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Muir-Byenup System Ramsar site: Climate-ready vulnerability assessment

Prepared for the Australian Government Department of Environment and Energy

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Australian Government

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Contents

Figures

Tables

Introduction

This case study of the Muir-Byenup System Ramsar site and another of Bool and Hacks Lagoons Ramsar site were prepared to test and illustrate application of the *Methodology for analysing the vulnerability to climate change of Ramsar wetlands sites* (Dunlop & Grigg 2019). They were implemented by the authors of the methodology, using generalised knowledge of the impacts of climate change on wetlands and readily available information about the sites in the recent past (largely the Ecological Character Descriptions and Ramsar Information Sheets, but also other material provided by the site mangers).

The case studies illustrate the steps of the methodology and will provide useful guidance in interpreting the analysis steps. However, ***they should not be regarded as definitive "CSIRO assessments" of the vulnerability of the two sites, and it should not be cited as such.*** They were not conducted by the site managers, nor through a deliberative group process drawing on a broad base of knowledge and local expertise, as it was intended the methodology should be implemented. They were also largely completed before final adjustments to the methodology were made so there may be some small inconsistencies.

The information presented in this analysis was from the following sources:

- Ecological character description (ECD): Farrell, C. and Cook, B. 2009. Ecological Character Description of the Muir-Byenup System Ramsar Site South-west Western Australia: Report prepared for the Department of Environment and Conservation, CENRM085. Centre of Excellence in Natural Resource Management, University of Western Australia. September 2009.
- Draft preliminary assessment of change in ecological character (2016)
- Information Sheet on Ramsar Wetlands (RIS) for the Muir-Byenup System, WA
- Department of Environment and Conservation 2012, Perup management plan 2012, Department of Environment and Conservation, Perth
- Conversations with staff from Biodiversity and Conservation Science within the Department of Biodiversity Conservation and Attractions (DBCA)
- Climate change projections from *Climate Change in Australia* https://www.climatechangeinaustralia.gov.au/
- Generalised (not site specific) knowledge about the impacts of climate change on wetland ecosystems
- Department of Water 2015, *Selection of future climate projections for Western Australia*, Water Science Technical Series, report no. 72, Department of Water,

Stage 1. Understanding context

Steps 1-8

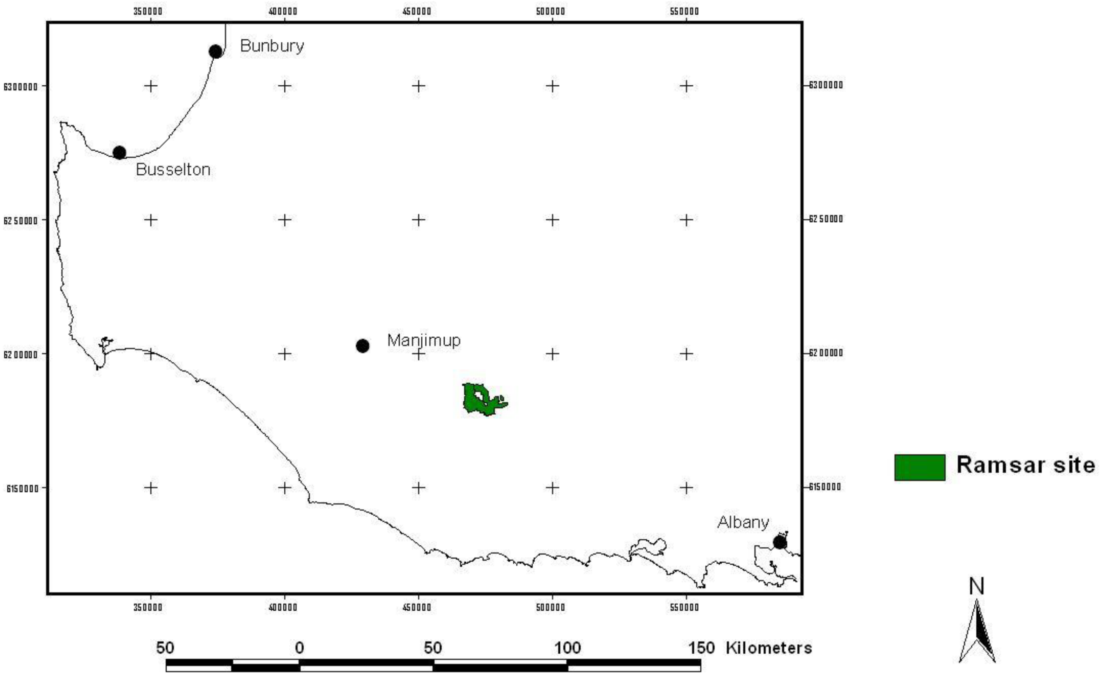


Figure 1 Location of Muir-Byenup Ramsar site

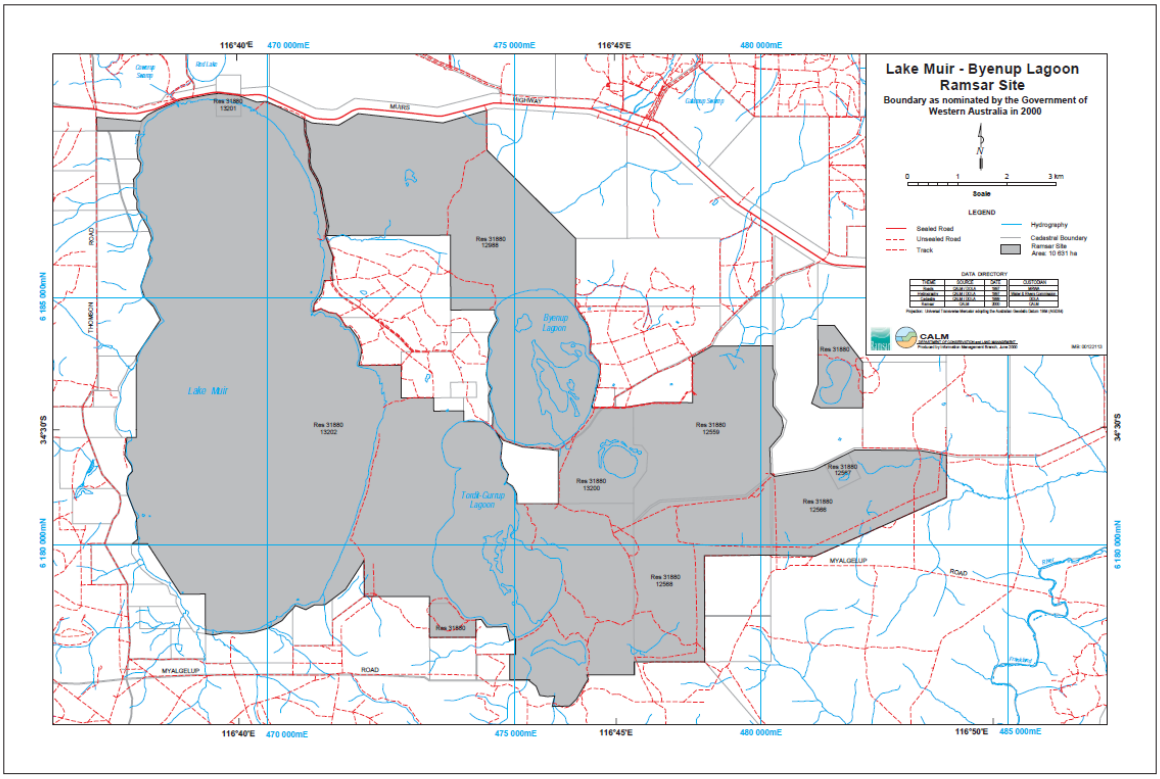


Figure 2 Map of the Muir-Byenup System

Table 1 Key characteristics of the site

<table>
<tr><th>CHARACTERISTICS</th><th>MUIR-BYENUP SYSTEM CASE STUDY</th></tr>
<tr><td>Physical description</td><td>

Partly inter-connected wetlands that range in size, salinity (saline to fresh), water permanence (permanent to seasonal) and substrate (peat and inorganic)

Site includes:

- Lake Muir (WA048)
- Byenup Lagoon (WA046)
- Tordit-Gurrup Lagoon
- Poorginup Swamp
- Neeranup Swamp
- Coorimup Swamp
- Wimbalup Swamp
- reserves in the surrounding area

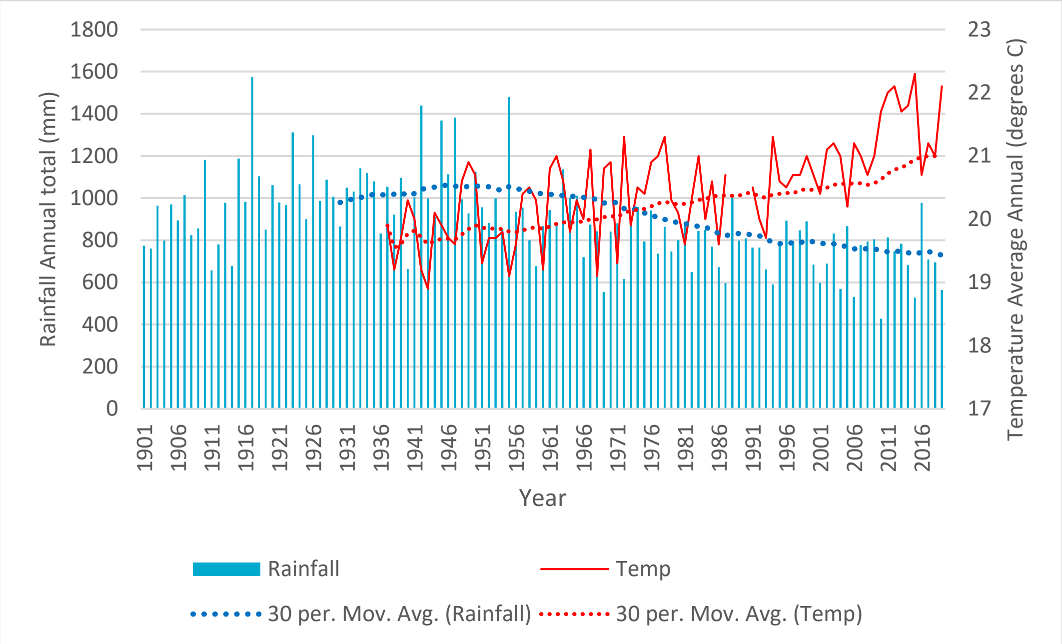
Physical features of the site as described in the 2009-2012 Ramsar Information Sheet (RIS)

The Muir-Byenup System Ramsar site contains an unusual complex of wetland types and includes: Lake Muir (4,600 ha); and the Byenup Lagoon System, comprising of smaller lakes and swamps (notably Byenup Lagoon, Tordit-Gurrup Lagoon and Poorginup Swamp: each 140-690 ha) and inter-connected flats, all of which are natural wetlands. Lake Muir and most of the other wetlands are terminal drainage basins.

Lake Muir is seasonal, often dry in autumn (dry for 9 out of 10 years between 1998-2008) with the maximum depth recorded since 1978 at 1.3 m. Lake Muir is a naturally saline wetland and acts as a shallow evaporating basin.

Byenup Lagoon is permanent with the maximum depth recorded at 2.6 m. Some of the other wetlands are permanent or near-permanent, though peaty, Poorginup Swamp usually shows little or no surface water, and the minor swamps and broad flats are inundated or waterlogged only in winter and spring. Poorginup Swamp is fresh and the other wetlands range from brackish to saline, with increased salinity in summer. Byenup Lagoon, Tordit-Gurrup Lagoon and Poorginup Swamp are peat swamps, formed by climatic conditions, very slow water movement and a shallow lake basin, and strongly influence water quality and provide a very effective filter and buffering capacity (Department of Environment and Conservation 2008). Poorginup Swamp is acidic and the other wetlands have a pH ranging from 7-9.

Current and historic climate - temperature and rainfall



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CHARACTERISTICS	MUIR-BYENUP SYSTEM CASE STUDY
	Groundwater (from ECD where more detail can be found) The Muir-Byenup System Ramsar site is part of a small internally draining groundwater basin and has groundwater TDS values ranging from 500 to 90,000 mgL-1 (0.5-90 ppt) (seawater ~35,000 mgL-1 , 35 ppt). The groundwater flow direction changes from southwest (in the north of the area) to west and northwest in the south of the area. Where the groundwater flows converge, the chain of wetlands exist. Groundwater is mostly discharged as evaporation through Lake Muir. **Surface water** (from ECD where more detail can be found) The Lake Muir-Unicup catchment is approximately 694 km2 and shares imprecise boundaries with the south-flowing drainages of the Tone, Deep and Frankland rivers (Smith 2003). Lake Muir, at approximately 41 km2 is the largest surface waterbody in the catchment, and is almost exclusively internally draining (Smith 2003). Other wetlands overflow to downstream wetlands or waterways such as the Tone or Frankland rivers (Smith 2003). Water is derived from minor seasonal streams of up to 5 km long within a surface catchment that covers about 38,500 ha (Department of Conservation and Land Management 2003). There are also a number of constructed channels that drain adjacent farming land and divert runoff into wetlands or directly into the Tone River (Smith 2003). Depending on rainfall, evaporation and groundwater connectivity, wetlands in the Muir-Unicup catchments are either; permanent or ephemeral, naturally fresh, naturally saline or seasonally alternating (Smith 2003). These wetlands can belong to groundwater systems overlying poorly conductive clays or they may be "windows" to deeper regional aquifers, depending on their position in the landscape (Smith 2003). The Lake Muir-Unicup catchment has been divided informally into a number of subcatchments, including: Lake Muir, Unicup and Yarnup (Figure 10) (Smith 2003). It is not a regulated system, and so changes in water level reflect climate and land use change. There are nearby wetlands that are not included within the Ramsar site (e.g. Noobijup Lake), and yet hold similar characteristics (e.g. peat, bird habitat).
Institutional context	Managed by Parks and Wildlife Service at the Department of Biodiversity, Conservation and Attractions Ramsar listed since January 2001 Water use managed by the Department of Water and Environmental Regulation Lands traditionally associated with the Noongar people Cooperative management of catchment with community participation
History of use and change	**Historic stages** History of land clearing (1960s and 70s) altered water balance and contributed to rising water tables and mobilisation of salt History of peat mining (e.g. Cowerup Swamp) Drainage works have contributed to salinisation Tordit-Gurrup acidification: • historically permanently inundated • declining rainfall since 1970s • lake bed dried summer/autumn 2013 • dried lake bed exposed soils and sediments containing sulphides which oxidised during rewetting and acid was mobilised within the water body • wildfire in 2013 burnt ~85ha including a peat area, which exacerbated acidification process by cracking and exposing the peat • significant decline in abundance and diversity of waterbirds at Tordit-Gurrup from 2015 (preceded by no trend from 2009 to 2014). **Current use** • no competing uses of water resources in the catchment: groundwater development is limited, and surface water allocation has been set to nil for reasons of environmental protection • no land use within the site other than nature conservation (e.g. revegetation activities) • surroundings and catchment: agriculture (grazing and tree plantations), peat mining, history of timber extraction from surrounding State Forest. Many of the tree plantations (Pine and Blue Gum) have been removed in recent years – with potential positive implications for water availability • human population of ~20 within the surface catchment

CHARACTERISTICS	MUIR-BYENUP SYSTEM CASE STUDY
Current stakeholders and their relationships (values at stake)	Site managers: Ramsar and state conservation values People and local organisations that have varying interest in conservation of wetlands: conservation and stewardship values, sense of responsibility, community connections. Land uses adjacent to the Ramsar listed wetlands, include tree plantation and mining of peat are known to increase risk to the wetland values. Recreation and tourism: The bird observatory is used for nature study/appreciation activities. The site is also a peaceful, scenic site for rest stops and overnight stays for travellers. Scientific and educational: • The Muir-Byenup peats are amongst the oldest in the world. Peat wetlands are rare in Western Australia, and the Muir-Byenup peat wetlands are among the most outstanding examples in the State. • Monitoring data and paleo-studies have are a rich source of insights into past climatic regimes, vegetation and fire history. • The bird observatory is a base for educational tours and field trips to increase awareness of and appreciation for multiple values of the Muir-Byenup system, including its history and conservation values (e.g. https://www.youtube.com/watch?v=qZcDcaqNWug). Bird watchers: (see recreation and tourism) Spiritual and inspirational: spiritual significance for the Noongar people, and at least one Aboriginal site occurs on the Ramsar site (Mulgarnup Swamp complex an important site for Aboriginal women). European historical sites within the site. The Ramsar site is included within the Lake Muir area registered on the Register of National Estate for its high aesthetic values. Local landholders: cooperative catchment management, including commercial and non-commercial tree crops for water quality improvement in the catchment, weed and pest control. Connections to and love of place fostered by stewardship activities (e.g. https://www.youtube.com/watch?v=GIDj2P3dYYY).
Ecological character description, listing criteria and other listed values	**ECD** Partly inter-connected wetlands that range in size, salinity (saline to fresh), water permanence (permanent to seasonal) and substrate (peat and inorganic) Internally draining catchment High diversity of flora species Important waterbird habitat and refuge Endemic freshwater fish and aquatic macroinvertebrates Hydrological regime is a critical component and process. The limit of acceptable change (LAC) for the Byenup Lagoon system is "Wetlands should not dry out to avoid acidification of acid sulfate soils and to maintain macroinvertebrate communities". The LAC is considered to be a good indicator of change with a high level of confidence. pH is a critical component and process. The ECD does not provide quantitative LAC, but presence of endemic aquatic macroinvertebrates is a surrogate measure, and is considered a good indicator of change with high level of confidence. **Ramsar Criteria descriptions in the 2009-2012 Ramsar Information Sheet (RIS)** C1: The Ramsar site is an excellent example of a wetland complex in a relatively undisturbed condition in the South-West Coast Australian Drainage Division (Environment Australia 2001). The peat based wetlands within the site are rare in Western Australia (Department of Environment and Conservation 2008; Environment Australia 2001) and they are also recognised as the most outstanding example in south-western Australia (Wetland Research and Management 2005). C2: The Ramsar site supports a number of species listed under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). Populations of three wetland dependent orchids *Caladenia christineae*, *Caladenia harringtoniae* and tall donkey orchid (*Diuris drummondii*) occur on the margins of Lake Muir and elsewhere in the Ramsar site. These orchids are listed as Vulnerable under the EPBC Act and inhabit seasonally inundated areas or wetland margins. The Ramsar site supports the freshwater fish species Balston's pygmy perch (*Nannatherina balstoni*), which is listed as Vulnerable under the EPBC Act. The Ramsar site also supports the Australasian bittern (*Botaurus poiciloptilus*), which is listed as Endangered under the IUCN Red List. In Western Australia, the Australasian bittern population is now much restricted, with the largest concentration thought to occur within the Ramsar site (IUCN 2008). C3: Peat and primary saline wetlands at the site support endemic species and populations of plant and animal species important for maintaining the biodiversity of the South-West Coast Australian Drainage Division. The site includes 21 'priority taxa' listed by the Western Australian Department of Environment and Conservation (DEC), including endemic plant taxa *Eryngium sp*. Lake Muir and *Tribonanthes sp.* Lake Muir. *Astartea sp*. Lake Muir is also endemic to the site. The majority of the

CHARACTERISTICS	MUIR-BYENUP SYSTEM CASE STUDY
	population of Wurmbea sp. Cranbrook also occurs at the Ramsar site. The Muir-Byenup System Ramsar site supports six of the eight endemic south-western Australian freshwater fish species including; the western pygmy perch (*Edelia vittata*), Balston's pygmy perch (*Nannatherina balstoni*), Nightfish (*Bostockia porosa*), Western Minnow (*Galaxias occidentalis*), black-striped minnow (*Galaxiella nigrostriata*) and mud minnow (*Galaxiella munda*). The Ramsar site also supports a number of important macroinvertebrate taxa, including 32 endemic taxa (Storey 1998). C4: The Muir-Byenup System Ramsar site supports thousands of Australian shelducks (*Tadorna tadornoides*) during their moulting phase. The Ramsar site supports breeding of little bittern (*Ixobrychus minutus*), spotless crake (*Porzana tabuensis*), Australasian bittern, black swan (*Cygnus atratus*) and Eurasian coot (*Fulica atra*). The Ramsar site is also used as a drought refuge by tens of thousands of waterbirds and supports 10 species identified under international migratory agreements (CAMBA, JAMBA, ROKAMBA, and CMS). C5: Up to 52,000 waterbirds (1989) have been counted at Lake Muir during periods of high water levels. Although there is no comprehensive data available on waterbird numbers since 1989, it is likely that the Ramsar site is still capable of regularly supporting more than 20,000 waterbirds as there has been no major change in water depth or salinity. Annual data on water depth, over a 25 year period, suggests that conditions were suitable for use by 20,000 waterbirds at least several times over this period. C6: The Ramsar site supports at least five, and possibly up to 10, Australasian bitterns, which exceeds the 1% population thresholds for south-western Australia (Wetlands International 2006). Although, no comprehensive counts have been made since 1991, there has been no major change in water quality or wetland vegetation at the site, suggesting that conditions remain suitable to support 1% of the south-western Australian population. The site also contains the core component of a wider suite of wetlands that constitutes one of the five remaining refuges for the south-western Australian population of Australasian bitterns.
Current threats and changes	Climate change impacts on hydrological and fire regimes Lake bed drying: • Declining rainfall since the 1970s has led to declining groundwater levels and lake water levels • Declining water levels have been attributed to climate change due to no competing uses for surface water and minimal groundwater development • Surface water level data collected in 2015-2016 show summer levels in all wetlands within the Muir-Byenup System Ramsar site are at a record long term low. Acidification due to lake bed drying: • Acidification event within the Tordit-Gurrup Lagoon led to surface water pH below 3, observed in winter 2013, reported to Australian Government September 2014. Declining pH has also been observed in Noobijup Lake (7km northeast of the site), indicating potential for impacts to extend beyond Tordit-Gurrup to other wetlands in the Muir-Byenup system. Fire: • When peat areas of the wetland is burned it exacerbates acidification by cracking and exposing the peat • Too frequent/inappropriate fires lead to destruction of peat, and retardation of regeneration of wetland shrub thickets used by breeding waterbirds Introduced plants and feral animals • Foxes, deer, cats, dogs, pigs, rabbits, horses • Introduced plants (e.g. *Typha orientalis*) in some wetlands Salinisation of surrounding areas Seismic activity and associated abrupt changes to hydrogeology All of the above, and interactions between them, include potential thresholds of permanent change from which there can be no return. Drainage works releasing acids from acid sulfate soils. Pathogens (e.g. *Phytophthora*, *Armillaria*) and pests Illegal vehicle access Eutrophication Loss of vegetation on neighbouring farms

CHARACTERISTICS	MUIR-BYENUP SYSTEM CASE STUDY
Responses to recent extremes	The changes described above have been extremes in rainfall and groundwater reductions, lake bed drying, acidification and fire.
Current management activities and priorities	The type and frequency of monitoring differs between the wetlands: • Water level • Water chemistry • groundwater level monitoring • Macroinvertebrate survey in 2015 • waterbirds Weed and pest control (in cooperation with landholders) Wetlands have been designated as a "Key Wetlands and Natural Diversity Catchment" under the Salinity Action Plan for WA. Commercial tree crops, non-commercial plantings or recharge and discharge areas have been undertaken as joint operations between DEC and landowners to improve water quality. Falling groundwater levels mean that groundwater licencing is becoming more important for groundwater management. There are threatened species which bring the potential for EPBC referrals and associated management priorities. It is part of a protected area and subject to prevailing government policies and decisions. **Tordit-Gurrup Lagoon** • Water supplementation to Tordit-Gurrup Lagoon has been considered but determined to not be feasible due to the lack of a sustainable water source. • Aerial application of lime has been considered, however, advice from peat researchers points to risks to health of peat and vegetation which comprise a significant area of the wetland. • Targeted applications of lime to central locations in the lake and the use of a carbon source to buffer acid-forming processes are under consideration, yet to be assessed (as reported in Sep 2016).

Stage 2. Scoping future impacts

Table 2 Uncertainties

UNCERTAINTIES
Detailed studies into the complex hydrogeology have highlighted uncertainties in the ability to accurately model water movement in the system or how it responds to altered rainfall. Focussed hydrogeological modelling has improved understanding of this complexity and its implications for future management decisions. It is very challenging to reduce uncertainties and ascertain the key drivers of the hydrogeology because there are multiple compounding factors, including: • complex flows that cannot be gauged (e.g. sheet flow, braided drainage systems, groundwater interactions between surface water and vegetation water demands) • paleovalley complexes that are difficult to fully characterise • a high level of heterogeneity across the site e.g. paleovalleys with poor water retention and highly variable hydroperiod interspersed with Holocene-based carbon rich substrate with high water retention and more predictable hydroperiod • varying degrees of connection/disconnection with groundwater reserves and surrounding land use influences • seismic activity that historically has moved water around and is likely to do so again in the future, e.g. opening up fissures that see rapid vertical water movement into or out of wetlands • initial intuition is a poor guide, with careful research commonly overturning preconceptions about how the system works
Mapping of peat within the Ramsar site has not been undertaken, and the extent of peat that was burnt in 2013 fire is unknown (as reported in Sep 2016 assessment).

UNCERTAINTIES
Uncertainty in whether the pH LAC has been exceeded at Tordit-Gurrup or not. September 2016 assessment states: "Data from an aquatic macroinvertebrate survey undertaken in 2015 (following on from the surveys in 1996/97 and 2003/04) are still being analysed and may take some time to complete due to the complex taxonomy of some invertebrate species (A. Pinder pers. comm. 23/12/2015). Therefore it is not clear at this stage whether the limit of acceptable change relating to pH has been exceeded at Tordit-Gurrup Lagoon."
Uncertain whether recent declines in waterbirds at Tordit-Gurrup are transient or part of a persistent longer-term trend
Uncertain current state and future trajectories of change for macroinvertebrates, vegetation, fish, amphibian and reptile populations and the degree to which they will be affected by threats such as increasing acidity and salinity.

Step 9 Key climate change concerns for the site

Table 3 Future ecological changes affecting the issue

FUTURE ECOLOGICAL CHANGES
Lower inflows and groundwater levels
Shift from permanent to ephemeral wetlands
Changing water temperature (due to direct temperature changes and also shallower water depths)
Changing fire regime, with increased exposure of peat lake beds to fire
Potential acidification impacts cascading through the wetland foodweb and ecosystem, altering composition of aquatic macroinvertebrates as well as frogs and fish, so impacting health of waterbirds landing in the wetlands
Reduced habitat for endemic and migratory species due to shrinking lake areas

Step 10 Salient aspects of projected climate change

CLIMATE CHANGE KEY MESSAGES

From Bureau of Meteorology

- Autumn rainfall has declined by 20% since 1970
- Average rainfall over southern Australia is predicted to continue to decline in comparison with the climate of 1980-1999

From Climate Change in Australia, Southern and South-western Flatlands sub cluster:

Average temperatures will continue to increase in all seasons (very high confidence).
More hot days and warm spells are projected with very high confidence. Fewer frosts are projected with high confidence.
A continuation of the trend of decreasing winter rainfall is projected with high confidence. Spring rainfall decreases are also projected with high confidence. Changes in other seasons unclear, although downscaling suggests a continuation of the observed autumn declines.
Increased intensity of extreme rainfall events is projected, with high confidence.
Mean sea level will continue to rise and height of extreme sea-level events will also increase (very high confidence).
A harsher fire-weather climate in the future (high confidence).
On annual and decadal basis, natural variability in the climate system can act to either mask or enhance any long-term human induced trend, particularly in the next 20 years and for rainfall. However, SSWFW is one region of the world with very high model consensus on forced drying during the observed period and in the near-term.

See comprehensive analysis specific to Muir-Byenup: James, CS, VanDerWal, J, Capon, SJ, Hodgson, L, Waltham, N, Ward, DP, Anderson, BJ & Pearson, RG 2013, Identifying climate refuges for freshwater biodiversity across Australia, National Climate Change Adaptation Research Facility, Gold Coast, 424 pp.

Step 11 Trajectories of future ecological change

Table 4 Trajectory of greatest plausible ecological change

TRAJECTORY OF GREATEST PLAUSIBLE ECOLOGICAL CHANGE
Groundwater levels do not rise (or continue to fall) leading to more extensive drying of lake beds and more frequent and long-lasting loss of permanent, open water
Exposed lake beds lead to increased acidification of water bodies.
Drier lake beds and changing fire regime increase risk of peat fires (which amplify acidification processes)
Lake drying shrinks habitat for endemic and migratory species, with cascading (uncertain) ecosystem impacts, including terrestrialisation and new opportunities for weeds, feral animals, pathogens and pests.
Acidification impacts macroinvertebrate and fish species with cascading (uncertain) ecosystem impacts
Changing rainfall patterns require shifting management practices for revegetation, restoration and weed management activities
Impacts on peat: smaller area, won't continue to develop, varying degrees of decaying and burning, and would lose its ecological function.
Critical thresholds are crossed with increased likelihood and/or frequency (e.g. wetting and drying of sulfate sediments leading to acidification, loss of permanence, conditions for bird breeding not met)

Step 12 – 13 Change-persistence table

Table 5 Change-persistence table

1. COMPONENTS, PROCESSES AND SERVICES (CPS) OF THE SITE	2. … ATTRIBUTES OF THIS FEATURE THAT MIGHT CHANGE	3. … ATTRIBUTES OF THIS FEATURE THAT COULD PERSIST	4. CHANGE IN MANAGEMENT OR DECISIONS REQUIRED FOR IDENTIFIED FEATURES IN COLUMN 3 TO PERSIST (OPTIONAL)	4. COMMENTS, OTHER CAVEATS OR ASSUMPTIONS (OPTIONAL)
Complex, unique hydrology supporting a wide diversity of types of lakes in an internally draining catchment	Water levels, temporal periods and spatial patterns of inundation are likely to reduce for all lakes and wetland types. Change in types of wetland, open water disappears, loss of permanence.	The system will remain wetter than the surroundings and there will be a diversity of moist environments and wetland types.	Degree of persistence will be affected by changes in management decisions such as groundwater regulation or surface water diversions between wetlands	Assumes ongoing minimal change in land use in the surrounding catchment.
Habitat for migratory and endemic birds	Changing diversity and abundance of birds supported. Possible loss of some classes (e.g. increasing salinity may see the loss of less salt-tolerant species).	Site becomes more important at a landscape scale as it continues to support a high diversity of birds in the site and broader landscape.	Higher dependency on management of threats (e.g. fire, weeds, feral animals) and changes to other CPS (e.g. water levels, vegetation, macroinvertebrates, fish, water quality)	
Breeding ground for migratory and endemic birds	Reduced diversity and abundance of breeding birds supported. More frequent failed breeding. Possible loss of some classes.	Site becomes more important at a landscape scale as it continues to support a high diversity of birds in the site and broader landscape.	Higher dependency on management of threats (e.g. fire, weeds, feral animals) and changes to other CPS (e.g. water levels, water quality, vegetation, macroinvertebrates, fish)	
Highly diverse vegetation, macroinvertebrate and fish species endemic to south-west WA	Changes in area, abundance and distribution of vegetation, macroinvertebrates and fish species. Reduction in open water vegetation. Fire could become a greater influence on vegetation types. Could lose fish and aquatic macroinvertebrates altogether. Could lose vegetation types. Shifts to more drought and saline-tolerant species. New species will move in.	Lower, but still high diversity of vegetation types along changing moisture, salinity and pH gradients, maintained by periodic inundation. Dryer conditions could be more favourable for persistence of orchids.	Higher dependency on management of threats (e.g. fire, weeds, feral animals) and changes to other CPS (e.g. water levels, water quality)	Assumption: favourability to orchids is an expert assessment that would need further verification.

1. COMPONENTS, PROCESSES AND SERVICES (CPS) OF THE SITE	2. … ATTRIBUTES OF THIS FEATURE THAT MIGHT CHANGE	3. … ATTRIBUTES OF THIS FEATURE THAT COULD PERSIST	4. CHANGE IN MANAGEMENT OR DECISIONS REQUIRED FOR IDENTIFIED FEATURES IN COLUMN 3 TO PERSIST (OPTIONAL)	4. COMMENTS, OTHER CAVEATS OR ASSUMPTIONS (OPTIONAL)
Habitat for threatened species	Current populations of threatened species likely to decline or worsen in condition. More species currently at the site likely to become threatened in the broader landscape.	The site is likely to become more important for currently and future threatened species as relative declines are likely to be larger in the broader landscape.	Higher dependency on management of threats (e.g. fire, weeds, feral animals) and changes to other CPS (e.g. water levels, water quality, vegetation, macroinvertebrates, fish)	
Peats in Byenup and Tordit-Gurrup Lagoons and Poorginup Swamp (among oldest peats in the world)	Smaller area, won't continue to develop, varying degrees of decaying and burning. Peat would lose its ecological function, and be susceptible to fires starting more easily and burning wider, deeper and longer.	There will still be old peat – it won't disappear completely. There will be a base, moist level that is not vulnerable to fire.	Higher dependency on management of fire and water levels	
Water chemistry (pH, salinity, nutrients)	Increased salinity in all wetlands. Increased acidification likely in currently acidified wetlands, and other peat wetlands.	A diversity of salinities will persist across the site. Non-peat wetlands unlikely to acidify? Nutrients loads to remain unchanged or reduced due to lower inflows, but potential increased concentration due to evapo-concentration.	Degree of persistence will be affected by changes in management decisions such as groundwater regulation or surface water diversions between wetlands	Assumes minimal change in land use in the surrounding catchment.
Large, varied waterbird population	Likely reduced abundance of birds that can be supported. Likely reduced diversity of birds and loss of some species.	Regionally (nationally) significant diversity of wetland birds.	Higher dependency on management of threats (e.g. fire, weeds, feral animals) and changes to other CPS (e.g. water levels, water quality, vegetation, macroinvertebrates, fish)	
Refuge site, e.g. drought refuge	Refuge habitat will be effective for less time and fewer refuge types. It will also be a refuge for pests, potentially amplifying associated threats.	Will remain wetter and more productive than surrounding landscape	Higher dependency on management of water levels, threats (e.g. fire, weeds, feral animals) and changes to other CPS (e.g. water levels, water quality, vegetation, macroinvertebrates, fish)	Comment: may also be a refuge for more weeds and feral animals
Diverse: every wetland is different	All wetlands will be drier with possible loss of some specific types	Every lake will continue to be different		

1. COMPONENTS, PROCESSES AND SERVICES (CPS) OF THE SITE	2. … ATTRIBUTES OF THIS FEATURE THAT MIGHT CHANGE	3. … ATTRIBUTES OF THIS FEATURE THAT COULD PERSIST	4. CHANGE IN MANAGEMENT OR DECISIONS REQUIRED FOR IDENTIFIED FEATURES IN COLUMN 3 TO PERSIST (OPTIONAL)	4. COMMENTS, OTHER CAVEATS OR ASSUMPTIONS (OPTIONAL)
Near pristine condition	No longer representative of historic baseline	Low level of local human interference in state and dynamics of the wetland = "natural", "wild", "pristine"?	Higher dependency on management of threats (e.g. fire, weeds, feral animals) and changes to other CPS (e.g. water level, water quality, vegetation, macroinvertebrates, fish), noting that regulation and engineering works would reduce "naturalness".	
Pollen and fossil charcoal records rich with insights to past climate change and vegetation responses in the region	Integrity and quality of the record may degrade with peat burning and decay.	The records will still be unique sources of past climate and vegetation records. These records may become more valuable given rapid biogeographical change.	Higher dependency on management of water levels and fire	
Bird observatory provides access to and information about the site, as well as scenic facilities for rest and nature appreciation	Utility of the site will change with reduced emphasis on water birds	Increased emphasis on flora and fauna appreciation. It will continue to have more birds than the surrounding areas. The site will remain as a welcome rest point providing shelter, information, and connection with nature.	Higher dependency on management of threats (e.g. fire, , weeds, feral animals)	
Regenerating Jarrah/Marri (free of *Phytophthera*) for catchment and water quality protection, becoming a future established forest	Changing fire regime will lead to shifts in species distribution and abundance?	Woodland will continue to provide valuable catchment management functions, and habitat for other flora and fauna.	Higher dependency on management of fire	
Unique aesthetic qualities at all scales	Changing details of aesthetic qualities	Pattern of unique aesthetics persist		
Aboriginal heritage	No longer representative of how sites were when used historically by Aboriginal people?	Continues to provide connection to country for Traditional Owners?		These answers are examples only and consultation with Traditional Owners is needed to characterise Aboriginal heritage values and how they might be affected

Steps 14-15 Values affected by changes

The assessment of which anticipated changes in CPS will affect which values is tabulated in Table 6. The labels refer to the following values:

ECD: The ecological character as characterised by the Ecological Character Description in the Ramsar Information Sheet for the site.

Ramsar: The Ramsar listing criteria.

Cons: Other conservation values not included in the ECD or Ramsar listing criteria.

Other: Other values associated with the site.

Table 6 Affected values associated with anticipated changes (bold indicates Ramsar values)

1. COMPONENTS, PROCESSES AND SERVICES (CPS) OF THE SITE	2 VALUES LIKELY TO BE AFFECTED BY CHANGED CPS	3. VALUES LIKELY TO PERSIST
Complex, unique hydrology supporting a wide diversity of types of lakes in an internally draining catchment	ECD	Cons, Other
Habitat for migratory and endemic birds	ECD	Ramsar, Cons, Other
Breeding ground for migratory and endemic birds	ECD	Ramsar, Cons, Other
Highly diverse vegetation, macroinvertebrate and fish species endemic to south-west WA	ECD	Ramsar, Cons, Other
Habitat for threatened species	ECD	Ramsar, Cons, Other
Peats in Byenup and Tordit-Gurrup Lagoons and Poorginup Swamp (among oldest peats in the world)	ECD	Ramsar*, Cons *until too degraded
Water chemistry (pH, salinity, nutrients)	ECD	
Large, varied waterbird population	ECD	Ramsar, Cons, Other
Refuge site, e.g. drought refuge	ECD	Ramsar, Cons, Other
Diverse: every wetland is different	ECD	Ramsar, Cons, Other
Near pristine condition	ECD	Ramsar, Cons, Other
Pollen and fossil charcoal records rich with insights to past climate change and vegetation responses in the region		Cons, Other
Bird observatory provides access to and information about the site, as well as scenic facilities for rest and nature appreciation	Cons	Cons, Other
Regenerating Jarrah/Marri (free of *Phytophthera*) for catchment and water quality protection, becoming a future established forest		Cons
Unique aesthetic qualities at all scales		Cons, Other
Aboriginal heritage	Other	Other

Step 16. Hydrological processes underpinning change and persistence of key values

Most of the identified changes in CPS are driven by anticipated reductions in surface water inflows and groundwater levels, both driven by lower rainfall. Changes in variability or extremes in rainfall (and associated runoff and groundwater recharge) may also see critical thresholds being crossed with increased likelihood and/or frequency (e.g. drying and wetting of sulphate sediments leading to acidification, loss of permanence, conditions for bird breeding not being met).

The complexity of the hydrology, and the associated hydrological interrelationships between the different wetlands in the site, means there is considerable potential for unanticipated outcomes as climate change unfolds. The complex heterogeneity of the hydrogeology also means that there can be particular locations at which valued CPS will be able to persist longer than in other places.

Stage 3. Interpretation

Step 17. Have a conversation about the data

- CPS that stand out as particularly subject to change in character or values
  - Changes in types of wetland, loss of open water, loss of permanence
  - Potential losses of some classes of birds, increases in failed breeding seasons, reduced abundance and diversity of birds
  - Loss of some fish and aquatic macroinvertebrates
  - Loss of some vegetation types
  - Populations of threatened species likely to decline or worsen in condition, and likelihood of more species becoming threatened
  - Peat no longer develops, and existing peat degrades due to burning and decay
  - Increased acidification in currently acidified wetlands, with potential for acidification in other peat wetlands
- CPS that stand out as likely to retain character or values
  - Continued diversity of wetland types
  - Continued importance at a landscape scale for supporting bird diversity
  - Continued high diversity of vegetation
  - Continued low level of human interference – 'natural', 'wild', 'pristine'
- Particularly focus on CPS that may change ecological character but retain their Ramsar values or other conservation values.
  - All of the changes in CPS identified as particularly subject to change in character will still retain Ramsar and other conservation values, and would still meet listing criteria.
- Each row in the table (CPS) represents a different trajectory of change. Are there particular trajectories that are different from the types of change that might result from current threats?
  - All of the identified changes in CPS are an intensification of changes already happening as a result of current threats

- Are the drivers of the changes in the table similar to or different from the threats that are currently managed?
    - Similar
- How important are interactions with other threats?
    - As changes unfold the site may also be a refuge for more weeds and feral animals
    - Interactions with changing fire regime, salinity and acid-sulfate soils are important
- Look at the site as a whole, is there general tendency for character to change? Do Ramsar or other conservation values tend to persist despite change in character?
    - There is a general tendency for character to change, but for Ramsar and other conservation values to persist despite change in character.
- How much change in the focus of management might be required to ensure values persist despite ecological changes anticipated in the table?
    - Potential new, deliberate management interventions (e.g. diverting water to priority areas, applying lime in response to increasing acidification)
    - An increased focus on managing intensification of other threats such as fire, weeds and feral animals
    - New management approaches for gauging whether changes such as terrestrialisation and acidification are inevitable, and if so appropriate management strategies for accepting change and focusing on values that can persist
- When might these ecological changes occur? What observation, monitoring or modeling would be needed to detect or confirm that various changes were inevitable?
    - Many of the anticipated changes are already occurring to some degree
    - Increased focus on monitoring and modelling hydrological and biogeochemical processes to better understand, anticipate and manage changes in water level and water quality (e.g. to inform decisions on groundwater regulation, surface water diversions, agroforestry)
    - Monitoring ecological response to change (especially birds, vegetation, fish, macroinvertebrates)
    - Given the complexity of the system, monitoring and modelling is needed to provide an evidence base for attributing observed changes to likely drivers and for assessing the extent to which changes are inevitable or can be influenced by management.
- Has this analysis changed your understanding of vulnerability to climate change and how it might be represented?
    - *Note this is a question to be answered by site managers, not the authors of this case study.*
- Has this analysis provided insights about near-term adaptation actions (noting that specific adaptation stages have not been included)?
    - *Yes, management options to assist in adapting to climate change that are being considered include:*
        - ensure nearby wetlands outside the Ramsar site are managed to preserve CPS of value that are at risk within the site. This could include increasing the area of the Ramsar site to include wetlands such as Noobijup Lake.

- Targeted management of fire regimes within wetlands
- Targeted monitoring of co-threatening processes such as weed coverage and feral animals
- Targeted management of weed infestations and presence of feral animals

Step 18. Document the key patterns

Most CPS are vulnerable to change in ecological character. CPS associated with peat are vulnerable to loss of Ramsar values.

General pattern for CPS for the site: changed components, processes and services.

General trend for the site: risks change in ecological character, but still meets Ramsar criteria and retains conservation values (noting that trajectories for peat counter this general trend).

Change processes that are dominant drivers: climate driven changes in hydrology, changes in species interactions, climate and hydrology driven changes in fire regime, acidification and salinity.

Change process causing most significant change: reduced rainfall and inflows.

Key factors that help reduce its vulnerability:

- very low anthropogenic threats
- high diversity and complexity allows for potential niches that can persist and opportunities for species to move between very different conditions.

Step 19. Consequences of the patterns

Note examples below are not the results of a systematic adaptation planning process, they are just examples that did emerge while exploring vulnerability.

Implication for vulnerability

The assessment suggests that some change in character is inevitable but with good management the site will retain internationally important wetlands.

To a large degree the anticipated changes represent an increase in current threats, which include direct effects of climate change as well as climate change interacting with other threats (potentially including new threats). There is likely to be some change in character, however the details will be difficult for management to predict and may also require additional resources, new research or new planning and policy frameworks to address them.

Implication for long-term planning and management

- Can you anticipate how new 'climate-ready objectives' could be formed, i.e. ones that are feasible and retain the values associated with the persisting CPS of the site (column 3, in Table 5) as it undergoes change?
    - Terrestrialisation of the site, wetlands changing type and character, and when to accept or resist these changes
    - Acidification, and whether it requires significant interventions (e.g. (managing wetting and drying, applying lime or other treatments) and how to manage if such interventions are not undertaken (e.g. management of consequences of acidifying water bodies);

    - Peat degradation and whether it requires significant engineering interventions (e.g. diverting water to maintain peat wetlands) and how to manage if such interventions are not undertaken
    - Exploring and managing long-term estate-level consequences as the site changes its ability to support birds
- Can you anticipate at when, on the trajectory of change, managers may need to switch from seeking to prevent change in ecological character to new objectives that accommodate change?
    - Managers are already facing this prospect.
- What change in management, from a focus on the current set of species (esp threatened) and hydrological regimes or resisting ecological change, might be required to preserve values associated with persisting CPS, while accommodating those aspects of change in ecological character that are inevitable?
    - Increased active monitoring of:
        - those attributes that are expected to persist, to inform management decisions about maintain values as ecological change occurs
        - those attributes expected to change and the drivers of change, to guide management but also as a form of accountability, providing clear evidence when long-term changing character is due to drivers that are beyond the influence of local site management (e.g. high frequency wetting and drying of sulfate soils, degradation of peat, changed fire regime)
    - Increased regional and cross-jurisdictional planning to ensure local management is responsive to the broader context and that decisions elsewhere in the landscape or Ramsar estate can support persistence of site values where possible (e.g. through additions to the Ramsar estate, or through management change in nearby non-Ramsar areas)

Implications for near-term planning and management

- What barriers can you foresee to changes in management? Include technical (knowledge), social (values) and institutional (rules) barriers.
    - Extremely complex hydrogeology that requires ongoing, dedicated specialist expertise in measurement, modelling and interpretation in order to adequately inform the management of water balance dynamics.
    - Complex and highly uncertain ecological response to changing hydrology will always be difficult to adequately characterise, predict and manage.
    - Noobijup Lake is outside the Ramsar site, but has CPS that are at risk within the Ramsar site, and in some cases holds better examples of them, and so increased management focus on Noobijup and other wetlands outside the site could help preserve values that can persist in the system. In practice, the day-to-day management decisions and priorities differ between Ramsar-listed and non-Ramsar sites, potentially limiting this opportunity (e.g. fire management guidelines are different inside versus outside a Ramsar site; aspiration for no change in character is paramount in Ramsar site whereas change in character is more acceptable in non-Ramsar sites; lower monitoring budgets for non-Ramsar sites; currently harder to manage other threats to Noobijup such as impacts from land use decisions on private land)
- Does the analysis provide any insights into priority monitoring or research, to better understand change in CPS or to guide new management or objective setting?
    - Changed monitoring objectives include providing an evidence base to distinguish between drivers of change that are beyond what management can control and those for which management actions could have beneficial outcomes. For example, examining the extent to which acidification and peat degradation can be controlled by managing groundwater and surface water flows and retention.
    - Research to identify the values that could be preserved with management in the face of change *and* are long-term priorities for stakeholders.
    - Estate-level monitoring and research to understanding the whole-of-region and estate-level consequences of changes anticipated at MB, to inform broader-scale assessment and planning.
    - Research on the extent to which engineering interventions would be effective at addressing acidification and peat degradation, and whether such interventions would reduce other values such as the naturalness of the site or the creation of new, unique habitats.
- What knowledge would be needed to help identify when changes in management or objective were appropriate, including biophysical, social and institutional?
    - Frequency and likely locations of drying/acidification events and rate of terrestialisation
    - Better understanding of the practical limits to ability of management to resist terrestrialisation, acidification and peat degradation
    - Social preferences on resisting change or keeping it “natural” and allowing change.

Step 20. Overall narrative

The Muir-Byenup Ramsar site is vulnerable to changes in several components, processes and services, but despite these changes is likely to continue to retain most Ramsar and other values.

The major climatic changes of concern for this site are lower rainfall, which would lead to a cascade of hydrogeological and ecological changes at the site. The extent and quality of peat ecosystems are likely to decline, and more generally the prevalence of permanent and/or open water is likely to decrease. This in turn would affect the health and/or viability of resident bird, fish and macroinvertebrate communities (including threatened species), and the site's capacity to support migratory bird populations. Threatening processes at the site are expected to increase, with the site most threatened by direct climate change impacts on the catchment, as well as other threats that will be amplified by changing climate and hydrology (e.g. acidification, fire, salinity, weeds and feral animals).

Despite these changes, many site values can be expected to persist: the site is likely to become more important at a landscape scale as it continues to support a high diversity of wetland types, birds, vegetation and aquatic species. It will also persist as a refuge that remains wetter and more productive than its surroundings. It will retain other values, including its unique aesthetic qualities and opportunities for flora and fauna appreciation.

The loss of active, natural peat development, could jeopardize its ability to meet Ramsar criterion #1. If it loses its capacity to support waterbird populations exceeding 20,000 then its ability to meet Ramsar criterion #5 is also at risk. It is likely to continue to meet other Ramsar criteria for which it was listed, however specific details may change (e.g. there may be new endangered species or threatened communities relevant to criterion #2).

In order to retain values as it changes, management will need to cope with:

1. an intensification of existing threats
2. a need to provide evidence for decisions that balance imperatives to resist changing ecological character versus accommodating inevitable changes
3. being prepared for more reporting obligations associated with Article 3.2 and EPBC Act
4. making evidence-based decisions about where to invest time and resources in the face of high levels of uncertainty
5. an increased role for communicating and negotiating with managers in other jurisdictions or sectors, neighbouring land owners and other stakeholders in order to retain values at a landscape scale (e.g. informing estate level interventions such as making additions to the Ramsar estate; working with local landholders for managing threats such as fire, weeds and feral animals; or coordinating hydrogeological research for characterising hydrogeological dynamics that extend beyond the site boundaries).

The drivers of change are a complex mix of climate, hydrogeological and ecological processes whose current dynamics are not fully understood, and so increased monitoring and modelling will be required to understand and explore possible future dynamics and management responses.

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