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Climate Change Impacts on Wetlands in Victoria and Implications for Research and Policy

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Front cover photo: Wetland in Wimmera, Western Victoria (Phil Papas)

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Summary

There is growing scientific evidence that human-induced climate change is occurring. Victoria's climate is among the driest and most variable globally, and drought is a recurring event. Ecosystems in Victoria are particularly vulnerable to climate change. Victoria has experienced rising temperatures and declining rainfall since 1950, culminating in severe and prolonged drought since 1997. This report assesses the impacts of climate change on wetlands in Victoria and identifies critical areas where further research is required. It also discusses policy implications.

Wetlands are among Victorian ecosystems most vulnerable to climate change. The most pronounced effects on wetlands will be altered hydrological regimes and more frequent or intense extreme weather events (heatwaves, droughts, storms and floods). Low-lying coastal wetlands and shallow wetlands that rely on direct precipitation are most likely to be affected by climate change. A future hotter and drier climate may reduce many wetlands in size, convert some wetlands to dry land, or shift one wetland type to another. Climate change and rising sea levels will likely lead to a significant loss and degradation of wetlands and associated biodiversity in Victoria.

The research needs are in five critical areas: (1) analysing and projecting wetland threats; (2) predicting wetland response; (3) assessing wetland vulnerability; (4) understanding wetlands in the landscape; and (5) supporting management decisions. The report proposes a multi-tiered development of models to assist policy and management decision-making, depending on available knowledge, information and data and the types of questions being driven by policy and management. The proposed modelling framework allows the critical research areas above to be prioritised, given different levels of enquiry.

There needs to be a value shift towards a true sustainable development for mitigating against and adapting to climate change, as economic prosperity and human health and wellbeing rely on healthy natural systems. The management of wetlands must take into account the inevitable impacts of climate change. The past century is no longer a reasonable guide to the future for wetland policy and management. It is important to recognise the important role of wetlands in climate change mitigation and adaptation. Their management must integrate adaptation strategies (actions that help ecosystems accommodate changes adaptively) and mitigation strategies (actions that reduce anthropogenic influences on climate) into overall plans. Science underpins informed policy, and the urgency, severity and complexity of the problems demand an increased focus on climate change impacts and adaptation research on wetlands.

Wetland policy and management should not be based solely on predicting climate change impacts and then developing a response. In the areas where scientific understanding is limited and unpredictability or large uncertainties remain, precautionary measures need to be taken at both the local and the landscape scale. Policies need to consider the connectedness and interdependence of natural systems with human systems. Human systems have to become much more adaptable in the face of climate change. A 'whole of government' approach to integrated environmental, economic, political and social policy, planning and service delivery should be established.

1 Introduction

Earth's climate has varied naturally throughout its history, with cycles of warming and cooling. However, there is growing scientific evidence that human-induced climate change, primarily through increases in greenhouse gas concentrations resulting from burning fossil fuels and deforesting large areas of land, is occurring (Solomon et al. 2007). Changes in the long-term climate will be superimposed on large daily, seasonal and yearly variability, leading to significant changes in extreme weather events. As greenhouse gases introduced into the atmosphere today will remain there for hundreds of years before being removed by natural processes, their warming influence would continue for centuries even if greenhouse gas concentrations were to be stabilised. Consequently, we are already committed to further warming (Wigley 2005), and anthropogenic climate change is inevitable. Future changes in climate may be rapid compared to historical changes (Solomon et al. 2007), and the climate system appears to be changing faster than earlier thought likely (Steffen 2009).

Anthropogenic climate change is having a significant impact on physical and biological systems globally (Parmesan and Yohe 2003; Root et al. 2003; Parmesan 2006; Rosenzweig et al. 2008). In Australia, signs of the impact of recent climate change are already evident in a variety of species and ecosystems (Hughes 2003; Hennessy et al. 2007). Some of the most obvious biological changes are the timing of biological events and large-scale shifts in the geographic ranges of species. Lentic and lotic ecosystems were considered to be most sensitive to land use change, exotic species, and climate change in a global-scale assessment (Sala et al. 2000). Of all ecosystems, freshwater aquatic ecosystems appear to have the highest proportion of species at risk of extinction by climate change (Millennium Ecosystem Assessment 2005). Not least because of their higher sensitivity to climate change and limited capacity for adaptation (Carpenter et al. 1992; Firth and Fisher 1992; Lake et al. 2000; Lodge 2001; Poff et al. 2002; Millennium Ecosystem Assessment 2005), coastal and inland wetlands have been identified as among the ecosystems most vulnerable to climate change worldwide (Bates et al. 2008) and in Australia (Hennessy et al. 2007). Furthermore, climate change is only one way in which the environment and human activities are affecting wetlands. Victorian wetlands are already at risk of loss and degradation due to pressures arising from natural processes and human activities such as drought, drainage, altered water regime and salinisation. Climate change is superimposed onto these non-climatic pressures on wetlands (Schindler 2001; Wrona et al. 2006).

Victoria's climate is among the driest and most variable, globally. Drought is a recurring event. People and ecosystems in Victoria are particularly vulnerable to climate change. Victoria has already experienced rising temperatures and declining rainfall since 1950, culminating in severe and prolonged drought since 1997 (Gallant et al. 2007; Bond et al. 2008; Murphy and Timbal 2008). These changes in climate are at least partly attributable to anthropogenic forcing (Karoly and Braganza 2005a,b; Nicholls 2006; Murphy and Timbal 2008; Steffen 2009) and are likely to persist (Suppiah et al. 2007; Pitman and Perkins 2008). Impacts from climate change are inevitable in the decades ahead, and wetlands are among the ecosystems most at risk in Victoria. Understanding the impacts of climate change on Victoria's wetlands is essential to adapting to climate change and to making good planning decisions about our wetlands into the future. This report aims to assess the impacts of climate change on wetlands in Victoria in the light of the scientific literature, identify critical areas where further research is required, and discuss policy implications.

2 Climate and wetlands

In this report wetlands are defined as areas that have permanently or temporarily shallow lentic water, or that have soil that is saturated at or near the surface. They include lakes, estuaries, mudflats, shores and bays. Wetlands depend on, are shaped by, and affect climate. Climate and wetlands are interconnected in complex ways, and any change in either can induce a change in the other.

Climate has an overall role in controlling physical, chemical and biological processes and species composition in ecosystems, affecting their ecological structure, function and biodiversity. Significant and persistent changes in both the mean and the variability of climate variables determine the impacts of climate change on wetlands. They range from the direct effects of the changes in climatic variables (e.g., temperature, precipitation and drought) to indirect effects through interactions with non-climatic drivers (e.g., land and water use, species interactions, and disturbances such as bushfire, salinisation, eutrophication and acidification). Indirect effects of climate change may be equally as important as direct effects. Responses of wetland ecosystems to changes in climate involve complex interactions of biotic and abiotic components and processes and their landscape context. The responses of wetlands to climate change are a result of a balance between changes in water regime, temperature, nutrient cycling, physiological acclimation and community reorganisation (Oechel et al. 2000). Furthermore, climate change will not be the same in different regions of Victoria. As a result, wetland responses will depend on location, wetland type and local conditions.

Wetland ecosystems are fundamentally linked to hydrology, which creates the physico-chemical conditions that make them different from well-drained terrestrial or fully aquatic deepwater systems (Mitsch and Gosselink 2000). Thus wetlands are naturally sensitive to changes in hydrology. Climate change and variability are the biggest factors affecting water availability and reliability (DSE 2008a). The ecological consequences of climate change on wetlands will depend largely on changes in hydrological regime and water quality. The most pronounced effects will occur through altered hydrological regimes and more frequent or intense extreme weather events (heatwaves, droughts, storms and floods) (Bates et al. 2008).

Conversely, changes in wetland ecosystems can modify energy, water, and gas fluxes and so affect climate. Earth's climate is a result of complex interactions between the solar, oceanic, terrestrial, aquatic, atmospheric, and living components that make up the planet Earth's system. Wetlands play two important roles in ecosystem feedbacks to climate: as sinks and sources of greenhouse gases, and as regulators of climate.

Besides water vapour, the greenhouse gases—carbon dioxide (CO_2), methane (CH_4), tropospheric ozone (O_3) and nitrous oxide (N_2O)—contribute approximately 60%, 20%, 10% and 6% to global warming, respectively; a minor contribution is made by chlorofluorocarbons and volatile organic compounds (Dalal and Allen 2008). Wetlands are among the most important, but also the most complex, biomes in relation to the balances of carbon and greenhouse gases (Lloyd in prep.). They are different to other biomes in that they have the ability to sequester large amounts of carbon in their waterlogged soils. In fact, they are net sinks for carbon dioxide and provide the largest below-ground stores of carbon. This is a consequence of a high primary production and the eventual deposition of dead and decaying litter in the anaerobic region of the soil, where the normal production of carbon dioxide during decomposition is slowed or completely inhibited by the lack of oxygen, especially in cold conditions. However, methane produced in these anaerobic conditions in wetlands contributes 22% of the annual methane flux to the atmosphere (Harriss and Frolking 1991). It is the interplay between waterlogging, high plant productivity, sequestration of carbon in the soil, and production of carbon dioxide and methane that make some types of wetlands (e.g., peatlands) among the most important terrestrial surfaces in relation to climate change (Lloyd in prep.).

The potential net contribution to global warming from wetlands is very large, primarily due to methane emissions (Dalal and Allen 2008). Furthermore, wetlands that are dried can become a net source of carbon dioxide (but with possible reduction of methane), serving as a positive feedback to global warming (Burkett and Kusler 2000). But different wetland types have markedly different greenhouse gases and carbon balances. The role that wetlands will play in the global picture of carbon storage and methane emissions in the future is very uncertain and the processes involved are complex.

Because water vapour is released into the atmosphere from wetlands by transpiration and evaporation, wetlands influence climate through evaporative cooling, cloud formation, and precipitation. Wetlands also have a significant role in the hydrological cycle of whole catchments (Bullock and Acreman 2003). For example, the draining of large wetlands may cause changes in moisture recycling and a decrease of precipitation in particular months, when local boundary conditions dominate over the large-scale circulation (Kanae et al. 2001).

3 Wetlands in Victoria

The climate of Victoria is characterised by a range of different climate zones. Annual rainfall, for example, ranges from very low in the hot, dry wheat belt of the Wimmera and Mallee in the west to very high in the cool wet temperate climate of the eastern highlands (Figure 1). There are also extensive semi-arid plains with low rainfall in the west of the state. There are approximately 16 700 non-flowing wetlands over one hectare in area in Victoria, totalling 540 900 hectares. Of these 12 800 (covering 432 800 hectares) are natural and 3900 are artificial.

Victorian wetlands vary greatly in character and distribution (Environment Australia 2001). They range from alpine bogs and mossbeds, riverine wetlands, fresh and saline lakes and salt pans, costal estuaries and mudflats, shores and bays to human-made impoundments, sewage ponds and farm dams. Wetlands are distributed unevenly across the landscape in Victoria. Large freshwater wetlands occur along the lower reaches of rivers discharging into the Gippsland Lakes. Numerous smaller wetlands are found in south-west Victoria, where there are extensive areas of shallow freshwater marshes and meadows. The majority of riverine wetlands occur along the Murray and Goulburn Rivers in northern Victoria. Significant artificial wetlands occur at current or former saltworks sites near Melbourne and Geelong, and at sewage treatment plants servicing Melbourne.

Different wetland types characterise different landscapes. Freshwater meadows are very common in the Glenelg Hopkins and Wimmera Catchments. Shallow and deep freshwater marshes also occur in these areas and in the Gippsland Plain bioregion. Saline wetlands are a feature of the southern Victorian Volcanic Plains (where non-volcanics intersect the new volcanics) and the Wimmera River, Mildura, Lake Tyrrell and Kerang areas.

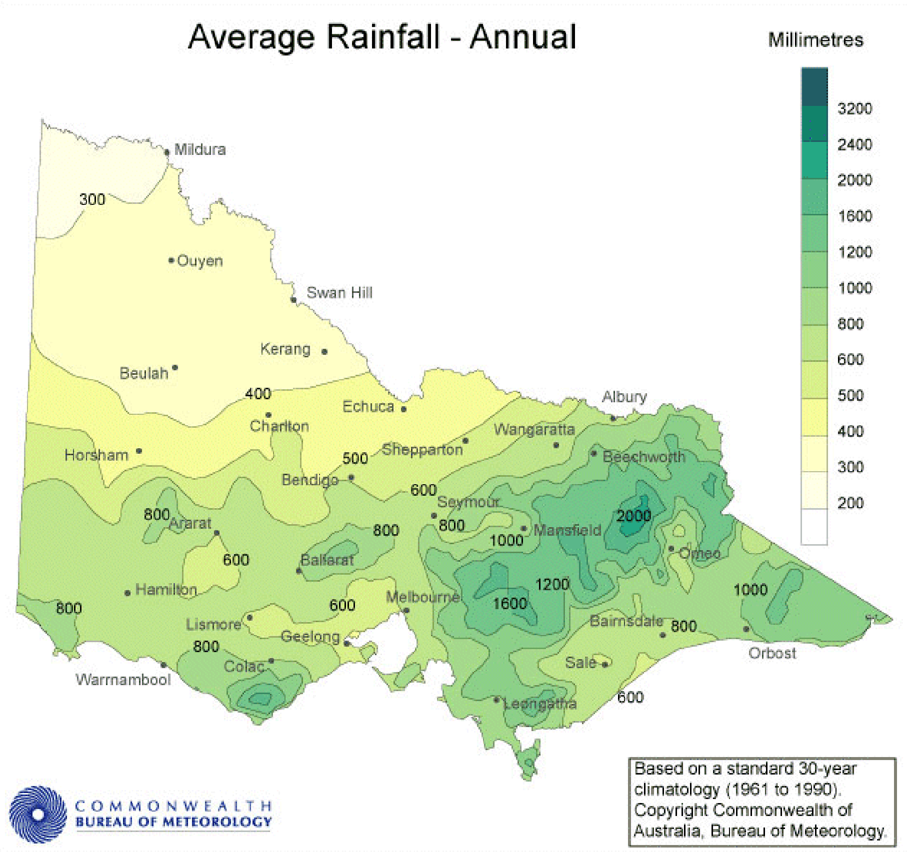

Figure 1. Annual rainfall in Victoria (30-year average). Source: Bureau of Meteorology

4 Regional climate projections

CSIRO and the Bureau of Meteorology have projected regional changes in a wide range of climate variables from the results of 23 climate models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Solomon et al. 2007) and different IPCC scenarios for greenhouse gas emissions (Pearce et al. 2007). Regional projections of climate change for Victoria are given by CSIRO for 2030 and 2070, relative to the period 1980–1999, under three emissions scenarios (DSE 2008b).

The greenhouse gas emissions scenarios, which project emissions growth from 1990 to the end of the 21st century, consider a range of assumptions about demographic change, economic growth and technological developments likely to influence future emissions. Three different emissions scenarios have been used to calculate climate projections: low, medium and high emissions scenario. Uncertainties in projected regional climate change in 2030 are mostly due to differences between the results of the climate models rather than the different emissions scenarios. Beyond 2030, the magnitude of projected climate changes is much more strongly affected by emissions. Results of recent emissions inventories show that anthropogenic greenhouse gas emissions are currently tracking near the IPCC high emissions scenario (Global Carbon Project 2009), indicating that climate change in the upper ranges are more likely to occur.

Climate models are the best tools we have for projecting the future climate. Changes in radiative forcing of the climate system under corresponding emissions scenarios are used as inputs to climate models. Regional climate projections are difficult because of the uncertainty at each level of analysis: greenhouse gas emissions scenarios, the relationship between these emissions scenarios and the concentration of greenhouse gases in the atmosphere, the response of the climate to that concentration, and the linkage between global circulation and regional models. Especially, the importance of wetlands in the global carbon cycle needs to be better assessed and integrated into climate models. The cumulative nature of these uncertainties means that the range of regional climate projections can be considerable. In particular, precipitation — the principal input variable for wetlands — is not adequately simulated in present climate models (Kundzewicz et al. 2007). However, it is well established that precipitation variability will increase because of climate change, and projections of future temperatures are more consistent (Kundzewicz et al. 2007).

In general, Victoria's future climate is likely to be hotter and, for most of the state, drier. Sea level will rise. Heatwaves, drought, fire, and flooding from extreme rainfall and coastal storm surges are likely to increase in severity and frequency. Table 1 summarises the projected changes for the 10 Catchment Management Areas in Victoria. Projected regional changes relevant to wetlands follow.

Temperature

Victoria is expected to warm at a slightly faster rate than the global average. The north and east of the state are expected to experience greater temperature increases than the south and west. By 2030, annual average temperatures are expected to increase by between 0.6 °C and 1.2 °C, and by 2070 by between 0.9 °C and 2.0 °C under the low emissions scenario, or by between1.8 °C and 3.8 °C under the high emissions scenario. Temperature increases are likely to be greatest in spring and summer and least in winter.

Rainfall

Annual average rainfall in Victoria is expected to change by –9% to +1% by 2030, and by 2070 by –14% to +2% under the low emissions scenario, or –25% to +3% under the high emissions scenario. The greatest decreases in rainfall are likely to occur in winter and spring, while heavy rainfall intensity is most likely to increase in summer and autumn. The drying is likely to be greater in southern regions.

Snow

Snow projections for Australia, including Victorian alpine systems, based on temperature and precipitation changes, indicate that snow area, duration and depth are likely to decline, with larger changes expected at lower elevations. The low emissions scenario would have only a minor impact on snow conditions by 2020, reducing the average length of the snow season by about 5 days and the peak snow depth by around 10%. The high emissions scenario would result in the average snow season shortening by 30 to 40 days by 2020.

Drought

Climate change will increase the frequency and severity of drought in Victoria. By 2070 the frequency of drought is likely to increase by between 10% and 80% in the southern half of the state and by between 10% and 60% in the northern half. The frequency and areal extent of exceptionally hot years and exceptionally dry years in Victoria are likely to increase in the future (Hennessy et al. 2008). The mean projections indicate that, by 2010–2040, exceptionally hot years are likely to affect about 75% of the region and occur every 1.3 years on average. By 2010–2040 exceptionally low rainfall years are likely to affect about 10% of the region and occur about once every 12 years on average. By 2030, exceptionally low soil moisture years are likely to affect about 11% of the region and occur about once every nine years on average.

Evaporation

Evaporation is determined by net radiation at ground level, atmospheric humidity, wind speed, and temperature. Evaporation is expected to increase as temperatures rise, with the largest increases expected in winter. By 2030 the annual average potential evaporation is likely to increase by 1–5%, and by 2070 by 1–8% under the low emissions scenario or 2–16% under the high emissions scenario.

Runoff

Runoff amplifies climate signals. The amount of water that reaches water catchments is not proportional to rainfall since it also depends on soil moisture levels. In Australia, various hydrological modelling and climate sensitivity studies indicate that, as a ‘rule-of-thumb’, a 1% change in mean annual rainfall will result in a 2–3% change in mean annual catchment runoff (Chiew & McMahon 2002; Chiew 2006; Jones et al. 2006). Projected reductions in rainfall and higher rates of evaporation will result in less runoff to water catchments. CSIRO has estimated the likely future changes in runoff to Victoria’s 29 catchments. By 2030, catchments in the northeast and southeast may experience up to 30% less runoff, those in the northwest between 5% and 45%, and those in the southwest between 5% and 40%. By 2070, runoff into catchments in East Gippsland may change by between –50% and +20%, depending on changes in rainfall. The rest of the state can expect declines between 5% and 50%.

Table 1. Regional projections of mean temperature and rainfall changes by 2070 under two emissions scenarios for the 10 Victorian Catchment Management Areas (DSE 2009).

CMA / Season	LOW EMISSIONS SCENARIO		HIGH EMISSIONS SCENARIO	
Mallee	Water for irrigation –45%			
Spring	temp +1.5°C	rain –11%	temp +2.9°C	rain –20%
Summer	temp +1.6°C	rain –2%	temp +3.1°C	rain –3%
Autumn	temp +1.4°C	rain –2%	temp +2.8°C	rain –3%
Winter	temp +1.2°C	rain –8%	temp +2.3°C	rain –16%
Wimmera	Runoff –10% to –50%			
Spring	temp +1.4°C	rain –11%	temp +2.7°C	rain –21%
Summer	temp +1.5°C	rain –4%	temp +2.9°C	rain –7%
Autumn	temp +1.3°C	rain –3%	temp +2.6°C	rain –5%
Winter	temp +1.1°C	rain –7%	temp +2.2°C	rain –13%
Glenelg Hopkins	Runoff –10% to –50%			
Spring	temp +1.3°C	rain –11%	temp +2.4°C	rain –21%
Summer	temp +1.4°C	rain –5%	temp +2.7°C	rain –9%
Autumn	temp +1.3°C	rain –3%	temp +2.4°C	rain –6%
Winter	temp +1.1°C	rain –7%	temp +2.1°C	rain –12%
North Central	Runoff –5% to –50%			
Spring	temp +1.5°C	rain –11%	temp +2.9°C	rain –20%
Summer	temp +1.6°C	rain –2%	temp +3.1°C	rain –4%
Autumn	temp +1.4°C	rain –2%	temp +2.7°C	rain –4%
Winter	temp +1.2°C	rain –7%	temp +2.2°C	rain –13%
Corangamite	Runoff up to –50%			
Spring	temp +1.3°C	rain –11%	temp +2.5°C	rain –21%
Summer	temp +1.4°C	rain –5%	temp +2.7°C	rain –9%
Autumn	temp +1.3°C	rain –3%	temp +2.4°C	rain –6%
Winter	temp +1.1°C	rain –6%	temp +2.1°C	rain –11%

Table 1 (continued)

CMA / Season	LOW EMISSIONS SCENARIO		HIGH EMISSIONS SCENARIO	
Goulburn Broken	Runoff –5% to –50%			
Spring	temp +1.5°C	rain –11%	temp +2.9°C	rain –20%
Summer	temp +1.7°C	rain –2%	temp +3.2°C	rain –4%
Autumn	temp +1.4°C	rain –2%	temp +2.8°C	rain –5%
Winter	temp +1.2°C	rain –7%	temp +2.2°C	rain –12%
Port Phillip & Westernport	Runoff up to –50%			
Spring	temp +1.4°C	rain –12%	temp +2.6°C	rain –21%
Summer	temp +1.5°C	rain –4%	temp +3.0°C	rain –7%
Autumn	temp +1.3°C	rain –3%	temp +2.6°C	rain –5%
Winter	temp +1.1°C	rain –6%	temp +2.1°C	rain –11%
North East	Runoff –5% to –50%			
Spring	temp +1.6°C	rain –10%	temp +3.0°C	rain –19%
Summer	temp +1.7°C	rain –1%	temp +3.2°C	rain –2%
Autumn	temp +1.5°C	rain –3%	temp +2.8°C	rain –5%
Winter	temp +1.2°C	rain –7%	temp +2.3°C	rain –13%
East Gippsland	Runoff up to –50%			
Spring	temp +1.5°C	rain –10%	temp +2.8°C	rain –18%
Summer	temp +1.6°C	rain –1%	temp +3.0°C	rain –3%
Autumn	temp +1.4°C	rain –3%	temp +2.7°C	rain –5%
Winter	temp +1.2°C	rain –6%	temp +2.3°C	rain –12%
West Gippsland	Runoff –5% to –50%			
Spring	temp +1.4°C	rain –11%	temp +2.7°C	rain –20%
Summer	temp +1.5°C	rain –3%	temp +3.0°C	rain –6%
Autumn	temp +1.3°C	rain –3%	temp +2.6°C	rain –5%
Winter	temp +1.1°C	rain –6%	temp +2.2°C	rain –11%

Groundwater

Climate change will affect groundwater recharge rates and groundwater levels. Groundwater levels correlate more strongly with precipitation than with temperature, but temperature becomes more important for shallow aquifers and in warm periods (Kundzewicz et al. 2007). Groundwater systems generally respond more slowly to climate change than surface water systems. Little is known about the impacts on groundwater in Victoria. We expect that less rainfall and higher evaporation will reduce groundwater recharge, resulting in lower groundwater levels.

Fire

The hotter, drier climate for Victoria is likely to increase the frequency and intensity of bushfires. Compared to the period from 1974 to 2003, the number of 'extreme' fire danger days will generally increase by between 5% and 40% by 2020. The number of 'extreme' fire danger days is likely to increase by between 15% and 25% by 2050 under the low emissions scenario, and by between 120% and 230% under the high emissions scenario.

Sea level

Temperature rise has already resulted in warming of the oceans and melting of ice. Melting of ice sheets and glaciers, combined with the thermal expansion of seawater as the oceans warm, is causing a rise in sea levels, and the rate of rise is increasing (Church and White 2006). Global sea levels will likely rise by 18–59 cm by 2100 (relative to 1990), with a possible additional contribution from ice sheet melts of 10–20 cm (Solomon et al. 2007). However, further ice sheet contributions that cannot be quantified at this time due to inadequate scientific understanding may increase the upper limit of sea level rise substantially.

5 Effects of a changing climate

5.1 Hydrology

The dominant sources of water to wetlands are precipitation, surface runoff, groundwater discharge, and high or overbank stream flows. Evaporation, transpiration, seepage to groundwater, and overflow result in loss of water in wetlands. The balance of water inputs and outputs determines the hydrology of wetlands.

The changing climate will lead to decreases in precipitation, surface runoff and groundwater recharge and increases in evaporation and transpiration across much of Victoria, and drought will become more severe (DSE 2009).

The manner in which humans adapt to a changing climate will also greatly influence the future status of wetlands. The most important drivers of water use are population and economic development, and also changing societal views on the value of water and waterways. Water use, in particular irrigation water use, generally increases with temperature and decreases with precipitation (Kundzewicz et al. 2007). Increases in irrigation water demand as a result of climate change are likely. If conditions become drier, there is likely to be increased human demand for groundwater, which could negatively affect groundwater-dominated wetlands. In many wetlands that have shrunk mainly because of human water use and drainage, climate change is likely to exacerbate the shrinkage if it results in reduced net water availability.

Most wetland processes depend on catchment-level hydrology, which can be altered by bushfires, changes in land use, and changes in the management of surface water resources. Recharge of local and regional groundwater systems, the position of the wetland relative to the local topography, and the gradient of larger regional groundwater systems are critical factors in determining the variability and stability of moisture storage in wetlands in the climate zones where precipitation does not greatly exceed evaporation (Winter and Woo 1990). The projected increase in bushfires may result in short-term increases in wetland water inputs because of a reduction in vegetation cover, followed by longer-term reductions as water use by regenerating vegetation increases. Increased interception of water from land use changes such as new farm dams, greater groundwater extraction and an expansion of plantations would further reduce water availability for wetlands.

One consequence of reduced water availability and increasing water demand under climate change is expected to be a drying trend in inland wetland ecosystems. In addition, increased climate variability will lead to an increased hydrological variability of wetlands. More frequent or intense extreme weather events such as drought will enhance hydrologic disturbance of wetlands. Inland wetlands will be watered less often. A reduction in the frequency and magnitude of high flows of the rivers that inundate the floodplain, caused by lower precipitation and a consequential likely increase in diversion, would tend to dry out floodplain wetlands. During the current drought experienced in Victoria since 1997 we have observed that once-permanent deep freshwater marshes dried and ephemeral wetlands failed to fill at all. Reduced freshwater runoff will decrease freshwater input to coastal wetlands. Coastal wetlands will be inundated by seawater longer and more often because of sea level rise and storm surge.

The vulnerability of wetlands to a drying climate depends, in large part, on the sources of their water supply (Poff et al. 2002). Because Victoria's climate is among the driest and most variable in the world, the vulnerability of Victorian wetlands to climate change is strongly correlated with climate variability, in particular drought. Wetlands that depend upon precipitation and surface runoff are more sensitive to drying than those fed by groundwater (Winter 2000). Gitay et al. (2001) considered depressional wetlands with small catchments to be most vulnerable to climate change. In general, the shallower the water depth and the more dependent the water source on direct precipitation, the more likely these wetlands will be vulnerable to climate change. Shallow, intermittent wetlands in hot dry areas will disappear. Therefore, although the precise geography of the regional impacts is uncertain at present because of limitations in climate forecasting, the shallow freshwater meadows and marshes in the southwest of the state and on the floodplains of the Victorian Riverina bioregion are among inland wetlands most likely to be affected by climate change.

In conclusion, a future hotter and drier climate may reduce many wetlands in size, convert some wetlands to dry land, or shift one wetland type to another (e.g., seasonal wetlands may become ephemeral and permanent wetlands may become temporary). The projected changes in regional climate and rising sea level will likely lead to loss and degradation of many wetlands in Victoria.

5.2 Water quality

As air temperatures rise, so will wetland water temperatures. Wetland water temperatures will increase not only because of higher mean air temperatures but also because of greater radiant heating (a result of shallower water) and decreased inputs of cool groundwater. Southern wetlands will become more like wetlands in the north, and upland wetlands may become more like those at lower altitudes. Higher water temperature and increased variations in hydrology under the projected climate change are likely to affect water quality (Poff et al. 2002; Allan et al. 2005; Whitehead et al. 2009). Increases in the variability of wetland levels will also lead to highly variable changes in water quality.

Increasing water temperature reduces the capacity of water bodies to store dissolved oxygen, increasing the likelihood of anoxia. It also increases the decomposition rate of organic material, which in turn increases the biological oxygen demand, further decreasing the concentration of dissolved oxygen.

Increasing nutrient loading and sediment input from fire, erosion and flooding will increase water turbidity. Algal blooms will increase because of higher temperatures and increased nutrient runoff from more frequent and severe storm events, which will affect other wetland biota as well as human health and amenity. But these blooms may be constrained by salinity increases (Pittock 2003; Redden and Rukminasari 2008).

Groundwater-fed wetlands may become more acidic in a drier climate (Webster et al. 1990), whereas those fed by surface water may become more alkaline (Schindler 1997, 2001). If wetlands with acid sulfate sediments become dry and expose the sediments to the air, acidification of wetlands results. Other risks associated with acid sulfate soils include mobilisation of metals, deoxygenation of the water column and production of toxic gases.

Decreases in water levels can also increase the concentration of salts and pollutants, even in wetlands with normally low ionic or pollutant concentrations. In areas where the climate becomes hotter and drier, human activities to counteract the increased aridity (e.g., more irrigation, diversions and impoundments) might exacerbate secondary salinisation (Williams 2001; Nielsen and Brock 2009). On the other hand, a decrease in groundwater recharge may reduce the discharge of saline groundwater, so that one of the causes of secondary salinisation might diminish.

Decreased freshwater inputs can have both beneficial and detrimental impacts on coastal wetlands (Poff et al. 2002). A benefit could be a decrease in nutrients and toxic pollutants. During periods of sea level rise, coastal wetlands can persist only when they accrete soil vertically at a rate at least equal to water level rise (Cahoon et al. 1995). Because freshwater runoff carries sediments that increase accretion, there is concern that reduced freshwater runoff decreases the supply of sediments. Further, saltwater intrusion as a result of rising sea levels, increases in coastal storm surges, decreases in freshwater inputs, and increased drought frequency and intensity are very likely to expand the areas of salinisation of coastal freshwater aquifers and coastal wetlands (Pittock 2003; Wheeler et al. 2007; Victorian Coastal Council 2008). Coastal wetlands may disappear as a result of predicted increases in shoreline erosion, made worse by dieback of shoreline plants caused by increased salinity (Pittock 2003). Low-lying coastal wetlands are most likely to be affected by rising sea levels and storm surges.

5.3 Biota

Freshwater wetlands provide habitat for species that have adapted to widely varying soil moisture and chemical conditions. However, some species, such as odonate dragonflies, are habitat specialists and cannot survive anywhere else in the landscape. Individual organisms survive within specific ranges of temperature, water, and chemical conditions. If they are exposed to conditions outside their normal environmental range they must adapt or migrate, or they will perish (Lake et al. 2000; Poff et al. 2002; Moss et al. 2003; Chu et al. 2005; Xenopoulos et al. 2005; Heino et al. 2009). The sensitivity of a particular species is determined by intrinsic factors, including physiology (e.g., climatic preferences/tolerances and metabolic requirements), ecology (e.g., life history, habitat use, behaviour, dispersal, and biotic and abiotic interactions) and genetic diversity (Williams et al. 2008).

5.3.1 Species adaptation and vulnerability

All organisms should have some intrinsic capacity to adapt to changing conditions; this may be by evolution (i.e., through natural selection) or ecological adaptation (i.e., physiological and/or behavioural plasticity). Two prerequisites must exist for adaptive responses to be successful in countering rapid climate change (Williams et al. 2008). These are (1) biogeographic connectivity to allow organisms to reach suitable habitat/climate space/refugia, and (2) adequate time to allow adaptive changes to occur. Projected rates of climate change are very likely to exceed rates of evolutionary adaptation in many species (Hennessy et al. 2007). In most cases, ecological adaptation is likely to be more important than evolutionary adaptation in regard to the minimisation of impacts in the short term (Williams et al. 2008). This is because plasticity acts within a generation, whereas evolution involves multiple generations. Trait plasticity is determined by a combination of factors, including phylogenetic constraints, degree of niche specialisation, spatial scale of operation, behavioural flexibility, microhabitat adjustments, and physiological tolerance ranges (Nylin and Gotthard 1998). Some species have already used pre-existing flexibility to respond to a changing climate, including shifts in distribution, contraction to refugia, shifts in temporal activity (diel and seasonal), acclimatisaton, shifts in habitat/microhabitat use, and changes in biotic interactions (Hughes 2000; Walther 2002; Parmesan and Yohe 2003; Parmesan 2006). Some species will be sensitive and vulnerable, whereas others will be naturally buffered and resilient to climate-influenced disturbances. In general, the species most at risk from climate change are likely to include those with small physiological tolerance ranges, low reproductive rates, long generation times, slow life history, strong dependence on climatic cues to trigger life-cycle events, restricted or isolated distributions, specialised habitat or host requirements, low mobility and low genetic diversity (Hughes and Westoby 1994; Lovejoy and Hannah 2005; Williams et al. 2008; Brook 2009). A changing climate modifies habitat and affects the traits such as morphology, physiology, phenology and behaviour of organisms, subsequently biotic interactions and population processes, and ultimately community, biodiversity, ecosystem and geographic species distributions (Schindler 1997; Poff et al. 2002; Wrona et al. 2006; Heino et al. 2009).

5.3.2 Habitat change

Habitat change caused by climate change includes wetland desiccation, increasing hydrological variability and deterioration of water quality. Small increases in the variability of precipitation regimes will significantly impact wetland plants and animals at different stages of their life cycle (Burkett and Kusler 2000; Keddy 2000). Biodiversity in seasonal wetlands can be strongly affected by changes in precipitation and soil moisture (Bauder 2005). Prolonged dry periods promote the terrestrialisation of wetlands and may lead to the loss of aquatic biota and the invasion of non-wetland species, including woodland species. Drying will also affect the migration of birds that use wetlands as stopovers in their migration to breeding sites (Kingsford and Thomas 1995; Kingsford et al. 1999). Complete drying of wetlands will lead to a profound loss of biodiversity.

Declines in water quality and changes in water chemistry will affect wetland biodiversity. Direct and indirect responses to climate change will vary within and between all levels of the taxonomic hierarchy and may be related to the proportions of cold-water, cool-water, and warm-water species in a taxonomic group (Heino 2001). Cold-water species may not be able to find suitable thermal conditions to escape novel, stressful thermal conditions (Wrona et al. 2006). Warm-water species will be generally positively affected. Increasing temperatures may generally speed up plant growth and rates of decomposition, and lengthen growing seasons. Changes in water chemistry through carbon dioxide enrichment have the potential to alter species composition in some wetland types, independently of hydrologic or water quality changes. This is because some groups of plants are more responsive to higher carbon dioxide concentrations than others because of fundamental physiological differences (Poff et al. 2002). Salinisation of coastal wetlands will change the vegetation distribution. For example, increasing salinity has played a role in the expansion of mangroves into adjacent marshes throughout south-eastern Australia during the past 50 years (Saintilan and Williams 1999).

5.3.3 Changes in populations and communities

There is an emerging theory that increasing variation in climate need not necessarily decrease population growth rates (Drake 2005). A change in growth rate of populations of aquatic organisms in response to climate change is predicted to depend on the shape of the typical numerical response of the taxon, which is in turn a function of how dependent the taxon is on rainfall-driven resources (e.g., copepods are aquatic predators that rely on herbivores) (Huntley and Lopez 1992; Drake 2005). For those taxa directly dependent on a climate driver such as temperature (e.g., plankton and other exotherms), increased variability in temperature may increase the long-term population growth rates (Gillooly and Dodson 2000). In contrast, species that rely on rainfall-dependent resources are predicted to have a concave response to a reduction in the resources (Davis et al. 2002; Sibly and Hone 2002), and increased rainfall variability in this case is predicted to decrease the long-term population growth rate (Drake 2005).

The community composition of a wetland could be determined by the addition of species that migrate to an environment that is favourable for them, and the loss of species that cannot survive there. Studies in the northern hemisphere have revealed phenological trends since the mid 20th century that are likely to be responses to recent climate change (Walther et al. 2001; Walther et al. 2002). These changes are often in the timing of spring activities and behaviours, such as earlier migration of diadromous fish, earlier choruses and spawning in amphibians, earlier mating of lizards, earlier migration of birds, earlier shooting and flowering of plants, earlier nesting of sea turtles, earlier breeding and singing of birds, earlier arrival of migrant birds and earlier appearance of butterflies (Bull and Burzacott 2001; Dose and Menzel 2004; Weishampel et al. 2004; Piersma et al. 2005; Dose and Menzel 2006; Gordo et al. 2007; Taylor 2008). Since the timing of responses and the change in geographic range are not always synchronous in species, there may be a decoupling of species from their food sources, a disruption of symbiotic or facilitative relationships between species, and changes in competition between species (Winder and Schindler 2004). Owing to a combination of different responses between species and interactions that could theoretically occur at any point in a food web, some of the ecological communities existing today could easily be disaggregated in the future (Root and Schneider 2002; Burkett et al. 2005; Brook 2009).

5.3.4 Change in species distribution

Climate plays a key role in controlling species distributions, which on a broad scale are primarily determined by temperature. Geographical distributions ultimately determine the composition of regional species pools from which local communities are assembled (Tonn 1990). Shifts in latitude and altitude in the distributions of plants and animals living in wetland ecosystems may occur in response to a changing climate, similar to the observed recent movement of species ranges in response to shifts in climate zones (Hughes 2000; Parmesan and Yohe 2003; Root et al. 2003; Hickling et al. 2006). Some warm-water species will expand ranges. Species vary greatly in their abilities to disperse, so the success of plants and animals in colonising suitable habitats under a changing climate will be highly variable. It is possible that strong dispersers (e.g., some dragonflies and damselflies) are able to track changing climatic conditions more easily than those (e.g., fish) that would need suitable dispersal corridors to reach new regions and wetlands (Hickling et al. 2006). Many groups of freshwater organisms that inhabit isolated wetlands in a matrix of inhospitable terrestrial environments require suitable corridors in order to disperse to favourable habitats, tracking changing climate (Poff et al. 2002), so this is likely to be limited by habitat loss and fragmentation (Hennessy et al. 2007). For some wetland species, geographic barriers are so formidable that they are unlikely to be overcome in the timeframe projected for climate change.

5.3.5 Invasive species

Climate change is likely to benefit many exotic species (i) by reducing the resistance of ecosystems to invasion, (ii) through effects of altered climatic conditions on native species, and (iii) by increasing the invasive potential of exotic species (Thuiller et al. 2007). Invasive species are adaptable opportunists often among the first to occupy new or expanding areas where there is space and other resources necessary for colonisation and survival and a low enough density of competitors for colonisation to proceed to recruitment (Noble 1989). Ecosystems that fulfil these criteria have often suffered disturbance (producing space) or are undergoing stress (lowering competition). As a result of climate change, many wetlands may become suitable for the breeding populations of various invasive species (Rahel and Olden 2008). There may be many species currently outside their range that have not had the right conditions to expand their range – so-called sleeper invasives (Campbell 2008). For example, Mimosa (*Mimosa pigra*) existed in a small patch for 90 years before it expanded its range and invaded the wetlands of northern Australia. Cane Toads (*Bufo marinus*) are likely to spread further south in a drying climate. C4 plants are likely to have increased fitness due to increased CO_2 and may out-compete C3 plants and become invasive or more invasive (Dukes 2000). And the ranges of Mosquitofish (*Gambusia holbrookii*) and Weather Loach (*Misgurnus aguillicaudatus*) will probably expand in a warmer climate (Australian Centre for Biodiversity 2008). The number of invasive species is likely to increase in wetlands as a result of climate change.

5.3.6 Species extinction

The current extinction rate of freshwater species equals or exceeds that of species in other ecosystems, including tropical rainforests (Ricciardi and Rasmussen 1999; Xenopoulos et al. 2005; Dudgeon et al. 2006). Research on climate change effects on biodiversity has concentrated on the terrestrial realm. The responses of terrestrial species to recent (Parmesan and Yohe 2003; Root et al. 2003; Pounds et al. 2006) and past (Benton and Twitchett 2003) climate change raise the possibility that anthropogenic climate change will accelerate species extinction. The effect of future climate change on biodiversity has been predicted to be unprecedented, with 15–37% of terrestrial species possibly becoming extinct because of climate change alone in the next 50 years (Thomas et al. 2004). For freshwater organisms, the greatest challenges in adapting to climate change will be related to the degree to which certain aquatic habitats are diminished, the abilities of species to disperse to higher latitudes or altitudes, and the ability to overcome the effects of increased isolation of aquatic habitats due to human activities (Poff et al. 2002). Due to the combined effects of temperature and water stress, the extinction of some amphibians and aquatic species is projected in Costa Rica, Spain and Australia (Pounds et al. 2006). We would expect aquatic species, and particularly wetlands-dependent species, to fare much worse than is indicated for terrestrial species because the decrease in the extent of suitable habitat is likely to be greater (Street and Grove 1979; Mason et al. 1994).

6 Climate change impact modelling for wetlands

Wetland ecosystems are highly complex, so we cannot simply extrapolate past trends to predict how wetlands might change in the future. Models are essential to predict the impacts of climate change on wetlands because they enable us to analyse, simulate, manipulate and visualise systems over various temporal and spatial scales, taking into account interactions and feedbacks. Observations, experiments, and theory are used to construct and refine models that represent wetland ecosystems and make predictions about their future behaviours. The ability of ecological models to translate climate projections into meaningful predictions of how wetlands are likely to respond depends on the level of understanding of the processes that govern the ecosystem, the availability of empirical data, and the predictive power of the model. Confidence in models comes from their ability to reproduce observed patterns. Results from models lead to better understanding of the linkages between wetlands and climate conditions and inspire more observations and experiments. Over time, this iterative process will result in more accurate and reliable predictions of the impacts of climate change on wetlands. Another strength of modelling lies in diagnostic tools, especially integration, synthesis and scenario analysis.

Scientific literature on modelling ecological responses of wetlands to climate change at a regional level in Victoria is scarce. We review the published models on the impacts of climate change on wetlands. Some of the models could be applicable to Victoria. The modelling approaches can be divided into three tiers (Acreman et al. 2009):

Tier 1: This involves a *qualitative* assessment of potential risks posed by a changing climate, and is called 'risk screening'. For example, Winter (2000) considered the impact of climate change on wetlands using conceptual qualitative understanding of processes in different landscape locations. Preston and Jones (2008) undertook a qualitative screening-level risk assessment for Australia's 325 surface water management areas by aggregating a suite of six climatic and non-climatic risk indicators. They found that 16% (by area) of Australia's nationally significant wetlands are in 'high' or 'very high' risk catchments, while 53% of the area of the Ramsar wetlands of Australia are in at-risk catchments.

Tier 2: This involves a generic *quantitative* assessment to identify potential consequences of climate change. In this tier, models need to include important processes but can have generalised form and parameters that are broadly applicable to areas or regions, as they are not intended to represent details of specific sites. There is a paucity of methods and studies of this type for wetlands. The following are some examples.

- A modelling assessment of water balance was undertaken for the UK and Ireland using current and future climate scenarios (Dawson et al. 2003). The results showed that water availability could increase in winter across the whole region. Northwest Ireland and northwest Scotland could have a small increase in water availability in the summer. Other regions would experience little change or have decreased water availability during the summer months, this being most severe in southeast England.
- Jin (2008) modelled the combined effects of salinisation and hydrological variation on wetlands. The model showed that wetland biodiversity exhibits non-linear responses to changing salinity and hydrology, with thresholds of collapse and recovery. Increases in mean temperature, decreases in mean precipitation, and increased seasonal hydrological variability would reduce wetland resilience, increasing the risk associated with salinisation. On the other hand, the changing climate could create opportunities for the recovery of wetlands that have already been severely degraded by salinity, because increased seasonal hydrological variability renders the systems more responsive to management intervention.

- Linked water resource and biodiversity meta-models were used to examine the impacts of socio-economic and climate change scenarios on wetlands in two contrasting regions of the UK (Harrison et al. 2008). The water resource meta-model examined the effects of climate and socio-economic change scenarios on high and low river flows. The biodiversity meta-model analysed possible impacts, and options for adaptation, for a selection of species representing fen, blanket bog and raised bog communities.
- Acreman et al. (2009) presented a framework for evaluating regional wetland ecohydrological response to climate change. This can be used for combining models and available data to provide an intermediate level of assessment that is appropriate at the regional scale to highlight broad issues. The framework can be implemented with few data and a general conceptual understanding of wetland processes. It is thus fit for the purpose of general assessment. It does not attempt to model all wetland processes at a detailed level and does not provide precise results for specific wetland sites.

Tier 3: This approach involves a more detailed quantitative assessment to establish the magnitude and probability of the consequences of a changing climate and hence the future risk for particular locations. This level of approach requires models that represent all relevant processes and parameter values at the site of interest. A drawback is that it cannot be readily applied on a regional basis because of the amount of data required, hence the need for the intermediate Tier 2 approach and the preliminary Tier 1 approach. An example of the Tier 3 approach is the work of Johnson et al. (2005) that used a hydrologic and wetland vegetation dynamics model to show that the most productive habitat for breeding waterfowl in the North American prairie pothole region would shift under a drier climate from the centre of the region to the wetter eastern and northern fringes.

7 Research needs

Research builds adaptive capacity and enables better scientific understanding and better decisions. Our understanding of the impacts of climate change on wetlands is improved through observations, experiments, theoretical studies, and modelling. Observations and experiments are the foundation for our understanding. The difficulty is that several decades of biological and environmental data collection are needed to be able to quantify any signal attributable to directional climate change. Multiple lines of evidence can be pursued by the use of many different scientific techniques, including:

- statistical and process-based modelling
- analysis of long-term observational physical, chemical and biological data sets
- palaeolimnological reconstructions to extend time series and explore processes over longer time-scales
- the use of space-for-time substitution on the assumption that future climate analogues can be found in space
- experiments in laboratories or in the field under controlled climate conditions.

These different techniques are powerful, especially when used together. Large temporal and spatial scales and the complexity that result from climate change acting along multiple pathways will increasingly require new technologies, new concepts and new methods, as well as an interdisciplinary systems-based approach—one that includes environmental, social, cultural and economic considerations.

The threats posed by climate change have been identified for over 20 years (Peters and Darling 1985; Williams et al. 1994) and the research priorities have been identified to protect Australia's biodiversity from the impact of climate change (Hilbert et al. 2007), but support has not been in place for the magnitude of research effort required (Morton et al. 2009). In particular, there is a lack of investment in research on climate change impacts and adaptation. Current research activities on Australia's biodiversity and ecosystems under a changing climate are listed in Appendix 1.

The ability to quantify climate change impacts on wetlands in Victoria is limited by uncertainty in all stages of the modelling process. Information on the impacts of climate change on wetlands is limited and often speculative. Current knowledge of what generates biodiversity, the functional roles of species and biodiversity in wetland ecosystems and the relationships between wetland ecosystems and ecosystem drivers is inadequate. Climate change impacts on water quality are poorly understood, particularly with respect to the impact of extreme events (Takahashi et al. 2001). Few results are available on the socioeconomic aspects of climate change impacts related to wetlands, including climate change impacts on water demand. For many groups of freshwater organisms, dispersal abilities of species are poorly known (Bohonak and Jenkins 2003). The lack of empirical data is notorious and critical (Kundzewicz et al. 2008). And there is far less information about how the wetlands and the associated biodiversity in Victoria have changed and will change in response to climate change.

Although general trends can be predicted with some confidence, enormous uncertainties remain in predicting the ecological responses of individual wetlands (including unique or rare wetlands) to climate change. Research is urgently needed to fill knowledge gaps and reduce uncertainty as well as manage uncertainty. The research can be approached at many levels, from the components and processes level, the ecosystem level through to the landscape level, enabling changes in Victoria's wetlands to be monitored and projected in time and space. We recognise the following critical areas of research.

Threats

While we know the key threats to the wetlands in Victoria, we lack quantitative information on the extent, magnitude and rate of change of many existing and emerging threats and cannot accurately forecast future trends, both locally and regionally. Climate change is only one of many biophysical and socioeconomic drivers that affect wetland ecosystems, so any threat analysis must account for multiple threats and their interactions. More accurate and reliable projections of regional climate and non-climatic stressors of wetlands could be achieved with models that integrate disciplines and are based on a better understanding of the underlying processes and changing environmental and socioeconomic forces that change threats over time and space. As ecological systems experience impacts from a changing climate, social and economic systems will also be affected. Understanding coupled socioeconomic–ecological systems is important.

Responses

Models are needed to predict the response of wetland ecosystems to multiple threats as well as management interventions. Management interventions need to be evaluated particularly when multiple threats exist. Long-term monitoring and experimental programs are needed to improve the understanding of the key processes that control wetland responses, which is of fundamental importance because it serves as a foundation for building and testing models that predict the dynamics of wetland ecosystems.

A key objective is to understand the resilience of wetlands (that is, their capacity to tolerate disturbance and perturbation without shifting into a fundamentally different state) under multiple threats, including changes in climate, land use and water use. A rare short-term event or small change might cause a non-linear response, pushing a wetland across a critical ecological threshold that could represent a point of no return and the loss of resilience. It is an important goal for future research to understand non-linear responses and critical ecological thresholds of collapse and recovery, and to identify the early indicators of the threshold change.

Vulnerability

Vulnerability is the degree to which a system is exposed to, and affected by, threats. An understanding of both threats and responses is therefore required to assess wetland vulnerability. The most vulnerable wetlands are those close to collapse thresholds. Management interventions can modify the threats and responses and thus alter wetland vulnerability. To protect and restore wetlands it is crucial to know what is needed to maintain and enhance biodiversity, ecosystem function and resilience, and to be able to estimate acceptable mitigation levels and evaluate the effectiveness and limits of adaptation options for minimising vulnerability. If protection and restoration prove impracticable, it may be necessary to develop adaptation measures to assist the transformation of wetlands into novel ecosystems, with the consequences understood.

Wetlands in the landscape

A landscape is a network of interacting systems and processes. Research is needed to enable us to understand interconnections among systems and processes in the landscape so we can develop tools and methods for holistic catchment management. All wetlands in Victoria should be characterised and mapped. An important first step will be to gain an understanding of wetland distribution, extent and hydrology over broad spatial scales. Data on the distribution, dispersal abilities and available dispersal corridors for wetland species needs to be acquired. It is critical to understand and model the shifts and changes in the geographical distributions of wetlands and wetland species (including alien species), the influence of wetlands on landscape properties (e.g., connectivity, biodiversity, and resilience), and the influence of a transformed landscape on wetlands, in light of a changing climate. Given the likely loss and degradation of many wetlands as a result of climate change in Victoria, it is essential to identify and protect key wetlands for the health and function of a whole landscape. In particular, some wetlands may form thermal and hydrological refuges in the face of climate variability and extremes (e.g., drought) or may provide stepping stones to aid migration to an area where the climate is more suitable. Such wetlands need to be identified and conserved in order to provide capacity for landscape recovery and connectivity.

Decision support

Facilitating the survival and adaptation of wetlands in the face of climate change depends not only upon our ability to get the science right, but also upon our ability to integrate that knowledge with the considerations of environmental, social, cultural and economic dimensions into policy development and management. Research is needed to provide robust methods for decisions that must invariably be made under uncertainty and trade-off. Because there are neither the resources nor the time to protect all wetlands that are under threat, wetlands will have to be prioritised in terms of adaptation planning, regulation and investment decisions that can be applied at the state level and at a regional level.

Modelling is the most appropriate available research tool for addressing many of the research priorities. The tiered modelling approach described in section 6 can be used to develop models, depending on the nature of questions and the availability of knowledge, information and data. Modelling may start at a lower tier and progress towards a higher tier. The following modelling approaches are suggested as a start, to offer practical ways forward in addressing the research priorities:

Tier 1

- threat analysis
- vulnerability of wetlands at the landscape level
- key wetlands in the landscape
- wetland prioritisation method.

Tier 2

- wetland responses in general
- shifts and changes in geographical distributions of wetlands and their dependent species
- influence of wetlands on landscape properties
- influence of transformed landscape on wetlands
- robust methods for decision-making under uncertainty and trade-off.

Tier 3

- wetland requirements for maintaining and enhancing biodiversity, ecosystem function and resilience
- evaluation of management actions
- responses of individual wetlands
- vulnerability of individual wetlands.

8 Policy implications

Climate change is a global phenomenon with regional implications that add to the many human-induced impacts on wetlands. It is another major impact we need to understand in order to prioritise wetlands for protection and other actions aimed at reversing or mitigating the current trajectory of loss and degradation. Because of the magnitude and ubiquity of climate change effects we are compelled to reflect on past policy, management and other decision-making processes and to improve them for the future. Appendix 2 provides some background on Victoria's wetland policies. The policy implications are presented below.

Value shift

A value shift towards truly sustainable development is most important for mitigating against and adapting to climate change. We need to recognise that economic prosperity and human health and wellbeing rely on healthy natural systems. Healthy environment and healthy economy should go hand in hand. Discussions of human aspiration, the nature of consumerism, the formation of attitudes and the roles of education, media and ideology may need to be part of policy development alongside managing land and water resources to protect and enhance wetland extent and condition, emissions targets, impacts, carbon trading and renewable energy.

Vision building, strategic planning and target setting for Victorian wetlands

Policy for wetlands must incorporate inevitable impacts of climate change. The past century is no longer a reasonable guide to the future for wetland policy and management. The assumption of an unchanging hydrology is no longer appropriate because of substantial changes in water availability and water demand. We cannot simply refer to the past as a basis for establishing reference conditions for wetland management. The strategic goals for managing the effects and changes described previously for wetlands in Victoria are to minimise the vulnerability of wetlands and to adapt without losing wetland functions and services at the landscape scale. Wetland managers need to view a broader range of wetland states as desirable. These may include novel or dynamic local assemblages that maintain functioning but not necessarily species identity. Wetland policy makers may need to re-evaluate operational definitions and guidelines, such as what constitutes an invasive species or when a species can be added to a risk list. Managing reduced freshwater quantity and increased hydrological variability and sea levels is central for wetlands in the face of climate change. Decisions about allocating water between the needs of human and the environment is a major challenge. Actions that focus solely on parts of ecosystem (e.g., particular species or communities) are unlikely to be effective over the long term. A systems approach to holistic catchment management needs to be considered in order to achieve the strategic goals.

Policy will need to consider integrating adaptation strategies (actions that help ecosystems accommodate changes adaptively) and mitigation strategies (actions that reduce anthropogenic influences on climate) into overall plans. Adaptive strategies include resistance options (maintain status quo and forestall ecosystem changes), resilience options (improve the capacity of ecosystems to return to desired states after disturbance), and response options (facilitate transition of ecosystems from current to new states) (Millar et al. 2007). Mitigation strategies include options to reduce anthropogenic climate change. Climate change response strategies, processes, and mechanisms should recognise the importance of some types of wetlands (such as peatlands) as significant carbon storages. Wetland conservation and restoration is a necessary means to reduce greenhouse gas emission. Examples of potential areas of action associated with these strategies for wetlands are given in Table 2. There is no 'one size fits all' approach to all future challenges, and the best strategy is to combine different strategies for a region and for individual wetlands. Wetlands or wetland species of high conservation value may warrant resistance strategies to maintain them. For more widespread species and wetlands, a focus on resilience might be most appropriate.

Protecting all of the very large number of wetlands in Victoria is not a practical option. Prioritising wetlands will need to be considered in order to determine the most efficient allocation of resources. Key elements of the priority setting include the vulnerability and significance of wetland and the feasibility, cost, benefit and uncertainty of action.

Support for climate change adaptation science

Science underpins informed policy on climate change. The urgency, severity and complexity of the problems demand increasing the funding for research on climate change impacts on wetlands. The identified research needs from the strategic, long-term planning should be systematically addressed. The research programs and projects should be coordinated. The systematic, coordinated research approach will concentrate resources and efforts, improve cost effectiveness and avoid market failure such as duplication or omission. The condition of Australian aquatic ecosystems, the magnitude of the threats they face and the power of ecosystem science to present holistic understanding and management solutions, provide an ineluctable case for greater focus on ecosystem science in Australia with large-scale, long-term research programs (Likens et al. 2009). Access to data, information archives and knowledge transfer should be improved.

Table 2. Examples of potential areas of action in association with a portfolio of strategies for wetlands (modified from Roberts 2009).

Strategy	**Examples of actions**
RESISTANCE Ignore eventual change, focus on very short-term Actively maintain the status quo Shies away from any changes in ecosystem	Environmental watering
RESILIENCE Improve capacity to recover from disturbances Remove or reduce non-climatic stressors	Increase wetland biodiversity Improve riparian buffer zones Improve catchment land-use management Remove introduced species including live stock Reduce habitat fragmentation, destruction and pollution Control surface water and groundwater extraction Protect from fire Improve connectivity
RESPONSE Encourage gradual adaptation and transition to inevitable change Mimic, assist or enable processes such as dispersal, migration, colonisation	Extend species ranges by planting out and translocation of fauna Assist migration — deliberately place propagules or juveniles in likely future habitats (e.g., fish stocking) Protect refugia Restore /create wetlands Provide buffers to allow migration of coastal wetlands
MITIGATION Reduce anthropogenic climate change	Reduce greenhouse gas emissions Sequester carbon (e.g., plant trees and reduce land clearing)

Precautionary management

Research will inform the most effective ways to manage wetlands and enable the prioritisation of wetlands to target finite resources for mitigation and adaptation. Responses to the climate change challenge will evolve over time as knowledge accumulates. Because climate change may lead to unpredictable responses of wetlands, policy and management should not be solely based on predicting climate change impacts and then developing a response. In the areas where scientific understanding is limited and unpredictability or large uncertainties remain, precautionary measures need to be taken at both the local and the landscape scale. Such a strategy would complement a long-term commitment to research for better management with efficient resource allocation, reduced costs and clearly quantified benefits.

Integrate with policies for other sectors

Policies need to consider the connectedness and interdependence of natural systems and human systems. Human systems have to become much more adaptable in the face of climate change. A ‘whole of government’ approach to integrated environmental, economic, political and social policy, planning and service delivery should be established. The final goal should be an integration of all policies as a framework for long-term, sustainable development. Conservation and restoration of wetlands that reliably provide a range of ecosystem services to human society over time are fundamental bases to the quality of life and to economic prosperity. Wetlands play an important role in climate change mitigation and adaptation, including carbon storage and sequestration, flood mitigation, water supply, providing refuge, and mitigating the impacts of sea level rise. Policy making in related policy areas (e.g., water, catchment management, agriculture, forestry, energy, mining, health and recreation) needs to be aware of the potential impacts of sector-based decisions on wetlands. Policies in these sectors that seek positive outcomes or that cause no deterioration to wetlands should be the goal, and those that potentially damage wetlands should be avoided.

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Appendix 1 Current research on Australia's biodiversity and ecosystems under a changing climate

	Project	PIs/Agencies	Objectives/Output	Start Date	End Date
Environment Australia Research activities A number of significant projects are underway assessing the vulnerability of Australia's biodiversity to climate change and facilitating the sharing of research and information about climate change impacts on biodiversity. The results of this work will inform government policy and management of Australia's biodiversity under a changing climate.	Climate change impacts on the National Reserve System	Department of the Environment and Water Resources CSIRO	The study will assess the implications of climate change for management of the National Reserve System, using the Interim Biogeographic Regionalisation of Australia framework. The results will be critical to the management of the National Reserve System, including its future development at a national and regional scale.	–	–
	National Ecological Meta Database	Department of the Environment and Water Resources Bureau of Meteorology Macquarie University University of Melbourne	The National Ecological Meta Database is an online database that has the potential to be used for research and analysis on climate change impacts on species and ecosystems. Information for the database is being sourced from State agencies, CSIRO, farmers, ecological and field naturalists groups, botanic gardens and the ARC Earth System Science Network. Web: www.bom.gov.au/nemd Reports: Biodiversity conservation research in a changing climate – Workshop Report, 2007 National Biodiversity and Climate Change Action Plan 2004–2007 Climate Change Impacts on Biodiversity in Australia	–	ongoing
CSIRO Climate Adaptation Flagship - Managing species and natural ecosystems Australia's natural species and ecosystems are highly vulnerable to climate change and will have difficulty in adapting to the rate and extent of	Implications of Climate Change for Australia's National Reserve System	Michael Dunlop and Peter Brown, CSIRO Sustainable Ecosystems	http://www.climatechange.gov.au/impacts/publications/nrs-report.html Note, wile this work focuses to some extent on the National Reserve System it covers biodiversity conservation in general and much of it is applicable to conserving wetlands under climate change.	2006	2007

projected changes. This Theme focuses in three areas: (1) Predicting the responses of natural ecosystems to climate change, and developing adaptation options to improve their resilience. (2) Reducing the threats posed by invasive species, bushfires and habitat loss through development of well prioritised response strategies. (3) Incorporating climate change adaptation measures into conservation and natural resource management policies and strategies. Theme Leader: Dr Trevor Booth.	Climate-driven changes in Tasmanian intertidal fauna: 1950's to 2000's	Nicole Pitt (UTas), Elvira Poloczanska (CAF), Alistair Hobday (CAF)	In Tasmania, surveys based on historical data from the 1950's have revealed that 17 of 32 (53%) intertidal species have shifted their distribution southward along the east coast of Tasmania, an average increase of 145 km. A similar result was obtained for the west coast of Tasmania with 7 of the 32 (22%) shifting their distribution southward with an average of 150 km increase. Based on these results the thermal tolerance of a species can limit their distribution, however, other factors can not be ruled out	October 07	June 08
	Changes in distribution and abundance of rocky shore fauna: climatic warming signals from Australia's east coast .	Samuel Smith (UQ), Anthony Richardson (CAF/UQ), Elvira Poloczanska (CAF), Ian Tibbets (UQ)	Historical comparison revealed 14 of 34 species moving poleward, consistent with changes in ocean temperature. Abundance of temperate species showed a significant decline while there was a concomitant increase in the abundance of tropical species. It was concluded that the biogeographic boundary is driven by ocean current patterns that preclude northward planktonic dispersal of species with a larval duration of < 60 days.	–	–
	AUSAid: Climate Change and Ecological Assets in the South-East Asian Region	Craig Miller	Research Question: Can we develop a spatially explicit systematic process to ensure that conservation policy takes livelihoods and the realities of climate change into consideration? What did the project produce? a scalable, nested classification system in a GIS that incorporates biophysical attributes with socio-economic trends and then projects changes due to aspects of climate Milestone report for this project: Towards Regionally Relevant Biodiversity, Poverty and Climate Change Policy: A Report on the Los Banos Workshop.	1/07/2008	30/06/2009
	Climate change impacts on ecosystems and ecosystem processes	David Hilbert	-	1/07/2007	30/06/2010
	Weed Response to Cyclones in the Wet Tropics Rainforests: impacts and adaptation	Helen Murphy	Monitoring over long time-periods is necessary to provide information to managers about: • what types of invasive species are likely to have significant long-term impacts on rainforests following cyclones. • what types of habitat are most at risk from weeds following cyclones. • the best approach for pro-active and post-cyclone management of weed species to	1/01/2009	31/12/2009

			minimise long-term impacts to rainforests.		
	Resilience Concept Paper	Mark Stafford-Smith	-	1/01/2009	30/06/2009
	Impacts of Climate Change on Victorian Alpine Ecosystems	Richard Williams	-	1/07/2008	31/12/2012
	WfO Climate Impacts P&T Ecosystems	Alistair Hobday	-	1/07/2008	30/06/2009
	Developing socio-economic frameworks for impacts of marine climate change	Alistair Hobday	-	1/07/2008	30/06/2009
	Records of Past Climate	Ron Thresher	-	1/07/2008	30/06/2010
	Spatial planning for a changing ocean	Alistair Hobday	-	1/02/2009	31/01/2012
	Fire weather and fuel availability (Previously A1.4 Grassland Curing J67021)	Stuart Matthews	-	1/07/2008	30/06/2010
	Fire behaviour modelling (previously A1.1 Fuel & Fire Behaviour Modelling)	Miguel Cruz / Jim Gould	-	1/07/2008	30/06/2010
	Data for DCC East coast vulnerability Study	Matt Plucinski / Jim Gould, UTAS	-	1/07/2008	30/06/2010
	Scoping study for the Salmonoid Aquaculture Industry	Jim Gould, UTAS	-	1/07/2008	30/06/2010
	Combustion dynamics	Andrew Sullivan	-	1/07/2008	30/06/2010
	Climate change implications for weed management in South Australia	Darren Kriticos	-	1/03/2009	30/06/2009
	Impacts of Climate Change on National Reserve System	David Hilbert	-	1/01/2009	28/02/2010
EWATER	Landscape Analysis	Angela Arthington, Griffith University Mike Stewardson, University of Melbourne	Research projects in this program apply new methods of landscape analysis to understand and model river ecosystem responses to natural drivers (such as hydrology and climate), human disturbances (such as climate change, river engineering, land use, flow regulation, estuary management and invasive alien species), and restoration interventions (such as land use controls, environmental flows, riparian rehabilitation, habitat improvements, establishment of connectivity) from micro- to macro scales, in rural and urban catchments.	-	-
DSE Environment Policy and Climate Change Division: Climate Change Impacts and Adaptation Group	Regional implications of the potential impacts of climate change on the Phillip Island Penguin Colony	Western Port Greenhouse Alliance	Report to DSE on completion Progress reports and final report	Commenced 5 March 2008	Due for completion – early 2009

	Vulnerability of Victorian forest ecosystems to climate change	Rod Keenan and Stefan Arndt, School of Forest and Ecosystem Science, University of Melbourne	• Final report on completion	To commence January 2009	Concludes early 2010
	International Tundra Experiment (ITEX)	Ary Hoffman, Bio 21, University of Melbourne DSE investigator – Ian Mansergh	ITEX is a worldwide scientific network of experiments focusing on the impact of climate change on selected plant species in tundra and alpine vegetation. Further information: www.itex-science.net/, http://www.geog.ubc.ca/itex/ Scientific journal articles are produced – some are completed	-	-
	Integrated assessment of the impacts of climate change on Victorian alpine ecosystems	Ary Hoffman, Bio 21, University of Melbourne	Final report on completion to DSE and Parks Vic	2008	2012
	Potential biological Indicators of climate change: Evidence from phenology records of plants along the Victorian coast.	ARI Latrobe University	http://www.climatechange.vic.gov.au/greenhouse/wcmn302.nsf/childdocs/-F69C1BA1EA42C09CCA2572E400183782?open	-	August 2008
	The influence of climate variability on numbers of three water bird species in Western Port, Victoria, 1973–2002	L. E. Chambers (Bureau of Meteorology) R. H. Loyn (ARI)	Paper available: http://www.springerlink.com/content/f015qn0125656162/	-	2006
	Potential impacts of a changing climate on selected terrestrial ecosystems of Northern Victoria.	Graeme Newell, Matthew White. Peter Griffioen (ARI)	• Report still in draft mode will publish as ARI Tech report, and possibly in other venues • Still to do: this supercedes the work of Newell, Cheal & Griffioen from 2001	August 2008	-
	Climate change and potential distribution of weeds	Jackie Steel, Biosciences Research Division, DPI	Final report available: see http://www.climatechange.vic.gov.au/greenhouse/wcmn302.nsf/childdocs/-F69C1BA1EA42C09CCA2572E400183782?open	-	June 2008
	Bushfire Weather in South-East Australia	Climate Institute	This report builds on the 2005 climate change assessments (see above), providing a more detailed and up-to-date analysis of predicted climate change for south-eastern Australia. It directly relates climate change factors to measures of fire weather which largely influence the frequency and intensity of bushfires.	-	September 2007

Appendix 2 Wetland policies in Victoria

In Victoria, there are a number of policies that include wetlands in their content:

- *Our Water Our Future* White Paper (2004)
- *Victorian River Health Strategy* (2002)
- *Native Vegetation Management — A Framework for Action* (2002)
- *Victorian Coastal Strategy* (2008)
- *Victorian Biodiversity Strategy* (1997)
- *Management of Victoria's Wetlands — Strategic Direction Statement* (2002).

The *Victorian Strategy for Healthy Rivers, Estuaries and Wetlands* will add to this along with the *Victorian Land and Biodiversity at a Time of Climate Change* white paper and the *Natural Systems Theme of the Climate Change* white paper.

The draft Climate Change Green Paper policy theme (Anderson 2008) included these aims:

1. Protect, maintain and enhance natural systems in the face of climate change.
2. Understand and value the services that natural systems provide.
3. Build social and ecological resilience, recognising the connectedness and inter-dependence of natural systems with human systems.
4. Improve adaptive capacity, by assessing and managing critical risks and thresholds, and by building natural and social capital.
5. Develop integrated and adaptive decision making processes that are robust in the context of uncertainty and complexity and well-supported by evaluation and reporting.
6. Support the role of communities in building resilience to climate change risk, and address barriers to behavioural change and institutional adaptation.

(See the full list of proposed policies under each of these headings policy areas in Table 3.)

Table 3. Summary of policies for adaptation of natural systems to climate change from the draft Climate Change Green Paper policy theme (Anderson 2008).

Area for policy action	Potential policies
A. Resilience based policy Resilience theory informing climate change strategy and decision making Three priority programs to build resilience to climate change: ▪ Assessing and managing risk in order to maintain systems (including natural systems) within critical thresholds ▪ Building adaptive capacity by improving natural and social capital, so that systems can better withstand shocks,	1) Improve landscape diversity and connectivity
	2) Reframe riparian management, in order to deliver multiple beneficial outcomes, such as flood buffering, connectivity, carbon planting, biodiversity and soil carbon
	3) Develop a portfolio of policy instruments to influence drivers of land-use change
	4) Establish Future Floods program to improve information, modelling, warning systems and planning guidance for flood response
	5) Establish a sustainable funding model for investment in adaptation and natural system projects
	6) Using adaptive and integrative decision making processes across different scales (see *B: Adaptation decision making and policy integration*)

Area for policy action	Potential policies
adapt and self-organise ▪ Addressing barriers to social adaptation that may hinder behavioural change or institutional adaptation	
B. Adaptation decision making and policy integration Developing decision making processes which are adaptive and integrative, taking into account uncertainty and the changing climate	1) Development of a generic decision making framework for adaptive and integrative decision making for climate change
	2) Mainstream this adaptive decision making across government, as part of core business and a key component in the response to climate change
	3) Improve information collection, analysis, modelling and reporting systems, to support feedback and review processes within adaptive management and governance
	4) More decisions to take into account/consider climate change
C. Risk management and knowledge gaps Developing risk-based decision making approaches to climate change that address connected natural and social systems Addressing key knowledge and process gaps in terms of climate change risk	1) Development of risk decision making tools for climate change, that use probabilistic and values-based approaches, can factor in uncertainty and are participative
	2) Embedding these tools within an adaptation decision making framework
	3) Mainstreaming these as key components in the response to climate change
	4) As part of the *Flora and Fauna Guarantee Act* review, develop methodology for establishing a list of species particularly threatened by climate change. Also, consider amendments to FFG Act and funding arrangements better manage species and habitats threatened by climate change.
	5) Supporting decision making through significant investment in climate science, including potential impacts of step-change events and thresholds
	6) Longitudinal and spatially explicit, quantitative scientific research of international standing on the impacts of climate change in Victoria,
D. Valuing natural capital and ecosystem services Valuing and managing natural capital and ecosystem services Strategic planning, investment and management of landscapes in the future Expansion of ecoMarkets	1) Develop a conceptual framework to value and manage natural capital, and develop methodologies that place economic value on ecosystem services
	2) Assess ecosystem services and natural capital to inform climate change decision making
	3) Integrate these measures into government economic assessments
	4) Further use of market-based approaches to help drive price discovery
	5) Prepare Victoria's landowners for the carbon market – government will need to work with landowners in areas such as education/information programs; development of enterprise level self-assessment tools; supporting development of landowner pooling/brokering services and identifying public/private partnership opportunities for carbon sequestration
	6) Using the carbon market as a way of achieving biodiversity and land protection benefits. This can be done through provision of information, market design and integrating ETS with ecoMarkets to enable harmonisation of the incentive to produce carbon (the ETS will encourage plantations of trees) and the incentive to grow native habitat (provided through ecoMarkets)
	7) Expand ecoMarkets to address new challenges and drivers in relation to climate change, including using its capacity to model the impact of climate change on rural and regional Victoria, including environmental assets such as stream flow, water quality, carbon sequestration; and commodity production and variability including predicted yields for crops and pasture based commodities
E. Social adaptation	1) Research and address barriers to social adaptation, focusing particularly on behavioural change and institutional adaptation

Area for policy action	Potential policies
Engaging with communities and conducting research to inform social adaptation priorities	2) Review government policies, programs and operations to ensure that these support, rather than hinder, social adaptation
	3) Develop a community engagement framework
	4) Developing structural adjustment programs that maintain and enhance economic activity while delivering public good outcomes, for example, improved levels of ecosystem services

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