework also requires that business and the community have important roles in addressing climate change risks so the governments will pursue a partnership approach to adaptation to manage risks and identify opportunities of climate change.

The Framework identifies two priority areas for potential action: 1) building understanding and adaptive capacity, and 2) reducing vulnerability in key sectors and regions. Water resources and biodiversity are the first two sectors identified in this latter priority, and potential areas of action are presented in Table 16. The Framework notes that the National Water Initiative (NWI) and other water management frameworks are central to dealing with reduced water availability due to climate change and information on climate change will be essential for water managers.

The Australian Government, through the Department of Climate Change and Energy Efficiency has, amongst other actions, supported the National Climate Change Adaptation Research Facility (NCCARF) to generate the information needed by decision-makers in government, vulnerable sectors and communities to manage the risks of climate change. The National Climate Change Adaptation Research Plan for Freshwater Biodiversity outlines the specific research priorities to address gaps in the information available to manage and conserve freshwater biodiversity under climate change (Bates et al. 2011).

Table 16 Potential areas of national action to reduce vulnerability in the water resources and biodiversity sectors as outlined by COAG (2007)

Key sector	Potential actions
Water resources	Research to address key knowledge gaps about climate and water resources, needed to implement the NWI and other water management initiatives. This will include research on: • high quality projections of climate variables relevant to supply and demand of water resources, • understanding impacts of climate change on water resources and dependent ecosystems; and • methods and approaches to integrating climate change related risks into water management. Work with the water industry to ensure that climate change impacts and risks are incorporated into water resource and infrastructure planning and management, including: • assessing the implications of changes in extreme rainfall events for water infrastructure, • updating estimates of probable maximum precipitation and rainfall extremes for use in products such as the Australian Rainfall and Runoff Handbook to reflect likely climate change, and • jurisdiction's dam safety authorities to review major dam safety policies to accommodate the impacts of climate change.
Biodiversity	Review the *National Biodiversity and Climate Change Action Plan 2004-2007*, developed by the Natural Resource Management Ministerial Council, and outline strategic national directions and actions post 2007. Establish a national programme of research on the impacts of climate change on biodiversity and ecosystem processes. The research will address: • terrestrial, aquatic and marine and estuarine ecosystems with a focus on analysis of changing distribution and phenology, the interactions and combined impacts of climate change and other threatening processes, and identification of critical thresholds for natural ecosystems and approaches to increasing their resilience to climate change impacts including connectivity, and • the implications of climate change for existing strategies, such as the National Reserve System, and planning for threatened and migratory species and ecological communities. Provide practical guidance on how to integrate existing and emerging knowledge about climate change into management of disturbance regimes in areas managed for biodiversity conservation. Assess the vulnerability of Australia's World Heritage properties and Ramsar wetlands to the impacts of climate change. Regular reviews of management plans for each World Heritage property will explicitly consider vulnerability to climate change impacts and plans will include actions, where necessary, to reduce vulnerability or manage impacts. Finalise and implement key steps in the *Climate Change Action Plan* for the Great Barrier Reef.

The 1994 COAG national water reform agenda represented an agreement on a national strategy for ecologically sustainable development, and a recognition for the first time that the environment was a legitimate user of water (COAG 1994). The agreement established the basis for catchment-level water resource planning and the separation of land and water titles. The *National Water Initiative 2004* aimed to achieve a nationally compatible market, regulatory and planning systems of managing surface and groundwater resources that optimised economic, social and environmental outcomes (COAG 2004). It committed federal and state governments to:

- prepare water plans with provision for the environment,
- address over-allocated or stressed water systems,
- introduce registers of water rights and water accounting standards,
- expand water trading,
- improve pricing for water storage and delivery, and
- meet and manage urban water demands.

The National Water Commission, established in 2004, implements the NWI and undertakes biennial assessments of each jurisdiction's performance against national commitments.

Table 17 Summary of adaptation plans and/or strategies

Jurisdiction	Climate change adaptation plan/strategy?	Implementation plan?	Actions for freshwater biodiversity?	Climate change risks integrated into water/ biodiversity management?
Australia	Yes	No	++	++
Tasmania	No		+	++
South Australia	Yes	Yes	+++	++
Western Australia	Yes	No	+	+
Northern Territory	Yes	No	+	+
Queensland	Yes	Yes	+++	++
New South Wales	No		+	++
Australian Capital Territory	Yes	Yes	++	+++
Victoria	Yes	Yes	+	+++

This table includes released draft documents in each jurisdiction across Australia, and whether they have an associated implementation plan. Also noted is the degree to which these plans and strategies address water management as follows:
"+" indicates few actions addressing freshwater biodiversity.
"++" indicates mention is made of ensuring climate change considerations are taken into account, or freshwater biodiversity is referred to as a priority, but actions are vague or no guidance provided, or, climate change risks have been considered in an ad hoc manner in water management.
"+++" indicates thorough and explicit integration: actions explicitly addressing freshwater ecosystems and/or biodiversity, and climate change risks are integrated into water management.

The Australian Government has progressively expanded its involvement in the management of water resources, and in 2007 the Commonwealth *Water Act 2007* was introduced to implement key national water resource management reforms, e.g. the preparation of a Basin Plan for the Murray-Darling Basin. In 2008, the Australian Government introduced *Water for the Future*, a long-term initiative aimed at better balancing the water needs of communities, farmers and the environment (DEWHA 2010). This initiative prioritises taking action on climate change, using water wisely, securing water supplies and supporting healthy rivers, which are being delivered through a $12.9 billion investment including infrastructure investments to help water users adapt to a future with less water, purchase water for the environment, manage water quality, and renew commitment to national water reform.

Most states and territories across Australia have a final or draft climate change adaptation strategy, or are in the process of developing one and have released discussion papers to obtain community feedback, e.g. Tasmania and the NT. All adaptation plans and strategies are aligned with the National Climate Change Adaptation Framework (COAG 2007). Table 17 summarises the level of planning and implementation of climate change adaptation across Australia, and the degree to which adaptation plans address water management and freshwater biodiversity. Some states have climate change risks very well integrated into their water and biodiversity management strategies, which is where they have chosen to address climate change adaptation for water ecosystems rather than in the state adaptation plan (e.g. Victoria).

While all jurisdictions (except WA) have committed to a reduction in greenhouse gas emissions, and all except SA and the ACT explicitly support carbon pricing, there is some variation in their overall adaptation approach. The NT is taking a predominantly emissions-reduction approach through improving energy efficiency and land management practices, and retaining their capped water allocations policy.

Queensland and particularly WA are focussing on improving efficiencies in both water and energy sectors and improving the management of demand for water and energy. South Australia, WA and Queensland are all looking to diversify the sources of water they will need to rely upon in the future, with SA particularly looking to reduce their reliance on water from rivers and natural ecosystems. These three states all mention their aim to increase the reliance on recycled water, but SA and WA are explicit in stating recycled water will not be introduced into drinking water supplies. Queensland notes that work is needed to manage public perceptions of water availability and water sources. Tasmania is notable for having some of the most detailed and fine-scale information on projected climate change, but is still in the process of developing an adaptation plan.

The states that stand out as being well-integrated and having detailed and explicit actions to facilitate adaptation of freshwater ecosystems under climate change, whether as part of their climate change or water management policies are South Australia, Queensland, ACT and Victoria. For example, disaster-management is a key feature of these plans, especially in Queensland, as is better integration between land and water management and planning. Western Australia and NSW, while both having detailed proposals for biodiversity management, appear to have climate change, water and land management relatively isolated from each other. Interestingly, WA is the only jurisdiction with a thorough, independent and transparent prioritisation framework for waterway management, but the degree to which the framework is being, or is intended to be, used is unclear. Management prioritisation of waterways in other jurisdictions remains a gap in the policy frameworks reviewed here, although Victoria's triage approach during times of water scarcity provides a starting point.

Victoria stands out as having very clear and integrated policies across climate change adaptation, water management and biodiversity management, followed by Queensland and South Australia. Victoria aims to be flexible in response to climate variability and is the only state that has explicit policies and guidelines on how to manage water during extreme events such as droughts, when there is not enough water available to meet all the demands upon it, i.e. a triage approach which they have labelled "seasonally adaptive management". Victoria also aims to adapt through improving water efficiency, including using works and measures to deliver environmental flows where possible and cost-effective. While some states make mention of conserving biodiversity in response to climate change by improving resilience and connectivity, e.g. ACT, Queensland, the means by which this might occur are still somewhat vague. Victoria is again notable by being the only jurisdiction to spatially identify flagship areas for biodiversity management, and corridors to provide connectivity between and among these flagship areas, in explicit response to climate change projections and current land tenure. Their strategy states that improving government processes and natural resource management, and using market instruments to encourage biodiversity management should facilitate successful biodiversity adaptation. Queensland also stands out as being the only jurisdiction to call for proper valuing and accounting of ecosystem services, suggesting a similar emphasis on using market instruments to manage natural resources under climate change. It appears Queensland's reliance on nature-based tourism and land management already provides an incentive for such an approach.

Of note is the fact that, of the states that suffered severe water shortages during the Millennium Drought, SA and Queensland have already made good progress on "future-proofing" of water resources, facilitating their adaptation to climate change. In particular, south-east Queensland has the most stringent regulatory framework for water use by governments, businesses and households, and an explicit community education program (Waterwise) that will facilitate community preparedness. South Australia is developing a strong emphasis on storm-water harvesting, and Victoria is planning on a greater reliance on triage and water delivery efficiencies.

Like Victoria's, the adaptation strategies of Queensland and the ACT are notable for encouraging communities to take advantage of opportunities that climate change might bring. For example, Queensland and the ACT are innovative for valuing novel ecosystems and regarding already-modified urban green spaces as opportunities for biodiversity adaptation and conservation under climate change. Such an approach has not been explicitly proposed for freshwater biodiversity by any jurisdictions. The ACT is also promoting the adoption of green areas by education institutions (including tertiary institutions) for nature-based education.

Victoria, SA and Queensland have a strong focus on regional planning and close partnerships between state and local governments or regional agencies. Local and regional agencies provide a good conduit of communication between local communities and state-wide policy frameworks, ensuring the state is sensitive to local circumstances and knowledge, and are well-placed to address adaptation that is likely to be required at the local level. It appears a strong local/regional focus for adaptation allows for the very clear articulation of roles and responsibilities across multiple community sectors, and therefore a greater chance of successful adaptation. It is notable that these jurisdictions have conducted considerable community consultation as part of their strategy development.

Similarly, these states place a strong emphasis on adaptive management and have clear implementation plans with regular reviews, usually between four and ten years.

The ACT however, is notable in monitoring and evaluating adaptation, with independent monitoring and review every three years.

In conclusion, it appears that good integration among climate change adaptation, water management and land management and planning, combined with a strong regional focus, the ability to be flexible and regular monitoring and review, are the adaptation options and policy frameworks likely to provide the best chances of successfully conserving freshwater biodiversity under climate change.

3.5 Planning and policy needs

The following items summarise the key concerns around planning and policy that emerged from our consultations and review. Each is elaborated in subsections 3.5.1 to 3.5.9 below.

1. Revisions of planning tools and policies to respond to likely changes in water yield resulting from climate change.
2. Updating and maintaining key data sources
3. Potential for perverse outcomes resulting from adaptation actions in other sectors
4. Plethora of planning and policy instruments
5. Improve knowledge, monitoring and forecasting of changes to groundwater
6. Improve stakeholder ‘buy in’
7. Ecosystem change
8. Flexibility
9. Systems or tools to aid in setting priorities.

3.5.1 Revisions of planning tools and policies

Planning tools and policies are currently being revised to align with state and federal responses to likely changes in water yield resulting from climate change. While some agencies have broad policies on climate change, adaptation approaches are mixed in with mitigation strategies, and this can confuse stakeholders and provide further barriers to implementing adaptations (Moser 2010, Moser 2012). Several agencies noted that substantial policy and planning revisions were underway, but systematic approaches to identifying barriers to adoption (e.g. Ekstrom et al. 2011) are scarce. We discuss key gaps in policy development further in section 4.4.

3.5.2 Updating and maintaining key data sources

There were two components to this concern: resources to update biodiversity data bases, and the infrastructure needed to take advantage of improved hydrological and climatic data.

It was widely acknowledged that many of the data sources for biodiversity are old (CFEV was last updated in 2008, and the last national assessment of river health was completed in the early 2000s) or that support for some services (e.g. Atlas of Living Australia) is uncertain. Current data are critical to ensure that the biota still exist in the systems for which adaptations are being planned and implemented. Importantly, improved, current and accurate location data are needed to address gaps in our knowledge of limits to distributions

The next IPCC GCMs will become available in 2014, with improved scenarios as well as improved modelling. There is a clear need to downscale this information and provide a smoother pathway to integrate these improvements with data base and risk assessment tools that underpin decision support systems. As part of the improvements in this chain of modelling tools, it would be important to review the performance of rainfall-runoff models to ensure that they provide the best predictions for low flows and cease to flow events, since these attributes are most likely to be critical to in-stream and riparian biota.

3.5.3 Potential for perverse outcomes resulting from adaptation actions in other sectors

It is likely that human demands for more secure agricultural and urban supply will foreclose adaptation options for conserving freshwater biodiversity. New irrigation schemes to increase agricultural resilience, for example, may divert water away from freshwater systems at inappropriate times, and the attendant changes in land use may alter hydrology and groundwater interactions. These conflicts may also arise between conservation priorities. Adaptations for fire management (e.g. priority areas for protection) may not coincide with priority areas for freshwaters, or environmental watering may take water away from in-stream conservation measures. Clearly, there is a need to develop decision support frameworks that expose these conflicts clearly so that priorities have a better chance of being set transparently.

3.5.4 Plethora of planning and policy instruments

Freshwater biodiversity conservation faces extra challenges owing to the multiplicity of instruments from different sectors that affect it. As well as regulatory instruments for managing water, terrestrial policies can affect freshwater assets directly (e.g. changes to riparian vegetation, changes in runoff resulting from changes in land-use). These intersect with heritage protection, wildlife and threatened species instruments, and there are additional treaties and obligations specific to freshwaters (e.g. Ramsar-listed wetlands). Confusion amongst stakeholders is often further compounded by the separation of terrestrial and water management planning processes. Frameworks for unifying planning for water and land management need to be further developed, critiqued and refined. Additionally, there was a strong feeling that adaptation tools should be integrated into existing planning and policy frameworks for biodiversity management rather than 'reinventing the wheel' for freshwater assets. It was acknowledged that some frameworks need or are currently being revised to accommodate climate change agendas.

3.5.5 Improve knowledge, monitoring and forecasting of changes to groundwater

Notwithstanding considerable recent progress in mapping and assessing risks to groundwater (Sheldon 2011), knowledge of recharge rates and the contributions made by groundwaters to surface flows remains spatially patchy (Harrington et al. 2009, Sheldon 2011). Underestimating groundwater inputs could yield unduly pessimistic assessments of the persistence of surface waters. Similarly, rivers and wetlands with substantial groundwater inputs may resist rises in temperature, and could potentially provide thermal refugia. Knowledge and monitoring of groundwater needs substantial investment to improve the accuracy of forecast changes to surface flows, as well as forecasting changes to the groundwater itself and the biota and specialised ecosystems that depend on it (Harrington et al. 2009, Tixier, Wilson and Williams 2009, Gilfedder et al. 2012).

3.5.6 Improve stakeholder 'buy in'

It was acknowledged that better use could be made of procedures and tools that are more collaborative and that actively engage stakeholders through the entire adaptive management cycle (Wondolleck and Yaffee 2000), and these could help 'normalise' adaptation (Dovers 2009). Tools available include social learning (Muro and Jeffrey 2008, Steyaert and Jiggins 2007), adaptive co-management (Cundill and Fabricius 2009) and fostering 'environmental champions' in community networks (Taylor, Cocklin and Brown 2012). Criteria for success that are usually cited for these approaches include: early stakeholder involvement, openness and humility in negotiations, building capacity and trust, making and maintaining explicit links with institutions and community groups, and, of course, sufficient resources and time to foster and maintain the collaboration (Wondolleck and Yaffee 2000, Mostert et al. 2007, De Boer and Bressers 2012).

It should be acknowledged that these processes have their critics: they are time consuming, can be resource-intensive, and the processes themselves are poorly defined, making direct comparisons across case studies difficult (Cundill and Rodela 2012, Steyaert and Jiggins 2007, Muro and Jeffrey 2008, Ostrom, Janssen and Anderies 2007). Less collaborative approaches (e.g. market reform, regulation) may be more appropriate in some situations (Leeuwis 2000), although, in most cases a pluralistic approach that combines many different instruments will likely prevail, with the “mix” of tools varying depending on local circumstances, opportunities and constraints (Ostrom et al. 2007).

Clearly, then, there is a need to develop and use collaborative processes more frequently and rigorously, but also be mindful of the potential biases and limitations of some of the frequently used participatory processes (Kaltenborn, Thomassen and Linnell 2012) (Frittaion, Duinker and Grant 2011).

3.5.7 Ecosystem change

As climate change intensifies, changes to the composition and processes of ecosystems are inevitable. Terrestrial ecologists acknowledge the potential for novel combinations of species or communities to evolve (Gilfedder et al. 2012), and it seems inevitable that cool-adapted species will need to move to higher altitudes, while those that are already at their thermal limits in the highlands may become extinct simply because they will run out of habitats that are sufficiently cool to support them (Davis, Lake and Thompson 2009, Morrongiello et al. 2011). Accordingly, ecological communities will likely change, and novel combinations of species will appear. This means that many, often ‘iconic’ freshwater landscapes will change beyond recognition. This will challenge the emotional and intellectual attachments we have to these landscapes, and will demand rethinking of our current ‘static’ views of ecological communities and the instruments we have developed to protect them (e.g. listing of communities, design and implementation of reserve systems)

Translocations are frequently mooted as adaptation options to conserve species (e.g. Morrongiello et al. 2011) but they need careful risk assessment and management to avoid unintended deleterious outcomes (e.g. changed community structure, trophic cascades, loss of genetic diversity in or extinction of non-target taxa).

3.5.8 Flexibility

Substantial uncertainties remain in climate projections. In some of the case studies, divergent scenarios emerged from different downscaled GCMs. A further source of uncertainly identified was that forecasts may change with improved models and updated ecological data. These uncertainties present significant challenges both to managers and to communication with stakeholders. It was recognised that while many adaptation options could be reversible should predictions prove erroneous (e.g. cease-to-take rules), others could be costly (e.g. dam construction) or impossible to reverse (e.g. translocation).

As a first step, some advocated focussing on the ‘worst’ predictions first, with ‘worst’ generally corresponding with the driest predictions (e.g. the CSIRO model). However, even the driest model was not consistently the driest either in space or over time, and a simple contrast between ‘wet’ and ‘dry’ models oversimplifies the changes in frequency and intensity of events—high as well as low flows—that may be more important to the biota than long term ‘average’ flows.

Accordingly, flexibility of planning and policy responses was identified as crucial. This flexibility can only be achieved if data and modelling are kept current and if policy frameworks include strong commitments to monitoring and ‘closing the adaptive management cycle’. This implies regular review of implementation, planning and policy goals.

3.5.9 Systems or tools to aid in setting priorities

Workshops and discussions identified a clear need to develop a system of scoring adaptation options for different scenarios. The Project Prioritisation Protocol (PPP) developed for ranking recovery projects for threatened species (DPIPWE 2010, Joseph, Maloney and Possingham 2008) was recommended as a possible procedure. The efficiency of a given project is computed as:

$$\mathrm{Efficiency} = \frac{\mathrm{Benefit} \times \mathrm{Success}}{\mathrm{Cost}}$$

where ‘Benefit’ is calculated as the difference between the probability of the species being secure with and without the project, ‘Success’ is the likelihood of the project’s success (assessed at a number of levels), and ‘Cost’ is the sum of the costs of the actions within a given project. Further details of the implementation of PPP are described by Joseph et al. (2008), and an example applied to threatened species prioritisation is given in DPIPWE (2010).

Table 18 Example of scoring framework for on-ground adaptation options for native fish

Adaptation option	Benefit-Cost-Risk	Lack of Barriers	Social acceptability	Score	Rank
Riparian planting for shade	3	3	3	9	1
Connect flow	3	2	2	7	2
Exclude aliens	3	3	1	7	2
Monitoring	2	2	3	7	2
Restore fish passage	1	1	3	5	5
Restore spawning habitat	2	1	2	5	5
Provide thermal refuge	1	1	2	4	7

Prioritising adaptation options have some additional complexities Pahl-Wostl (Pahl-Wostl 2009) Moser and Ekstrom (Moser and Ekstrom 2010), and Hobday et al. (2012) have proposed a framework of scoring adaptation options on three ‘tools’: benefit-cost-risk (which is similar to PPP), barriers to adoption (cf. Moser and Ekstrom 2010), and social acceptability. The combination of these three scorings allows an overall assessment of the adaptation options within a given scenario. A hypothetical example for on-ground options to conserve native fish is given in Table 18. For illustrative purposes, each criterion is scored on a 3-point scale with a score of ‘3’ denoting a high-benefit, low-cost and low-risk option for benefit-cost-risk, that there are few barriers to its adoption and that it has high social acceptability. Options are then ranked on their scores, with those scoring highest being the most feasible or preferred options or actions.

3.6 Communication

A common issue identified by the full range of stakeholders in our consultation and communication activities was that climate change is potentially the greatest challenge facing humanity. However, the overwhelming scientific evidence that human activities are the main driver of climate change is constantly undermined by misleading counter-claims from persons with vested interests in maintaining current carbon emissions, promulgated in the mass media (Moser 2010). To some extent, this is exacerbated by the difficulty of illustrating climate trends without the distractions of short-term weather variability, and the variability itself, both in local climate and between climate model outputs, further complicates communication. These are significant obstacles to communicating research and policy outcomes; moreover, distrust of climate change can sometimes prevent meaningful community engagement in the first place.

In terms of policy development, the focussed interviews held with personnel from key water management agencies (Box 1, page 34) revealed some common themes. The most prominent was that policy development was in its infancy for accommodating projected climate change while conserving freshwater biodiversity. In each state and territory there is clear acknowledgement that climate change needs to be explicitly integrated into water policy. However, the variation between projections of impacts on water resources, combined with incomplete knowledge of freshwater ecosystem responses to prolonged climate change, makes this a challenging prospect that policy-makers across the country are grappling with. In most cases agencies noted policy discussions had advanced beyond what was publicly available, and foreshadowed a number of different processes being pursued for adaptation to climate change.

For the time being, existing policy appears to be providing interim measures for conserving freshwater biodiversity under climate change. For example, in states and territories where water allocation is largely abstracted from unregulated rivers, caps on water abstraction (e.g. Northern Territory) and minimum flow rules (e.g. Tasmania) are designed to protect in-stream values during high risk periods (e.g. during low summer flows). In jurisdictions where water is allocated according to annual forecasts and delivered via regulated rivers (e.g. in the Murray-Darling Basin), allocations are flexible and adjusted to projected climate conditions. Furthermore, most areas require that existing water policy should take climate change into account by including climate scenarios in the development of water management plans. For example, Tasmania now requires that all major developments provide 95% reliability of water resources under the ‘CSIRO dry scenario’ modelled in the Tasmanian Sustainable Yields (TSSY) project. This has already resulted in rejection of some development proposals.

In areas where there are not yet fully-developed policies for conserving freshwater biodiversity under climate change, this appears to be due to scarce resources, particularly human resources, rather than an unwillingness to develop policy. Policy development relies on reliable climate projections and a reasonable level of knowledge of freshwater ecosystem responses, as well as proper consultation with a range of stakeholders, so can take some time. In most cases, highly sophisticated tools exist to spatially identify areas of high priority for protection, and well-developed hydrological data are also available, but the frameworks for formalising their use in water management planning are still being developed.

A third theme that emerged both from the focussed interviews and stakeholder consultations was acknowledgement that biodiversity (i.e. species composition) in any given water body was likely to change, and that novel combinations of species or novel ecological communities would emerge as the climate changes. However, there was uneven appreciation of the implications of this for current instruments for conserving biodiversity, and this issue has been further developed in NCCARF project FW1109 (Dunlop et al. 2012). From our discussions at the NCCARF Freshwater Biodiversity Adaptation Research Showcases, it appears that many stakeholders have yet to move beyond an intellectual acknowledgement of this issue. Many of us are emotionally attached to particular freshwater landscapes as they have existed in living memory. ‘Letting go’ of such iconic features such as upland sphagnum wetland complexes and lowland riparian forests is difficult for scientific investigators, let alone local stakeholders. Moreover, we noted that much of the current biodiversity and species protection instruments were based on static assumptions about species composition and ecological community types. Accordingly, there will need to be reform and revision of biodiversity legislation as well as the ongoing water sector reforms to accommodate the new realities that climate change will force upon us.

Finally, discussions at the NCCARF Freshwater Biodiversity Adaptation Research Showcases identified a number of issues and opportunities that need to be pursued to better ‘join the dots’ between projections and adapation actions nationwide. These are listed here with cross references to the NCCARF projects. The final reports of these (unavailable at the time of writing this project) should be consulted for further explanations.

- There is probably a lower limit to the spatial resolution of climate projections, even from dynamically downscaled modelling. While most stakholders were comfortable with regional, state-wide and national scales, varations at the site level and some fine-scale within-catchment scales are unlikely to be captured by the modelling (NCCARF project FW1101 Robson et al. 2012, NCCARF project FW1107 VanDerWal et al. 2012).
- At fine spatial and temporal scales, some reaches and waterbodies may become decoupled from regional climate changes, and afford refuges for the persistence of freshwater biodiversity. It will important to identify these evolutionary refuges since these are likely to persist and have allowed the persistence of relict species in the past (NCCARF project FW1106 Davis et al. 2012).
- Local scale interventions (e.g. riparian plantings, new anthopogenic aquatic habitats) hold considerable promise to either ameliorate the effects of climate change or provide refuges and novel habitats for freshwater organisms (NCCARF project FW1101 Robson et al. 2012, NCCARF project FW1105 Thompson et al. 2012)

4. DISCUSSION, GAPS AND FUTURE RESEARCH DIRECTIONS

4.1 Biophysical modelling

Overall, the hydrological modelling proceeded smoothly and provided a wealth of potentially useful metrics to relate with ecological responses. However, the information base that relates ecological responses to a given hydrological variable is often patchy, and the strategic, basic research that underpins flow-response relationships has progressed slowly for a number of well-documented reasons (Poff et al. 2010). As a result, the choices of hydrological variables inevitably involve some subjective expert opinion, and the variables that are chosen will vary between biodiversity assets and between regions.

4.1.1 Modelling water temperature variables

While the physics of water temperature responses to air temperature is well-established (Mohseni and Stefan 1999), predicting water temperature variables from modelled air temperatures remains problematic, and requires further research. We found that temperatures would be overestimated in rivers with known substantial connections to karst groundwater (Figure 16), and other, local factors (e.g. shading, orientation, water depth, changes in discharge) can strongly affect water temperatures (e.g. Davies et al. 2004, Pedersen and Sand-Jensen 2007, Webb, Clack and Walling 2003). Moreover, many wetlands have substantial cover by plants of different configurations, and differences in water colour, depth and groundwater contributions can further alter the basic relationship with air temperature, even to the extent that it is problematic to estimate whether or not a wetland will dry out.

While a variety of mechanistic and statistical approaches have been proposed for improving predictions of water temperature, few of the predictor variables are available consistently at sufficiently fine scale resolution to provide useful tools for regional or state-wide applications. For example, percentage cover of rivers and water bodies by riparian vegetation has not been mapped directly for all freshwaters in the CFEV data base. To achieve this at sufficiently fine spatial scales consistently across Tasmania would probably require expensive remote sensing via LIDAR. We note that such coverage is available across Victoria, and that local-scale modelling approaches have been developed by NCCARF project FW1101 to guide riparian plantings, so the prospects are good for better predictions of water temperatures after some further, focussed research.

4.1.2 Ecological knowledge

A number of ecological issues recurred both during the research and in workshops and discussions. These are summarised in Table 19. An overarching issue is the interaction between human responses to climate change and the responses in the biota themselves. Sala et al. (2000) speculated that interactions between these and a number of other drivers (e.g. nitrogen deposition, biotic exchanges) increase the uncertainties in projecting changes to biodiversity.Table 19 summarises the major gaps identified in this research.

Table 19 Summary of ecological knowledge gaps

Knowledge gap	Research objective or limitation
Barriers to dispersal	How species disperse across landscapes; time spans for migration; which factors limit or enhance their ability to migrate or disperse.
Surface water-groundwater interactions	The extent of groundwater, recharge rates; the impact of current unlimited extraction rates; whether local streams extract or deliver water to groundwater aquifers.
Stress thresholds	Thermal tolerance thresholds are known for few species, therefore it is difficult to predict future impacts of climate change and potential positive or negative feedbacks. Similarly, hydrological thresholds remain poorly documented for many groups and processes.
Time spans for recovery processes	Adaptation or remediation programs are usually limited by funding arrangements. Time spans are too short to identify any adverse effects and monitoring programmes are linked to the same funding schedule.
Propagule storage and viability	Longer periods between flooding of wetlands, and shorter periods of inundation may exceed the viability of seeds and other propagules. Many invertebrates have drought-resistant life stages, but there has been little research into how long they remain viable without inundation.

4.1.3 Updating climate change models

Global climate models (GCMs) are being revised, and The Intergovernmental Panel on Climate Change will release the 5th Assessment Report (AR5) in 2014. It will be expected to contain improved global climate modelling under updated emissions scenarios.

The AR5 also is planned to contain some new features including greater regional detail on climate change impacts, adaptations and mitigation strategies, as well as risk management and framing of responses relevant to Article 2 of the UNFCCC, which concerns stabilising greenhouse gas concentrations in the atmosphere at a level that “would prevent dangerous anthropogenic interference with the climate system” (IPCC 2012).

With this in mind it is still unlikely that Tasmania or similar-sized regions will be covered by sufficiently fine-scale GCM outputs. Accordingly, there will be a need to downscale the GCM outputs using a similar if not the same approach to that used in CFT (i.e. use of CCAM to downscale to 0.05 degree grid). Similarly these downscaled outputs would require adjustments, again as per CFT, to allow for use in runoff modelling.

4.2 Risk assessments

Internationally ecological risk assessment with regard to possible impacts of complex drivers like climate change is still in a highly developmental phase. The initial development of ecological risk assessment was focused largely within the field of environmental exposure to toxicants, and much of the literature, methodologies and jargon have been ‘captured’ by that focus. The core elements of standardised risk assessment protocols such as those outlined in the ISO Standard Principles and Guidelines for Risk Management for Australia and New Zealand (SA/SNZ 2009) are highly relevant, especially the use of the analytical elements and concepts of hazard, consequence and risk. However the framework within which these elements are used must be flexible and developed to account for multiple interacting hazard and contextual drivers, interactions between effects and consequences, and multiple links between the magnitude of consequence and pre-existing contexts.

An additional desirable feature is the ability to explicitly include uncertainty in the risk analysis. A wide range of uncertainties exist in the area of the study reported here. They include uncertainties around global climate modelling (multiple models with their own inherent uncertainties, multiple possible future projections), climate downscaling, hydrological modelling, and the uncertain knowledge based around the quantification and direction of links between hydrological and temperature drivers and ecological responses. Thus at the very least, a probability-based approach to including uncertainty in any risk framework is highly desirable.

Use of approaches such as Bayesian Belief Network modelling allows for such complexity, while also capturing uncertainty. Limitations of the BBN approach used here include:

- The use of static rather than the newly developed dynamic BBN modelling approaches, to allow for temporal evolution of climate projections and lagged environmental responses;
- The absence of quantified driver-response data (i.e. reliance on expert opinion);
- The related use of categorical node states, instead of continuous variables (partially overcome by ensuring that CPT’s contain a spread of probabilities among adjacent state values);

The reliance on expert opinion in this study reflects the absence of specific, quantified response measures to a wide range of ecosystem components or to change in key aspects of hydrological and thermal regimes. Fully populating such models with relevant and contextualised data will be a challenging, potentially impossible exercise. As such the continuous development, at regional and national scales of hydro-ecological responses and thermal tolerances (including accounting for adaption) should be a major focus of ongoing research.

This should be accompanied by continuous national investment in the compilation and interpretation of published knowledge (both grey and white) on driver-response relationships for the aquatic environment – an idea already expressed in Australia through initial tool scoping and development in the areas of causal criteria development (Norris et al. 2008), multiple lines and levels of evidence (MLLE) and Eco Evidence (e.g. Nichols et al. 2011). The continuous development of criteria-based evidentiary data and knowledge archives along with evidence-based knowledge tools such as Eco Evidence should be a high national priority.

4.3 *Prioritisation of adaptation options*

Comprehensive listings of adaption options are widely available and have been reviewed comprehensively (Mawdsley 2011, Mawdsley, O'Malley and Ojima 2009), even at regional scales in parts of Australia (Gilfedder et al. 2012); the challenge is to organise this material so that end-users can better access information relevant to their jurisdiction and spatial scale. While this has been recognised in policy documents from some state agencies, decision support can be improved by developing tools such as PPP (Joseph et al. 2008) or similar schemes (Hobday et al. 2012, Wintle et al. 2011) that explicitly quantify costs as well as benefits. The complexities of prioritisation also need to be contextualised with other imperatives. Procedures such as scenario planning (sensu Peterson, Cumming and Carpenter 2003) provide frameworks within which to draw out all issues within a basin or region (e.g. O'Connor et al. 2005), although freshwater-focussed applications of this tool have tended to have traditional foci on water quantity and quality rather than biodiversity *per se* (e.g. Rehana and Mujumdar 2011, March, Therond and Leenhardt 2012, Mahmoud, Gupta and Rajagopal 2011).

It is important that stakeholder buy-in of adaptation options be fostered in order to maximise the opportunities for implementation. Early and continuing, meaningful engagement with landholders and end-users has been important in bridging the 'implementation gap' (Knight et al. 2008) in conservation planning (Barmuta, Linke and Turak 2011). However, scenario planning may not guarantee broad community support. The workshop processes and commitments of time and resources required of participants may skew the issues covered away from the concerns of the majority within a region (Kaltenborn et al. 2012), and participants may vary in their ability to 'suspend disbelief' (Frittaion et al. 2011) which could hamper a group's capacity to grapple with the long-term and often extreme scenarios that are likely given current failures internationally to engage with meaningful mitigation or reduction of emissions.

4.4 *Policy and planning challenges*

The advent of linked downscaled climate modelling and modelling of catchment and hydrological processes now allows for refinement in projections of climate-driven risk to aquatic environments. Changes in key variables that describe hydrological regimes can be modelled and the implications for specific processes and components of aquatic ecosystems can now be explored. In addition, downscaling of climate projections allows comparative spatial and temporal assessment of hazard and risk, as well as comparative assessments among aquatic ecosystem components (e.g. relative risk to riparian vegetation vs. in-stream biota). Uncertainties can be identified and built into adaptation processes.

Thus risk to key ecological components and aquatic habitats from changes induced by climate change in temperature and hydrological regimes can be addressed both quantitatively and semi-quantitatively. The ability to link the results of these fine-scale assessments to policy and regulatory frameworks is, however, severely constrained. Even given a favourable governance culture, mechanisms to allow progressive or iterative uptake of risk implications for environmental assets at property to catchment scales into policy and regulation are haphazard at best.

At a broad scale, frameworks for water access entitlement and planning are now structured to enable flexibility and adaptive responses to climate change. While not directly aimed at addressing climate change *per se*, much of the reform undertaken in the water sector over the past 10–15 years has been aimed at providing certainty and flexibility in relation to a natural resource that is highly variable both seasonally and long-term. Most of this reform has, however, been focused on non-environmental water uses.

Under the National Water Initiative, governments have agreed that water access entitlement holders are to bear the risks of any reduction in, or reduced reliability of, their water allocations, as a result of seasonal or long-term changes in climate (COAG 2004, COAG 2007). For most jurisdictions, the policy context is relatively clear in that the environment will not be required to forego additional water to maintain the volume and/or reliability of water entitlements.

In this policy context, the key opportunity within the water management arena for adaptive uptake of climate risk implications is through the development and periodic review and modification of water management planning tools, such as water management or water resource plans. These mechanisms allow water resources to be assessed up front, and for decisions to be made about how much of the resource is available for allocation, how much of the resource is to be retained for the environment, and the rules under which water may be extracted and shared.

Where these mechanisms are not overly constrained by statutory requirements, the opportunity remains to include considerations of climate-change driven risk into planning mechanisms, and instruments such as water allocation limits, water sharing rules, environmental water allocations and licence arrangements.

As an important first step, future climate data are starting to be incorporated within hydrological models to determine water yield and availability under various climate change scenarios (e.g. DSE 2012, DSE 2009, CSIRO 2009a, DEWNR 2012b, DEWNR 2012a, DERM 2011). Using this approach, water allocation limits within water management plans can be determined based on future climate, rather than past climate. This provides flexibility—as climate models are refined, hydrological model outputs can be generated accordingly, and allocation limits periodically reviewed and adjusted as necessary.

Using tools such as the *CSIRO Sustainable Yields* project (e.g. CSIRO 2009b, CSIRO 2009a), assessment of the reliability of major water supply infrastructure is being undertaken, with the results forming part of the broader assessment of whether to publicly fund such projects. In the Tasmanian case, the Commonwealth and Tasmanian Governments have agreed that irrigation infrastructure needs to achieve a minimum of 95% reliability under the ‘worst case’ climate change scenario to obtain public funding.

Whilst these approaches do not directly address risks, at a finer scale, to key ecological components and aquatic habitat from climate change, they do take a ’water regime‘ approach in which risks to aquatic ecosystems are addressed broadly.

Specific risks to key ecological components and aquatic habitat will need to be addressed through mechanisms such as provisions within water management plans, including water sharing rules and environmental water allocations. The advent of systematic assessment tools such as Tasmania’s Conservation of Freshwater Ecosystem Values database and the First Assessment of River and Wetland Health national protocol will assist in identifying ecosystem assets and the likely impacts of climate change upon those assets (through linkages to hydrological models). However, the development of such mechanisms is likely to be challenging, particularly where water resources are already at high levels of allocation or efforts are being made to address over-allocation.

While water reform is a large part of conserving freshwater biodiversity, we also need to acknowledge that policy instruments for biodiversity management *per se* (e.g. legislation for threatened species and ecological communities, reserves, biosecurity) will also need to respond to the challenges posed by changing climate, and water managers will need to be able to articulate water reforms with the changes in the biodiversity policy landscape.

There has been limited development of pathways for integrating the traditional evolution of planning and policy with the needs for climate change adaptation for aquatic ecosystems. Formal mechanisms for the uptake of knowledge about identified risks from climate change into policy and legislative instruments remain undeveloped, partially due to the difficulty of incorporating the uncertainty of future impacts into management plans. However, many water management plans include a requirement for periodic review, which can incorporate reassessment of water availability. An even bigger gap, however, is the ability to integrate multiple adaptation strategies (some working at different scales) to achieve specific adaptation objectives for individual assets or asset groups within regions or catchments. This is particularly the case where a mix of water management and non-water management is required. This reflects the ongoing challenge of catchment management where multiple management agencies, management actions, land and water tenures need to be engaged. Specific climate adaptation strategies are needed which enable integrated responses from relevant jurisdictions, NRM/CMA bodies and water managers, with a common set of objectives for managing aquatic ecosystems. Some of this philosophy is reflected in the Basin Plan for the Murray Darling Basin, but even here the lack of constitutional power in relation to land management largely restricts the focus to environmental water and related works and measures as the principal management levers.

APPENDIX 1: BBN LISTINGS

This appendix lists all the BBNs for each biodiversity asset, with a brief description of the main features of each network. A consistent colour scheme is used throughout: pink denotes a parent input variable, which uses data from hydrological or temperature modelling or CFEV, grey and cream indicate derived daughter input variables, beige denotes an output condition score.

The outputs from the macroinvertebrate (bug) BBN (e.g. Total Bug Abundance2) form a major component of the fish and platypus BBN condition scores, because the abundance of macroinvertebrates influences the food availability for these biota. Hydrology variables are the major drivers of projected macroinvertebrate condition, but water temperature also has a strong influence on macroinvertebrate abundance and community condition score (Figure 27).

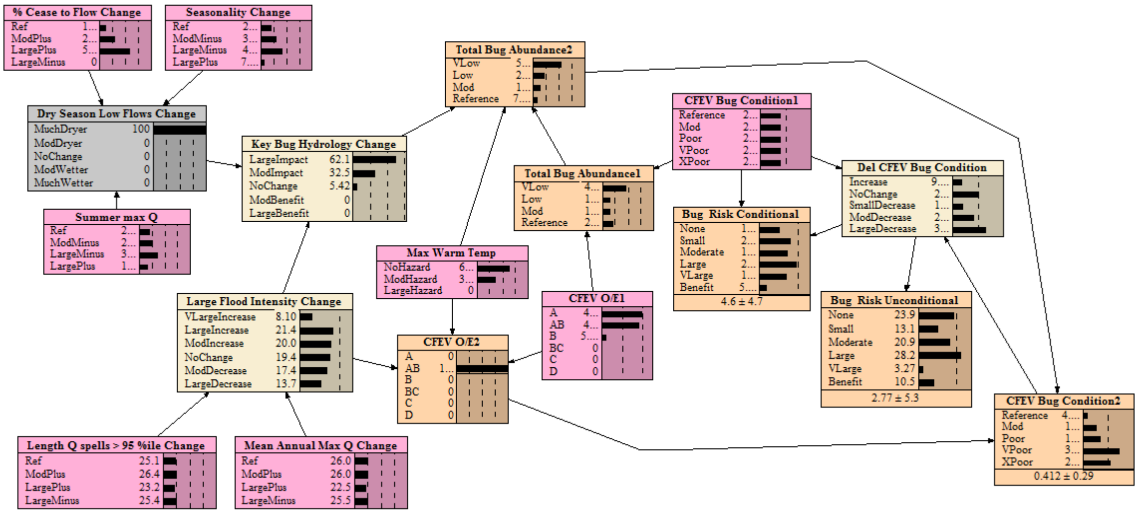


Figure 27 Macroinvertebrate (bug) BBN model nodes and connections

The frog and *Galaxiella pusilla* BBNs were both based on variables derived from the floodplain wetland BBN (Figure 28). In addition to the dominant hydrology input variables, the floodplain wetland BBN also included the CFEV wetland condition score and wetland area, as a surrogate for temperature effects. Changes to the flooding regime were important inputs to riparian vegetation condition and overall wetland condition.

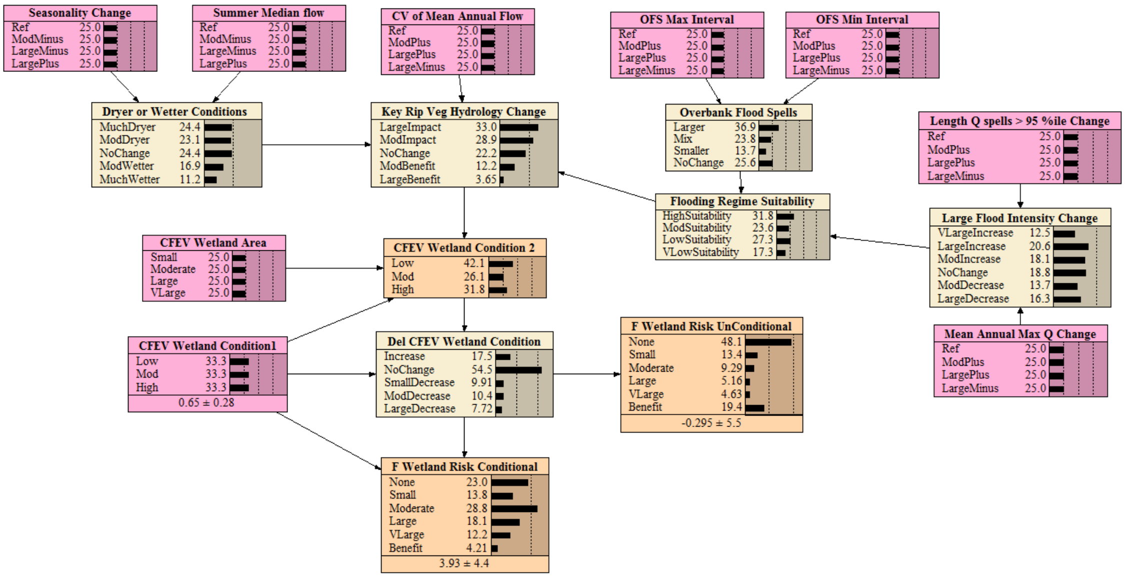


Figure 28 Floodplain wetland BBN model nodes and connections

The frog BBN was based on wetland condition scores, which were derived from the hydrology variables in the wetlands BBN, with recent and projected water temperatures as the major input variables influencing frog assemblages (Figure 29).

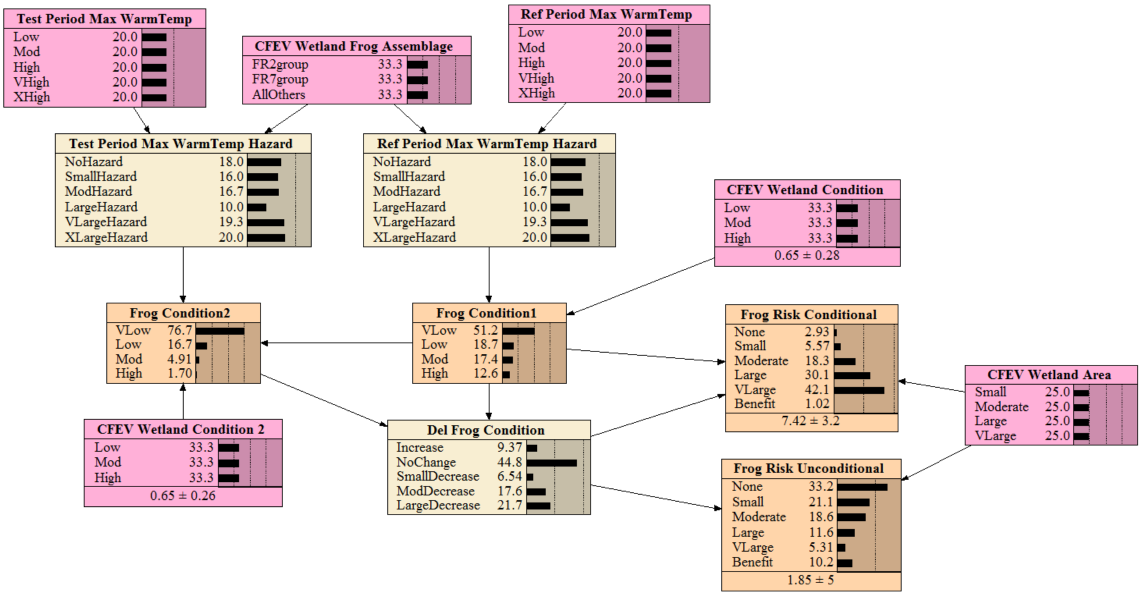


Figure 29 Frog BBN model nodes and connections

In contrast, the *Astacopsis gouldi* BBN used temperature and CFEV river attributes, including stream size, slope and substrate size, riparian vegetation condition and anthropogenic influences such as sedimentation and water abstraction as input variables. Water quality and light availability were derived from these input variables, which then contributed to the *A. gouldi* condition scores (Figure 30).

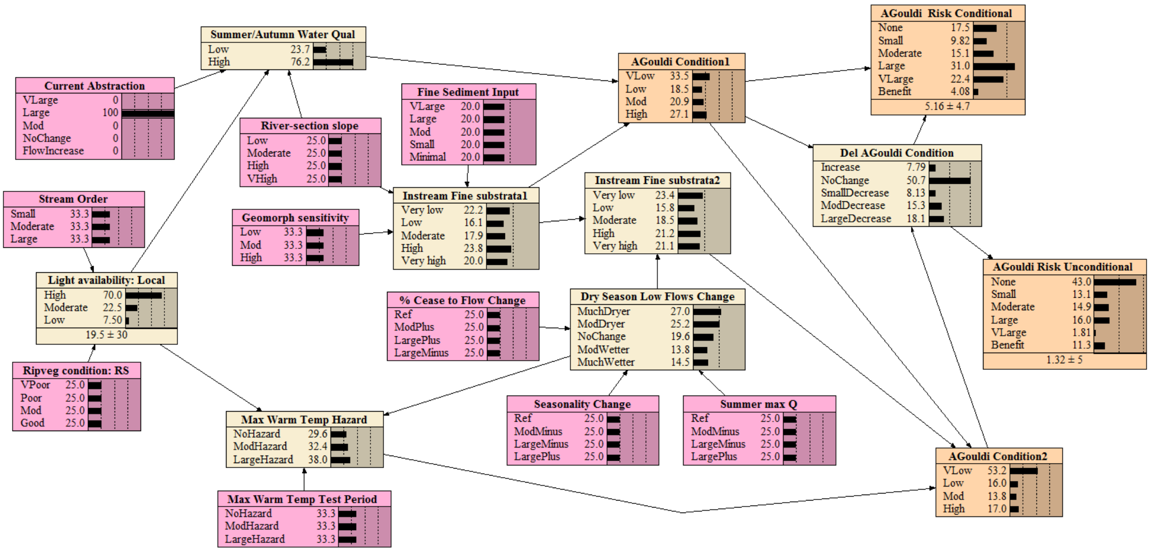


Figure 30 ***Astacopsis gouldi*** **BBN model nodes and connections**

Platypus risk scores for bank and browsing habitat were derived from hydrology variables, while current and projected macroinvertebrate abundance scores contributed risks for food availability. The BBN then predicted risks to future platypus abundance (Figure 31).

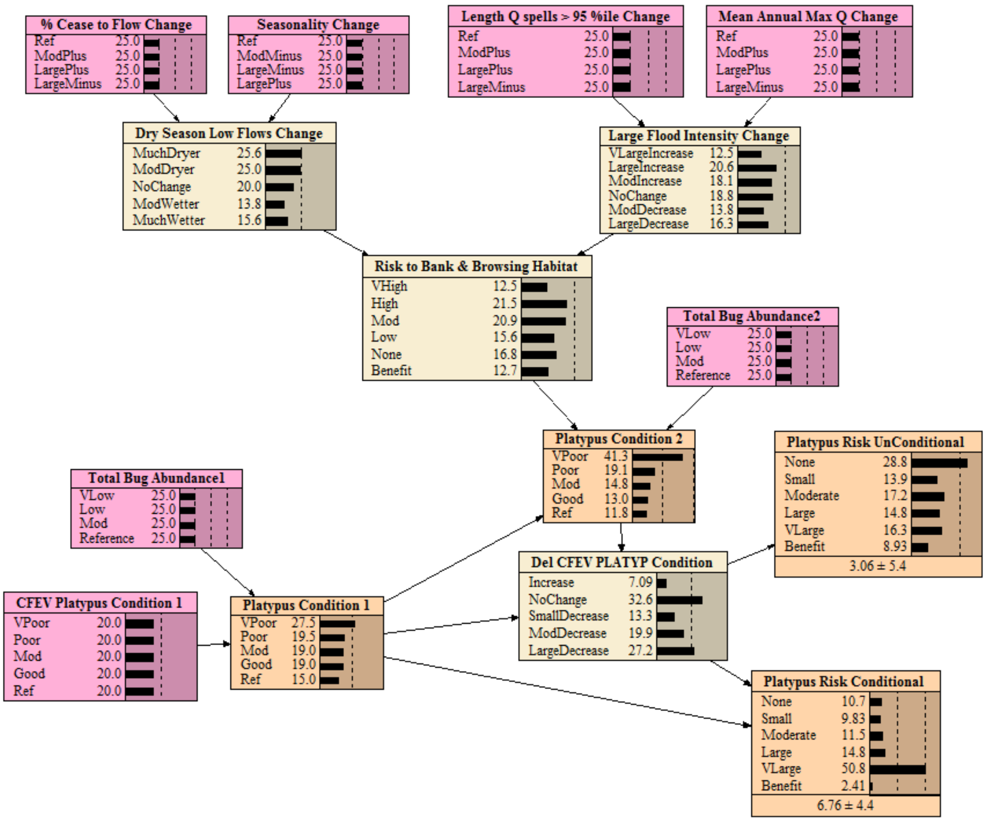


Figure 31 Platypus BBN model nodes and connections

Projected changes to the flow regime were defining input variables for the riparian vegetation BBN (Figure 32). Overbank flows are important for sediment deposition on the floodplain, for transfer of nutrients between the riparian zone and the stream, and for dispersal of seeds and propagules of riparian plants (Junk, Bayley and Sparkes 1989).

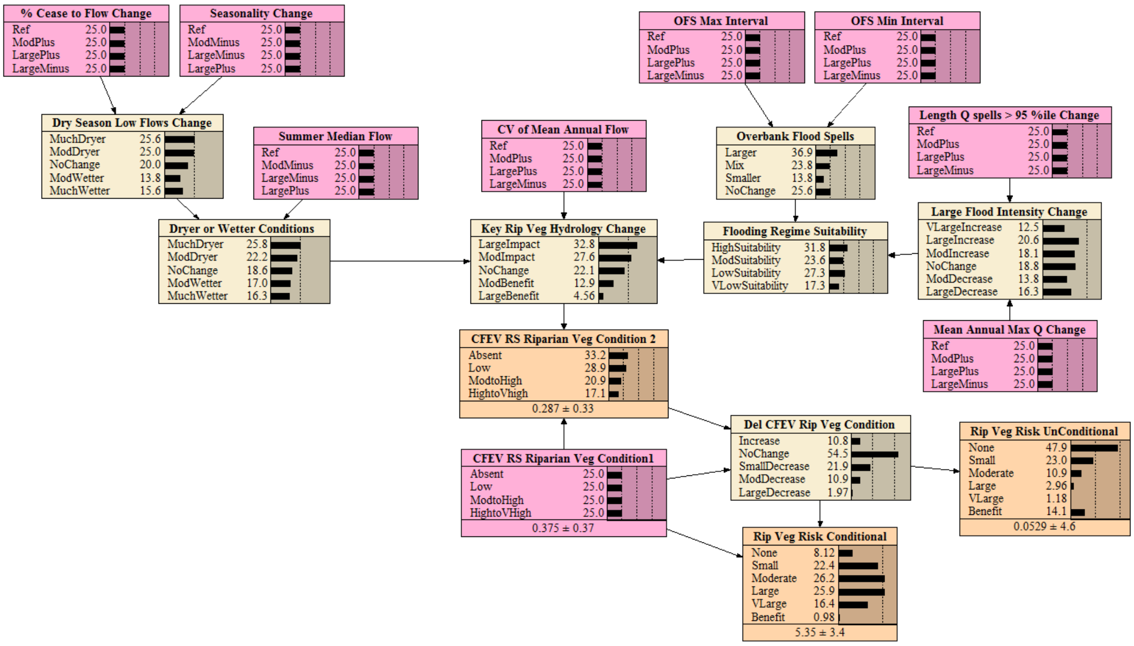


Figure 32 Riparian vegetation BBN model nodes and connections

Warmer temperatures are the greatest risk to brown trout populations under climate change. Adults and juvenile trout are vulnerable to higher maximum temperatures, and trout eggs are very sensitive to higher minimum temperatures (Moloney 2001), therefore these were key input variables to the BBN (Figure 33). Changes to hydrological variables were also important for maintenance of spawning and feeding habitat and nest sites. The abundance of native fish was also included in this BBN, as important prey items for trout.

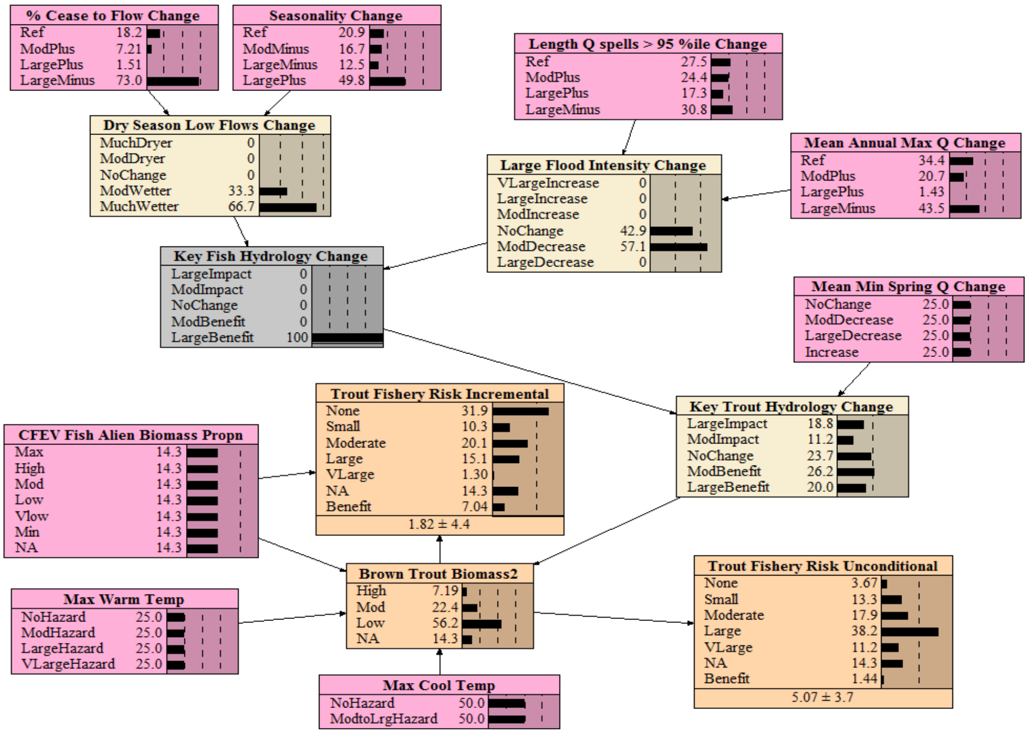


Figure 33 Brown trout BBN model nodes and connections

Changes to the hydrology variables were more important to the native fish BBN than temperature (
Figure 34). The biomass of exotic fish, such as trout, was an influential variable, because many native fish are only found in trout-free streams in Tasmania (Jackson 2004).

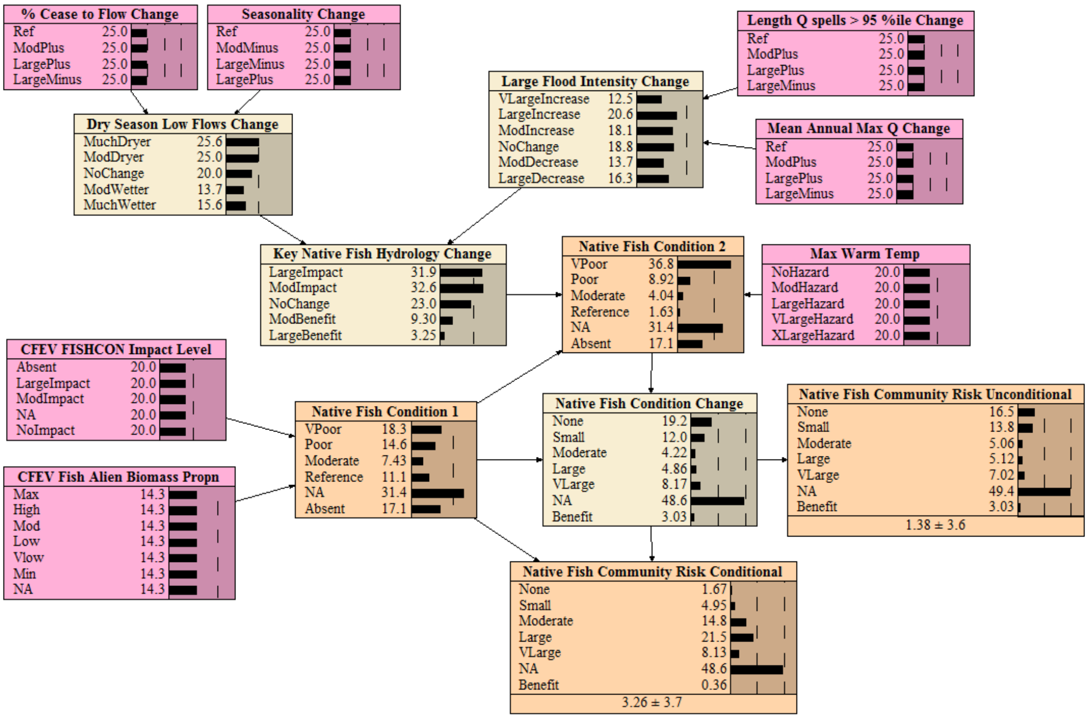


Figure 34 Native Fish BBN model nodes and connections

In contrast, the BBN for *Galaxiella pusilla*, a wetland species, was dominated by wetland condition input variables and water temperature (Figure 35).

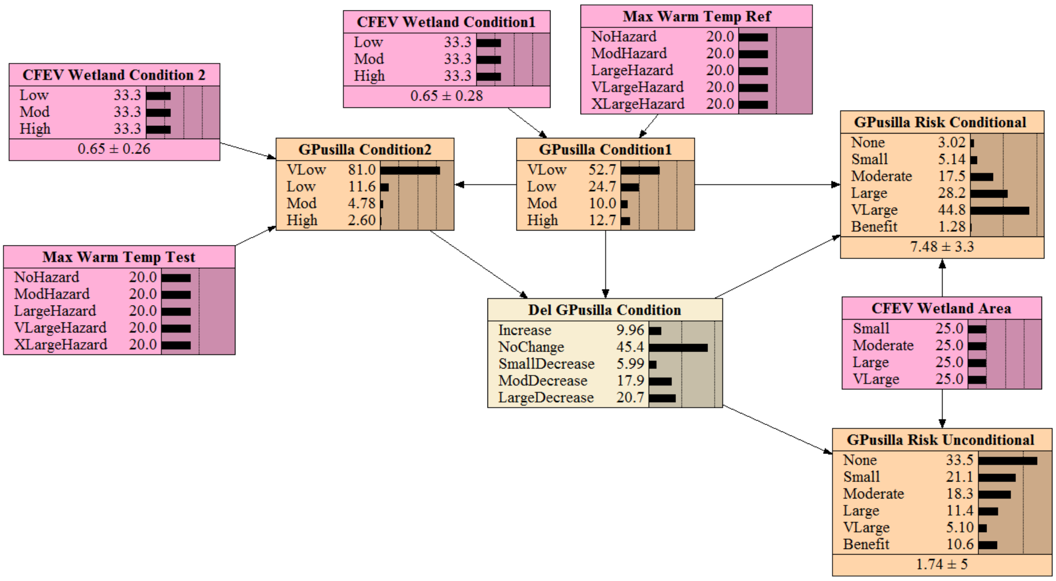


Figure 35 *Galaxiella pusilla* BBN model nodes and connections

In the non-floodplain wetland BBN, the change in the percentage of cease to flow events replaced the minimum and maximum overbank flows that were important drivers of the floodplain BBN, because dry season low flows are likely to impact on the drying regime of a wetland without connection to river flows (Figure 36).

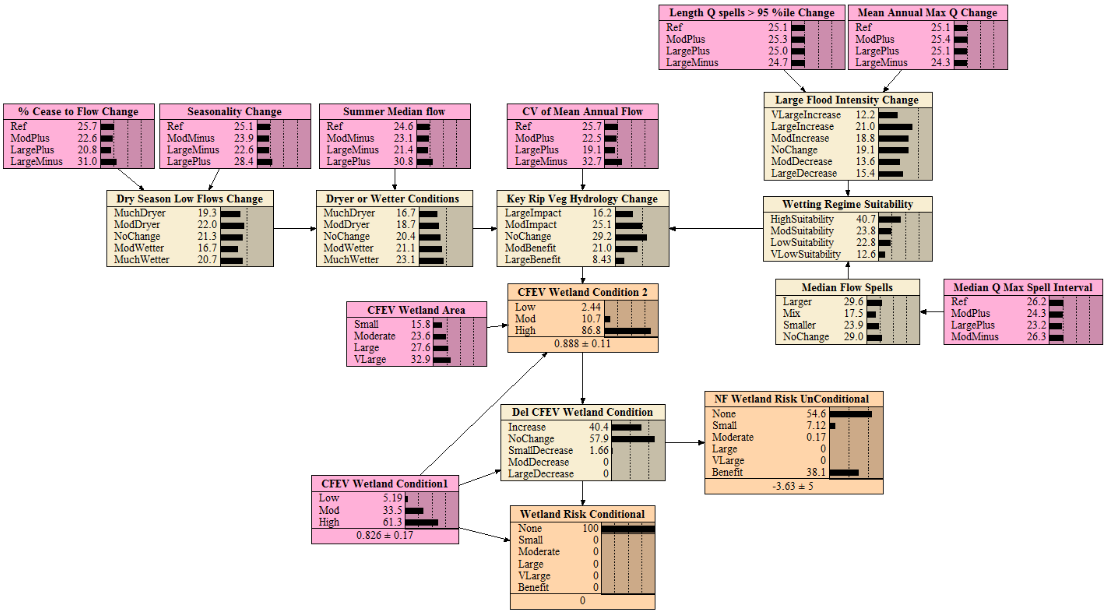


Figure 36 Non-floodplain wetland BBN model nodes and connections

APPENDIX 2: THERMAL TOLERANCE REFERENCES

The *Method* column indicates the type of study used to determine thermal limits, and the location where the study was conducted (in parentheses). CTM refers to *Critical Thermal Maximum* studies, but also includes LT_{50} (Lethal Temperature at which 50% of individuals died) studies. *Model* refers to studies where results are achieved by statistical modelling of local data or from data gleaned from published studies. *Mesocosm* refers to any study which was carried out in a laboratory tank or aquarium or in a chamber located in a field situation.

Species	Common Name	Status	Minimum temperature (^oC)	Maximum temperature (^oC)	Optimum temperature (^oC)	Reference	Method
Gambusia holbrooki	Mosquito fish	Exotic	3	41		Inland Fisheries Service (2012)	Summary (Tasmania)
Salmo trutta	Brown trout	Exotic		23.5 to 26.7	8 to 17	Moloney (2001)	Literature review (WA)
				18		Bond, Thomson et al. (2011)	Model (SE Australia)
				24.1		Eaton and Scheller (1996)	Model (USA)
				30		Elliott and Elliott (1995)	CTM experiment (UK)
Oncorhynchus mykiss	Rainbow trout	Exotic	10	22		Elliott and Elliott (1995)	CTM experiment (UK)
			0	29.8		Rodgers and Griffiths (1983)	CTM Experiment (USA)
			2	29.8		Currie, Bennett et al. (1998)	CTM experiment (USA)

Species	Common Name	Status	Minimum temperature (°C)	Maximum temperature (°C)	Optimum temperature (°C)	Reference	Method
Oncorhynchus mykiss	Rainbow trout	Exotic		26.5	10 to 22	References in Barton (1996)	Biology textbook (USA)
			4	> 18 (no ovulation, no viable eggs)		Pankhurst, Purser et al. (1996)	Mesocosm experiment (Tasmania)
			0	29.8		Currie, Bennett et al. (1998)	CTM Experiment (USA)
				24		Eaton and Scheller (1996)	Model (USA)
Salvelinus fontinalis	Brook trout	Exotic		< 29.8		Benfey (1996)	CTM experiment (Canada)
				22.4		Eaton & Scheller (1996)	Model (USA)
Salmo Salar	Atlantic salmon	Exotic		32.8		Elliott & Elliott (1995)	CTM experiment (UK)
Cyprinus carpio	Common Carp	Exotic		35.7		Jobling (1981)	Literature review
			2	40.6		References in Koehn (2004)	Literature review (Australia)
				41.3	29 to 32	Golovanov and Smirnov (2007)	CTM Experiment (Russia)
Gadopsis marmoratus	River black fish	Native	8	15		Bond et al (2011) Balcombe et al	Model (SE Aust) Model (SE Aust)

Species	Common Name	Status	Minimum temperature (°C)	Maximum temperature (°C)	Optimum temperature (°C)	Reference	Method
						(2011)	
Anguilla australis	Short-finned eel	Native		28		Jellyman (1974), cited in Richardson, Boubée et al. (1994)	CTM experiment (New Zealand)
				39.7	25.6 to 28.5	Simons (1986), cited in Richardson, Boubée et al. (1994)	CTM experiment (New Zealand)
					3 to 24	Humphries (1989)	Field experiment (Tasmania), inferred from distribution
Paragalaxias julianus	Western paragalaxias	Endemic			0 to 25 in lakes	Humphries (1989)	Field experiment (Tasmania), inferred from distribution
Galaxias maculatus	Jollytail	Native	3	22	18.1	Hickford and Schiel (2011)	Field experiment (New Zealand) – egg survival
					5 to 24	Humphries (1989)	Field experiment (Tasmania), inferred from distribution
				30.8	17.2 to 19.1	Simons (1986), cited in Richardson, Boubée et al. (1994)	CTM experiment (New Zealand)

Species	Common Name	Status	Minimum temperature (°C)	Maximum temperature (°C)	Optimum temperature (°C)	Reference	Method
Galaxias brevipinnis	Climbing galaxias	Native		27		Main (1988), cited in Richardson, Boubée et al. (1994)	CTM experiment (New Zealand)
					3 to 18	Humphries (1989)	Field experiment (Tasmania), inferred from distribution
					0 to 25 in lakes	Humphries (1989)	Field experiment (Tasmania), inferred from distribution
Galaxias truttaceus	Spotted galaxias	Native	4	22		Streams - Humphries (1989)	Field experiment (Tasmania), inferred from distribution
			0	29		Lakes - Humphries (1989)	Field experiment (Tasmania), inferred from distribution
***Neochanna cleaver* (ex *Galaxias cleaveri*)**	Tasmanian mudfish	Native			3 to 24	Humphries (1989)	Field experiment (Tasmania), inferred from distribution
Geotria australis	Pouched lamprey				3 to 24	Humphries (1989)	Field experiment (Tasmania), inferred from distribution
Pseudaphritis urvillii	Sandy	Native			3 to 18	Humphries (1989)	Field experiment (Tasmania), inferred from distribution
Nannoperca australis	Pygmy perch	Native	5 - 7	17 to 20		Humphries (1995)	Field experiment (Tasmania), inferred from distribution

Species	Common Name	Status	Minimum temperature (°C)	Maximum temperature (°C)	Optimum temperature (°C)	Reference	Method
Crinia signifera	Common froglet	Native	<5	34		Brattstrom (1970)	CTM experiment (Eastern Australia)
Limnodynastes peroni	Striped marsh frog	Native		37	13 to 22	Marshall and Grigg (1980)	CTM experiment on tadpoles (NSW)
			5	34		Brattstrom (1970)	CTM experiment (Eastern Australia)
Ornithorhynchus anatinus	Platypus	Native	0	30		Grant and Dawson (1978)	Field and mesocosm experiment (NSW)
Hydromys chrysogaster	Water rat	Native	15	< 35		Dawson and Fanning (1981)	Mesocosm experiment (NSW)
Astacopsis gouldi	Giant FW crayfish	Endemic	5	18	5 to 18	Hamr (1990); Lynch & Blühdorn (1997); Webb (2001), cited in Threatened Species Section (2006)	Field studies (Tasmania)
Anaspides tasmanicae	Mountain shrimp	Endemic		23	0 to 22	Swain and Reid (1983)	Field and CTM experiments (Tasmania)
Paratya curvirostris	Freshwater shrimp	Native conspecifics		24.6 to 26.8		Quinn and Hickey (1990)	CTM experiment (New Zealand)

Species	Common Name	Status	Minimum temperature (°C)	Maximum temperature (°C)	Optimum temperature (°C)	Reference	Method
Notonemouridae (*Austrocercella hynesi, A. alpina, A. tillyardi, A. illiesi)*	Stonefly eggs	Native conspecifics		Low or no hatching > 20	15 to 20	Brittain (1991)	Laboratory experiment on stonefly egg hatching and survival (NSW)
Notonemouridae	Stonefly nymph	Native Family		29.3 to 30.5		Dallas and Rivers-Moore (2012)	CTM experiment (South Africa)
Gripopterygidae	Adult stonefly	Native Family		22 to 23	Decreased longevity > 18°C air	Collier and Smith (2000)	CTM experiment (New Zealand)
Plecoptera	Stonefly nymphs	Native Order		23	< 19	Quinn and Hickey (1990)	Field experiment (New Zealand), inferred from distribution
***Centroptilum* sp.**	Mayfly	Native conspecifics		20.5		Davies, Cook et al. (2004)	Field and CTM experiment (Australia, south of 35° latitude)
Baetidae	Mayfly	Native Family		28.9 to 35.8		Dallas and Rivers-Moore (2012)	CTM experiment (South Africa)
Leptophlebiidae	Mayfly	Native Family		32.3 to 34.3		Dallas and Rivers-Moore (2012)	CTM experiment (South Africa)
Austroaeschna anacantha	Dragonfly	Native conspecifics		33.8		Davies, Cook et al. (2004)	Field and CTM experiment (Australia)

Species	Common Name	Status	Minimum temperature (°C)	Maximum temperature (°C)	Optimum temperature (°C)	Reference	Method
***Cheumatopsyche* sp. AV2**	Hydropsychid Caddis fly	Native conspecifics		28.1		Davies, Cook et al. (2004)	Field and CTM experiment (Australia)
Cheumatopsyche maculate	Hydropsychid Caddis fly	Native conspecifics		32.9		Dallas and Rivers-Moore (2012)	CTM experiment (South Africa)
***Hydrobiosis* sp.**	Adult Hydrobiosid Caddis fly	Native Family		31		Smith and Collier (2002)	CTM experiment (New Zealand)
Chimarra ambulans	Philopotamid Caddis fly	Native conspecifics		32.0		Dallas and Rivers-Moore (2012)	CTM experiment (South Africa)
Leptoceridae	Caddis fly	Native Family		31.6 to 33.9		Dallas and Rivers-Moore (2012)	CTM experiment (South Africa)
Naucoris obscuratus	Water bug	Native conspecifics		39.9		Dallas and Rivers-Moore (2012)	CTM experiment (South Africa)
***Culex* sp. (Culicidae)**	Mosquito larvae	Native conspecifics		39.9		Dallas and Rivers-Moore (2012)	CTM experiment (South Africa)
Potamopyrgus antipodarum	Hydrobiid snail	Common Exotic		30 to 35		Quinn, Steele et al. (1994)	CTM experiment (New Zealand)

Thermal tolerance references

BARTON, B.A. (1996) *General biology of salmonids*. In 'Principles of Salmonid Culture.' (Eds. W Pennel and BA Barton) pp. 29-96. (Elsevier: Amsterdam)

BENFEY, T.J. (1996) Use of all-female and triploid salmonids for aquaculture in Canada. *Bulletin of the Aquaculture Association of Canada* 2, 6-8.

BOND, N., THOMSON, J., REICH, P., and STEIN, J. (2011) Using species distribution models to infer potential climate change-induced range shifts of freshwater fish in south-eastern Australia. *Marine and Freshwater Research* 62(9), 1043-1061.

BRATTSTROM, B.H. (1970) Thermal acclimation in Australian amphibians. *Comparative Biochemistry and Physiology* 35(1), 69-103.

BRITTAIN, J. (1991) Effect of temperature on egg development in the Australian stonefly genus, *Austrocercella illies* (Plecoptera : Notonemouridae). *Marine and Freshwater Research* 42(2), 107-114.

COLLIER, K.J., and SMITH, B.J. (2000) Interactions of adult stoneflies (Plecoptera) with riparian zones I. Effects of air temperature and humidity on longevity. *Aquatic Insects* 22(4), 275-284.

CURRIE, R., BENNETT, W., and BEITINGER, T. (1998) Critical thermal minima and maxima of three freshwater game-fish species acclimated to constant temperatures. *Environmental Biology of Fishes* 51(2), 187-200.

DALLAS, H., and RIVERS-MOORE, N. (2012) Critical thermal maxima of aquatic macroinvertebrates: towards identifying bioindicators of thermal alteration. *Hydrobiologia* 679(1), 61-76.

DAVIES, P., COOK, B., RUTHERFORD, K., and WALSHE, T. (2004) *Managing high in-stream temperatures using riparian vegetation*. River Management Technical Guideline No. 5, Land and Water Australia, Canberra.

DAWSON, T.J., and FANNING, F.D. (1981) Thermal and energetic problems of semiaquatic mammals: A study of the Australian Water Rat, including comparisons with the Platypus. *Physiological Zoology* 54(3), 285-296.

EATON, J.G., and SCHELLER, R.M. (1996) Effects of climate warming on fish thermal habitat in streams of the United States. *Limnology and Oceanography* 41(5), 1109-1115.

ELLIOTT, J.M., and ELLIOTT, J.A. (1995) The effect of the rate of temperature increase on the critical thermal maximum for parr of Atlantic salmon and brown trout. *Journal of Fish Biology* 47(5), 917-919.

GOLOVANOV, V., and SMIRNOV, A. (2007) Influence of the water heating rate upon thermal tolerance in common carp (*Cyprinus carpio* L.) during different seasons. *Journal of Ichthyology* 47(7), 538-543.

GRANT, T.R., and DAWSON, T.J. (1978) Temperature regulation in the Platypus, *Ornithorhynchus anatinus*: maintenance of body temperature in air and water. *Physiological Zoology* 51(1), 1-6.

HICKFORD, M.J.H., and SCHIEL, D.R. (2011) Synergistic interactions within disturbed habitats between temperature, relative humidity and UVB radiation on egg survival in a diadromous fish. *PLoS ONE* 6(9), e24318.

HUMPHRIES, P. (1989) Variation in the life history of diadromous and landlocked populations of the Spotted Galaxias, *Galaxias truttaceus* Valenciennes, in Tasmania. *Marine and Freshwater Research* 40(5), 501-518.

HUMPHRIES, P. (1995) Life history, food and habitat of southern pygmy perch, *Nannoperca australis*, in the Macquarie River, Tasmania. *Marine and Freshwater Research* 46(8), 1159-1169.

INLAND FISHERIES SERVICE (2012) *Current List of Tasmanian Species*. Government of Tasmania, Hobart, http://www.ifs.tas.gov.au/ifs/goingfishing/fishspecies/folder.2006-07-24.0896173149/fish-facts, accessed 4 January 2012

JELLYMAN, D.J. (1974) Aspects of the biology of juvenile freshwater eels (Anguillidae) in New Zealand. Unpublished Ph.D. Thesis. Victoria University, Wellington, New Zealand

JOBLING, M. (1981) Temperature tolerance and the final preferendum—rapid methods for the assessment of optimum growth temperatures. *Journal of Fish Biology* 19(4), 439-455.

KOEHN, J.D. (2004) Carp (*Cyprinus carpio*) as a powerful invader in Australian waterways*. Freshwater Biology* 49(7), 882-894.

LYNCH, T. and BLÜHDORN, D.R. 1997. *Reservation assessment and habitat requirements of the giant Tasmanian freshwater lobster, Astacopsis gouldi.* Report to the Tasmanian RFA Environment and Heritage Technical Committee, Hobart.

MAIN, M.R. (1988) Factors influencing the distribution of kokopu and koara (Pisces: Galaxiidae). M.Sc. Thesis, University of Canterbury, New Zealand,

MARSHALL, E., and GRIGG, C.M. (1980) Acclimation of CTM, LD_{50}, and rapid loss of acclimation of thermal preferendum in tadpoles of *Limnodynastes peroni* (Anura, Myobatrachidae). *The Australian Zoologist* 20(3), 447-455.

MOLONEY, B. (2001) *Environmental requirements and tolerances of Rainbow trout (Oncorhynchus mykiss) and Brown trout (Salmo trutta) with special reference to Western Australia: A review*. Department of Fisheries, North Beach, WA.

PANKHURST, N.W., PURSER, G.J., VAN DER KRAAK, G., THOMAS, P.M., and FORTEATH, G.N.R. (1996) Effect of holding temperature on ovulation, egg fertility, plasma levels of reproductive hormones and in vitro ovarian steroidogenesis in the rainbow trout *Oncorhynchus mykiss*. *Aquaculture* 146(3-4), 277-290.

QUINN, J.M., and HICKEY, C.W. (1990) Characterisation and classification of benthic invertebrate communities in 88 New Zealand rivers in relation to environmental factors. *New Zealand Journal of Marine and Freshwater Research* 24(3), 387-409.

QUINN, J.M., STEELE, G.L., HICKEYy, C.W., and VICKERS, M.L. (1994) Upper thermal tolerances of twelve New Zealand stream invertebrate species. *New Zealand Journal of Marine and Freshwater Research* 28(4), 391-397.

RICHARDSON, J., BOUBÉE, J.A.T., and WEST, D.W. (1994) Thermal tolerance and preference of some native New Zealand freshwater fish. *New Zealand Journal of Marine and Freshwater Research* 28(4), 399-407.

RODGERS, D.W., and GRIFFITHS, J.S. (1983) Effects of elevated thermal regimes on survival of rainbow trout (*Salmo gairdneri*). *Journal of Great Lakes Research* 9, 421-424.

SIMONS, M. (1986) *Effects of elevated temperatures and thermal shock on fish larvae*. Waikato Valley Authority Technical Publication 42, 28 pp., Hamilton, New Zealand.

SMITH, B., and COLLIER, K.J. (2002) Living on the edge: putting the heat on adult aquatic insects. *Water and Atmosphere* 10(3), 16-17.

SWAIN, R., and REID, C.I. (1983) Observations on the life history and ecology of *Anaspides tasmaniae* Thomson (Syncarida: Anaspididae). *Journal of Crustacean Biology* 3(2), 163-172.

THREATENED SPECIES SECTION (2006) *Giant Freshwater Lobster Astacopsis gouldi Recovery Plan 2006-2100*. Department of Primary Industries and Water, Hobart, Tasmania.

APPENDIX 3: HYDROLOGY AND TEMPERATURE NODE STATES

BBN hydrology input node states, descriptions and values used in BBN modelling, with the node definition given in parentheses.

BBN hydrology input nodes	Node state	Node state description	State value
% Cease to Flow Change (number of days with flows < 0.1 ML/day)	Ref	Number of cease to flow days not different to reference period	-2.5 to +1.5%
	ModPlus	Moderate increase in cease to flow days	1.5 to 2.5%
	LargePlus	Large increase in cease to flow days	≥ - 2.5%
	LargeMinus	Large decrease in cease to flow days	≤ - 2.5%
Mean Annual Max Q Change (average annual maximum flow)	Ref	No change in average annual maximum flow from reference period	0.5 to 1.5
	ModPlus	Moderate increase in average annual maximum flow from reference period	1.5 to 2.0
	LargePlus	Large increase in average annual maximum flow from reference period	> 2.0
	LargeMinus	Large decrease in average annual maximum flow from reference period	< 0.5
Length Q spells > 95%ile Change (average duration (days) of spells above the 95th percentile of flows (ML/day))	Ref	No change in average duration of spells above the 95th percentile of flow from reference period	0.5 to 1.25
	ModPlus	Moderate increase in average duration of spells above the 95th percentile of flow from reference period	1.25 to 1.5
	LargePlus	Large increase in average duration of spells above the 95th percentile of flow from reference period	> 1.5
	LargeMinus	Large decrease in average duration of spells above the 95th percentile of flow from reference period	< 0.5
Seasonality Change (as a percentage of annual flow)	Ref	No change in flow during the 6 driest months from reference period	0.8 < 1.2
	ModMinus	Moderate decrease in flow during the 6 driest months from reference period	0.8 to < 0.9

BBN hydrology input nodes	**Node state**	**Node state description**	**State value**
	LargeMinus	Large decrease in flow during the 6 driest months from reference period	≤ 0.8
	LargePlus	Large increase in flow during the 6 driest months from reference period	≥ 1.2
Summer Max Q (summer maximum daily flow)	Ref	No change in summer maximum daily flow from reference period	0.75 to 1.5
	ModMinus	Moderate decrease in summer maximum daily flow from reference period	0.5 to 0.75
	LargeMinus	Large decrease in summer maximum daily flow from reference period	< 0.5
	LargePlus	Large increase in summer maximum daily flow from reference period	> 1.5
Mean Min Spring Q Change (spring minimum daily flow)	NoChange	No change in spring minimum flow	0.75 to 1.25
	ModDecrease	Moderate decrease in spring minimum flow	0.75 to 0.5
	LargeDecrease	Large decrease in spring minimum flow	< 0.5
	Increase	Increase in spring minimum flow	> 1.25
CV of Mean Annual Flow (coefficient of annual flow variability)	Ref	No change in coefficient of flow variation	0.5 to 1.25
	ModPlus	Moderate increase in coefficient of flow variation	1.25 to 1.5
	LargePlus	Large increase in coefficient of flow variation	> 1.5
	LargeMinus	Large decrease in coefficient of flow variation	< 0.5
OFS Max Interval (maximum interval between overbank flows)	Ref	No change in maximum interval between overbank flows	0.5 to 1.25
	ModPlus	Moderate increase in maximum interval between overbank flows	1.25 to 1.5
	LargePlus	Large increase in maximum interval between overbank flows	> 1.5
	LargeMinus	Large decrease in maximum interval between overbank flows	< 0.5
OFS Min Interval (minimum interval between overbank flows)	Ref	No change in minimum interval between overbank flows	0.5 to 1.25
	ModPlus	Moderate increase in minimum interval between overbank flows	1.25 to 1.5
	LargePlus	Large increase in minimum interval between overbank flows	> 1.5
	LargeMinus	Large decrease in minimum	< 0.5

BBN hydrology input nodes	Node state	Node state description	State value
		interval between overbank flows	
Summer Median Flow (summer median daily flow)	Ref	No change in summer median daily flows	0.75 to 1.5
	ModMinus	Moderate decrease in summer median daily flows	0.5 to 0.75
	LargeMinus	Large decrease in summer median daily flows	< 0.5
	LargePlus	Large increase in summer median daily flows	> 1.5
Median Q Max Spell Interval (median value of maximum high spell duration)	Ref	No change in maximum high spell duration	0.5 to 1.25
	ModPlus	Moderate increase in maximum high spell duration	1.25 to 1.5
	LargePlus	Large increase in maximum high spell duration	> 1.5
	LargeMinus	Large decrease in maximum high spell duration	< 0.5

BBN node temperature thermal tolerance risk scores and values for biota

BBN temperature nodes	Node description	Node risk score	Node risk value
Max Warm Temp (Native Fish)	75 percentile of maximum daily temperatures for warmest 4 months (Dec-Mar) in degrees Celsius. Maximum temperature above fish thermal threshold for test period	NoHazard	< 20 °C: Generally within optimum for all taxa
		ModHazard	20 - 25 °C: *Retropinna tasmanica* and by inference *Prototroctes maraena* and others under stress
		LargeHazard	25 to 30 °C: *Retropinna tasmanica* and by inference *Prototroctes maraena* and others locally extinct; *Galaxias* spp. under stress
		VLarge Hazard	30 to 35 ° C: *Galaxias* spp. locally extinct; *Anguilla* spp. under stress
		XLargeHazard	> 35 °C: *Anguilla* spp. locally extinct; all taxa locally extinct

BBN temperature nodes	Node description	Node risk score	Node risk value
Max Warm Temp (Bugs)	75th percentile of maximum daily temperature for warmest 4 months (Dec-Mar) in degrees Celsius. Maximum temperature above bug thermal threshold for test period	NoHazard	< 22.5 °C
		ModHazard	22.5 to 25°C
		LargeHazard	25 to 28 °C
Max Warm Temp (Frogs)	75th percentile of maximum daily temperatures for warmest 4 months (Dec-Mar) in degrees Celsius. Maximum temperature above frog thermal threshold for test period	Low	< 22 °C
		Mod	22 to 24 °C
		High	24 to 25 °C
		VHigh	25 to 27 °C
		XHigh	> 27 °C
Max Warm Temp (*A. gouldi*)	75th percentile of maximum daily temperatures for warmest 4 months (Dec-Mar) in degrees Celsius. Maximum temperature above *A. gouldi* thermal threshold for test period	NoHazard	< 18 °C
		ModHazard	18 to 22 °C
		LargeHazard	> 22 °C
Max Warm Temp (Brown trout)	75th percentile of maximum daily temperatures for warmest 4 months (Dec-Mar) in degrees Celsius. Maximum temperature above Brown Trout thermal threshold for test period	NoHazard	< 15 °C (within feeding optimum)
		ModHazard	15 to 20 °C
		LargeHazard	20 to 28 °C
		VLargeHazard	> 28 °C
Max Cool Temp (Brown trout)	75th percentile of maximum daily temperatures for coolest 4 months (May-Aug) in degrees Celsius. Maximum temperature above trout egg survival threshold in coolest months	NoHazard	< 13 °C (within optimum generally)
		ModtoLrgHazard	>13 °C (above upper threshold)
Max Warm Temp Ref	75th percentile of maximum daily temperatures for warmest 4 months (Dec-Mar) in degrees Celsius for the reference period	Low	< 22 °C
		Mod	22 to 24 °C
		High	24 to 25 °C
		VHigh	25 to 27 °C
		XHigh	> 27 °C

APPENDIX 4: INPUT NODE DETAILS FOR RIVERS

River BBN input nodes	Node description	Score value	Node condition score and state description
CFEV O/E1	Macroinvertebrate Observed/Expected ranked abundance index Based on AUSRIVAS O/E impairment bands	0.8 to 1.3	A impairment band: equivalent to natural
		0.6 to 1.0	AB impairment band: moderately impaired
		0.4 to 0.8	B impairment band: significantly impaired
		0.3 to 0.7	BC impairment band: significantly to severely impaired
		0.2 to 0.5	C impairment band: severely impaired
		0.0 to 0.3	D impairment band: extremely impaired
CFEV Bug Condition1	Macroinvertebrate condition score, based on composition and abundance	1.0	Reference: natural total density, natural assemblage
		0.8 to 0.99999	Mod: near-natural total density, near-natural assemblage
		0.4 to 0.79999	Poor: reduced total density, significantly altered assemblage
		0.2 to 0.39999	VPoor: reduced total density, severely altered assemblage
		0 to 0.19999	XPoor: low – very low density, severely altered assemblage
CFEV FISHCON Impact Level	Native fish condition score, based on impact from dams and flow modifications	- 9	Absent: native fish absent
		0	LargeImpact: intense impact of large dams, altered flow or acid drainage on native fish populations
		0.5	ModImpact: moderate impact of large dams, altered flow or acid drainage on native fish populations
		1	NoImpact: no impact of large dams, altered flow or acid drainage on native fish populations
		999	n/a: artificial channel, not assessed for condition
CFEV Fish Alien Biomass Propn	Index of proportion of native or exotic fish biomass	0	Max: exotic fish abundant, native fish biomass proportion = 0
		0.32 to 0.4	High: exotic fish abundant, mean native fish biomass proportion = 0.32
		0.3 to 0.65	Mod: exotic fish moderately abundant, mean native fish

River BBN input nodes	Node description	Score value	Node condition score and state description
			biomass proportion = 0.4
		0.4 to 0.8	Low: exotic fish low probability, mean native fish biomass proportion = 0.65
		0.8	VLow: exotic fish low probability, mean native fish dominant proportion > 0.8
		1	Min: exotic fish absent or very low proportion
		999	NA: artificial channel, not assessed for condition
CFEV Platypus Condition 1	Platypus condition score, based on CFEV measure of platypus population condition. Based on components of a population viability analysis and the known spread of the mucormycosis fungal disease (*Mucor amphiborium*) in 2004. Platypus condition is assumed to be influenced by land clearance in and adjacent to the riparian zone (CFEV 2005).	0.4	VPoor: platypus population in poor condition, known Mucor infestation area, native riparian vegetation almost entirely absent, stream order >1
		0.5	Poor: platypus population in moderate to poor condition, known Mucor infestation area, mostly native riparian vegetation
		0.6	Mod: platypus population in moderate to poor condition, known Mucor infestation area, mixed native and cultural riparian vegetation, stream order >1, OR not in known Mucor area, native vegetation mostly absent, stream order >1
		0.8	Good: platypus population close to natural condition, mixed native and cultural riparian vegetation, not in known Mucor infestation area, stream order > 1
		1	Ref: platypus population essentially natural, not in Mucor area, riparian vegetation mostly native
River-section slope	Gradient (rise/run)	Low	< 0.005
		Moderate	0.005 to 0.02
		High	0.02 to 0.04
		Very High	> 0.04
River Naturalness Score	Generated from a combination of equally-weighted *geomorphic condition* and *biological condition* indices from CFEV	Geomorphic condition input variables	Sediment input score; hydrological class; sediment capture by dams; river regulation score; geomorphic sensitivity score

River BBN input nodes	Node description	Score value	Node condition score and state description
		Biological condition input variables	Platypus condition score; fish condition score; exotic fish biomass; bug condition score; riparian vegetation condition score; willow (*Salix sp.*) abundance score
Current abstraction	Upstream accumulated abstraction category, based on upstream accumulated regulation index	1 to 3	FlowIncrease: reduction in water abstraction
		4 to 5	NoChange: no change in current water abstraction
		6	ModDecrease: moderate decrease in water abstraction
		7	LargeDecrease: large decrease in water abstraction
		8	VLargeDecrease: very large decrease in water abstraction
Fine Sediment Input	Sediment input score, from anthropogenic influences	1	VLarge: very large anthropogenic increase in sediment input
		2	Large: large anthropogenic increase in sediment input
		3	Mod: moderate anthropogenic increase in sediment input
		4	Small: small anthropogenic increase in sediment input
		5	Minimal: minimal to no anthropogenic increase in sediment input
Geomorph sensitivity	Geomorphic responsiveness score of channel to anthropogenic change in flow or sediment regime	0	Low: low responsiveness (e.g. bedrock control)
		0.5	Mod: moderate responsiveness
		1	High: high responsiveness (e.g. alluvial and fine sediment system)
		999	Artificial channel, not assessed for condition
RipVeg condition: RS	Condition score for riparian zone vegetation (within 50 m buffer)	1	VPoor: no native vegetation occurring within the riparian zone
		2	Poor: 0 to 20% of total riparian buffer zone as native vegetation
		3	Mod: 20 to 80% of total riparian buffer zone as native vegetation
		4	Good: more than 80% of total riparian buffer zone as native vegetation
Stream Order	Strahler stream order at 1 : 25,000 scale – Surrogate for	Small	Orders 1 to 3

River BBN input nodes	Node description	Score value	Node condition score and state description
	width for impact of riparian forest on shading levels First order streams omitted from mapping.	Moderate	Orders 4 to 6
		Large	Order > 6

BBN river model output node descriptions, input variables for each node, node states and values. n/a indicates an undefined output value, determined by input variable scores

River BBN output nodes	Node description	Input nodes	Node states	Node values
Dry Season Low Flows Change	Direction and intensity of change in dry season flows	1. % Cease to Flow Change 2. Seasonality Change	MuchDryer	n/a
			ModDryer	n/a
			NoChange	n/a
			ModWetter	n/a
			MuchWetter	n/a
Dryer or Wetter Condition	Direction and intensity of change in watering regime from 'wet' to 'dry'. Inputs are variables to which riparian vegetation are particularly sensitive	1. Dry Season Low Flows Change 2. Summer Median Flow	MuchDryer	n/a
			ModDryer	n/a
			NoChange	n/a
			ModWetter	n/a
			MuchWetter	n/a
Overbank Flood Spells	Average interval between overbank flood spells. A longer interval is considered a higher risk to riparian vegetation	1. OFS Max Interval 2. OFS Min Interval	Larger: high risk	n/a
			Mix: moderate risk	n/a
			Smaller: low risk	n/a
			NoChange: no risk	n/a
Flooding Regime Suitability	Rating of suitability of flooding regime to maintain reference condition riparian vegetation	1. Overbank Flood Spells 2. Large Flood Intensity Change	HighSuitability	n/a
			ModSuitability	n/a
			LowSuitability	n/a
			VLowSuitability	n/a
Key Rip Veg Hydrology Change	Direction and intensity of change in key hydrology drivers for riparian vegetation	1. Dryer or Wetter Conditions	LargeImpact	n/a
			ModImpact	n/a
			NoChange	n/a

River BBN output nodes	Node description	Input nodes	Node states	Node values
			ModBenefit	n/a
			LargeBenefit	n/a
CFEV RS Riparian Veg Condition 2	Projected proportion of total riparian buffer zone as native vegetation	1. CFEV RS Riparian Veg Condition1	Absent	n/a
			Low	n/a
			Modtohigh	n/a
			HightoVHigh	n/a
Del CFEV Rip Veg Condition	Change in riparian vegetation condition	1. CFEV RS Riparian Veg Condition1 2. CFEV RS Riparian Veg Condition 2	Increase	n/a
			NoChange	n/a
			Small Decrease	n/a
			ModDecrease	n/a
			LargeDecrease	n/a
Rip Veg Risk Conditional	Level of risk to riparian vegetation community from changes to the hydrological regime. Conditional on the original riparian vegetation condition state.	1. Del CFEV Rip Veg Condition 2. CFEV RS Riparian Veg Condition1	None	- 2 to +1
			Small	1 to 3
			Moderate	3 to 6
			Large	6 to 8
			VLarge	8 to 10
			Benefit	-2 to -10
Rip Veg Risk Unconditional	Level of risk to riparian vegetation community from changes to the hydrological regime. Not conditional on the original riparian vegetation condition state.	1. Del CFEV Rip Veg Condition	None	1 to 3
			Small	3 to 6
			Moderate	6 to 8
			Large	8 to 10
			VLarge	-2 to -10
			Benefit	1 to 3
Large Flood Intensity Change (riparian vegetation, bugs, platypus, native fish, brown trout)	Measure of change in intensity (magnitude, duration) of large floods capable of destroying or modifying instream habitat	1. Length Q spells>95%ile Change 2. Mean Annual Max Q Change	VeryLargeIncrease	n/a
			LargeIncrease	n/a
			ModIncrease	n/a
			NoChange	n/a
			ModDecrease	n/a
			LargeDecrease	n/a

River BBN output nodes	Node description	Input nodes	Node states	Node values
Total Bug Abundance1	Total abundance of macroinvertebrates	1. CFEV O/E1 2. CFEV Bug Condition1	VLow: Very low total density	n/a
			Low: Low total density	n/a
			Mod: Near-natural total density	n/a
			Reference: Natural total density	n/a
Total Bug Abundance2	Projected total abundance of macroinvertebrates	1. Total Bug abundance1 2. Key Bug Hydrology Change 3. Max Warm Temp	VLow: Very low total density	n/a
			Low: Low total density	n/a
			Mod: Near-natural total density	n/a
			Reference: Natural total density	n/a
Key Bug Hydrology Change	Direction and intensity of change in key hydrology change for invertebrates	1. Dry Season low flow change 2. Large flood intensity change	LargeImpact	10
			ModImpact	5
			NoChange	0
			ModBenefit	-5
			LargeBenefit	-10
Dry Season Low Flow Change (bugs)	Direction and intensity of change in dry season flows	1. % Cease to flow change 2. Seasonality change 3. Summer Max Q	MuchDryer	n/a
			ModDryer	n/a
			NoChange	n/a
			ModWetter	n/a
			MuchWetter	n/a
CFEV O/E2	Predicted macroinvertebrate Observed/Expected ranked abundance index	1. CFEV O/E1 2. Large flood intensity change 3. Max warm temperature	0.8 to 1.3	A impairment band: equivalent to natural

River BBN output nodes	Node description	Input nodes	Node states	Node values
	Based on AUSRIVAS O/E impairment bands		0.6 to 1.0	AB impairment band: moderately impaired
			0.4 to 0.8	B impairment band: significantly impaired
			0.3 to 0.7	BC impairment band: significantly to severely impaired
			0.2 to 0.5	C impairment band: severely impaired
			0.0 to 0.3	D impairment band: extremely impaired
CFEV Bug Condition2	Predicted macroinvertebrate condition score, based on composition and abundance	1. CFEV O/E2 2. Total bug abundance2	1.0	Reference: natural total density, natural assemblage
			0.9 to 1	Mod: near-natural total density, near-natural assemblage
			0.6 to 0.9	Poor: reduced total density, significantly altered assemblage
			0.3 to 0.6	VPoor: reduced total density, severely altered assemblage
			0 to 0.3	XPoor: low – very low density, severely altered assemblage
Del CFEV Bug	Change in	1. CFEV Bug	Increase	n/a

River BBN output nodes	Node description	Input nodes	Node states	Node values
Condition	macroinvertebrate condition from reference to test period	Condition1 2. CFEV Bug Condition2	NoChange	n/a
			SmallDecrease	n/a
			ModDecrease	n/a
			LargeDecrease	n/a
Bug Risk Unconditional	Level of hazard to macroinvertebrate community from hydrological impacts on habitat (low flows and floods) and temperature changes. Not conditional on original bug condition state	1. Del CFEV Bug Condition	None	0
			Small	2.5
			Moderate	5
			Large	7.5
			VLarge	10
			Benefit	-10
Bug Risk Conditional	Level of hazard to macroinvertebrate community from hydrological impacts on habitat (low flows and floods) and temperature changes. Conditional on original bug condition state	1. Del CFEV Bug Condition 2. CFEV Bug Condition1	None	0
			Small	2.5
			Moderate	5
			Large	7.5
			VLarge	10
			Benefit	-10
Native Fish Condition1	Overall condition of fish community; reflects change in richness and abundance of native and exotic fish species	1. CFEV FISHCON Impact Level 2. CFEV Fish Alien Biomass Proportion	VPoor	n/a
			Poor	n/a
			Moderate	n/a
			Reference	n/a
			NA	n/a
			Absent	n/a
Native Fish Condition2	Predicted overall condition of fish community; reflects change in richness and abundance of native and exotic fish species	1. Native Fish Condition1	VPoor	n/a
			Poor	n/a
			Moderate	n/a
			Reference	n/a
			NA	n/a
			Absent	n/a
Native Fish	Change in the	1. Native Fish	None	n/a

River BBN output nodes	Node description	Input nodes	Node states	Node values
Condition Change	condition of native fish from the reference state	Condition1 2. Native Fish Condition2	Small	n/a
			Moderate	n/a
			Large	n/a
			VLarge	n/a
			NA	n/a
			Benefit	n/a
Native Fish Community Risk Conditional	Level of hazard to the fish community from hydrological impacts on habitat (low flows and floods) and temperature change. Conditional on original native fish condition	1. Native Fish Condition Change 2. Key Native Fish Hydrology Change	None	0
			Small	2.5
			Moderate	5
			Large	7.5
			VLarge	10
			NA	0
			Benefit	- 10
Native Fish Community Risk Unconditional	Level of hazard to the fish community from hydrological impacts on habitat (low flows and floods) and temperature change. Not conditional on original native fish condition	1. Native Fish Condition Change	None	0
			Small	2.5
			Moderate	5
			Large	7.5
			VLarge	10
			NA	0
			Benefit	- 10
Dry Season Low Flows Change (platypus, Astacopsis and native fish)	Direction and intensity of change in dry season flows between reference and test periods	1. % Cease to Flow 2. Seasonality Change	Much dryer	n/a
			Moderately dryer	n/a
			No change	n/a
			Moderately wetter	n/a
			Much wetter	n/a
Risk to Bank and Browsing Habitat (platypus)	Level of hazard to burrow and/or feeding habitat quality, due to low flows drying out shallow productive feeding areas or	1. Dry season low flows change 2. Large flood intensity change	VHigh	n/a
			High	n/a
			Mod	n/a
			Low	n/a

River BBN output nodes	Node description	Input nodes	Node states	Node values
	high flows drowning out/eroding bank burrow habitats.		None	n/a
			Benefit	n/a
CFEV Platypus Condition 2	Projected CFEV Platypus Condition Score. Not conditional on the effect of Bug Abundance	1. Platypus Condition 2	VPoor	0.4
			Poor	0.5
			Mod	0.6
			Good	0.8
			Ref	1
Platypus Condition 1	Platypus condition score based on CFEV platypus condition score and abundance of macroinvertebrates, which are the main prey source for platypus.	1. Total Bug Abundance1 2. CFEV Platypus Condition	VPoor	Platypus population in poor condition
			Poor	Platypus population in moderate to poor condition
			Mod	Platypus population in moderate to poor condition
			Good	Platypus population in close to natural condition
			Ref	Platypus population in essentially natural condition
Platypus Condition 2	Projected platypus condition score based on the influence climate change on the hydrology, habitat quality and food availability	1. Platypus Condition 1 2. Risk to Bank and Browsing Habitat 3. Total Bug Abundance2	VPoor	Platypus population in poor condition
			Poor	Platypus population in moderate to poor condition
			Mod	Platypus population in moderate to poor condition
			Good	Platypus population in close to natural

River BBN output nodes	Node description	Input nodes	Node states	Node values
				condition
			Ref	Platypus population in essentially natural condition
Del CFEV PLATYP Condition	Change in Platypus Condition	1. Platypus Condition 1 2. Platypus Condition 2	Increase	n/a
			NoChange	n/a
			SmallDecrease	n/a
			ModDecrease	n/a
			LargeDecrease	n/a
Platypus Risk Unconditional	Hazard to platypus population from hydrological impacts on habitat suitability and food availability, not conditional on original Platypus Condition state	1. Platypus Condition 2	None	0
			Small	2.5
			Moderate	5
			Large	7.5
			VLarge	10
			Benefit	-10
Platypus Risk Conditional	Hazard to platypus population from hydrological impacts on habitat suitability and food availability, conditional on original Platypus Condition state		None	0
			Small	2.5
			Moderate	5
			Large	7.5
			VLarge	10
			Benefit	-10
Key Fish Hydrology Change	Direction and intensity of change in key hydrology drivers for fish	1. Dry Season Low Flows Change 2. Large Flood Intensity Change	LargeImpact	n/a
			ModImpact	n/a
			NoChange	n/a
			ModBenefit	n/a
			LargeBenefit	n/a
Key Trout Hydrology Change	Direction and intensity of change in key hydrology drivers for riverine brown trout	1. Key Fish Hydrology Change 2. Mean Min Spring Q Change	LargeImpact	n/a
			ModImpact	n/a
			NoChange	n/a

River BBN output nodes	Node description	Input nodes	Node states	Node values
			ModBenefit	n/a
			LargeBenefit	n/a
Brown Trout Biomass2	Projected biomass of brown trout due to influence of hydrology on adult and juvenile habitat quality and nest dewatering; maximum temperature in warm months on juvenile and adult survival and maximum temperature in cool months for egg survival	1. Key Trout Hydrology Change 2. CFEV Fish Alien Biomass Propn 3. Max Warm Temp 4. Max Cool Temp	High	n/a
			Mod	n/a
			Low	n/a
			NA	n/a
Trout Fishery Risk Incremental	Level of hazard to status of brown trout fishery, based on impact on standing stock from temperature and hydrology changes to habitat. Conditional risk to recruitment and survival relative to original biomass	1. Brown Trout Biomass2 2. CFEV Fish Alien Biomass Propn	None	n/a
			Small	n/a
			Moderate	n/a
			Large	n/a
			VLarge	n/a
			NA	n/a
			Benefit	n/a
Trout Fishery Risk Unconditional	Level of hazard to status of brown trout fishery, based on impact on standing stock from temperature and hydrology changes to habitat. Not conditional on original biomass	1. Brown Trout Biomass 2	None	n/a
			Small	n/a
			Moderate	n/a
			Large	n/a
			VLarge	n/a
			NA	n/a
			Benefit	n/a
Light availability: Local	Light availability to stream surface, as controlled by riparian shading and stream size (stream order as surrogate for width). State definitions based on the Tasmanian	1. Ripveg condition: RS 2. Stream Order	High	n/a
			Moderate	n/a
			Low	n/a

River BBN output nodes	Node description	Input nodes	Node states	Node values
	River Condition Index (TRCI) shading thresholds			
Summer/Autumn Water Qual	Water quality, based on night-time minimum dissolved oxygen concentration, daytime water temperatures	1. Current Abstraction 2. River Section Slope 3. Current Abstraction 4. Light availability: Local	Low	< 4 ppm night time dissolved oxygen, warm daytime temperatures
			High	> 4 ppm night time dissolved oxygen, cool to warm daytime temperatures
Instream Fine substrate1	Proportion of fines (sand and silt) in substrata.	1. Fine Sediment Input 2. Geomorph sensitivity 3. River-section slope	VLow	0 to 5%
			Low	5 to 10%
			Moderate	10 to 40%
			High	40 to 60%
			VHigh	> 60%
Instream Fine substrate2	Projected proportion of fines (sand and silt) in substrata.	1. Instream Fine substrate1 2.Dry Season Low Flows Change	VLow	0 to 5%
			Low	5 to 10%
			Moderate	10 to 40%
			High	40 to 60%
			VHigh	> 60%
Dry Season Low Flows Change (Astacopsis)	Direction and intensity of change in dry season flows	1. Seasonality Change 2. Summer max Q 3.% Cease to Flow Change	MuchDryer	n/a
			ModDryer	n/a
			NoChange	n/a
			ModWetter	n/a
			MuchWetter	n/a
Max Warm Temp Hazard	Temperature hazard, as mediated by local shade conditions,	1. Max Warm temp Test Period 2. Light availability: Local	NoHazard	n/a
			ModHazard	n/a

River BBN output nodes	**Node description**	**Input nodes**	**Node states**	**Node values**
	especially for narrow streams. Maximum temperature above *Astacopsis gouldi* thermal threshold	3. Dry Season Low Flow Change	LargeHazard	n/a
AGouldi Condition1	*Astacopsis gouldi* population density score	1.Summer/Autumn Water Qual 2. Instream Fine substrata1	VLow	n/a
			Low	n/a
			Mod	n/a
			high	n/a
AGouldi Condition2	Projected *Astacopsis gouldi* density condition score	1. AGouldi Condition1 2. Max Warm Temp Hazard 3. Instream Fine substrata2	VLow	n/a
			Low	n/a
			Mod	n/a
			high	n/a
Del AGouldi Condition	Change in *Astacopsis gouldi* density between reference and test period	1. AGouldi Condition1 2. AGouldi Condition2	Increase	n/a
			NoChange	n/a
			SmallDecrease	n/a
			ModDecrease	n/a
			LargeDecrease	n/a
AGouldi Risk Conditional	Level of hazard to *Astacopsis gouldi* from temperature and hydrological change impacts on habitat. Conditional on original population state	1. AGouldi Condition1 2. Del AGouldi Condition	None	- 2 to +1
			Small	1 to 3
			Moderate	3 to 6
			Large	6 to 8
			VLarge	8 to 10
			Benefit	-2 to -10
AGouldi Risk Unconditional	Level of hazard to *Astacopsis gouldi* from temperature and hydrological change impacts on habitat. Not conditional on original population state	1. Del AGouldi Condition	None	- 2 to +1
			Small	1 to 3
			Moderate	3 to 6
			Large	6 to 8
			VLarge	8 to 10
			Benefit	-2 to -10

APPENDIX 5: INPUT NODE DETAILS FOR WETLANDS

Wetland BBN discrete input variables, node descriptions, node score values and descriptions

Wetland BBN input nodes	Node description	Score value	Node condition score and state description
CFEV Wetlands Condition 1	Condition rating for wetlands. Generated from a combination of inputs weighted in order of influence: Native vegetation, Hydrology, Catchment disturbance, Water quality, Sediment input	0 to 0.6	Low: severely altered from natural condition
		0.601 to 0.85	Moderate: significantly altered from natural condition
		0.8501 to 1	High: natural or near-natural condition
CFEV Wetland Frog Assemblage	Frog assemblage type (CFEV species groups)	FR2group Western Tasmania	*Limnodynastes peroni, Limnodynastes dumerili insularis, L. dumerili variegatus, Litoria ewingi, L. raniformis, L. burrowsae, Crinia signifera, C. tasmaniensis, Geocrinia laevis, Bryobatrachus nimbus, Pseudophryne semimarmorata*
		FR7group Furneaux Islands, and south east Tasmania	*Limnodynastes tasmaniensis, L. dumerili insularis, Litoria ewingi, L. raniformis, Crinia signifera, C. tasmaniensis, Pseudophryne semimarmorata*
		All other groups (n = 6), with subsets of species list	*Limnodynastes tasmaniensis, L. dumerili insularis, L. peroni, Litoria ewingi, L. raniformis, Crinia signifera, Pseudophryne semimarmorata, C. tasmaniensis, Geocrinia laevis*
CFEV Wetland	Area class of wetland	0 to 1 ha area	Small

Area	CFEV value divided by 10 000 to convert m^2 to hectares for Netica input	10 to 100 ha area	Mod
		100 to 1000 ha area	Large
		>1000 ha area	VLarge
CFEV Wetland Condition 2	Predicted naturalness score for the wetland	0 to 0.6	Low: severely altered from natural condition
		0.601 to 0.85	Moderate: significantly altered from natural condition
		0.8501 to 1	High: natural or near-natural condition

BBN wetland model output node descriptions, input variables for each node, node states and values

Wetland BBN output nodes	Node description	Input nodes	Node states	Node values
Dryer or Wetter Conditions	Direction and intensity of change in watering regime from 'wet' to 'dry' with inputs that are particularly important to wetlands	1. Seasonality Change 2. Summer Median Flow	MuchDryer	n/a
			ModDryer	n/a
			NoChange	n/a
			ModWetter	n/a
			MuchWetter	n/a
Overbank Flood Spells	Average interval between overbank flow spells where larger is high risk to wetland condition	1. OFS Max Interval 2. OFS Min Interval	Larger	n/a
			Mix	n/a

Wetland BBN output nodes	Node description	Input nodes	Node states	Node values
			Smaller	n/a
			NoChange	n/a
Large Flood Intensity Change	Change in intensity (magnitude, duration) of large floods capable of destroying or modifying in-stream habitat	1. Length Q spells > 95%ile Change 2. Mean Annual Max Q Change	VLargeIncrease	n/a
			LargeIncrease	n/a
			ModIncrease	n/a
			NoChange	n/a
			ModDecrease	n/a
			LargeDecrease	n/a
Flooding Regime Suitability	Rating for suitability of flooding regime to maintain reference condition wetland vegetation	1. Overbank Flood Spells 2. Large Flood Intensity Change	HighSuitability	n/a
			ModSuitability	n/a
			LowSuitability	n/a
			VLowSuitability	n/a
Key Rip Veg Hydrology Change	Direction and intensity of change in key hydrology drivers for wetland vegetation	1. CV of Mean Annual Flow 2. Dryer or wetter Conditions	LargeImpact	n/a
			ModImpact	n/a
			NoChange	n/a
			ModBenefit	n/a

Wetland BBN output nodes	Node description	Input nodes	Node states	Node values
			LargeBenefit	n/a
Wetting Regime Suitability	Rating for suitability of wetting regime to maintain reference condition wetlands	1. Large Flood Intensity Change 2. Median Flow spells	HighSuitability	n/a
			ModSuitability	n/a
			LowSuitability	n/a
			VLowSuitability	n/a
Median Flow Spells	Maximum interval between median spells of flow, where larger is high risk to wetlands	1. Median Q Max Spell Interval	Larger	n/a
			Mix	n/a
			Smaller	n/a
			NoChange	n/a
Dry Season Low Flows Change	Direction and intensity of change in dry season flows	1. % Cease to Flow Change 2. Seasonality Change	MuchDryer	n/a
			ModDryer	n/a
			NoChange	n/a
			ModWetter	n/a
			MuchWetter	n/a
CFEV Wetland Condition 2	Projected condition score for wetlands	1. CFEV Wetland Condition 1 2. CFEV Wetland Area 3. Key Rip Veg Hydrology Change	Low	0 to 0.6
			Mod	0.6 to 0.85

Wetland BBN output nodes	Node description	Input nodes	Node states	Node values
			High	0.85 to 1
Del CFEV Wetland Condition	Change in wetland condition between reference and test periods	1. CFEV Wetland Condition 1 2. CFEV Wetland Condition 2	Increase	n/a
			NoChange	n/a
			SmallDecrease	n/a
			ModDecrease	n/a
			LargeDecrease	n/a
Wetland Risk Unconditional	Level of hazard to wetland condition from hydrological regime changes. Not conditional on original wetland condition state	1. Del CFEV Wetland Condition	None	-2 to +1
			Small	1 to 3
			Moderate	3 to 6
			Large	6 to 8
			VLarge	8 to 10
			Benefit	-2 to -10
Wetland Risk Conditional	Level of hazard to wetland condition from hydrological regime changes. Conditional on original wetland condition state	1. Del CFEV Wetland Condition 2. CFEV Wetland Condition 1	None	-2 to +1
			Small	1 to 3
			Moderate	3 to 6
			Large	6 to 8

Wetland BBN output nodes	Node description	Input nodes	Node states	Node values
			VLarge	8 to 10
			Benefit	-2 to -10
Ref Period Max Warm Temp Hazard	Hazard level posed to frog assemblage by mean maximum temperature for warmest months in degrees Celsius for reference period	1. CFEV Wetland Frog Assemblage 2. Ref Period Max Warm Temp	NoHazard	100 % species unstressed
			Small Hazard	10 to 30 % species close to tolerance level
			ModHazard	20 to 30 % spp lost
			LargeHazard	30 to 70 % spp lost
			VLargeHazard	< 30 % spp remaining
			XLarge Hazard	No species remaining
Test Period Max Warm Temp Hazard	Hazard level posed to frog assemblage by mean maximum temperature for warmest months in degrees Celsius for test period	1. CFEV Wetland Frog Assemblage 2. Test Period Max Warm Temp	NoHazard	100 % species unstressed
			Small Hazard	10 to 30 % species close to tolerance level
			ModHazard	20 to 30 % spp lost
			LargeHazard	30 to 70 % spp lost
			VLargeHazard	< 30 % spp

Wetland BBN output nodes	Node description	Input nodes	Node states	Node values
				remaining
			XLarge Hazard	No species remaining
Frog Condition 1	Frog assemblage condition score	1. CFEV Wetland Condition 2. Ref Period Max Warm Temp Hazard	VLow	n/a
			Low	n/a
			Mod	n/a
			High	n/a
Frog Condition 2	Projected frog assemblage condition score	1. Frog Condition 1 2. CFEV Wetland Condition 2 3. Test Period Max Warm Temp Hazard	VLow	n/a
			Low	n/a
			Mod	n/a
			High	n/a
Del Frog Condition	Change in frog condition between reference and test periods	1. Frog Condition 1 2. Frog Condition 2	Increase	n/a
			NoChange	n/a
			SmallDecrease	n/a
			ModDecrease	n/a
			LargeDecrease	n/a

Wetland BBN output nodes	Node description	Input nodes	Node states	Node values
Frog Risk Conditional	Level of hazard to frog assemblage from temperature changes and hydrological change impacts on habitat. Conditional on original frog assemblage condition state	1. Frog Condition1 2. Del Frog Condition 3. CFEV Wetland Area	None	-2 to +1
			Small	1 to 3
			Moderate	3 to 6
			Large	6 to 8
			VLarge	8 to 10
			Benefit	-2 to -10
Frog Risk Unconditional	Level of hazard to frog assemblage from temperature changes and hydrological change impacts on habitat. Not conditional on original frog assemblage condition state	1. Del Frog Condition 2. CFEV Wetland Area	None	-2 to +1
			Small	1 to 3
			Moderate	3 to 6
			Large	6 to 8
			VLarge	8 to 10

Wetland BBN output nodes	Node description	Input nodes	Node states	Node values
			Benefit	-2 to -10
GPusilla Condition1	*Galaxiella pusilla* population condition rating	1. CFEV Wetland Condition1 2. Max Warm Temp Ref	VLow	n/a
			Low	n/a
			Mod	n/a
			High	n/a
GPusilla Condition2	Projected *Galaxiella pusilla* population condition rating	1. GPusilla Condition1 2.CFEV Wetland Condition 2 3. Max Warm Temp Test	VLow	n/a
			Low	n/a
			Mod	n/a
			High	n/a
Del GPusilla Condition	Change in *Galaxiella pusilla* population condition rating between reference and test periods	1. GPusilla Condition1 2. GPusilla Condition2	Increase	n/a
			NoChange	n/a
			SmallDecrease	n/a
			ModerateDecrease	n/a

Wetland BBN output nodes	Node description	Input nodes	Node states	Node values
			LargeDecrease	n/a
GPusilla Risk Conditional	Level of hazard to *Galaxiella pusilla* population from temperature and hydrological changes to habitat. Conditional on original population condition state	1. GPusilla Condition1 2. Del GPusilla Condition 3. CFEV Wetland Area	None	-2 to +1
			Small	1 to 3
			Moderate	3 to 6
			Large	6 to 8
			VLarge	8 to 10
			Benefit	-2 to -10
GPusilla Risk Unconditional	Level of hazard to *Galaxiella pusilla* population from temperature and hydrological changes to habitat. Not conditional on original population condition state	1. Del GPusilla Condition 2. CFEV Wetland Area	None	-2 to +1
			Small	1 to 3
			Moderate	3 to 6
			Large	6 to 8
			VLarge	8 to 10
			Benefit	-2 to -10

APPENDIX 6: HYDROLOGY MAPS

The following maps are the full set of maps of predicted changes to river hydrology variables. Each panel gives the proportional change to that hydrology variable between the Reference Period (1961–1990) and each of the Recent Period (1991–2009), Period 1 (2010–2039), Period 2 (2040–2069) and Period 3 (2070–2099). A *decrease* in a variable is shown in red, and an *increase* in blue.

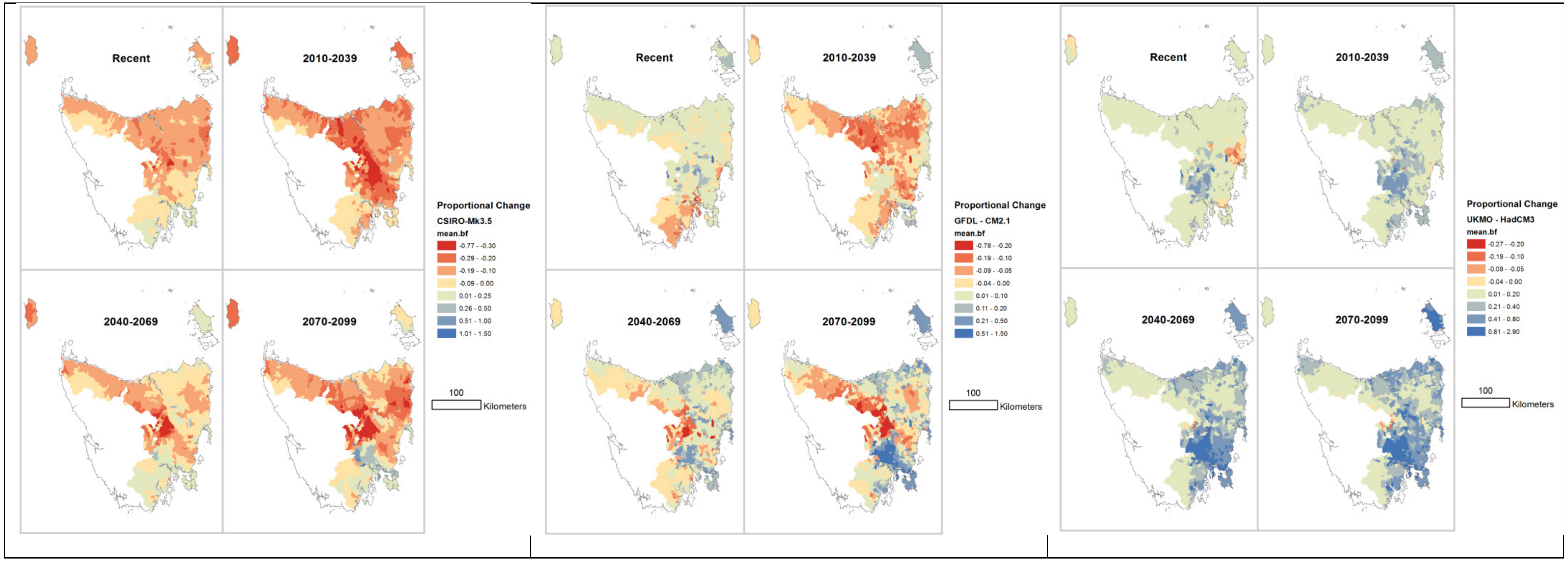


Figure 37 The proportional change in mean base flow from the Reference Period

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

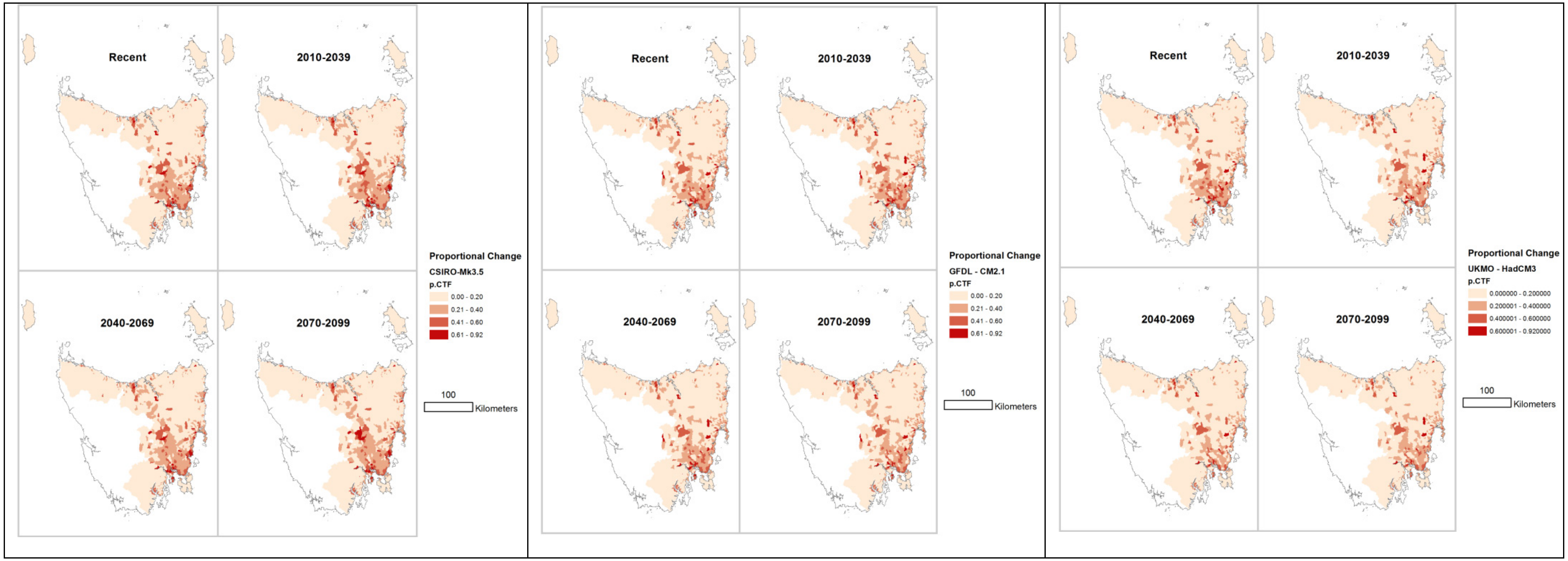


Figure 38 The proportional change from the Reference Period in the number of cease to flow days

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

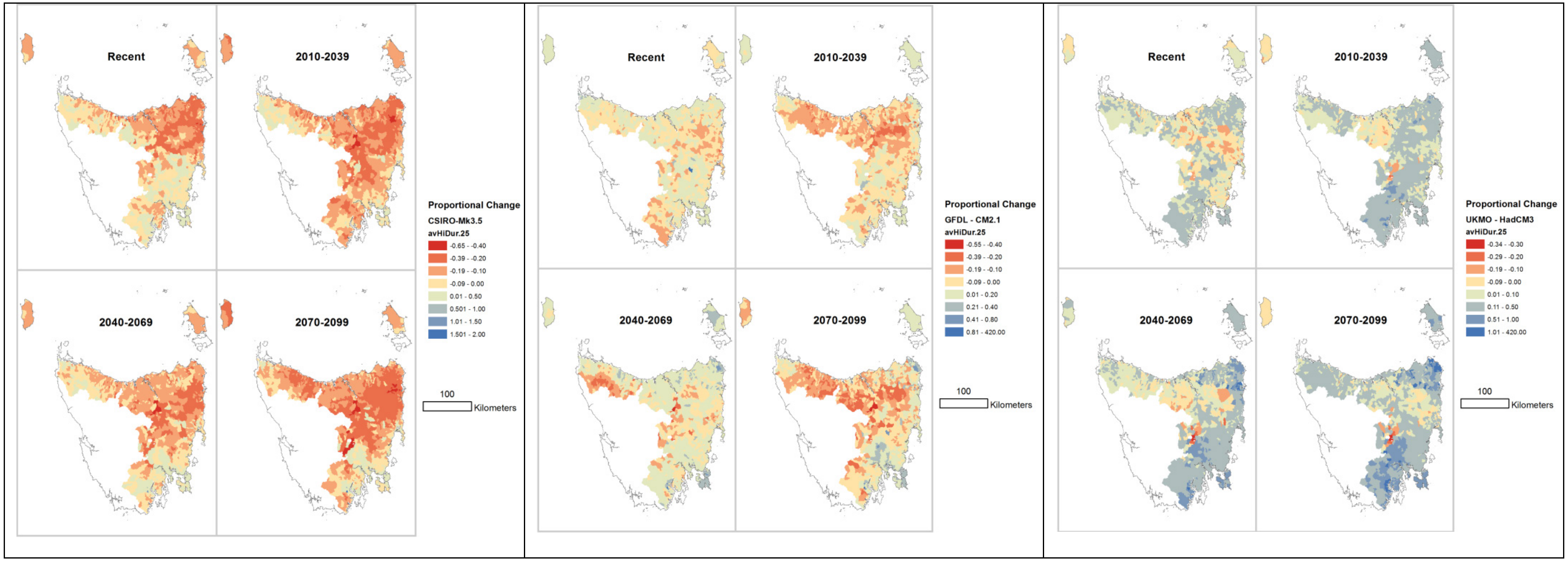


Figure 39 The proportional change from the Reference Period in the average duration of spells above the 25th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

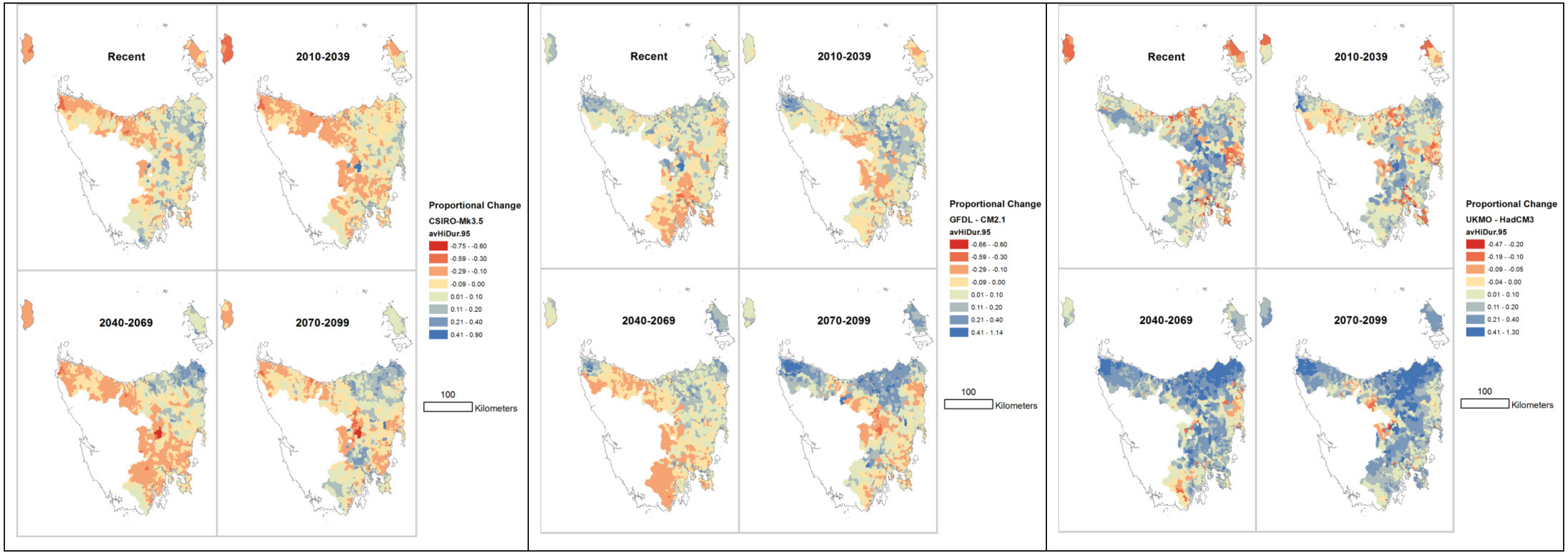


Figure 40 The proportional change from the Reference Period in the average duration of spells above the 95th percentile of flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

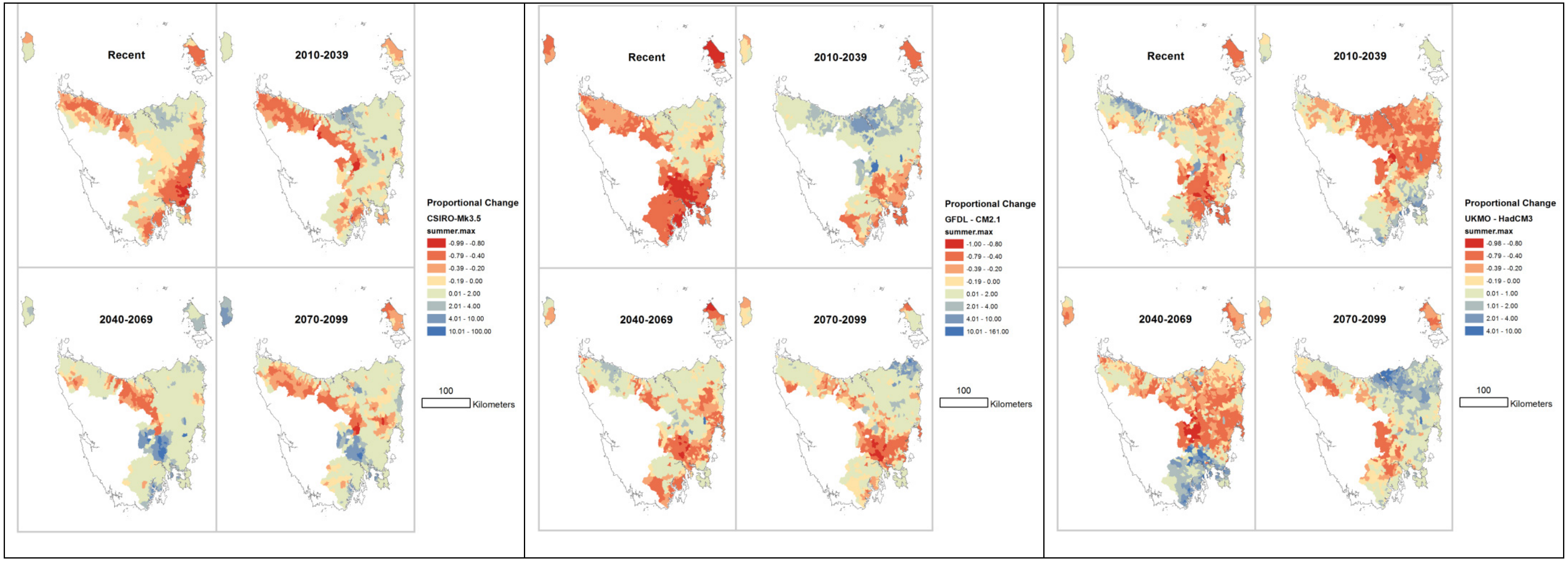


Figure 41 The proportional change from the Reference Period in the summer maximum daily flow

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

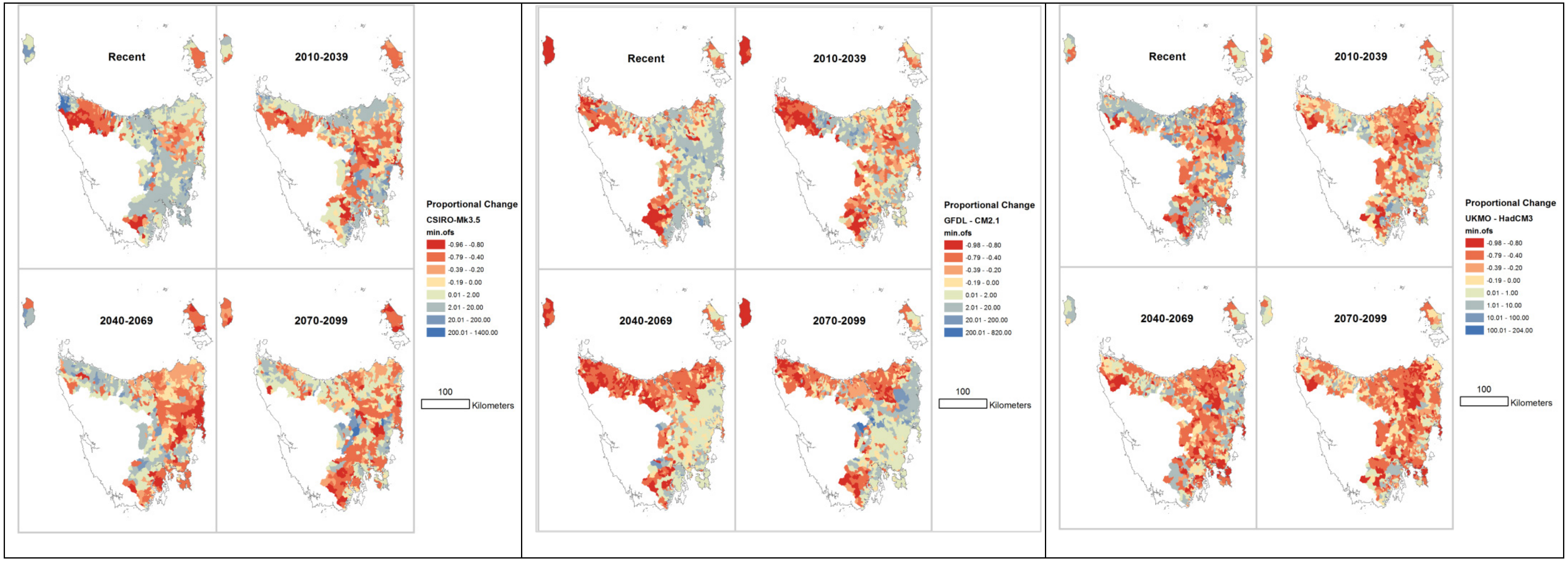


Figure 42 The proportional change from the Reference Period in the minimum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

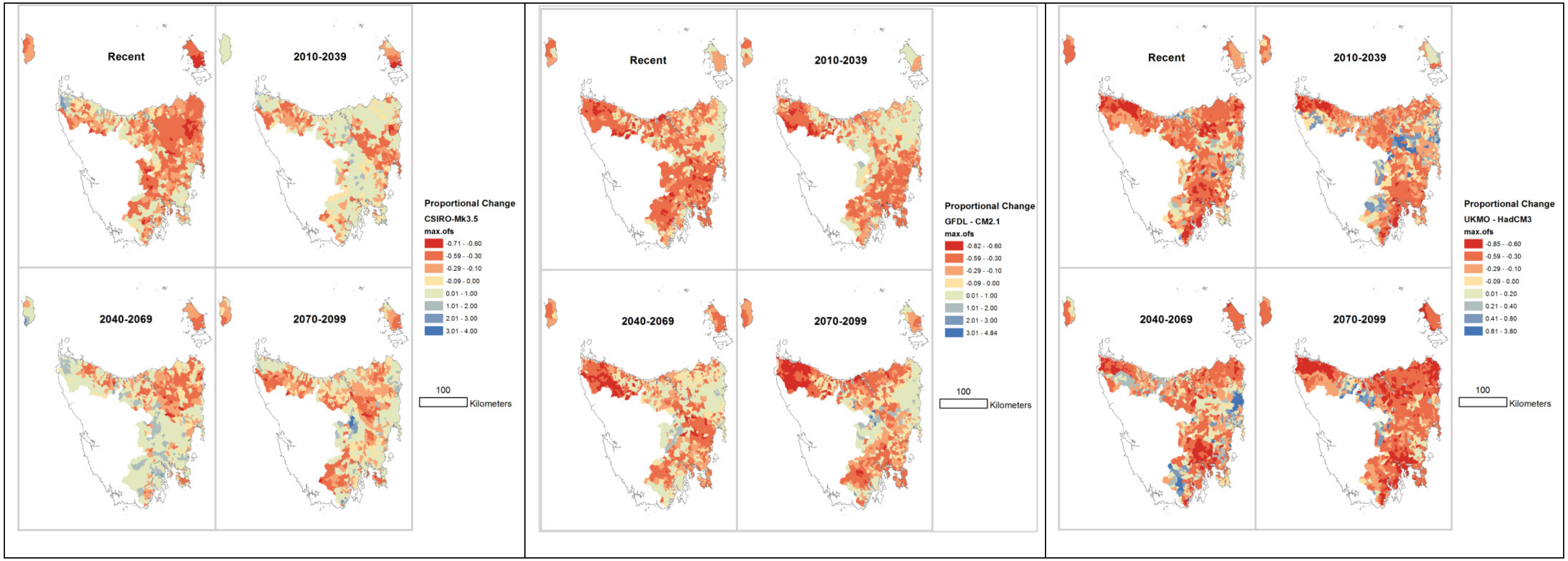


Figure 43 The proportional change from the Reference Period in the maximum period between overbank flows

The maps show the proportional change for the CSIRO (left panel) GFDL (centre) and UKMO (right panel) model predictions

APPENDIX 7: BBN MAPS

The following maps are conditional risk results from the BBN models that were not presented in the main report, including maps for Period 2. In each panel, risk scores vary between blue for a benefit to the condition of that ecosystem component, green indicates no change in condition, and yellow, orange and red denote increasing risk to the condition.

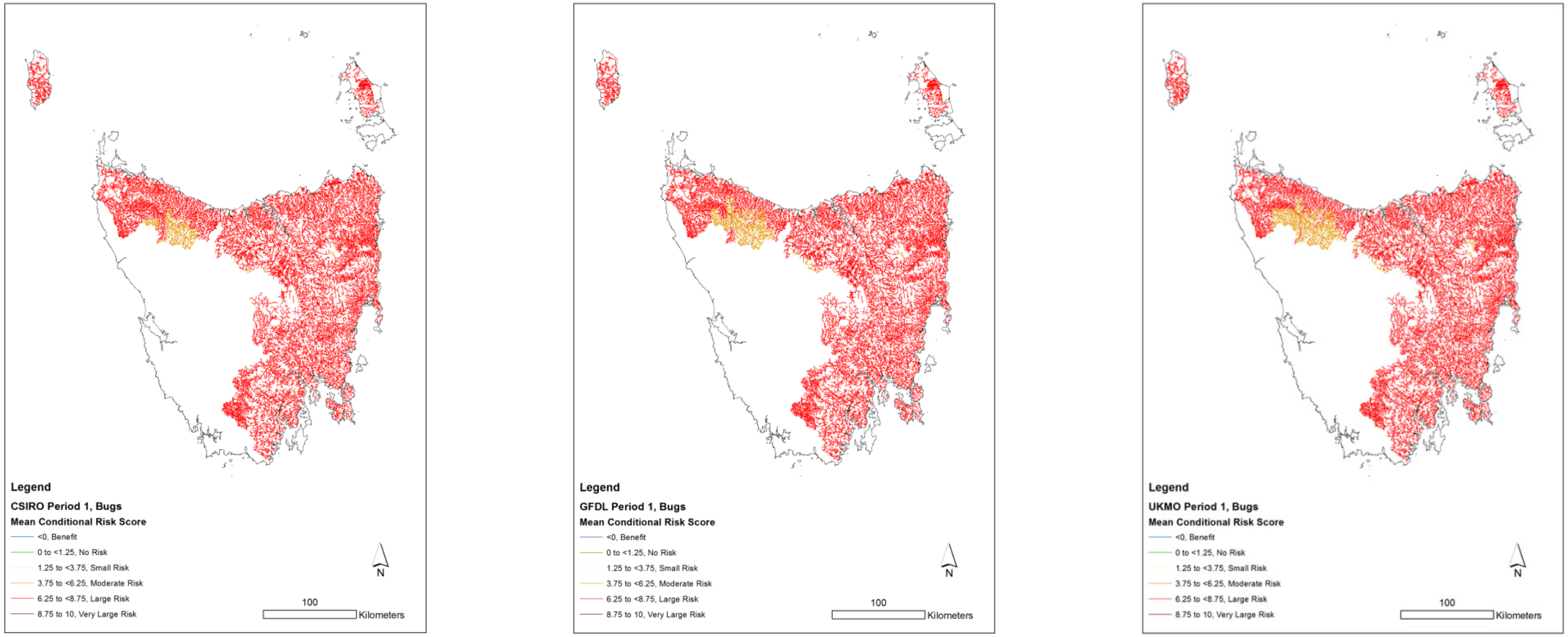


Figure 44 Macroinvertebrate community conditional risk scores for Period 1

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 1

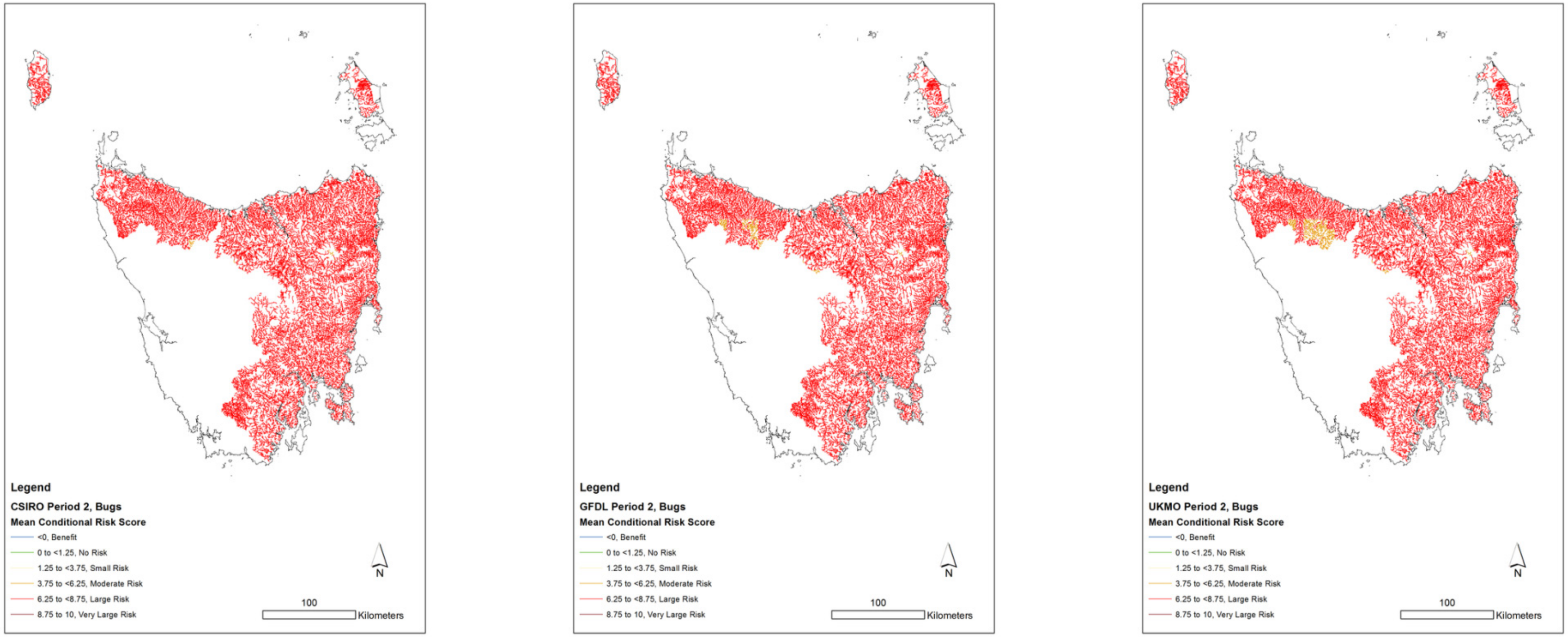


Figure 45 Macroinvertebrate community conditional risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

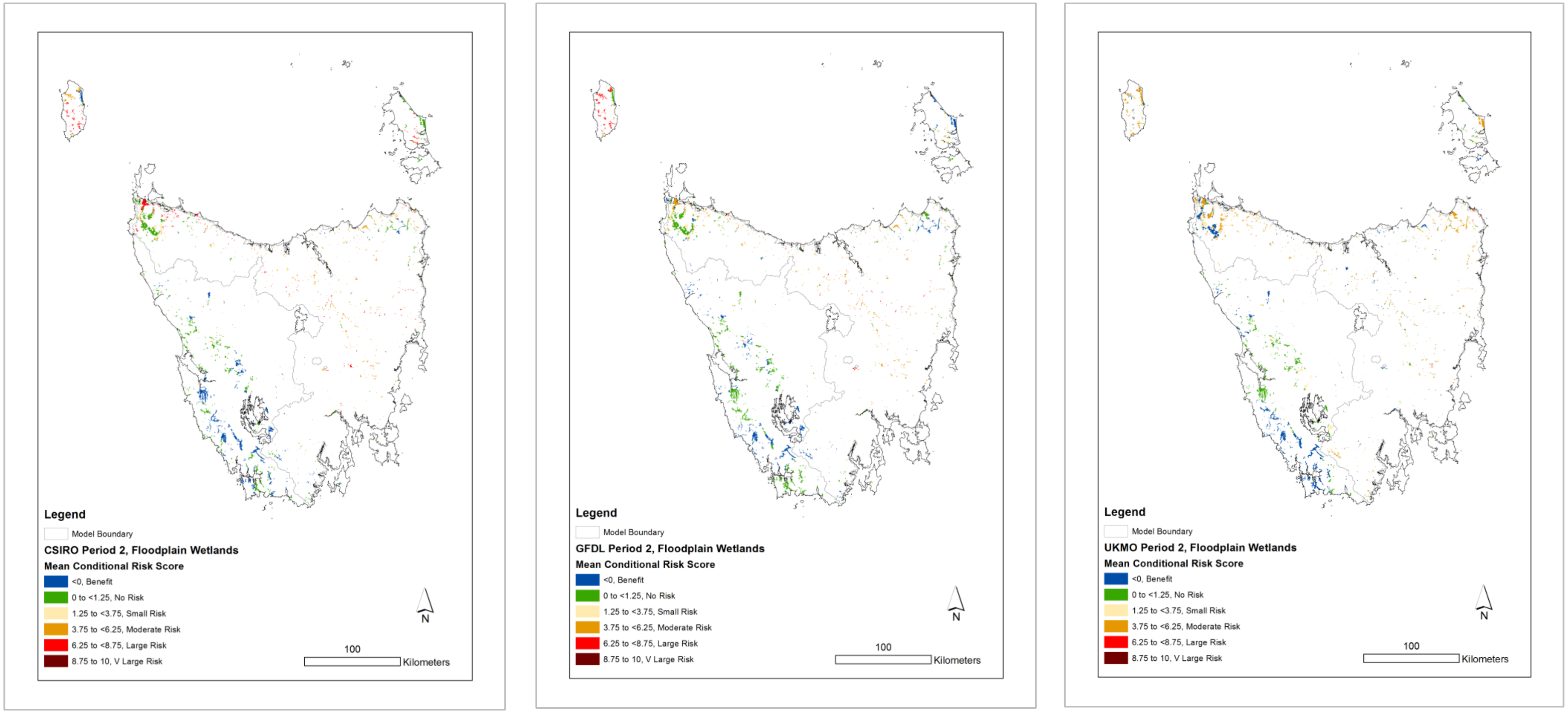


Figure 46 Floodplain wetland risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

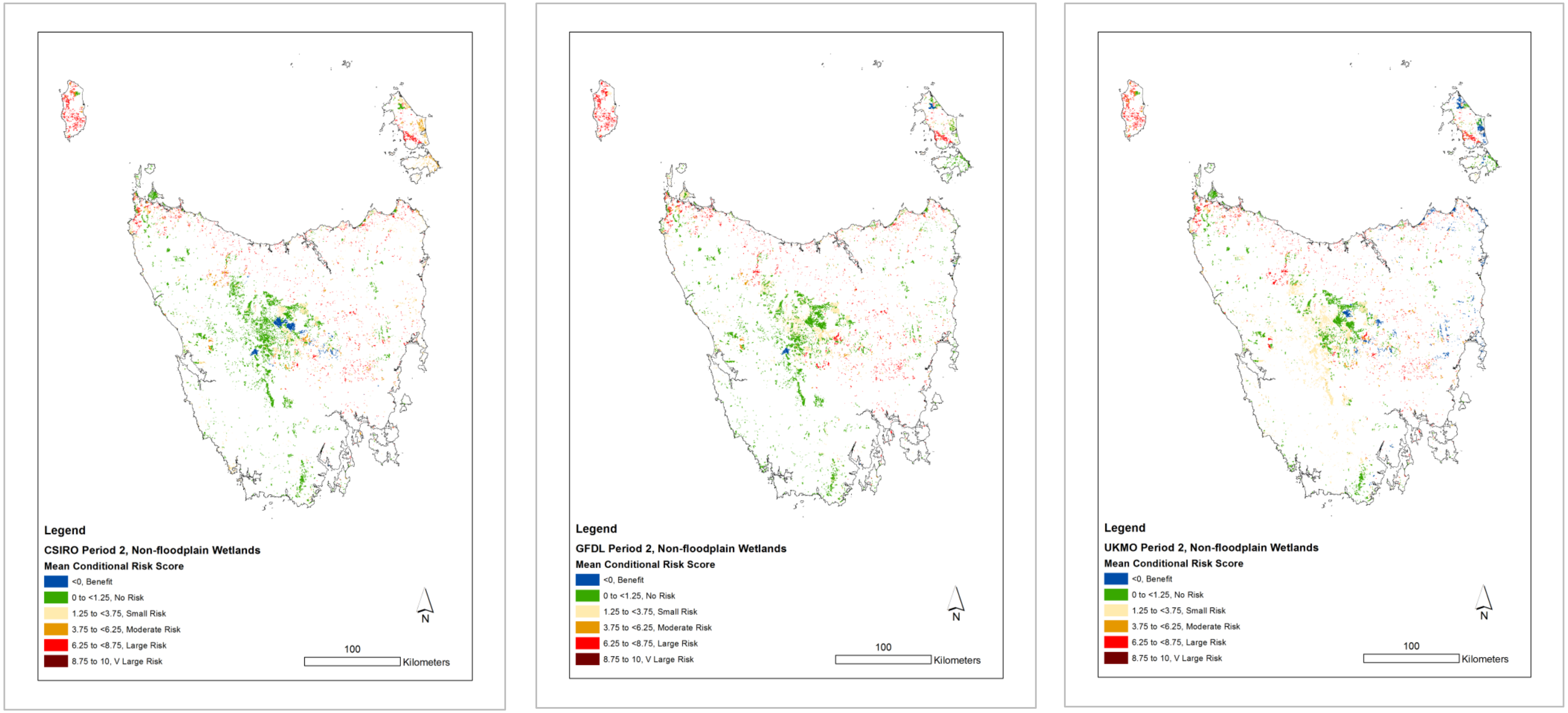


Figure 47 Non-floodplain wetland conditional risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

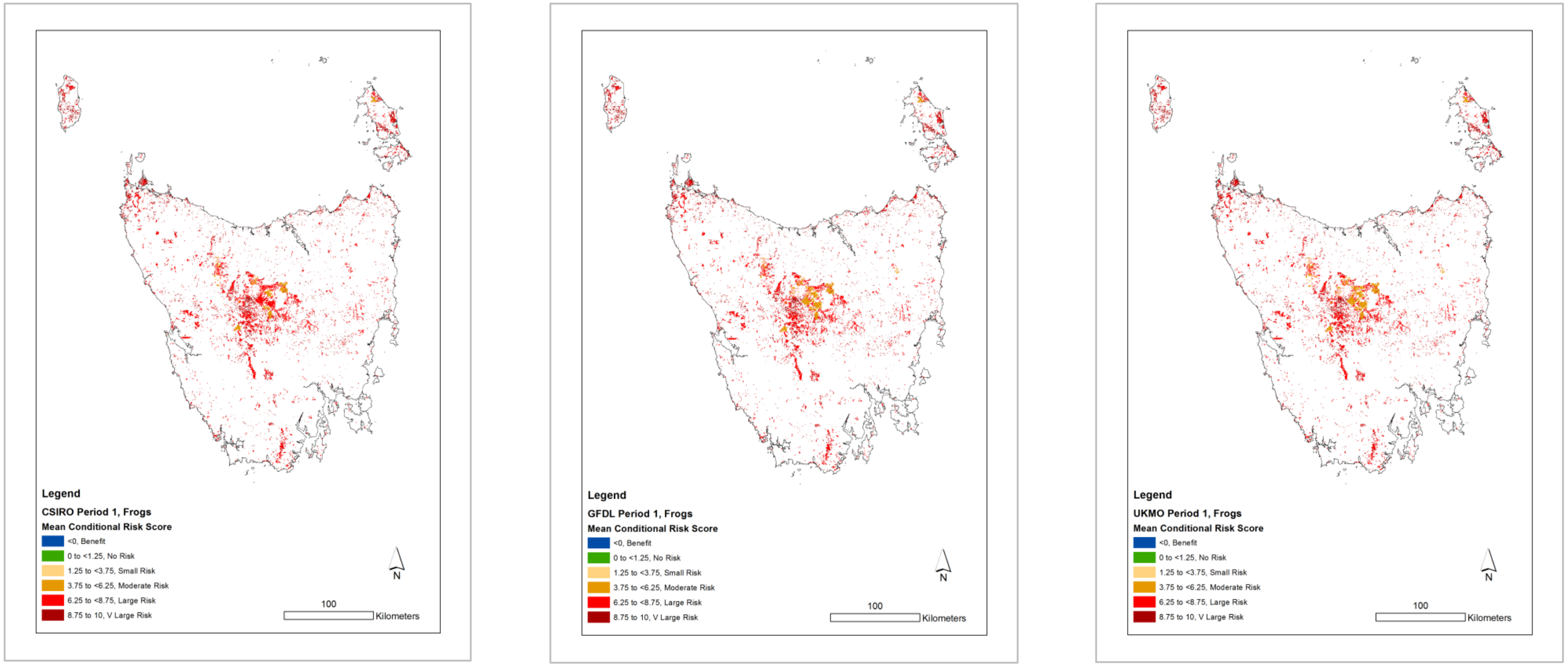


Figure 48 Frog community conditional risk scores for Period 1

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 1

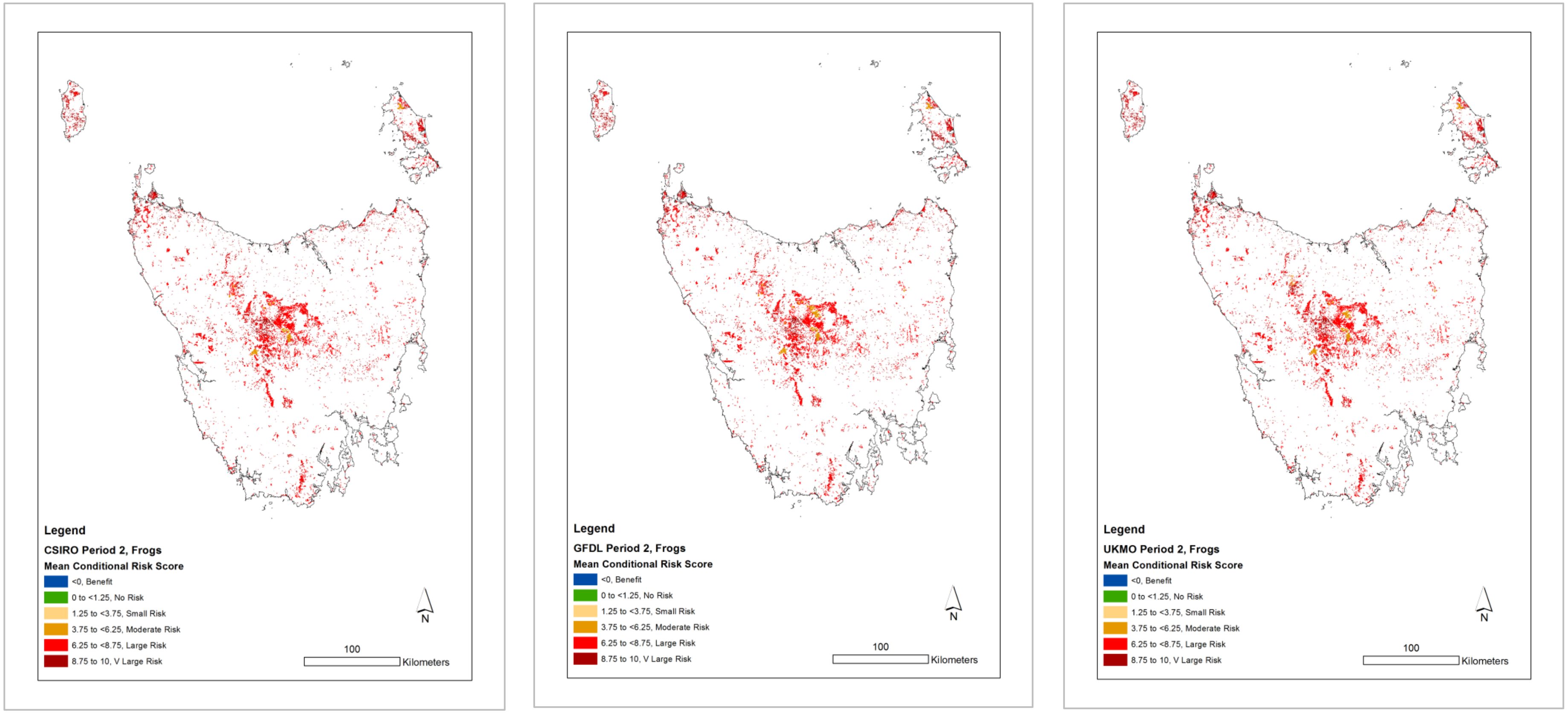


Figure 49 Frog community conditional risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

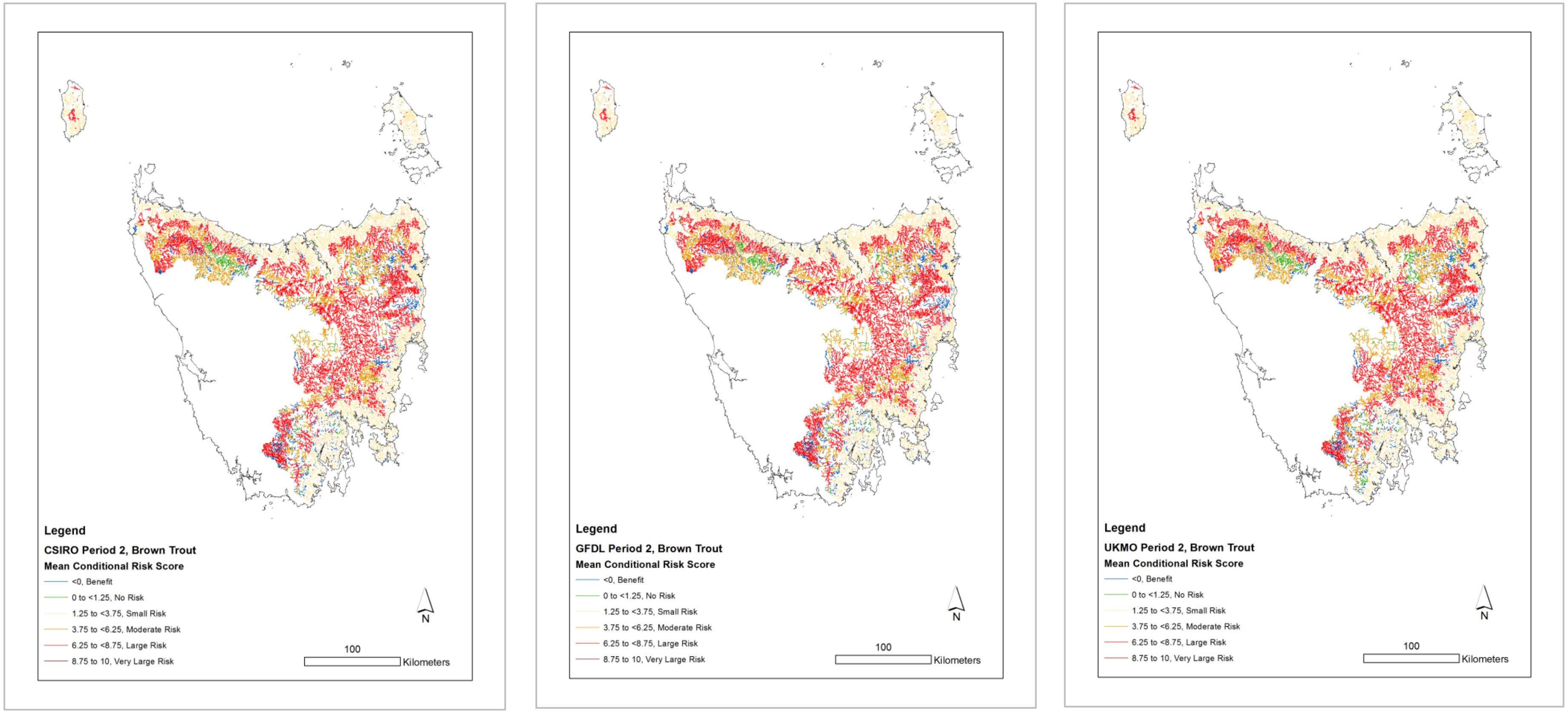


Figure 50 Brown trout conditional risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

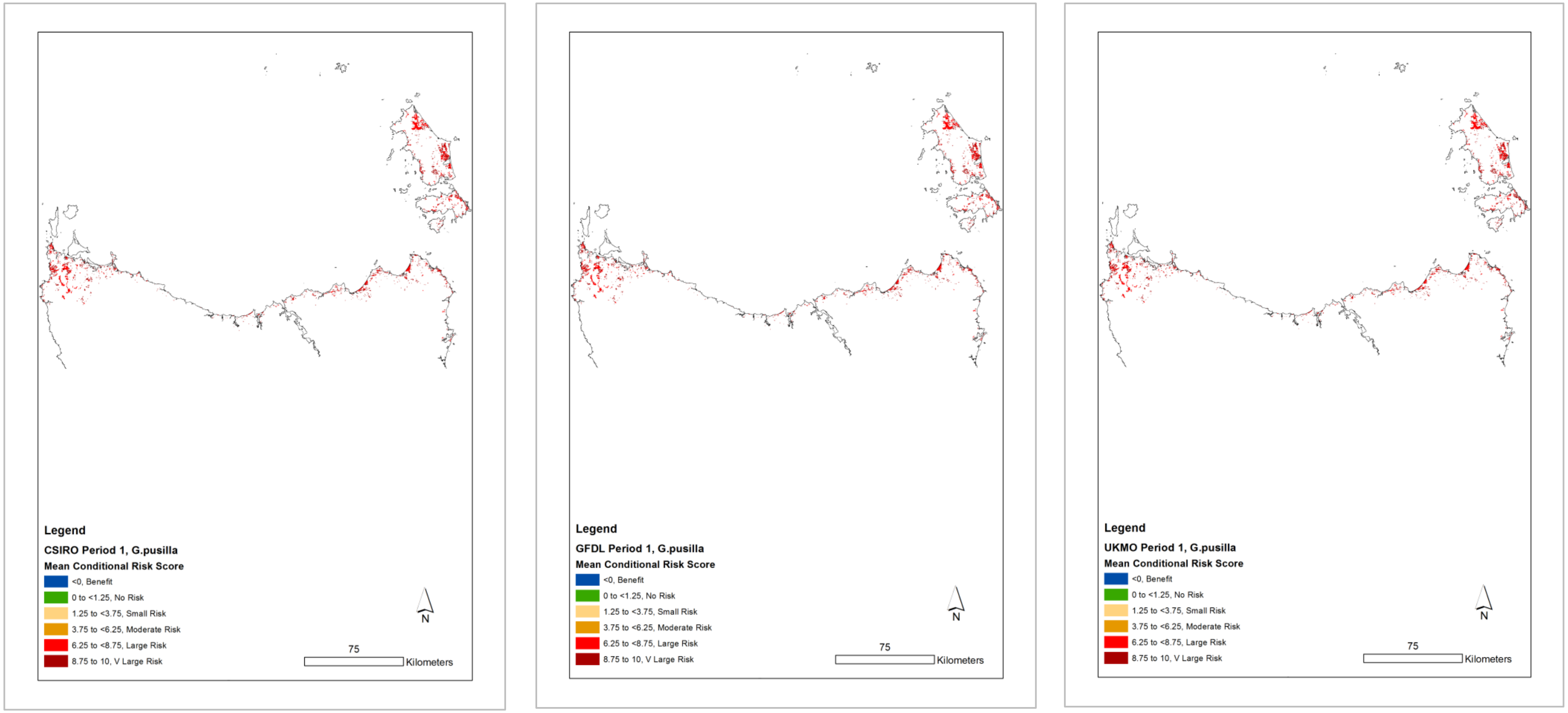


Figure 51 *Galaxiella pusilla* conditional risk scores for Period 1

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 1

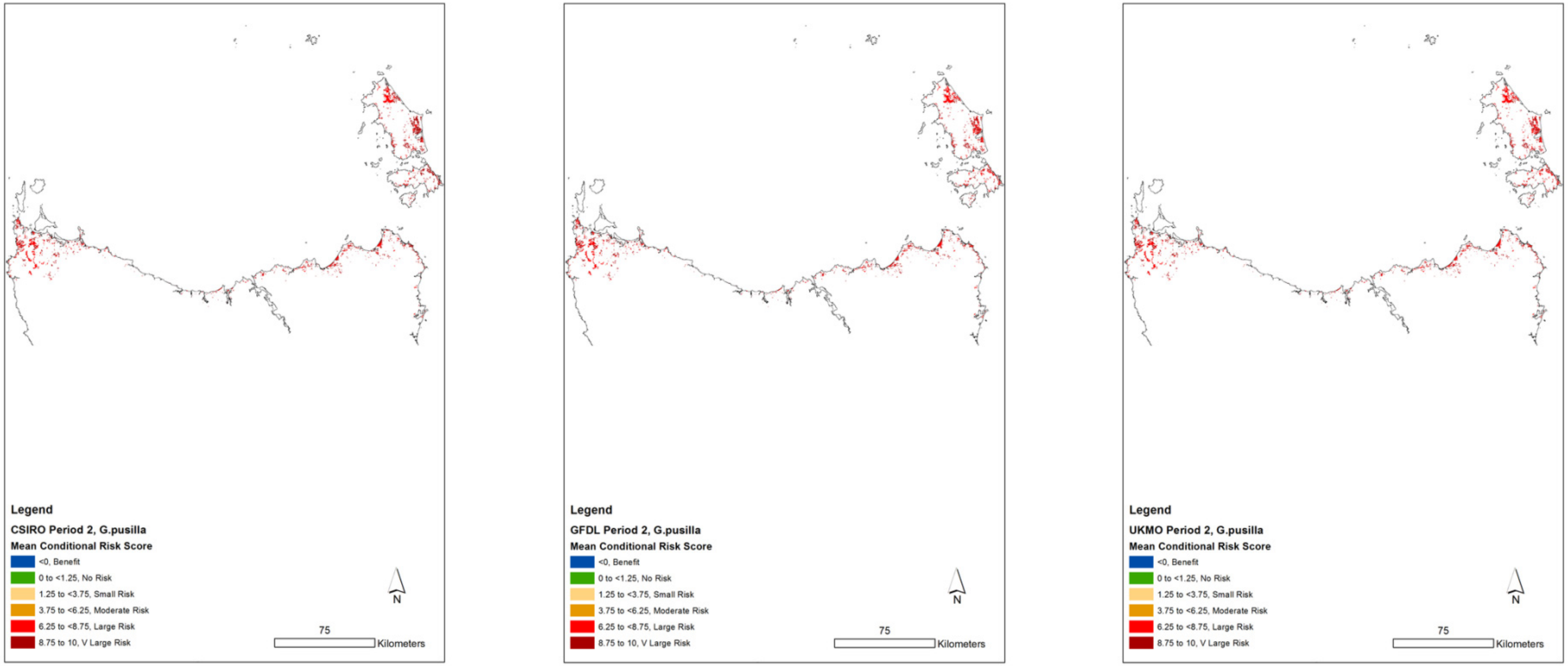


Figure 52 *Galaxiella pusilla* conditional risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

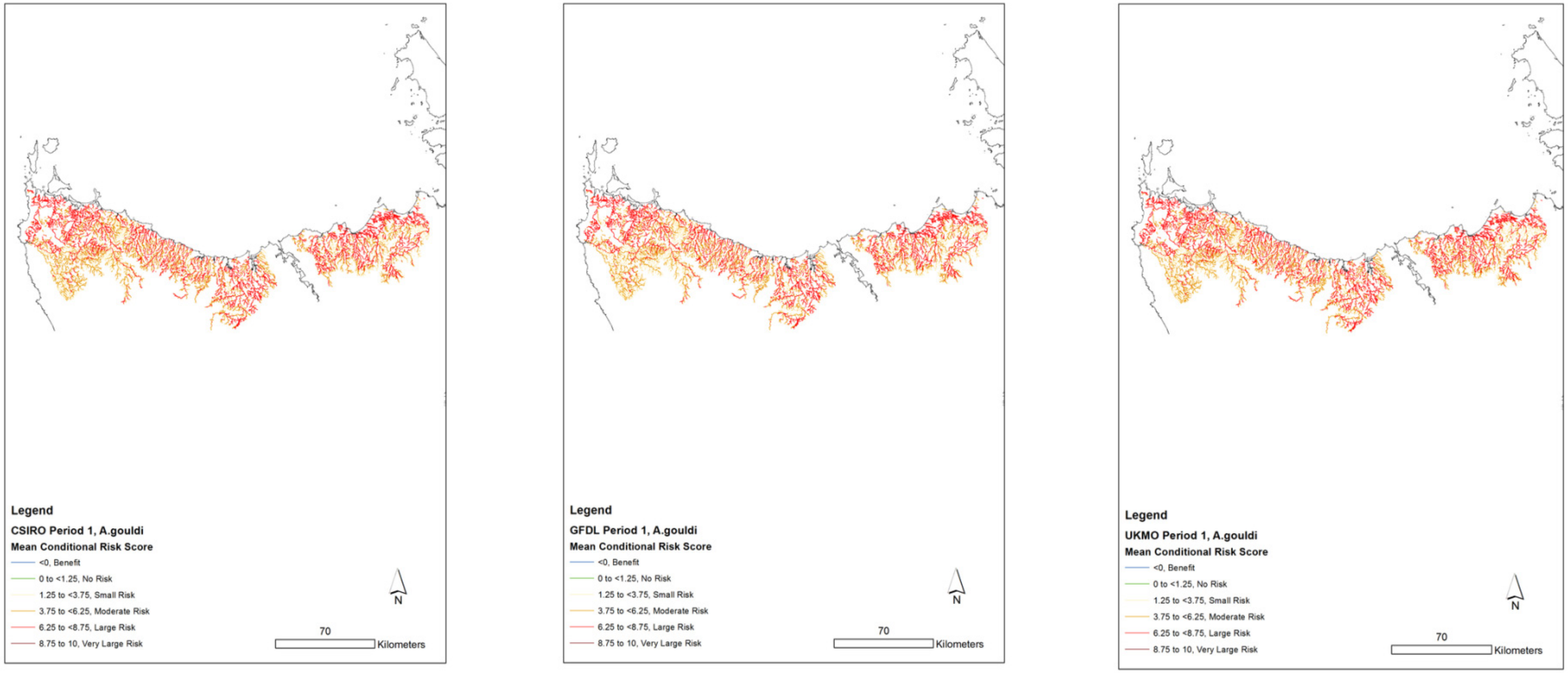


Figure 53 *Astacopsis gouldi* conditional risk scores Period 1

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 1

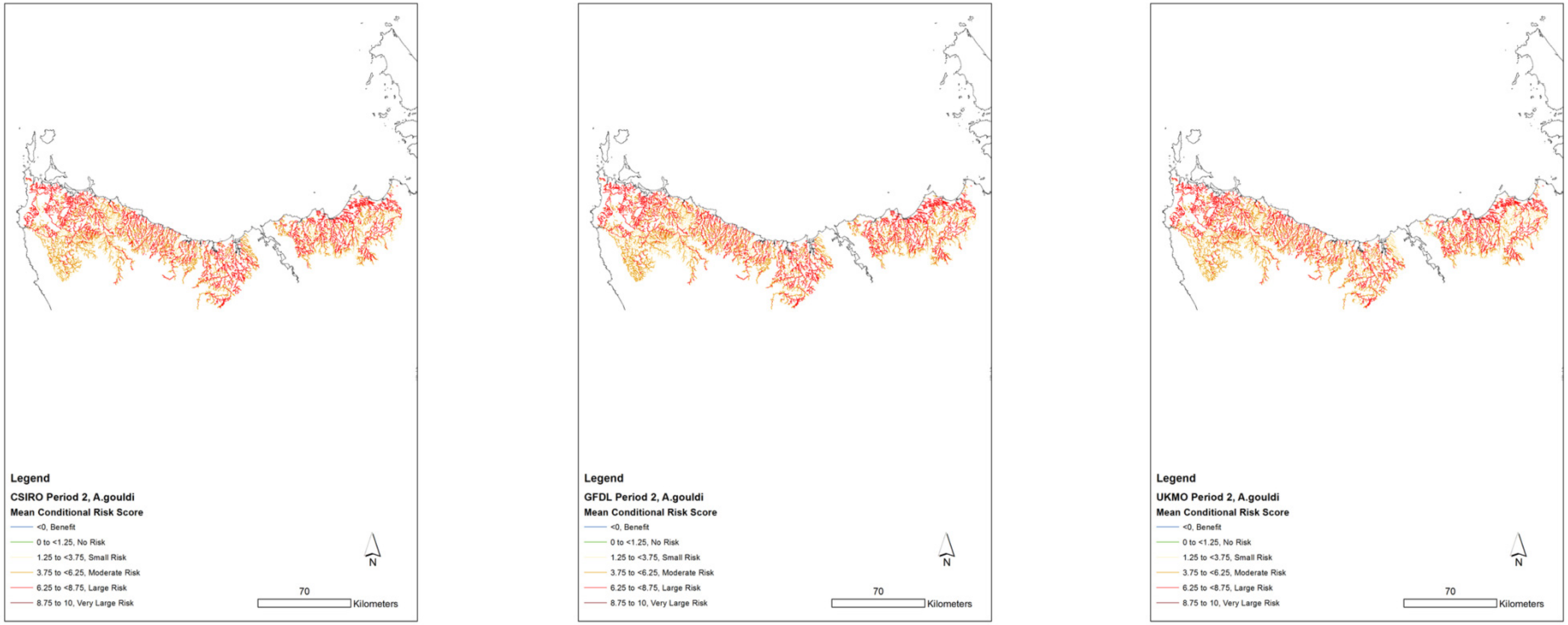


Figure 54 *Astacopsis gouldi* conditional risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

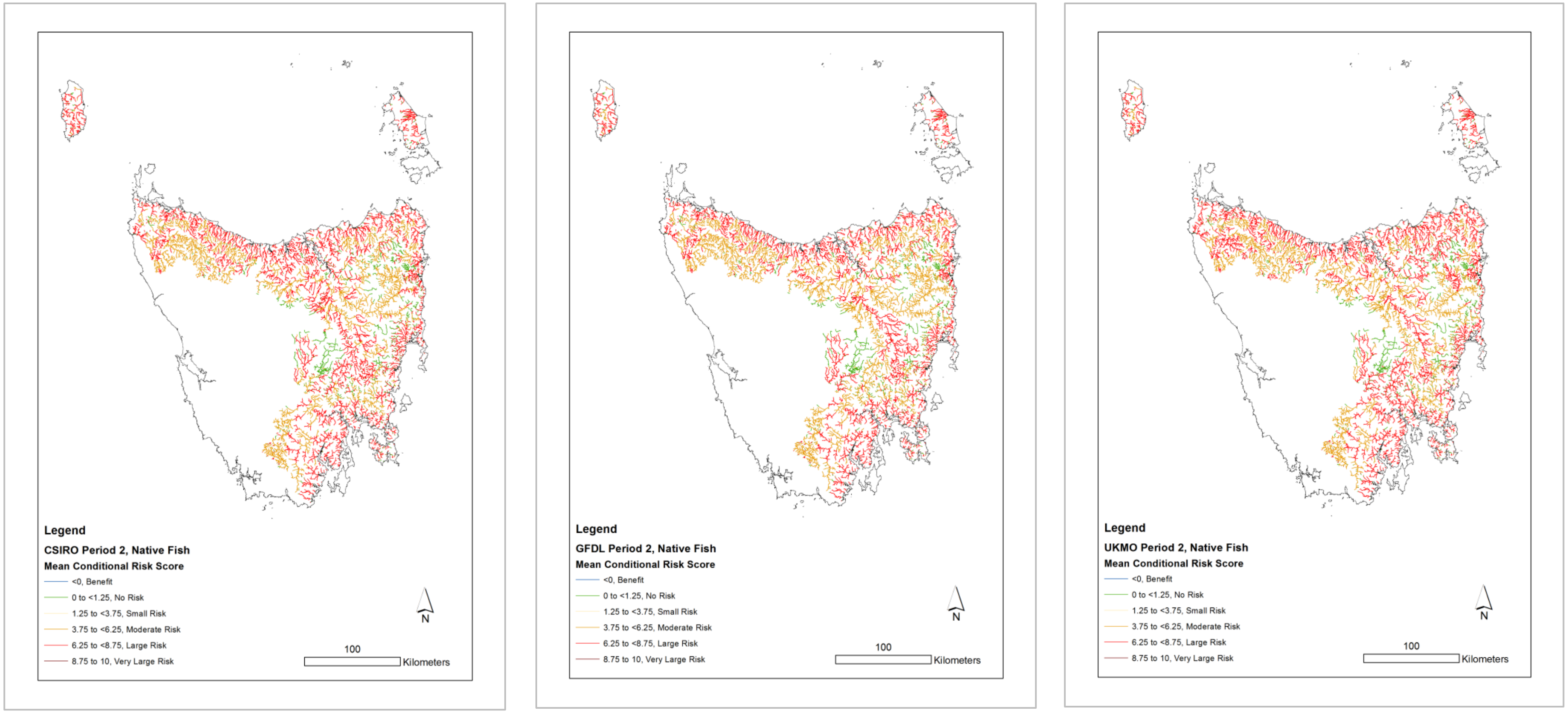


Figure 55 Native fish community conditional risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

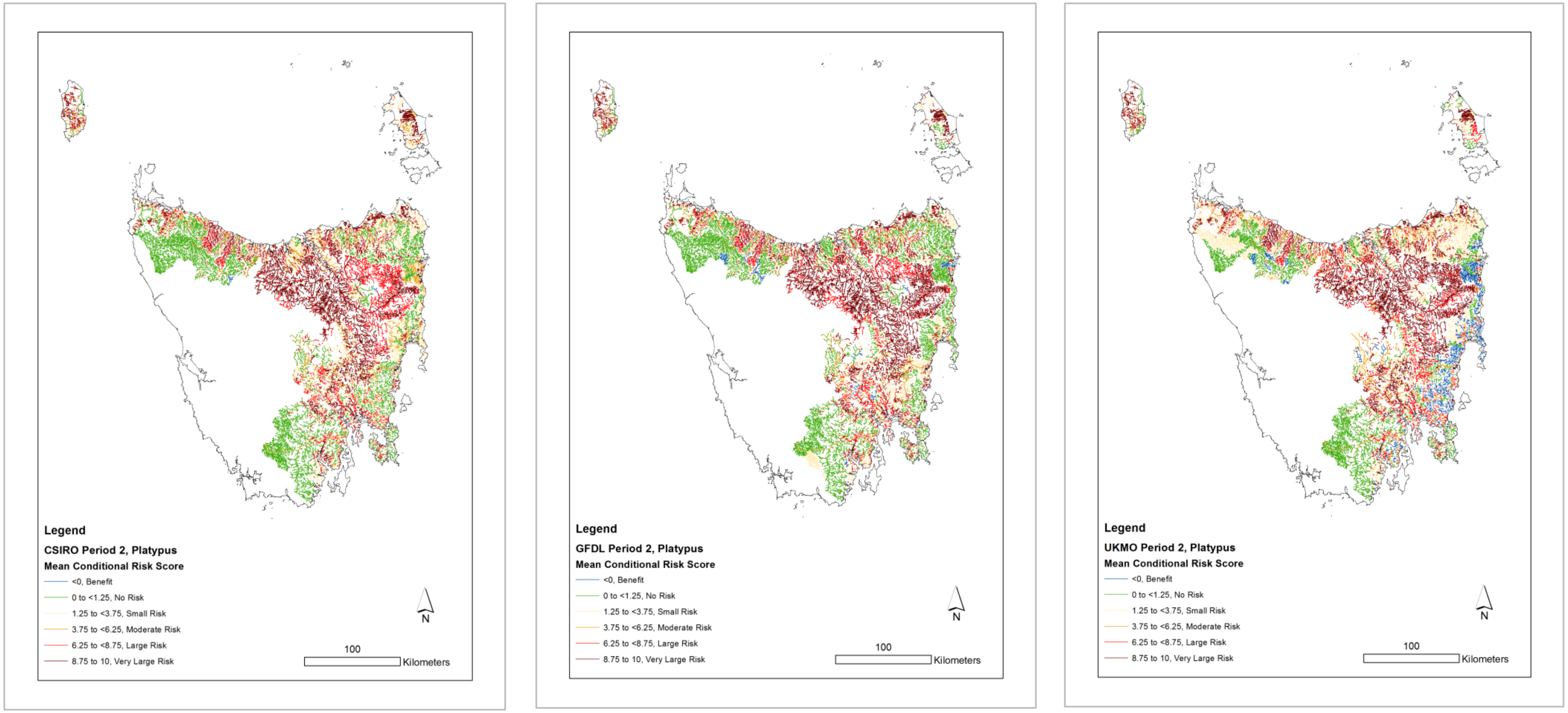


Figure 56 Platypus population conditional risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

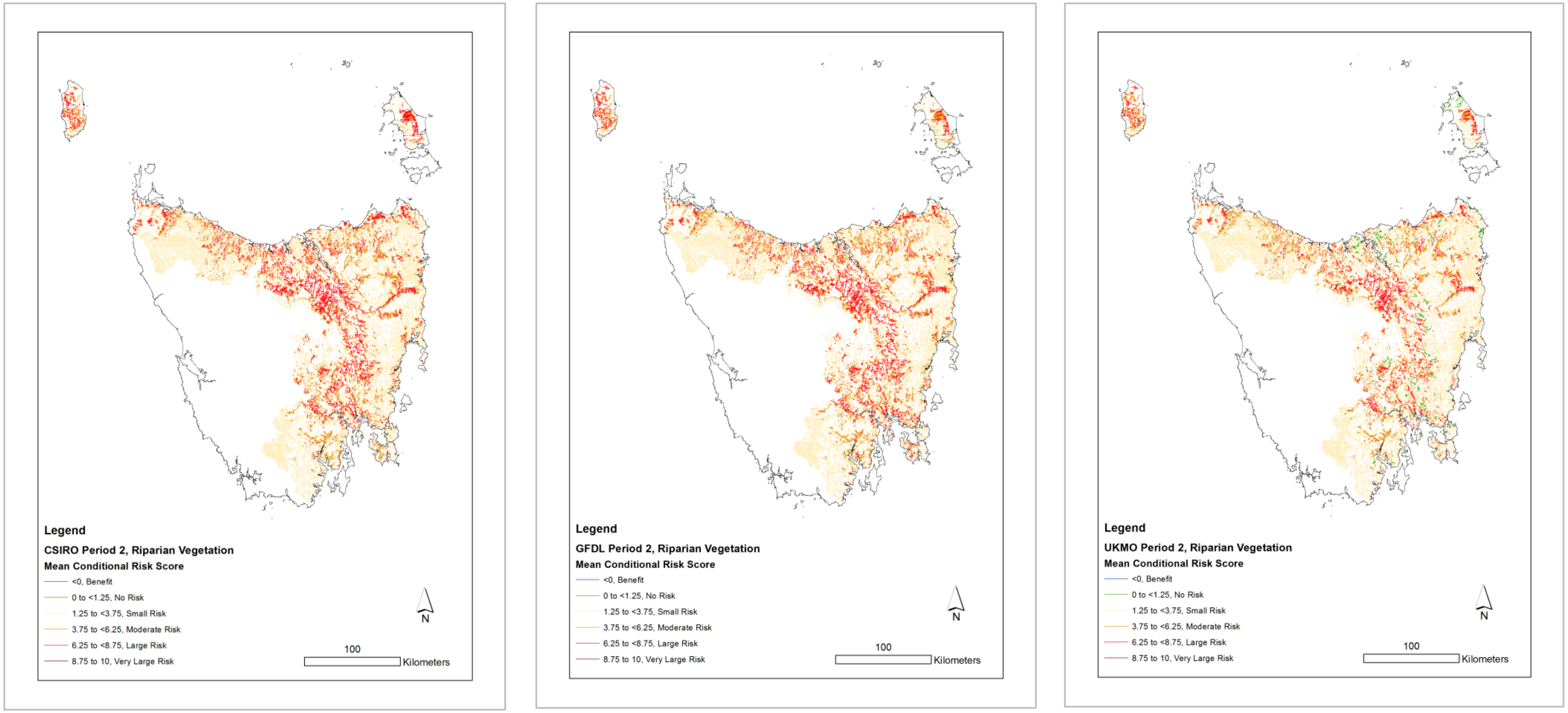


Figure 57 Riparian vegetation conditional risk scores for Period 2

The CSIRO (left panel) GFDL (centre) and UKMO (right panel) BBN model predictions for Period 2

REFERENCES

ALA. Atlas of Living Australia website at http://www.ala.org.au accessed June 2012.

ALDOUS, A., FITZSIMONS, J., RICHTER, B. & BACH, L. 2011. Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research,* 62**,** 223-231.

ALLISON, I., BINDOFF, N. L., BINDSCHADLER, R. A., COX, P. M., DE NOBLET, N., ENGLAND, M. H., FRANCIS, J. E., GRUBER, N., HAYWOOD, A. M., KAROLY, D. J., KASER, G., LE QUÉRÉ, C., LENTON, T. M., MANN, M. E., MCNEIL, B. I., PITMAN, A. J., RAHMSTORF, S., RIGNOT, E., SCHELLNHUBER, H. J., SCHNEIDER, S. H., SHERWOOD, S. C., SOMERVILLE, R. C. J., STEFFEN, K., STEIG, E. J., VISBECK, M. & WEAVER, A. J. 2009. The Copenhagen Diagnosis, 2009: Updating the World on the Latest Climate Science. Sydney, Australia, 60pp.: The University of New South Wales Climate Change Research Centre (CCRC).

ARAVINTHAN, V. 2005. Reclaimed wastewater as a resource for sustainable water management. In *Southern Region Engineering Conference: Managing Resources for a Sustainable Future (SREC 2005),* eds. D. Thorpe, U. Yadav, C. Snook & G. Liang. Toowoomba, Australia.

AUBLE, G. T. & SCOTT, M. L. 1998. Fluvial disturbance patches and cottonwood recruitment along the upper Missouri River, Montana. *Wetlands,* 18**,** 546-556.

BALCOMBE, S. R., SHELDON, F., CAPON, S. J., BOND, N. R., HADWEN, W. L., MARSH, N. & BERNAYS, S. J. 2011. Climate-change threats to native fish in degraded rivers and floodplains of the Murray–Darling Basin, Australia. *Marine and Freshwater Research,* 62**,** 1099-1114

BARMUTA, L. A., LINKE, S. & TURAK, E. 2011. Bridging the gap between 'planning' and 'doing' for biodiversity conservation in freshwaters. *Freshwater Biology,* 56**,** 180-195.

BATES, B., BUNN, S. E., BAKER, P., COX, M., HOPKINS, A., HUMPHREYS, B., LAKE, S., WILLGOOSE, G. & YOUNG, B. 2011. National Climate Change Adaptation Research Plan for Freshwater Biodiversity. In *NCCARF Publication*. Gold Coast, Queensland.

BENDIX, J. & HUPP, C. R. 2000. Hydrological and geomorphological impacts on riparian plant communities. *Hydrological Processes,* 14**,** 2977-2990.

BENNETT, J. C., LING, F. L. N., GRAHAM, B., GROSE, M. R., CORNEY, S. P., WHITE, C. J., HOLZ, G. K., POST, D. A., GAYNOR, S. M. & BINDOFF, N. L. 2010. Climate Futures for Tasmania: water and catchments technical report. Hobart, Tasmania: Antarctic Climate & Ecosystems Cooperative Reserach Centre.

BILBY, R. E. 1981. Role of organic debris dams in regulating the export and particulate matter from a forested watershed. *Ecology,* 62**,** 1234-1243.

BOND, N., LAKE, P. & ARTHINGTON, A. 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia,* 600**,** 3-16.

BOND, N., THOMSON, J., REICH, P. & STEIN, J. 2011. Using species distribution models to infer potential climate change-induced range shifts of freshwater fish in south-eastern Australia. *Marine and Freshwater Research,* 62**,** 1043-1061.

BOOTH, D. J., BOND, N. & MACREADIE, P. 2011. Detecting range shifts among Australian fishes in response to climate change. *Marine and Freshwater Research,* 62**,** 1027-1042

BOULTON, A. J. & LAKE, P. S. 2008. Effects of drought on stream insects and its ecological consequences. In *Aquatic insects: challenges to populations,* eds. J. Lancaster & R. A. Briers, 81 - 102. Wallingford: CABI Publishing.

BYRON, I., CURTIS, A. L. & LOCKWOOD, M. 2001. Exploring burnout in Australia's Landcare program: a case study in the Shepparton region. *Society and Natural Resources,* 14**,** 901-910.

CAISSIE, D. 2006. The thermal regime of rivers: a review. *Freshwater Biology,* 51**,** 1389-1406.

CASANOVA, M. T. & BROCK, M. A. 2000. How do depth, duration and frequency of flooding influence the establishment of wetland plant communities? *Plant Ecology,* 147**,** 237-250.

CFEV DATABASE V1.0. 2005. Conservation of Freshwater Ecosystem Values Project, Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment, Tasmania.

CHAN, T. U., HART, B. T., KENNARD, M. J., PUSEY, B. J., SHENTON, W., DOUGLAS, M. M., VALENTINE, E. & PATEL, S. 2012. Bayesian network models for environmental flow decision making in the Daly River, Northern Territory, Australia. *River Research and Applications,* 28**,** 283-301.

CHATTERJEE, A., PHILLIPS, B. & STROUD, D. A. 2008. Wetland management planning. A guide for site managers. WWF, Wetlands International, IUCN & Ramsar Convention, 76pp.

CHESSMAN, B. C. 2009. Climatic changes and 13-year trends in stream macroinvertebrate assemblages in New South Wales, Australia. *Global Change Biology,* 15**,** 2791-2802.

CLARK, J. S. 2005. Why environmental scientists are becoming Bayesians. *Ecology Letters,* 8**,** 2-14.

COAG. 1994. *The Council of Australian Governments' Water Reform Framework.* Canberra, Australia.: Environment Australia, Commonwealth of Australia.

COAG. 2004. *Intergovernmental agreement on a National Water Initiative*. Canberra, Australia.: Council of Australian Government, Commonwealth of Australia.

COAG. 2007. *National Climate Change Adaptation Framework.* Canberra, Australia.: Council of Australian Governments, Commonwealth of Australia.

CORNEY, S. P., KATZFEY, J. J., MCGREGOR, J. L., GROSE, M. R., BENNETT, J. C., WHITE, C. J., HOLZ, G. K., GAYNOR, S. M. & BINDOFF, N. L. 2010. Climate Futures for Tasmania: climate modelling technical report. Hobart, Tasmania: Antarctic Climate and Ecosystems Cooperative Research Centre.

CSIRO. 2009a. *Climate change predictions and impacts on runoff for Tasmania. Report two of seven to the Australian Government from the CSIRO Tasmania Sustainable Yields Project.* Hobart, Tasmania.: CSIRO Water for a Healthy Country Flagship, Australia.

CSIRO. 2009b. *Water availability for Tasmania. Report one of seven to the Australian Government from the CSIRO Tasmania Sustainable Yields Project.* Hobart, Tasmania.: CSIRO Water for a Healthy Country Flagship, Australia.

CUNDILL, G. & FABRICIUS, C. 2009. Monitoring in adaptive co-management: Toward a learning based approach. *Journal of Environmental Management,* 90**,** 3205-3211.

CUNDILL, G. & RODELA, R. 2012. A review of assertions about the processes and outcomes of social learning in natural resource management. *Journal of Environmental Management,* 113**,** 7-14.

DALLAS, H. F. 2008. Water temperature and riverine ecosystems: An overview of knowledge and approaches for assessing biotic responses, with special reference to South Africa. *Water South Africa,* 34**,** 393-404.

DAVIES, B. R., THOMS, M. & MEADOR, M. 1992. An assessment of the ecological impacts of inter-basin water transfers, and their threats to river basin integrity and conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 2**,** 325-349.

DAVIES, P., COOK, B., RUTHERFORD, K. & WALSHE, T. 2004. Managing high in-stream temperatures using riparian vegetation. River Management Technical Guideline No. 5 Canberra: Land and Water Australia.

DAVIES, P. & SLOANE, R. 1987. Characteristics of the spawning migrations of brown trout, *Salmo trutta* L., and rainbow trout, *S. gairdneri* Richardson, in Great Lake, Tasmania. *Journal of Fish Biology,* 31**,** 353-373.

DAVIES, P. E. 1989. Relationships between habitat characteristics and population abundance for Brown Trout, *Salmo trutta* L., and Blackfish, *Gadopsis marmoratus* Rich., in Tasmanian streams. *Marine and Freshwater Research,* 40**,** 341-359.

DAVIS, J., SUNNUCKS, P., THOMPSON, R., SIM, L., PAVOLVA, A., MORAN-ORDONEZ, A., BOX, J. B., MCBURNIE, G., PINDER, A., CHOY, S., MCNEIL, D., HUGHES, L., SHELDON, F. & TIMMS, B. 2012. Building the climate resilience (and resistance) of arid zone aquatic ecosystems and freshwater biodiversity. Monash University, SARDI/DOW, NRETAS, DERM QLD, Griffith University, University of New South Wales. Presentation available from http://www.nccarf.edu.au/publications/building-climate-resilience-arid-zone-freshwater-biota-identifying-and-prioritising. Accessed 12 March 2013.

DAVIS, J. A., LAKE, P. S. & THOMPSON, R. L. 2009. Freshwater biodiversity and climate change. In *Managing Climate Change: Papers from the Greenhouse 2009 Conference,* eds. I. Jubb, P. Holper & W. Cai, 73-85. Melbourne: CSIRO Publishing.

DE BOER, C. & BRESSERS, H. 2012. New strategies for implementing locally integrated stream restoration projects. *Environmental Practice,* 14**,** 26-34.

DERM. 2011. *Climate Change: Adaptation for Queensland. Issues Paper.* Brisbane, Australia.: Department of Environment and Resource Management, State of Queensland.

DEWHA. 2010. *Securing Our Water Future.* Canberra, Australia.: Department of the Environment, Water, Heritage and the Arts, Commonwealth of Australia.

DEWNR. 2012a. *Our Place, Our Future: State Natural Resources Management Plan South Australia 2012-2017.* Adelaide, Australia.: Department of Environment, Water and Natural Resources, Government of South Australia.

DEWNR. 2012b. *Prospering in a Changing Climate: a climate change adaptation framework for South Australia.* Adelaide, Australia.: Department of Environment, Water and Natural Resources, Government of South Australia.

DNRM. 2002. Current knowledge and enveloping technology for controlling evaporation from on-farm storage. Queensland: Rural Water Use Efficiency Initiative, Department of Natural Resources and Mines.

DORAN, N. E. 1999. Burrowing Crayfish (Engaeus) Group Recovery Plan 2001-2005 Hobart.: Threatened Species Unit, Parks and Wildlife Service.

DOVERS, S. 2009. Normalizing adaptation. *Global Environmental Change,* 19**,** 4-6.

DOYLE, R. B. & HABRAKEN, F. M. 1993. The distribution of sodic soils in Tasmania. *Australian Journal of Soil Research,* 31**,** 931-947.

DPIPWE. 2009. Macquarie River Broadwater Ecosystem Assessment. Water Assessment Aquatic Ecology Report Series, Report No. WA 09/03. Hobart, Tasmania: Water & Marine Resources Division. Department of Primary Industries, Parks, Water and Environment.

DPIPWE. 2010. Prioritisation of Threatened Flora and Fauna Recovery Actions for the Tasmanian NRM Regions. Nature Conservation Report 10/03. Hoabrt, Tasmania: Threatened Species Section, Department of Primary Industries, Water & Environment.

DPIW. 2008a. Conservation of Freshwater Ecosystem Values (CFEV) project Technical Report. . Hobart, Tasmania.: Conservation of Freshwater Ecosystem Values Program. Department of Primary Industries and Water.

DPIW. 2008b. Conservation of Freshwater Ecosystem Values (CFEV) Project Technical Report: Appendices. Conservation of Freshwater Ecosystem Values Project. Hobart, Tasmania.: Department of Primary Industries and Water.

DSE. 2009. *Securing Our Natural Future. A white paper for land and biodiversity at a time of climate change.* Melbourne, Australia.: Department of Sustainability and Environment, State of Victoria.

DSE. 2012. *Improving Our Waterways. Draft Victorian Waterway Management Strategy.* Melbourne, Australia.: Department of Sustainability and Environment, State of Victoria.

DSEWPC. 2012a. *Astacopsis gouldi* in Species Profile and Threats Database. Department of Sustainability, Environment, Water, Population and Communities, Canberra. Available from: http://www.environment.gov.au/sprat. Accessed 6 December 2012

DSEWPC. 2012b. *Galaxiella pusilla* in Species Profile and Threats Database. Department of Sustainability, Environment, Water, Population and Communities, Canberra. Available from: http://www.environment.gov.au/sprat. Accessed 7 Dec 2012. .

DUNLOP, M., PARRIS, H., KROON, F. & RYAN, P. 2012. Contributing to a sustainable future for Australia's biodiversity under climate change: conservation goals for dynamic management of ecosystems. CSIRO Climate Adaptation National Flagship. Presentation available from http://www.nccarf.edu.au/publications/contributing-sustainable-future-australia%E2%80%99s-biodiversity-under-climate-change. Accessed 24 March 2013.

EKSTROM, J. A., MOSER, S. C. & TORN, M. 2011. Barriers to Climate Change Adaptation: A Diagnostic Framework. California Energy Commission Publication Number: CEC-500-2011-004.

ESRI. 2011. ArcGIS Desktop 10. Redlands, CA, USA: Environmental Systems Research Institute.

FEENSTRA, J. F., BURTON, I., SMITH, J. B. & TOL, R. S. J. 1998. Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies. Amsterdam: United Nations Environment Programme and Institute for Environmental Studies.

FRANKLIN, J. F., SWANSON, F. J., HARMON, M. E., PERRY, D. A., SPIES, T. A., DALE, V. H., MCKEE, A., FERRELL, W. K., MEANS, J. E., GREGORY, S. V., LATTIN, J. D., SCHOWALTER, T. D. & LARSEN, D. 1992. Effects of global climatic change on forests in northwestern North America. In *Global Warming and Biodiversity,* eds. R. L. Peters & T. E. Lovejoy, 244–254. New Haven: Yale University Press.

FRITTAION, C. M., DUINKER, P. N. & GRANT, J. L. 2011. Suspending disbelief: Influencing engagement in scenarios of forest futures. *Technological Forecasting and Social Change,* 78**,** 421-430.

GILFEDDER, L., MACGREGOR, N., BRIDLE, K., CARTER, O. & SPROD, D. 2012. Implementing Adaptation to Climate Change in Terrestrial and Freshwater Natural Environments in Tasmania. Report on an expert workshop held in Hobart, Tasmania on 28-29 November, 2011 Report to the Department of Primary Industries, Parks, Water & Environment, Hobart.

GOODERHAM, J. & TSYRLIN, E. 2002. *The Waterbug Book: a guide to the freshwater macroinvertebrates of temperate Australia*. Collingwood, Vic., Australia: CSIRO Publishing.

GRANT, T. R. & DAWSON, T. J. 1978. Temperature regulation in the Platypus, *Ornithorhynchus anatinus*: maintenance of body temperature in air and water. *Physiological Zoology,* 51**,** 1-6.

GREGORY, S. V., SWANSON, F. J., MCKEE, A. & CUMMINS, K. W. 1991. An ecosystem perspective of riparian zones. *Bioscience,* 41**,** 540-551.

GURUNG, S. 2006. Tasmanian Acid Drainage Reconnaissance. 2. Disitribution of acid sulphate soils in Tasmania. Tasmanian Geological Survey Record 2001/06. Rosny Park: Mineral Resources Tasmania.

HARDIE, S. A., WHITE, R. W. G. & BARMUTA, L. A. 2007. Reproductive biology of the threatened golden galaxias *Galaxias auratus* Johnston and the influence of lake hydrology. *Journal of Fish Biology,* 71**,** 1820-1840.

HARRELL, F. E., JR. 2001. *Regression modelling strategies: with applications to linear models, logistic regression and survival analysis*. New York: Springer-Verlag.

HARRINGTON, G. A., CROSBIE, R., MARVANEK, S., MCCALLUM, J., CURRIE, D., RICHARDSON, S., WACLAWIK, V., ANDERS, L., GEORGIOU, J., MIDDLEMIS, H. & BOND, K. 2009. Groundwater assessment and modelling for Tasmania. A report to the Australian Government from the CSIRO Tasmania Sustainable Yields Project. Australia: CSIRO Water for a Healthy Country Flagship.

HASSALL AND ASSOCIATES. 2007. Technical review of irrigated agriculture in the Macquarie and Gwydir river catchment. Sydney: Report prepared by Hassall and Associates Pty Ltd, Sydney, for the NSW Department of Environment and Climate Change.

HAZELL, D., CUNNNINGHAM, R., LINDENMAYER, D., MACKEY, B. & OSBORNE, W. 2001. Use of farm dams as frog habitat in an Australian agricultural landscape: Factors affecting species richness and distribution. *Biological Conservation,* 102**,** 155-169.

HAZELL, D., HERO, J. M., LINDENMAYER, D. & CUNNINGHAM, R. 2004. A comparison of constructed and natural habitat for frog conservation in an Australian agricultural landscape. *Biological Conservation,* 119**,** 61-71.

HOBDAY, A., CHAMBERS, L. E. & ARNOULD, J. P. Y. 2012. *Developing adaptation options for seabirds and marine mammals impacted by climate change. Marine NARP Project FRDC 2011/533.*

IPCC. 2012. Summary for the IPCC's Fifth Assessment Report (AR5). Intergovernmental Panel on Climate Change (http://www.ipcc.ch/pdf/ar5/ar5-leaflet.pdf , 17.12.2012).

JACKSON, J. E. 2004. Tasmanian Galaxiidae Recovery Plan 2004-2008. Hobart: Inland Fisheries Service.

JEFFREY, S. J., CARTER, J. O., MOODIE, K. M. & BESWICK, A. R. 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling and Software,* 16**,** 309-330.

JENKINS, K. M., KINGSFORD, R. T., WOLFENDEN, B. J., WHITTEN, S., PARRIS, H., SIVES, C., ROLLS, R. & HAY, S. 2011. Limits to climate change adaptation in floodplain wetlands: the Macquarie Marshes. Final report to the National Climate Change Adaptation Research Facility.

JOSEPH, L. N., MALONEY, R. F. & POSSINGHAM, H. P. 2008. Optimal allocation of resources among threatened species: a project prioritization protocol. *Conservation Biology,* 23**,** 328-338.

JUNK, W. J., BAYLEY, P. B. & SPARKES, R. E. 1989. The flood pulse concept in river-floodplain systems. *Special Publications of the Canadian Journal of Fisheries and Aquatic Sciences,* 106**,** 110-127.

KALTENBORN, B. P., THOMASSEN, J. & LINNELL, J. D. C. 2012. Island futures-Does a participatory scenario process capture the common view of local residents? *Futures,* 44**,** 328-337.

KIERN, A. S. & AUSTIN, E. K. 2012. Limits and barriers to climate change adaptation for small inland communities affected by drought. Canberra: Final report to the National Climate Change Adaptation Research Facility.

KINGSFORD, R. T. & NORMAN, F. I. 2002. Australian waterbirds: products of the continent's ecology. *Emu,* 12**,** 47-69.

KLAMT, M., THOMPSON, R. & DAVIS, J. 2011. Early response of the platypus to climate warming. *Global Change Biology,* 17**,** 3011-3018.

KNIGHT, A. T., COWLING, R. M., ROUGET, M., BALMFORD, A., LOMBARD, A. T. & CAMPBELL, B. M. 2008. Knowing but not doing: Selecting priority conservation areas and the research-implementation gap. *Conservation Biology,* 22**,** 610-617.

KONDOLF, G. M., CADA, G. F., SALE, M. J. & FELANDO, T. 1991. Distribution and Stability of Potential Salmonid Spawning Gravels in Steep Boulder-Bed Streams of the Eastern Sierra Nevada. *Transactions of the American Fisheries Society,* 120**,** 177-186.

LAWLER, J. J. 2009. Climate Change Adaptation Strategies for Resource Management and Conservation Planning. *Annals of the New York Academy of Sciences,* 1162**,** 79-98.

LEEUWIS, C. 2000. Reconceptualizing participation for sustainable rural development: towards a negotiation approach. *Development and Change,* 31**,** 931-959.

LESTER, P. J., MITCHELL, S. F. & SCOTT, D. 1994. Effects of riparian willow trees (*Salix fragilis*) on macroinvertebrate densities in two small Central Otago, New Zealand, streams. *New Zealand Journal of Marine and Freshwater Research,* 28**,** 267-276.

LINACRE, E. T. 1993. Data-sparse estimation of lake evaporation, using a simplified Penman equation. *Agricultural and Forest Meteorology,* 64**,** 237-256.

LINDENMAYER, D. B. & LIKENS, G. E. 2010. The science and application of ecological monitoring. *Biological Conservation,* 143**,** 1317-1328.

LYNCH, T. & BLÜHDORN, D. R. 1997. Reservation assessment and habitat requirements of the giant Tasmanian freshwater lobster, *Astacopsis gouldi* Hobart: Report to the Tasmanian RFA Environment and Heritage Technical Committee.

MAHMOUD, M. I., GUPTA, H. V. & RAJAGOPAL, S. 2011. Scenario development for water resources planning and watershed management: Methodology and semi-arid region case study. *Environmental Modelling and Software,* 26**,** 873-885.

MARCH, H., THEROND, O. & LEENHARDT, D. 2012. Water futures: Reviewing water-scenario analyses through an original interpretative framework. *Ecological Economics,* 82**,** 126-137.

MAWDSLEY, J. 2011. Design of conservation strategies for climate adaptation. *Wiley Interdisciplinary Reviews: Climate Change,* 2**,** 498-515.

MAWDSLEY, J. R., O'MALLEY, R. & OJIMA, D. S. 2009. A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. *Conservation Biology,* 23**,** 1080-1089.

MAZEROLLE, M. J., DESROCHERS, A. & ROCHEFORT, L. 2005. Landscape characteristics influence pond occupancy by frogs after accounting for detectability. *Ecological Applications,* 15**,** 824-834.

MCGLONE, M. & WALKER, S. 2011. Potential effects of climate change on New Zealand's terrestrial biodiversity and policy recommendations for mitigation, adaptation and research. 1-77.

MCMURRAY. D. 2006. Impact of farm dams on streamflow in the Tod River catchment, Eyre Pensinsula, South Australia. Adelaide, S.A.: Department of Water, Land and Biodiversity Conservation.

MDBA. 2010. The Living Murray: Planned works in the Koondrook-Perricoota Forest. Deniliquin, NSW: Murray-Darling Basin Authority.

MDBC. 2004. Native Fish Strategy for the Murray-Darling Basin 2003-2013. Canberra, ACT, available at www.mdbc.gov.au, downloaded 07.12.2012: Murray-Darling Basin Commission.

MOHSENI, O. & STEFAN, H. G. 1999. Stream temperature/air temperature relationship: A physical interpretation. *Journal of Hydrology,* 218**,** 128-141.

MOHSENI, O., STEFAN, H. G. & ERICKSON, T. R. 1998. A nonlinear regression model for weekly stream temperatures. *Water Resources Research,* 34**,** 2685-2692.

MOLONEY, B. 2001. Environmental requirements and tolerances of Rainbow trout (*Oncorhynchus mykiss*) and Brown trout (*Salmo trutta*) with special reference to

Western Australia: A review. In *Fisheries Research Report No. 130*, 1-28. North Beach, WA: Department of Fisheries.

MORRILL, J. C., BALES, R. C. & CONKLIN, M. H. 2005. Estimating stream temperature from air temperature: implications for future water quality. *ASXE, Journal of Environmental Engineering,* 121**,** 139-146.

MORRONGIELLO, J. R., BEATTY, S. J., BENNETT, J. C., CROOK, D. A., IKEDIFE, D. N. E. N., KENNARD, M. J., KEREZSY, A., LINTERMANS, M., MCNEIL, D. G., PUSEY, B. J. & RAYNER, T. 2011. Climate change and its implications for Australia's freshwater fish. *Marine and Freshwater Research,* 62**,** 1082-1098.

MOSER, S. C. 2010. Communicating climate change: History, challenges, process and future directions. *Wiley Interdisciplinary Reviews: Climate Change,* 1**,** 31-53.

MOSER, S. C. 2012. Adaptation, mitigation, and their disharmonious discontents: An essay. *Climatic Change,* 111**,** 165-175.

MOSER, S. C. & EKSTROM, J. A. 2010. A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America,* 107**,** 22026-22031.

MOSTERT, E., PAHL-WOSTL, C., REES, Y., SEARLE, B., TÀBARA, D. & TIPPETT, J. 2007. Social learning in European river-basin management: barriers and fostering mechanisms from 10 river basins. *Ecology and Society,* 12(1)**,** article 19.

MOWLING, F., DUNN, H., VOLLER, P., HOUSHOLD, I., BLACKHALL, S., SPINK, A., LLOYD, L., BUTCHER, R. & HALE, J. 2010. Moulting Lagoon Ramsar Site: Ecological Character Description. Canberra: Department of Sustainability, Environment, Water, Population and Communities.

MURO, M. & JEFFREY, P. 2008. A critical review of the theory and application of social learning in participatory natural resource management processes. *Journal of Environmental Planning and Management,* 51**,** 325-344.

NEWTON, A. C., STEWART, G. B., DIAZ, A., GOLICHER, D. & PULLIN, A. S. 2007. Bayesian Belief Networks as a tool for evidence-based conservation management. *Journal for Nature Conservation,* 15**,** 144-160.

NICHOLS, S., WEBB, A., NORRIS, R. & STEWARDSON, M. 2011. *Eco Evidence analysis methods manual: a systematic approach to evaluate causality in environmental science*. Canberra, A.C.T.: eWater Cooperative Research Centre.

NICOL, S. J., LIESCHKE, J., LYON, J. & HUGHES, V. 2002. Resnagging Revolution: River Restoration Through Resnagging. Final report to AFFA River Rehab program.

NILSSON, C. & SVEDMARK, M. 2002. Basic principles and ecological consequences of changing water regimes: Riparian plant communities. *Environmental Management,* 30**,** 468-480.

NORRIS, R., NICHOLS, S., RANSOM, G., WEBB, A., STEWARDSON, M., LISTON, P. & MUGODO, J. 2008. *Causal criteria analysis methods manual: a systematic approach to evaluate causality in environmental science*. Canberra, A.C.T.: eWater Cooperative Research Centre.

NVA. Natural Values Atlas. (www.naturalvaluesatlas.tas.gov.au),© State of Tasmania, accessed April 2012.

O'CONNOR, M. H., MCFARLANE, M., FISHER, J., MACRAE, D. & LEFROY, T. 2005. The Avon River Basin in 2050: Scenario planning in the Western Australian Wheatbelt. *Australian Journal of Agricultural Research,* 56**,** 563-580.

OLDEN, J. D. & NAIMAN, R. J. 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. *Freshwater Biology,* 55**,** 86-107.

ORMEROD, S. J. 2009. Climate change, river conservation and the adaptation challenge. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 19**,** 609-613.

OSTROM, E., JANSSEN, M. A. & ANDERIES, J. M. 2007. Going beyond panaceas. *Proceedings of the National Academy of Sciences,* 104**,** 15176-15178.

PAHL-WOSTL, C. 2009. A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Global Environmental Change,* 19**,** 354-365.

PALMER, M., LETTENMAIER, D., POFF, N. L., POSTEL, S., RICHTER, B. & WARNER, R. 2009. Climate change and river ecosystems: protection and adaptation options. *Environmental Management,* 44**,** 1053-1068.

PALMER, M. A., REIDY LIERMANN, C. A., NILSSON, C., FLÖRKE, M., ALCAMO, J., LAKE, P. S. & BOND, N. 2008. Climate change and the world's river basins: anticipating management options. *Frontiers in Ecology and the Environment,* 6**,** 81-89.

PANKHURST, N. W., PURSER, G. J., VAN DER KRAAK, G., THOMAS, P. M. & FORTEATH, G. N. R. 1996. Effect of holding temperature on ovulation, egg fertility, plasma levels of reproductive hormones and in vitro ovarian steroidogenesis in the rainbow trout *Oncorhynchus mykiss*. *Aquaculture,* 146**,** 277-290.

PARKS AND WILDLIFE SERVICE. 2007. Moulting Lagoon Game Reserve (Ramsar Site) Management Plan 2003. Hobart, Tasmania: Department of Tourism, Arts and the Environment.

PEDERSEN, N. L. & SAND-JENSEN, K. 2007. Temperature in lowland Danish streams: Contemporary patterns, empirical models and future scenarios. *Hydrological Processes,* 21**,** 348-358.

PETERSON, G. D., CUMMING, G. S. & CARPENTER, S. R. 2003. Scenario planning: A tool for conservation in an uncertain world. *Conservation Biology,* 17**,** 358-366.

PINHEIRO, J. C. & BATES, D. M. 2000. *Mixed-Effects Models in S and S-Plus*. New York, NY, U.S.A.: Springer-Verlag.

PITTOCK, J. & FINLAYSON, C. M. 2011. Australia's Murray–Darling Basin: freshwater ecosystem conservation options in an era of climate change. *Marine and Freshwater Research,* 62**,** 232-243.

PITTOCK, J., FINLAYSON, C. M. & HOWITT, J. 2012. Beguiling and risky: 'environmental works and measures' for wetland conservation under a changing climate. *Hydrobiologia***,** 1-21.

PITTOCK, J. & HARTMANN, J. 2011. Taking a second look: climate change, periodic relicensing and improved management of dams. *Marine and Freshwater Research,* 62**,** 312-320.

POFF, N. L., ALLAN, J. D., BAIN, M. B., KARR, J. R., PRESTEGAARD, K. L., RICHTER, B. D., SPARKS, R. E. & STROMBERG, J. C. 1997. The natural flow regime. *BioScience,* 47**,** 769-784.

POFF, N. L., BRINSON, M. M. & DAY, J. W. 2002. Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems in the United States, Technical Report, Pew Center on Global Climate Change. 56 pp. . Arlington, USA.

POFF, N. L., RICHTER, B. D., ARTHINGTON, A. H., BUNN, S. E., NAIMAN, R. J., KENDY, E., ACREMAN, M., APSE, C., BLEDSOE, B. P., FREEMAN, M. C., HENRIKSEN, J., JACOBSON, R. B., KENNEN, J. G., MERRITT, D. M., O'KEEFFE, J. H., OLDEN, J. D., ROGERS, K., THARME, R. E. & WARNER, A. 2010. The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. *Freshwater Biology,* 55**,** 147-170.

PRINGLE, C. M., NAIMAN, R. J., BRETSCHKO, G., KARR, J. R., OSWOOD, M. W., WEBSTER, J. R., WELCOMME, R. L. & WINTERBOURN, M. J. 1988. Patch dynamics in lotic systems - the stream as a mosaic. *Journal of the North American Benthological Society,* 7**,** 503-524.

QIU, D., WU, Z., LIU, B., DENG, J., FU, G. & HE, F. 2001. The restoration of aquatic macrophytes for improving water quality in a hypertrophic shallow lake in Hubei Province, China. *Ecological Engineering,* 18**,** 147-156.

R CORE DEVELOPMENT TEAM. 2012. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing.

REHANA, S. & MUJUMDAR, P. P. 2011. River water quality response under hypothetical climate change scenarios in Tunga-Bhadra river, India. *Hydrological Processes,* 25**,** 3373-3386.

RICHARDSON, A. M. M., DORAN, N. & HANSEN, B. 2006. The geographic ranges of Tasmanian crayfish: extent and pattern. *Freshwater Crayfish,* 15**,** 347-364.

RICHTER, B. D., BAUMGARTNER, J. V., WIGINGTON, R. & BRAUN, D. P. 1997. How much water does a river need? *Freshwater Biology,* 37**,** 231-249.

RICHTER, B. D. & THOMAS, G. A. 2007. Restoring environmental flows by modifying dam operations. . *Ecology and Society,* 12**,** 12: (online).

ROBSON, B. J., CHESTER, E. T., BEATTY, S., CHAMBERS, J., CLOSE, P., COOK, B., DAVIES, P. M., LETSTER, R., LYMBERY, A., MATTHEWS, T. & MORGAN, D. 2012. Novel methods for managing freshwater refuges against climate change in southern Australia Murdoch University, University of Western Australia, Deaking University. Presentation available from http://www.nccarf.edu.au/publications/novel-methods-managing-freshwater-refuges-against-climate-change-southern-australia. Accessed 24 March 2013.

SA/SNZ. 2009. AS/NZS ISO 31000:2009 Risk Management - Principles and Guidelines. Sydney, Australia and Wellington, New Zealand: Standards Australia/ Standards New Zealand.

SALA, O. E., III, F. S. C., ARMESTO, J. J., BERLOW, E., BLOOMFIELD, J., DIRZO, R., HUBER-SANWALD, E., HUENNEKE, L. F., JACKSON, R. B., KINZIG, A., LEEMANS, R., LODGE, D. M., MOONEY, H. A., OESTERHELD, M., POFF, N. L., SYKES, M. T., WALKER, B. H., WALKER, M. & WALL, D. H. 2000. Global biodiversity scenarios for the year 2100. *Science,* 287**,** 1770-1774.

SCANLON, A. P., FISH, G. J. & YAXLEY, M. L. 1990. Behind the Scenery: Tasmania's landforms and geology. Hobart, Tasmania: Department of Eductaion and the Arts.

SCHMIDT, E. 2007. Monolayer barriers for evaporation control from storage dams. Queensland: CRC Irrigation Futures.

SCHMIDT, E. J. 2009. Reducing evaporation losses - opportunities for cost effective water savings. Swan Hill, Vic: Irrigation and Drainage Conference.

SCHREIDER, S. Y., JAKEMAN, A. J., LETCHER, R. A., NATHAN, R. J., NEAL, B. P. & BEAVIS, S. G. 2002. Detecting changes in streamflow response to changes in non-climatic catchment conditions: Farm dam development in the Murray-Darling basin, Australia. *Journal of Hydrology,* 262**,** 84-98.

SHANAHAN, M. & BOLAND, A. M. 2008. Recycled water in agriculture - theory to practice. Melbourne, Australia: Proceedings of Irrigation Australia Conference.

SHELDON, R. 2011. *Water connectivity in Tasmania. Preliminary assessment and risk analysis. Groundwater Management Report Series Report No. GW 2011/02*. Hobart, Tasmania: Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment.

SHENTON, W., HART, B. T. & CHAN, T. 2011. Bayesian network models for environmental flow decision-making: 1. Latrobe River Australia. *River Research and Applications,* 27**,** 283-296.

SHERMAN, B. S. 2000. Scoping Options For Mitigating Cold Water Discharges From Dams, Consultancy Report 00/21. Canberra, 47 pp.: CSIRO Land and Water.

SNADDON, C. D., WISHART, M. J. & DAVIES, B. R. 1998. Some implications of inter-basin water transfers for river ecosystem functioning and water resources management in southern Africa. *Aquatic Ecosystem Health & Management,* 1**,** 159-182.

STEWART-KOSTER, B., BUNN, S. E., MACKAY, S. J., POFF, N. L., NAIMAN, R. J. & LAKE, P. S. 2010. The use of Bayesian networks to guide investments in flow and catchment restoration for impaired river ecosystems. *Freshwater Biology,* 55**,** 243-260.

STEYAERT, P. & JIGGINS, J. 2007. Governance of complex environmental situations through social learning: a synthesis of SLIM's lessons for research, policy and practice. *Environmental Science and Policy,* 10**,** 575–586.

TAYLOR, A., COCKLIN, C. & BROWN, R. 2012. Fostering environmental champions: A process to build their capacity to drive change. *Journal of Environmental Management,* 98**,** 84-97.

THOMPSON, R., BEARDALL, J., GRACE, M. & BERINGER, J. 2012. Impacts of elevated temperature and CO_2 on the critical processes underpinning resilience of aquatic ecosystems Monash University. Presentation available from http://www.nccarf.edu.au/publications/impacts-elevated-temperature-and-co2-critical-processes-underpinning-resilience-aquatic. Accessed 25 March 2013.

THREATENED SPECIES SECTION. 2006. Giant Freshwater Lobster *Astacopsis gouldi* Recovery Plan 2006-2100. Department of Primary Industries and Water, Hobart, Tasmania.

TIXIER, G., WILSON, K. & WILLIAMS, D. 2009. Exploration of the influence of global warming on the chironomid community in a manipulated shallow groundwater system. *Hydrobiologia,* 624**,** 13-27.

TURAK, E., MARCHANT, R., BARMUTA, L. A., DAVIS, J., CHOY, S. & METZELING, L. 2011. River conservation in a changing world: invertebrate diversity and spatial prioritisation in south-eastern coastal Australia. *Marine and Freshwater Research,* 62**,** 300–311.

VANDERWAL, J., JAMES, C., WILLIAMS, S., RESIDE, A., PEARSON, R. G., BURROWS, D., WALTHAM, N., CAPON, S. J., KENNARD, M. J., PUSEY, B. J., WARD, D. & BUNN, S. E. 2012. Identification and characterization of freshwater refugia in the face of climate change. James Cook University and Griffith University. Presentation available from http://www.nccarf.edu.au/publications/identification-and-characterization-freshwater-refugia-face-climate-change. Accessed 23 March 2013.

VEAC. 2008. Identifying flood-dependent natural values on the Victorian floodplains of the River Murray and its tributaries. Version 1.0. Melbourne, Vic., Available at www.veac.vic.gov.au/reports/352-VEAC_Red_Gum_Flood-dependent_natural_values_Report_V1-0.pdf [accessed 12 November 2012]: Victorian Environmental Assessment Council.

VERSTRAETEN, G. & PROSSER, I. P. 2008. Modelling the impact of land-use change and farm dam construction on hillslope sediment delivery to rivers at the regional scale. *Geomorphology,* 98**,** 199-212.

WALKER, K. F. & THOMS, M. C. 1993. Environmental effects of flow regulation on the lower River Murray, Australia. *Regulated Rivers-Research & Management,* 8**,** 103-119.

WALSH, C., STEWARDSON, M., STEIN, J. & WEALANDS, S. 2007. Sustainable Rivers Audit Filters Project Stage 2. School of Enterprise, The University of Melbourne, Melbourne: Report to Murray Darling Basin Commission.

WALSH, T. & WALSH, B. 2011. Survey of the Giant freshwater Crayfish (*Astacopsis gouldi*) at Nelson Bay River. Report by Bronwyn Walsh and Todd Walsh of Kannunah Pty Ltd for Pitt and Sherry Ptd Ltd.

WARD, J. V. 1985. Thermal characteristics of running waters. *Hydrobiologia,* 125**,** 31-46.

WARD, J. V. 1998. Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biological Conservation,* 83**,** 269-278.

WATTS, R. J., RICHTER, B. D., OPPERMAN, J. J. & BOWMER, K. H. 2011. Dam reoperation in an era of climate change. *Marine and Freshwater Research,* 62**,** 321-327.

WEBB, B. W., CLACK, P. D. & WALLING, D. E. 2003. Water-air temperature relationships in a Devon river system and the role of flow. *Hydrological Processes,* 17**,** 3069-3084.

WEBB, J. A., STEWARDSON, M. J. & KOSTER, W. M. 2010. Detecting ecological responses to flow variation using Bayesian hierarchical models. *Freshwater Biology,* 55**,** 108-126.

WEN, L., LING, J., SAINTILAN, N. & ROGERS, K. 2009. An investigation of the hydrological requirements of River Red Gum (Eucalyptus camaldulensis) Forest, using Classification and Regression Tree modelling. *Ecohydrology,* 2**,** 143-155.

WINTLE, B. A., BEKESSY, S. A., KEITH, D. A., VAN WILGEN, B. W., CABEZA, M., SCHRÖDER, B., CARVALHO, S. B., FALCUCCI, A., MAIORANO, L., REGAN, T. J., RONDININI, C., BOITANI, L. & POSSINGHAM, H. P. 2011. Ecological-economic optimization of biodiversity conservation under climate change. *Nature Climate Change,* 1**,** 355-359.

WONDOLLECK, J. M. & YAFFEE, S. L. 2000. *Making collaboration work: lessons from innovation in natural resource management*. Washington, D.C. and Covelo, California: Island Press.

WOODWARD, G., PERKINS, D. M. & BROWN, L. E. 2010. Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B,* 365**,** 2093-2106

NCCARF
National
Climate Change Adaptation
Research Facility

Australian Government
National Water Commission

UTAS