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Policy considerations for managing wetlands under a changing climate

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Abstract. Drawing on the experience and lessons of wetland researchers and managers in Australia and New Zealand, we examined the implications of climate change for wetland policy and management, and identified potential adaptation responses and the information needed to support these. First, we considered wetland vulnerability to climate change, focusing on wetland exposure and sensitivity. We then outlined the existing policy context for dealing with climate change, with an emphasis on the Ramsar Convention on Wetlands. We then considered how the objectives and targets for wetland management can be set in the face of climate change, how management can be adapted to climate change given the uncertainties involved, and how we can monitor and evaluate wetland condition in the face of climate change. We concluded with a set of principles to guide adaptation of wetland conservation and management policy to climate change.

Additional keywords: adaptation, inland wetland ecosystems, vulnerability, Ramsar Convention.

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Introduction

Wetlands throughout the world have long been subject to high levels of degradation and loss caused by human activities (Finlayson and D'Cruz 2005; Davidson 2014; Gardner *et al.* 2015). Since it came into force in 1975, the Ramsar Convention on Wetlands has been the principal policy instrument for protecting wetlands globally by committing Contracting Parties (i.e. national governments) to designate sites as Wetlands of International Importance (Ramsar Sites) and to monitor and effectively manage these, so as to maintain their ecological character, as well as making wise use of all wetlands (Gardner and Davidson 2011). The juxtaposition of the extent of wetland loss alongside the activities of the Convention led Finlayson (2012) to question the effectiveness of the policy setting for wetlands.

It is increasingly recognised that wetlands are highly vulnerable to anthropogenic climate change and this is likely to have significant consequences for their ecological character (Finlayson *et al.* 2006; Capon *et al.* 2013; Junk *et al.* 2013). Although it is also acknowledged that wetlands respond to changes in climate over different timescales, the focus in the present paper when referring to climate change is on changes resulting from human activities. Within this context, climate change can affect the ecological character of wetlands both directly (e.g. by the effects of warming) and indirectly through interactions with other pressures and stressors (Finlayson *et al.* 2006; Capon and Bunn 2015). This has considerable ramifications for existing policy and management for maintaining the ecological character of wetlands because non-climatic anthropogenic pressures can further affect wetland responses to the climate (Pittock *et al.* 2010) and adds further support for the question raised by Finlayson (2012) about the policy settings for wetlands.

Whereas the Ramsar Convention covers a wide range of wetland types, we focus specifically on non-marine wetlands, including both inland wetlands and coastal and estuarine wetlands influenced by tides, but not primarily marine. Wetlands dominated by marine influences, such as, for example, coral reefs and kelp forests, are excluded from our analysis because their vulnerability to climate change and appropriate adaptation actions are likely to differ in many cases. However, many of the general principles we discuss here will still be applicable. In doing this, we have not provided an overview of wetland policies or more generic conservation or natural resource policies that cover wetland management, but point to recent interest in such policies and, in particular, to Peimer *et al.* (2017) who have recently reviewed national-level wetland policy settings and identified strengths and gaps.

Although there are existing conceptual frameworks for assessing change in the ecological character of wetlands (Finlayson *et al.* 2005; Davis and Brock 2008, DEWHA 2008; Ramsar Convention Secretariat 2010*a*, 2010*b*), identifying and evaluating these changes, and their drivers, in the context of climate change, is particularly problematic. Wetland-policy makers and managers, therefore, require guidance on how to assess and respond to the actual or potential consequences of climate change, especially given the formal obligation of Contracting Parties under the Ramsar Convention to report any adverse changes in Wetlands of International Importance, and the ongoing degradation of wetlands globally.

In the past, the Ramsar Convention has considered its position on climate change in relation to other international treaties (e.g. the United Nations Framework Convention on Climate Change) as well as the various policy positions held by individual Contracting Parties, but has not delivered specific guidance on how to respond to the obligations under the Convention in the face of such change (Finlayson *et al.* 2016; Gell *et al.* 2016). There is a need for the Ramsar Convention to develop a consistent and in-depth approach for dealing with the global phenomenon of anthropogenic climate change because this will affect the ecological character of many, if not all, wetlands (Finlayson 2013).

Policy and management for the conservation of wetlands under a changing climate, therefore, require a review of how objectives and targets are set as well as the actions employed to achieve these. Monitoring and evaluation of wetland policy and management interventions also need to be developed with awareness of climate change and its implications for ecosystems. Although such changes may ultimately be transformative for wetland policy and management, adaptations must be developed in the first instance that consider the existing policy context of the Ramsar Convention and the relevant policies and national legislation of Contracting Parties that give effect to this.

Here, we examine the implications of climate change for wetland policy and management to identify potential adaptation responses and the information needed to support these. First, we consider wetland vulnerability to climate change, focusing on exposure and sensitivity. We then outline the existing policy context for wetland conservation and management, including current approaches dealing with anthropogenic climate change, with an emphasis on global wetland policy. Where relevant, we draw on the case studies of Australia and New Zealand, which collectively represent a wide range of climatic zones and contain a high diversity of wetland types.

Against this background, we then consider

(1) how can objectives and targets for wetland conservation and management be set and revised in light of climate change;
(2) how can wetland management best address the uncertainties caused by climate change; and
(3) how can we monitor and evaluate the condition of wetlands that are responding to climate change?

We conclude with a set of key principles to guide adaptation of wetland conservation and management policy to climate change.

Wetland vulnerability to climate change

Although virtually all species and ecosystems are expected to experience the effects of climate change, wetlands are recognised as among the most vulnerable (Hughes 2011, Capon *et al.* 2013). In this sense, vulnerability is expressed as the relationship between the exposure and sensitivity of wetlands to changes in the climate (Gitay *et al.* 2011). Because of their low-lying position in the landscape, wetlands are typically subject to high levels of exposure to climatic changes because they experience both local changes and the cumulative effects of changes in the surrounding landscape, as well as being exposed to a wide range of extreme climatic events (such as, e.g. floods, droughts, intense storms and fires; Capon *et al.* 2013). They also tend to have a high degree of sensitivity to climatic changes because of their responsiveness to changes in water regimes (Capon and Bunn 2015) and temperature (Hamilton *et al.* 2013). High levels of modification and degradation of wetlands may increase their sensitivity to climate change and limit their capacity to adapt, further increasing their vulnerability. However, highly modified and simplified wetlands may be less sensitive to climate-change effects if their values have been significantly degraded already. Although there is a prevalent view that the probable impacts of climate change on wetlands may be relatively minor in comparison with other anthropogenic stressors (e.g. river regulation), the interaction of climate change with existing threats is of widespread concern, particularly given the uncertainties involved (Finlayson *et al.* 2006; Kingsford *et al.* 2011).

Exposure of wetlands to climate change depends on their regional and topographic position, as well as the emissions scenario that will unfold. Wetlands throughout the world are exposed to increasing concentrations of atmospheric carbon dioxide, as well as warming to varying degrees. Changes to precipitation are particularly important drivers of climate-change impacts in wetlands, with systems reliant on rainfall and runoff likely to be more vulnerable than groundwater-fed systems (Winter 2000). Projected changes to precipitation are highly variable both regionally and among global climate models and emission scenarios.

Effects on water quantity are likely from changes in rainfall and increased temperature and evaporation. Hydrological changes and increased temperature will also affect most biogeochemical processes, in turn altering water quality. Drying, for example, may transform some wetlands from sinks to sources of potentially damaging solutes, e.g. nitrate, sulfate, sodium (Freeman *et al.* 1993). Turbidity and the physical form of wetlands are also susceptible to climate-change impacts because patterns of erosion and sedimentation are highly sensitive to changes in precipitation. Fine-grained alluvial systems are likely to be particularly vulnerable (Goudie 2006).

Wetlands in coastal regions are likely to be further affected by sea-level rise and increased frequency and intensity of extreme storm-surge events (Finlayson *et al.* 2006; Day *et al.* 2008). Coastal wetlands in areas with low relief, such as the extensive freshwater wetlands of Kakadu in northern Australia, are particularly susceptible to saltwater intrusion, with large areas likely to be affected as a result of relatively small increases in the sea level (Bayliss *et al.* 1997; Eliot *et al.* 1999; BMT WBM 2010). Changes in salinity following sea-level rise will then affect the community structure of wetland plants and animals (Schallenberg *et al.* 2003; Finlayson *et al.* 2013). Sea-level rise may further affect changes to geomorphological processes triggered by precipitation change and shifts in vegetation structure.

Wetlands will also be exposed to increases in the intensity of many extreme climatic events, such as fires and cyclones. These processes are likely to affect the natural zonation of many wetland assemblages. In coastal wetlands, for example, the distribution of mangroves, saltmarsh and transitional coastal vegetation communities are likely to shift, although, in some cases, the physical nature of the landscape or built infrastructure will limit such expansion (Rogers *et al.* 2014).

Climate change affects wetland biota both directly and indirectly as a result of secondary effects on the abiotic character of wetlands. Collectively, these changes may mean that the environmental requirements of many species are no longer met or that their tolerance levels are exceeded in their present habitats (Schallenberg *et al.* 2003; Steffen *et al.* 2009). Some species may be able to adapt *in situ*, whereas others may respond by moving or retreating into refugial habitats (James *et al.* 2013). However, the rapid pace of current climate change is likely to exceed the capacity of many organisms to adapt in these ways (Visser 2008). Some wetland biota, including cosmopolitan and invasive species, may benefit from climate change and increase their abundances or ranges as a result. Nonetheless, changes to wetland species composition and extinctions are anticipated (Steffen *et al.* 2009).

The sensitivity of wetland ecosystems and their components and processes to climate change can be aggravated, or, in some cases, alleviated, by other stressors. Drying trends, for instance, are typically occurring in regions where human pressures on water resources are already high. Similarly, climate-change impacts may influence the sensitivity of wetland ecosystems to existing stressors. For example, lowland swamps are exposed to greater disturbance from altered water regimes in situations where they are already associated with flood-protection infrastructure (Dudley *et al.* 2010). The resilience of wetland systems, or the capacity to recover once a pressure is reduced, to different disturbances also varies considerably. Wetlands that have developed under dynamic and variable climatic conditions, e.g. desert wetlands, are often perceived as being more able to adapt to climate change (Füssel and Klein 2006). However, the intrinsic adaptive capacity of many wetland species and ecosystems to climatic changes, either by *in situ* adaptation (e.g. behavioural change or genetic adaptation) or through range shifts (e.g. contraction of population distributions to refuges), is likely to be significantly constrained by the many non-climatic human pressures to which many wetlands are subject (Capon *et al.* 2013; Finlayson *et al.* 2013; Saintilan *et al.* 2013; Bodmin *et al.* 2016).

Current policy context

Most existing international and national environmental institutions were established under the assumption that the environment is largely stationary, with natural variation in hydrology and other biophysical factors centring on a static mean (Milly *et al.* 2008). Consequently, inter-governmental conventions such as Ramsar, along with most national environmental laws, commonly have set targets for conservation policy and management either for specific sites, with defined boundaries, or populations of particular species, within certain ranges or abundances, or both. The Ramsar Convention has established the world's largest network of protected areas with over 2240 sites, covering over 2.16×10^6 km^2, given in the List of Wetlands of International Importance as of 2015 (www.ramsar.org; accessed 12 November 2016). Under the Convention, Contracting Parties are required to prepare and implement appropriate management plans for listed wetland sites and to report on adverse changes in their ecological character, which is defined as the combination of ecosystem components, processes and benefits/services that characterise a wetland at a given point in time (Finlayson *et al.* 2011). Conservation of wetland species is addressed by the Ramsar Convention through a focus on maintaining their habitats, especially areas important for the completion of life cycles and for migratory fauna. To conserve a representative range of wetland types, the Convention also relies on a classification system that defines wetland types on the basis of structural and functional categories (Finlayson 2017). However, listing of sites as Wetlands of International Importance has also led some Contracting Parties to emphasise the maintenance of the conservation values at the time of listing, rather than the restoration of previous values or consideration of the history of change in the wetland (Finlayson *et al.* 2016; Gell *et al.* 2016).

Increasing recognition that the past is no longer sufficient for understanding the future, is exposing institutional gaps in Australia, especially with regards to the provisions for managing important wetlands affected by climate change in the Ramsar Conventions (Pittock *et al.* 2010). In particular, Pittock *et al.* (2010) pointed to the Australian Government policy decision whereby a report of an adverse change in ecological character would not be made where climate change is the principal cause of a change until such time as the Convention provided guidance on an approach to this issue. Pittock *et al.* (2010) further contended that because climate change is human-induced, it should be treated in the same manner as other human-induced pressures, in line with the requirements under the Convention to report human-induced changes in the ecological character of Ramsar sites.

In addition to the conservation of internationally and nationally important wetland sites, many countries and institutions also have 'no net loss' wetland policies, requiring sites that are to be lost for development or other reasons to be off-set by wetland conservation elsewhere (Gardner *et al.* 2012). This concept has been adopted by the Ramsar Convention in relation to sites lost 'in the urgent national interest' or that have irretrievably lost the values for which they were listed. However, replacing wetland sites with 'like for like' is practically, politically and socially, very challenging (Pittock *et al.* 2010; Gardner *et al.* 2012). In recognition of the high level of wetland loss, a further global policy initiative has seen many national governments agree, under the Aichi Targets process of the Convention on Biological Diversity, to conserve at least 17% of the area of inland water ecosystems by 2020 (CBD 2010). However, in Australia (and at the global level), the conservation of existing freshwater protected areas and conservation planning continue to lag far behind the terrestrial and marine realms (Fitzsimons and Robertson 2005; Suski and Cooke 2007; Nel *et al.* 2009).

The Global Biodiversity Outlook and Global Environmental Outlook assessments position climate change, along with growing population, wealth and consumption, as one of several major global changes affecting the environment (SCBD 2010; UNEP 2012). However, although Contracting Parties to the Ramsar Convention have legal obligations to protect wetlands against negative, anthropogenic changes in ecological character, many climate-change impacts on wetlands and their species are beyond the influence of local wetland managers, e.g. changes in inter-continental habitat of migratory waterbirds (Pittock *et al.* 2010; Lukasiewicz *et al.* 2016). Furthermore, in contrast to those associated with non-climatic pressures, objectives and targets for wetland conservation in relation to climate change and climate adaptation are currently flexible and largely dependent on the regional policy position of Contracting Parties.

In addition to the policy direction provided by the Ramsar Convention, some Contracting Parties have policies that provide for climate-change planning for wetlands. Within New Zealand, the *Resource Management Act* (1991) and the recent *National Policy Statement (NPS) for Freshwater Management* (2014) both have provisions for decision makers to have regard for climate change. For example, the NPS directs municipal councils to consider the 'reasonably foreseeable impacts of climate change' when setting freshwater objectives and limits. Within Australia, the *Water Act* 2007 supports sustainable development of the water resources of the Murray–Darling Basin and other matters of national interest. The *Act* includes some consideration of climate-change adaptation, such as identification of climate change as a risk to water resources in the Basin, and identifies strategies to manage those risks. The Basin Plan that was developed as one component of the *Act* considers risks from climate change, aiming to improve knowledge on the impact of climate change on environmental water requirements, and ensuring that water-dependent ecosystems are resilient to climate change and variability, including extreme weather events. Although the Plan further aims to reduce consumptive diversions so as to buffer the impacts to the environment until more is known about the implications of climate change, this strategy has been criticised as inadequate (Pittock and Finlayson 2011; Pittock *et al.* 2015).

Setting objectives and targets for wetlands under climate change

The implications of climate change for wetland ecology necessitate a major review of conservation objectives and targets (Matthews and Wickel 2009; Catford *et al.* 2013). For the Ramsar Convention, the overarching issues raised by climate change concern what wetland policy and management should aim for, given that change in ecological character is highly probable under a changing climate. Solutions will differ depending on the broad adaptation strategy adopted by decision-makers (Table 1). The Convention has adopted an *avoid–mitigate–compensate* framework for maintaining the ecological character of wetlands (Gardner *et al.* 2012; Ramsar Convention 2012). This is supported by several decisions that recognise this

Table 1. Broad adaptation strategies and their implications for setting conservation objectives and targets

Adaptation strategy	Examples of relevant adaptation actions	Implications for setting conservation objectives and targets	Key knowledge needs
Avoid	Sea walls, barrages, water-controlling structures (e.g. weirs)	Maintain existing objectives and targets	Monitoring and evaluation against pre-determined baseline
Accommodate or mitigate	Revegetation, retreat	Revised objectives and targets based on societal choices about values to conserve, while considering the sacrifice or abandonment of other values	Links between wetland ecology and societal values
Accept and compensate	Offsetting	Open-ended or minimal objectives and targets that promote limited intervention	Monitoring and evaluation to understand potential trajectories

three-stage approach, while imperatively avoiding wetland loss. Although not all Contracting Parties use the *avoid–mitigate–compensate* framework, they do often have a similar framework. However, the Ramsar Convention did not specifically link this framework with efforts to address the impacts of climate change on wetlands, possibly as a consequence of the reticence of the Convention to produce specific guidelines for addressing climate change (Finlayson 2013; Gell *et al.* 2016). The three broad steps in the *avoid–mitigate–compensate* framework in the context of climate change are outlined below.

(1) Avoiding climate change

In some cases, managers may seek to *avoid* the effects of climate-change impacts and, thereby, maintain existing objectives and targets. However, given the actual and projected impacts of climate change, this strategy is increasingly untenable, not to mention being expensive and risky (e.g. Capon *et al.* 2013; Kopf *et al.* 2015). Nevertheless, such an approach may be particularly appropriate in the short term for very high-value assets, whereas longer-term strategies can be developed and implemented.

(2) Accommodating or mitigating climate change

The intermediate strategy is to *accommodate* or *mitigate* climate change by choosing strategic, proactive interventions to retain a broader area and range of wetland types, more species and a greater diversity and value of ecosystem services. Setting objectives and targets for conservation that compensate for climate change involve significant societal choices regarding the ecological values for protection (or enhancement) and, therefore, the nature and scale of species and ecosystem types to be targeted. Consequently, transitioning to targets for wetland conservation policy and management that compensate for climate change requires deciding on what should be conserved, at what scale, and with what levels of uncertainty, for example, with respect to timing and impacts (Kopf *et al.* 2015).

(3) Accepting and compensating for climate change

An alternative strategy for setting conservation objectives and targets under a changing climate, in many ways diametrically opposed to the avoidance strategy, is to *accept* and *compensate* for the inevitability of changes or loss of values. Many of the probable ecological impacts of climate change, such as changes in species distributions, are largely beyond management control and, to some degree, must be accepted by society (e.g. Catford *et al.* 2013; Kopf *et al.* 2015). An acceptance strategy promotes the development of 'open-ended' conservation objectives that allow for a range of possible futures and support minimal levels of management intervention (Hughes 2011; Kopf *et al.* 2015). However, such an approach might be criticised for abandoning aspirational target-driven conservation goals and ignoring negative outcomes of human pressures (Hughes 2011). In this context, the acceptance of significant impacts from climate change may discourage wetland managers from taking direct action to rescue or otherwise defend these natural assets.

Even within the context of the *avoid–mitigate–compensate* framework, climate change will inevitably bring change to wetlands. Although climate change is affecting the character and distribution of wetlands, a similar diversity of wetland types as that which exists today is likely to persist under a changing climate, although some novel wetland types may also emerge (e.g. Catford *et al.* 2013). For example, although some coastal wetlands may be lost to sea-level rise or peat wetlands may be lost to drying, new wetlands of the same types may spontaneously develop (Pethick 2002; Acreman *et al.* 2009). Accommodating climate change, therefore, necessitates a greater emphasis on setting conservation targets at landscape, regional and even continental scales, such as, for example, protection of a range of wetland types, and the adoption of systematic conservation-planning principles such as those proposed by Margules and Pressey (2000) and Pressey *et al.* (2007). In such scenarios, at a site-scale, where most wetland management interventions necessarily occur, more open-ended, 'acceptance' conservation targets may be appropriate (Table 1). However, where a wetland is both highly valued and highly vulnerable to climate change, such as isolated, persistent desert lakes, highly interventional 'avoid' type targets may be appropriate, at least in the short term. With respect to wetland biota, this broadening of scale may require a focus on maintaining or restoring corridors for movement in response to shifting conditions, such as, for example, along rivers to cooler, higher altitudes (Lukasiewicz *et al.* 2013) and networks of wintering and migratory staging areas for migratory species (MacLean *et al.* 2008). Protection of refuges that enable wetland biota to persist in contracted ranges is also likely to be important (Davies 2010; Olden and Naiman 2010). However, some wetland species are unlikely to be able to migrate or survive in new locations because of barriers or the disappearance of suitable habitat (e.g. Bayliss *et al.* 1997; Davies 2010). In such cases, conservation targets may need either to accept some level of biodiversity loss or to conserve species through assisted translocation or *ex situ* conservation actions (e.g. seed banks; Capon *et al.* 2013).

Climate change also compels a broadening in the scope, as well as the scale, of wetland conservation targets. In particular, holistic approaches to adaptation necessitate a greater emphasis on ecological function rather than ecosystem structure alone, and social goals, including livelihoods, cultural values, community engagement and education, also require consideration. There is also a critical need to redress the current lack of indigenous participation in wetland management, including water allocation and catchment management in the intact, cultural landscapes of central and northern Australia (Jackson *et al.* 2005). Conservation targets for wetlands should include ecological functions and ecosystem services as well as key species, given that the Convention has included these within its definition of ecological character. An emphasis on ecological functions and ecosystem services can promote integrative adaptation strategies that incorporate a broader range of values and actions and limit the potential for maladaptation arising from overly narrow goals (Capon and Bunn 2015). In this sense, actions that are taken to avoid or reduce vulnerability in one system can often be maladaptive where they lead to greater vulnerability in other systems, sectors or social groups.

Adapting wetland management

In developing adaptation strategies for wetland management, decision-makers are faced with a confusing array of potential

Table 2. Adaptation phases for wetland management, with examples of relevant adaptation measures and information needs

Adaptation phase	Objectives or approach	Relevant adaptation measures (examples)	Key knowledge needs
Now	Build resilience	• Manage existing stressors (e.g. pollution) • Riparian restoration • Flow restoration • Strengthen protected-area networks • Restore connectivity • Improved catchment management • Increase adaptive capacity of community, including stewardship organisations	Monitoring and evaluation against pre-determined baselines
Soon	Address specific impacts	• Focus on non-climatic stressors exacerbated by climate change • Land acquisition • Altered water-management regimes	Monitoring and evaluation to understand potential trajectories Palaeoecological techniques could be used to evaluate potential trajectories of change
Eventually	Transformative management	• Managed retreats and offsets • Species translocations • Hard engineering structures (e.g. water regulators) • Ecological engineering (e.g. over-restoration)	Links between wetland ecology and societal values

options (e.g. Pittock *et al.* 2012; Capon *et al.* 2013). However, whereas some of these might be considered transformative (e.g. species translocations), the majority of proposed adaptation measures are incremental and tend to involve existing tools and strategies presented within a framework of risk and uncertainty and may even be maladaptive in some contexts (Lukasiewicz *et al.* 2013, 2016).

The spatial extent or scope of existing management efforts, for example, may vary in relation to predicted climate-change impacts, such as, for example, greater focus on specific pest species that are likely to become more prevalent under climate change or protection of areas predicted to become future biodiversity hotspots. In general, proposed adaptation actions are designed either to build resilience to climate change through the management of existing threats, strengthening of protected area networks or ecosystem restoration, or are otherwise designed to address specific issues associated with exposure and sensitivity to climate change through 'hard' or ecological engineering actions (Capon *et al.* 2013; Lukasiewicz *et al.* 2013, 2016). Although there are limits to what protected-area design can achieve in terms of climate-change adaptation, enhancing protected-area management can help reduce non-climatic stresses and increase resilience of the ecosystem, as well as enabling efficient adaptive management (Pittock *et al.* 2008, Olds *et al.* 2014). 'Soft' adaptation measures that promote cultural and institutional change, for example, education, are also likely to be essential for effective adaptation to climate change.

Determining adaptation priorities presents a major challenge for wetland managers and requires a flexible, reflective and responsive approach to planning and management. Key factors influencing the selection of adaptation measures include their cost, likely efficacy, potential benefits (including additional benefits beyond adaptation), reversibility, stakeholder support, risk of failure and risk of maladaptation or perverse outcomes (Lukasiewicz *et al.* 2013). Because climate-change risks and uncertainties change over time as new information becomes available or the biophysical and socio-political context shifts, these considerations will also change, necessitating different adaptation decisions at different times. Consequently, we recommend that in developing a toolkit of adaptation options for Ramsar wetland managers, potential actions might be considered in relation to three broad phases or timeframes (i.e. now, soon and eventually) that may also accord with a growing severity of climate-change impacts (Table 2).

(1) Adapting now

In the first phase ('now'), adaptation actions should focus on building wetland resilience to predicted climate-change impacts. In particular, adaptation strategies might have at their core the early implementation of 'no-regret' actions that protect or restore ecological character and contribute to ecological resilience or resistance against future climate-change impacts. For wetlands, such measures will include actions that address existing, non-climatic pressures (e.g. pollution; Robertson and Funnell 2012) and, in many cases, restore or rehabilitate major ecosystem components subject to human modification, such as, for example, flow regimes, physical morphology and vegetation structure (Schallenberg *et al.* 2010; Bino *et al.* 2014*a*). At regional scales, actions associated with improved catchment management, especially the protection and restoration of connectivity within and among wetland habitats, will also build climate resilience for individual wetlands as well as for ecological processes that occur over landscape scales.

Flexible governance (i.e. the ability of institutions and communities to adapt in a changing environment) and rigorous adaptive co-management are essential for the effective management of complex, socio-ecological systems (Armitage *et al.* 2009; Plummer 2013). In many cases, planning and implementation of actions in the first phase of an adaptation strategy will necessitate supporting changes in governance to improve alignment in policy, reduce redundancy in planning and maximise cross-sectoral efficiencies and benefits. Similarly, developing adaptive co-management frameworks can facilitate a pathway through highly complex, multilevel, hydrological, ecological and social processes (and institutional arrangements). Whereas watershed- or catchment-scale management remains the key spatial framework, ultimately, integration of governance, legislative and regulatory frameworks across sectors and scales is essential for effective wetland management (Kingsford *et al.* 2011).

Local-scale, 'bottom-up', co-management frameworks also provide an effective approach to developing integrated, participatory and adaptive governance arrangements, particularly because they can be tailored to specific socio-ecological contexts (Berkes 2009). These may be particularly effective for managing wetlands in remote, decentralised regions, such as many of the indigenous cultural estates in central and northern Australia where socio-ecological systems are highly varied and complex, and local cultural and livelihood values and community management aspirations are high (Jackson *et al.* 2005). These community-based, participatory adaptation planning arrangements can also facilitate the consideration of a wider range of climate-change impacts and adaptation options and further enable the development of 'bottom-up' vulnerability assessments, management strategies and monitoring designs (e.g. Bino *et al.* 2014*a*).

Implementing governance arrangements that ensure the timely collection and assessment of information regarding wetland vulnerability, climate-change impacts and other pressures is also likely to be critical in the first phase of any adaptation strategy. Decisions made in later phases will strongly depend on ecological response models based on appropriate observations and understanding of long-term changes in the ecological character (Finlayson *et al.* 2016). Knowledge of ecosystem services provided by wetlands, and the ecological patterns and processes underpinning these, will also be crucial for decisions regarding the priorities for adaptation action (Capon and Bunn 2015).

(2) Adapting soon

In the second phase ('soon'), actions will need to be more closely related to particular climate-change effects occurring within the specific biophysical context of concern. Wetland managers will have to grapple with impacts that transpire despite global mitigation efforts, while also addressing new and stronger anthropogenic pressures that occur in response to climate change (e.g. higher demand for water resources; Capon *et al.* 2013). The use of formal decision support systems such as Bayesian belief networks (Ticehurst *et al.* 2007, Gawne *et al.* 2012) and multi-criteria decision analysis (Zsuffa *et al.* 2013), which are easily iterated with updated information, may prove useful in the adaptive management of wetlands within the context of climate change.

Existing management approaches for dealing with such pressures may need to be substantially revised where threats are exacerbated by climate change directly or indirectly as a result of interactions among multiple stressors. If adaptive management strategies, including monitoring, and other flexible governance arrangements, have been effectively implemented in phase one, decision-making in this second phase of adaptation should be informed by a greater understanding of wetland vulnerabilities and likely responses to impacts. This may enable more direct attention to climate-change effects in wetland management and the consideration of more explicit adaptation actions such as land acquisition in areas adjacent to wetlands or significant changes to water management regimes.

(3) Adapting eventually

In the third phase ('eventually'), more transformative adaptation options may be required to protect highly valued wetland components and services where these are also highly threatened by direct and indirect climate-change impacts. This may involve the use of hard infrastructure to protect some wetland assets, ecological-engineering techniques that promote *in situ* transformation (e.g. over-restoration such as planting riparian zones with fast-growing, high-shade species) or the assisted translocation of wetland assets (e.g. species; Capon *et al.* 2013). In each of these cases, actions to protect specific high-value wetland assets or ecosystem services are likely to entail a magnified risk to non-targeted assets and services, as well as a higher degree of failure, and thus should be implemented with safety margins and regular reviews (Capon *et al.* 2013; Capon and Bunn 2015). These risks are illustrated by the negative consequences of the 'environmental works and measures' (infrastructure) being implemented in the Murray–Darling Basin (Pittock *et al.* 2012). In other cases, threats to wetlands may be so great that such adaptation options are perceived to exceed reasonable levels of expense and risk. Consequently, sacrifice of some wetlands may be required, such as, for example, delisting Ramsar Sites from the Ramsar Convention or relinquishing previous management regimes, although these are very likely to be seen as measures of last resort, such as outlined by the Ramsar Convention for delisting of sites (Pittock *et al.* 2010). Investment may be more effectively directed in these instances, by offset programs, to areas that are less vulnerable to climate change or that support new or improved ecosystem services.

In sequencing adaptation options through these three phases, it is important that trigger points and thresholds are identified through monitoring to help determine when new actions should be implemented. This helps keep options open and avoids path dependency, but importantly too, avoids unnecessary expenditure. Thresholds can account for the ability of a wetland to survive in its current form and may define particular wetland conditions, which, once attained, indicate that a different management approach or phase is required (Barnett *et al.* 2014; Wise *et al.* 2014).

Monitoring and evaluation

Monitoring and evaluation are two essential inter-related prerequisites of any management-planning framework for wetlands (Finlayson 1996*a*, 1996*b*; Ramsar Convention Secretariat 2010*a*), and are expected to be more critical under a climate-affected future where assessing change and responses to adaptation will be important (Pittock *et al.* 2010). Set up properly, monitoring and evaluation underpin the feedback loops of

Table 3. Link between the ecological relevance and early warning capability of indicators used for measuring change in wetlands
Adapted from van Dam *et al.* (1999)

Early warning capability					
High		Medium			Low
Low level of ecological relevance					High level of ecological relevance
Subcellular, e.g. DNA alterations	Physiological, e.g. respiration, heart beat, feeding inhibition	Whole organism: Chronic, sublethal, e.g. reproduction, growth	Whole organism: Acute, lethal, i.e. mortality	Population responses	Community-based responses, e.g. rapid biological assessment

management frameworks to track the success and failure of management strategies and the ability to achieve agreed conservation objectives. Although the Ramsar Convention provides guidance for establishing monitoring programs and management plans (Finlayson 1996*a*; Ramsar Convention Secretariat 2010*a*), these have not specifically considered the projected impacts of climate change.

The Ramsar Convention defines monitoring as a hypothesis-based exercise, to differentiate it from the more general 'surveillance' and 'survey' activities that are often conducted in many wetlands (Finlayson 1996*b*; Finlayson *et al.* 1999; Ramsar Convention Secretariat 2010*a*). Monitoring is based on the selection of indicators that are used to determine the extent of change that has occurred in a wetland and whether this exceeds either an ecological or a management threshold. However, because there can be significant uncertainties about how the climate will change over time, and how those changes will manifest themselves on wetlands, it may prove difficult to identify plausible thresholds that can then be tested. These uncertainties are likely to be minor in the short term and increase over time; however, uncertainties will are likely to vary, given that climate projections indicate a range of possible scenarios for wetlands.

The use of indicators suitable for reporting on multiple stressors, including climate change, could promote greater efficiency and broader adoption by natural resource-management agencies. For example, national monitoring of water quality in New Zealand lakes is required for State of the Environment reports and enables long-term assessment of temperature-induced changes on lake systems (Hamilton *et al.* 2013). However, experience in the Murray–Darling Basin in south-eastern Australia has shown that data collected for one purpose may not be suitable for addressing other aims, at times being inconclusive or punctuated by gaps, and open to contradictory interpretations (Colloff *et al.* 2015; Kingsford *et al.* 2015).

When considering what to monitor, or what indicators to use, a variety of social, economic and environmental criteria should be considered. The choice of an ecological indicator is a critical step for supporting management actions, because a failure to detect thresholds in an ecosystem or species can significantly affect decision making and ignore important information (Eiswerth and Haney 2001). Given limited resources, biotic surrogates of wetland condition have often been used, and these should be easily detectable, measurable and sensitive to ecological change. Waterbirds, among the more conspicuous of wetland animals, are a vital component of wetland function, and have been regularly used as indicators of the condition of a wetland (Kingsford and Auld 2005; Bino *et al.* 2014*b*). Native freshwater fish and invertebrate communities are also directly influenced by changes in flow regimes (Death *et al.* 2016), making them potential climate response indicators. Wetland vegetation is strongly influenced by hydrological changes and is commonly used as an indicator of the condition of a wetland (Clarkson *et al.* 2004; DSE 2007). Physico-chemical indicators that are used to monitor trends in ecological processes, such as water regimes, are important for evaluating the cause of biotic shifts (Schallenberg *et al.* 2003, 2010).

The Ramsar Convention has recommended monitoring early warning indicators whenever feasible, but also points out that many indicators with high ecological relevance, such as waterbirds or fish, may not provide sufficient early warning (van Dam *et al.* 1999; Ramsar Convention Secretariat 2010*b*). Indicators that provide early detection capabilities (e.g. physiological indicators) may be different from ecological indicators that would be selected to monitor the state of key ecological values of wetlands (see Table 3). This is an important consideration and, given limited resources to address wetland management issues, may provide a basis for a clear understanding of the value of monitoring and the capacity to understand both the extent and cause of change and its significance. The Convention has considered the limits of acceptable change in wetlands (Ramsar Convention Secretariat 2012), but has not provided guidance for the establishment of such limits.

Identifying trigger levels and thresholds indicating when new actions should be implemented, is also required. Trigger levels should include consideration of the lead-up times required for the actions to come into effect, including time for engagement with stakeholders and accessing funding. As actions become more transformative and potentially controversial, longer lead-up times for stakeholder engagement may be required. Engaging with stakeholders and realising the benefits that can accrue from citizen science can assist with obtaining the information needed for identifying limits of change and triggers. The Convention has also recognised the importance of engaging with local communities and indigenous peoples to support wetland management and monitoring, as has occurred in both Australia and New Zealand (Townsend *et al.* 2004; Ens *et al.* 2012).

There has been increasing interest in the use of conceptual models to determine how and when changes in wetlands may become obvious and to illustrate the links between cause and effect. Models of ecosystem behaviour, such as state and transition models (STMs or S&T models), can provide flexible conceptual frameworks of change (Westoby *et al.* 1989) and are fully compatible with approaches suggested by the Convention for describing the ecological character of a wetland and evaluating the extent or importance of any change. STMs are grounded on the concept of a collection of possible alternative states, each with a domain of requirements, separated by thresholds of transitions between states (Briske *et al.* 2008). State and transition models are particularly useful to communicate understanding of ecosystem dynamics among scientists, managers and policy makers (Ludwig *et al.* 1996), as well as in identifying alternative management opportunities (Czembor and Vesk 2009; Bino *et al.* 2013). There is a real need for selecting indicators and monitoring approaches that can signal that a system is nearing a threshold or tipping point (Capon *et al.* 2015).

As climate change intensifies, potentially surpassing those changes brought about by river regulation or agriculture-induced nutrient loading, established adaptive management approaches will need to be revised because changes from climate may become apparent faster than changes as a result of management.

This requires a change in attitude towards ongoing quantitative monitoring, aimed at assessing the outcomes of management actions and to continuously improve ecological response models. Through the application of vulnerability and risk-assessment approaches, it is feasible to focus on those biogeographical regions where the projected impacts caused by climate change are cause for concern. For example, reduced rainfall is expected to occur in the northern and eastern areas of New Zealand and the predicted reductions in rainfall are most likely to affect bog and gumland wetland types in New Zealand (Bodmin *et al.* 2016). In Australia, greatest rainfall reduction is expected to occur in southern Australia (CSIRO and Bureau of Meteorology 2015). Conceptualisation of the risk of climate change has been used to consider the consequences for wetlands along the Murray River, located in this region. (Pittock and Finlayson 2011). The Ramsar Convention has provided guidance for risk and vulnerability assessment (van Dam *et al.* 1999; Gitay *et al.* 2011) within an integrated framework for inventory, assessment and monitoring (Ramsar Convention Secretariat 2010*b*).

Evaluation provides an opportunity to integrate the results from monitoring, along with feedback from stakeholders about particular wetlands within the scope of an appropriate management plan. It enables decisions to be made about what has been achieved, what changes should be implemented, and what information is available for sharing with stakeholders. The evaluation process can be broken up into three cycles with varying time-scales, dependent on the inherent dynamics of the system. The first relates to the evaluation of whether management actions are successful in achieving set goals, and either re-validating management strategies or developing new ones accordingly. The second evaluates the accuracy of the underlying model of the system, on which management strategies were initially developed. The third evaluates the success or failure to reach desired states and whether there is a need to change goals and objectives to more tangible ones. The outcomes of the evaluation will also inform, for Ramsar Sites, the urgency in responding to likely or actual human-induced changes in the ecological character of a wetland.

Principles for adapting wetland policy and management under climate change

Our examination of the implications of climate change for wetland policy and management was based on the three questions presented in the Introduction. We conclude with a set of key principles to inform wetland conservation and management policy within the context of climate change; these are as follows:

(1) Objectives and targets for wetland management should look mainly (but not exclusively) to accommodate and compensate for climate change, rather than accepting or avoiding impacts, especially in early phases of adaptation.

Given expected changes in wetland species and habitats this is more likely to be achievable by emphasising the benefits that can accrue by protecting wetland functions and ecosystem services as well as (or instead of) key species.

(2) Objectives for wetland management under climate change should include ecological, social and economic targets across multiple scales and consider ecological issues including representativeness, connectivity and refugial values.

Setting such objectives and targets will involve significant societal choices and will rest on decisions concerning what should be conserved and at what scale. In some cases, it may be necessary to accept some level of biodiversity loss.

(3) Flexible, governance and adaptive co-management frameworks across multiple scales and sectors are essential to managing wetlands under climate change.

Such frameworks should each be specific to a given situation, reflecting the diversity and complexity of social-ecological systems.

(4) Easily reversed, no-regret or low-regret adaptation options with multiple, cross-sectoral benefits should be implemented in the initial phases of adapting wetland management.

This should be in concert with the introduction or strengthening of adaptive management frameworks, especially relevant monitoring and spatial decision-support tools (to explore trade-offs and build consensus).

(5) Long-term management strategies should identify triggers for new actions, including novel or high-risk adaptation options (e.g. species translocations) and should plan for such eventualities.

It may be difficult to identify such triggers, given significant uncertainties about the rates and directions of climate change as well as the particular responses of wetlands. Conceptual modelling may assist with the identification of triggers.

(6) Scientific monitoring and evaluation of management strategies are needed.

This is to enable decisions to be made about what has been achieved, what changes and trade-offs should be implemented, whether there is a need to modify goals and objectives, and what information is available for sharing with stakeholders.

Research should focus on determining relationships between ecological patterns and processes and wetland values and ecosystem services and how these may respond to climate change and management actions. Although the Ramsar Convention has prepared extensive guidance for Contracting Parties on how to implement appropriate management plans for listed wetlands and to report on adverse change in their ecological character, it has not delivered specific guidance on how to respond to these in the context of climate change. With this in mind, the above-described principles are intended as a step to address this gap and provide wetland managers with guidance on responding to the increasingly dire condition of wetlands worldwide, which, in many cases, will be exacerbated by climate change.

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