Climate Change in Queensland under Enhanced Greenhouse Conditions

Report, 2004-2005

Report on research undertaken for Queensland Departments of State Development, Main Roads, Health, Transport, Treasury, Public Works, Primary Industries and Fisheries, Environmental Protection and Natural Resources and Mines, Queensland Rail, SunWater and CS Energy

by

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Important Disclaimer

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The report was formatted by Julie Siedses.

List of Commonly used Abbreviations and Acronyms

CC50	CSIRO's Conformal Cubic Atmospheric Model run at 50 km resolution
CCCM	Canadian Centre Climate Model
DAR125	CSIRO's regional climate model "DARLAM" run at 125km resolution
DKRZ	Deutsches Klimarechenzentrum (German High Performance Computing Centre for Climate- and Earth System Research)
ECHAM4/OPY3	European Climate Model
ENSO	El Niño Southern Oscillation
GBR	Great Barrier Reef
GCM	General Circulation Model – also Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
HadCM3	Hadley Centre Coupled Atmosphere/Ocean General Circulation Model
IQQM	Integrated Quality Quantity Model
IPCC	Intergovernmental Panel on Climate Change
MSLP	Mean Sea Level Pressure
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environment Prediction
OLR	Outgoing Radiation-Longwave
RCM	Regional Climate Model
SetNet	Sediment River Network Model
SEACI	South East Australia Climate Initiative
SOI	Southern Oscillation Index
SRES	Special Research Emission Scenarios
SST	Sea Surface Temperature
TAR	Third Assessment Report (IPCC)

Summary for Policymakers

Regardless of future emissions, there is general scientific consensus that atmospheric levels of greenhouse gases have already reached the point where climate change is inevitable. Indeed the impacts of human-induced climate change have already begun to emerge across the world.

In order to respond and possibly mitigate some of these future changes it is crucial that a full scientific understanding about the global climate system and it's links to likely regional impacts is understood. Climate change is also likely to result in "surprises" and investment in climate science is important to reduce the uncertainty of future projections and support well thought out policy responses.

Observational evidence shows that over the last 50 years Queensland's climate has on average become both warmer and drier. Projections strongly support a continuation of these trends in the future with temperatures increasing by up to 2^{o}C and rainfall tending toward decrease over much of the state in the range of –13% to +7% by 2030.

Extreme historical climate events have already highlighted some areas of future climate risk in Queensland such as health and lifestyle; major infrastructure; industry; transport; water availability and security; the built environment; energy generation and distribution; land use planning; development; primary industries; natural systems and biodiversity.

A continuation of current climate trends in response to human influence on the global climate system will impose increasing costs upon the government, business and the wider community in term of managing and mitigating impacts. This may erode the government's ability to deliver on key elements of its community outcomes and related priorities, including regional development and efforts to foster new industries.

In a number of areas, the government is faced with important strategic decisions in the short to medium term where climate already plays an important role and thus climate change must be considered. Areas of particular concern include:

- expectations that in addition to observed warming trends, and resultant increases in evaporation, climate change will continue to deliver declining rainfall along coastal areas of Queensland, including the south east, with implications for the provision of adequate water supplies;
- likely increases in both average and extreme temperatures across the state as well as increases in extreme rainfall events will place increasing pressure on emergency response plans and services;
- the impact of climate change on extreme rainfall events and the implications for Queensland flood risk and land-use planning decisions associated with managing urban growth in the south-east; and
- the impacts of changes in average climate and extremes on the development of sustainable infrastructure and housing codes.

Given the current costs of extreme climate events on Queensland's economy, climate change related increases in extremes may result in significant increases in the cost of impacts. At present the costs of extreme events (excluding droughts) in Queensland such as flooding, severe storms, cyclones and bushfires amounts to $111.7 million, $37.3 million, $89.8 million and $0.4 million respectively (average calculated from 1967 to 1999 in 2001 dollars), per annum. (BTE, 2001; Coleman, 2003; Leigh *et al.,* 1998; and Pittock *et al.,* 1999 – full references in Appendix 3.) Historically, while the insurance industry has borne between 9 and 39% of the total cost of damage, the Federal and State Governments have been required to bear the remaining 60 to 90%. With extreme events expected to intensify as a result of climate change the costs to government, the economy and the wider community are expected to increase.

Queensland's multi-billion dollar tourism industry is at risk due to expectations that iconic ecosystems, notably the Great Barrier Reef and the World Heritage listed rainforest ecosystems of north Queensland will suffer damage.

Climate change may also bring about a greater risk of tropical diseases with vector borne diseases, such as dengue fever, of particular concern. In addition adverse health impacts are also expected in response to the changes in the frequency and duration of heatwaves, increased toxic blue-green algal blooms in water supplies and through direct injury resulting from increases in the intensity of severe weather events. Similarly climate change is likely to change the current range and incursion frequency of pests and weeds resulting in increased costs of control and eradication.

Average rainfall is expected to continue to decline in coastal areas south of Cairns, in particular in central and south-east coastal Queensland (1 to 4% decline in rainfall per degree of global warming), suggesting that water availability and water quality are at risk in key population and economic centres.

Increasing average temperatures and declining average rainfall will also pose significant challenges to current land management practices and agriculture in Queensland. Climate change will thus influence the suitability of areas for grazing and agricultural production requiring a re-evaluation of enterprise type and production mix, with flow-on impacts on marketing, distribution and international trade of commodities.

Thus with climate change expected to impact more broadly across a number of sectors, incorporating climate change considerations into planning and decision-making frameworks will allow measures to be taken to minimise future risks and costs. Given the extensive range of possible climate change impacts the research undertaken on this issue is not simply of benefit to the Queensland Government, but will also benefit local governments, government-owned-corporations, business and the wider community.

Table of Contents

Climate Change Scenarios for Queensland

Authors: Kathleen McInnes and Janice Bathols

Executive Summary

Climate projections have been developed utilizing newly available climate model simulations. The twelve models that produced the most realistic representation of current climate conditions were used for the scenario development. Future changes in rainfall tend toward decrease over much of the state with annual average changes in the range of −13% to +7% by 2030 and −40 to +20% by 2070 compared to averages calculated over the 1961 to 1990 period. Strong decreases in rainfall are projected for winter with most of the inland regions projected to change in the range of −26% to +7% by 2030 and −80% to +20% by 2070. Widespread reductions in rainfall are also projected over much of the state in spring, with decreases in the range of 0% to 20% by 2030 and 0 to 80% by 2070. In summer, increases or decreases of equal magnitude are possible over much of the state except for the eastern side of the Cape York Peninsula and the south-west of the state where there is a greater tendency towards rainfall increases in the range of −7% to +13% by 2030 and −20% to +40% by 2070. In autumn, there is a tendency toward rainfall decreases over much of the southern and eastern parts of the state in the range of −13% to +7% by 2030 and −40% to +20% by 2070. In the centre and west of the state, stronger decreases in the range of 0 to 20% by 2030 and 0 to 80% by 2070 are possible.

The average rainfall change derived from the twelve models' patterns of rainfall change indicates that in the annual average, rainfall decreases of between one and two percent per degree of global warming occurs across much of Cape York Peninsula, the south-east of the state and some coastal areas in between while stronger decreases of between two and four percent occur across much of inland Queensland. These can be combined with projections of average global temperature increase of 0.54 to 1.24° by 2030 and 1.17 to 3.77°C by 2070, to calculate the rainfall changes expected by these times.

Annual average temperatures over much of the interior of the state are projected to increase by 0.3 to 2.1°C by 2030 and 0.9 to 6.4°C by 2070. Along the coast and much of Cape York Peninsula, the range of warming is smaller with annual increases ranging from 0.2 to 1.6°C by 2030 and 0.7 to 4.8°C by 2070. Increases over the coastal ocean are in the range of 0.2 to 1.3°C higher by 2030 and 0.7 to 4.0°C higher by 2070. Some seasonal variations occur also with stronger increases possible in central Queensland in spring and summer.

Potential evaporation in coastal areas is projected to increase by between 1 and 8 % by 2030 and 2 and 24% by 2070 annually except on the east coast of Cape York Peninsula where increases of between 1 and 21% occur by 2030 and 2 and 64% by 2070. Over much of the interior of the state the range of increase is between about 1 and 13% by 2030 and 2 and 40% by 2070. In summer and autumn, increases in potential evaporation in the range of 1 and 21% by 2030 and 2 and 64% by 2070 occur over Cape York Peninsula while more moderate increases in the range of 1 and 8% by 2030 and 2 and 24% by 2070 are expected in the southwest and larger possible increases of up to 13% by 2030 and 40% by 2070 are possible in the southeast. In winter, the largest increases in potential evaporation are projected to occur in the southeast of the state in the range of 1 to 21% by 2030 and 2 to 64% by 2070. A similar pattern to winter is seen in spring although the range of increase in the southeast of the state is smaller, ranging from 2 to 16 % by 2030 and 4 and 48% by 2070.

Model selection

Since the last round of projections was completed, a new set of model simulations from international climate modelling groups have become available to CSIRO for use in its climate projections. These additional simulations use a selection of the SRES scenarios. A summary of the available simulations is given in Table 1. For the purposes of model assessment these available models total nineteen, noting that for some models there exist an older simulation conducted using an emissions scenario based on IS92a or a 1% compounding increase in CO_2 as well as the more recent simulations carried out using various different SRES scenarios.

Table 1. Climate model simulations analysed in this report. Further information about the non-CSIRO simulations may be found at the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/). Note that D125 and CC50 are Regional Climate Models

Centre	Model	Emissions Scenarios post-1990 (historical forcing prior to 1990)	Years	Horizontal resolution (km)	Symbols used in the report
Canadian CC	CCCM1	1% increase in CO_2 p.a.	1900–2100	~400	CM1
Canadian CC	CCCM2	IS92a	1961-2100	~400	CM2
Canadian CC	CCCM2	CO_2+ aerosol SRES, A2, B2	1900-2100	~400	CM2S
CCSR, Japan	CCSRNIES	SRES, A1, A1F1,A1T,A2,B1,B2	1890-2100	~500	CCSRS
CSIRO, Aust	Mark2	IS92a	1881–2100*	~400	MK2
CSIRO, Aust	Mark2	SRES A2 (four simulations), SRES B2	1881–2100*	~400	MK2S
CSIRO, Aust	DARLAM	IS92a	1961-2100	125	D125
CSIRO, Aust	Mark3	SRES A2	1961-2100	~200	MK3
CSIRO, Aust	CC	SRES A2	1961-2100	50	CC50
DKRZ, Germany	ECHAM3/LSG	IS92a	1880-2085	~600	ECM3
DKRZ, Germany	ECHAM4/OPYC3	IS92a	1860–2099	~300	ECM4
DKRZ Germany	ECHAM4/OPYC3	CO_2+O_3 + aerosol, SRES A2, B2	1990-2100	~300	ECM4S
GFDL	GFDL	1% increase in CO_2 p.a.	1958–2057	~500	GFDL
GFDL	GFDL	Varying insolation + aerosol, SRES A2, B2	1961-2100	~500	GFDLS
Hadley Centre, UK	HadCM2	1% increase in CO_2 p.a. (four simulations)	1861–2100	~400	HCM2
Hadley Centre, UK	HadCM3	IS92a	1861-2099	~400	HCM3
Hadley Centre, UK	HadCM3	CO_2+O_3 + aerosol, SRES, A2, B2	1950-2099	~400	HCM3S
NCAR –CSM	NCARCSM	SRES A2	2000-2099	~300	NCARCS
NCAR-PSM	NCARPSM	CO_2+ aerosol SRES, A1B, A2, B2	1980-2099	~300	NCARPS

As in previously prepared scenarios, the development of climate change projections on a regional scale relies on analysing as many climate model simulations as feasible to ensure that uncertainty due to the climate sensitivity inherent in different models is captured. A prerequisite for the inclusion of a GCM into the climate projections is that it adequately simulates present climate conditions and so each of the models are assessed on their ability to simulate current climate averages of sea level pressure, average temperature and rainfall using two statistical measures.

Observed and simulated patterns for 1961-1990 were compared for their pattern similarity using the pattern correlation coefficient, and for magnitude differences using the root mean square error (RMS). A pattern correlation coefficient of 1.0 indicates a perfect match between observed and simulated spatial patterns while an RMS error of 0.0 indicates a perfect match between observed and simulated magnitudes. For mean sea level pressure, the National Center for Environmental Predictions (NCEP) analyses over a region encompassing Australia, bounded by 110-160ºE and 10-45ºS were used as a basis for comparison. For temperature and rainfall, Bureau of Meteorology gridded data available over the land areas within 130-155ºE and 10-30ºS were used for assessing model performance. The comparisons were carried out for each season.

To compare the overall performance of each model, a simple point system based on thresholds was devised. Models with an RMS error greater than 2.0 were assigned a demerit point. Additionally, a demerit point was assigned for models with a pattern correlation below 0.8 for MSLP and temperature and 0.6 for rainfall. Considering the three variables and the four seasons considered, a maximum of 24 points would indicate failure to achieve these minimum requirements for any variable in any season. Using this system, the poorest performing models were CCSR, NCAR-CGM, GFDL and ECHAM3 with scores between 7 and 13. The best performing models included DAR125, HADCM3, CC50 and Mark2 with scores of two or less. Skill scores for MSLP indicated that models generally captured the spatial pattern of pressure well in all seasons but RMS error in some models was higher in winter and spring where the strength of the subtropical ridge across the continent was either over or underestimated. For temperature, the RMS error in some of the lowest resolution models was high during winter and spring and this appeared to be due to the models' failing to capture the strong temperature contrasts associated with the east coast topography during the colder months. RMS errors for rainfall were generally well captured in all seasons except summer where some models failed to produce the strong rainfall in the north of the state. Based on overall performance, it was decided to exclude the four poorest performing models from the scenario development since the realism in the present climate representation throughout the year was generally poor.

Data processing and pattern extraction

The large number of model simulations retained for scenario development cover a wide range of different emissions scenarios and therefore different rates of warming. To eliminate the dependence of each model simulation on the emissions scenario used, each model simulation is linearly regressed against its own globally averaged warming signal yielding a pattern of change per degree of global warming. For any particular model run with a set of emissions scenarios, or an ensemble of runs for a particular scenario, the resulting patterns of change show strong similarity to each other and are therefore averaged to produce a single pattern of change for each variable considered. For models such as CCM2, HADCM3 and ECHAM4, this included the pattern of change for the older IS92A scenario also. This procedure yielded a set of 12 patterns for each model variable for each season.

The twelve patterns of change were then ranked and condensed into a single colour-coded map in which each colour represents the range of possible change simulated by the models from the second lowest to the second highest. The exclusion of the highest and lowest values is to minimize the influence of outliers on the projections and in doing so, reduce the range of possible change. The patterns of change per degree of global warming are then converted to projections of future change by scaling them with the IPCC globally averaged warming curves.

Projected changes in average climate conditions for Queensland

In this section, projections of future rainfall changes in Queensland are presented based on the patterns of change for the twelve models discussed in the previous section. The projections are expressed as a range of change. The range incorporates the quantifiable uncertainties associated with the range of future emissions scenarios, the range of global responses of climate models, and model to model differences in the regional pattern of climate change.

Rainfall

Figure 1 presents the projections of average rainfall conditions by around 2030 and 2070 relative to 1990. The two dates are selected to provide information relevant to both short term and long term planning horizons. The conditions of any particular year will continue to be strongly affected by natural climate variability, which cannot be predicted.

Projected annual average ranges tend toward decrease over much of the state in the range of −13% to +7% by 2030 and −40 to +20% by 2070. The Cape York Peninsula and a small region in the south-west of the state indicate that increases or decreases of around 7% are possible by 2030. By 2070, this range increases to 20%. In summer, increases or decreases of equal magnitude are possible over much of the state except for the eastern side of the Cape York Peninsula and the south-west of the state where there is a greater tendency towards rainfall increases in the range of −7% to +13% by 2030 and −20% to +40% by 2070. In autumn, there is a tendency toward rainfall decreases over much of the southern and eastern parts of the state in the range of −13% to +7% by 2030 and −40% to +20% by 2070. In the centre and west of the state, stronger decreases of up to 20% are possible by 2030 and these decreases could drop to 80% by 2070. The strongest possible decreases in rainfall are projected for winter with most of the inland regions projected to change in the range of −26% to +7% by 2030 and −80% to +20% by 2070. The ranges of change are narrower in the south of the state and along the coastal regions in the east. Over much of the state in spring, rainfall is projected to decrease from 0% to −20% by 2030 and by up to 80% by 2070.

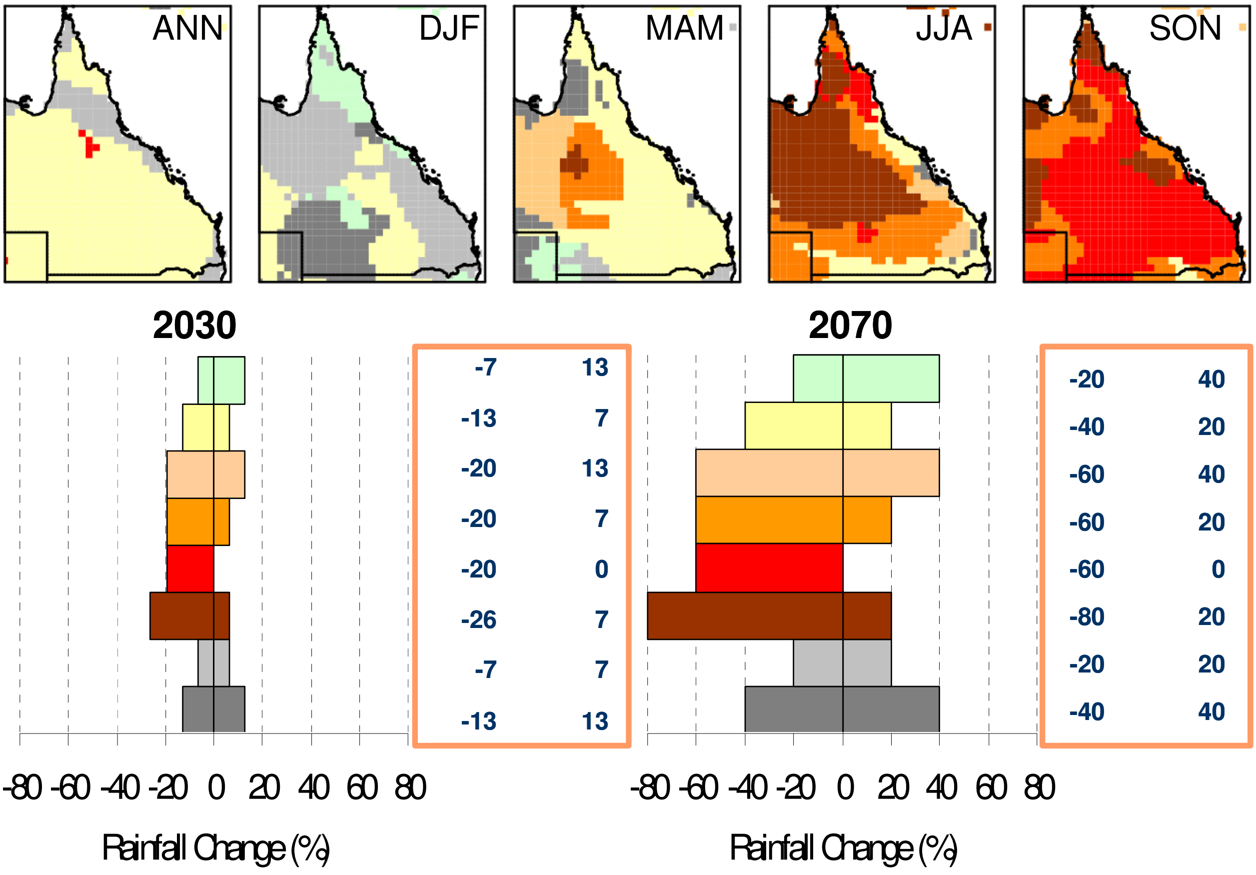

Figure 1. Average annual and seasonal rainfall change (%) for 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps

There is strong similarity between the projections produced this year and those produced for last year's report. The main difference is a slight narrowing in one range of possible change (indicated by the colour apricot in Figure 1) from -26% to +13% for 2030 last year to -20% to +13% for 2030 in this year's projections. This is despite there being two additional models included in the projections.

The projections presented in Figure 1 convey information about the possible range of change but no information on the likelihood of any particular change taking place. In the absence of probabilistic projections, and in view of the fact that for rainfall in particular, where both increases and decreases are possible, it is informative to present additional information about the nature of the rainfall change. The first of these is a map of the number of models that project either increase or decrease in rainfall as shown in Figure 2. In the annual average, the majority of models indicate rainfall decrease over most of the state except for the northern tip of Cape York Peninsula where seven out of twelve models indicate rainfall increase. During summer, where the projections in Figure 1 indicated large areas where rainfall change could go either way, Figure 2 again shows that over much of the state, the majority of models indicate rainfall decreases although nine out of twelve models indicate increased rainfall on the northern tip of the Cape York Peninsula. In autumn rainfall decreases are indicated by most models in the east of the state while in the west, the sign of the change is less certain with about half of the models indicating increase and half decrease. In winter and spring, the majority of models indicate rainfall decreases with the central and southern parts of the state in spring showing that all twelve models indicate rainfall decreases.

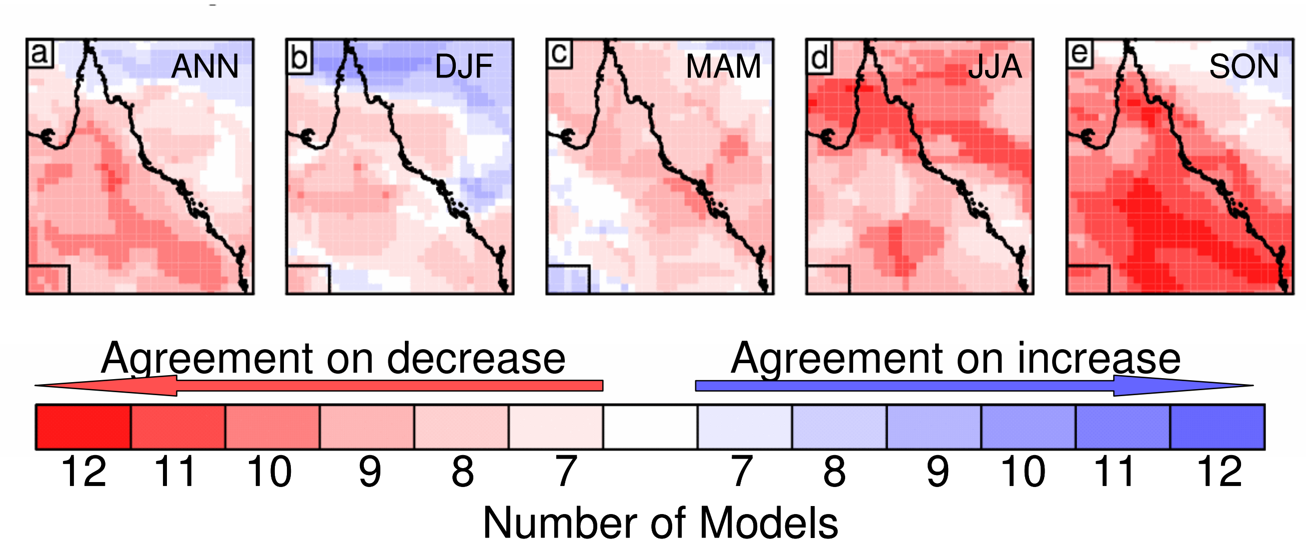

Figure 2. Map showing agreement between the twelve models on the sign of the rainfall change. Areas of white indicate where half of the models indicated increase and half of the models indicated decrease

An average of the twelve patterns of rainfall change per degree of global warming is presented in Figure 3. In the annual average, rainfall decreases of between one and two percent occur across much of Cape York Peninsula, the south-east of the state and some coastal areas in between while decreases of between two and four percent occur across much of inland Queensland. In summer, increases in rainfall of up to about two percent occur in the north of Cape York Peninsula while increases of up to one percent occur in the southwest of the state. Elsewhere, rainfall decreases of up to two percent occur. In autumn, decreases up to about four percent occur in all except the far west of the state where some slight increases occur. In winter and spring, strong rainfall decreases occur reaching ten percent to the south of the Gulf of Carpentaria in the winter and between four and eight percent across the state in spring.

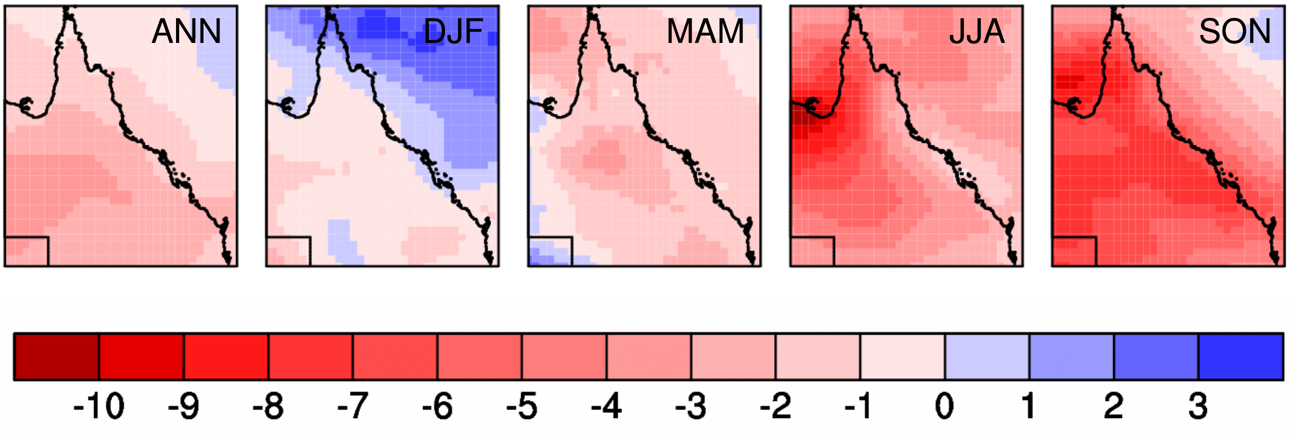

Figure 3. The average of the twelve patterns of rainfall change per degree of global warming. Units are % rainfall change per degree of global warming

Temperature

Figure 4 represents the changes in average temperature by around 2030 and 2070 relative to 1990 over Queensland and surrounding ocean regions. In all seasons, the maps indicate greater amount of warming and a larger range of possible warming in the southwest. Annual average temperatures are 0.3 to 2.1℃ higher by 2030 and 0.9 to 6.4℃ higher by 2070. To the northeast, there is a smaller range of possible warming and the upper range of this warming is lower with changes in annual average temperatures ranging from 0.2 to 1.6℃ higher by 2030 and 0.7 to 4.8℃ higher by 2070. Increases over the ocean are in the range of 0.2 to 1.3℃ higher by 2030 and 0.7 to 4.0℃ higher by 2070 and this range of change is expected in all seasons.

Similar patterns of change are seen in the seasonal temperature projections with the largest range of change in the southwest of the state. The highest increases in temperature in the southwest occur in summer and spring in the range 0.4 to 2.3℃ by 2030 and 1.1 to 7.2℃ by 2070. In all seasons, the smallest increases in temperature are projected to occur at the northern tip of Cape York Peninsula and are in the range of 0.2 to 1.3℃ higher by 2030 and 0.7 to 4.0℃ higher by 2070.
In the southeast of the state, the range of temperature change is expected to be 0.2 to 1.6℃ higher by 2030 and 0.7 to 4.8℃ higher by 2070.

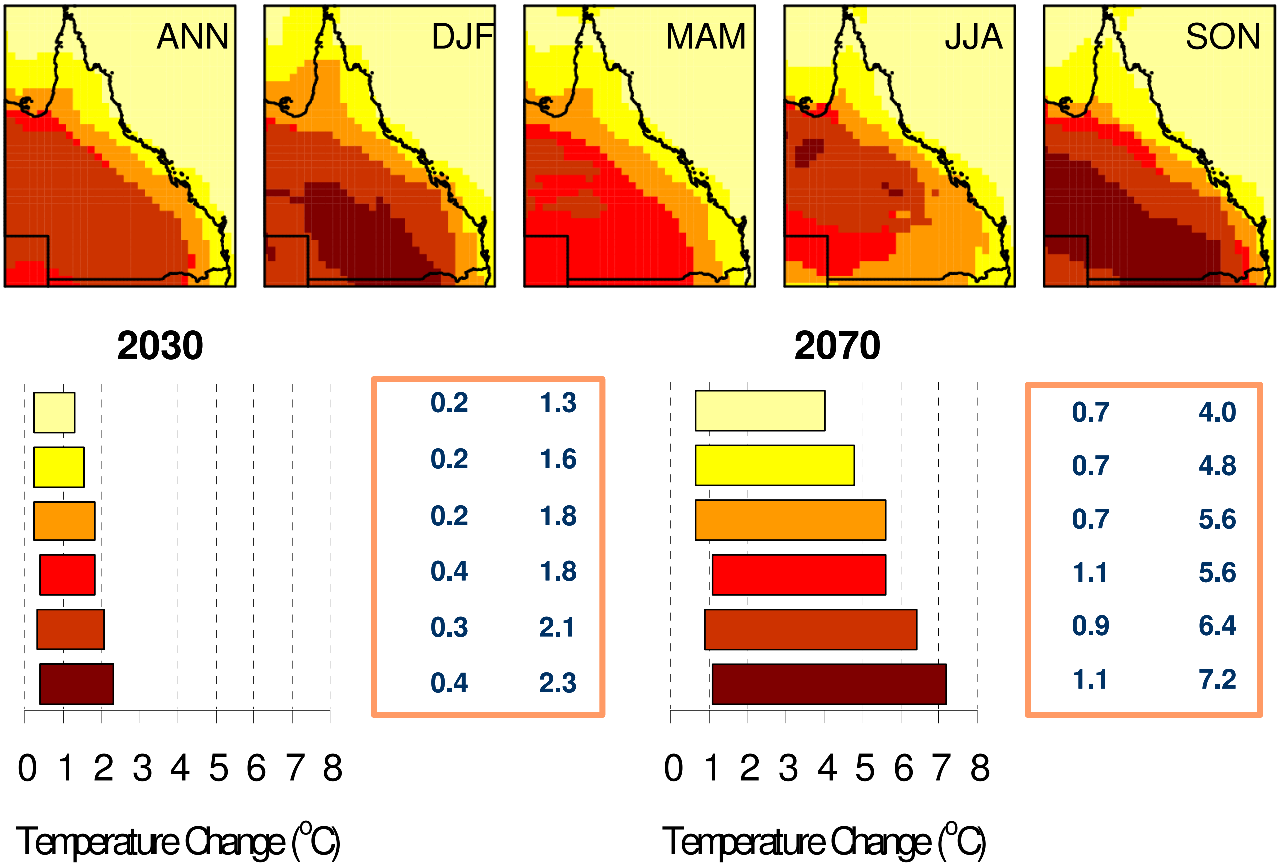

Figure 4. Average annual and seasonal temperature change (°C) for 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps

Potential Evaporation

Figure 5 presents the 1961-1990 climatological values for point potential evaporation. In the annual average, potential evaporation exceeds 2900 mm in the west of the state while minimum values less than 1900 mm are found in the far southeast of the state. Greatest potential evaporation occurs in the summer in the hotter drier southwest of the state while over the northern half of Cape York Peninsula, the summer monsoon leads to lower potential evaporation. Cooler conditions in the south of the state in winter bring about lower values of potential evaporation under 300 mm while the hotter drier conditions over Cape York Peninsula produce relatively high values of potential evaporation. Changes in potential evaporation are shown in Figure 6. In the annual average, potential evaporation in coastal areas is projected to increase by between 1 and 8 % by 2030 and 2 and 24% by 2070 except on the east coast of Cape York Peninsula where increases of between 1 and 21% occur by 2030 and 2 and 64% by 2070. Over much of the interior of the state the range of increase is between about 1 and 13% by 2030 and 2 and 40% by 2070. In summer, large possible increases in potential evaporation occur over Cape York Peninsula in the range of 1 and 21% by 2030 and 2 and 64% by 2070 while further south, more moderate increases in the range of 1 and 8% by 2030 and 2 and 24% by 2070 are expected in the southwest and larger possible increases of up to 13% by 2030 and 40% by 2070 are possible in the southeast. It should be noted that the large changes in potential evaporation over Cape York Peninsula in summer and autumn are relative to lower base climate value and so in absolute terms are less dramatic than they appear in Figure 6. In winter, the largest increases in potential evaporation are projected to occur in the southeast of the state in the range of 1 to 21% by 2030 and 2 to 64% by 2070. A similar pattern to winter is seen in spring although the range of increase in the southeast of the state is smaller, ranging from 2 to 16 % by 2030 and 4 and 48% by 2070.

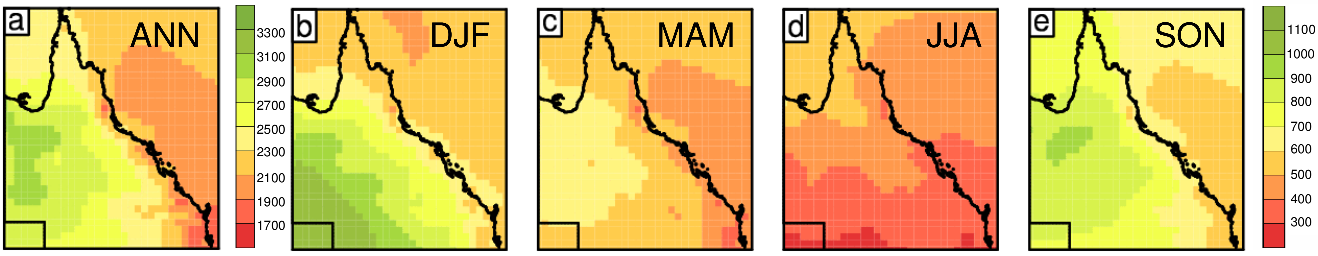

Figure 5. Average annual and seasonal point potential evaporation (mm)

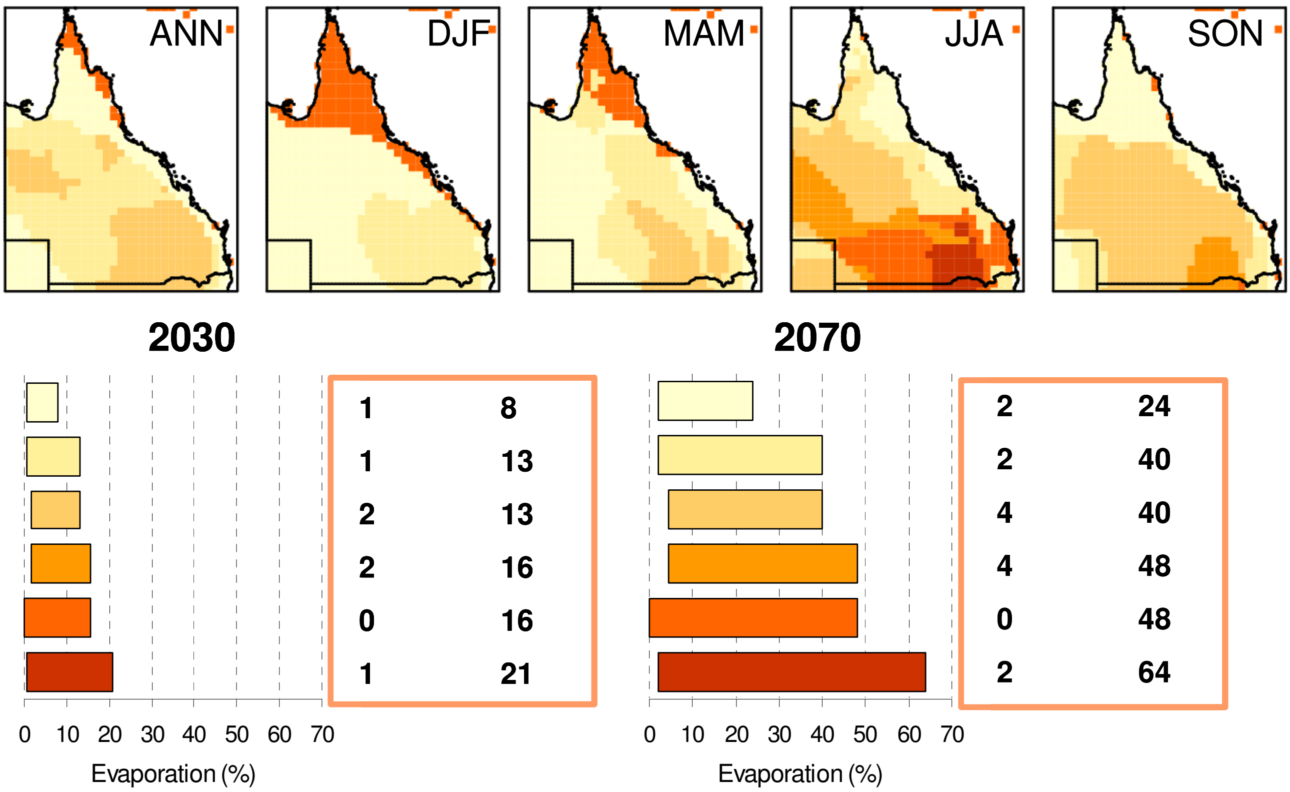

Figure 6. Average annual and seasonal potential evaporation change (°C) for 2030 and 2070 relative to 1990. The coloured bars show ranges of change for areas with corresponding colours in the maps

Climate Change impacts on the Water Resources of the Fitzroy River Basin

Authors: Roger Jones, Paul Durack, Cher Page and Jim Ricketts

Executive Summary

Climate change impacts on the water resources of the Fitzroy River Basin have been developed by coupling CSIRO's OzClim scenario generator with the IQQM rainfall runoff model.

The study has involved:

- Development of climate change scenarios for the Fitzroy River Basin for 2030 and 2070 based on the Inter-governmental Panel on Climate Change (IPCC) scenarios and regional precipitation and potential evaporation from 11 general circulation models (GCMs)

- Coupling the Fitzroy River Basin IQQM model to CSIRO's OzClim scenario generator and evaluated for baseline conditions

- Determine a dry, median and wet scenario based on projected ranges of global warming and catchment rainfall change for 2030 and 2070. These produced ranges of change in mean annual flow of -31 to +22% by 2030 and -65% to +80% by 2070

- Developed a flow-weighting method of averaging annual rainfall and potential evaporation changes to allow for the high seasonality of flow in the Fitzroy River

- Run a thorough risk analysis using the full suite of 11 GCMs, with two different sampling strategies to constrain uncertainty and provide most likely ranges of change change in mean annual, lowest 10% and highest 90% flows for the basin

The findings of this study are summarised below:

- The most likely change in mean annual flow for the Fitzroy River (obtained by trimming the most unlikely 5% from the upper and lower tails of the distribution) is -15% to +5% by 2030 and -40% to +15% by 2070 (to the closest 5% change)

- There is an approximately 1 in 3 change of flow increasing and a 2 in 3 chance of mean annual flow decreasing

- Median flow changes indicate a slight decrease when compared to observed flows recorded from 1900–1990

- Low flows are likely to reduce by more than average flows if average flow decreases. (Net increases in low flows are possible if mean flow increases)

- The extent of changes in high flows is highly dependent on changes to wet season rainfall and are likely to be close to changes in average flows

- High flows are likely to increase if summer rainfall increases

- Uncertainty analysis indicates that changes in timing and amount of summer rainfall as a function of global warming, constitute almost three quarters of the total range of uncertainty in mean annual flow.

- Risk analytic techniques significantly constrain the ranges of change in average stream flow even where wide ranges of change are possible

Introduction

This assessment quantifies the impact of climate change on streamflow in the Fitzroy River Basin. It is divided into two parts: the first part describing how the assessment system is constructed with a set of results describing the driest, median and wettest scenarios based on the range of available climate scenarios. The second part describes a risk assessment, where techniques developed by CSIRO are applied to assess the most likely outcomes based on the range of regional climate change assessed from a suite of climate models.

The method used couples OzClim, CSIRO’s climate change scenario generator, to the Integrated Quality Quantity Model (IQQM) developed by the NSW Department of Infrastructure, Planning and Natural Resources (DIPNR, formerly the Department of Land and Water Conservation; Department of Land and Water Conservation, 1995) and applied in Queensland by the Department of Natural Resources, Mines and Energy (DNRME). The Fitzroy River Basin IQQM was developed by the Surface Water Assessment Group of Resource Sciences Centre’s Water Assessment and Planning Group as part of the Water Allocation and Management Plan (WAMP) process.

The results quantify the magnitude and direction of change in total mean annual streamflow for the entire catchment in 2030 and 2070, providing upper and lower estimates of change. They take into account the major scientific uncertainties and uncertainties in future greenhouse gas emissions that affect the magnitude of global warming and direction and magnitude of regional climate change.

Part I - Impact Assessment Modelling

The overall approach in this project was to perturb historical records daily rainfall and potential evaporation providing the input to the Fitzroy Basin IQQM with a series of climate change scenarios for 2030 and 2070. The IQQM was then run for each scenario and the resulting streamflow compared with baseline streamflow calculated using historical climate data. The climate scenarios were monthly mean changes calculated from climate change patterns linearly interpolated to a 0.25° grid, the aim being not to create highly precise scenarios from individual climate models but to sample as large a range of uncertainty as possible. The results from this study are being used in a risk analysis taking account of the major climate uncertainties affecting water resources at the Basin scale.

OzClim, CSIRO's climate change scenario generator (Page and Jones, 2001) was coupled to the IQQM for the entire Fitzroy River Basin and the entire process automated, allowing multiple scenarios to be run from a prescribed set of climate scenarios. A single model run takes thirty to forty minutes, and several dozen can be scheduled in a single batch, in a system designed to explore the effect of climate change uncertainty.

Climate change scenarios were created from global warming projections developed by the Intergovernmental Panel on Climate Change (IPCC, 2001) and from regional patterns of climate change calculated from a suite of GCMs. Global warming was multiplied with regional patterns of change within OzClim to create a range of regional monthly changes for rainfall and potential evaporation. These changes were then used to perturb the daily input files of rainfall and pan evaporation used as input to the Fitzroy Basin IQQM. The input climate files were infilled series of total daily rainfall and pan evaporation across the Fitzroy catchment from 1900–1990.

IQQM contains two main models. Changes to run-off were simulated using the Sacramento model (Burnash et al., 1973). Changes to runoff in turn affect streamflow, storage and allocations as defined by a pre-existing set of rules in the IQQM river basin model, which represents the physical components of the basin (dams, river reaches, demand centres etc.) and the operational management rules of the basin system. Altered rainfall and evaporation also affect crop water requirements and irrigation demands of the basin.

The coupled system of OzClim and IQQM comprises a rapid assessment framework through which multiple scenarios can be run. This system follows 7 major steps:

1. A no climate change base case was established with rainfall-runoff models used to simulate inflows for all sub-catchments of the Fitzroy system and checked with data provided by the Surface Water Assessment Group;
2. Climate change scenarios in the form of mean monthly factors were applied to daily rainfall and evaporation sites in the Fitzroy River Basin;
3. Changes in runoff and streamflow were estimated for each sub-catchment rainfall-runoff model;
4. The simulated streamflow sequences from the rainfall-runoff model for each of the sub-catchments were used as inputs to individual Fitzroy River Basin IQQM components at the relevant locations within the basin;
5. Individual IQQMs were run for the relevant locations within the Fitzroy Basin. The time period that these simulations are run for is dependent upon the historical data available for each of the input locations. The following scenarios were run:
    a. No climate change: based on historical climate records only;
    b. 2030: the historical sequence is modified to represent the range of possible climate change that will be experienced by the year 2030;
    c. 2070: as above but for 2070;

6. The modified sequence of streamflows and irrigation diversion for each location were output by IQQM;
7. These files were compared with the baseline to determine the impact of climate change on total catchment streamflow.

The Fitzroy Basin System

The Fitzroy Basin is one of the largest in Queensland, covering an area of approximately 142,500 km^2. It includes the catchment of the Fitzroy River and its major tributaries: the Dawson, Comet, Nogoa, Mackenzie, Isaac and Connors Rivers. The Fitzroy is the largest river basin on the east coast of Australia, and drains to the southern end of the Great Barrier Reef, just south-east of Rockhampton. The catchment is one of the richest areas in the state in terms of land, mineral and water resources, and supports grazing, irrigated and dryland agriculture, mining, forestry and tourism land uses. It contains about 10% of Queensland's agricultural land and 95% of the catchment is under agricultural land-use comprised of about 87% grazing and 8% cropping.

The climate of the Fitzroy Basin is subtropical to tropical, ranging from humid near the coast to semi-arid inland. There is a wide range of diverse environments within the catchment, comprising higher rainfall areas of the Great Dividing Range near the coast with up to 1,200 mm of mean annual rainfall declining to approximately 500 mm inland. There is a pronounced wet season in the summer months which produces high seasonal flows and frequent flood events following monsoonal downpours and tropical cyclones. Flows are highly variable, with many of the rivers having very low flows, or drying altogether during the dry season.

The Fitzroy Basin system is divided into the following sub-systems: Isaac–Connors, Nogoa, Comet, Upper Dawson, Lower Dawson, Upper Mackenzie, Lower Mackenzie and the (lower) Fitzroy (see Figure 7). Figure 8 expresses the stream network, location of major nodes and topography of the Fitzroy River Basin.

Figure 7. The Fitzroy River Basin showing major catchments

Figure 8. Stream Network, location of major nodes, topography and subcatchments of the Fitzroy River Basin

The Climate Change Scenarios

Projected Climate change

Climate scenarios were selected to quantify as large a change in catchment streamflow due to climate change as possible. Three major climate-related uncertainties were accounted for. The first two are global uncertainties, which include the future emission rates of greenhouse gases and the sensitivity of the climate system's response to the radiative balance altered by these gases. Both uncertainties are portrayed in Figure 9, which shows the range in global warming to 2100, based on the Special Report on Emission Scenarios (SRES; Nakiçenovic et al., 2000) and IPCC (2001). The dark grey shading shows emission-related uncertainties, where all the SRES scenarios have been applied to models at constant 2.5℃ climate sensitivity. The light grey envelope shows the uncertainty due to climate sensitivity ranging from 1.5–4.5℃ (measured as the warming seen in an atmospheric climate model when pre-industrial CO_2 is doubled). These uncertainties contribute about equally to the range of warming in 2100.

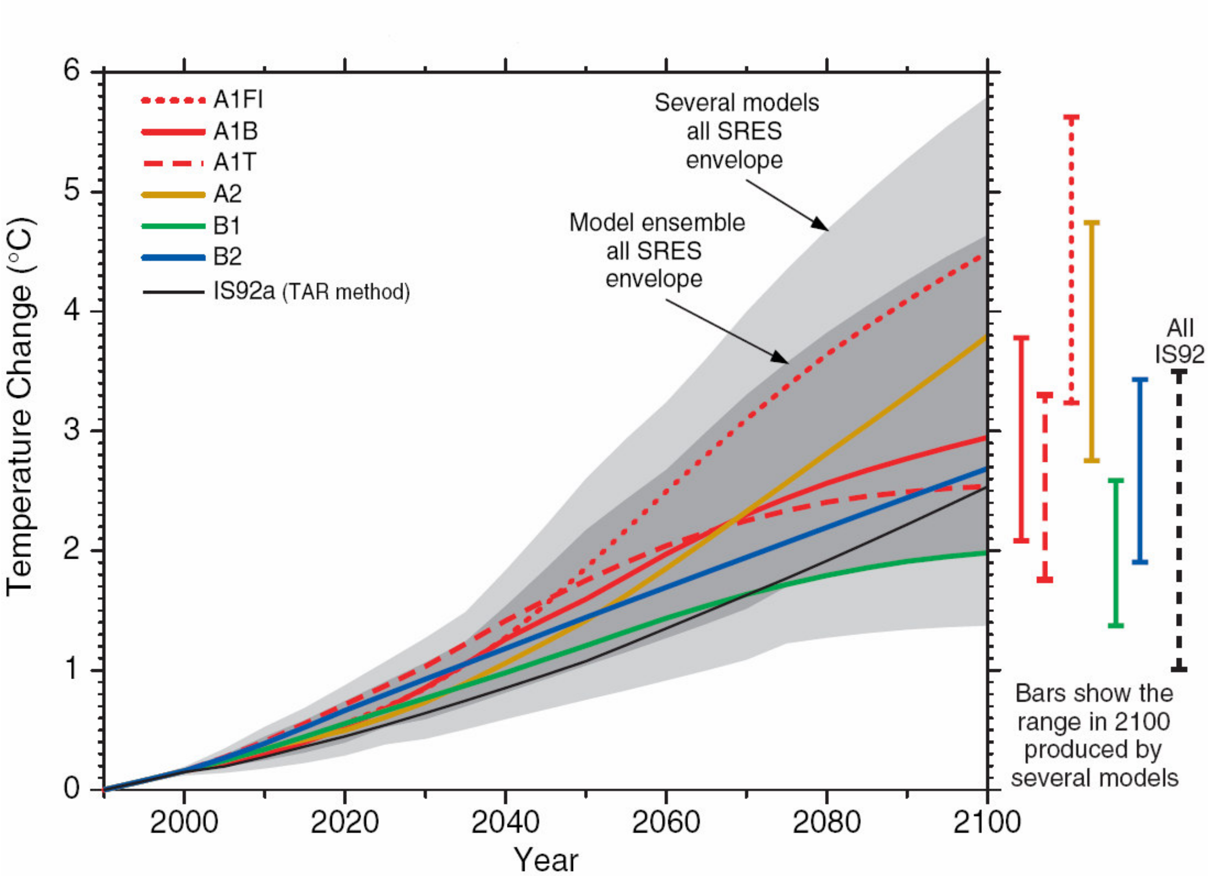

Figure 9. Global mean temperature projections for the six illustrative SRES scenarios using a simple climate model tuned to a number of complex models with a range of climate sensitivities. Also for comparison, following the same method, results are shown for IS92a. The darker shading represents the envelope of the full set of thirty-five SRES scenarios using the average of the models results. The lighter shading is the envelope based on all seven model projections (from IPCC, 2001)

The third major uncertainty is regional, described by changes to mean monthly rainfall and potential evaporation. To capture the ranges of these regional changes, we use projections from a range of international GCMs, as well as GCMs and Regional Climate Models (RCMs) developed by CSIRO.

Projections of regional climate change and model performance in simulating Queensland's climate have been described by McInnes and Bathols (Section 1 of this document). Here, we have access to a similar suite of climate model results as summarised in Section 1 with the limiting factor being the availability of projections for potential evaporation.

Regional climate projections for Queensland have been reported in Cai et al. (2003) and updated by McInnes and Bathols (Section 1) as part of the current year's work. They investigated the ability of the models to simulate sea level pressure, temperature and rainfall, discarding the four poorest-performing models from subsequent analysis. The subset models surveyed for this climate change impacts on water resources of the Fitzroy River Basin study are summarised in Table 2.

Table 2. Climate model simulations analysed in this report. Further information about the non-CSIRO simulations may be found at the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/). Note that D125 and CC50 are Regional Climate Models

Centre	Model	Emissions Scenarios post-1990 (historical forcing prior to 1990)	Years	Horizontal resolution (km)	Symbols used in the report
Canadian CC	CCCM2	IS92a	1961–2100	~400	CM2
Canadian CC	CCCM2	CO2+ aerosol SRES, A2	1900–2100	~400	CM2S
Canadian CC	CCCM2	CO2+ aerosol SRES, B2	1900–2100	~400	CM2S
CSIRO, Aust	Mark2	IS92a	1881–2100	~400	MK2
CSIRO, Aust	DARLAM	IS92a	1961–2100	125	D125
CSIRO, Aust	Mark3	SRES A2	1961–2100	~200	MK3
CSIRO, Aust	CC	SRES A2	1961–2100	50	CC50
DKRZ Germany	ECHAM4/OPYC3	IS92a	1990–2100	~300	ECM4S
Hadley Centre, UK	HadCM3	IS92a	1861–2099	~400	HCM3
Hadley Centre, UK	HadCM3	CO2+O3 + aerosol, SRES, A2	1950–2099	~400	HCM3S
Hadley Centre, UK	HadCM3	CO2+O3 + aerosol, SRES, B2	1950–2099	~400	HCM3S

In the region surrounding the Fitzroy River Basin, annual rainfall projections range from slightly wetter, to much drier than the historical climate of the past century. Seasonally, changes are uncertain in DJF and to a lesser extent in MAM but are dominated by decreases in JJA and SON. Over successive generations of climate models, estimates of rainfall change have become drier, but increases in the Fitzroy River region remain plausible.

Regional temperature increases inland at rates slightly greater than the global average, with the high-resolution models showing the steepest gradient away from the coast. Ranges of change are shown in McInnes and Bathols (Section 1). Changes to potential evaporation increases in all cases, with increases greatest when coinciding with significant rainfall decreases.

Potential evaporation

When dealing with evaporation, it is important to define precisely the nature of evaporation being addressed. Evaporation can be divided into potential and actual evaporation. On land, the term evaporation usually refers to the combination of evaporation from non-vegetated surfaces and transpiration from plants or, more strictly, evapotranspiration. Here, we use the term evaporation with the understanding that it also includes transpiration where relevant.

Potential evaporation denotes the potential of an overpassing airmass to evaporate available water from open water or soil, and transpire water from plants. Actual evaporation is the resulting water evaporated, which depends on the amount of energy absorbed by a plant, water or soil surface, the water available to be evaporated and the capacity of the above airmass to remove that water. Potential evaporation is a more useful factor in climate impact studies because it refers to the atmospheric demand for moisture that might otherwise be available for plant water use or hydrological purposes.

Three different types of potential evaporation are commonly used. Pan evaporation is routinely measured by meteorological agencies as the evaporation of water from a 1.2 m diameter pan with a depth about 0.5 m (the A-Class Pan). Pan evaporation is used to represent potential evaporation but its measurement is highly error prone, so hydrologists often prefer to calculate potential evaporation from models using climatic variables such as temperature, humidity, solar radiation or sunshine hours, and sometimes wind speed, when assessing surface water balance. Point potential evaporation is most similar to pan evaporation and measures evaporation at a point. Areal potential evaporation takes into account the ability of evaporation over large areas to modify the passing airmass, so is less than point potential evaporation (or pan evaporation). Areal potential evaporation is relevant for areas larger than about 10 hectares in size (e.g. lakes, forests, large paddocks), being an area large enough to modify the overpassing airmass.

Potential and actual evaporation can be related through the principle of complementarity (Bouchet, 1963). When water evaporates from the surface, it moistens and cools the air above. Under the principle of complementarity, point potential and actual evaporation added together will equal twice the areal evaporation (Figure 10). The greater rainfall (or moisture at the surface) becomes, the higher actual evaporation will be, and the lower potential evaporation will be. Therefore, pan evaporation measures the evaporation of water at a point and will always be much higher than lake evaporation or areal potential evaporation as measured over a larger area.

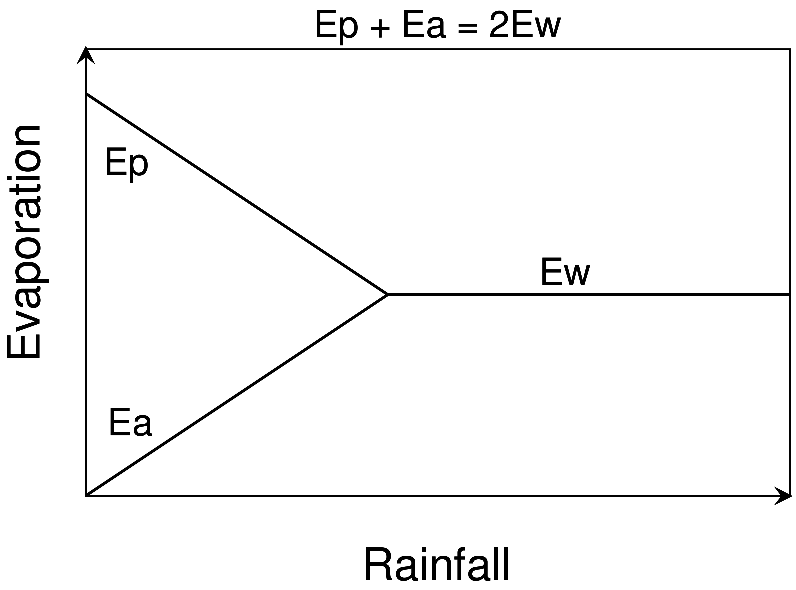

Figure 10. Schematic diagram of the principle of complementarity. Ep is point potential evaporation, Ea is actual evaporation and Ew is areal potential evaporation

In their modelling of runoff in IQQM, DNRME have used A-Class Pan data but apply a scaling factor to approximate areal evaporation, using estimates of lake evaporation and Morton's Complementary Areal Evaporation Method (Morton, 1983).

An evaporation climatology for Australia produced for the Bureau of Meteorology (2001) provides maps for average total monthly point potential, areal potential and actual evaporation from 1961–1990 calculated using Morton's (1983) method. This used as input: average temperature, relative humidity and downward solar radiation. We have produced estimates of point potential and areal potential evaporation from a number of climate models using the same method. Point potential and areal potential evaporation increased in most months and regions across the models, increasing on a seasonal basis over Australia in all models, although areal potential evaporation increases by about ⅔ the rate of point potential evaporation. We have used changes to areal potential evaporation in preference to point potential evaporation because it is more realistic for estimating hydrological change.

Climate change patterns

Patterns of climate change calculated as percentage change per degree of global warming were created for monthly changes in rainfall and areal potential evaporation from a range of models (see McInnes and Bathols, Section 1). In OzClim, these are linearly interpolated onto a 0.25° grid (the simplest form of downscaling). Changes are averaged for a specific area.

Area average changes for the Fitzroy River Basin are shown in Table 3. Two models, the ECHAM4 and DARLAM125 models show rainfall increases, whereas all the other models show decreases. All models show increases in areal potential evaporation, but those changes are inversely correlated with rainfall change, with a correlation co-efficient of -0.77. This shows that increasing rainfall results in lesser increases in potential evaporation, an outcome that is physically consistent with having generally cloudier conditions in situation where rainfall increases. This will produce a "double jeopardy" situation if mean rainfall decreases because this will be accompanied by relatively larger increases in potential evaporation.

Table 3. Changes in rainfall, point potential and areal potential evaporation for the Fitzroy River Basin, simulated by the models in Table 1, expressed as a percentage change per degree of global warming

Model	Rainfall	Areal Potential Evaporation	Point Potential Evaporation
Mark2	-2.50	3.37	5.8
Mark3	-4.97	3.57	5.39
CC50	-6.26	5.50	9.45
DARLAM125	2.58	3.77	5.39
CCCM2	-1.09	3.36	4.47
CCCM2-A2	-0.72	3.03	
CCCM2-B2	-0.29	2.65	
ECHAM4/OPYC3	3.37	3.26	2.26
HadCM3	-5.03	5.06	8.31
HadCM3-A2	-3.81	4.87	
HadCM3-B2	-8.27	5.91	

Seasonal changes are shown in Figure 11 where the mean monthly change for both rainfall (P) and areal potential evaporation (Ep) per degree of global warming is shown with the upper and lower extremes. The seasonal distribution of projected rainfall change shows a slight bias towards increase in the wet season (January, February and March) and a strong bias towards decrease in the dry season (September, October and November). Changes in Ep are much more certain, always increasing and showing a slight inverse relationship with rainfall, with deviations of only few percent per degree of global warming between models.

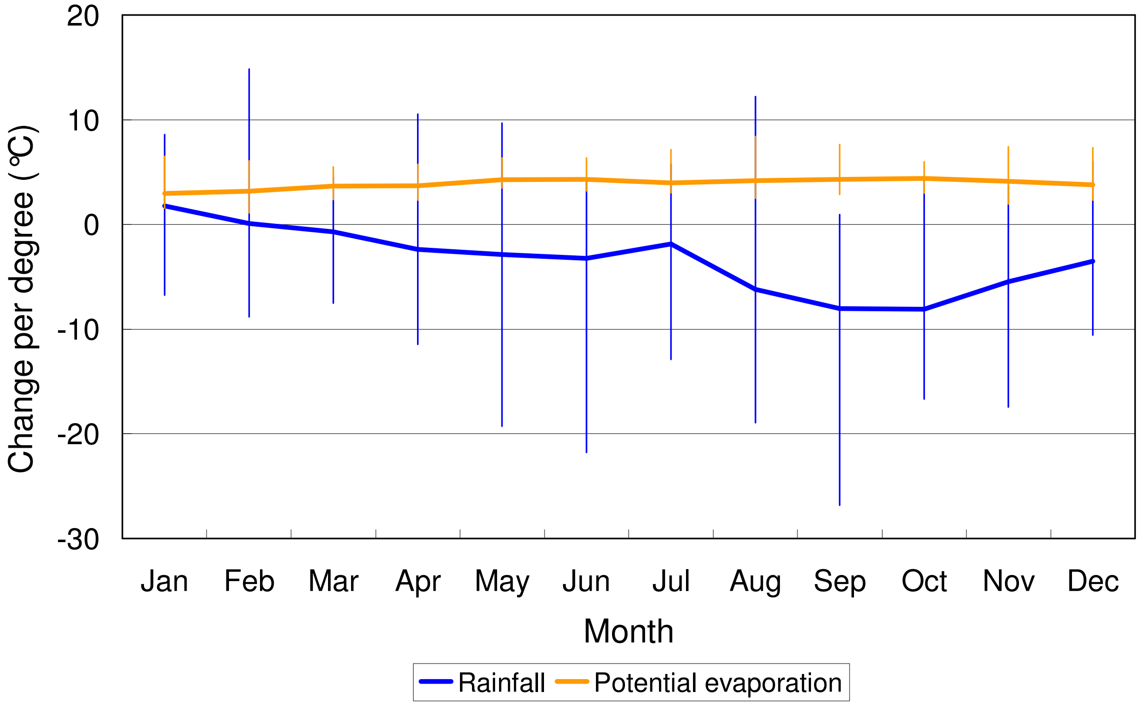

Figure 11. Average monthly change in P and Ep from the eleven climate models shown in Table 3 with one standard deviation

Climate change Scenarios

This report presents the range of possible changes provided by dry, wet and median scenarios change for the Fitzroy River Basin in 2030 and 2070. This range combines the range of global warming from IPCC (2001) and the climate change model patterns in Table 3. These provide an initial set of estimates for possible hydrological change and set the scene for a risk analysis of possible changes to water resources in the Basin.

The three scenarios are:

1. A dry climate change scenario where global warming follows the A1T greenhouse gas scenario in 2030 and the A1F scenario in 2070, both forced by high climate sensitivity with regional rainfall and areal potential evaporation changes expressed by the British HadCM3-B2 GCM.
2. A median climate change scenario where global warming follows the A1B greenhouse gas scenario forced by a medium climate sensitivity with regional rainfall and potential evaporation changes expressed by the CSIRO Mark 3 GCM (2030 and 2070)
3. A wet climate change scenario where global warming follows the A1T greenhouse gas scenario in 2030 and the A1F scenario in 2070, both forced by high climate sensitivity, with regional rainfall and potential evaporation changes expressed by the German ECHAM4 GCM

These scenarios are summarised in Table 4. Note that the A1T greenhouse gas scenario contributes to the highest warming in 2030 and A1F in 2070. This is because the lack of sulphate emissions, which have a cooling affect, in the A1T scenario in 2030 compared to A1F, which is a “dirtier” scenario. By 2070 the high emissions in A1F have outstripped the sulphate emissions making it the scenario with the greatest radiative forcing by that time.

Table 4. Dry, median and wet climate change scenarios for 2030 and 2070 over the Fitzroy River Basin

Scenario	Dry	Median	Wet
2030			
Global warming scenario	A1T	A1B	A1T
GCM	HadCM3 B2	CSIRO Mark3	ECHAM4
Global mean warming (℃)	1.24	0.85	1.24
Change in annual rainfall (%)	-10.3	-2.1	4.2
Change in annual potential evaporation (%)	7.3	2.9	4.0
2070			
Global warming scenario	A1F	A1B	A1F
GCM	HadCM3 B2	CSIRO Mark3	ECHAM4
Global mean warming (℃)	3.77	2.30	3.77
Change in annual rainfall (%)	-31.2	-5.7	12.7
Change in annual potential evaporation (%)	22.3	7.7	12.3

These simulations represent most of the possible ranges of change in average climate over the Fitzroy River Basin by 2030 and 2070 respectively. Note that the dry and wet climate scenarios are both forced by a high greenhouse gas scenario and climate sensitivity. This is because in locations where either increases or decreases in rainfall are possible, the more the globe warms, the larger these accompanying regional changes will become. Therefore, if we wish to look at the extremes of possible changes in catchment response to climate change, then both the wet and dry scenarios will utilise the higher extreme of plausible global warming.

Model Construction and Calibration

System inflows are the total measure of surface runoff and base-flow feeding into streamflow in the Fitzroy River Basin. This is carried out using the Sacramento rainfall-runoff model, which is incorporated into the IQQM.

Overview of Sacramento rainfall-runoff model

The hydrologic modelling component of this study applies rainfall and areal evaporation change from the three selected climate change scenarios to a large number of historical time series, to determine impacts on the surface water regime of the Fitzroy River Basin. This involves extensive daily rainfall-runoff modelling for each of the sub-catchments.

The Sacramento rainfall-runoff model has been used in previous climate change studies where IQQM has been perturbed according to a range of climate scenarios (e.g. Jones and Page, 2001; O'Neill et al., 2003). The Sacramento model is a physically based lumped parameter rainfall-runoff model (Burnash et al., 1973). The processes represented in the model include; percolation, soil moisture storage, drainage and evapotranspiration. The soil mantle is divided into a number of storages at two levels. Upper-level stores are related to surface runoff and interflow, whereas baseflow depends on lower-level stores. Streamflows are determined based on the interaction between the soil moisture quantities in these stores and precipitation. Sixteen parameters define these stores and the associated flow characteristics, of which ten have the most significant effect on calibration. The values for all sixteen parameters are derived based on calibration with observed streamflows. Burnash et al. (1973) describe storage details, their interactions, procedures and guidelines for initial parameter estimations.

Model set-up and calibration

The Sacramento rainfall-runoff model was previously configured and calibrated for the sub-catchments of the Fitzroy River Basin by the QDNRM. This calibration was based on records of historic streamflow, historic rainfall and A-Class pan evaporation. The details are summarised in a report by the Water Allocation Project Group (WAPG, 2003; Technical Report 3).

The IQQM was supplied by the WAPG as individual segments that needed to be integrated to obtain end-of-system flows for the Basin. Sixteen sub-catchments were calibrated by the WAPG, which were then grouped to run under four separate IQQM models. Our technique was to run each segment separately, then compare that with a baseline supplied by QDNRM. Because of the uncertainty surrounding the model version and the precise status of system files for each sub-catchment, if the model largely reproduced baseline climate files supplied by the WAPG, we deemed the coupling successful. In each case, the IQQM was coupled to OzClim and run from within the OzClim command systems under a scenario of zero change to both precipitation and potential evaporation.

A series of major nodes were checked to determine whether they closely matched the flow data provided by the WAPG. These included Callide Node 30, Connors Node 192, Nogoa Node 211, several nodes from Dawson catchment and the lower Fitzroy at Node 250. Figure 12 shows the latter, demonstrating that a reasonably close fit (r^2 = 0.97) between the WAPG source files and coupled OzClim-IQQM system has been achieved.

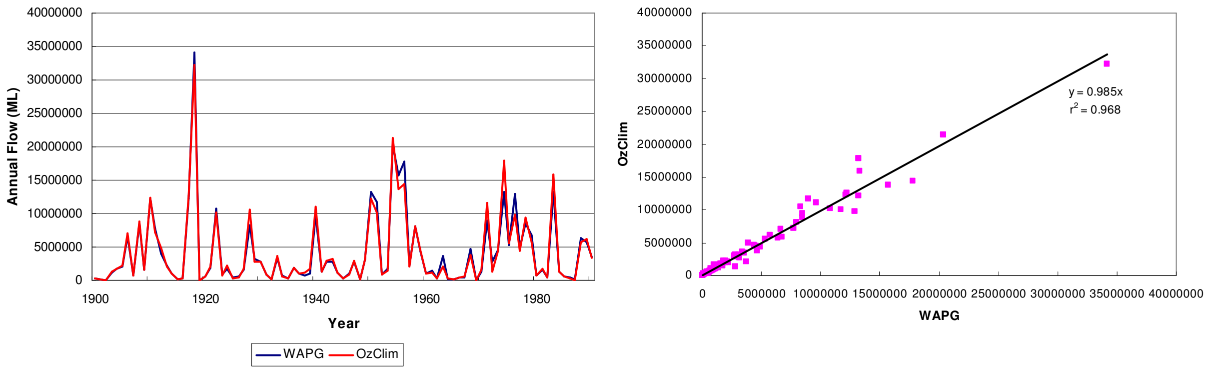

Figure 12. Comparison of lower Fitzroy flows (Node 250) produced by the WAPG and the coupled OzClim-IQQM system

Application of the climate change factors

Base data is comprised of 91 years of daily data from 1900 to 1990 for climate stations across the Basin. Within OzClim, Percentage changes for precipitation and evaporation for each month of projected years 2030 and 2070, and each station within each sub-catchment, were multiplied with the base data. The monthly changes for rainfall and potential evaporation in change per degree from each climate model are shown in Figure 11.

Generation of modified system flows

IQQM was then run normally, calculating each of the major system IQQMs in turn, and then estimating end-of-system flows for the lower Fitzroy River. These were then compared with the base case as shown in Figure 12.

Results of Impact Assessment

Annual flow changes

The results show that based on this set of scenarios, either increases or decreases in stream flow and water supply are possible for the Fitzroy River Basin. The mean change for the Basin ranges from approximately -30 to +20% by 2030 and from -65% to +80% by 2070. Table 5 shows the change in mean annual flow for each of the scenarios applied to the IQQM model. Note that even though the GCM providing output for the median scenario, CSIRO Mark3, shows decreases in average annual rainfall, seasonal increases during the wet season (+2.5% per degree of global warming over December, January and February) have an overall positive impact on streamflow.

Table 5. Changes in mean annual stream flow for the lower Fitzroy River for dry, median and wet climate change scenarios for 2030 and 2070

Scenario	**Dry**	**Median**	**Wet**
2030			
Global warming scenario	A1T	A1B	A1T
GCM	HadCM3 B2	CSIRO Mark3	ECHAM4
Global mean warming (°C)	1.24	0.85	1.24
Change in annual rainfall (%)	-10.3	-2.1	4.2
Change in annual potential evaporation (%)	7.3	2.9	4.0
Change in streamflow @ Node 250	-30.9	3.3	22.1
Change in 10th percentile (low) flow	-56.4	-8.4	4.8
Change in 90th percentile (high) flow	-36.0	3.3	13.6
2070			
Global warming scenario	A1F	A1B	A1F
GCM	HadCM3 B2	CSIRO Mark3	ECHAM4
Global mean warming (°C)	3.77	2.30	3.77
Change in annual rainfall (%)	-31.2	-5.7	12.7
Change in annual potential evaporation (%)	22.3	7.7	12.3
Change in streamflow @ Node 250	-65.0	20.1	80.0
Change in 10th percentile (low) flow	-100.0	-31.2	63.9
Change in 90th percentile (high) flow	-65.3	22.9	65.1

Changes in high low annual flows also occur at different rates than changes in mean flow. Low flows decrease faster than the mean for scenarios where rainfall decreases. High flows decrease significantly when there are large decreases in the mean but increase where there is little change in the mean. This is a response to summer rainfall changes. In situations where the average flows show little change under climate change, flow variability can increase substantially.

Changes in high flows may be under-estimated because the scaling method – applying uniform changes in average rainfall to daily data – does not allow for non-uniform changes in daily rainfall. Increases in extreme daily rainfall may be expected to occur in most instances. We have also found that such patterns will hold for regional changes, i.e. if mean rainfall increases in one season, then daily rainfall increases will occur across the range of falls with a bias towards the upper end, and decreases in another season, then only the highest extremes (e.g. 99th percentile) are likely to increase (O'Neill et al., 2003). Figure 14 expresses the changes in flow exceedance for the wet, median and dry scenarios – it is clear from this figure that larger decreases are projected (deviation from the baseline), when compared to the possibility of lesser increases to streamflow.

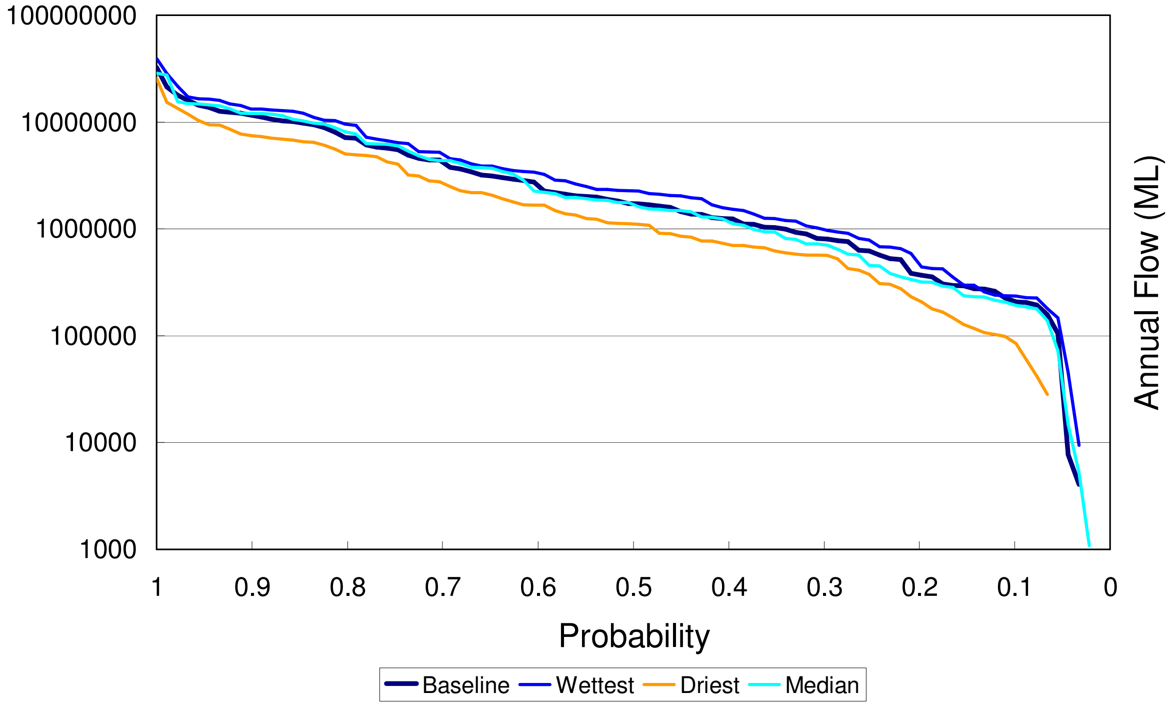

Figure 13. Changes in flow exceedance curves for the baseline, dry, median and wet scenarios for the lower Fitzroy River (Node 250) in 2030. Note where the truncated line denotes years of low flow

Seasonal flow changes

The uncertainties surrounding possible changes to mean annual flows are large, with climate changes suggesting that substantial increases or decreases in flow are possible. However climate scenarios for Queensland (McInnes and Bathols, see Section 1) show that winter-spring projections of rainfall are negative for most climate models. Consistent with these projections Figure 14 shows that all three scenarios of simulated flow show decreases in the dry season, even the wettest scenario.

The median scenario, from CSIRO Mark 3 shows changes consistent with those for the 10th and 90th percentile flows shown in Table 5, where dry season flows decrease and wet season flows increase. This supports an increase in both interannual and seasonal variability, although the increase in interannual variability assumes that underlying patterns driving that variability such as ENSO behave similarly in the way they do today.

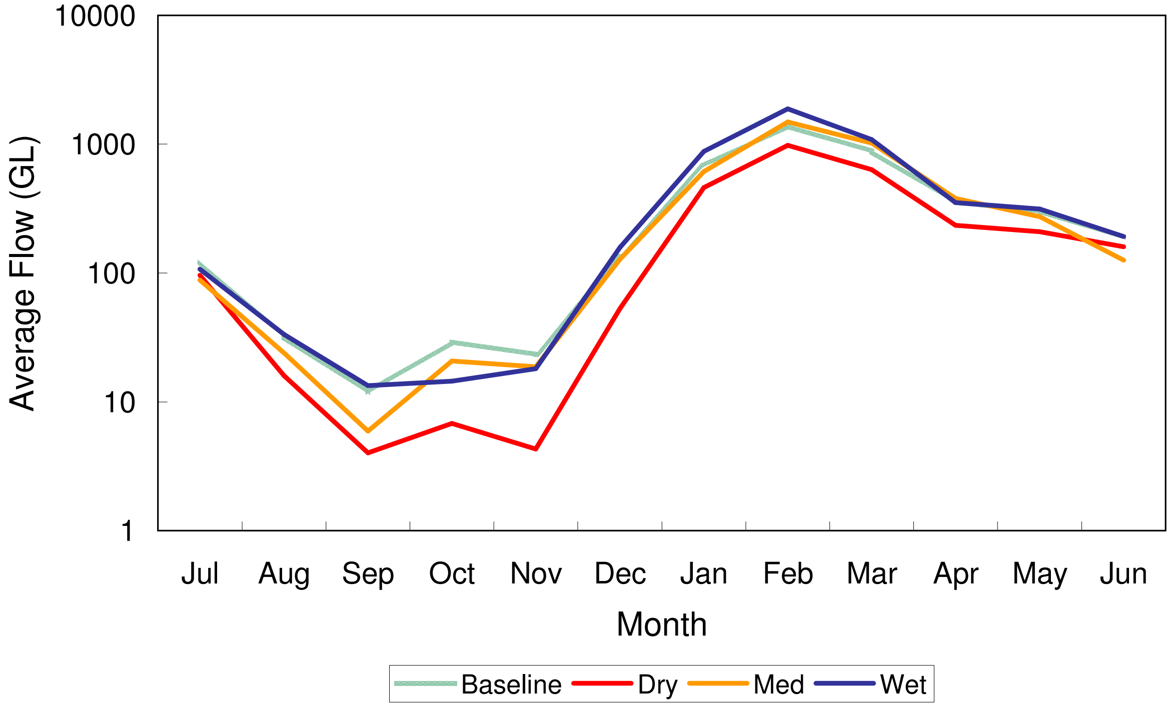

Figure 14. Simulated average monthly flow for the lower Fitzroy River Basin under dry, median and wet scenarios for 2030

Part II – Risk Analysis

Methodology

Here we use methods of risk analysis developed by CSIRO to assess the risk posed by climate change to water supply in the Fitzroy River Basin. These methods are primarily designed to manage climate change uncertainties and their impact on processes impacting on water supply. Other aspects of uncertainty within the water cycle, such as land-use change, or demand change, have not been addressed.

Although fairly straightforward, the assessment process is detailed and resource-intensive, requiring a great deal of baseline data, and multiple simulations of the OzClim-IQQM modelling system. Analysis of the model results is used to construct a simplified statistical version of the relationship between climatic inputs and mean streamflow to analyse climate uncertainties. Input ranges of mean change in global warming, and regional rainfall and potential evaporation are constructed. Each range has an assumed underlying probability distribution that can be based on expert analysis, the testing of model results and statistical theory. Monte Carlo sampling is then conducted to create probability distributions for pre-specified combinations of those ranges with the aim of producing a probability density function for change in mean streamflow. The sampling of several ranges of input uncertainty will produce a result that favours the central tendencies rather than the extremes.

In constructing and applying those techniques, the following uncertainties were addressed:

- The range of global warming was applied for due to unmitigated climate change according to the SRES scenarios. In 2030 the range is 0.55–1.24°C and in 2070 is 1.17–3.77°C.
- Changes in precipitation (P) were taken from the full range of change for each quarter from the sample of eleven climate models, weighted to allow for seasonal flow distribution.
- The difference between samples in any consecutive quarter could not exceed the largest difference observed in the sample of eleven climate models.
- Change in areal potential evaporation (Ep) was partially dependent on P ($\delta Ep = 3.60 - 0.15\delta P$, standard error = 0.96, randomly sampled using a Gaussian distribution, units in percent change).
- Quarterly changes in P and Ep were then summed to obtain an annual estimate with a “flow-weighting” to allow for the highly seasonal distribution of river flow.
- These changes were then applied to a simple statistical model representing various aspects of change in flow to assess “most likely” changes under a range of assumptions.

Construction of ranges of climate change

Establishment of precipitation ranges

Average quarterly changes in P and Ep from the eleven climate models investigated are listed in Table 6. They show seasonal trends similar to those shown in Figure 11, where summer-autumn rainfall changes are higher than those in winter-spring. Mean annual change per degree ranges between +3.3% and -8.0%. The correlations associated with changes between successive quarters ranges from 0.4 to about 0.7 suggesting that the seasonal patterns of more positive (or at least less negative) change in summer and negative changes in winter are consistent across the different climate models, with some models being wetter or drier in terms of annual rainfall change. Previously, this relationship has been assessed as being independent (Page and Jones, 2001), but the data in Table 6 shows considerable dependence between each quarter and the next with correlations ranging between 0.39 and 0.68. For this reason, we have allowed for a degree of dependence in the sampling strategy. This is described in coming sections.

Table 6. Change per degree of global warming for eleven climate models for the Fitzroy River Basin

Model	**Change per °C global warming**				
	DJF	MAM	JJA	SON	ANN
Rainfall					
CSIRO: Mark 3:	2.7	-2.5	-14.4	-6.6	-2.5
CSIRO: Mark 2:	-3.9	-2.4	-9.7	-7.3	-5.0
CSIRO: Cubic Conformal:	-4.8	-2.7	-13.8	-8.9	-6.3
CSIRO: DARLAM 125km:	1.7	7.6	3.2	-1.7	2.6
CCGM2:	0.8	-2.3	-0.4	-4.3	-1.1
CGCM2 SRES A2:	0.0	-0.6	1.8	-4.0	-0.7
CGCM2 SRES B2:	0.7	-0.2	-1.0	-2.1	-0.3
ECHAM4:	8.0	1.1	2.2	-3.4	3.4
HadCM3:	-0.4	-8.4	-3.6	-12.3	-5.0
HadCM3 SRES A2:	-3.7	-3.6	-0.1	-6.6	-3.8
HadCM3 SRES B2:	-7.1	-5.3	-4.0	-17.1	-8.3
Correlation with previous quarter	0.66	0.46	0.42	0.40	
Areal Potential Evaporation					
CSIRO: Mark 3:	3.7	7.0	9.1	5.5	5.8
CSIRO: Mark 2:	5.3	5.0	5.0	6.0	5.4
CSIRO: Cubic Conformal:	6.4	6.1	14.2	12.8	9.4
CSIRO: DARLAM 125km:	3.8	3.6	3.9	6.2	4.5
CCGM2:	5.4	6.1	4.6	5.8	5.5
CGCM2 SRES A2:	1.1	2.5	5.3	4.7	3.2
CGCM2 SRES B2:	0.7	2.2	3.0	3.5	2.3
ECHAM4:	7.1	8.4	8.6	9.5	8.3
HadCM3:	3.5	3.0	4.1	3.5	3.5
HadCM3 SRES A2:	3.7	7.0	9.1	5.5	5.8
HadCM3 SRES B2:	5.3	5.0	5.0	6.0	5.4

If we wish to forecast the direction and magnitude of regional rainfall change using climate model output, there is no single established methodology for doing so. The main aim pursued here is to construct ranges of change as a function of global warming with attached likelihoods, in order to analyse risk. Several different constructions can be applied, but there is limited guidance about which may be the most realistic. For example, differently constructed ranges may include:

- A high and low extreme informed by the highest and lowest simulated outcome with a uniform probability of occurrence across the range. This assumes that all outcomes in the range have a uniform probability and those outside the range have zero probability.
- As above, but the extreme outcomes have been omitted. The resulting range may be given a probability or may just be communicated as the “most likely” range with limited guidance as to underlying assumptions. Both the IPCC range of climate model sensitivity for CO_2 doubling (1.5℃ to 4.5℃; IPCC, 2001) and the Australian regional projections of climate change (CSIRO, 2001) are of this type.
- A probability distribution function created from underlying assumptions based on statistical theory, expert opinion and/or elicitation of stakeholder views.
- Probabilities weighted to reflect skill scores created from analyses of model performance.
- Treatment of individual scenarios through different sampling strategies, such as the use of fuzzy numbers, attaching a probability to each scenario.
- A probability density function created from the analysis of individual model outputs.

Some of the considerations relating to how individual model samples relate to each other in a statistical sense include:

- The convergence in results, or agreement, between different climate models.
- The levels of sample independence between models

The level of sample independence between models is influenced by:

- Underlying physics – whether the model represents physical relationships in common with other schemes or is unique. Each climate model has its own structure and physics, but how independent is it really?
- A selected greenhouse gas scenarios run with one model may produce very different results compared to other models.
- A downscaled model may produce different results to the parent model – are they independent, co-dependent or part of an ensemble?
- The level of stochastic uncertainty in a single climate change simulation (a signal to noise issue) and whether ensemble runs are available.

A significant body of literature on the use of these methods in forecasting regional climate change is emerging, but these methods have not yet been systematically tested in how they affect the results of climate impact assessments. Note also, that these concerns do not apply to changes in natural variability that may occur independently of greenhouse-induced climate change. Strategies for doing so are described in later sections.

In this work, we test several different ranges of change for rainfall. The uppermost consideration in doing so is to represent the uncertainties between different models in order to explore where they differ and where they agree. This is considered to be more important than other factors such as stochastic uncertainty or in how small differences in the underlying scenarios that drive the model are represented (e.g. the inclusion of sulphate aerosols in SRES model runs, but not in the earlier IS92a runs – see Table 2).

Ranges with uniform probability

The first set of ranges we produce are delimited by the highest and lowest estimates in Table 6 and have a uniform probability across the range; i.e. any value occurring between the highest and lowest is equally likely to occur – the extremes themselves are very unlikely to be encountered (having a probability of 0 and 1 in a cumulative probability distribution), though individual samples in that range may come close. This is the most conservative assumption, but loses all information that can be gained from the climate models except for quantifying the extreme outcomes. The limits are shown in Table 7 and the methodology described below.

Co-dependence between different quarters was ensured by removing Monte Carlo samples from the analysis that exceeded the limits set by the maximum difference downwards (or minimum difference upwards in DJF) and maximum different upwards between quarters. A trial of 1,000 Monte Carlo independent samples of all four months delimited by the upper and lower limits, culled any samples where the size of the difference in change between quarters exceeded the maximum shift up or down in the original sample. This methodology removed physically unrealistic scenarios from the sample, a number of almost ⅔ of the entire sample size. The resulting correlations are shown in Table 7 and are within reasonable levels of confidence considering the original sample size of eleven climate models.

Table 7. Range limits, difference limits and correlation between different quarters for uniform ranges of rainfall change over the Fitzroy River Basin

	DJF	MAM	JJA	SON
Lower limit	-7.1	-8.4	-14.4	-17.1
Upper limit	8.0	7.6	3.2	-1.7
Max difference in a downwards direction	2.8	-8.0	-11.9	-13.1
Max difference in an upwards direction	11.9	6.0	4.8	7.8
Correlation between model scenarios	0.66	0.46	0.42	0.40
Correlation between Monte Carlo-generated samples	0.72	0.49	0.40	0.33

Ranges with non-uniform probability

Ranges with non-uniform probability are more difficult to construct because of the numerous possible approaches. The first step is to look at the distribution of the individual scenarios of rainfall change, which are shown in Figure 15. The scenarios are irregularly distributed across the range, with several outliers, but are clearly not normally distributed. Therefore, a frequentist approach, which would base uncertainty on the average of the distribution and its standard deviation, is not appropriate. Morgan and Henrion (1990) show a number of examples where such methods have been used and subsequently shown to significantly under-estimate the real uncertainty.

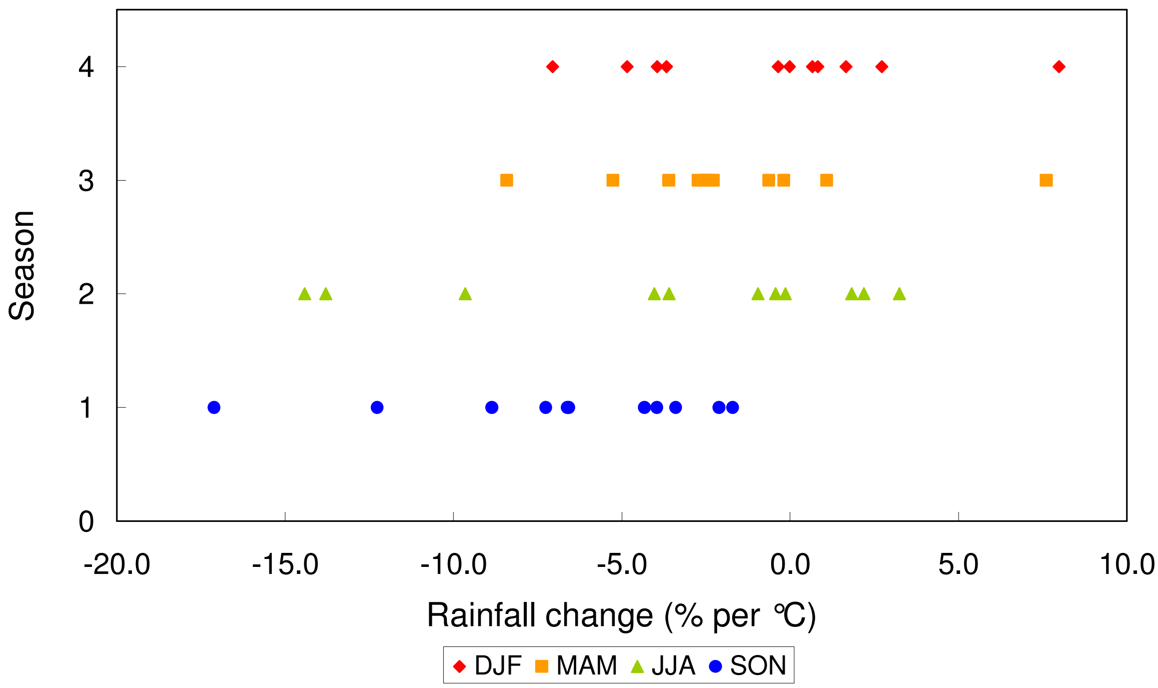

Figure 15. Quarterly ranges in precipitation change per degree of global warming for the Fitzroy River Basin taken from eleven climate models. Seasons 1, 2, 3, and 4 are summer, autumn, winter and spring, respectively

Figure 16 shows the models of origin for the changes in rainfall shown in Figure 15. The single model from German DKRZ Institute, the ECHAM4 model is the wettest. The three Canadian CCCM models are the same version (CGCM2) run for different scenarios that fall within a 2% range, so resemble an ensemble. However, the three British Hadley models (HadCM3) show a substantial spread, even though they are forced by the three same scenarios as the CCCM models. The four CSIRO models cover the full range from dry to wetter outcomes. There are two regional climate models nested in the CSIRO Mark2 GCM that project different rainfall changes to the parent model. In contrast to the dry Mark2 model the DARLAM model produces the wettest projections in two seasons. The CC50 produced similar results in three quarters, but differ in summer, the most important quarter in terms of streamflow. In summary, the results are not clear on the issue of whether all different models should be considered independent, and on how statistically dependent models from within the same laboratory actually are.

If all the scenarios are treated as being evenly distributed within a range of uncertainty with the extremes, the resulting probability distribution is sigmoidal in shape (Figure 17). Uniform distributions are fairly straight, larger uncertainties have a lower slope and the more normally-shaped distributions will show a greater sigmoidal character. The distributions shown in Figure 15 and Figure 17 allow the sampling of quarterly rainfall changes on both a uniform basis and by treating each model-based sample as an equally weighted and statistically independent sample.

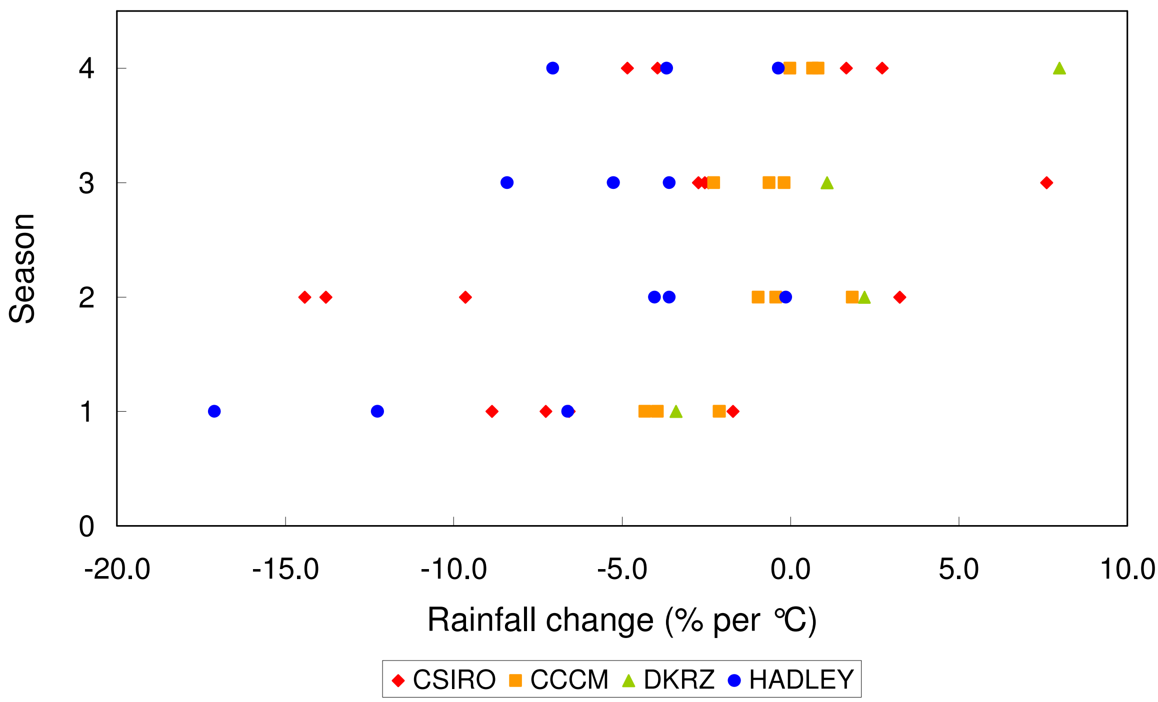

Figure 16. Quarterly ranges in precipitation change per degree of global warming for the Fitzroy River Basin taken from eleven climate models, showing the origin of the models. Seasons 1, 2, 3, and 4 are summer, autumn, winter and spring, respectively

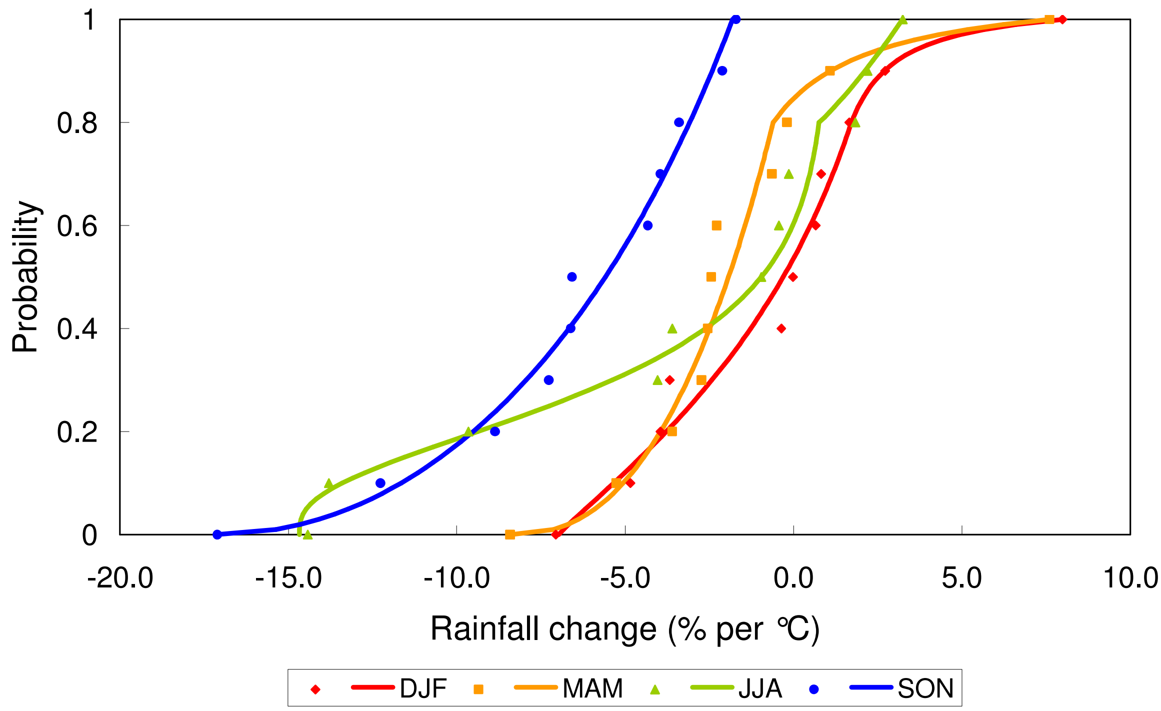

Figure 17. Fitted curves for all model-derived scenarios of changes in mean quarterly rainfall per degree of global warming for the Fitzroy River Basin. Probability is probability of being wetter than a given value of rainfall

Rainfall, potential evaporation relationship

Past Queensland reports have shown that changes in rainfall and potential evaporation are co-dependent with each other and independent of specific model scenarios. Therefore, it is possible to construct a relationship by which it is possible to estimate changes in potential evaporation from rainfall change. Figure 18 shows the relationship between P and Ep over the Fitzroy River Basin for each quarter. The relationship between rainfall and potential evaporation change is highest in DJF, presumably because of the close relationship between cloud cover and rainfall during the height of the wet season. A single regression for all four quarters was chosen for use in Monte Carlo sampling.

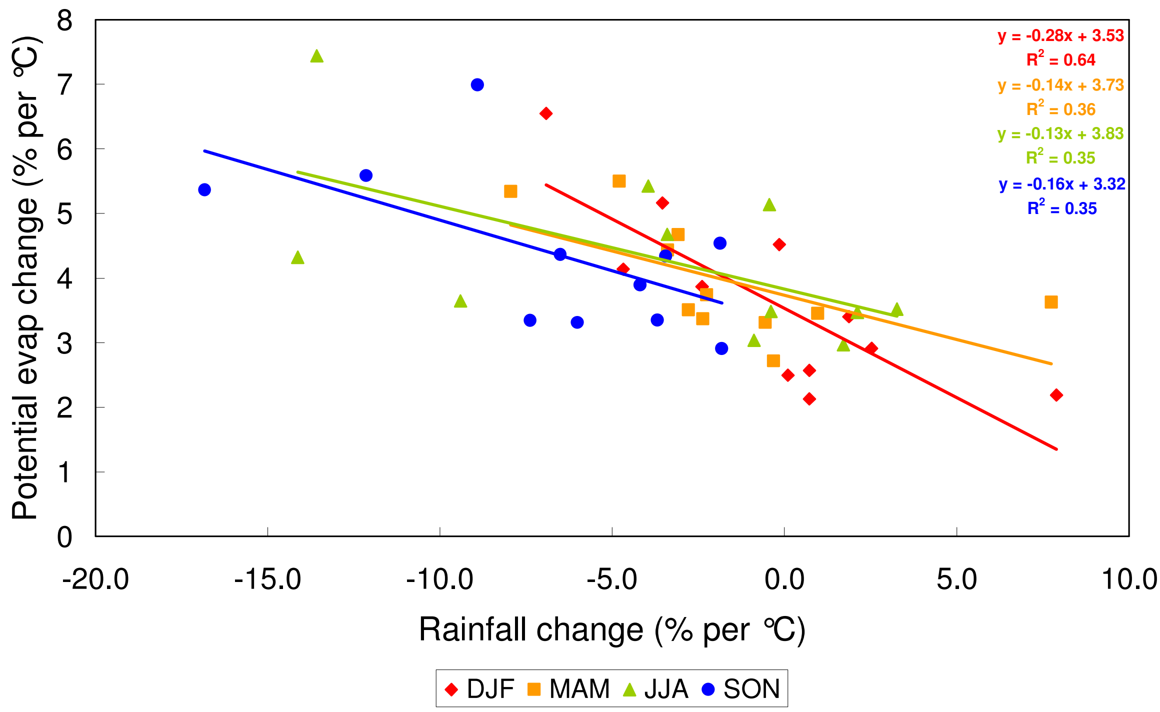

Figure 18. Seasonal relationships between rainfall and potential evaporation change per degree of global warming simulated by eleven climate models over the Fitzroy River Basin.

Statistical model of mean flow

This section describes the development of a statistical relationship to estimate the hydrological sensitivity of changes in annual runoff produced by the IQQM model to changes in mean annual rainfall (P) and areal potential evapotranspiration (Ep). Hydrological model sensitivity to climate change is as the change in mean annual runoff (δQ) resulting from changes in mean annual precipitation (δP) and areal potential evapotranspiration (δEp) produced by a specific hydrological model. δQ can be expressed as:

$\delta Q = f(\delta P, \delta Ep)$ Equation 1

where δQ is change in mean annual runoff, δP is change in mean annual precipitation, δEp is change in mean annual areal potential evapotranspiration, all measured in percent. Recent work shows that the response in Q is fairly consistent across a number of rainfall-runoff models where the P/Ep ratio ranges between about 0.5 and 2 (Jones and Page, 2001; Chiew et al., 2005).

For example, Jones and Page (2001) coupled a climate change scenario generator to a catchment-scale hydrological model for the Macquarie River in eastern Australia, applying over 50 scenarios. They found that Equation 1 could be expressed as:

$\delta Q = A\,\delta P + B\,\delta Ep$ Equation 2

where A and B are constants. Factor A is a measure of the sensitivity of the model to change in P and factor B to change in Ep. This linear relationship performed well over most of the range of potential change except for exceptionally large decreases in rainfall where the relationship became non-linear. This simple relationship estimated percent change to mean annual flow with a standard error of ±2% mean annual flow for the Macquarie catchment (Jones and Page, 2001).

We tested this relationship for the 33 scenarios of low, median and high global warming in 2030 forcing P and Ep changes from the eleven climate models listed in Table 5, where the output ranged from -31% to +22% (Table 4). For each month, we estimated the monthly average change for the entire catchment for P and Ep, and then averaged those to obtain annual δP and δEp, weighted to allow for the mean seasonal variations in both P and Ep.

When those values were used to create a regression relationship as in Equation 2, the results were satisfactory for most of the 33 simulations but the results from two climate models produced large errors. The summary of results is shown in Table 8, showing an r^2 of 0.88 and a standard error of ±4.0% of mean annual flow. This was considered to be too poor to use for risk analysis.

These errors originate with the high seasonality of rainfall and resulting flow peaks in the Fitzroy River (Figure 19). This relationship shows that a sustained increase in rainfall from September to January results in a large peak flow in February. Soils within the catchment, usually free of moisture at the end of the dry season gradually become moister over the spring months while runoff remains low. Once those become saturated in January and February, large flows result. Therefore, changes in December to February rainfall will have a larger impact than changes at any other time of the year.

Table 8. Results of regression tests to estimate hydrological sensitivity of Fitzroy River Basin (see Equation 2)

Test Number	Description	A	B	r2	SE
Test 1	Annual average P and Ep	3.42	-0.68	0.88	4.02
Test 2	Flow weighted averages of P and Ep = Month+1	3.17	-0.85	0.94	2.84
Test 3	Flow weighted averages of P and Ep = Quarter+1	3.28	-0.43	0.97	1.95

Two more tests were undertaken to allow for the seasonality of flow. The first applied weighting for river flow in the month following rainfall to average monthly values of δP. For example changes in January rainfall, which currently comprises 15% of annual rainfall, would instead comprise 33%, which is the proportion of annual river flow occurring in February. Therefore, changes in the months December to February become more prominent while rainfall changes during the dry season lose influence. Test 2 in Table 8 shows an increase in r^2 to 0.94 and a reduction in standard error to ±2.8%. Test 3 simplifies this so that average quarterly totals are used with the weighting shifted forward one month, i.e. December to February rainfall is weighted according to the annual proportion of January to March river flow. The weightings used are shown in Table 9.

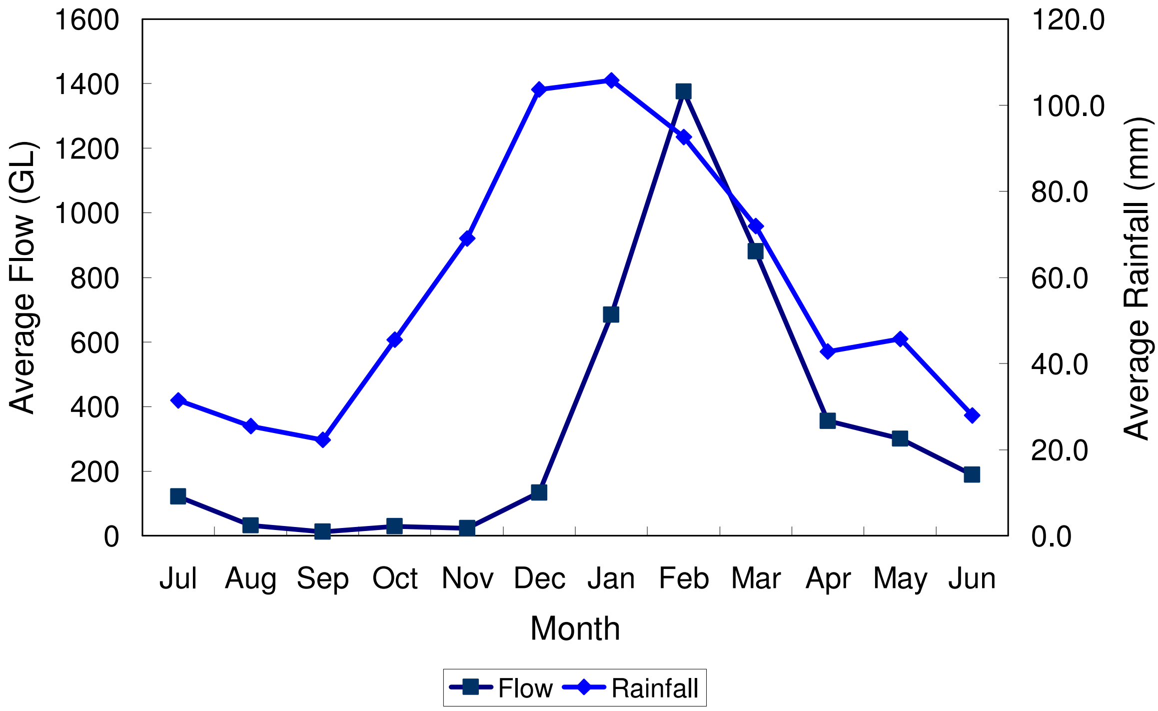

Figure 19. Average seasonal river flow and rainfall for the lower Fitzroy River, 1900–1990

Table 9. Seasonal weightings for calculating annual change to precipitation and potential evaporation based on rainfall and river flow lagged by one month

Period	DJF	MAM	JJA	SON	ANN
Rainfall	302	160	85	137	684
Seasonal weighting	0.44	0.23	0.12	0.20	
Period	JFM	AMJ	JAS	OND	ANN
Flow (Q+1)	2940	845	166	186	4137
Seasonal weighting	0.71	0.20	0.04	0.05	

The results from using these weightings (Table 8), show the r^2 increasing to 0.97 and standard error reducing to ±2.0% of mean annual flow. This is considered acceptable for use in risk analysis, because it reduces a large and complex model to a very simple relationship with surprisingly little loss in accuracy (Note: this only holds for mean annual flow, not the whole set of very comprehensive IQQM outputs).

A linear model based on equation 2 using flow-weighted average rainfall was fitted for all data from 2030 and 2070 (sixty-six scenarios) and a series of sixty-five sensitivity scenarios producing flow changes for changes in rainfall ranging from +15 to -15% in 3% increments and potential evaporation from 0% to 10% also in 3% increments.

The effect of weighting rainfall changes according to their impact on seasonal flow can be seen in Figure 20, where all the models show more positive or less negative changes in average annual rainfall change, than using the straightforward climatic average. All models became 0.1% to 3.0% “wetter” in terms of mean annual rainfall change per degree of global warming. This is because of the pattern of rainfall change shown in Figure 11 is weighted towards more positive outcomes in the wet season compared to the dry season. The largest shifts upwards in weighting for the Mark3 and HadCM3 models produced most of the improvements seen in Table 7. A further test that correlated the time series of simulated monthly flow with rainfall, and then weighted rainfall according to the proportion of flow in that month produced a slightly higher correlation but was not adopted as a technique because its extra data requirements and complexity outweighed its benefits.

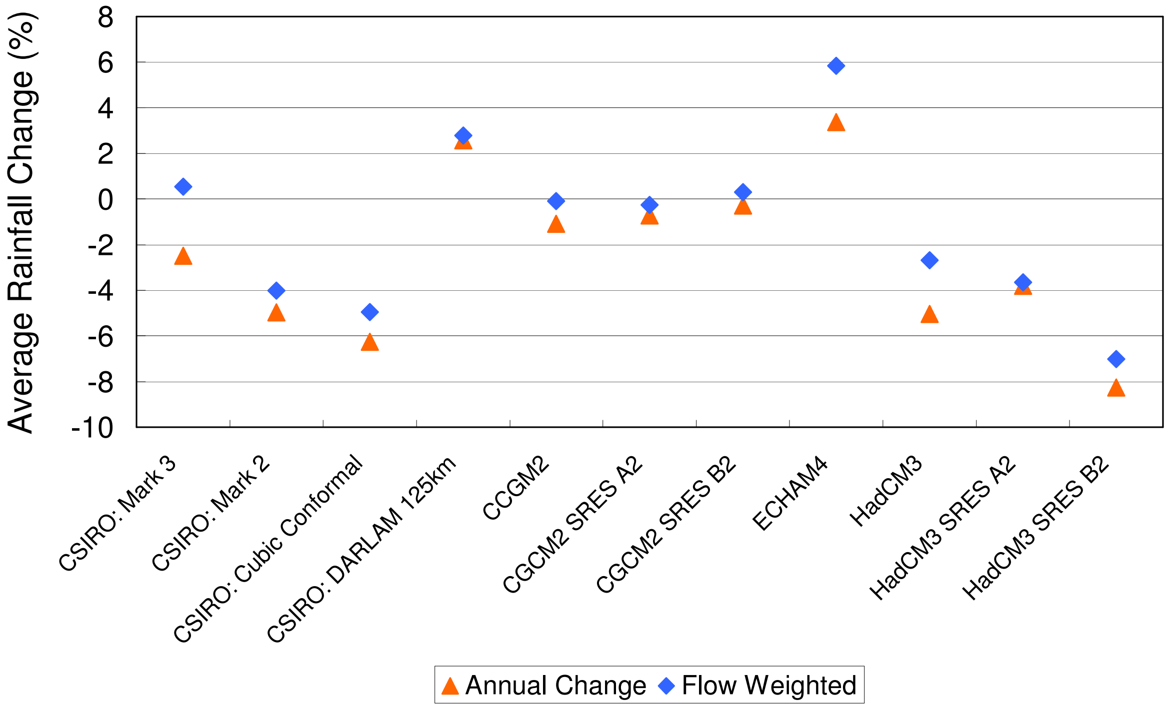

Figure 20. Average annual and flow-weighted changes in rainfall per degree of global warming for the Fitzroy River Basin

Risk analysis results

Several techniques were used to test a how underlying assumptions concerning climate change uncertainties may affect the likelihood of changes in river flow of the Fitzroy River, measured from the historical baseline of 1900–1990. The results produce a probability distribution for changes in flow due to the enhanced greenhouse effect, which can be examined in terms of:

- “What is the most likely outcome?”
- “What are the most extreme changes (within plausible limits)?”
- “What is the likelihood of exceeding a nominated change in flow?”
- “What are the most significant underlying uncertainties affecting the results?”

As stated earlier, the risk analysis of climate change on catchment yield depends on a number of assumptions on how the underlying uncertainties should be managed and on the methods used in statistical analysis. Several tests were undertaken.

Test 1: Uniform ranges of rainfall

The first test is the most conservative in its assumptions. All of the contributing ranges of climate uncertainty, except for Ep, are randomly sampled in a uniform probability distribution bounded by the extremes quantified in the previous chapter.

1. The range of global warming was applied for due to unmitigated climate change according to the SRES scenarios (IPCC, 2001). In 2030 the range is 0.55–1.24°C and in 2070 is 1.17–3.77°C. The contributing range of climate uncertainty to this range is 1.7–4.2°C at $2\times CO_2$. Sampling was uniform across the range.
2. Changes in precipitation (P) per degree of global warming were taken from the full range of change for each quarter from the sample of eleven climate models. Sampling was uniform across each of the ranges, units in percent change.
3. The difference between samples in any consecutive quarter could not exceed the largest difference observed in the sample of eleven climate models. This step disqualified about ¾ of the one million samples, leaving approximately 250,000.
4. Change in potential evaporation (Ep) per degree of global warming is partially dependent on P ($\delta Ep = 3.60 - 0.15\delta P$, standard error = 0.96) and was randomly sampled using a Gaussian distribution; units in percent change.
5. Quarterly changes in P and Ep per degree of global warming were then multiplied by the value of global warming for 2030 and 2070 sampled in Step 1.
6. Quarterly changes in P and Ep were then summed to obtain an annual estimate with a “flow-weighting” to allow for the highly seasonal distribution of river flow.
7. These changes were then applied to a simple statistical model (Equation 2 for 2030 and 2070) representing change in average annual flow from the baseline.

The results for 2030 are shown in Figure 21. They make an interesting contrast to the dry, median and wet scenarios shown in Part 1 that were derived, respectively, from: the driest model forced by the highest global warming projected for that date, from the median model in terms of annual mean rainfall change forced by the median global warming and from the wettest model again forced by the highest global warming. The most extreme changes in flow for those scenarios was +22% to -31%. The addition of flow-weighted annual average P and Ep means that all models became 0.1% to 3.0% “wetter” (in terms of mean annual rainfall change per degree global warming), and that the median climate model, Mark3 became the third wettest. In Figure 15, the extreme outcomes are +28% and -33%, but the previous values of +22% to -31% are only 0.13% and 0.05% likely to be exceeded, respectively. The median flow in this distribution is -4%.

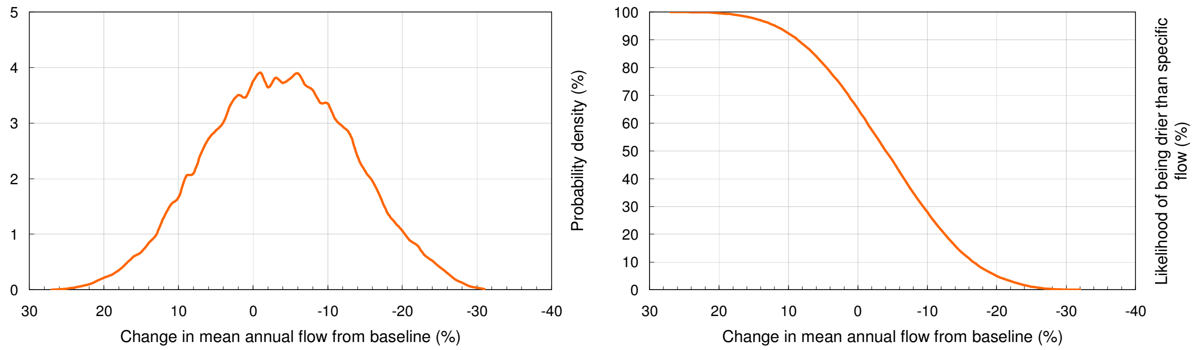

Figure 21. Likelihoods of change in mean annual flow for the Fitzroy River in 2030. The left-hand chart shows probability density, binned for every 1% change in mean annual flow. The right-hand chart shows the probability of mean annual flow being drier than a specific change (as measured from the x-axis)

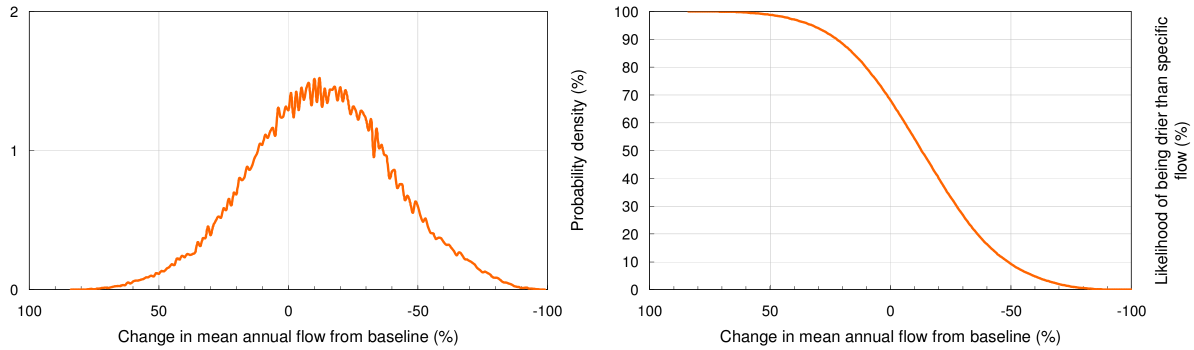

Figure 22. Likelihoods of change in mean annual flow for the Fitzroy River in 2070. The left-hand chart shows probability density, binned for every 1% change in mean annual flow. The right-hand chart shows the probability of mean annual flow being drier than a specific change (as measured from the x-axis)

The statistics of test 1 indicate that there is a 2 in 1 chance of a reduction in mean annual flow; that while the entire range has a spread of >60%, the most likely 90% of outcomes have a spread of 32%, ranging from +12% to -20%; and the most likely ⅔ of outcomes have a spread of 19%, from +6% to -14%. The changes show similar patterns for 2070 but the range is much larger (Figure 22). The entire range shows a spread of 185%, ranging from +85% to -100% with a median of -13%. The most likely 90% of outcomes have a spread of 92%, ranging from 33% to -59%; and the most likely ⅔ of outcomes have a spread of 53%, from +14.0% to -40%. Decreases in mean annual flow are about as likely as in 2030. Note that the simple model has little skill at the extremes of the range of change, but significant skill in the centre of the range.

Test 2: non-Uniform ranges of rainfall

Test 2 is administered in a similar manner to test 1 except that a non-uniform probability is constructed for rainfall changes. Each climate model is given equal weighting in a probability distribution for quarterly changes per degree of global warming. This assumes that each projection of rainfall change is equally likely to occur irrespective of its origin, version and driving scenario. The procedure was largely the same as in Test 1 except for the way that rainfall change was sampled. The quarterly distributions are shown in Table 9. Seasonal weightings for calculating annual change to precipitation and potential evaporation based on rainfall and river flow lagged by one month were randomly sampled then multiplied by global warming to estimate quarterly changes in rainfall. These were then totalled using the flow weighting technique described in the Statistical model of mean flow section.

The difference between the results here compared with those from Test 1 is substantial (Figure 23). The spread of the range between lowest and highest outcome is similar, but the median increases to -2%, the most likely 90% of outcomes have a spread of 20%, ranging from +6% to -18%; and the most likely ⅔ of outcomes have a spread of 10%, from +2% to -8%. This is a reduction of about 10% in the range of uncertainty of what is “most likely” in both cases.

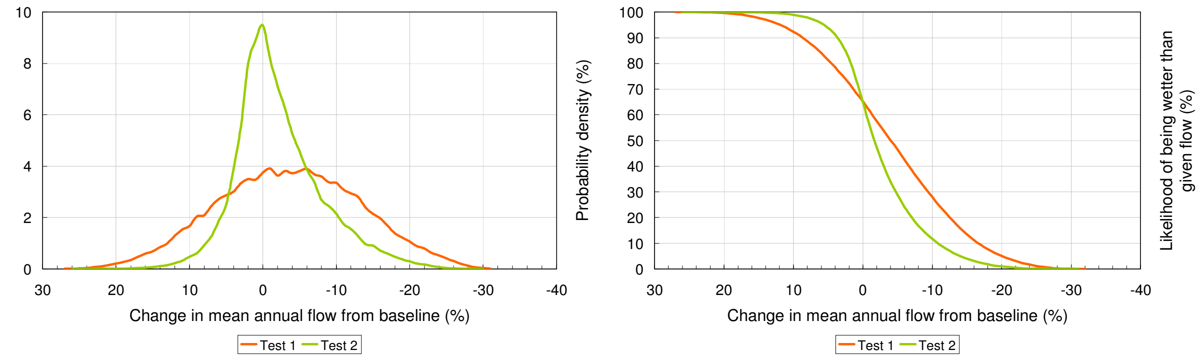

Figure 23. Comparison of probability distributions for change in mean annual flow for the Fitzroy River in 2030, comparing uniform sampling of rainfall changes (Test 1) with non-uniform sampling (Test 2). The left-hand chart shows probability density, the right-hand chart shows the probability of mean annual flow being drier than a specific change (as measured from the x-axis)

The non-uniform distributions in Figure 23 do not seem very different to the uniform distributions, but even with this amount of non-linearity the differences in the results are marked. Both the median and mode become slightly wetter, but the largest impact is in the increase in probability density around the central tendencies. Although the extremes are little changed, outcomes in the range +4% to -7% are shown as being much more likely.

The difference between the results of Test 1 and 2 for 2070 are similar to those for 2030 (Figure 24). The median increases from -8% to -1% and the mode increases from -12% to +2%. The reduction in the most likely 90% of outcomes goes from a spread of 92% to one of 55% (14% to -41%), approximately ⅓. The reduction in the most likely ⅔ of outcomes reduces from a 53% spread to 28% (4% to -24%).

These tests show that adding information about the likelihood of rainfall changes over and above the quantified extremes, can significantly constrain uncertainties. In Section 9.4, we undertake a sensitivity analysis to determine where improvements in the understanding of probabilities may have the greatest effect.

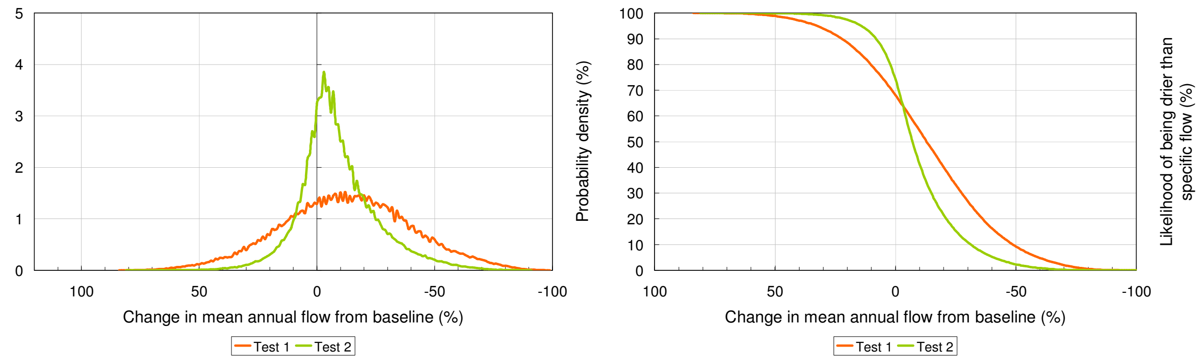

Figure 24. Comparison of probability distributions for change in mean annual flow for the Fitzroy River in 2070, comparing uniform sampling of rainfall changes (Test 1) with non-uniform sampling (Test 2). The left-hand chart shows probability density, the right-hand chart shows the probability of mean annual flow being drier than a specific change (as measured from the x-axis)

Low and high flow changes

In addition to looking at mean annual flow, we investigated changes to the 10th percentile (driest 10% of years) and 90th percentile (wettest 10% of years) annual flows for both 2030 and 2070. The regression values used in the simple model for change in mean and the 10th and 90th percentile flows are shown in Table 10.

Table 10. Regression results for mean annual, 10th percentile and 90th percentile flows for 2030 and 2070 for the lower Fitzroy River (see Equations 2 and 3)

	A	B	r2	SE
Mean annual flow	3.2803	-0.2736.	0.93	7.92
10th percentile	5.8410	-0.5507	0.88	18.34
90th percentile	3.0111	-0.5982	0.91	8.10

The 10th percentile flows have a closer relationship with the climatic-average changes (not shown) rather than the flow-weighted changes. This is logical because the lowest flows occur as a result of sustained year-round drought rather than seasonal shortages. In contrast, the 90th percentile flows showed a stronger relationship with flow-weighted changes. However, to keep our results consistent with the same set of inputs, 10th percentile flow changes here are calculated from flow-weighted changes in rainfall and potential evaporation.

The results for both 2030 and 2070 are shown in Figure 25. Consistent with the seasonal changes shown in Figure 14, 10th percentile flows are likely to show a greater decrease than mean or high flows, the only exception being if all flows increase it is possible, though less likely that low flows may increase more than average flows. In the drier scenarios, the Fitzroy River is simulated as being dry in more than 10% of years. In contrast, high flows change at a similar rate to average flows, and can be more or less, depending on the net change in rainfall during the height of the wet season. Furthermore, our method of scaling rainfall changes each value of daily rainfall by the same amount and does not allow for likely increases in the most intense falls. This implies that the changes to 90th percentile flows may be somewhat under-estimated. However, the amount of work required to carry out this type of analysis with a risk analytic framework is beyond our current resources.

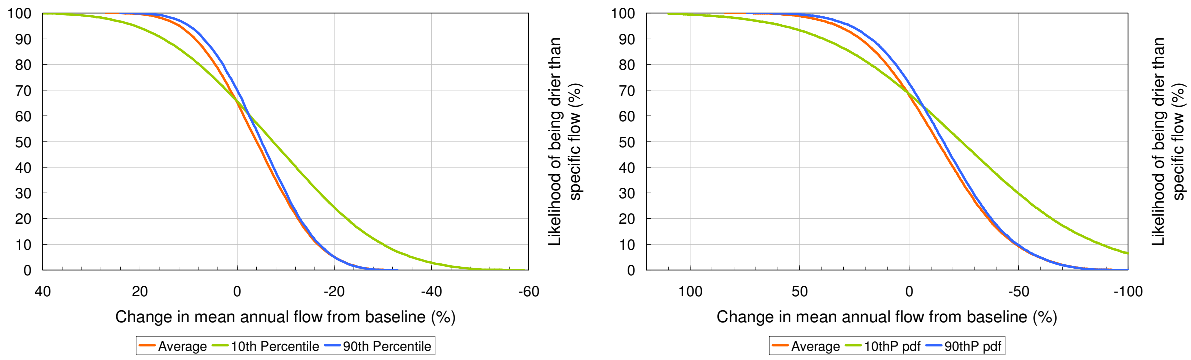

Figure 25. Likelihoods of change in mean annual, 10th percentile and 90th percentile flows for the Fitzroy River in 2030 and 2070. Results are expressed as the probability of flow being drier than a specific change (as measured from the x-axis)

Applying non-uniform changes in rainfall, the changes to the 10th and 90th percentile flows followed similar patterns to those in mean flow. The distribution becomes much tighter for the “most likely” outcomes, though having little impact on the very extremes.

Uncertainty analysis

Uncertainty analysis is useful for testing the sensitivity of the results to change in different inputs. We tested uncertainty by fixing each of the major inputs at a median value, then giving the others free play. If the range of outcomes continues to be large, then that variable has little influence on the outcome. If it is small, then that variable has a significant influence on the results.

The results of that exercise show that potential evaporation as a function of both global warming and rainfall has little independent influence (about 1%). The magnitude of global warming influences about 30% of the total outcome. The most significant impact is through rainfall change as a function of global warming (i.e. regional rainfall change as it is forced in direction and rate of change by the magnitude of warming), which influences over 90% of the total uncertainty. Even if the magnitude of change in 2030 was assessed independently of warming (i.e. assessed as a percentage change without reference to warming) it would still influence about ⅔ of the total uncertainty. Finally, we kept DJF rainfall constant while varying all the other uncertainties, and its contribution to total uncertainty was still 72% (Table 11). This shows that uncertainty in DJF rainfall is the single largest uncertainty facing the assessment of possible flow changes on the Fitzroy River Basin. Knowledge of how the wet season may change as a function of global warming is the single-most important piece of information in assessing how the water resources of the catchment may fare under climate change.

Table 11. Contribution of different elements of climate change to changes in annual flow in the Fitzroy River in 2030

2030	Limits of Range	Range	Contribution to Uncertainty
All	+27.4 to -34.2	61.6	
Constant global warming	+19.3 to -24.0	43.3	30%
Constant P (4 seasons)	-1.5 to -6.8	5.3	92%
Constant P (DJF)	3.6 to -13.7	17.3	72%
Constant Ep	27.5 to -33.7	61.2	1%

Conclusions and recommendations

Summary of risk analysis

In this study we have assessed the likelihood of changes to mean annual flow by perturbing input data to the Fitzroy River Basin Integrated Quality Quantity Model according to quantified ranges of climate change for 2030 and 2070. These ranges incorporate the range of global warming according to the IPCC Third Assessment Report (IPCC, 2001), regional changes in rainfall and areal potential evaporation encompassing the results from eleven different climate models runs from four different modelling groups.

Assessments undertaken without uncertainty management show that the ranges of change from the driest and wettest extremes of regional climate change indicate a very wide range of change in mean annual flow ranging from approximately -30 to +20% by 2030 and from -65% to +80% by 2070. Even if a median outcome is used for planning, this outcome is clearly unsatisfactory when such a wide range of change is possible.

By applying risk analysis techniques based on the Monte Carlo sampling of climate change applied to a simplified version of the Fitzroy IQQM's simulated flow response, we were able to significantly constrain climate change-related uncertainties.

Conclusion: *risk analytic techniques have the potential to significantly constrain uncertainties affecting water resources under climate change.*

One of the difficulties in linking changes in average rainfall to a simple model of hydrological response to climate change for the Fitzroy catchment was the pronounced seasonality of flow. The median scenario according to annual rainfall change, produced by the CSIRO Mark 3 model, actually yielded the third wettest outcome from the set of eleven model-derived scenarios.

To allow for this pronounced seasonality we developed a flow-weighting method of averaging monthly rainfall and potential evaporation changes to obtain a flow-weighted annual average for both variables. Using this technique, the median model-based scenario presented in Table 4 would have been attached to the CGCM2 A2 model simulation, which produced changes of -3.7% and -8.0% in 2030 and 2070 compared to the changes of +3.3% and +20.1% respectively, produced by the Mark3 model.

Conclusion: *methods of flow-weighted climate averaging can better link seasonal rainfall changes to seasonal streamflow flow patterns and greatly improve the skill of simplified models in undertaking risk analysis of climate-driven flow changes.*

Investigation of the relationship between rainfall and areal potential evaporation shows that changes to the two are co-dependent and independent of specific climate models. Their correlation is 0.64 between quarterly changes in change per degree of global warming across a population of eleven climate models for a total of 44 samples. Incorporating this co-dependence into random sampling reduces the uncertainty associated with changes to potential evaporation to about 1% of the total range of streamflow change.

Conclusion: *Rainfall and potential evaporation changes are co-dependent, with larger increases in potential evaporation being associated with reductions in rainfall and smaller increases in potential evaporation with increases in rainfall.*

Risk analyses were undertaken by the Monte Carlo sampling of quarterly changes in rainfall and potential evaporation for a prescribed range of global warming in 2030 and 2070. When each quarter was randomly sampled on a uniform probability distribution and screened to reject changes between quarters that exceed quarterly differences in the original sample, only 25% of the total number of random samples was retained.

Although the resulting ranges for mean annual flow in 2030 and 2070 were slightly larger than those produced by the driest and wettest of climate model-based scenarios, the resulting probability distribution function greatly favoured the central tendencies (Table 12). The analyses showed that approximately ⅔ of the outcomes indicated reductions in streamflow with ⅓ increases.

Risk analysis methods accounting for the distribution of regional changes in rainfall show great promise for further reducing the spread of the “most likely” outcomes for changes in stream flow. We chose to represent the most likely 90% and the most likely ⅔ in terms of the range of outcomes. Using uniform sampling of the range of rainfall change, the most likely 90% occupies approximately half of the total range and the most likely ⅔ occupies ⅓ of that range. Under the non-uniform sampling of rainfall change, these reduce to less than ⅓ and one-fifth of that range.

Table 12. Likelihoods of changes in mean annual flow for the Fitzroy River Basin in 2030 and 2070 for the three different analytic methods used in the report. All values are in percent change from the baseline average

Method	**Driest**	**5%**	**16.6%**	**Median**	**83.3%**	**95%**	**Wettest**
2030							
Model-based scenario	-31			3			22
Uniform random sampling	-33	-20	-14	-4	6	12	28
Non-uniform random sampling	-31	-14	-8	-2	2	6	27
2070							
Model-based scenario	-65			20			80
Uniform random sampling	-100	-59	-40	-13	14	33	85
Non-uniform random sampling	-92	-41	-24	-7	4	14	82

	Entire range	**Most likely 90%**	**Most likely ⅔**
2030			
Model-based scenario	53.0		
Uniform random sampling	61	32	19
Non-uniform random sampling	58	20	10
2070			
Model-based scenario	145		
Uniform random sampling	185	92	53
Non-uniform random sampling	174	55	28

Conclusion: *risk analytic techniques can significantly constrain the likelihoods of change in average stream flow even where wide ranges of change are possible.*

Conclusion: *the most likely change in mean annual flow for the Fitzroy River due to climate change is -15% to +5% by 2030 and -40% to +15% by 2070. Changes outside this range are possible, but unlikely.*

Changes in low (10th percentile) and high (90th percentile) annual flows from the baseline were also investigated. Reductions in dry season rainfall in all models compared to both positive and negative changes in the wet season in all climate models mean that reductions in low flows are highly likely compared to both the baseline and with respect to changes in mean flows.

Conclusion: *low flows are very likely to reduce by more than average flows if average flows decrease. Net increases in low flows from the baseline are possible if mean flow increases.*

Conclusion: *changes in high flows are highly dependent on changes to wet season rainfall and are likely to be close to changes in average flows, or higher, if summer rainfall increases.*

Limitations of the assessment

There are a number of limitations in this assessment that will affect the interpretation and application of its results. These limitations concern:

- uncertainty linked to the greenhouse effect;
- the limitations of climate modelling, which affect how subsequent output can be used,
- the method of scenario construction,
- the application of those scenarios to the impact model,
- the relationship between climate change and ongoing climate variability, and
- hydrological model uncertainties.

Greenhouse-related uncertainties

Climate change uncertainties can be divided into scientific uncertainties and socio-economic uncertainties. Many scientific and some socio-economic uncertainties can be reduced by improved knowledge that can be simulated within models. Some certainties are irreducible; for example, the chaotic behaviour of systems or future actions of people affecting rates of greenhouse gas emissions. Some uncertainties will be reduced through human agency; for example adaptation to reduce the impacts of climate change or the mitigation of climate change through greenhouse gas reductions.

In this report, the major greenhouse-related uncertainties we have accounted for are climate sensitivity (model sensitivity to atmospheric radiative forcing), regional climate change (managed by using a suite of climate models providing a range of regional changes, checked for their ability to simulate the current Queensland climate; see the first part of the report) and a range of no-policy greenhouse gas scenarios (the IPCC SRES).

Climate model limitations

The main limitations of climate models, apart from incomplete knowledge, which is addressed above, relates to scale. Much of the variability within the real climate is emergent from very fine-scaled processes that may not be well represented in climate models, particularly those models with coarser resolution. The two major limitations relate to changes in the interannual and daily variability of rainfall. A further limitation relates to the coarse resolution of topography, not thought to be a major contributor to regional uncertainty over most of Australia. Incomplete or partially known physical processes also limit climate models – the most significant of those being limited to the behaviour of clouds under climate change, which contributes to climate model sensitivity, mentioned in the previous section.

Interannual rainfall variability is subject to large scale teleconnections, so requires a fully coupled climate models of sufficient vertical and horizontal resolution to be adequately simulated. However there is as yet no real agreement between different models as to how important phenomena, such as the El Niño – Southern Oscillation phenomenon may behave under climate change. Each rain event is also limited in scale to the size of the grid spacing in the model. Essentially, each rain event occurs across a whole grid box, which tends to reduce its intensity because fine-scale convection processes cannot easily be produced. Therefore, although climate models indicate increases in daily rainfall intensity, these increases are generally under-estimated under all but the finest resolution regional models. Methods are currently being explored to combine both global and local influences in fine scale model simulations but as yet this data is not available for impact studies. However, a few specialised climate runs would also fail to properly address a range of uncertainties that a larger set of models can provide. This is one reason why we have not traditionally relied heavily on downscaled rainfall data.

Scenario construction methods

Climate scenario construction needs to strike a balance between representing a realistic set of changes and uncertainty using available resources. Rainfall is the main driver in simulating hydrological change and can potentially change across a range of temporal and spatial scales. Obviously, it is difficult to produce scenarios that represent all changes that a model can realistically simulate or to compensate for those changes where model simulations indicate a change but where the output cannot be used directly (as in downscaling).

In this project, we use the OzClim climate scenario generator which has climate change patterns from a number of different models installed: most importantly for this project, monthly patterns of change per degree of global warming for average rainfall and areal potential evapotranspiration. These patterns contain normalised representations of local change as a function of global warming that can be re-scaled using a wide range of average global warming to provide changes representing the outcomes for each climate model for any date from 1990 to 2100. Mitchell (2003) has shown this method to be valid for the range of global warming provided by IPCC (2001). Therefore, by using a range of climate models we are representing as wide a range of local climate change that can reliably be quantified.

However, changes to climate variability have not been explicitly represented in these scenarios. This would require access to large volumes of high-resolution data and likely involve intensive downscaling methods for data from many models, which we do not have the resources to undertake.

Scenario application

The method of scenario application we have used is to multiply daily changes in rainfall and potential evaporation by a single monthly value of percentage change, the so-called uniform perturbation method. This assumes that all values within that month will change by the same amount e.g. -5%, without any changes in daily variability. This method has been automated within the OzClim system, allowing us to batch-run a large number of scenarios in a relatively short time, a capacity which at the moment is unique.

Studies of daily rainfall output from climate models indicate that extreme rainfall is likely to increase, except where decreases in the mean are large. The number of raindays appears likely to decrease, except for larger increases in rainfall. Even for situations where mean rainfall does not change, climate models indicate increases in extreme falls and a decrease in lighter falls and the number of rain days. As detailed in the previous section, we do not have the resources to test the impacts of such changes.

The application of changes in monthly mean to historical daily data means that changes in annual and seasonal mean rainfall are well represented, but not differential changes in daily rainfall or the number of raindays. Where such changes have been simulated from CSIRO Mark2 data, they produce increases of several percent (Chiew et al., 2003) but this rainfall output was not downscaled further, which would increase the simulated intensities of the heaviest falls.

The perturbation of historical data also means that interannual variability is largely preserved (it is altered somewhat by interseasonal changes), so the underlying assumption is that the pattern of dry and wet years will not be greatly altered under climate change. (There is no compelling reason from the investigation of climate model data to either confirm or deny this). This is one reason why long time series of historical data are preferred, so that a reasonable sample of climate variability can be assessed for potential change.

Climate change and variability

The method of scenario application used in this study does not incorporate longer-term changes in climate variability that have been known to occur in the past, beyond those contained in the baseline data. Abrupt changes in rainfall regime affecting both means and variability are known to occur several decades apart but the dynamics of these changes are not well understood and as yet are unpredictable. Vivès and Jones (2005) identify a downward shift in eastern Australia, including the Fitzroy River region, in the period 1890–1895, but of several shifts occurring since, none have clearly occurred in the Fitzroy River catchment. Further investigation would help to identify changes such as those identified by Vivès and Jones (2005) and Power et al., (1999).

A risk analysis carried out for the Macquarie River Basin in New South Wales indicates that both benign and severe combinations of climate and climate variability are possible. To properly assess the ongoing risks of climate on water resources in the Fitzroy River, both the enhanced greenhouse effect and potential changes independent of greenhouse will also need to be taken into account. In this regard, this assessment has been limited by the availability of input data from the IQQM model, limiting us to the years 1900–1990. Such shifts cannot easily be diagnosed within a decade of occurring; an understanding of their dynamics may help to locate them shortly after they occur so that their inherent risks can be better understood.

Hydrological uncertainties

Impact assessments using different hydrological models indicate that the models themselves may have varying sensitivity to climate change (e.g. Boorman and Sefton, 1987; Chiew et al., 2005). Further work comparing the sensitivity of the Sacramento rainfall-runoff model used in IQQM to other commonly used Australian rainfall-runoff models which have been tested for their sensitivity, would help put the results provided here in a broader context.

Jones and Durack (2005) have produced estimates of runoff for a range of catchments in Victoria based on calculating A and B factors for Equation 2 as a factor of the runoff co-efficient of a catchment. For the Fitzroy River Basin, a runoff co-efficient of 4.2% calculated from the baseline average volume of flow and annual average rainfall of 684 mm, produces A and B values of 3.33 and -0.78 respectively. This relationship validates well for the thirty-three climate model scenarios for 2030 with an average error of 1.8% in annual flow, showing that the Sacramento model produces similar results to the SIMHYD and AWBM models investigated by Chiew et al. (2005). The larger changes in 2070 were not simulated as well.

The simple hydrologic model used hare and by Chiew et al. (2005) is less accurate than the rainfall-runoff model and is not reliable for large positive or negative changes in flow. Here, the model produces reasonably reliable output to changes of about ±50%. It also produced errors with two sets of three climate model scenarios for both 2030 and 2070, implying that not all climate change scenarios could be accurately represented by flow-weighted averaging and average rainfall and potential evaporation changes. However, the simple model is very useful at representing flows in the most likely range of change and, for 2030, produced a standard error of only 2% for mean annual and 90th percentile flow, larger for the 10th percentile flows.

Summary and Recommendations

The methods and results described and presented in this section show that the potential of risk analysis to reduce uncertainty about future streamflow change is considerable. Despite large uncertainties in the spread of possible results, uncertainties that explode the further into the future one looks, the most likely range is much more constrained. In terms of planning that takes account of those changes, it is possible to focus on the most likely outcomes, with a watching brief being held to ensure that climate change is not likely to shift outcomes beyond that range.

However, changes affecting water resources due to the greenhouse effect will not occur in isolation. Ongoing changes in climate variability over decadal scales, suggests a whole of climate approach needs to be taken. Non-climatic effects will also affect yield, for example: the development of farm dams, re-afforestation and other forms of water harvesting.

Vulnerability analysis, assessing how a system can cope with carrying degrees of change can also help determine whether planning needs are urgent, within the scope of projected changes, or whether an incremental, or do-nothing approach is warranted. For example, Jones and Page (2001) concluded that water users in the Macquarie River catchment were vulnerable if mean annual flow reduced by >10% in a drought-dominated rainfall regime, >20% in a normal rainfall regime and >30% in a flood-dominated regime.

Recommendations for further research include:

- Weighting models according to their skill in simulating current climatology, or in their reproduction of the 20th century climate over Australia to further constrain rainfall uncertainty.
- Investigate modes of decadal rainfall variability for the region.
- Add the latest 15 years of climate data to the IQQM input and conduct further analysis to bring the model and analysis up to date.
- Conduct further assessment of potential changes in wet-season rainfall, which is the largest driver of changes water supply, to constrain uncertainties.
- Develop plans to ensure security to dry season water resources, including environmental flows, because of the likelihood of reduced dry season streamflow.
- Assess system vulnerability to water supply and quality to add context to projected changes in catchment water balance.
- Assess current water strategies in light of possible changes.

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Climate Change impacts on Sediment and Nutrient load of the Fitzroy River Basin

Authors: Bob Cechet, Paul Durack, Roger Jones and Scott Wilkinson

Executive Summary

Climate change impacts on the Sediment and nutrient load of the Fitzroy River Basin have been developed by coupling CSIRO's OzClim scenario generator with the SedNet sediment modelling package.

The study has involved:

- Development of climate change sensitivity scenarios for the Fitzroy River Basin for 1, 2 and 4°C climate change based on the full suite of SRES scenarios developed by the Inter-governmental Panel on Climate Change (IPCC)
- Obtaining the output from 3 representative general circulation models (GCMs) and deriving patterns of change for the Fitzroy River Basin expressed by these
- Determining available limited SedNet input datasets required for considering climate change scenarios
- Run a thorough risk analysis using the sensitivity scenarios described above to attempt to explore the range of uncertainty for the basin

The findings of this study are summarised below:

- The input data provided for these sensitivity scenarios was not event-based and as a consequence, did not adequately assess likely changes to sediment flows due to climate change
- The model (using annual mean input data) was found to be very insensitive to very large increases or decreases to input climatic variables of rainfall and potential evapotranspiration (PET)
- The major contributor of sediment loading to the Fitzroy River, is due to the process of hillslope erosion
- The range of observed sensitivity (optimised in the model) does not capture likely ranges expressed in representative climate change scenarios for the basin
- New model output scheduled for development at CSIRO in the second half of 2006 (and early 2007) may provide the necessary new regionalisation parameters to successfully utilise the SedNet package
- More collaborative research is required to utilise the functionality of the SedNet model effectively, with future event-based climate change scenarios required to accurately assess climate change impacts to sediment flows in the Fitzroy River Basin

Introduction

The brief for this study involved the coupling of the CSIRO OzClim climate change scenario generator to the Sediment River Network Model (SedNet). SedNet constructs sediment and nutrient budgets for river networks and was developed as part of the National Land and Water Resources Audit by CSIRO Land and Water. The model has been recently applied to the Fitzroy basin in two studies; one reported by Brodie et al. (2003), and one undertaken in a collaborative DNRM/QEPA/CSIRO Land and Water project to be reported in November 2005. The SedNet modelling expertise in the Fitzroy, combined with the important climate changes expected in the basin make it an ideal area in which to investigate climate change impacts on sediment and nutrient fluxes. The brief initially included the assessment of potential changes in nutrient load, however was not completed as the nutrient transport package within SedNet was still being developed (available November 2005).

This report documents a preliminary investigation to determine the likelihood that SedNet can be used to investigate climate change impacts on sediment and nutrient fluxes in the Fitzroy basin. This investigation utilises likely mean annual climate change projections across the basin using CSIRO's OzClim climate change scenario generator, and analysis of the further work required to predict resultant changes to sediment and nutrient fluxes. Climate surfaces for input into the SedNet model have been produced, however it has been determined that the task of running SedNet in a “new or modified” regional climate also requires generation of other specialised inputs relating to sediment transport in the catchment. Additionally, the use of event-based scenarios, which capture climate changes to rainfall intensity, will provide a much more accurate representation of simulated changes to sediment transport in a changing climate.

Hydrology

Stream flow is highly variable with a seasonal bias towards higher summer flows. Limited data indicates that annual sediment delivery to the estuary is 5 million tonnes (Fitzroy Basin Association) with accompanying high levels of nutrients and some pesticides. The catchment has recognised land degradation problems including all forms of soil erosion by water, and soil fertility decline.

Flood Risk

Due to its large size and fan-like shape, the Fitzroy River catchment is subject to severe flooding following heavy rainfall events. The Fitzroy River at Rockhampton has a long and well documented history of flooding with records dating back to 1859. Figure 26 shows the significant flood peaks recorded at Rockhampton during the last 150 years.

The Fitzroy’s major tributaries: the Dawson, Mackenzie and Connors Rivers rise in the eastern coastal ranges and in the Great Dividing Range and join together about 100 kilometres west of Rockhampton. Major floods originate in either the Dawson or the Connors-Mackenzie Rivers. Significant flooding in the Rockhampton area can also occur from heavy rain in the local area below Riverslea. Significant flooding is chiefly associated with either the nearby coastal crossing of a tropical cyclone or a slow moving low-pressure rain depression in the catchment region.

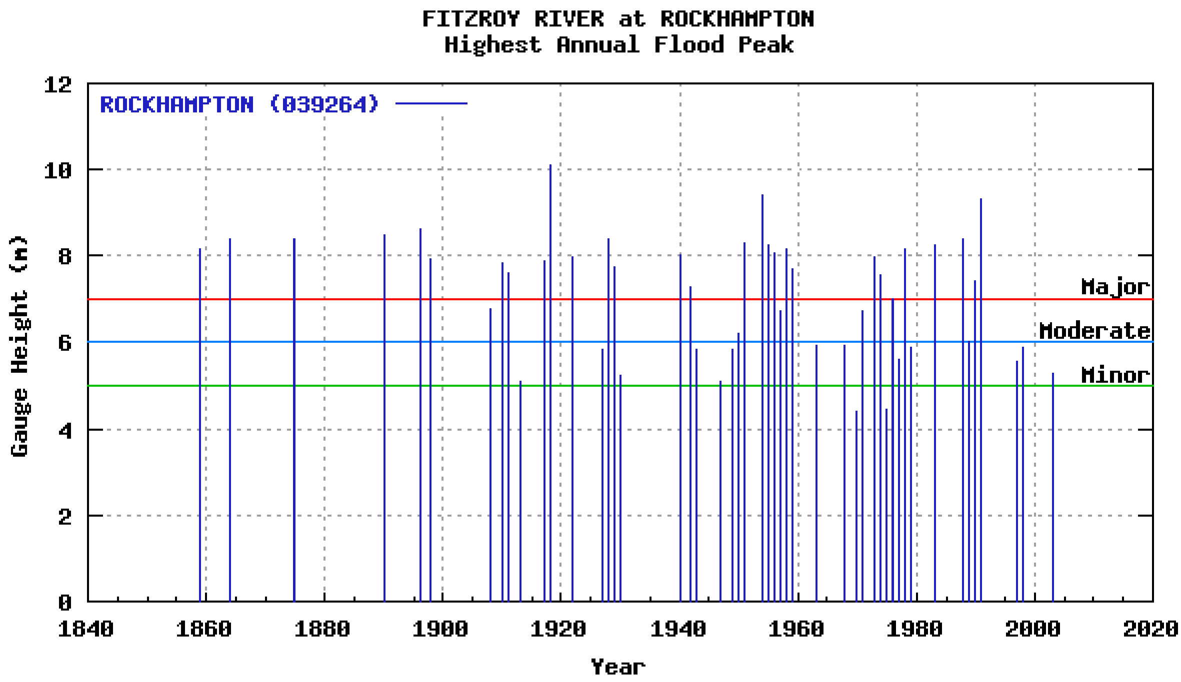


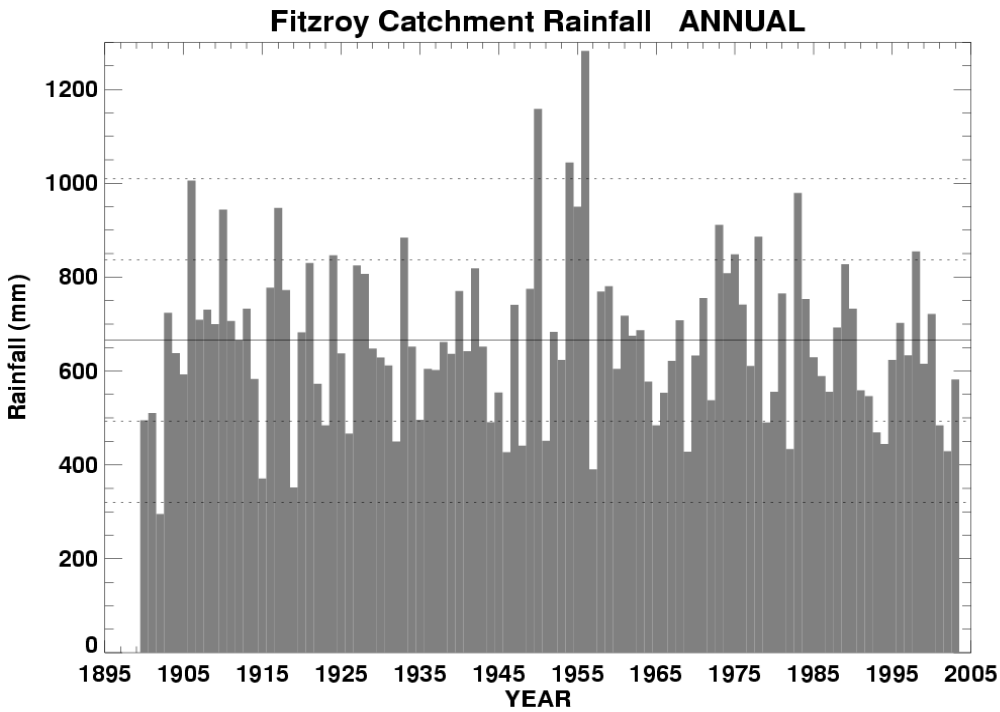
Figure 26. Fitzroy River significant flood peaks 1840-2003 (Rockhampton gauge)

Table 13. Fitzroy Basin catchment area-average rainfall for all months, season, April to October, November to March and annual values. Data sourced from the BoM 0.25 degree monthly climatology 1900-2003

Month/Period	Average mm	Standard deviation mm	Maximum recorded rainfall mm	Minimum recorded rainfall mm
January	102.3	62.9	449.2	10.6
February	98.6	69	415.9	13.7
March	69.3	50.8	239	4.7
April	40	39.2	215.2	2.3
May	37	36.4	229.3	1.5
June	35.3	33.4	228.5	1.3
July	30.9	32.7	180.3	1.4
August	23.9	22.2	123.5	1.1
September	25.4	25.3	140.8	1.5
October	47.1	30.1	173	5.2
November	65.3	37.2	183.7	4.2
December	90.1	48.4	229.8	14.9
Summer	292.0	107.2	633.7	100.8
Autumn	146.2	83.6	493.5	25.1
Winter	90.1	57	301.6	8.2
Spring	137.9	64.7	340.3	26.9
April to October	239.6	99.3	595.2	46.8
November to March	425.6	134.2	974	181.8
Annual	665.2	172.3	1281.9	295.2

Table 13 indicates the monthly and seasonal rain distribution over the Fitzroy River Basin. Most rain falls between November to March (64%). The summer season (December to February) is the wettest season (44% of annual rainfall) and the season with the most severe rainfall events. The severity of flooding is dependent on condition of ground surface and existing soil moisture.

Figure 27 indicates the variability in both annual and also summer season rainfall for the Fitzroy Basin (area averaged). Significant summer rainfall events (greater than one standard deviation above the mean) do not correlate well with significant annual rainfall periods.



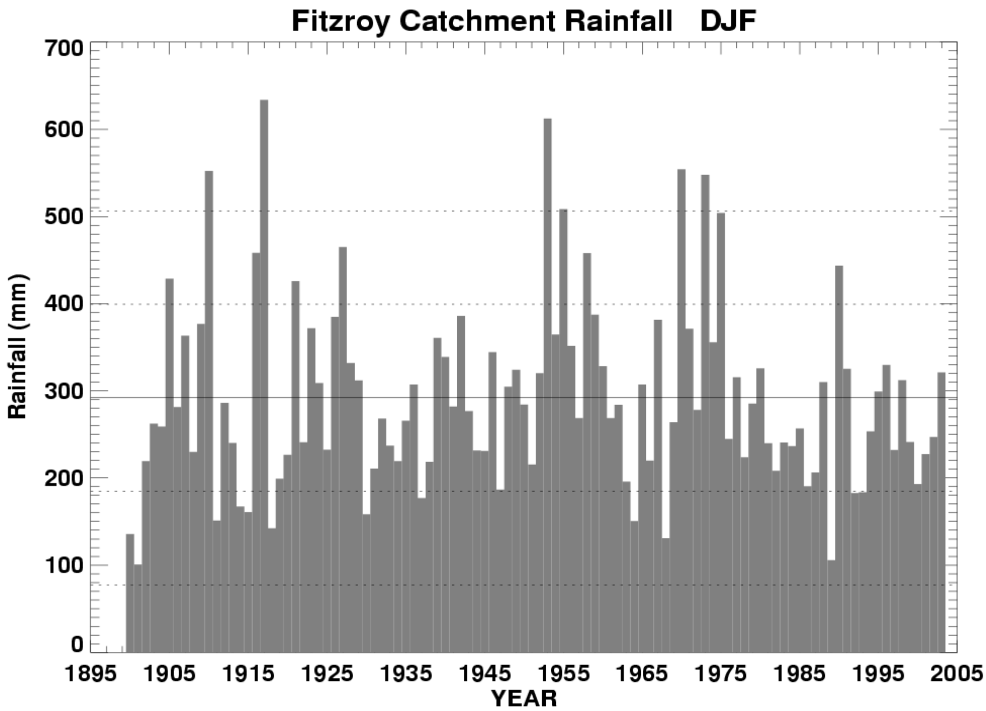


Figure 27. Time-series of the Fitzroy River Basin total annual and total summer catchment area-averaged rainfall. The solid horizontal line depicts the long-term mean. The broken lines depict one and two standard deviations from the mean respectively (Data sourced from the BoM 0.25 degree monthly climatology)

Sediment Budget

Land use types and coverage in the Fitzroy Basin consists of Forest/Savannah (10%), grazing (85%) and cropping (5%; Brodie et.al., 2003). Grazing land was the source of 91.4% of the sediment exported onto the Great Barrier Reef (GBR). Table 14 shows the different contributions of suspended sediments and nutrients estimated from a range of studies. These estimates of suspended solids vary by a factor of up to 8.5.

Table 14. Estimated annual contributions of suspended sediments and nutrients (total nitrogen and total phosphorous) to the Great Barrier Reef (GBR) from the Fitzroy River Basin. Reproduced from table 8.54 of Brodie et al., 2003

	Suspended Sediments (kT/yr)	**Total Nitrogen (T/yr)**	**Total Phosphorous (T/yr)**
Current	2911	8071	2140
Furnas (2003)	2230	5101	1001
Belperio (1983)	2200		
Moss et al. (1; 1992)	1774		
Moss et al. (2; 1992)	1861		
Neil et al. (2002)	10466		
Horn et al. (1998)	4330		
NWLRA (2001)	2640		
Bloesch et al. (1997)	15200		

Table 15. Current erosion budget for the Fitzroy Basin estimated by Brodie et al. (2003) according to erosion type, showing the bulk of sediments sourced from hillslope erosion

Erosion Type	**Fitzroy River Basin**	**Annual Percentage**
Gully	3830	33.1
Bank	638	5.5
Hillslope	7092	61.4
Total	11559	100

Figure 28 shows the spatial contribution of suspended sediment exported to the coast. There are more than two orders of magnitude in the contribution of sediment from east to west in the basin. The coastal and near-coastal regions of the Fitzroy Basin are the largest sources, this distribution being largely consistent with annual rainfall distribution.

The only two estimates available also show considerable variation in the nutrient budget for the Fitzroy Basin under the present climate. Given such uncertainty, an impact assessment under climate change will only roughly indicate the magnitude of possible changes.

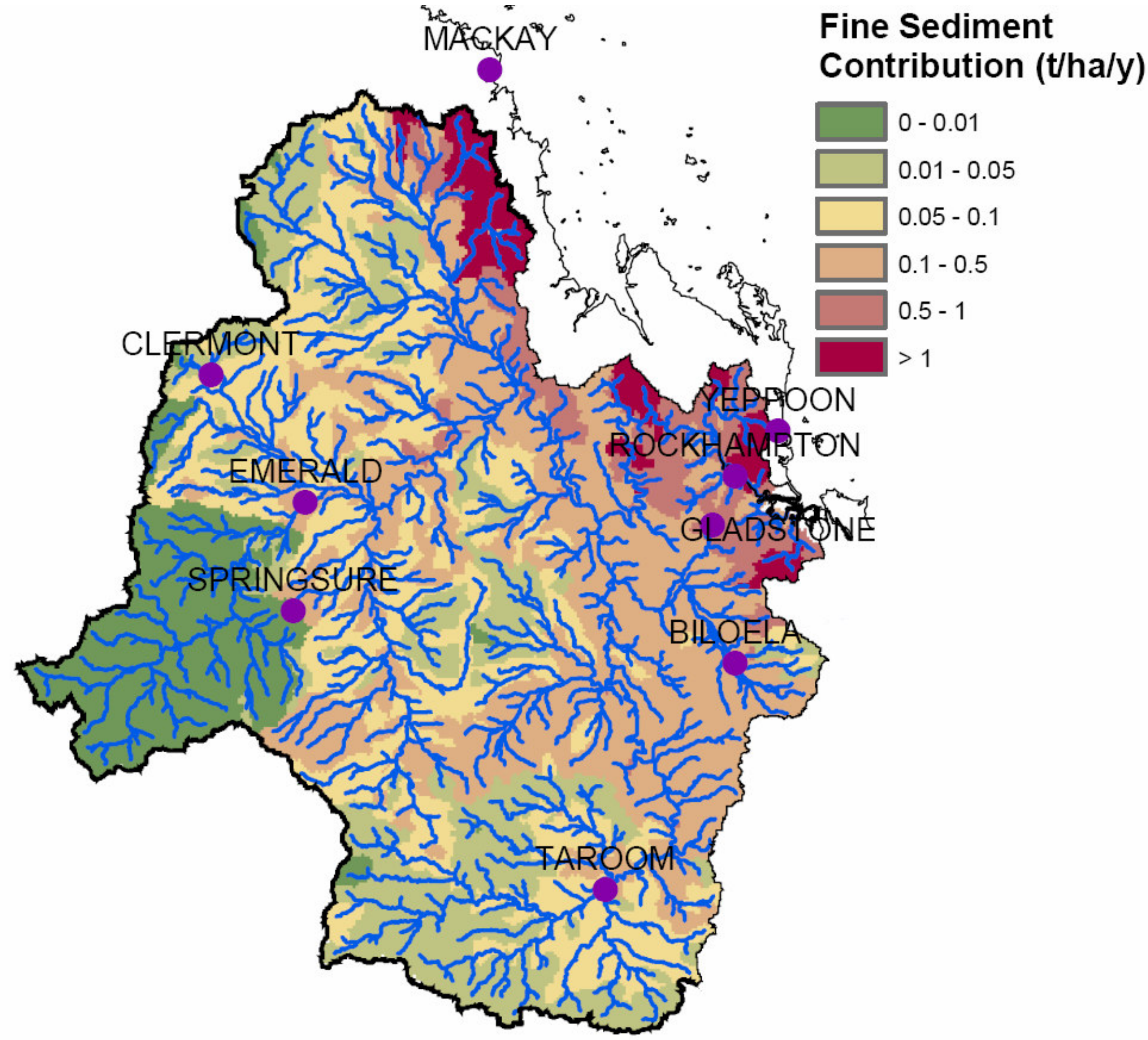


Figure 28. Contribution of suspended sediment (T/ha/yr) exported to the coast (from Brodie et al., 2003)

Meteorology

The SedNet sediment budget model requires the following two meteorological fields:

- Annual Rainfall
- Annual Potential Evapotranspiration to Rainfall ratio

Additionally, SedNet requires rainfall erosivity calculated from the maximum 30 minute rainfall intensity – projected changes to rainfall erosivity were not available for this study. In order to run the model, the existing baseline field was utilitised.

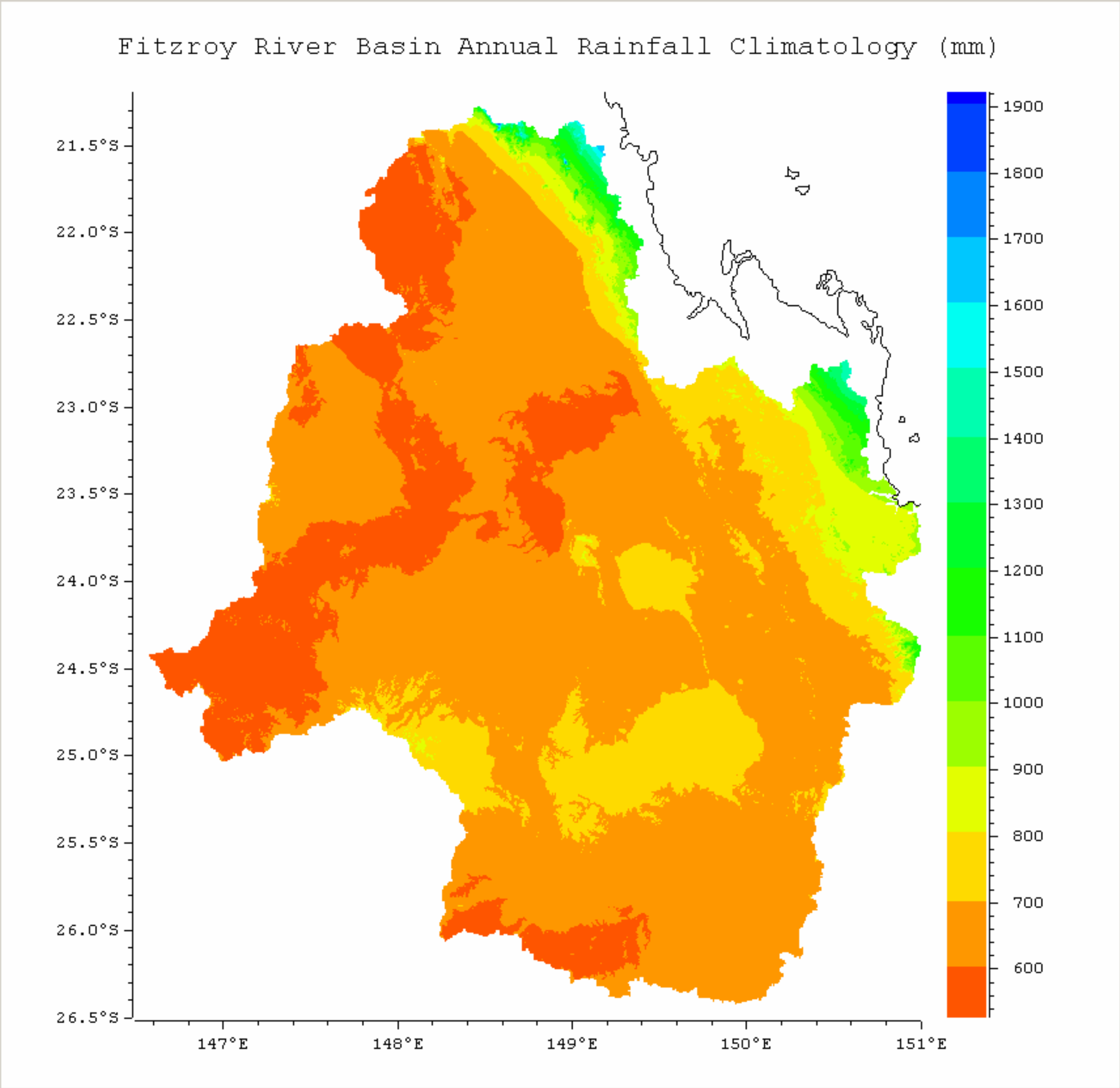


Figure 29. Fitzroy River Basin; Annual rainfall

The meteorological fields for the Fitzroy River Basin were supplied by CSIRO Land and Water. These fields included a rainfall climatology at 250m resolution sourced from the Bureau of Meteorology (BoM), see Figure 29, and the PET/Rainfall grid also at 250m resolution. The annual potential evapotranspiration data was derived from the Australian Natural Resources Data Library, with this data developed using the Priestley-Taylor method and is expressed in Figure 30. The original resolution of the PET grid was 500m, however was resampled to 250m resolution of the rainfall data, and the ratio grid produced.

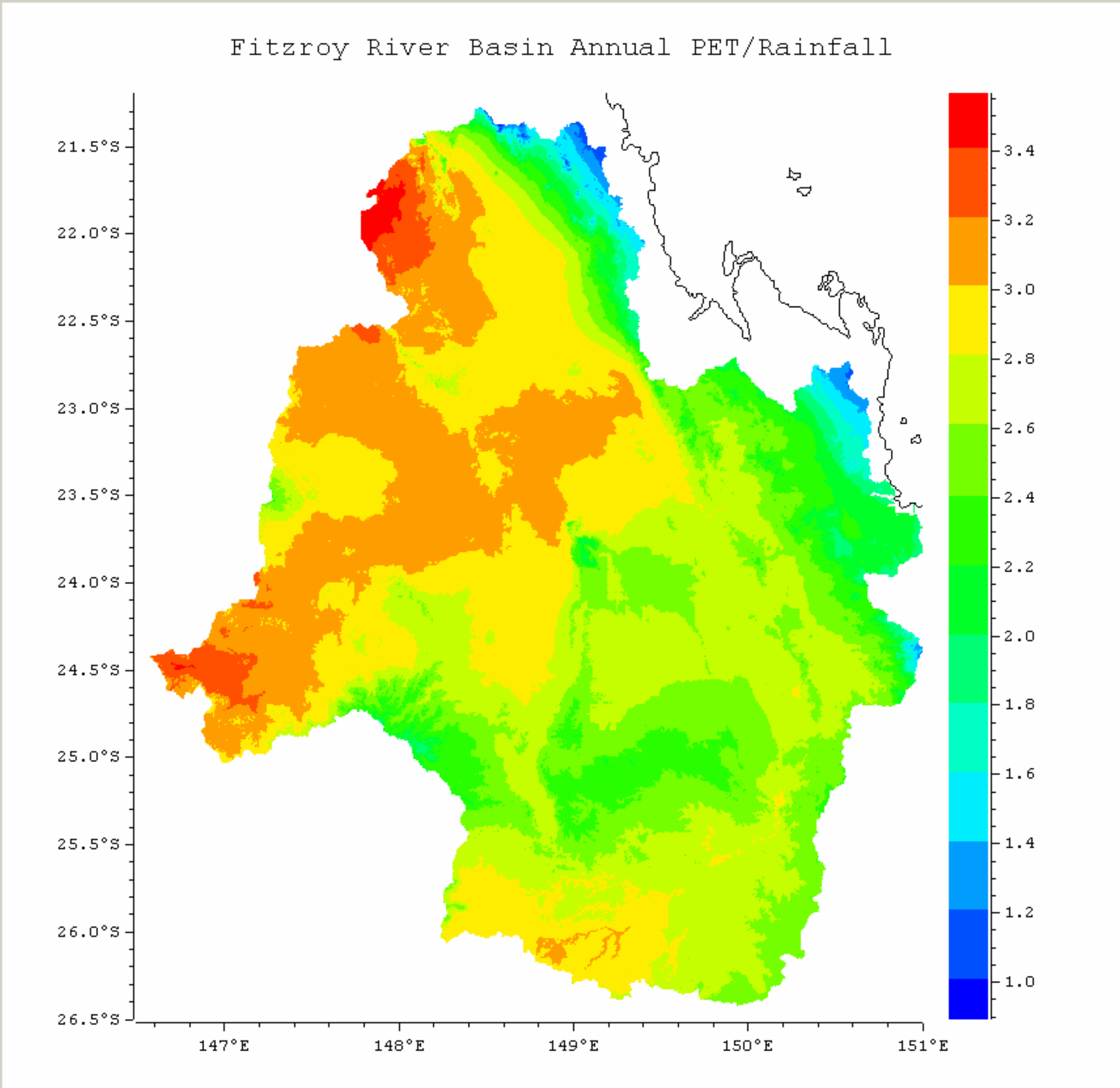


Figure 30. Fitzroy River Basin; Annual potential evapotranspiration (PET)/ Annual rainfall

The data shown in Figure 29 and Figure 30 represent the baseline or current climate information required by the SedNet model. The agreed task was to produce a range of future climate conditions for the Fitzroy Basin region based on the output of a number of general circulation models that have performed reasonably well in correctly depicting the current climate of the Queensland region.

In order to perturb the baseline climate information for the Fitzroy River Basin provided by CSIRO Land and Water, it was necessary to link model outputs with the variables required, rainfall and PET. Climate models output the rainfall changes directly, however the PET sources are not the same as those generated using the Priestley-Taylor method. Figure 31 expresses the two fields which were selected for comparison.

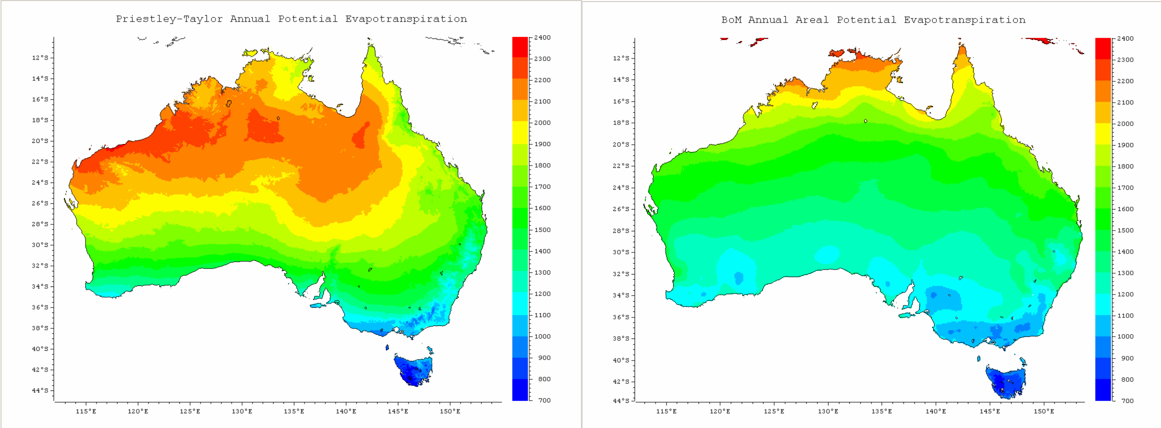


Figure 31. Priestley-Taylor Annual Potential Evapotranspiration (sourced from the Australian Natural Resources Data Library) and BoM 1961-1990 Annual Areal Potential Evapotranspiration

Annual Areal Potential Evapotranspiration was the closest in magnitude to the Priestley-Taylor series, and as a consequence, model patterns depicting changes to PET were selected from this model output.

The following section examines the climate change considerations regarding rainfall and potential evapo-transpiration employing six general circulation models. The models and their horizontal resolution are listed in Table 16.

Table 16. Climate Models used and their horizontal resolution

General Circulation Model (GCM)	Horizontal Resolution (km)
CSIRO Conformal-Cubic regional model (CC50)	~50
CSIRO DARLAM regional model (D125)	~125
CSIRO Mark 3 (Mark3)	~200
Hadley Centre HadCM3 (HadCM3_A2)	~400
Hadley Centre HadCM3 (HadCM3_B2)	~400
DKRZ, Germany ECHAM4 (ECH4)	~300

Projected climate changes

The change in annual rainfall over the Queensland region with regard to global warming (Figure 32) is complex with the sign of the change being uncertain. The four models at the top of Figure 32 show a general decrease in annual rainfall over the Queensland region. We have the highest confidence in these models because of their ability to simulate the climate of the later part of the 20th century in the Queensland region. Nevertheless, we cannot discount outright the results of the lower two panels in Figure 32 belonging to ECH4 and D125. These two models are the oldest simulations in the set, and in fact both models have been superseded at their host organisations (Max Planck Institute, Hamburg & CSIRO, Melbourne). D125 has been superseded by the CC50 shown in panel (a) of Figure 32. Even though later model simulations tend towards drier outcomes, the earlier models are still considered to be plausible.

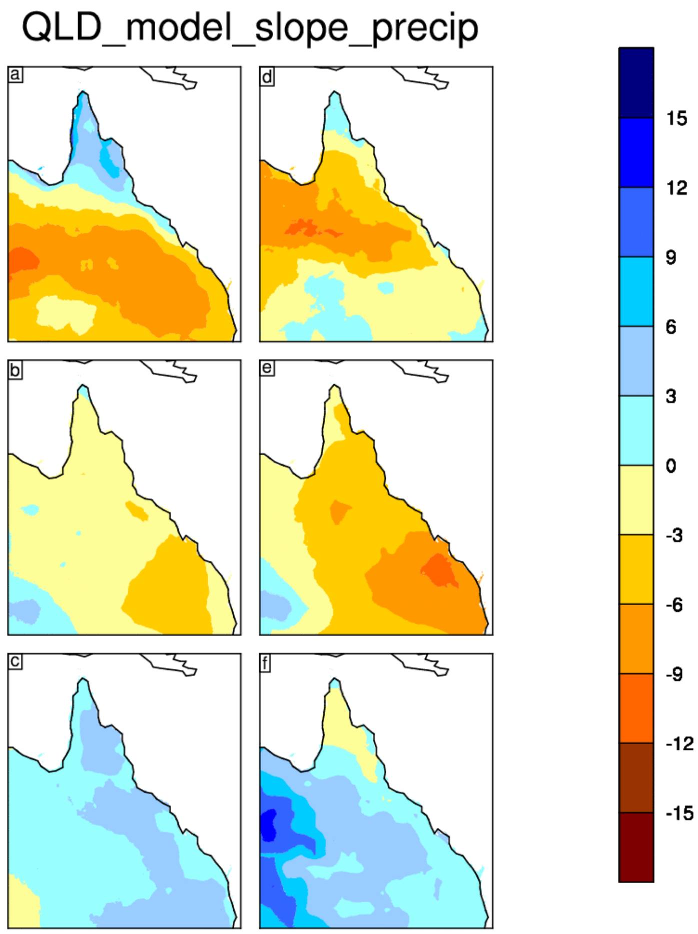


Figure 32. Percentage (%) change in annual rainfall per C of global warming over Queensland for six climate models: (a) CC50, (b) HadCM3_A2, (c) ECHAM4, (d) Mark 3, (e) HadCM3_B2 and (f) D125

Figure 33 shows a close-up of Figure 32 centred over the Fitzroy Basin. A gradient in rainfall change near the Queensland coast is evident in the (a) CC50 and (d) Mark 3 models.

Analysis of the synoptic meteorology under both current and future climate conditions suggests a strengthening of tropical disturbances but possibly not an increase in their frequency (Walsh et al., 2004). Stronger systems than those that now provide most of Queensland's coastal rainfall may push further inland, producing a gradient in the annual rainfall change that decreases inland. However, the low horizontal resolution of these models (Table 16) makes it very difficult to accurately resolve the coastal processes and the magnitude of rainfall change in the coastal belt of the Fitzroy Basin thus limiting the ability to capture the likely changes in the future sediment loads given the greatest proportion originate in the narrow coastal zone (Figure 28, Brodie et al., 2003).

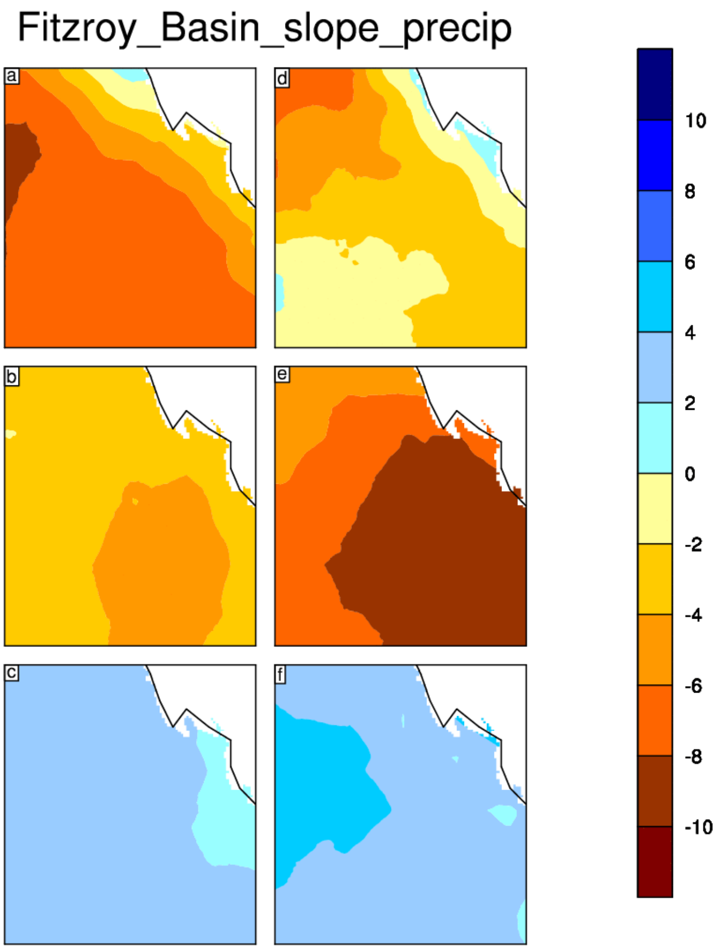


Figure 33. Percentage (%) change in annual rainfall per C of global warming as in Figure 33, centred over the Fitzroy River Basin

Figure 34 shows summer rainfall over the Fitzroy Basin. High summer rainfall with associated flooding is estimated to generate and transport the vast majority of the Fitzroy River's annual sediment budget to the sea. Only the relatively high resolution CC50 model (panel (a) Figure 34; 50 kilometre horizontal resolution) depicts a gradient in rainfall change in this season. Tropical storm activity is most severe in this season, and the predicted increase in severity under climate change forcing would result in the maximum amplitude from this gradient in rainfall change in the summer season – the peak period of contributing rainfall to streamflow in the Fitzroy River Basin.

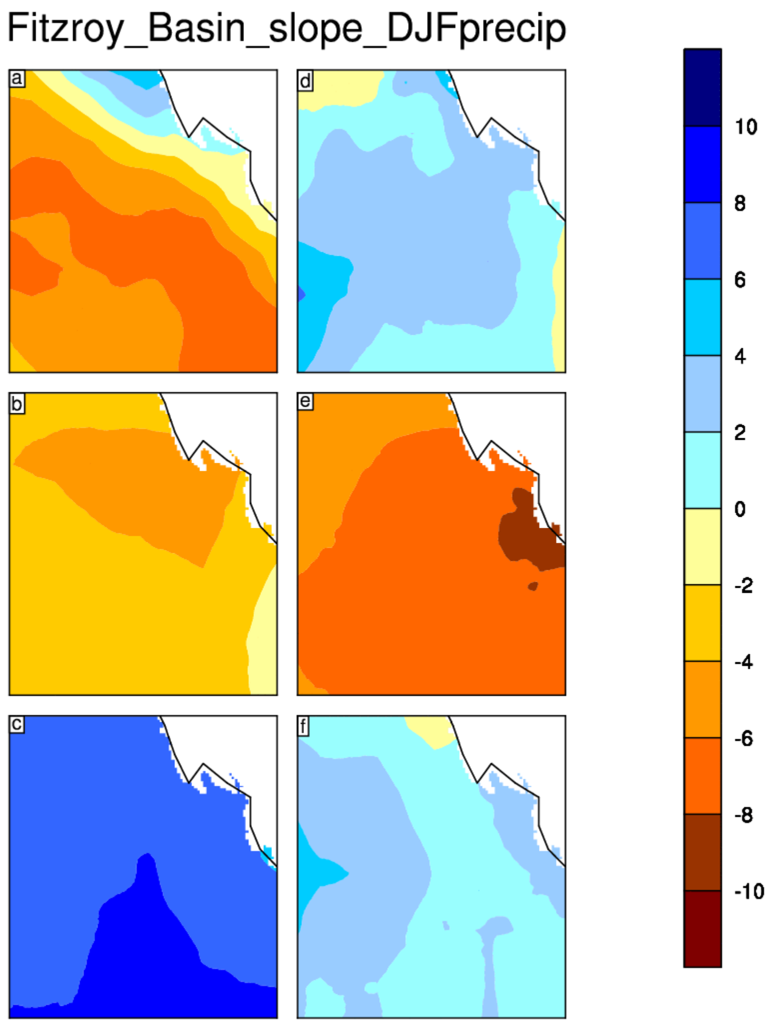


Figure 34. Percentage (%) change in summer (DJF) rainfall per C of global warming as in Figure 32 centred over the Fitzroy River Basin

In summary annual rainfall projections range from slightly wetter, to much drier than the historical climate of the past century, with a tendency for stronger decreases inland and slight increases or decreases along the coastal fringe. Seasonally, changes are uncertain in DJF and to a lesser extent in MAM but are dominated by decreases in JJA and SON. Over successive generations of climate models, estimates of rainfall change have become drier, but increases in the Fitzroy River region remain plausible. However our confidence is limited by having only a few high-resolution runs in CSIRO models. Higher-resolution runs in GCMs from other laboratories would help determine the nature of rainfall change near the coast, where both coastal climatology and topography may influence those changes.

All six models used for this study depicted increases in surface temperature for the Queensland region (except the tip of the Cape York Peninsula in the ECHAM4 model output) with respect to global warming. This results in increases in potential evaporation (also known as potential evapotranspiration; PET) per degree of global warming for all models (Figure 35). However, the magnitude of the increase varies significantly. The coastal region generally is the least affected, because surface warming near the coast is less than inland and decreases in atmospheric moisture content are not as large.

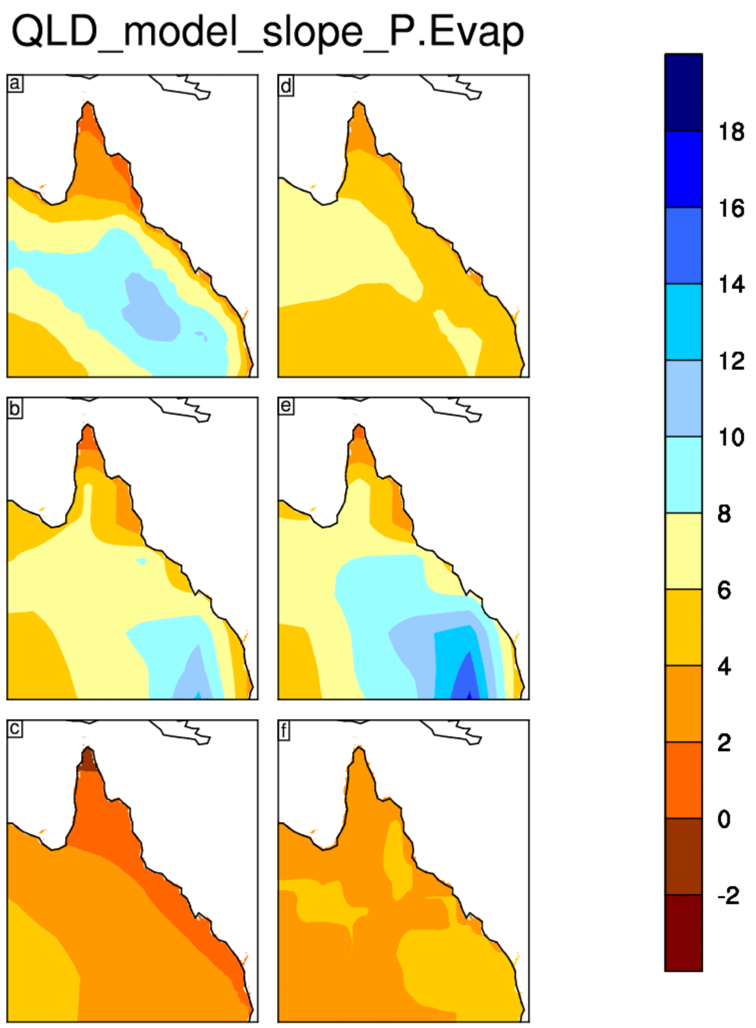


Figure 35. Percentage (%) change in annual potential evaporation per C of global warming over Queensland for six climate models: (a) CC50, (b) HadCM3_A2, (c) ECHAM4, (d) Mark 3, (e) HadCM3_B2 and (f) D125

Once again, the CC50 shows the most realistic gradient in the PET near the Queensland coast expected as reflected in slower changes to both temperature and atmospheric moisture nears the coast compared to further inland (see Figure 36).

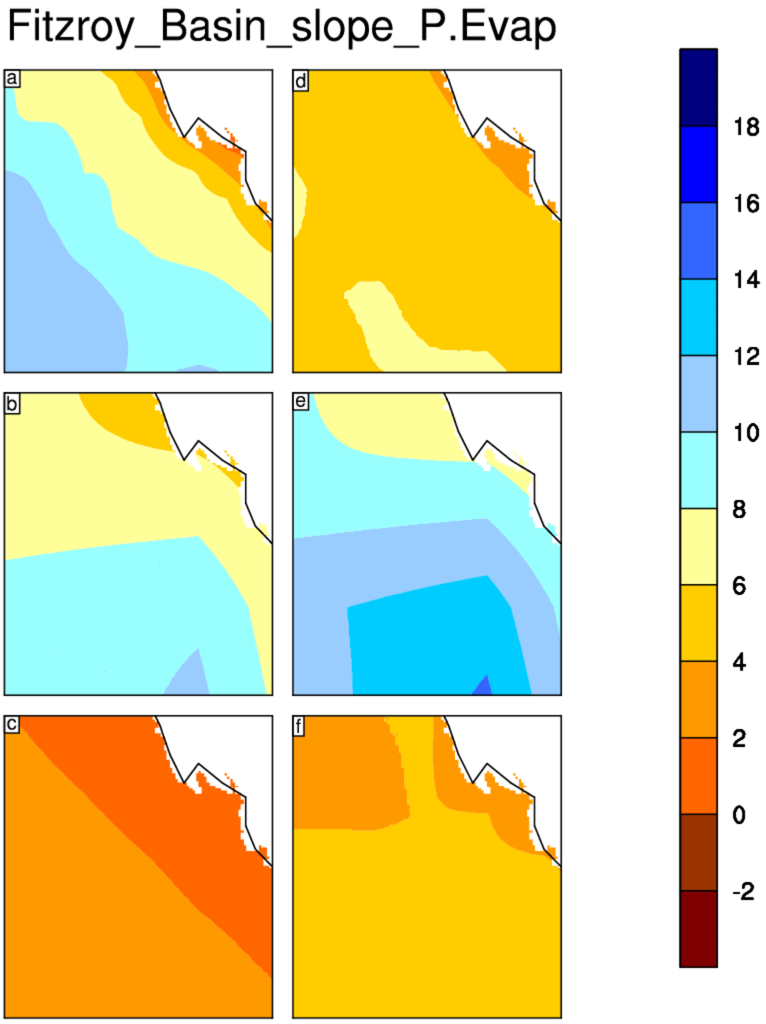


Figure 36. Percentage (%) change in annual potential evaporation per C global warming as in Figure 35 centred over the Fitzroy River Basin

In summary, simulated annual PET change in the Fitzroy River Basin, indicates larger increases inland with smaller increases near the coastal fringe. Decreases are possible near the coast if rainfall and cloud cover increases are sufficiently high, but appear to be unlikely.

Fitzroy Basin: Extreme rain rate considerations

Figure 37 is based on an analysis of daily rainfall data (all months) from an ensemble of CSIRO Mark3 model experiments generated by Watterson, 2005. Lows in surface pressure on the full grid (1.8° resolution) at the end of each model day were examined, and the previous 24 hour rainfall at the centre is noted as a rain rate (mm per day). The extreme rate from all days in a 30-year period (1961–90) for 9 simulations was examined to reduce noise. The field represents typical 30-year extremes (all months) of daily rain averaged over the 1.8° grid spacing at the centre of low pressure systems (rain from all days will be somewhat greater again). The field has been smoothed and linearly interpolated for plotting.

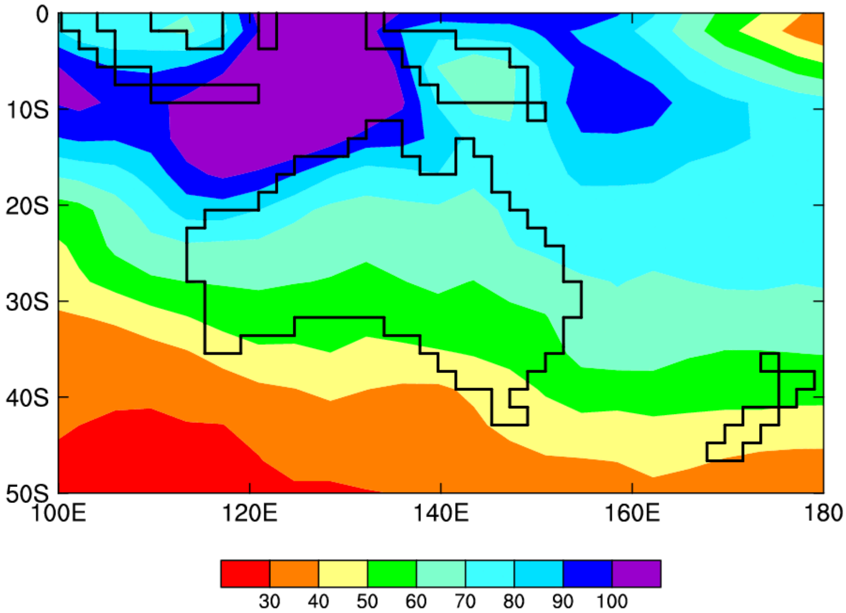


Figure 37. Typical extreme rainfall rate (mm/day) for the current climate (1961-1990, 30 year period) simulated by an ensemble of CSIRO Mark 3 GCM control experiments

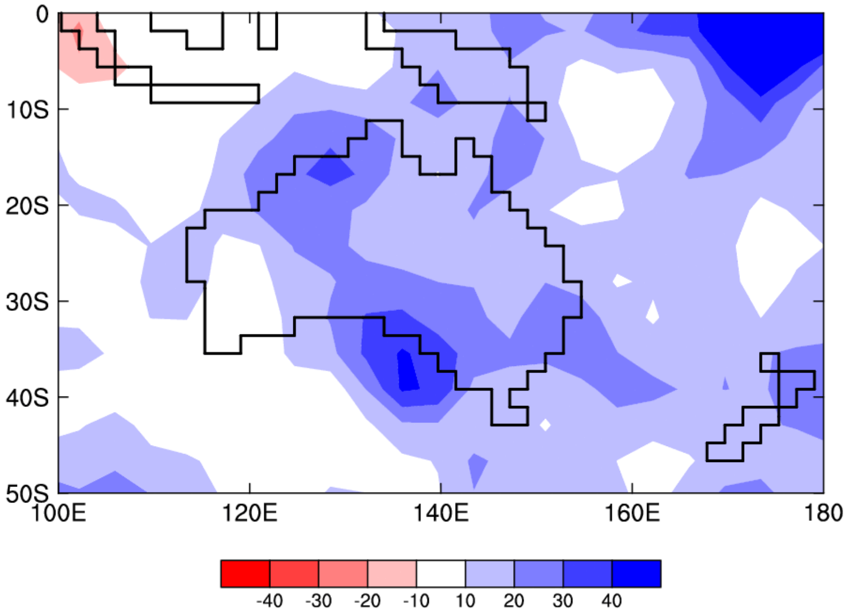


Figure 38. Percentage (%) change per C global warming in extreme rainfall (ensemble of period 2071-2100, with a global warming of 2.8C simulated by the CSIRO Mark 3 GCM)

The field for the 2071–2100 period is based on the average of three 30-year warm periods, smoothed as for 1961–90 period shown in Figure 37. Figure 38 shows the percentage change in the extreme rainfall rate, as determined from the difference between two smoothed fields of future and current climate. The global warming from CSIRO Mark3 (A2 scenario) to 2071–2100 is 2.8°C. An increase of at least 10–20% in the volume of extreme rainfall by 2071–2100 for the Queensland coastal region is simulated. This is despite a decrease in mean rainfall amounts.

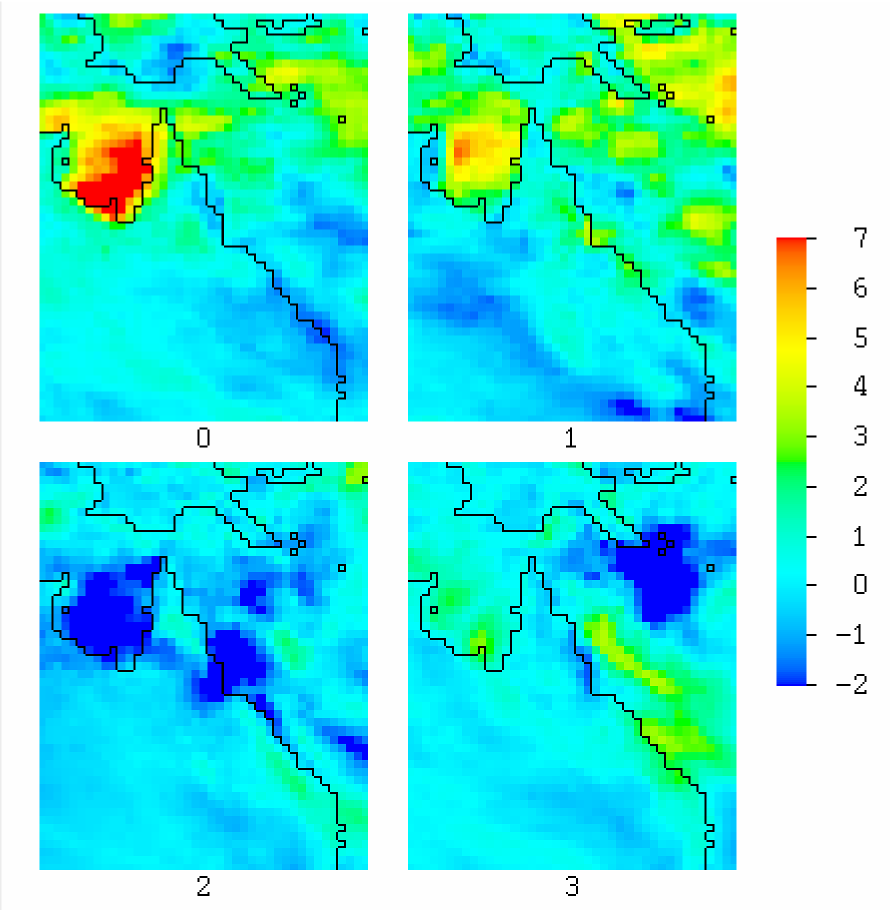


Figure 39. Percentage (%) change per C global warming for the 95th percentile of monthly rainfall (CC50) for the months of (0) January, (1) February, (2) March and (3) April

Figure 39 depicts the percentage change of the 95th percentile of monthly rainfall (extreme high amounts) per degree of global warming for the months of January to April. One in twenty months will experience a monthly rainfall at or above the 95th percentile value. The increases along the Queensland coastal region in most, but not all months, supports the results shown in Figure 38 that indicate a higher occurrence of extreme rainfall for the Queensland region under global warming. A decrease in mean rainfall and rain days (not shown) indicates an increase in the length of dry periods between extreme rainfall events which themselves are likely to be more intense. Simulated increases in extremes are generally larger where the average coastal rainfall is maintained or increased.

SedNet Overview

The SedNet model constructs sediment budgets for river networks to identify patterns in the material fluxes. A sediment budget is an account of the major sources, stores and fluxes of material. SedNet defines a stream network as a series of links extending between stream junctions. Sediment budgets are computed for each link. SedNet uses spatial modelling to combine measurements of river discharge, a basic understanding of material transport processes and geographical mapping of soils, vegetation cover, geology, terrain and climate.

SedNet has been designed for a range of different users with different backgrounds such as catchment and regional planners, waterway managers, water and catchment management authorities and environmental consultants, and can assist effective targeting of catchment and river management actions to improve water quality and riverine habitat. This can assist extension providers and natural resource management agencies to investigate the relative effectiveness of different management strategies on long-term sediment loads and yields from river networks. SedNet version 2.0 onwards also constructs nutrient budgets and the causes of water quality problems will also be addressed. SedNet can identify the major processes involved in the delivery of sediment (and nutrients) to rivers within a catchment to determine the types of actions likely to be most effective. SedNet has been successful in assisting with planning of catchment management actions by identifying erosion hotspots in the catchment so targeting on-ground works. A full description of the SedNet model is contained in Wilkinson et al. (2004).

Once users are satisfied with the baseline (current) scenario, they are able to use SedNet to simulate the effect of proposed changes in catchment management on the sediment and nutrient fluxes in the river network.

For this study, CSIRO's OzClim climate change scenario generator was coupled to SedNet, in an effort to gauge the sensitivity of the sediment transport to a range of possible future climate change. The SedNet climate parameters developed by OzClim include:

- Average annual rainfall
- Average annual ratio of potential evapo-transpiration divided by annual rainfall

Some clear improvements to the methodology have been highlighted by this study, which include using projected changes to streamflow data (and not the baseline streamflow as was utilised), and generating new climate change projections for hillslope and gully erosion which requires climate change projections of 30 minute rainfall intensity.

SedNet Parameter Contributions

Stream flow considerations

Climate change projections for the Fitzroy Basin indicate that the mean annual PET and Rainfall will change. The best advice available from CSIRO Atmospheric Research indicates that rainfall is likely to decrease over most of the basin region. However, the highest horizontal resolution model utilised in the comparison (CC50) showed that the coastal fringe may indeed experience a small increase. High resolution general circulation modelling of the Queensland region to be undertaken in 2004–05 (at approximately 14 km horizontal resolution) will help to resolve coastal effects in the basin. All models utilised for this study show an increase in the regional surface temperature for the Fitzroy Basin under varying levels of global warming. PET is expected to increase for all models (as shown in Figure 36) with the largest increases expected inland. These changes have the effect of a larger percentage change on the PET/rainfall ratio utilised in the SedNet model.

In addition, the increase in rainfall variability (shown in Figure 38 and Figure 39) imply that a greater proportion of flow will be overbank. There will be reduced soil moisture with lower mean rainfall or longer dry periods between the more extreme rainfall events, which will also effect the type and frequency/cover of surface vegetation. Therefore, a change in the mean annual flow (MAF) will most likely be accompanied by an increase in overbank flow. We therefore need to redefine the PET/rainfall ratio and MAF relationship (Figure 40), and also the other regionalisation relationships discussed below.

Capturing the climate change effects on flow variability will involve use of a rainfall-runoff hydrology model to synthesise daily flow timeseries under climate change scenarios. These timeseries can then be loaded into SedNet alongside new mean annual rainfall and potential evapotranspiration datasets, utilising inputs simulating a more realistic climate change projection and use of the SedNet model.

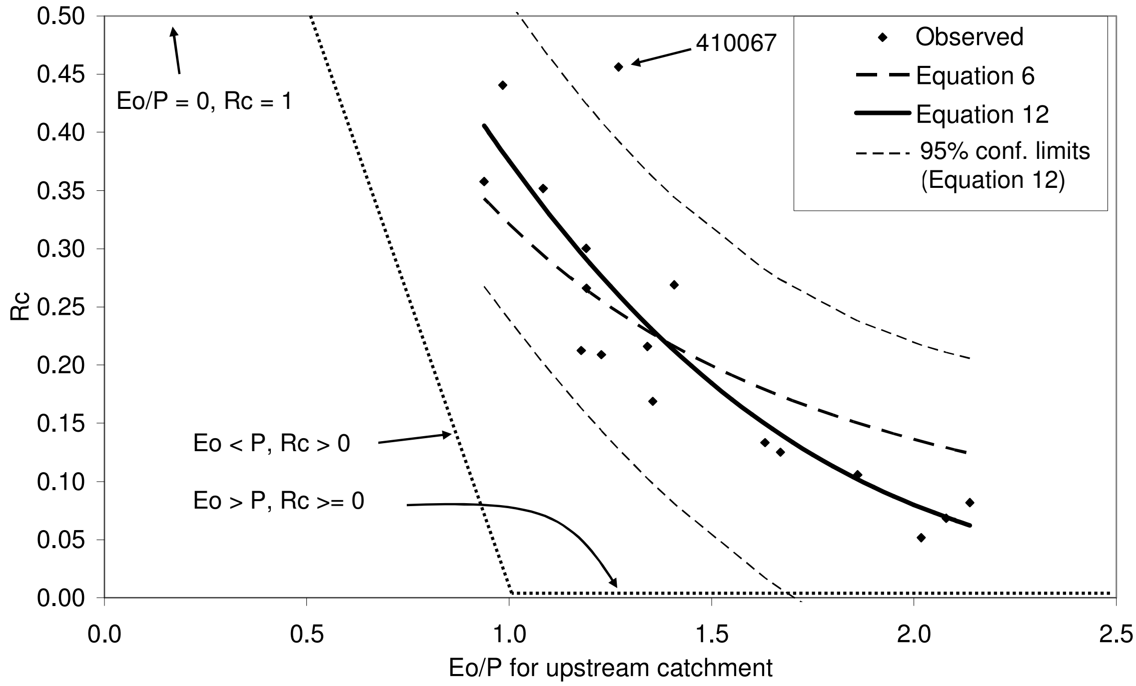


Figure 40. Regionalisation of runoff coefficient Rc (Eo is the potential evapo-transpiration and P is precipitation) The dotted lines represent physical constraints on Rc

Hillslope Erosion (RUSLE; Revised Universal Soil Loss Equation)

The majority of the sediment in the Fitzroy Basin sediment budget is caused by “hillslope erosion” in the near coastal region of the basin (see Table 15 and Figure 28). The Fitzroy Basin regionalisation for “hillslope erosion” contains two factors that depend on the regional climate and therefore require re-calculation in a changed climate.

The methodology within SedNet for calculating the hillslope erosion utilises the Revised Universal Soil Loss Equation (RUSLE). The RUSLE calculates mean annual soil loss (tonnes/ha/year) as a product of six factors: rainfall erosivity factor (R), soil erodibility factor (K), hillslope length factor (L), hillslope gradient factor (S), ground cover factor (C) and supporting practice factor (P) (Lu et al., 2001).

$$Y = R\,K\,L\,S\,C\,P \qquad (1)$$

The K L & S factors are not climate dependent, and the P factor is generally set to 1.

The rainfall erosivity factor (R) and ground cover factor (C) are climate dependent and therefore need to be updated for any climate change assessment.

Rainfall Erosivity (R) is defined as the mean annual sum of individual storm erosion index values, EI_{30} , where E is the total storm kinetic energy and I_{30} is the maximum rainfall intensity in 30 minutes. Both these terms are expected to increase for the Fitzroy Basin region under climate change forcing. Yu and Rosewell (1996a, 1996b) proposed a rainfall erosivity model in which, EI_{30} is related to the daily rainfall amount. An experiment could be designed to investigate the validity of this relationship by collecting high temporal resolution rainfall data at locations where long record pluviograph data is available.

Ground cover (C) measures the combined effect of all interrelated cover and crop management variables. This involves separating the satellite-derived NDVI vegetation signal into three components: perennial, seasonal and random using time series decomposition. Regression equations were used to estimate vegetation cover using monthly averaged NDVI and site measurements. SOILOSS (Rosewell, 1993) was used to calculate monthly soil loss ratio (SLR), and this estimate is weighted with a fraction of the rainfall erosivity (R) associated with the corresponding month in the calculation of the annual C factor. Mean monthly surface vegetation cover is the other determinant of sheetwash and rill erosion on hillslopes that will be affected by climate change. Forecasting the effect of climate change scenarios on vegetation cover will be inexact, but may be approached by determining relationships between current mean-monthly vegetation cover and rainfall, temperature and other climate variables. Vegetation cover under the climate change scenarios can then be modified given the predicted change in these variables.

Fitzroy Basin: Climate dataset

Using the information depicted in Figure 32 to Figure 36, we have produced new rainfall and PET-rainfall ratio datasets for the Fitzroy Basin, for a global warming of one, two and four degrees.

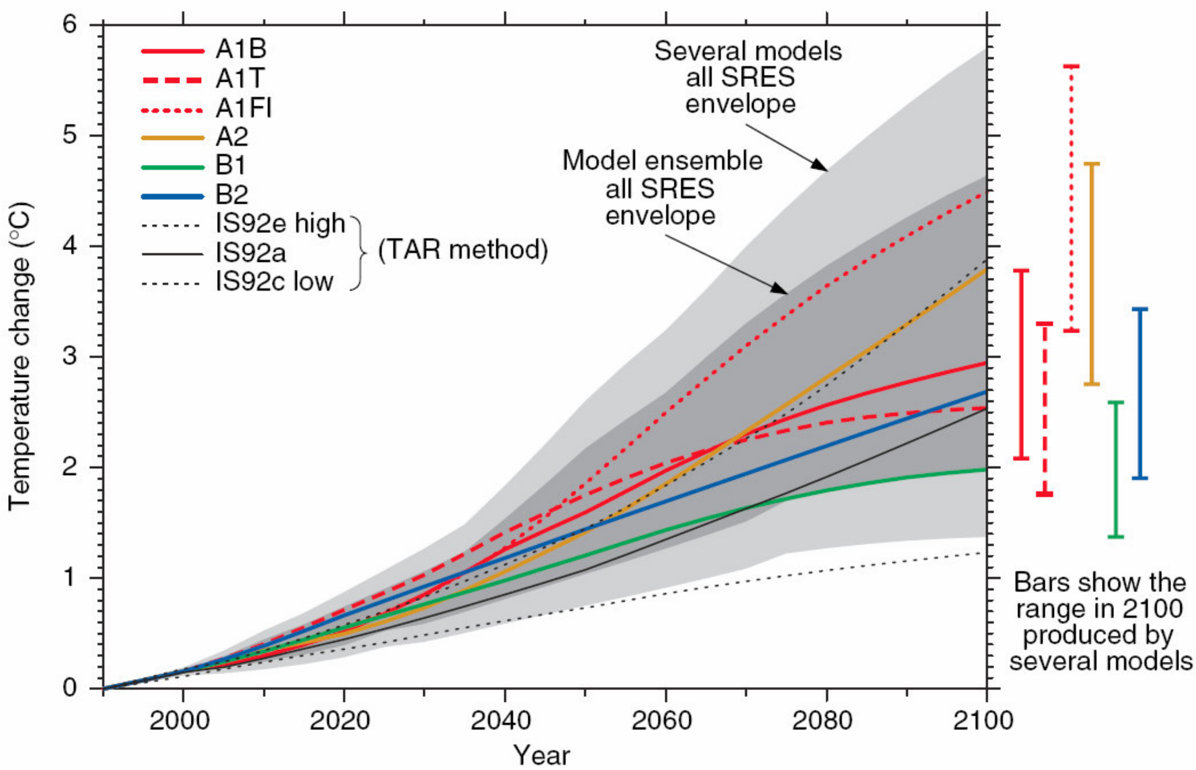


Figure 41. Global mean temperature projections for the six illustrative SRES scenarios using a simple climate model tuned to a number of complex models with a range of climate sensitivities. Also for comparison, following the same method, results are shown for IS92a. The darker shading represents the envelope of the full set of thirty-five SRES scenarios using the average of the model results. The lighter sharing is the envelope based on all the seven model projections (from IPCC, 2001)

Figure 41 shows the 21st century occurrence years for these warmings with respect to the major IPCC SRES climate scenarios. Considering an average of the scenarios shown in Figure 16, a one degree warming occurs in about 2040; a two degree warming in about 2070; and a four degree warming not until well into the next century. Please keep in mind that these scenarios do not consider any significant greenhouse gas abatement programs in force during the 21st century.

New rainfall and PET-rainfall ratio grids for the Fitzroy Basin and for input to SedNet, have been produced for each of the six models and for each of the three global warming scenarios. This data can be used to explore the effect of the possible future range in climate change on sediment production in the Fitzroy Basin once the new regionalisations with respect to runoff and the RUSLE R & C factors have been developed.

Fitzroy Basin: Suggested future work to complete assessment

CSIRO, as part of the new South East Australian Climate Initiative (SEACI) has agreed to undertake high resolution modelling of eastern Australia (~20 km horizontal resolution utilising the CSIRO Conformal-Cubic model). This new data, which is scheduled for release in the latter half of 2006 (and additional runs scheduled for early 2007) will be of sufficient resolution to both investigate regional rainfall change along the Queensland coastal fringe and also to provide a new regionalisation for both runoff and for the R factor in RUSLE. For the western part of the Fitzroy Basin, predicting runoff under regimes with long dry periods is difficult because the soil properties change, affecting the runoff. This will also affect erosion from rain-splash.

Determination of a new C factor for RUSLE will both revise the methodology utilised in the 2001 National Land & Water Resource Audit, by using a new 23 year dataset of BRDF corrected NDVI vegetation information, and also relating the range of values obtained for each land-use type during those 23 years to the rainfall measured. In this way, we can use the variability of the past/present climate to indicate vegetation conditions for the mean of future climates. The horizontal resolution of the NDVI satellite derived dataset (8km) was a limiting factor in the previous determination. Australian satellite NDVI datasets at 4km resolution are now available since 1981 and at 1 km resolution since 1992. The Bureau of Rural Sciences (BRS) has developed a 25 metre resolution analysis of land use capability. We should consider two scenarios: one that assumes no land use change and the other that assumes some relationship between rainfall and land use.

Determination of a climate change effected streamflow timeseries are additional inputs required by SedNet. These could be generated from specific rainfall and evapotranspiration climate change scenarios with an emphasis on generating new event-based records. These new scenarios will then allow SedNet to determine scenario based flow metrics which are required for calculating; bank erosion rates, reservoir and floodplain deposition.

Rainfall erosivity is an important determinant of sheetwash and rill erosion on hillslopes, and a dominant sediment source in the Fitzroy River Basin. Rainfall erosivity is determined using the spatial variation in 30 minute storm intensity. It maybe possible, using the new CSIRO model results planned for 2006 (and 2007) to provide plausible climate change scenarios for this climatic variable.

Table 17. Fitzroy River Basin; Current "best estimate" of trend in sediment/nutrient budget changes due to two likely scenarios of climate change

Fitzroy River Basin	**Sediments**	**Nutrients**
Scenario 1. Decreased annual rainfall inland Maintain annual coastal rainfall Increase in PET Decrease in runoff Maintain current EI_{30} (R factor) Decrease in RUSLE C factor	Slight Decrease	-
Scenario 2. As for Scenario 1 but slight increase in R factor	Current level	-
Scenario 3. As for Scenario 2 but increase coastal rainfall	Slight Increase	-
Scenario 4. As for Scenario 2 but significant increase in R factor	Significant Increase	-

Table 17 presents an indication only, based on our current understanding of annual rainfall and potential evapo-transpiration changes detailed here coupled with our understanding of the sensitivities inherent in the regionalisations for runoff and also for hillslope erosion, for the likely direction and possible range of change that can be expect for sediment and nutrient transport to the GBR from the Fitzroy catchment.

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