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Queensland's biodiversity under climate change:

freshwater aquatic ecosystems

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PREAMBLE

This report is one of seven background documents prepared by the CSIRO Climate Adaptation Flagship for the Queensland Government. Content from this report contributed to the synthesis report titled “Queensland's biodiversity under climate change: impacts and adaptation” by Williams *et al.* (2012a).

The seven background reports are:

A. Overview of climate change in Queensland (Williams & Crimp 2012)

B. Ecological scaling of terrestrial environmental change (Ferrier *et al.* 2012)

C. Terrestrial ecosystems (Murphy *et al.* 2012)

D. Freshwater aquatic ecosystems (Kroon *et al.* 2012)

E. Coastal and marine ecosystems (Bustamante *et al.* 2012)

F. Ecosystem services (Williams *et al.* 2012b)

G. Adaptation principles and options (Dunlop *et al.* 2012)

Riparian vegetation, Beatrice River, North Queensland (credit: CSIRO science image EM0490)

EXECUTIVE SUMMARY

This report examines the effects of climate change on freshwater biodiversity in Queensland's wetlands, defined as "areas of permanent or periodic/ intermittent inundation, whether natural or artificial, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6m".

Current threats to Queensland's freshwater biodiversity, namely overexploitation, water pollution, flow modifications, habitat destruction and degradation, and invasion by non-native species, are likely to be compounded and eventually superseded by the effects of climate change. At a regional scale, we assess the impacts of climate change by combining the nine Queensland Freshwater Biogeographic Provinces with Queensland's five drainage divisions into five regions that reflect drainage divisions for river flow as well as for riverine ecosystems that are biogeographically distinct.

Freshwater aquatic ecosystems are altered by climate change via direct and indirect pathways. The direct pathways are obvious (Section 2): (i) changes in global temperature are reflected in equivalent changes in water temperatures of streams, lakes, wetlands, etc; (ii) an increase in air temperature will result in increased water temperature, longer stratification periods in reservoirs and lakes, as well as advances in spring events and delays in autumn events; (iii) intensification of coastal winds mainly due to higher cyclonic activity will increase shore erosion, alter mixing patterns, and lead to changed salinity conditions in coastal lakes and estuaries; (iv) changes in precipitation and evaporation will result in changes of hydrological cycles, river flow regimes, sediment and nutrient transport, and can promote salinisation; (v) flow regime classes will change due to decrease in precipitation; (vi) there will be reduction of water availability in large parts of Queensland; (vii) sea level rise will result in inundation of coastal freshwater ecosystems, saltwater intrusion in coastal groundwater systems, and upstream movement of the tidal influence (see also Bustamante *et al.* 2012); and (viii) increased CO_2 absorption may result in fresh water becoming more acidic, and in some cases an increase in phytoplankton productivity or a decrease in, for example molluscs, is possible.

Indirect pathways by which freshwater ecosystems are altered also have to be accounted for when looking at ecological change as a result of climate change (Section 2): (i) levels of dissolved oxygen tend to decrease due to increasing temperature, possibly decreasing wind speeds, and expected increase in eutrophication caused by nutrient enriched run-off; and (ii) changes in air temperature will lead to changes in evaporation impacting mainly shallow water bodies and wetlands by reducing water levels.

Finally, there is not only an effect of long-term changes in global climate variables on aquatic ecosystems but also one associated with a change in their short-term variability; that is, changes in seasonality and increased probability of extreme events (Section 2): (i) intensification of cyclones associated with high wind speeds can alter morphometry via wave action, and change mixing patterns in standing water bodies; (ii) increased intensity and probability in occurrence of extreme events (precipitation associated with floods, heat waves, cyclones) will lead to irreversible changes in the physical environment of freshwater systems (morphology, connectivity, water balance); and (iii) droughts will most probably increase in intensity and extent.

In combination with the current threats to Queensland's freshwater biodiversity, noted above , the main effects of climate change are (Section 3): (i) changes in species' behaviour and physiology due to changing environmental envelopes; (ii) changes in species' abundance, distribution and resilience to climate variability due to changes in habitat availability and connectivity; (iii) changes in species' resistance, resilience and exposure to extreme events and diseases; (iv) changes in annual ecosystem productivity and nutrient status due to changes in phenology; (v) geographic changes in ecosystem types due to more frequent and/or more intense extreme events; and (vi) changes in overall riverine patterns and processes and freshwater ecosystem services.

Queensland's freshwater ecosystems provide a variety of provisioning, regulatory, cultural and supporting services for natural, urban and production systems (Section 4). Whilst the maintenance of freshwater biodiversity contributes to the delivery of these ecosystem services, no linear relationship exists between the two. Climate change is expected to affect the delivery of ecosystem services, in particular through changes in flow regime, carbon sequestration and (terrestrial and freshwater) biodiversity.

On a regional scale, the main changes for Queensland lakes, wetlands, and rivers probably will be (Section 5): (i) extension of arid and semi-arid regions in eastern direction; (ii) some arid and semi-arid swamps will most likely change their frequency and duration of inundation, possibly dry out permanently; (iii) Region E (Lake Eyre and Bulloo) will probably see an increasing loss of swamps or change to long dry periods due to increased evaporation and lower precipitation; (iv) coastal and sub-coastal swamps might decrease in water inflow in South-East Queensland (region C) and the eastern Murray-Darling region (D) during the dry season; (v) decrease in oxygen levels in coastal and sub-coastal lakes (region B, C) during stratification periods; (vi) state-wide increasing problems with cyanobacteria in lakes due to increasing temperatures; (vii) non-floodplain clay pan lakes in the western Murray-Darling region (D) will probably experience decreasing water level or even dry out; (viii) coastal lakes, especially coastal dune lakes, might suffer from saltwater intrusion; (ix) more western Great Artesian Basin spring wetlands will experience an increase in evaporation and thus the threat of drying out; and (x) decreasing precipitation might increase the intermittency of river streamflow during summer months.

Current threats to freshwater biodiversity, namely overexploitation, water pollution, flow modifications, habitat destruction and degradation, and invasion by non-native species, need to be reduced in a triage-based approach, to minimise the detrimental impacts of climate change (Section 6). Albeit not specifically designed to deal with climate change impacts, current policy frameworks, such as the Wild Rivers Act 2005, the Water Act 2009 and the Sustainable Planning Act 2009, provide opportunities to increase the resilience of freshwater ecosystems in the face of climate changes. New policy and legislation, addressing both current threats and climate change, may need to be developed to specifically deal with the large-scale, long-term and severe impacts from climate change.

1. INTRODUCTION

Queensland's aquatic ecosystems occur over a large gradient of climate conditions, ranging from tropical, sub-tropical, warm temperate to hot arid climate zones. Currently, nine Freshwater Biogeographic Provinces are identified in Queensland (Figure 1), containing a total of 76 river basins (Queensland DERM 2010). The Western Cape and Gulf, Lake Eyre and BulloP, Murray-Darling, Central, and South-East provinces all have a low relief ratio, with evaporation exceeding rainfall in the latter four provinces. In contrast, the remaining four eastern biogeographic provinces have a high relief ratio with perennial streams and rivers.

Aquatic ecosystems in Queensland cover approximately 4.1% of Queensland's mainland area, or nearly 71,000 km^2 (EPA 1999). In Queensland, all aquatic ecosystems fall under the definition of wetlands, being "*areas of permanent or periodic/ intermittent inundation, whether natural or artificial, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6m*" (EPA 1999). Seasonal and intermittently inundated wetlands comprise 69% of the total, with tidal (mangroves and saline coastal flats, 14%) and other (17%) wetlands making up the remainder. Permanently inundated wetlands cover only 0.7% of Queensland (approximately 12,000 km^2), and include more than 1,125,000km of major waterways. While the term "wetland" is used formally for every inland freshwater system in Queensland (DERM 2011f), here we follow the more classical classification of streams and rivers, lakes (including reservoirs and ponds), floodplains, and wetlands (e.g. see Polunin 2008), to highlight ecological responses of these specific "wetland" components to climate change.

Freshwater biodiversity in Queensland, as in other areas around the world, are being threatened by overexploitation, water pollution, modification of water flows and hydrology, habitat destruction and degradation, and invasion by non-native species (Dudgeon *et al.* 2006; Malmqvist & Rundle 2002). Whilst little research has been conducted on the specific responses of freshwater ecosystems to climate change (Section 3), it is likely that climate change will influence the degree to which current threatening processes further affect aquatic biodiversity and ecosystem services in the medium to long-term (Morrongiello *et al.* 2011). The direction and rate of change in aquatic biodiversity and associated ecosystem services will differ across Queensland's region, as it depends on the pathway of climate impact on environmental drivers that influence aquatic ecosystems.

To examine the effects of climate change on freshwater biodiversity in Queensland at a regional scale, we combine the nine Queensland Freshwater Biogeographic Provinces (Figure 1) with Queensland's five drainage divisions (Figure 2) as follows:

- A: Western Cape and Gulf: Freshwater provinces JD and WCG without Normanby river catchment. This is identical to drainage division IX.
- B: Coastal and sub-coastal region: Freshwater provinces CT, EC, WT, and Normanby river catchment. This equals the drainage division I without the South-East coast.
- C: South-East coast: Freshwater provinces SE and WL, being the southern part of drainage division I.
- D: Murray-Darling: Identical to drainage division IV and freshwater province MD.

- E: Lake Eyre and Bulloo: Identical to freshwater province LEB being a combination of drainage divisions X and XI.

This combination (Figure 3) reflects drainage divisions for river flow as well as for riverine ecosystems that are biogeographically distinct. The knowledge about aquatic biodiversity and the potential impacts of climate change across these provinces and drainage divisions is variable. Wetland mapping and classification has been completed for the whole state in 2009, while the aquatic biodiversity is currently being assessed and mapped under the Aquatic Conservation Assessments (DERM 2011a). This variation in knowledge about aquatic biodiversity in Queensland is not a true reflection of its relative importance, but rather a research, monitoring and assessment bias which should be overcome when Aquatic Conservation Assessments have been completed across the State (Clayton *et al.* 2006).

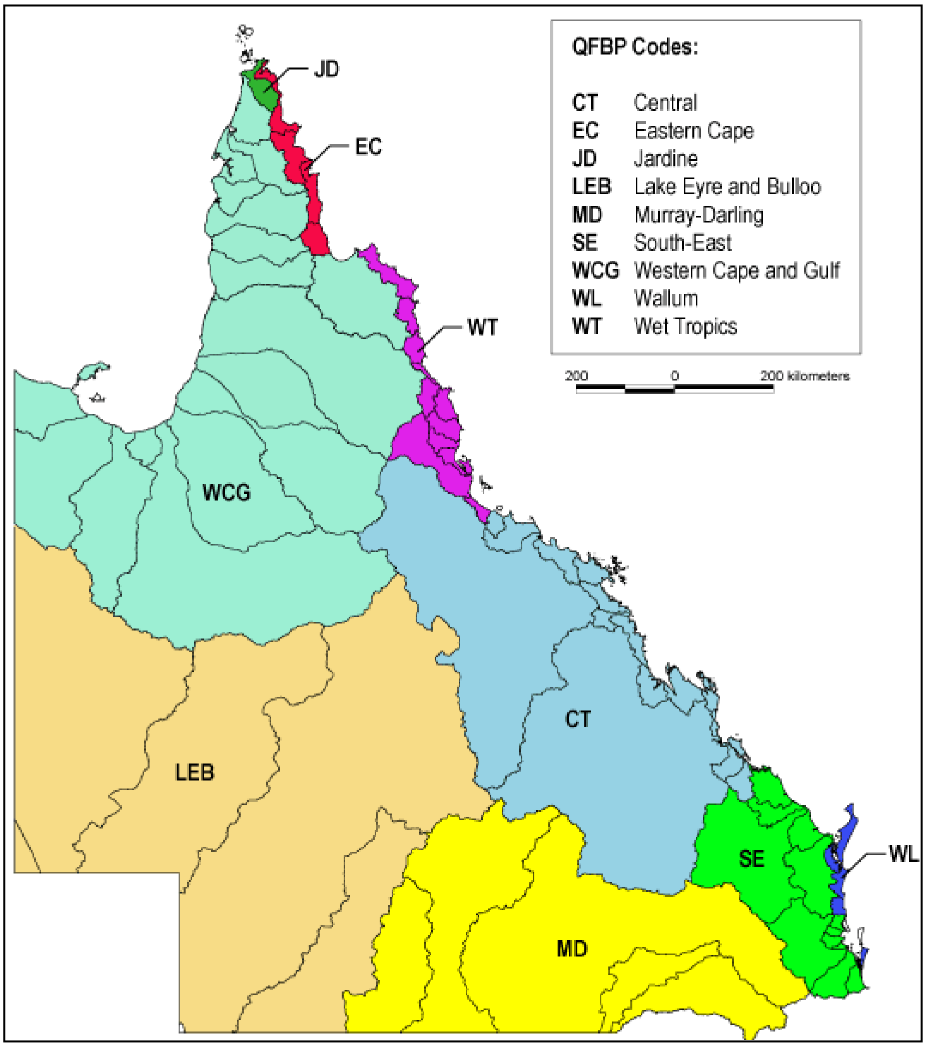

Figure 1: The State of Queensland with the nine freshwater biogeographic provinces[1] (DERM 2010b).

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[1] freshwater biogeographic provinces derive from http://www.epa.qld.gov.au/wetlandinfo/site/ScienceAndResearch/ConceptualModels/Riverine/FBP.html (accessed 08 June 2011)

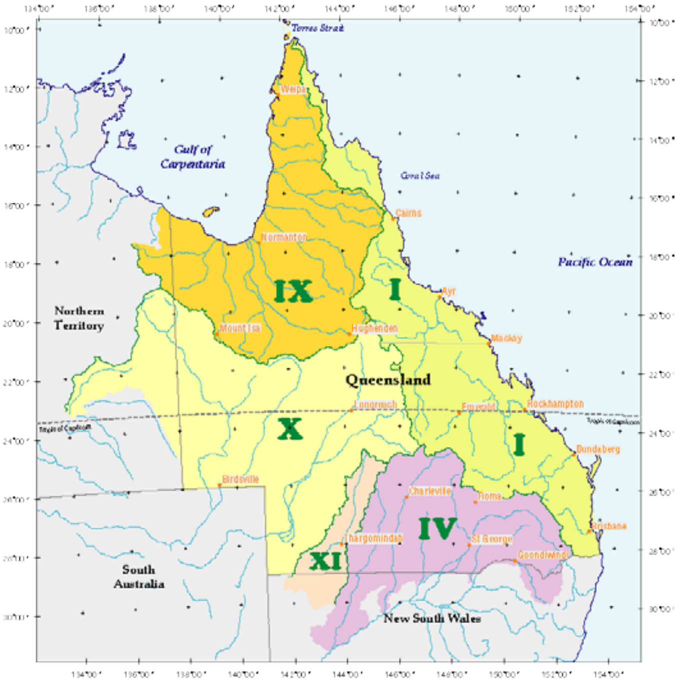

Figure 2: The State of Queensland with the individual drainage divisions[2] (DERM 2001).

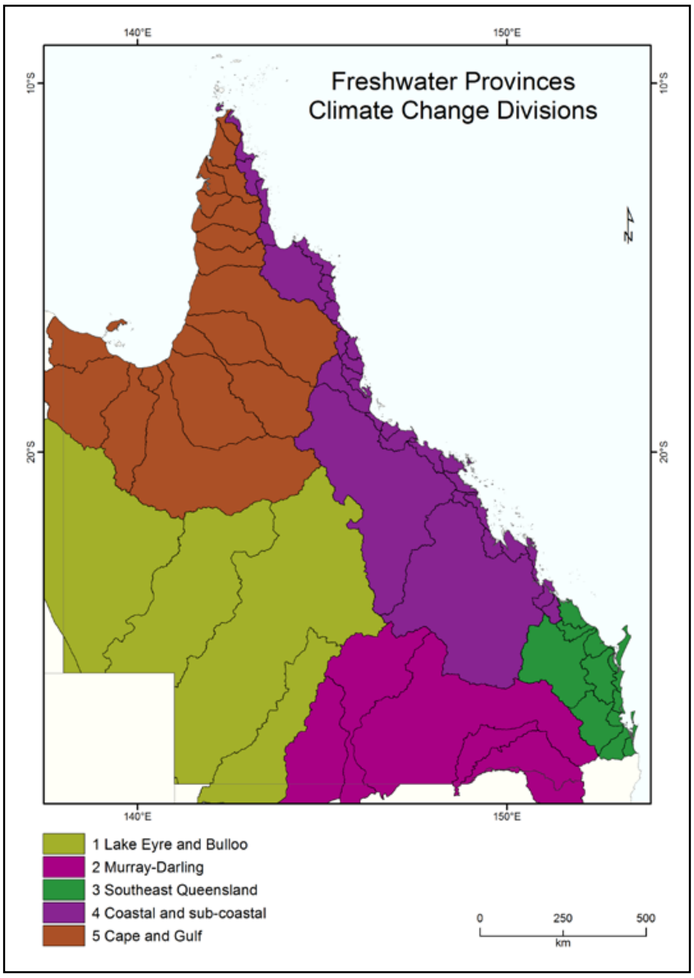

Figure 3: Combination of Queensland drainage divisions and freshwater bioregional provinces for regional assessment of climate change drivers on freshwater aquatic ecosystems.

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[2] Basin boundaries and names derive from http://www.derm.qld.gov.au/watershed/precomp/nf_tsi/drn_divs.htm (accessed 08 June 2011)

2. ENVIRONMENTAL CHANGE

2.1 Introduction

The major impacts of climate change on freshwater aquatic systems manifest themselves in a multitude of factors (e.g., CSIRO & BOM 2007; IPCC 2007; Steffen *et al.* 2009; Whitfield *et al.* 2010), which will change the environment for freshwater aquatic systems. Changes in air temperature are already occurring and will enhance in the future. This will not only increase water temperatures in lakes, wetlands and rivers but will also be affecting mixing regimes and stratification patterns in lakes (Peeters *et al.* 2007; Winder & Schindler 2004). Precipitation in large parts of Queensland will further decline while evaporation of open water bodies currently shows no significant trend but might increase in future (Jovanovic *et al.* 2008) leading to a reduction in available fresh water and possible salinisation of wetlands in arid regions. Sea level rise will not only lead to increased coastal erosion and impacting mangroves, seagrass etc (see Bustamante *et al.* 2012) but will shift the border between marine and freshwater systems inland, and have the potential to change salinity levels in coastal freshwater wetlands (DCC 2009; Schallenberg *et al.* 2003). Other changes in freshwater ecosystems will be triggered by changes in pH due to rewetting of dried acid soils or by increased dissolution of carbon dioxide or changes in abiotic water constituents like decreasing oxygen levels as a result of increasing productivity and possible lengthening of stratification in lakes. Beside the gradual changes in mean temperature, precipitation, etc., also a change in variance of climate variables is expected leading to increasing probability of extreme events (IPCC 2007). The number of heat waves, intensity of floods and cyclones is expected to increase, having the potential to heavily modifying freshwater aquatic systems by drying and flushing. Changes in precipitation patterns will also give rise to changes in streamflow regimes modifying connectivity between river stretches and extend of floodplains.

2.2 Air temperature

Temperature increase over Queensland in the last decades show that the largest changes occurred in southern Queensland, and was most pronounced in the south-western corner (see Whitfield *et al.* 2010), (see Figure 8 in Williams & Crimp 2012). It is expected that future changes will show a similar pattern of increase in mean temperatures (see Figure 18 in Williams & Crimp 2012). These increases in air temperature will result in increased water temperature in all freshwater ecosystems, with rising river and lake temperatures over the last centuries being well documented (e.g., Fang & Stefan 2009; Kaushal *et al.* 2010; Schneider & Hook 2010; van Vliet *et al.* 2011). For example, in the Darling River an increase in 4°C in air temperature will result in an increase of 3.2°C in water temperature (van Vliet *et al.* 2011). However, this temperature increase is generally lowered with decreasing discharge. In the aforementioned example a decrease in river discharge by 40 % will lead to a temperature increase of only 2.9 C. Lake temperatures have been rapidly warming for the period 1985–2009 with an average rate of 0.045 ± 0.011°C yr^{-1} in mean night-time surface temperature (Schneider & Hook 2010). Taking into account, that nightly air temperatures have increased faster than daily temperatures (Karl *et al.* 1993), this implies a slightly smaller increase in overall mean daily water temperatures. A decrease in diurnal temperature differences will lead to less surface mixing and thus more stable stratification in lakes (e.g., Fang & Stefan 1999). The period of stratification will usually be prolonged, starting earlier in spring (Peeters *et al.* 2007; Winder & Schindler 2004). Although changes in temperature have the biggest impact on stratification, other factors like changes in wind speeds or irradiance will modify the temperature stratification (e.g., Jöhnk *et al.* 2008).

2.3 Precipitation

In the last 60 years or so, Queensland experienced a steady trend of reduced average annual rainfall (see Figure 13 in Williams & Crimp 2012). The recent La Nina event (2010/11), however, deviated from this trend; but over the long-term average annual precipitation is expected to decrease over most of Queensland. This will further sharpen the already persistent declining trend in rainfall with reductions up to 5 mm/year expected, mainly in the eastern regions (Whitfield *et al.* 2010). As a consequence, mean annual stream flows are also expected to decline. However, intense periods of rainfall during La Nina events will continue to result in periodic extreme floods.

Lake levels usually do not vary significantly with precipitation while there is a balance between inflow, precipitation and outflow. However, inflows can change stratification, for example, isolating a deep cold layer. Direct precipitation to the surface of the reservoir is not a significant contributor to reservoir volume, but stratification and volume will change due to increased inflows from the wider catchment. Declining precipitation patterns and associated reduced inflow rates is expected to significantly affect terminal lakes like the saline lake in the Lake Eyre Basin (e.g., Williams 2002) and, more generally, wetlands in arid regions (Roshier *et al.* 2001). In combination with increased evaporation rates (see Whitfield *et al.* 2010), these lakes and wetlands will increasingly be prone to salinisation.

2.4 Runoff and streamflow

As an integrating result of precipitation and catchment properties runoff and river streamflow are the basic ingredients to maintain freshwater aquatic systems. Lakes and wetlands receive their waters mainly from diffusive catchment runoff or directly through river flow. A change in runoff and streamflow volumes will lead to immediate changes in wetland properties. In extreme cases these are drying out of shallow wetlands and flooding of floodplains. Thus, ecosystems might experience a change from a freshwater system to a terrestrial one and vice versa on time scales ranging from short seasonal events (perennial wetlands) to long interannual events. A prediction of average annual runoff across Australia for a 1 deg C warming scenario for 2030 for the 10% (dry), median, and 90% (wet) percentiles are shown in Figure 4.

In flat topography only a smaller proportion of Australia's rainfall becomes runoff; due to the high rate of evapotranspiration, temporal and spatial variability in rainfall. In regions like Cape and Gulf, where annual rainfall is much higher, higher runoff volumes result (Figure 5). Changes in seasonal precipitation pattern are translated into amplified changes in runoff and thus river flow. This means, a small reduction in rainfall can lead to a much larger reduction in water availability (Chiew *et al.* 2011). On the other hand, increases in the probability in heavy rainfall events will lead to an increased probability of extreme floods. Thus, low lying arid and semi-arid regions will experience a possibly over-proportional decline in streamflow under declining precipitation, while the regions of higher rainfall in coastal and sub-coastal region would probably experience more intense floods while reducing mean annual streamflow volumes.

Decreasing annual precipitation in combination with unchanged or possibly increased evaporation will lower lake levels, reduce river flow rates and groundwater recharge, and has the potential to reduce the extent of wetlands and floodplains. This will not only result in an alteration in global river discharge but also a shift in the timing of peak flow (Döll & Zhang 2010). For south-eastern Australia, Chiew et al (2009) predicted a 6% decrease in annual mean flow averaged over the entire study area for a 0.9 C increase in global average surface air temperature. However, the authors state that there is considerable uncertainty in the estimates. Groundwater recharge in the Murray-Darling Basin is estimated to drop by 12% under dry future scenarios (Crosbie *et al.* 2010). Lowering water levels in shallow lakes and wetland due to evaporation may also increase productivity in these wetlands due to nutrient enrichment.

Reduced river discharge is associated with reduced flow velocity and thus, reduced capacity to transport sediment in suspension, both in terms of grain size and quantity (Gao 2008). It is thus expected that sediment and nutrient transport during most of the year will be significantly lowered. During floods, however, an increase in sediment and nutrient transport is expected due to higher flow volumes, potentially higher erosion in the catchment area, and overbank flow contributing significantly to the total sediment and nutrient budget in the river (e.g., Wallace *et al.* 2009), for the Tully and Murray catchments). Whilst floods are a critical driver of floodplain processes (i.e., the flood pulse concept: Junk *et al.* 1989), enhanced sediment and nutrient transport may have detrimental impacts such as decreasing light levels through increased turbidity (Tockner *et al.* 2010). Reduced river discharge also favours increases in the biomass of small and juvenile fish as well as in-channel recruitment (V. Matveev, CSIRO, personal communication).

Streamflow represents the integrated effect of several factors (soil, vegetation, topography) of a catchment modulating the runoff characteristics. To understand geographic pattern of streamflow variability due to changes in climate (temperature, precipitation, evaporation) and its impact on riverine ecosystems it is thus necessary to set-up a classification system. A ecohydrological classification system for Australia was developed by Kennard et al. (2010) and Pusey et al. (2009) based on the six key facets of a flow regime: magnitude, timing, variability, predictability, duration, rates of rise and fall (Poff *et al.* 2006). They used information from 830 stream flow gauges across Australia, of which 191 are located in Queensland. Twelve distinctive flow regime classes were identified that broadly differed in the degree of flow predictability and variability, the seasonal discharge pattern, flow permanence (i.e., perennial versus varying degrees of intermittency) and variations in the magnitude and frequency of extreme events (for a definition of the classes see Table 5.2 in Pusey *et al.* 2009). They show distinct distribution across Queensland. Under climate change it is expected that these streamflow classes will change; that is, a shift in regional distribution will be likely, and incur changes in associated ecosystems.

Overall, a decrease in run-off will reduce the long-term average water availability. This would negatively impact the amount of water available for irrigation, while in the same time drought conditions would increase the demand for irrigation due to increased evapotranspiration. Also the availability of drinking water from freshwater storages will decline under decreasing run-off, reservoirs receiving less water.

2.5 Sea level rise

Sea level rise by melting ice shields and expanding water masses in the oceans have already led to a rise of 10 cm over the period 1920-2000 on the Australian coast, and is expected to be 0.8 m at the end of the century possibly reaching 1 m (DCC 2009; Whitfield *et al.* 2010). This figure is higher than reported in IPCC (2007), and reflects improved knowledge since the preparation of the fourth assessment report. Such a rise in connection with an increase in intensity of tropical cyclones and storm surges will lead to inundation of coastal freshwater systems, saltwater intrusion into groundwater, upstream movement of the tidal influence, and associated shift in the freshwater-saline water boundary (DCC 2009; Schallenberg *et al.* 2003).

2.6 Carbon dioxide

Atmospheric CO_2 concentration steadily increases world-wide, resulting in dissolution of additional CO_2 in water and associated changes in pH levels in aquatic systems. This effect is small compared to variations in pH related to geochemical settings in catchments and streams, e.g. soil-pH in Queensland range from 4.0 to 8.5 (Ahern *et al.* 1994; de Caritat *et al.* 2010). However, on a local scale a change in pH might still shift the pH balance to more acidic and lead to, e.g., increased release of metals from soils. This effect can become particularly severe after rewetting of dried acid soils, which will result in the release of significant amounts of metals like aluminium, copper or zinc reaching levels a 100 times higher than the Australian water quality guidelines (Simpson *et al.* 2010). Changes in land-use can result in significant acidification in river catchments (Tibby *et al.* 2003), thus obscuring the effect of increase in atmospheric CO_2.

2.7 Evaporation

Increased air temperatures, and possibly higher radiation due to decreased cloudiness, will increase potential evapotranspiration (the amount of water that could evaporate and transpire from plants if sufficient water was available) in Queensland and thus increase under future warming (CSIRO & BOM 2007; Whitfield *et al.* 2010). Contrary to this, pan evaporation which measures the quantity of water evaporated from a small open water surface, show a slightly decreasing trend mostly non-significant across Australia despite the warming trend that Australia has experienced in the last decades (Jovanovic *et al.* 2008). The trend map in annual pan evaporation during the period 1970-2010 shows a larger decrease across the northern half of Queensland as compared to the southern part (see Figure 12 in Williams & Crimp 2012). It is not conclusive how this trend will transform into future scenarios. Whilst for open water bodies no significant trend for evaporation can be established, this does not rule out that there is a possible future change in evaporation from open water bodies (Fu *et al.* 2009; Gifford 2005).

2.8 Changes in abiotic water constituents

Lakes and wetlands are sensitive to climate, respond rapidly to change, and integrate information about changes in the catchment (Adrian *et al.* 2009; Schindler 2009; Williamson *et al.* 2009). Beside the direct effect discussed above a range of interacting physical, biological, and chemical processes will respond to climate change. For climate change effects on aquatic habitats and biodiversity major physical response terms are dissolved oxygen and nutrients like phosphorous and nitrogen. Global warming enhanced by decreasing wind speeds (e.g. during heat waves) will lead to higher water temperatures, earlier occurrence of stratification, longer stratification periods, and, as a consequence, decreasing oxygen levels in the bottom layers of lakes and reservoirs (Fang & Stefan 2009) and thus potentially anoxic conditions in the hypolimnion of eutrophic lakes. Increasing temperatures can increase trophic state (Trolle *et al.* 2011). However, in deep lakes reduced winter cooling can result in the persistence of small temperature gradients and thus incomplete mixing resulting in less upward mixing of nutrients (Straile *et al.* 2003). Thus, the effect of climate change on nutrient levels in lakes depends on geo-morphological characteristics, land use, and other interacting factors. Rivers and floodplain will like lakes experience decreased oxygen levels and changes in biogeochemistry due to the interaction of several climate drivers (Hamilton 2010).

Dissolution of additional CO_2 in freshwater systems will lead to changes in pH. In healthy freshwater bodies, pH generally varies between 6.5 and 8 or even higher, and dissolution of additional CO_2 will lead to a decline in buffering capacity and pH, similarly to oceanic systems. The pH of inland waters can also change as a result of changes in soil chemistry. If sulfidic sediments are present in the soils or wetland margins, drying can result in oxidization of the sulfidic minerals and generate acid sulfate soils (Baldwin *et al.* 2007; Hall *et al.* 2006). This may be a common problem in some parts of Australia, for example, more than 20% of 81 wetlands in the Murray-Darling Basin had sulfidic sediments at levels that could lead to ecological damage (Hall *et al.* 2006). Oxidation of sulfidic sediments can also cause other problems such as anoxia in the overlying water column and mobilization of metals from the sediments (see Baldwin *et al.* 2007). Thus, increased drying as a result of climate change, followed by flooding or rewetting may lead to major changes in water chemistry (depleted oxygen, very low pH), resulting in fish kills. Water managers should consider this potential when managing (Baldwin *et al.* 2007) or restoring (Hall *et al.* 2006) water bodies adjacent to acid sulfate soils, as the projected drying trends will exacerbate the existing problems.

2.9 Extreme events

Recent climate modelling predicts an increase in the frequency of more intense tropical cyclones (Emanuel 2005; Knutson *et al.* 2010) concomitant with a southward extension of tropical cyclone tracks (Leslie *et al.* 2007). Predictions around an increase in tropical cyclone frequency have been inconsistent (Emanuel 2005; Leslie *et al.* 2007), although a recent modelling study suggests that the globally averaged frequency of tropical cyclones will decrease (Knutson *et al.* 2010).

While overall wind speeds across Australia had a decreasing trend over the last 30 years (McVicar *et al.* 2008), average wind speed in the coastal zones are expected to increase slightly (2-5%, CSIRO & BOM 2007). These small changes make it unlikely that mixing regimes of lakes in Queensland will change due to projected changes in long-term wind climate. However, due to a possible intensification of tropical cyclones, shifting further southwards under global climate change scenarios (Leslie *et al.* 2007; Nott *et al.* 2007), extreme wind gust speeds might affect more coastal regions. Thus, an increase in wind speed and rainfall rates is likely (QCCCE 2011). Beside an increase in shore erosion such extreme wind events can alter the mixing regime of stratified lakes, and lead to pulses of sediment resuspension in shallow freshwater systems associated with nutrient pulses (e.g., James *et al.* 2008).

Beside short-term extreme events such as cyclones, droughts as a long-term extreme have the potential to change the aquatic environment drastically and possibly everlasting. For

Queensland, an increase in the number of exceptionally hot years is projected, which might become the rule and affect most parts of Queensland by 2040 (Whitfield *et al.* 2010). The occurrence and increased intensity of heat waves will alter the thermal regime of lakes and wetlands by increasing their surface temperature and stabilizing the stratification (Jöhnk *et al.* 2008). Unusually increased temperature will lead to higher biological productivity and reduction in oxygen levels in aquatic systems. Additionally, the effect of droughts generated by changing climate conditions is often exacerbated by current threatening processes, such as modification of water flows and hydrology. The major impacts of droughts on streams are reduction of stream flow, loss of connectivity, and an increase in stream temperature (Bond *et al.* 2008; Lake 2008; Sheldon *et al.* 2010). A reduced water level in conjunction with higher evaporation rates and reduced freshwater inflow will increase salinity levels. Salinisation of dryland lakes and wetlands is already a problem in parts of Australia (Lyons *et al.* 2007; Timms 2005). For standing waters droughts will reduce water levels, and in extreme cases shallow lakes and wetlands may completely dry out.

An increase of up to four percent in extreme rainfall is expected in the Cape York region during all the year and in western Queensland and the Gulf region in summer and autumn (Whitfield *et al.* 2010). Although overall precipitation in Queensland is expected to decrease under climate change conditions, such extreme rainfall events naturally result in high stream flow, increasing the probability of river floods. High flows will increase flow velocity and bed erosion in the head waters, and lead to higher connectivity, sediment deposition and nutrient enrichment in the floodplains (Junk *et al.* 1989; Lake *et al.* 2006).

2.10 Time scales of change

Changes in environmental drivers due to climate change will take place on different time-scales depending on the scale and magnitude of the associated driving forces. For example, flow discharge is directly linked to precipitation and water temperature reflects much of the temporal structure of the regional air temperature (Livingstone & Dokulil 2001), thus both effects are almost parallel to their drivers. A decrease in dissolved oxygen will get apparent only after the stratification in a lake has changed and thus lags behind the changes in climate variables.

The magnitude of changes also plays a role in triggering a change in environmental drivers. Changing a mixing regime by strong winds will take effect only if wind speed exceeds a threshold (set by the extent of the lake and its prevailing stratification) over which wind energy is sufficient to destroy the stratification. Sea level rise will have a significant influence on, for example, sea water intrusion into coastal lakes only after a certain threshold is exceeded. Below that threshold the natural barrier between marine and freshwater system prevents an intrusion. The magnitude in these cases is the trigger which will lead to an ecosystem change only after a certain time span of changing climate.

Extreme events can change their return period (recurrence frequencies) and their intensity under climate change conditions. The occurrence of such events can only be described by a certain probability. Thus, it is not possible to predict the consequences of a change in time like in the case of gradual changes, but only giving a probability that a change will occur in a time span of say 100 years. For example, there is a probability that cyclone activity will regionally increase in intensity and thus coastal erosion and saltwater intrusion probably increase. The effect can be evaluated only after a given time period, it will not happen gradually.

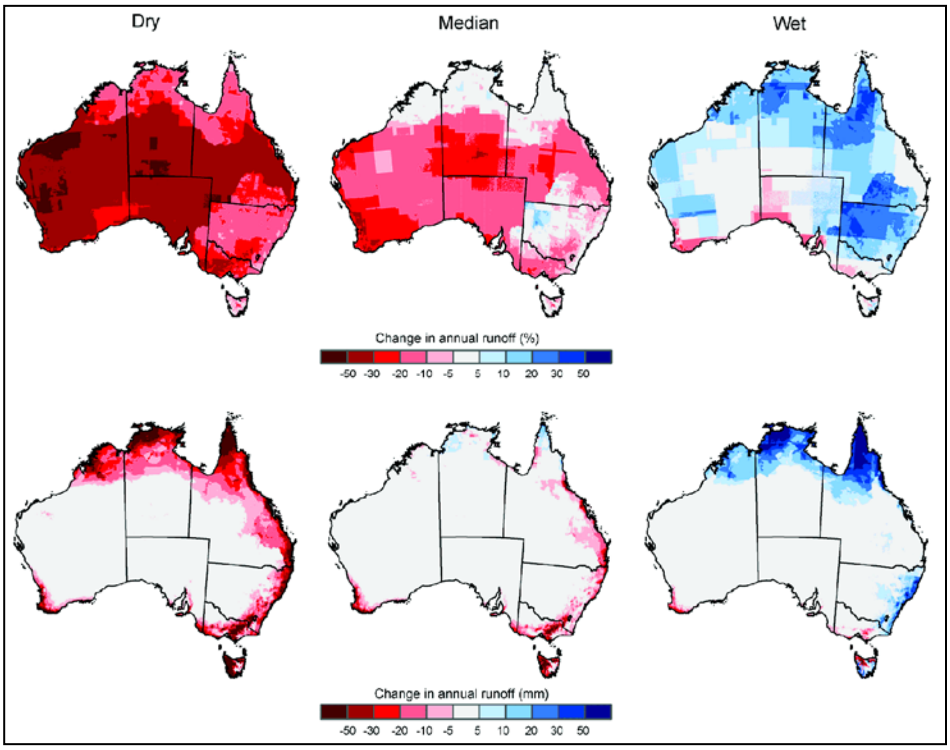

Figure 4: Change in average annual runoff for a 1 deg C global warming scenario (2010 relative to 1990) across Australia. The upper row shows percentage change and lower row the absolute changes for the 10% (dry), median, and 90% (wet) percentiles. Figures from Chiew and Prosser (2011).

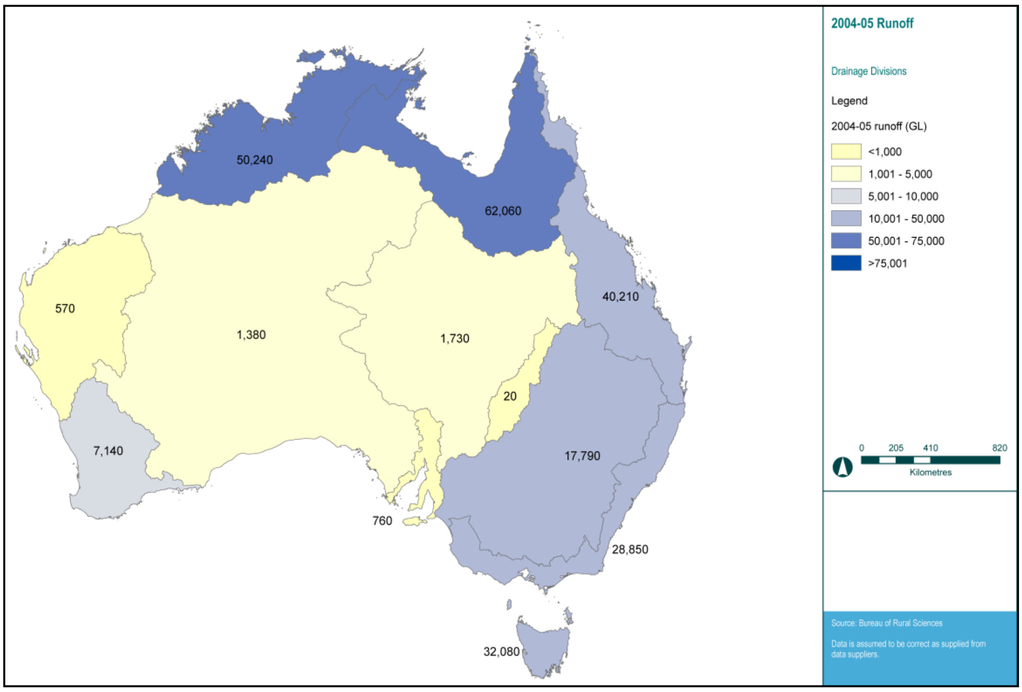

Figure 5: Australia's runoff volumes in 2004-05 from each drainage division (Source: Bureau of Rural Sciences[3]).

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[3] Australian Water Resources 2005, (NWC 2007), http://www.water.gov.au/MapPdfs/Fg20_BRS2010_0405_runoff_volume.pdf, Accessed 2011-06-22.

3. ECOLOGICAL CHANGE

3.1 Introduction

Aquatic ecosystems are particularly sensitive to climate change because numerous hydro-ecological processes respond to even small changes in environmental drivers (see Section 1.3). These processes may adjust gradually to changes in climate, or abruptly as environmental or ecosystem thresholds are exceeded, causing a dramatic switch in organisms or a change of state of the system. Thresholds may be physical (e.g., CO_2, pH, temperature); chemical (e.g., salinity, dissolved oxygen); or biological (e.g. algal blooms, invasive species). Depending on the aquatic environment, the environmental drivers through which climate change affects ecological change can act individually or synergistically.

In this section, we synthesise information on the potential effects of changes in environmental drivers due to climate change (see Section 1.3) on Queensland’s freshwater biodiversity. Climate change phenomena have already been detected in aquatic environments across the world (Rosenzweig *et al.* 2008; Walther *et al.* 2002). The effects of climate change are superimposed upon existing threats, namely overexploitation, water pollution, modification of water flows and hydrology, habitat destruction and degradation, and invasion by non-native species (Dudgeon *et al.* 2006; Malmqvist & Rundle 2002). Hence, the specific effects of climate change on aquatic biodiversity may be difficult to disentangle from the impacts of existing threats. We highlight case studies from Queensland’s freshwater ecosystem where information is available.

3.2 Changes in individual biology

Freshwater biodiversity is affected by changes in individual biology. As climate changes throughout a species geographic range, the biology of individuals responds to the resulting change in environmental drivers. In the freshwater environment, documented responses include changes in behaviour and physiology (e.g., Ficke *et al.* 2007; Geider *et al.* 2001; O'Reilly *et al.* 2003; Roessig *et al.* 2004) and changes in phenology (e.g., Parmesan 2006; Parmesan & Yohe 2003; Visser & Both 2005; Walther *et al.* 2002), and have a flow-on of effects on freshwater biodiversity. We are not aware of any reported changes in genetics in aquatic flora or fauna due to the effects of climate change.

3.2.1 Behavioural and physiological changes

Aquatic species have specific physiological and behavioural thresholds of temperature, dissolved oxygen, salinity and pH that determine, in part, their distribution (e.g., Pörtner & Peck 2010). Changes in these environmental variables will result in distributional shifts (see section 3.3), with flow-on effects on biotic interactions (see section 3.4).

Increased water temperatures will result in an increased respiratory oxygen demand in aquatic animals (e.g., Graham & Harrod 2009). Physiological thresholds have been documented for temperature for numerous Queensland’s freshwater fish species. For example, the spangled perch (*L. unicolour*) can survive temperatures from 5 to 44°C (Beumer 1979; Glover & Sim 1978; Llewellyn 1973), and tolerates rapid (1°C per hour) temperature changes (Gehrke &

Fielder 1988), with increased tolerance of higher temperatures with increasing size (Beumer 1979; Llewellyn 1973). Eggs from this species developed normally in temperatures from 16.0 to 29.0°C, with more rapid development but also greater egg mortality at higher temperatures (Llewellyn 1973). These extreme tolerances may enable the species to survive in harsh environments, such as irrigation channels, relatively cool floodwaters, and isolated, shallow waterholes. In contrast, other freshwater fish species show less tolerance of high water temperatures, such as the eastern rainbowfish (*Melanotaenia splendida splendida*) (Beumer 1979). Water temperature can also have an almost immediate effect on the behaviour of native freshwater fish, as demonstrated by Astles *et al.* (2003) in preference – avoidance responses with juveniles.

Freshwater fish can use physiological mechanisms to compensate for low dissolved oxygen levels. Physiological acclimation or adaptation can take place at any of the four steps involved in oxygen transport from the environment to tissue cells: ventilation of gills (water convection); diffusion of O_2 from water to blood; blood gas transport (convection); and, diffusion of O_2 from blood to tissue cells (Jensen *et al.* 1993). Fish species differ in their capability to change any of these four steps to adjust to a hypoxic environment (Jensen *et al.* 1993). For example, spangled perch (*L. unicolor*) can survive dissolved oxygen concentrations as low as 1 mg/L (Glover & Sim 1978), and tolerates oxygen depletion to 5% saturation for at least 30 minutes (Gehrke & Fielder 1988). Large gill surface area may aid this species in temporarily surviving hypoxic waters (Gehrke 1987). Oxygen tolerance levels, however, are not independent of temperature, with an increase in water temperature resulting in an increase in ventilation, heart and oxygen consumption rates (Gehrke & Fielder 1988).

Native freshwater fish also have a variety of behavioural responses to low dissolved oxygen levels, including obligate air breathing in tarpon (*Megalops cyprinoides*) (Wells *et al.* 1997, and references therein), and facultative air breathing in native gobiids such as flathead gudgeon (*Philypnodon grandiceps*), empirefish (*Hypseleotris compressa*), dusky frillgoby (*Bathygobius fuscus*), and exquisite sand-goby (*Favonigobius exquisitus*) (Gee & Gee 1991). The non-native three-spot gourami (*T. trichopterus*) breaths air apparently irrespective of dissolved oxygen levels (Herbert & Wells 2001). For obligate water breathers, such as barramundi (*Lates calcarifer*) (Wells *et al.* 1997), air breathing is not an option. Behavioural avoidance of low oxygen levels has been demonstrated in fishes (Höglund 1961; Shelford & Allee 1913), including the native empirefish (*H. compressa*) and barramundi (*L. calcarifer*) (Pearson *et al.* 2003a; Pearson *et al.* 2003b), suggesting that areas with low oxygen levels create barriers to movement.

Freshwater fish species will differ in their response to acute and chronic changes in salinity of freshwater ecosystems. For example, both adult and juvenile spangled perch (*L. unicolor*) tolerate gradual acclimation to salinities ranging from 0 to 35.5‰ for three months, and survive direct transfer from 35.5 to 0‰ (Beumer 1979). Slow acclimation LD_{50}s of adult fly-specked hardyhead (*C. stercusmuscarum*) and western carp gudgeon (*H. klunzingeri*) were 43.7 g/L and 38.0 g/L, respectively (Williams & Williams 1991). Salinity thresholds can vary across different life history stages, such as in eastern rainbowfish (*M. splendida splendida*) where juveniles and adults died during gradual acclimation to 17.8‰ and 26.7‰, respectively (Beumer 1979), which corresponds with slow acclimation LD_{50} values of 29.8 g/L for adults (Williams & Williams 1991). Direct transfer of adults provided an estimated LD_{50} value of 20.8 g/L for adults (Williams & Williams 1991), while reverse direct transfer of juveniles and adults from

26.7‰ to freshwater resulted in 100% mortality (Beumer 1979). Juvenile barramundi (*L calcarifer*) have a wide salinity tolerance, being able to survive salinities from freshwater to 36‰ (Russell 1987).

Acidification of freshwater ecosystems can have detrimental impacts on fish, including acute mortality, reduced growth, skeletal deformities, reproductive failure, and increased uptake of heavy metals (Haines 1981). Fish species can use various physiological mechanisms to adapt to low pH (Fromm 1980; Haines 1981; McDonald 1983; Randall & Lin 1993; Wendelaar Bonga & Dederen 1986). However, they have only been described for one native fish species, barramundi (*Lates calcarifer*) in experiments that simulated live-transport (Paterson *et al.* 2003). Sex ratio in non-native cichlids and poecilids is strongly affected by pH (Römer & Beisenherz 1996), although the exact mechanism through which this occurs is currently not clear. Behavioural avoidance of low pH levels has been documented in laboratory studies well within the magnitude of concentrations in acidified systems (Haines 1981), albeit not in any local freshwater fish species. Field observations of acid avoidance behaviour in freshwater fish are scarce; such behaviour is usually inferred from lack of fish in acidic zones (e.g., Åtland & Barlaup 1996; Johnson & Webster 1977). In contrast to marine ecosystems (e.g., Hofmann *et al.* 2010), no reports were found on the effect of acidification on freshwater organisms.

3.2.2 Phenology

Phenology relates variation in climate with periodic biological phenomenon. In contrast to terrestrial and marine ecosystems, very few changes in phenology have been documented in freshwater environments. In a meta-analysis across terrestrial, freshwater and marine taxa in the UK, Thackeray et al. (2010) demonstrated phenological advances in primary producers, primary consumers and secondary consumers in freshwater ecosystems, consistent with an increase in mean lake surface temperatures over the last 30 years. Two examples of detailed studies in freshwater ecosystems comprise advances in seasonal phytoplankton blooms (Winder & Schindler 2004) and spawning of fish (Ahas 1999). Phytoplankton blooms in a lake in the USA have advanced by 19 days in the 40 years up to 2002 as a result of earlier spring stratification, whilst increases in water temperature and food availability resulted in a more varied response of two zooplankton species (Winder & Schindler 2004). Similar conditions may promote an earlier start of blooms of possibly toxic cyanobacteria in lakes (e.g., Paerl & Huisman 2008; Paerl & Huisman 2009), as has been predicted for Queensland's reservoirs (Garnett *et al.* 2003). Providing suitable physio-chemical conditions prevail, such as very low flow and high nutrient concentrations, cyanobacteria can also cause bloom in rivers as occurred along 1,000 km of the Barwon-Darling River in 1991 (Bowling & Baker 1996).

A rise in water temperature induces spawning in many fish species, including freshwater fish species in Queensland (Lake 1967; Pusey *et al.* 2004). For example, an increase in reproductive summer coincides with a period of increasing water temperature, although the actual spawning stimulus is unknown (Milton & Arthington 1983). Specific spawning temperatures have been documented for native species such as western carp gudeon (*Hypseleotris klunzingeri*) and freshwater catfish (*Tandanus tandanus*) (Lake 1967), spangled perch (*Leiopotherapon. unicolor*) (Llewellyn 1973), silver sillago (*Sillago sihama*) (Römer & Beisenherz 1996), as well as for non-native species such as the three-spot gourami (*Trichogaster trichopterus*) (Degani 1989) and mosquitofish (*Gambusia holbrooki*) (Meffe 1991). Spawning in freshwater fish can be induced by a multitude of factors, for example a concomitant increase in water temperature and water levels, such as in the yellowbelly (*Macquaria ambigua*) (Lake 1967). Hence, advances in temperature and flood levels as a result of climate change may affect timing of spawning, although only one such example has been documented for freshwater fish (Ahas 1999).

3.2.3 Genetic changes

Genetic changes in adaptation to climate change have not been documented in Australia's freshwater species. It is likely that extreme events, such as floods and droughts, will affect the exchange of genetic material by either expanding or limiting dispersal pathways (Lake 2008). For example, recent work on the native golden perch (*Maquaria ambigua*) demonstrated that hydrological variability was a strong predictor of genetic diversity within drainage basins (Faulks *et al.* 2010). Maintaining connectivity within basins in the face of climate change is therefore paramount to sustaining the species' evolutionary potential (Faulks *et al.* 2010).

3.3 Changes in distribution and abundance

Freshwater biodiversity is affected by changes in species' distribution and abundances. In Queensland, both distribution and abundances would have changed significantly since the first published studies (Macleay 1883), due to overexploitation, water pollution, modification of water flows and hydrology, habitat destruction and degradation, and invasion by non-native species (Dudgeon *et al.* 2006; Malmqvist & Rundle 2002). The effects of climate change are likely to further compound these existing threats and associated impacts on Queensland's aquatic biodiversity (DERM 2010a).

Range shifts are a common phenomenon in aquatic ecosystems, and particularly along river stretches, where species respond diurnally, seasonally or annually to occupy habitats with favourable environmental drivers (e.g., Tockner *et al.* 2008). Local adaptation may occur where species can adapt to chronic changes in environmental drivers, whereas other species may move into new habitats where connectivity exists (e.g., Ficke *et al.* 2007). For example, the distribution of invasive fish species, such as *G. holbrooki* (Meffe 1991) and *Tilapia mariae* (Shafland & Pestrak 1982), is most likely restricted by their lack of tolerance to low temperature. Increased water temperature may extend their distributional range into sub-tropical and elevated regions of Queensland. In coastal areas, permanent range shifts occur when salinity gradients are permanently altered and large estuarine habitat areas are turned into freshwater habitats, due to altered hydrological regimes, changes in land use and pollution (Nilsson *et al.* 2005; Tockner & Stanford 2002). Predicted rises in sea level will result in saltwater intrusion and associated shifts in freshwater and saltwater boundaries, with concomitant shifts in species based on their level of salt tolerance and changes in species assemblage composition from freshwater to more salt tolerant ones (Schallenberg *et al.* 2003). Changes in precipitation and evaporation will result in temporal and spatial shifts of connectivity between aquatic habitats and habitat availability. For example, predicted changes in Queensland's river discharge may impact the number of fish species, with estimated reductions from 0 to 50% predicted across Queensland's basins (Döll & Zhang 2010; Xenopoulos *et al.* 2005). Aquatic biodiversity in small tributaries may be affected in particular being more prone to fluctuations in discharge and temperature (Malmqvist *et al.* 2008). Furthermore, extreme flood and drought events will result in temporal and spatial shifts of primary productivity and foodweb dynamics, and may have genetic and demographic consequences for lotic species (Faulks *et al.* 2010; Malmqvist *et al.* 2008). Overall, it is expected that range shifts of individual species and changes in species composition will occur in Queensland, with invasive species expected to increase their distributional range. The exact trends in local abundances and distributional shifts are difficult to predict for Queensland's aquatic biodiversity, without more research that covers the entire range or at least the relevant extremes of species' distribution.

In non-riverine systems, such as lakes, reservoirs and isolated wetlands, dispersal of aquatic flora and fauna is in general limited by lack of connectivity. Although many lakes are supersaturated with CO2 due to decomposing organic matter from the catchment (Cole *et al.* 1994), phytoplankton productivity in eutrophic freshwater is expected to increase up to 50% for some species as atmospheric CO2 doubles (Schippers *et al.* 2004). Freshwater with low alkalinity will be most sensitive to such a CO2 increase leading to a change in phytoplankton composition (Schippers *et al.* 2004). In Queensland, a large part of freshwater systems is made up of arid or semi-arid lakes with usually only intermittent water supply. As a result of a predicted decrease in run-off due to decreased precipitation and increased evaporation, "(i) episodic lakes will fill less frequently and dry more quickly, (ii) intermittent (seasonally filled) lakes will be of shorter duration and smaller extent, and (iii) permanent salt lakes will shrink and become more saline" (in the sense of Jellison *et al.* 2008). Large episodically filled lakes may fill less frequently but perhaps more intensely during flood pulses (Jellison *et al.* 2008; Williams 2002). Such changes in the hydrological water balance may further lower water levels in dry evaporative basins and in small catchments (Polunin 2008), resulting in changed size and salinity of arid and semi-arid lakes. Freshwater shortage and associated water salinisation is a serious threat for the abundance of aquatic biodiversity (Timms 2005), with salinisation of lakes in Western Australia leading to an 80% reduction in biodiversity (waterbirds, wetland vegetation, aquatic invertebrates) (Lyons *et al.* 2007). Similarly, the effects of drought and saline intrusion on freshwater biodiversity are likely to be pronounced in coastal floodplains (Malmqvist *et al.* 2008).

3.3.1 Diseases

Disease risk may increase in terrestrial and marine biota with increased climate warming (Harvell *et al.* 2002). Host-parasite dynamics in aquatic environments may also be affected through changes in transmission opportunities and host susceptibility (Marcogliese 2001). In freshwater systems, increased surface water temperature has been related to increased occurrences of the outbreak of diseases, particularly in aquaculture facilities (e.g., Chi *et al.* 1999, and references therein). For example, temperature plays an important role in infection and pathogenicity of grouper nervous necrosis virus (Chi *et al.* 1999). This virus is one of the nodaviruses responsible for viral nervous necrosis disease, which have been documented in larvae and juveniles of species that occur in Queensland, such as barramundi (*L. calcarifer*) (Chi *et al.* 1999; Munday *et al.* 1992). In contrast, climate warming may limit the geographic ranges of some diseases, such as chythrid epizootic disease, which requires cool, moist, high-altitude conditions (Harvell *et al.* 2002). Similarly, increased acidity of surface waters may result in increased susceptibility of fish to infections. The seasonal occurrence of epizootic ulcerative syndrome (EUS), or red spot disease, has been related to acid sulfate soil discharge (Callinan *et al.* 1996). EUS is a cutaneous ulcerative disease affecting freshwater and estuarine fish in Australia, Southeast Asia, South Asia and East Asia (Callinan *et al.* 1996), and has been documented in Queensland (Rodgers & Burke 1981). Extinction in some species due to an increase in the probability of diseases is likely, but might be regionally bound and not a process gradual in time.

3.3.2 Extinction

Extinctions of entire species due to climate change have recently been reviewed by Parmesan (Parmesan 2006). Climate change may cause species to go extinct if expansion is not possible due to reduced habitable area or geographic barriers (Parmesan 2006). In Queensland, the survival of aquatic species with restricted and fragmented distributions is under particular threat of extinction due to climate change. For example, fish species may not be able to sustain long-term tolerance or avoidance of hypoxic conditions, and exposure to hypoxic conditions may impair fish reproduction (Wu *et al.* 2003) or can result in fish kills (Dawson 2002). Similarly, exposure to reduced pH levels resulted in increased mortality in juvenile barramundi (L. calcarifer; Paterson *et al.* 2003), and acidic water ($pH < 5.0$) and high concentrations of dissolved aluminium have been linked to fish kills in Australia (Brown *et al.* 1983; Hart *et al.* 1987; Russell & Helmke 2002). While pH values below 3-4 are lethal to most fish species (Wendelaar Bonga & Dederen 1986), elevated concentrations of inorganic aluminium are most likely the primary cause for fish mortality in these acidified waters (Driscoll *et al.* 1980).

3.4 Changes in biotic interactions

Interactions across trophic levels may be severely disrupted by climate change impacts due to altered synchrony (Visser & Both 2005). In freshwater environments, changes in precipitation and evaporation will result in temporal and spatial shifts of primary productivity and foodweb dynamics. For example, predator-prey peaks interactions may change due to increasing asynchrony, such as documented in altered peak phytoplankton bloom and zooplankton abundances in a USA lake (Winder & Schindler 2004). Increased water temperatures will affect a wide range of ecosystem processes (Kaushal *et al.* 2010) such as biological productivity and stream metabolism (e.g., Yvon-Durocher *et al.* 2011). As a consequence, a higher incidence of eutrophication can be expected (Trolle *et al.* 2011). Both asynchrony and changes in primary production will have subsequent flow on effects to higher levels of the foodweb, although the exact impacts are difficult to predict in complex systems. To the best of our knowledge, long-term time series in Queensland’s aquatic ecosystems have not been examined for the occurrence of altered asynchrony across trophic levels.

3.5 Interactions with other threatening processes

The effects of climate change are superimposed upon existing threats to freshwater ecosystems, namely overexploitation, water pollution, modification of water flows and hydrology, habitat destruction and degradation, and invasion by non-native species (Dudgeon *et al.* 2006; Malmqvist & Rundle 2002). In this section, we provide a brief overview of these five threats in a Queensland context, and give some examples how climate change may compound the effects of these existing threats.

3.5.1 Overexploitation

Whilst commercial fishing in freshwater systems is close to non-existent in Queensland, many coastal and marine species depend on freshwater habitats and flows (e.g., Robins *et al.* 2005). In contrast, approximately 640,000 recreational fishing events take place annually in freshwater systems (rivers, lakes, dams), translating into 11% of the total recreational fishing effort (Henry & Lyle 2003). Similarly, the indigenous fishing effort in Queensland's freshwater systems is only 10% of the total effort, with approximately 13,000 freshwater fishing events taking place annually (Henry & Lyle 2003). Whether freshwater fisheries in Queensland are overexploited is currently unknown. A follow-up recreational fishing survey is currently being conducted by the Queensland Government, with results expected in mid-2012. This will provide important information on long term monitoring of catches, effort and participation, crucial for freshwater fisheries resource management, including in the context of climate change (Ficke *et al.* 2007).

3.5.2 Water pollution

Across Queensland, information on water quality in rivers is available for seven out of the nine regions (Coysh *et al.* 2008). In this Queensland State of the Environment report, total phosphorus and total nitrogen concentrations in most rivers across all seven regions are rated of concern or poor, with concentrations in the Murray Darling region being poor in all cases (Coysh *et al.* 2008). High nutrient concentrations in freshwater ecosystems, in combination with low flow conditions (e.g., Bowling & Baker 1996), high water temperature (Mehnert *et al.* 2010), and stratification (Jöhnk *et al.* 2008), may lead to intensified blooming of possibly toxic cyanobacteria (Paerl & Huisman 2009). Cyanobacteria (or "blue-green algae") are an increasing threat for freshwater systems under climate change, as they produce toxins which can be fatal to, for example cattle, birds and humans, if swallowed with water in large quantities (e.g., Stewart *et al.* 2008). Reservoirs are especially vulnerable to cyanobacterial blooms and cyanotoxin release since they are used as drinking water resources (Leigh *et al.* 2010). In tropical and subtropical Queensland (McGregor & Fabbro 2000), 70 % of 47 reservoirs contained the toxin producing cyanobacterium species *Cylindrospermopsis raciborskii*. In Europe, this species has extended its range into northern lakes due to slightly increasing water temperatures (Padisák 1997; Wiedner *et al.* 2007).

Other species, such as *Anabaena* or *Microcystis*, are also known to favour increasing temperatures, more stable stratification and reduced surface mixing (Jöhnk *et al.* 2008). One of the largest cyanobacteria bloom occurred in 1991 along a 1,000-km stretch of the Barwon-Darling River, with very low flow conditions and high phosphorous concentrations leading to low N:P ratios favouring cyanobateria (Bormans *et al.* 2004; Bowling & Baker 1996). Such river blooms can persist over several months until they are washed away by the next flood. In combination with high nutrient concentrations, a shift to higher water temperatures and a relatively larger increase in night-time temperatures will further promote cyanobacteria species. This may lead to a dominance of tropical species like *C. raciborskii* with higher optimal temperature for growth (Shaw *et al.* 2001). Beside possible dominance of these species with associated loss of biodiversity, a spread to other lakes under increasing water temperatures is likely.

State-wide information on emission of contaminants, such as metal, organic chemical, and fuel burning chemicals, is presented in the atmosphere section of the 2007 State of the Environment report (Environmental Protection Agency 2008). However, information on contaminants in Queensland's freshwater ecosystems is not readily available, except for pesticide concentrations for the catchments draining into the Great Barrier Reef (e.g., Brodie *et al.* 2011). It is predicted that increasing water temperature will result in enhanced toxicity of contaminants (Noyes *et al.*

2009; Schiedek *et al.* 2007). However, we are not aware of any Queensland studies that have evaluated synergistic effects of increased temperature and contaminants on freshwater flora and fauna.

3.5.3 Modification of water flows and hydrology

In Queensland, abstraction of water is a significant threat to freshwater ecosystems (Ronan *et al.* 2008). Increasing demand for water, in combination with the pre-2011 drought, resulted in streamflow being well below the long-term average in all parts of Queensland except the north (Ronan *et al.* 2008). Population growth and increased human demand for fresh water, in combination with an expected decrease in long-term precipitation over most of Queensland, will result in further reductions of mean annual stream flows. In many freshwater ecosystems, this could result in reduced connectivity with surface freshwater systems (Gilbert *et al.* 2008), and reduced abundance of many species beyond the threshold for recovery (Malmqvist *et al.* 2008). In contrast, freshwater ecosystems in Queensland's arid lands are resilient to disturbances such as flash floods and drying, and may be the last to respond to climate change pressures (Gopal *et al.* 2008). Overall, however, it is expected that water resource development and management will affect the hydrology of freshwater ecosystems much more than climate changes (Vörösmarty *et al.* 2000), including in Australia (Lake & Bond 2007), at least in the short to medium term.

3.5.4 Habitat destruction and degradation

Intensive land uses may affect the condition of freshwater ecosystems. In Queensland, such land uses includes "land clearing, plantation forestry, irrigated and non-irrigated cropping, horticulture, animal production, mining, dredging and extractive activities", as well as urbanisation (Coysh *et al.* 2008). These land uses can have direct or indirect effects on the condition of freshwater ecosystems (e.g., Dudgeon *et al.* 2006). For example, the loss of wetland vegetation in the Murray Darling and North East Coast drainage divisions comprises approximately 30% of pre-clearing extent (Coysh *et al.* 2008). In other regions, remnant wetland comprised approximately 93% to 97% of their pre-clearing extent (Coysh *et al.* 2008).

Degradation or removal of riparian vegetation can result in profound changes in freshwater ecosystems. Clearing decreases the amount of organic matter and woody debris entering streams, decreasing sources of habitat and food for aquatic organisms (Pusey & Arthington 2003). Light penetration and stream temperatures increase, favouring growth of filamentous algae and macrophytes (Bunn *et al.* 1999b). Bank erosion and sediment loads increase (Prosser *et al.* 2001), resulting in the smothering and disappearance of habitat and food sources for invertebrates and fish (Koehn & O'Connor 1990). Further, nutrient input increases (Prosser *et al.* 2001) while nutrient uptake by primary producers changes (Udy & Bunn 2001), affecting water quality as well as nutrient pathways to secondary consumers such as fish (Bunn *et al.* 1999a).

In degraded habitats, increasing air temperature associated with climate change may result in enhanced increased in water temperatures (e.g. Kaushal et al. 2010), with potential flow-on effects on primary production and spread of invasive weeds.

3.5.5 Invasion by non-native species

In 2007, Queensland’s freshwater ecosystems contain at least 18 invasive fish species, one turtle, and several declared aquatic weeds (Wilson *et al.* 2008). These invasive species occur mostly in the South East and Coastal Queensland, and have a variety of environmental, social and economic impacts (Wilson *et al.* 2008). Wilson et al. (2008) report that “all invasive species have the potential to expand their distribution further west and along the coast”. With predicted increases in water temperature, the distribution of invasive fish species, such as *Gambusia. holbrooki* (Meffe 1991) and *Tilapia mariae* (Shafland & Pestrak 1982), may extend their distributional range into sub-tropical and elevated regions of Queensland.

3.6 Changes in response to disturbance regimes and extreme events

In addition to anthropogenic stressors, disturbances experienced by freshwater ecosystems include natural events, such as cyclones, floods and droughts. In most freshwater ecosystems, natural and anthropogenic disturbances interact, resulting in additive, synergistic or antagonistic responses (Cardoso *et al.* 2009; Rader *et al.* 2008; Robinson & Uehlinger 2008) . Here, we discuss the potential impact on freshwater ecosystems of extreme events that occur naturally, but are expected to increase in frequency and/or intensity with changing climate.

3.6.1 Cyclones

Through a combination of deposition and erosion, high intensity cyclones can significantly alter the geomorphology of Queensland’s coastal systems (e.g., Nott 2007). Thus, an increase in high intensity cyclones will irreversibly destroy freshwater habitats and generate new ones through, for example, landslides, sediment loading, the infilling of pools, and riparian destruction, as well as changing the connectivity between habitats. Increased wind speed will alter mixing patterns in lakes, wetlands, floodplains and estuaries in the coastal zone, and possibly affect buoyancy regulation of phytoplankton. Fish kills associated with low dissolved oxygen concentrations have been recorded in the Tully basin following cyclone Yasi in Far North Queensland.

3.6.2 Droughts

In Queensland, air temperature is predicted to increase particularly in southern Queensland and in the south-western corner, and the number of exceptionally hot years is expected to increase and affect most parts of the State by 2040 (see Whitfield *et al.* 2010). In combination with continued large-scale abstraction of water, it is likely that this will result in an increase duration and frequency of long-term droughts. For Australian freshwater systems, Bond et al. (2008) list the major impacts as “the loss of water and habitat availability, and the reduction, if not severing, of connectivity (lateral, longitudinal, and vertical)” (see also Lake 2008). Bond et al. (2008) provide a more detailed summary of the impacts of droughts on Australian freshwater ecosystems. Extremely and chronic low flows due to major droughts will exacerbate the effects of both diffuse and point-source pollution (Malmqvist *et al.* 2008). Overall, longer and more severe droughts could reduce the abundance of aquatic species in freshwater systems, including beyond the threshold for recovery (Malmqvist *et al.* 2008).

3.6.3 Floods

Floods are characterised by ponding of water adjacent to a river due to excess rainfall or overbank flow, and are a common natural disturbance in riverine landscapes (Poff *et al.* 1997). Natural floods are considered a driving force of river-floodplain ecosystems because of associated increases in productivity (Junk *et al.* 1989; see alsoRobins *et al.* 2005).

The predicted increase in extreme rainfall events in the Cape York region during all the year and in western Queensland and the Gulf region in summer and autumn (Whitfield *et al.* 2010) will increase the probability of river floods, including major floods. Increased stream flow will increase flow velocity and bed erosion in the head waters, and lead to higher connectivity, sediment deposition and nutrient enrichment in the floodplains (Junk *et al.* 1989; Lake *et al.* 2006). The nutrient pulse associated with extreme floods triggered by passing (sub)tropical cyclones have triggered cyanobacterial blooms (Jones & Poplawski 1998). Responses of freshwater ecosystems to severe flood disturbances include acute changes in water quality resulting in massive kills of finfish and benthic fauna (Burkholder *et al.* 2004; Mallin *et al.* 1999; Steffe *et al.* 2007). Large-scale flooding results in an immediate shift in taxa composition, which exceeds seasonal changes, followed by a recovery period varying in length from months to years, as has been documented for fish and macro-invertebrate assemblages in mountain streams (Matthews 1986; Roghair *et al.* 2002), coastal floodplains (Kroon & Ludwig 2010; Rayner *et al.* 2008) and estuaries (Burkholder *et al.* 2004; Mallin *et al.* 1999). Extreme flood events have the potential to distribute species to new locations, including invasive species, by mediating the mixing of species assemblages in floodplains, lakes, ponds, resulting in new locally adapted assemblages. In combination with reduced river flow rates, severe floods will result in, as yet unknown degrees of, temporal and spatial shifts of connectivity between aquatic habitats, habitat availability, and primary productivity/foodweb dynamics.

Aerial view of tropical rainforest adjoining the Barron River near Cairns, northern Queensland. 2000 (credit: Gregory Heath, CSIRO Land and Water, science image BU4366).

4. ECOSYSTEM SERVICES

4.1 Introduction

Ecosystem services are the “benefits that humans recognise as obtained from ecosystems that support, directly or indirectly, their survival and quality of life” (in the sense of Harrington *et al.* 2010; for details see Williams *et al.* 2012b). Following its seminal publication on ecosystem services (MEA 2005), ecosystem services are generally categorized into four classes (Harrington *et al.* 2010; Harrison *et al.* 2010b):

- Provisioning services: products obtained from ecosystems (e.g. food, water, fuel, materials for building, etc.),
- Regulatory services: benefits obtained from regulation of ecosystem processes (e.g. air quality regulation, climate regulation, water/flood regulation, disease and pest control, pollination, water purification, etc.),
- Cultural services: non-material benefits obtained from ecosystems (e.g. spiritual enrichment, recreation, education, aesthetic enjoyment, etc.), and
- Supporting services: necessary for the production of all other ecosystem services (e.g. soil formation, nutrient and water cycling, photosynthesis, etc.).

The human use of provisioning, regulating and cultural ecosystem services has increased over the last 50 years, in parallel with growth in human population and consumption (Carpenter *et al.* 2009). Simultaneously, the condition of most services has decreased, due to a variety of drivers of which climate change is one (Carpenter *et al.* 2009).

4.2 Ecosystem services from freshwater ecosystems

Whilst it is acknowledged that Queensland’s freshwater ecosystems provide essential ecosystem services to the people of Queensland and Australia (DERM 2010a) , no detailed assessment of these ecosystem services has been made, although see the recommendations and knowledge gaps identified by Davis et al. (2007). Building on this earlier work and to provide a preliminary indication of the potential services contributed by freshwater ecosystems at a State level, we synthesised information from regional (Maynard *et al.* 2010), national (Cork *et al.* 2007), and international (Harrison *et al.* 2010a; Harrison *et al.* 2010b) studies. Consistent with Williams et al. (2012b), we focus on the burgeoning international literature on freshwater ecosystems services, and use this in the context of the international literature on ecosystems services and biodiversity.

Similarly to other ecosystems, freshwater ecosystems provide essential services that benefit society, including habitat and breading area for fish and other aquatic animals, pollutant filters, provision for fresh water, and recreational and cultural values (Table 1) (Harrison *et al.* 2010a; Harrison *et al.* 2010b). In particular, freshwater ecosystems are key contributors to three provisioning services, four regulating, four cultural and all three supporting ecosystem services. The contribution of freshwater ecosystems to two provisioning and three regulating services is poorly known (although see the review by Davis *et al.* 2007, for Queensland's wetlands), whilst that to remaining services is considered to be minor (Table 1).

4.2.1 Provisioning services

In Queensland, rivers, lakes, wetlands and floodplains are important sources of *food and fibre*, through freshwater fisheries and aquaculture, seasonal cattle grazing, rice production, and indigenous hunting and gathering (e.g., see environmental indicators in Environmental Protection Agency 2008). Three of Queensland's rivers are dammed for hydropower generation (Barron, Brisbane, Tully) and make a key contribution to *energy*[4]. The contribution of many of Queensland's rivers and lakes to the non-consumptive use of *freshwater*, such as irrigation, cooling and mining, is extensive. The contribution of freshwater ecosystems to *ornamental resources* is thought to be minor but exists through the provision of fishing trophies and plants and animals for aquaria. Currently, little is known about the *biochemicals and natural medicines*, and *genetic resources* freshwater ecosystems may provide (although the phylogenetic structure of Queensland rainbow fish raises evolutionary questions; Page *et al.* 2004).

4.2.2 Regulating services

Queensland's rivers, lakes, wetlands and floodplains play a key role in regulating *water flow*. Specifically, wetlands and floodplains play an important role in flood retention, and as such contribute to *natural hazard* regulation (Davis *et al.* 2007). Through filtering and processing, microbial communities, algae, macrophytes and riparian zones all contribute to *water purification and waste treatment*. Wetlands and (forested) floodplains contribute to *climate regulation* of local and regional climates primarily through the uptake of carbon (Davis *et al.* 2007). Corridors by rivers and riparian zones could provide a migration pathway for native and non-native species and contribute to *seed dispersal* and *invasion*. The contribution of freshwater ecosystems to these latter two regulating services, as well as to *pest regulation*, *disease regulation* and *erosion regulation* is currently poorly known. Freshwater ecosystems do not contribute to *pollination* or *air quality regulation*.

4.2.3 Cultural services

The rivers, lakes, wetlands and floodplains in Queensland provide critical cultural services. The *spiritual and religious values* of freshwater ecosystems are significant to indigenous Australians, but likely less so to non-indigenous Australians. National parks and other protected areas that include freshwater ecosystems provide important *education and inspirational services*. Rivers and lakes in general contribute to *recreation and ecotourism*, including boating, rafting, canoeing, fishing, hiking, photography and wildlife viewing. Freshwater ecosystems, in particular the near-natural and most diverse sections of rivers are attractive to people and contribute to their *aesthetic values*. Finally, freshwater ecosystems are part of the *cultural heritage* of both indigenous and non-indigenous peoples, and are important in providing a *sense of place*. An overview of the private and social values of Australian wetlands is presented in Bennett and Whitten (2002), who were interested in the forces driving wetland owners to manage their wetlands.

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[4] For example, Stanwell Corporation, http://www.stanwell.com

4.2.4 Supporting services

Queensland's aquatic ecosystems provide three main supporting services to the other three categories of ecosystem services. First, rivers, wetlands and floodplains are key pathways for transport and accumulation of organic matter, thereby supporting *soil formation*. Second, *nutrient and water cycling* is supported through the hydrological and biogeochemical processes taking place in all types of aquatic ecosystems. Finally, photosynthesis by (semi-) aquatic plants, including cyanobacteria, phytoplankton, algae, macro-algae and riparian vegetation support *primary production* and underpins aquatic foodwebs. Groundwater recharge is also a feature of some wetland systems.

This preliminary assessment of ecosystem services provided by Queensland's freshwater ecosystems is a generalisation of information from regional, national and international sources. Hence, we acknowledge that considerable local and regional variation will exist in the ecosystem services described here. The South East Queensland Ecosystem Services Project (Maynard *et al.* 2010) is the only regional planning project that we know of that has assessed ecosystem services in Queensland. To inform future policy formulation and decision making for Queensland's freshwater ecosystems, particularly in the face of climate change, we recommend that the ecosystem services provided by these systems are assessed in more detail in other planning regions as well as across the State.

4.3 Freshwater biodiversity and ecosystem services

Biodiversity is defined as "the variety of living organisms and the ecological complexes of which they are part" (in the sense of Harrington *et al.* 2010). It covers "genetic, structural and functional components, which are derived from different organisational levels, from single individual organisms to species, populations, communities and ecosystems (in the sense of Harrington *et al.* 2010). Globally, the transformation of water systems around the world has resulted in a precipitous decline in freshwater biodiversity (Vörösmarty *et al.* 2000). For example, in the USA the recent and predicted extinction rates of freshwater fauna are five times higher than those for terrestrial fauna (Ricciardi & Rasmussen 1999).

The importance of biodiversity to the provision of ecosystem services is acknowledged (DERM 2010a), but the underpinning ecological processes often remain to be determined (Harrison 2010). There appears to be a general consensus in the literature, however, that the maintenance of biodiversity contributes to the delivery of ecosystem services (Anton *et al.* 2010; Luck *et al.* 2009). All components of biodiversity can contribute to ecosystem services and this has been conceptualised in different frameworks to guide ecological assessments (see Luck *et al.* 2009 for discussion). For example, water filtration services by freshwater ecosystems are provided by community level of organisation, such as wetland forests (Luck *et al.* 2009). In a recent paper, de Bello et al (2010) used functional traits to demonstrate how different organisms and communities influence ecosystem processes and thereby ecosystem services. For example, several functional traits of wetland forests, such as decomposability, growth form diversity, growth form composition, and leaf area, influence water purification through their effects on nutrient and sediment retention (de Bello *et al.* 2010). Hence, whilst recent progress has been made for ecosystems in the northern hemisphere, further research needs to be conducted to explicitly link freshwater biodiversity with freshwater ecosystem services in general, and in (sub-)tropical systems in particular.

4.4 Impact of climate change on freshwater ecosystem services

In Queensland, it is predicted that climate change will result in significant changes in environmental drivers underpinning ecological change in freshwater ecosystems (see section 1.3 and 1.4). In this section, we briefly contrast these changes with the main ecological processes underpinning the provision of key ecosystem services.

A flow regime that is within its natural range of variability is the main ecological process underpinning the provision of most key freshwater ecosystem services in Queensland. Those solely underpinned by a natural flow regime include *electricity* (hydropower), non-consumptive use of *freshwater* (irrigation, cooling and mining), and a variety of activities under *recreation and ecotourism*. Ecosystem services underpinned by a natural flow regime, as well as other ecological processes, include *food and fibre* (freshwater fisheries and aquaculture, seasonal cattle grazing, rice production, and indigenous hunting and gathering), *water flow regulation* (storage component of freshwater ecosystems), a variety of activities under *recreation and ecotourism*, services like *education and inspiration*, *aesthetic values*, and *sense of place*, and all three supporting ecosystem services (*soil formation*, *nutrient and water cycling*, and *primary production*). In the near future, mean annual stream flow will be further reduced due to the expected decrease in long-term precipitation and increased evaporation over most of Queensland, in combination with population growth and increased human demand for fresh water (Kenway *et al.* 2008; Lake & Bond 2007; Syktus *et al.* 2008). Hence, climate change is expected to detrimentally impact all these key ecosystem services, although the exact magnitude and direction of change is currently not known.

Other ecological processes that underpin the provision of key freshwater ecosystem services in Queensland include carbon sequestration and biodiversity. Carbon sequestration by wetland and floodplain vegetation is the main process underpinning regional and local *climate regulation*. It is expected that this may increase given the worldwide increase in atmospheric CO_2 concentration. Biodiversity *per se* underpins some key ecosystem services from Queensland's freshwater ecosystems.

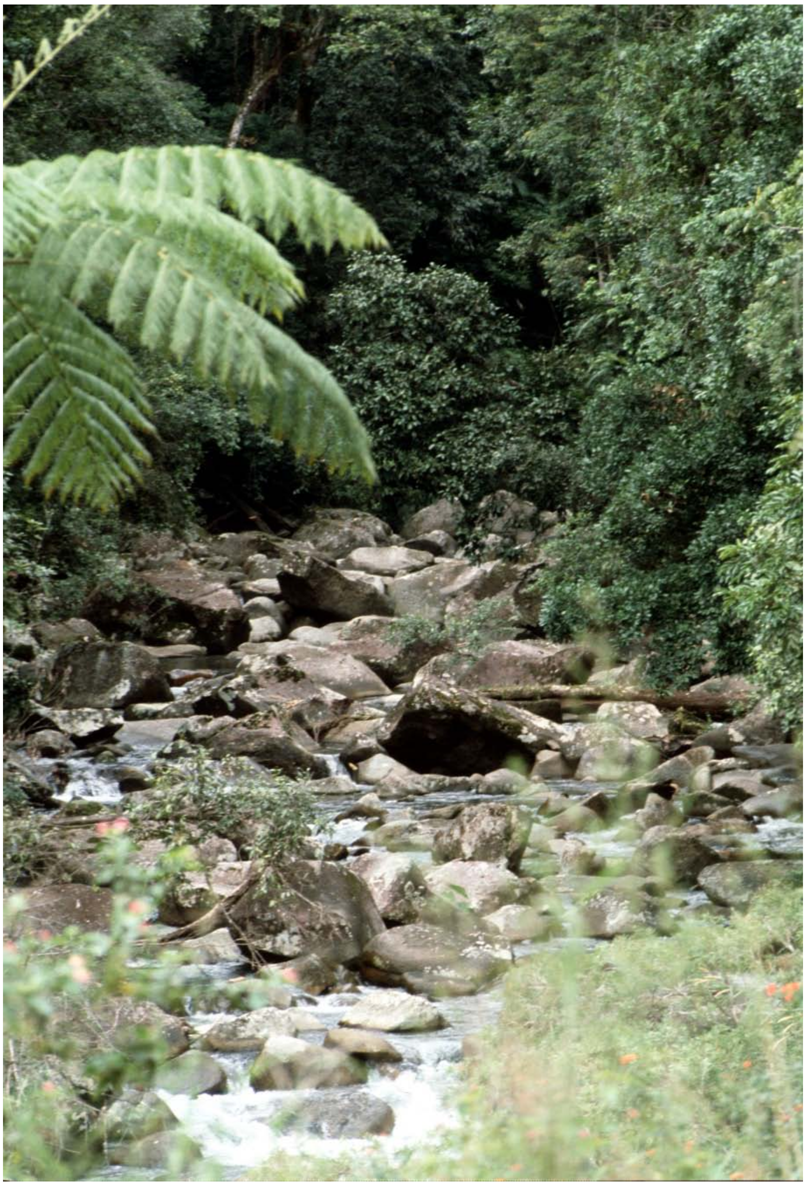
First, the extent and condition of the plant biodiversity of wetlands and floodplains is likely to determine in a large part the ability for retention of floodwaters, and hence contribute to *natural hazard regulation*. Reduction of wetland area due to climate change could severely hamper flood-control efforts in some regions (Gopal *et al.* 2008). Whilst the role of wetlands in providing biodiversity as an ecosystem service is widely acknowledged (e.g., Zedler 2003), *vice versa* the role of wetland biodiversity in contributing to flood retention has to the best of our knowledge not been assessed.

Second, filtering capacity of freshwater ecosystems underpins *water purification/waste treatment* and is clearly dependent on biodiversity, including microbial communities, algae, macrophytes and riparian zones.

Third, biodiversity influences *primary production* through photosynthesis by (semi-) aquatic plants, including cyanobacteria, phytoplankton, algae, macro-algae and riparian vegetation. This, in turn, underpins aquatic foodwebs thereby supporting the provision of various *food and fibre* ecosystem services and of organic matter for *soil formation*.

Fourth, freshwater biodiversity contributes to all cultural services, for example through iconic species such as important fisheries species, freshwater and estuarine crocodiles, and large riparian trees.

Finally, if catchment vegetation is taken as a component of freshwater biodiversity (see also the discussion of terrestrial ecosystems in Murphy *et al.* 2012), freshwater biodiversity could arguably contribute to the maintenance of a natural flow regime thereby providing a feedback loop to other key ecosystem services. It is expected that climate change will compound existing threats to freshwater biodiversity (see section 3.5), and result in a variety of ecological change types (see section 3) that could impact the delivery of key ecosystem services. However, similarly to flow regime, the exact magnitude and direction of change is currently not known.



Rocky Beatrice River, north Queensland (CSIRO science image EM4092).

5. REGIONAL VARIATION

5.1 Introduction

To describe environmental change phenomena at a regional scale, we combined the nine Queensland Freshwater Biogeographic Provinces with Queensland's five drainage divisions into five distinct freshwater aquatic regions (see Section 1 and Figure 3). This combination reflects drainage divisions for river flow as well as biogeographically distinct regions for lake and wetland ecosystems.

As the distribution of wetland types across Queensland reflects to some extent the biogeographic and climatic settings, future climate change patterns will have distinct effects on individual wetland types. For example, the arid and semi-arid lakes occur mainly in the south-west of Queensland (Region E – Lake Eyre and Bullo and parts of Region D – Murray-Darling), which coincides with the largest temperature increase to be expected over Queensland (see Williams & Crimp 2012) and similar trends in pan-evaporation rates. Future increases in air temperature and associated pan-evaporation will therefore have a high impact on arid and semi-arid lakes.

Queensland wetlands (DERM 2011c) are divided in three groups, reflecting palustrine (swamps), lacustrine (lakes), and riverine (rivers) wetlands. The palustrine and lacustrine wetlands are further divided whether they are floodplain or non-floodplain wetlands, according to biogeographic location; that is, arid, semi-arid, or coastal and sub-coastal, and include sub-typology according to vegetation types or salinity level. Table 3 (Appendix 3) gives an overview on the catalogued wetlands in Queensland and their types as listed in the Queensland Wetland Mapping (DERM 2011c). To facilitate further discussion on climate change impacts we focus on four groups for lacustrine and palustrine systems, as follows:

- semi-arid and arid lakes,
- coastal and sub-coastal lakes
- semi-arid and arid swamps, and
- coastal and sub-coastal swamps.

The settings for these different types as listed in Table 3 (Appendix 3) are described in detail in *Wetland Management Profiles* (DERM 2011e) and will not be reiterated here. It has to be stated, that the distinction between arid/semi-arid and coastal/sub-coastal wetlands is to a large extent a geographic one, thus reflecting current climate conditions. Climate change will have the capacity to drive a certain lake or swamp from one type to another and so change the environment of the ecosystem. It is this possible change which will be shown in the following sections.

Stream flow is characterized by a multitude of factors. A river will probably cross several different hydroclimatic zones and be influenced by runoff from sub-catchments with different settings. Thus, a discussion of the impact of climate change on rivers in Queensland is only possible using a categorization of streamflow taking into account a full set of attributes describing catchment climate, water balance, topography, substrate and vegetation cover. Here we use the ecohydrological classification scheme of (Kennard *et al.* 2010; Pusey *et al.* 2009) who divide between 12 river flow regimes across Australia differing in the degree of flow predictability and variability, seasonal discharge pattern, flow permanence, and variations in the magnitude and frequency of extreme events. Geographic, climatic and topographic factors are usually strong discriminators of these flow regime classes (see Table 5.3 in Kennard *et al.* 2010). Therefore, climate change can lead to a reclassification of rivers from one regime type to another, presumably incurring changes in ecosystems.

To qualitatively assess climate change impacts on Queensland freshwater systems we compare mean values for the main drivers – annual temperature and evaporation, and precipitation split into wet (DJF) and dry (JJA) quarter – with the location of the different wetland types and flow regime classes for three different climates:

- current (historical) climate situation is given by the 30-year mean centred around 1990,
- projected climate for moderate emission scenario with a medium climatic sensitivity as given by the IPCC scenario A1B for 2030, and
- projected climate for high emission scenario as given by the IPCC scenario A1FI for 2070.

These emission scenarios (IPCC 2000) are explained in more detail in Williams and Crimp (2012) and Harwood et al. (2010). This range of scenarios allows us to explore a range of possible changes.

5.2 Climate scenarios for Queensland

The climate for Queensland under low and high emission scenarios (A1B and A1FI respectively – see also (A1B and A1FI respectively – refer Williams & Crimp 2012) compared to the mean values for the 30-year period centred around 1990 show strong changes in all four variables used here (see Appendix 4, Figure 6). High mean annual temperature will extend south-east, reaching levels in southern Queensland currently experienced in the Cape and Gulf region (region A) under the high emission scenario. Evaporation heights as a “measure” for arid/semi-arid or wet conditions are generally expected to decrease mainly as a consequence of increasing temperature. While regions A (Cape and Gulf) and B (Coastal and sub-coastal) are less effected, regions D (Murray-Darling) and more so regions C (South-East coast) and E (Lake Eyre and Bulloo) will suffer an increase in evaporation. This might lead to an extension of arid and semi-arid regions in eastern direction since there is an equivalent decrease in precipitation during the wet quarter for south-eastern Queensland to expected, touching regions C, D, and southern parts of the coastal and sub-coastal region, B. Changes in precipitation rates during the dry quarter also show possible decrease shifting towards south-east. While there is a possible drop in precipitation over large parts of Queensland under climate change scenarios, the western Cape and Gulf and northern parts of the coastal and sub-coastal region (regions A and B) are likely not to change with respect to precipitation.

5.3 Impacts on regional wetlands

Comparing the geographic distribution of different wetland types with changing climate pattern allows a detailed analysis of change impacts on these wetlands. Not all possible combinations of wetland type (4) ~ climate field (4) ~ climate scenario (3) are shown here but a few were selected to highlight potential climate impacts. Here we only give rough qualitative estimates of possible outcomes of climate change. A more rigorous, quantitative analysis is needed to further validate our suggestions given below. In addition a collection of the current physical state of lakes and swamps would be helpful to support such a quantitative impact assessment.

5.3.1 Arid and semi-arid swamps

Swamps in semi-arid regions (Figure 7, Appendix 5) are subject to temporary but frequent inundation by freshwater and usually dry out in the dry season due to high evaporation. In the arid region the drying-wetting process of swamps is more irregular, many holding water only for weeks during a year or even only once in five years. This wetland type is highly influenced by precipitation and evaporation. A shift from semi-arid to arid and from sub-coastal to semi arid conditions will likewise lead to a shift in swamp type. Due to increasing evaporation and decrease in precipitation during the dry and/or wet quarter swamps might change their frequency and duration of inundation, possibly shifting some swamps from multiple inundations per year to once every couple of years or even dry out for ever in case flooding by streams is interrupted. The higher evaporation rates will also lead to faster salinisation (e.g., Timms 2005; Williams 2002). Consequences for ecosystems are loss of habitats, change in connectivity between swamps and connecting rivers, and changes in species composition due to higher temperatures and salinities. Region E will probably see an increasing loss of swamps or change to long dry periods due to increased evaporation and lower precipitation. Swamps in the western part of region D and between region E and B probably will undergo a shift to more dry conditions and thus some swamps might have to be re-categorized from semi-arid to arid.

5.3.2 Coastal and Sub-coastal swamps

As a geographical continuation, sub-coastal swamps might undergo a change in the regions adjacent to semi-arid regions shifting from very long inundation periods per year to smaller periods. Thus, shifting its type from sub-coastal to semi-arid (red bar in Figure 8, see Appendix 5). This will possibly lead to extinction of species needing a longer inundation period. Swamps in the north (region A) and those nearer to the coast (regions B and C) will experience no large changes during the wet period (see Appendix 5, Figure 7 and Figure 8) but possibly experience a decrease in water inflow in South-East Queensland and eastern Murray-Darling region during the dry season due to reduced precipitation.

5.3.3 Arid and semi-arid lakes

Lakes in the semi-arid and arid regions are less frequent than swamps; the majority are found on the floodplains in the arid region of Lake Eyre and Bulloo (E) and parts of Murray-Darling region (D). Like their swamp counterparts these lakes can cycle through wet and dry periods depending on the balance between freshwater inflow through streams and evaporation. This balance will also determine the salinity level in these lakes. A future decrease in precipitation and increase in evaporation will lead to a drop in water level and thus shift in shore vegetation, more pronounced dry periods for lakes which regularly dry out, and higher salinity levels possibly changing species composition. Temperature in such lakes also plays a major role; depending on the water depth a lake can buffer day-night temperature variations and lakes of several meters in depth (usually permanent lakes) will build up a stratification separating bottom from top layers. The latter will change the biogeochemistry, e.g. oxygen levels, depending on the length of stratification of these polymictic lakes (having several stratification periods per year). Increasing temperature and the higher probability of heat waves will lead to prolonged stratification periods with associated drops in bottom oxygen levels, which possibly can lead to fish kills. Higher temperature also means a higher probability for cyanobacteria blooms.

Temperature will increase all over Queensland. It is thus expected that problems caused by an increase in cyanobacteria blooms will be a state wide change phenomenon. However increased temperature (Figure 9) and evaporation rates in the western Lake Eyre region (E) might exaggerate threats. The decrease in precipitation, mainly during the dry quarter, will determine the dry periods of arid and semi-arid lakes. It might be expected that the (non-floodplain) clay pan lakes in the western Murray-Darling region (D) will be most affected by reduced precipitation and thus inflow in the dry (see red bars in Figure 9) as well in the wet season. With a drop in water level, dry out can be the consequence.

5.3.4 Coastal and Sub-coastal lakes

Most of the coastal and sub-coastal lakes are floodplain lakes and thus depending on river flow regimes. In region E, Cape York, projections of precipitation and runoff show only small changes and the large number of lakes will probably not experience any change in its water balance. However temperature increases under high emission scenarios might lead to a change in stratification and mixing regimes, probably increasing periods of stratification and promoting decrease in oxygen levels (Figure 8). In contrast to this, lakes in the southern region B, South-East coast (C) and eastern Murray Darling region (D), will be more influenced by changes in precipitation pattern, probably receiving less water during the dry period (Figure 8). Taken the higher probability of more frequent extreme floods under climate change conditions floodplain lakes in these regions will be replenished in an irregular way and in the same time receiving higher sediment loads.

Coastal lakes, especially coastal dune lakes, might suffer from saltwater intrusion either via saline groundwater or during storm surges due to sea level rise; see also Bustamante et al. (2012) for further discussion of coastal inundation processes. This would change the ecosystems of these lakes dramatically when going from fresh to brackish water.

5.3.5 Great artesian spring wetlands

Great artesian spring wetlands are formed by artesian springs from aquifers in the arid and semi-arid zone (mainly regions D and E). Also not directly impacted by climate change, the interplay between overuse of groundwater and thus decrease in water flow rates and increasing evaporation in the arid environment leads to a big threat for the extent and existence of such wetlands and their ecosystems. Figure 9 shows the geographic distribution of active artesian spring (Fensham 2006) in relation to evaporation. Under future climate change conditions the more western spring wetlands will experience an increase in evaporation and thus the threat of drying out.

5.3.6 Rivers in the 5 drainage divisions

The projection of average annual runoff (Figure 5) – 50% percentile – shows that there is the chance of only marginal changes in the wet Cape York and Gulf regions (A) with even a possible increase and in the Murray-Darling region (D). In all other regions a relative decrease is to be expected. Changes in the lower 10% percentile show a decrease in runoff across all coastal regions. For the regions south of Cape York this is also reflected in the dry quarter precipitation projected for 2030 and 2070 (see Figure 6). The change in runoff and to some extend in precipitation during different seasons will thus have some impact on the future variability of stream flow. To highlight this Figure 12a-c show the flow regime classes in relation to dry and wet precipitation.

Flow regime classes 1-4 with high permanence and high runoff magnitude (Figure 12) are confined to regions A and C reflecting the high runoffs expected in these areas. These will not be changed significantly under climate change scenarios, always experiencing higher precipitation than the rest of Queensland.

Flow regime classes 5-8 with intermittent permanence and medium to low runoff magnitude can be found mainly in the coastal and sub-coastal (B) and south-east region (C) (Figure 12b). Again precipitation in these regions is expected to be less prone to change in the wet quarter but will receive less precipitation in the dry quarter. This might increase the intermittency of these streams during summer months having less discharge.

Flow regime classes 9-12 with highly to extremely (regime class 12) intermittent flow are distributed over all of Queensland (Figure 12c). A decrease in precipitation will mainly affect flow regime classes 11 and 12 decreasing flow rates and increasing intermittency, most probably in the arid regions.

Lower mean annual flows in some drainage basins and decrease in discharge during the dry quarter will in some cases lead to a decrease in connectivity in river stretches and pools, more likely in the arid and semi-arid regions (E, D). Higher probability of more frequent and intense precipitation events with associated large runoff will lead to more frequent inundation of floodplain wetlands and thus increased biological activity. It will have negative effects on marine ecosystems due to the increased sediment and nutrient transport (see Bustamante *et al.* 2012).

6. ADAPTATION OPTIONS FOR FRESHWATER BIODIVERSITY UNDER CLIMATE CHANGE

6.1 Current management of freshwater biodiversity

In Queensland, freshwater biodiversity is managed under a raft of legislation, the main ones being the *Wild Rivers Act 2005*, *Water Act 2000*, the *Environmental Protection Act 1994*, the *Fisheries Act 1994*, and the *Nature Conservation Act 1992* (Kroon *et al.* 2004). A range of other legislation affects Queensland's freshwater biodiversity and ecosystems, including the *Agricultural and Veterinary Chemicals (Queensland) Act 1994*, the *Agricultural Chemical Distribution Control Act 1966*, the *Canals Act 1958*, the *Coastal Protection and Management Act 1995*, the *Forestry Act 1959*, the *Lake Eyre Basin Agreement Act 2001*, the *Land Act 2003*, the *Murray-Darling Basin Agreement 1992 / Murray-Darling Basin Act 1996*, the *National Environmental Protection Council (Queensland) Act 1994*, the *Tweed River Entrance Sand Bypassing Project Agreement Act 1998*, and the *Wet Tropics World Heritage Protection and Management Act 1993* (see Kroon *et al.* 2004).

The main Commonwealth legislation affecting Queensland's freshwater biodiversity is the *Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth). Here, we provide a brief summary of each of the main pieces of legislation, based primarily on Kroon et al. (2004).

The *Wild Rivers Act 2005* is administered by the Department of Environment and Resource Management (DERM), and provides for the preservation of the natural values of rivers that have all, or almost all, or their natural values intact (Table 4). The purpose is to be achieved mainly by establishing a framework that includes the declaration of wild river areas that will or may include the following: (i) high preservation areas; (ii) preservation areas; (iii) floodplain management areas; (iv) subartesian management areas. So far, a total of 10 river basins have been declared, namely Staaten, Settlement, Morning Inlet, Hinchinbrook, Gregory, Fraser, Lockhart, Stewart, Archer and Wenclock Basin Wild River Declarations, and one is currently being proposed for declaration (Cooper Creek Basin).

The *Water Act 2000* is administered by DERM, and provides for the sustainable management of water and other resources, a regulatory framework for providing water and sewerage services and the establishment and operation of water authorities. It is the main legislation for water quantity in freshwater and groundwater, setting out information needs and requirements for Water Resource Plans, Resource Operation Plans, Water Use Plans, licensing and permits, and riverine protection, at a State and catchment scale (Table 4). Resource Operation Plans have been finalised and Water Resource Plans implemented in most Queensland's catchments as well as for the Great Artesian Basin, with amendments and reviews underway in some of these (DERM 2011d). It also stipulates needs and requirements for water quality (mainly salinity) of surface and groundwater for Water Resource Plans, Resource Operation Plans, Water Use Plans, licensing and permits, and riverine protection at a catchment scale. In the development of these plans, DERM (2009) applies the concept of environmental flows which 'support the diversity of species and processes in aquatic ecosystems and maintain habitat conditions and river channel shape'. Under the *Water Act 2000*, an environmental flow objective, for a Water

Resource Plans means ‘a flow objective for the protection of the health of natural ecosystems for the achievement of ecological outcomes’.

Under the *Environmental Protection Act 1994*, administered by DERM, the *Environmental Protection (Water) Policy 2009* (EPP Water 2009) and the *Environmental Protection Regulation 2008* (EPR Act) seek to protect Queensland’s waters while allowing for development that is sustainable. Under the framework provided by the National Water Quality Management Strategy, the *Environmental Protection (Water) Policy 2009* provides for (i) identifying environmental values for Queensland waters, (ii) deciding and stating water quality guidelines and objectives to enhance or protect the environmental values, (iii) making consistent and equitable decisions about Queensland water that promote efficient use of resources and best practice environmental management, and (iv) involving the community through consultation and education, and promoting community responsibility (Table 4).

Environmental values and water quality guidelines and objectives have been established and scheduled for South-East Queensland, Mary Great Sandy region, most basins draining into the Great Barrier Reef, and some waters of the Murray Darling Basin (DERM 2011b). The EPR Act provides a regulatory regime for assessing and managing activities (such as industrial, commercial, mining, intensive animal and municipal operations) that cause point source pollution. To this effect, the EPR Act lists 64 Environmentally Relevant Activities (ERAs) involving environmental nuisance, including, but not limited to aquaculture, sewage treatment, extractive and screening activities, and waste disposal (DERM 2009).

The *Fisheries Act 1994* is administered by the Department of Employment, Economic Development and Innovation (DEEDI), and provides for the management, use, development and protection of fisheries resources and fish habitats and the management of aquaculture activities. The purpose of this Act is to provide for the use, conservation and enhancement of the community’s fisheries resources and fish habitats in a way that seeks to (a) apply and balance the principles of ecologically sustainable development, and (b) promote ecologically sustainable development (Table 4).

The *Nature Conservation Act 1992* is administered by DERM, and provides for the conservation of nature. The conservation of nature is to be achieved by an integrated and comprehensive conservation strategy for the whole of Queensland.

The Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* provides a national framework for environment protection, through a focus on protecting matters of national environmental significance and on the conservation of Australia's biodiversity. The EPBC Act is relevant for State Agencies in case of (i) “Matters of national environmental significance” and (ii) “Bilateral Agreements”. For Queensland State Agencies, “Matters of national environmental significance” include (i) World Heritage Properties (Great Barrier Reef, Fraser Island, Wet Tropics of Queensland, Central Eastern Rainforest Reserves, and Australian Fossil Mammal Site – Riversleigh), (ii) Ramsar wetlands of international significance (Bowling Green Bay, Shoalwater and Corio Bay, Great Sandy Strait, Moreton Bay, and Currawinya Lakes), (iii) Nationally listed threatened species and ecological communities, and (iv) Listed migratory species.

6.2 Management objectives for freshwater biodiversity

Currently, proposed management of freshwater biodiversity is outlined in the Queensland's draft biodiversity strategy (DERM 2010a). The two primary goals of the strategy are:

- Reverse the decline in biodiversity;
- Increase the resilience of species, ecosystems and ecological processes.

To achieve these two goals, the strategy has three primary objectives with key outcomes:

- Building protected areas on public and private land to provide sound foundations for landscape resilience, and to connect Queenslanders with nature;
- Conserving species to provide greater protection for species and their habitats, and to stabilize or recover at risk species populations;
- Managing the extent, condition and connectivity of natural environments to build ecological integrity and landscape resilience in the presence of climate change and other stressors.

The strategy includes a further three supporting objectives which outline an adaptive management framework for biodiversity conservation outcomes through building knowledge, managing responsively and valuing biodiversity. Each objective has associated strategies for implementation, with targets set for 2020 for the first two primary objectives, and non-time bound targets for the third primary objective.

6.3 Managing freshwater biodiversity and ecosystems under climate change

In Queensland, the impacts of climate change on freshwater ecosystems over the next 20 years or so are likely to compound the current threats to freshwater biodiversity. Our analysis suggests that out of the five main threats, widespread and extensive modification of water flows and hydrology has had detrimental impacts on Queensland's freshwater biodiversity and ecosystem services in particular. Overexploitation, water pollution, habitat destruction and invasion by non-native species (Dudgeon *et al.* 2006; Malmqvist & Rundle 2002) have also left their mark on Queensland's freshwater biodiversity (Environmental Protection Agency 2008). Hence, at least at this time-scale, climate adaptation options need to be considered in the context of the current main threats. In the longer term, the impacts of climate change on Queensland's freshwater ecosystems are likely to supersede those of current threats. Given that the response of freshwater biodiversity to climate change may not be observed for several years or decades due to time lags, adaptation needs to occur early and over similarly long timescales to ameliorate potentially wide-ranging effects on biodiversity and ecosystem services (Malmqvist *et al.* 2008).

Here, we outline climate adaptation options for freshwater biodiversity that address the goals and objectives of the Queensland draft biodiversity strategy (DERM 2010a), whilst acknowledging current threats and specific ecological change phenomena under climate change. Rather than being comprehensive, we propose some specific examples under current legislation that may assist in thinking through the development of adaptation options. In doing so, we acknowledge that existing policy frameworks are not set up to address climate change impacts specifically, and using them “to meet the challenge posed by climate change could lead to the same systemic problems that hare pervaded the management of non-climate change threats” (Boer 2010). However, developing new policy frameworks to address climate change impacts on freshwater biodiversity is beyond this project.

6.3.1 Protection and rehabilitation of flow regime

In Queensland’s wetlands, modifications of flow regimes due to a combination of water resource development and climate change are likely to have the greatest impact on freshwater biodiversity and ecosystem services. According to Kingsford (2011), “protection and rehabilitation of flow regimes represents the greatest challenge for conservation of most rivers and wetlands”.

Queensland is one of the few areas in the world with free-flowing rivers and tributaries, including rivers in the north-east of the Coastal and sub-coastal, the Cape and Gulf, and Lake Eyre and Bulloo Climate Change Divisions (Figure 1). These rivers are expected to be more resilient in the face of climate change than regulated rivers (Palmer *et al.* 2008). However, the level of resilience in free-flowing rivers may vary and depend on the local and regional environmental changes across the difference Divisions. Protection of these rivers from future development is likely to increase the opportunity for these freshwater ecosystems to remain resilient in response to future changes. In Queensland, the declaration of river systems as a ‘Wild River Area’ under the *Wild River*s *Act 2005* (Qld) is providing a relatively strong climate adaptation tool (Boer 2010). Such declarations protect rivers from clearing or draining of wetlands or construction of in-stream dams and weirs. Boer (2010) reports that declarations could also “be used to protect ecosystems that provide important climate change refugia for aquatic species”.

In Queensland, water resource planning and management is conducted in Water Resource Plans and Resource Operation Plans under the *Water Act 2000*. In the development of these plans, DERM (2009) applies the concept of environmental flows, considering the needs of specific plants and species, types of river habitat, and where relevant, groundwater dependent ecosystems. Whilst not defined as a specific amount of water that is reserved for a river, environmental flows do refer to specific characteristics of flow regime, including frequency, timing, magnitude and duration (see also Poff *et al.* 1997). To provide greater flexibility in the allocation of environmental flows in the face of climate change, regional, down-scaled projections of precipitation, evaporation and stream flow are needed to guide future water resource planning, allocations and management (Boer 2010). Water Resource Plans are renewed and replaced every 10 year, providing an opportunity for adaptive management of freshwater biodiversity and ecosystems in the face of climate change.

In Queensland, water-related development, such as pumps, diversion channels, weirs, dams or bores, take or interfere with water in a watercourse, lake, spring, aquifer or from overland flow. Approvals for these works are dealt with under the *Sustainable Planning Act 2009*. Moreover, artificial physical barriers to flow, such as flood mitigation, drainage structures, and extensive road, rail and cane rail networks, have been constructed since European settlement (e.g. see (Carter *et al.* 2007; Lawson *et al.* 2010; Marsden *et al.* 2006), and are dealt with under a variety of Acts. These interferences can have detrimental impacts on the health and resilience of Queensland’s freshwater ecosystems which can be further exacerbated with predicted changes in climate. To improve connectivity and protect freshwater biodiversity, provisions may need to be made on regulated rivers to adjust dam and weir operations to sustain environmental flows (Palmer *et al.* 2008). In addition, detrimental impacts could be minimised by assessing the need for these structures through a re-licensing framework (e.g., Pittock & Hartmann 2011), and removal or refurbishment of these structures (Kingsford 2011).

View across extensive coastal flood plains and estuaries to Hinchinbrook Island, northern Queensland, 1999 (credit: Gregory Heath, CSIRO Land and Water, 1999, science image BU5468).

Burdekin River south of Townsville in far north Queensland, 1992 (credit: John Coppi, CSIRO Land and Water, science image BU6526).

7. CONCLUSIONS

Freshwater biodiversity in Queensland is threatened by overexploitation, water pollution, modification of water flows and hydrology, habitat destruction and degradation, and invasion by non-native species. The predicted impacts of climate change are superimposed upon, and may eventually supersede these threats. Main impacts are likely to include (i) increased water temperature, (ii) changes in flow regime and associated reduction in water availability, (iii) inundation and salinisation of coastal freshwater ecosystems, and (iv) acidification of surface waters. Unlike the terrestrial and marine realms, the current dearth of information on ecological impacts in Queensland's freshwater ecosystems as a result of climate change makes it difficult to predict the direction and magnitude of change. However, based on the burgeoning international literature we expect that the effects of climate change on environmental variables will result in the following ecological changes. First, individual species may change their behaviour and physiology as a result of changes in temperature, hydrology, dissolved oxygen, salinity, and acidity. Species may be able to adapt, depending on habitat connectivity, move, or otherwise may go locally extinct. Next, this may have flow-on effects on overall species' abundance, distribution and resilience to climate variability, as well as to their resistance, resilience and exposure to extreme events and diseases. Associated changes in phenology will affect ecosystem productivity and nutrient status. Finally, extreme events, such as more frequent and/or intense cyclones, floods and droughts, will result in geographic changes in ecosystem types and associated changes in riverine landscape function.

To minimise the detrimental impacts of climate change on Queensland's freshwater biodiversity, the current threats to freshwater biodiversity need to be reduced in a triage based approach. Current policy frameworks, such as the *Wild Rivers Act 2005*, the *Water Act 2009* and the *Sustainable Planning Act 2009*, provide opportunities to do this, as well as to increase the resilience of freshwater ecosystems in the face of climate changes. For example, the decadal renewal and replacement of Water Resource Plans under the *Water Act 2000* enables adaptive management of environmental flows, including in the face of climate change. However, few of these frameworks address the specific challenges posed by climate change, and applying them in the context of climate change may further perpetuate the systemic problems that have characterised the management of current threats to freshwater biodiversity. To specifically deal with the large scale, long term and severe impacts from climate change, new policy and legislation may need to be developed that addresses both current threats and climate change.

Example of the impacts of bare ground on water quality, effects of cattle grazing in the Burdekin River catchment, Queensland (credit: CSIRO Land and Water, science image BU7021).

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APPENDIX 1: ECOSYSTEM SERVICES PROVIDED BY QUEENSLAND'S FRESHWATER ECOSYSTEMS

Table 1: Ecosystem services provided by Queensland's freshwater ecosystems, including rivers, lakes, wetlands and floodplains. * indicate key services from freshwater ecosystems.

Category	Ecosystem services	Contributions by Freshwater Ecosystems
Provisioning	Food and fibre*	Fisheries, Freshwater aquaculture, Cattle grazing, Rice production, Indigenous hunting and gathering
	Timber/fuel/energy*	Hydropower generation
	Freshwater*	Non-consumptive use (e.g. irrigation, cooling, mining)
	Ornamental resources	Fishing trophies, Aquaria
	Biochemicals /natural medicines	Poorly known
	Genetic resources	Poorly known
Regulating	Pollination	None
	Seed dispersal	Migration pathways for native species
	Pest regulation	Poorly known
	Disease regulation	Poorly known
	Invasion resistance	Migration pathways for non-native species
	Climate regulation*	Local and regional climates
	Air quality regulation	None
	Erosion regulation	Poorly known
	Natural hazard regulation*	Flood protection
	Water flow regulation*	Quantify and quality of water, Flood retention
	Water purification/ waste treatment*	Consumptive use (e.g. food, cooking, drinking water, sanitation)
Cultural	Spiritual and religious values	Places and associated ceremonies
	Education and inspiration*	National Parks and other protected areas, Arts
	Recreation and ecotourism*	Bathing, rafting, canoening, angling, hiking, photography, wildlife viewing
	Cultural heritage	Historical places and associated stories and songs
	Aesthetic values*	Near-natural and most diverse sections
	Sense of place*	Special or unique places
Supporting	Soil formation*	Transport and accumulation of organic matter
	Nutrient and water cycling*	Hydrological and biogeochemical processes
	Primary production*	Photosynthesis by aquatic and riparian plants

APPENDIX 2: REGIONAL VARIATION IN ENVIRONMENTAL CHANGE

Table 2: Regional variation in environmental change due to climate change based on the five freshwater aquatic regions. (+, 0, -) signify the relative strength of the impact.

Freshwater aquatic region Environmental change	A – Western Cape and Gulf	B – Coastal and sub-coastal	C – South-East coast	D – Murray-Darling	E – Lake Eyre and Bulloo
Air temperatures	+	+	+	+	+
	Rising water temperature in streams and standing waters: more stable stratification in lakes and earlier onset of stratification, longer period of stratification, reduction in oxygen levels, increased threat of cyanobacteria blooms				
Precipitation	0	0/-	0/-	-	-
		Reduced annual stream flow in rivers, reduced sediment transport			
				Lower water level in standing waters (lakes, swamps). Disruption in connectivity; increased salinity	
Runoff and streamflow	0	-	-	0/-	-
		Higher intermittency of rivers with low discharge, reduced mean discharge, increased probability of intense floods.			
Sea level rise	+	+	+	0	0
	Saltwater intrusion into coastal freshwater systems, upstream movement of tidal boundary (saline~freshwater)				
CO_2 absorption	+	+	+	+	+
	Increase in bioavailable carbon: increase in pH (depends on geochemical settings, might not be possible to relate to climate change)				
Evaporation	0/+	0/+	0/+	+	+
	Only small changes in pan evaporation in the last decades,but expected to increase with rising temperature; lower water levels				
				Drying out of swamps and shallow lakes, reduced number of spring wetlands, increased salinity	
Dissolved oxygen and nutrients	- +	- +	- +	- +	- +

Freshwater aquatic region Environmental change	A – Western Cape and Gulf	B – Coastal and sub-coastal	C – South-East coast	D – Murray-Darling	E – Lake Eyre and Bulloo
	Decrease in oxygen levels in the bottom layers of stratified lakes and streams, changes in nutrient levels non-conclusive possibly increasing				
Biogeographic settings	0	+	0	+	
		Increase in stream connectivity during flood pulses; vanishing of coastal freshwater systems due to sea water intrusion		Decrease in stream connectivity and vanishing of standing waters during droughts.	
Extremes: Cyclonic activity	+	0/+	0	0	0
	Wind forced alteration of mixing regimes of stratified lakes; pulses of sediment resuspension associated with increased nutrient release				
Extremes: Heat waves	+	+	+	+	+
	Increased surface temperature and stability of stratified lakes, temperature increase in streams, often associated with decrease in oxygen levels, increase in evaporation and associated decrease in water level				
Extremes: Drought	0	+	+	+	+
		Decrease of water level in standing waters (lakes, ponds, wetlands); drying out of small ponds, wetlands; salinisation of freshwater systems; reduction in stream flow, decrease in sediment and nutrient transport; disruption in connectivity			
Extremes: Floods	+	+	+	+	+
	Increased flow velocity, increased river bed erosion, higher transport of sediment and nutrients, Increased connectivity during flood pulses; high nutrient availability in floodplains				

APPENDIX 3: QUEENSLAND WETLAND GROUPS

Table 3: Queensland wetland groups (lacustrine, palustrine, and riverine) used in this report.

ID	Wetland type
1	Coastal/ Sub-Coastal saline swamps
2a	Coastal/ Sub-Coastal non-floodplain tree swamps (Melaleuca and Eucalypt)
2b	Coastal/ Sub-Coastal non-floodplain wet heath swamps
2c	Coastal/ Sub-coastal non-floodplain grass, sedge and herb swamps
3	Coastal/ Sub-Coastal non-floodplain (spring) swamps
4a	Coastal/ Sub-coastal floodplain tree swamps (Melaleuca and Eucalypt)
4b	Coastal/ Sub-Coastal floodplain wet heath swamps
4c	Coastal/ Sub-coastal floodplain grass, sedge and herb swamps
5	Coastal/ Sub-Coastal tree swamps (palm)
6	Coastal/ Sub-coastal floodplain lakes
7	Coastal/ Sub-coastal non-floodplain rock lakes
8a	Coastal/ Sub-coastal non-floodplain sand lakes (Window)
8b	Coastal/ Sub-coastal non-floodplain sand lakes (Perched)
9	Coastal/ Sub-coastal non-floodplain soil lakes
10	Arid/ Semi-arid saline swamps
11a	Arid/ Semi-arid floodplain tree swamps
11b	Arid/ Semi-arid floodplain lignum swamps
11c	Arid/ Semi-arid floodplain grass, sedge, herb swamps
12a	Arid/ Semi-arid non-floodplain tree swamps
12b	Arid/ Semi-arid non-floodplain lignum swamps
12c	Arid/ Semi-arid non-floodplain grass, sedge, herb swamps
13	Arid/ Semi-arid non-floodplain (spring) swamps
14	Arid/ Semi-arid saline lakes
15	Arid/ Semi-arid fresh floodplain lakes
16a	Arid/ Semi-arid fresh non-floodplain lakes
16b	Arid/ Semi-arid fresh non-floodplain lakes - claypans
40	Artificial/ highly modified wetlands (dams, ring tanks, irrigation channels, drains, canals)

APPENDIX 4: FRESHWATER BASINS AND PROJECTED CLIMATES

Current and future projected climate under low and high emission scenarios (A1B and A1FI).

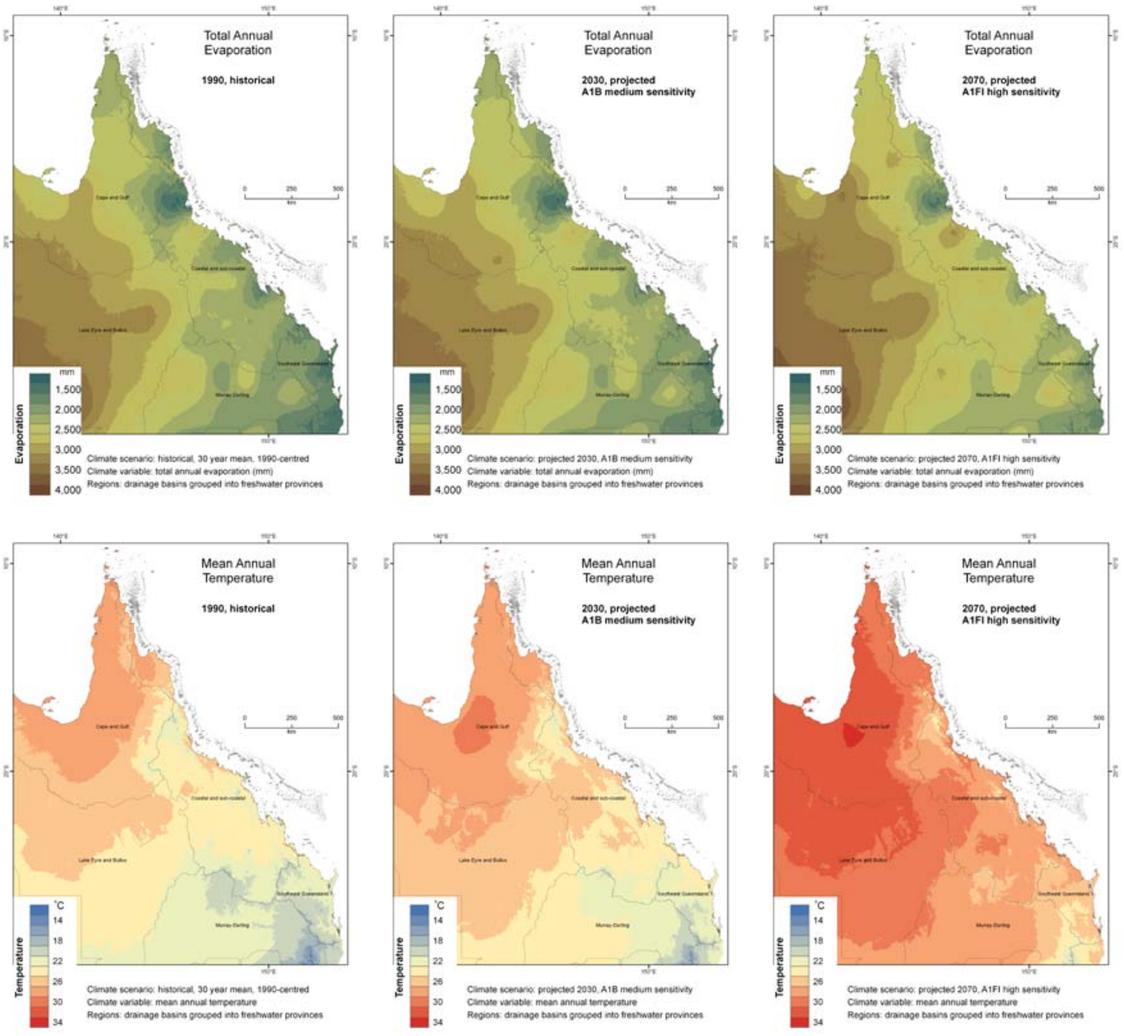

Figure 6: Current and future projected climate under low and high emission scenarios (A1B and A1FI) given for mean annual temperature (first row), mean annual evaporation rates (second row), mean precipitation rates for the dry season, JJA (third row) and the wet season, DJF (fourth row). Emissions scenarios and climate projections relevant to this report are described in Williams and Crimp (2012). Continued over page

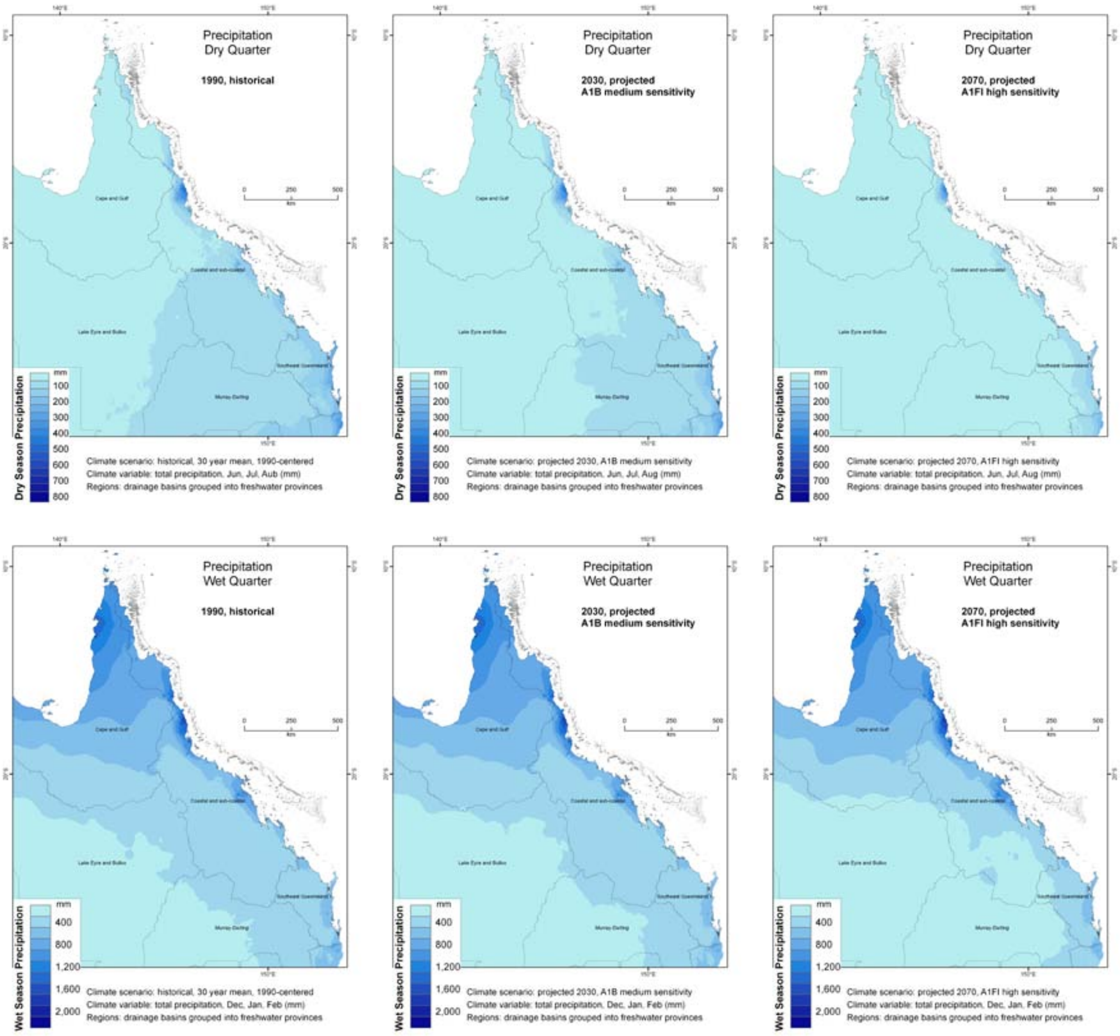

Figure continued from previous page: Current and future projected climate under low and high emission scenarios (A1B and A1FI) given for mean annual temperature (first row), mean annual evaporation rates (second row), mean precipitation rates for the dry season, JJA (third row) and the wet season, DJF (fourth row). Emissions scenarios and climate projections relevant to this report are described in Williams and Crimp (2012).

APPENDIX 5: DISTRIBUTION OF LAKES AND SWAMPS AND PROJECTED CLIMATES

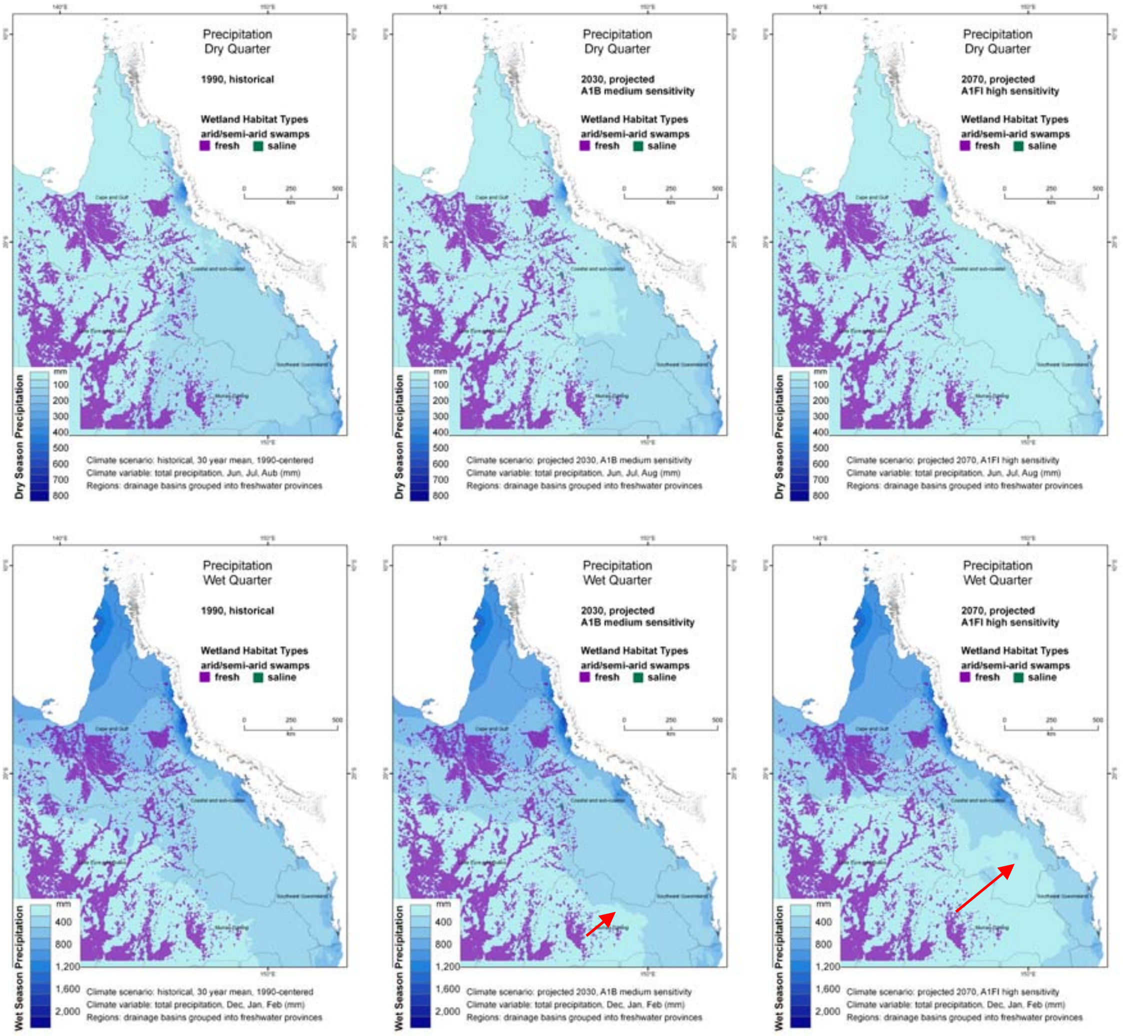

Figure 7: Distribution of arid and semi-arid swamps in relation to dry and wet quarters of precipitation. Red arrows indicate regions of possibly larger changes or shifts in wetland types.

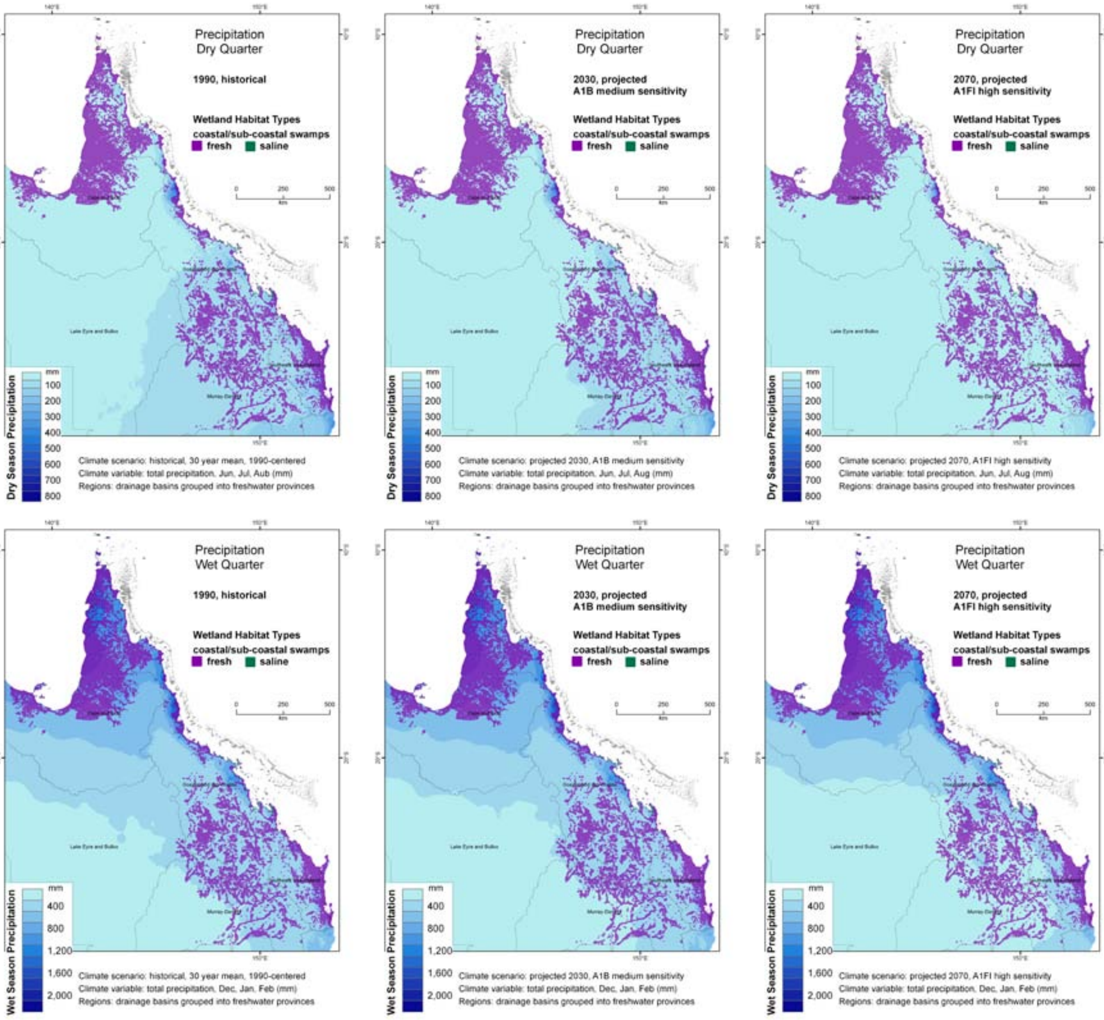

Figure 8: Distribution of coastal and sub-coastal swamps in relation to dry and wet quarters of precipitation. Bars indicate regions of possibly larger changes or shifts in wetland types.

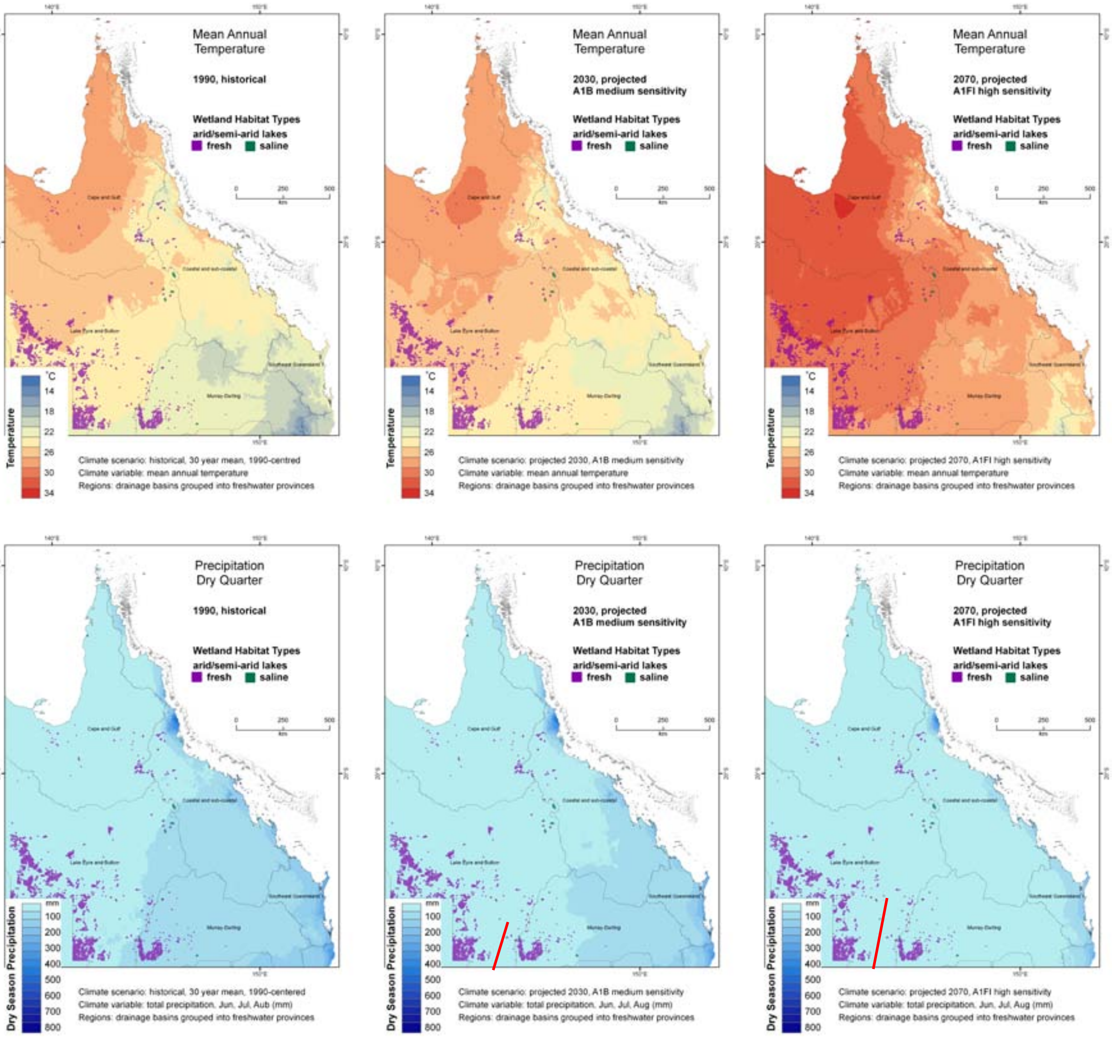

Figure 9: Distribution of arid and semi-arid lakes in relation to temperature and dry quarter of precipitation. Bars indicate regions of possibly larger changes or shifts in wetland types. Red bars indicate the regions to the west that might be expected to be most affected by reduced precipitation and thus water inflow in the dry.

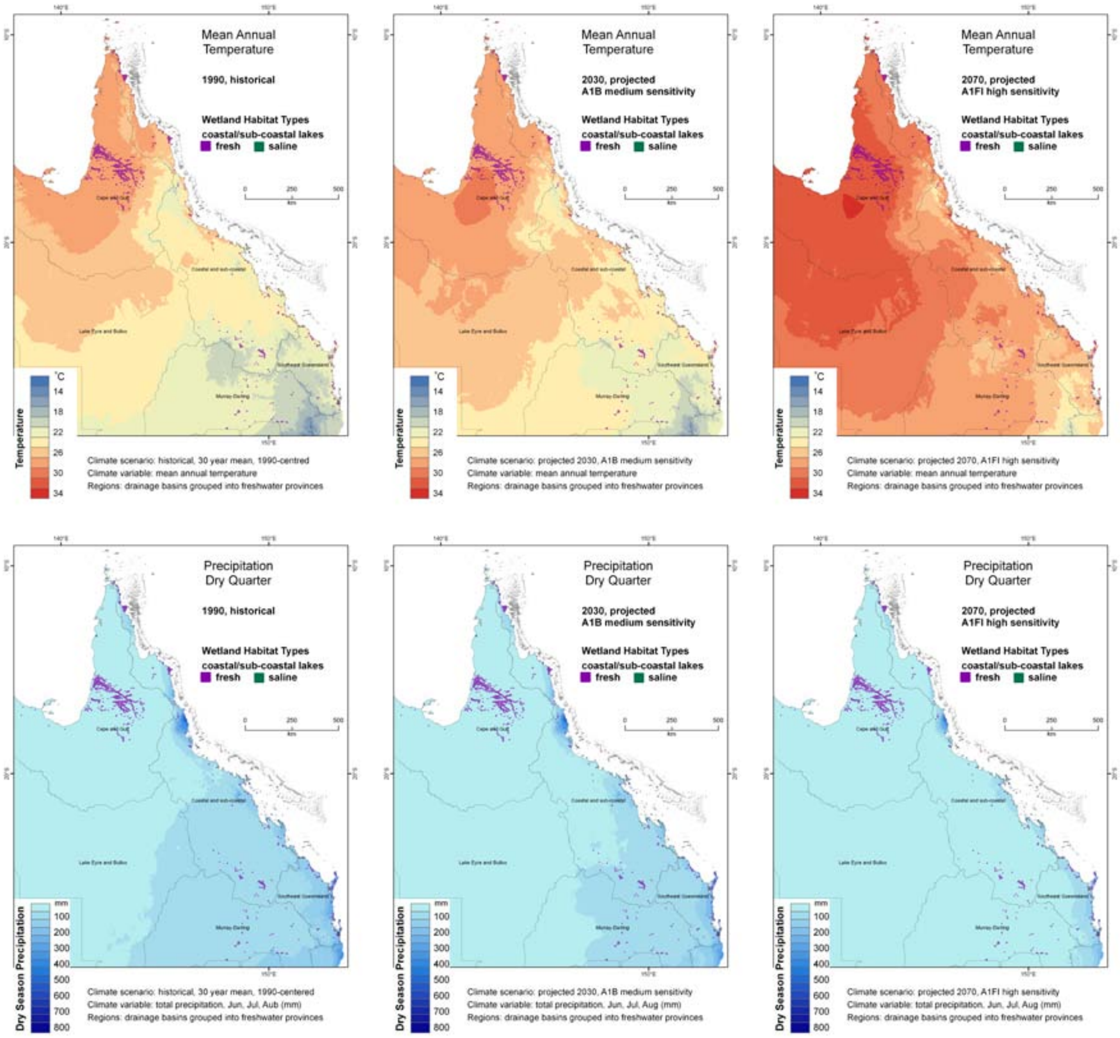

Figure 10: Distribution of coastal and sub-coastal lakes in relation to temperature and dry quarter of precipitation. Bars indicate regions of possibly larger changes or shifts in wetland types.

APPENDIX 6: ARTESIAN SPRING WETLANDS AND EVAPORATION

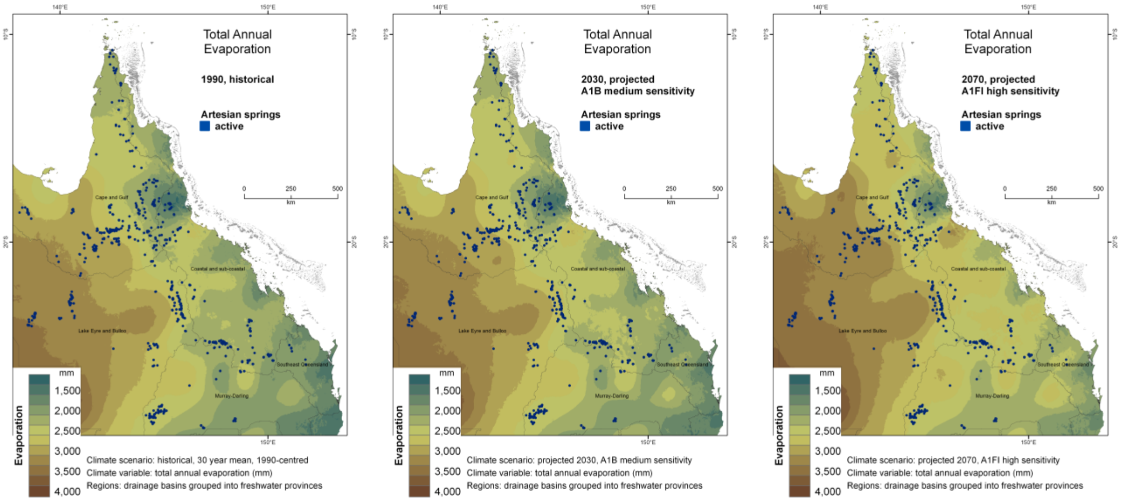

Figure 11: Geographic distribution of artesian springs in relation to evaporation (Fensham 2006).

APPENDIX 7: STREAM FLOW REGIME CLASSES AND PROJECTED RAINFALL

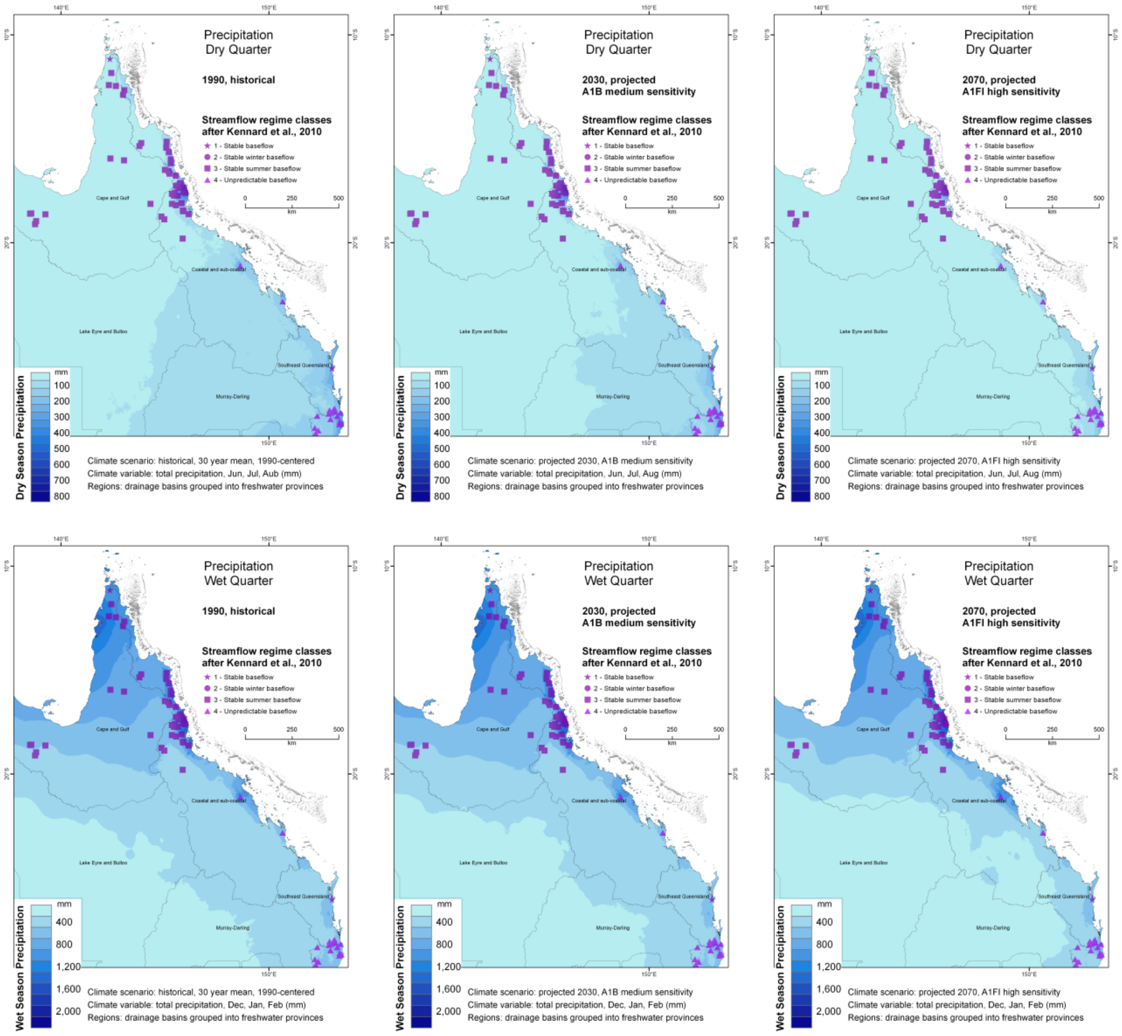

Figure 12: Distribution of flow regime classes for 191 gauges in Queensland in relation to dry and wet quarters of precipitation. a) Flow regime classes 1-4 with high permanence and runoff magnitude. Figure b) and c) continued over page.

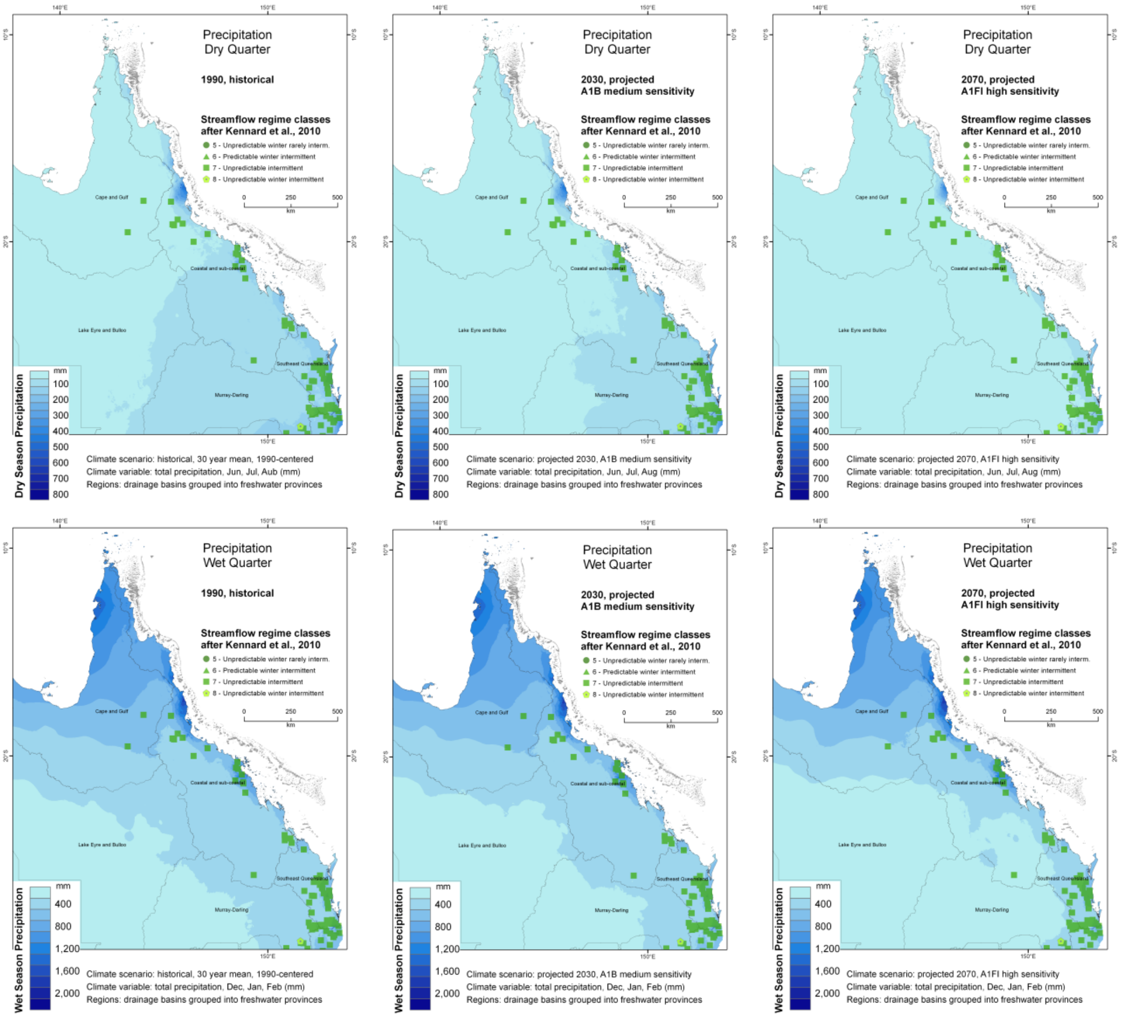

Figure continued from previous page: b) Flow regime classes 5-8 with intermittent permanence and medium to low runoff magnitude. Figure c) continued over page.

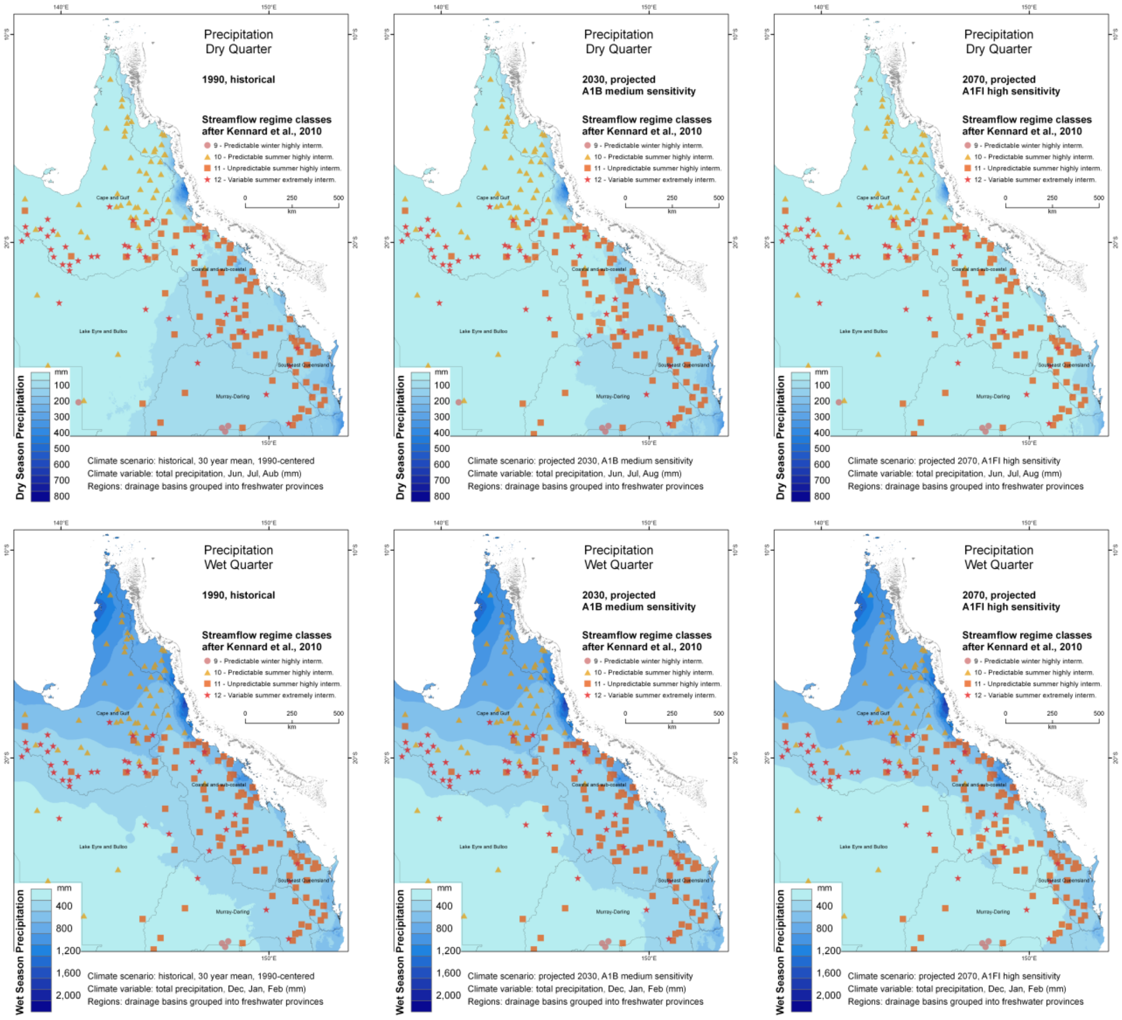

Figure continued from previous page: c) Flow regime classes 9-12 with highly to extremely (regime class 12) intermittent flow.

APPENDIX 8: STATE AND FEDERAL LEGISLATION PROTECTING QUEENSLAND'S FRESHWATER BIODIVERSITY VALUES

Table 4: Examples of current initiatives under key State and Federal legislation for protecting Queensland's freshwater biodiversity values.

Biodiversity values (reverse declines and build resilience)	Species	Ecosystems	Landscapes
Species (individuals, populations and meta-populations) *Nature Conservation Act 1992; Environment Protection Biodiversity Conservation Act 1999 (C'wlth)*	Species Conservation and Management Plans (e.g. stream dwelling rainforest frogs of the Wet Tropics region); Convention on Conservation of Nature in the South Pacific (1976); Convention on Biological Diversity (1992); Convention on the Conservation of Migratory Species of Wild Animals (1979); Japan-Australia Migratory Bird Agreement (JAMBA, 1981); China-Australia Migratory Bird Agreement (CAMBA, 1988); Republic of Korea-Australia Migratory Bird Agreement (ROKAMBA, 2007).	Convention for the Protection of the Natural Resources and Environment of the South Pacific (SPREP Convention) (1986); Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention) (1971).	Convention on the Conservation of Nature in the South Pacific (Apia Convention, 1986); Convention for the Protection of World Cultural and Natural Heritage (1972).
Ecosystems (communities and assemblages of species, meta-communities) *Fisheries Act 1994*	Fisheries management plans.	Fisheries management plans; Declaration of fish habitat areas.	
Ecological processes (natural systems, landscapes and regions) *Wild Rivers Act 2005; Water Act 2000; Environmental Protection Act 1994*	Environmental flow objectives; Environmental values; Water quality guidelines and objectives.	Environmental flow objectives; Environmental values; Water quality guidelines and objectives.	Declaration of wild river areas; Water Resource Plans, Resource Operation Plans, Water Use Plans; Environmental Protection Policies (Water).

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