Australian Government
Commonwealth Environmental Water Holder

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# Assessing Vulnerability for use in Determining Basin-scale Environmental Watering Priorities

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**Acknowledgement of the Traditional Owners of the Murray–Darling Basin**

The Commonwealth Environmental Water Holder (CEWH) respectfully acknowledges the Traditional Owners, their Elders past and present, their Nations of the Murray–Darling Basin, and their cultural, social, environmental, spiritual and economic connection to their lands and waters.

**Other Acknowledgments**

The Assessing Vulnerability for use in Determining Basin-scale Environmental Watering Priorities project (the project) was undertaken in partnership with the Murray Darling Basin Authority (MDBA) who provided extensive staff time and guidance. Geoscience Australia also supported the project through provision of advice, staff time and Wetlands Insights Tool data.

The CEWH would like to thank the above partners and the consultant team who assisted in delivering the project and this report. The team included: Jennifer Hale, Dr Shane Brooks, Dr Heather McGinness, Cherie Campbell and Enzo Guarino.

# Abbreviations

| | |
|---|---|
| ANAE | Australian National Aquatic Ecosystem |
| BAEWP | Basin Annual Environmental Watering Priorities |
| BWS | Basin-Wide Environmental Watering Strategy |
| CEWH | Commonwealth Environmental Water Holder |
| DELWP | Department of Environment, Land, Water and Planning |
| DIWA | Directory of Important Wetlands in Australia |
| EPBC Act | Environment Protection and Biodiversity Conservation Act 1999 |
| MAD | Median Absolute Deviation |
| MDBA | Murray-Darling Basin Authority |
| NDVI | Normalised Differential Vegetation Index |
| WIT | Wetland Insights Tool |

# Executive summary

The planning and prioritisation of environmental water is a key step to achieving the long-term environmental outcomes of the Basin-wide environmental watering strategy. The method for determining Basin annual environmental watering priorities is constantly improving and aims to consider a wide range of factors including vulnerability of ecosystems and the biota that depend on them. The availability of Basin-wide data, particularly from remote sensing has increased dramatically in the past few years and represents an opportunity to develop and implement a systematic approach to identifying vulnerable ecosystems and biota. This project developed and tested a GIS based method for assessing vulnerability (at Basin scale) for two of the four Basin-wide environmental watering strategy (BWS) themes, native vegetation, and waterbirds.

The method is underpinned by a logic, consistent with other vulnerability assessments, whereby vulnerability is a product of condition (how sensitive biota are to withstand environmental change and their ability to adjust to those changes) and stress (exposure to adverse environmental changes).

Spatial indicators of condition and stress were based on our conceptual understanding of inundation dependent vegetation communities and waterbirds. Conceptual models of the factors that affect vulnerability were developed for each theme and guided the selection of indicators. While initially a long list of potential indicators was developed for each theme, the availability of suitable data at a Basin-scale limited the final selection. The final list comprised three indicators of condition for vegetation (tree stand condition, vegetation cover and "greenness") with three indicators of stress (time since last inundation, inundation extent and soil root zone moisture) and four indicators of condition for waterbirds (abundance, species richness, breeding abundance, breeding species richness) with four indictors of stress (extent of inundation, time since last inundation, rainfall, "greenness" of vegetation).

Indicators are not scored absolutely but assigned to rank categories from better to worse condition and from low to high stress. Two different methods were used for assigning indicators into ranks. For most indicators, a change from baseline conditions has been used. For a small number of indicators, absolute thresholds based on known species / function group tolerances have been established.

The results of the condition, stress and vulnerability assessment can be presented in two ways: spatially as a map or temporally in a table. The spatial presentation allows visual comparisons of different areas in the Basin at a single point in time. The temporal presentation of results allows visual comparison of a single spatial unit across multiple years. A series of Jupyter notebooks has been developed that contains the method and would allow for annual assessment of vulnerability for waterbirds and native vegetation with available input data.

The method appears to provide a robust way of assessing condition, stress and vulnerability at large spatial scales despite data limitations, uncertainties and the assumptions that underpin the method. The comparisons with the Millennium Drought (where there is empirical evidence of a decline in condition and increase in stress and vulnerability) revealed expected patterns with high vulnerability suggesting the method is sensitive to revealing patterns of vulnerability to water stress that can inform management. It must be recognised, however, there will always be better, finer-scale information to inform watering requirements at the site and local scale.

Priorities for environmental water will require consideration of a variety of factors such as cultural value, feasibility, watering history and competing priorities. The vulnerability assessment as described here, can provide a valuable input to the prioritisation process for environmental water.

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# About this project

## Introduction

### *Context*

Environmental water management is the primary mechanism for achieving the long-term environmental outcomes in the Basin-wide environmental watering strategy (BWS; MDBA 2019) and Basin Plan objectives and targets. Deciding where environmental water should be managed involves a combination of feasibility (capacity to deliver water to different sites within the managed floodplain), current and antecedent climate, ecological condition, and identifying priorities of a diverse group of water managers that include Basin States, the Commonwealth Environmental Water Holder (CEWH) staff, Murray Darling Basin Authority (MDBA) and First Nation's people.

The Basin annual environmental watering priorities (BAEWP) are a key component of the Basin Plan's Environmental Watering Plan (Basin Plan Chpt 8). They guide the annual planning and prioritisation of environmental watering across the MDB and represent the steps needed to achieve the long-term environmental outcomes in the Basin-wide environmental watering strategy (BWS) and through them, the Basin Plan's ecological objectives and targets. They also aim to support the statutory function of the CEWH (s8.03). Environmental water holders are required to annually report on the use of water for the environment with regard to the BAEWP.

The Basin Plan Chapter 8, Part 6 establishes the principles and method to determine priorities for applying environmental water. The method as stated in the Basin plan is general in nature and comprises (ss8.60 (2)):

> The method to determine priorities for applying environmental water is to:
>
> a) determine the resource availability scenario; and
>
> b) determine the management outcomes that apply to the resource availability scenario; and
>
> c) consistent with the management outcomes that apply to the resource availability scenario, determine the provisional priorities for applying environmental water by applying the principles set out in Division 1 to priority environmental assets and priority ecosystem functions; and
>
> d) refine those priorities based on seasonal, operational and management considerations in accordance with section 8.62.

The method for determining BAEWP is constantly improving, but currently does not encompass all the principles as established in the Basin Plan. A clear gap in determining Basin priorities is analysis of the core stressors (vulnerability) influencing the achievement of Basin-scale outcomes.

Technology is rapidly evolving and there have been corresponding rapid improvements in environmental data availability within the Basin from on-ground monitoring programs, but especially in the field of geospatial information. This increase in spatial data availability comes not only from increasingly accessible satellite data, but also from derived outputs (e.g., Water Observations from Space (WoFs), the Wetlands Insight Tool (WIT), climate forecasts and vegetation condition modelling). These accessible spatial data, often at the whole of Basin scale, present an opportunity to improve identification and prioritisation of aquatic ecosystems that would benefit most from environmental water in a given year, and the achievement of BWS objectives and targets with improved environmental outcomes.

A framework for identifying environmental water priorities based on vulnerability has been developed and a trial completed for black box (*Eucalyptus largiflorens*) communities (Overton et al. 2018). There was also some informal exploration of options for waterbirds done by McGinness et al. in 2020. This project seeks to build on previous work and refine and adapt prior frameworks for two of the four BWS themes; native vegetation and waterbirds.

## *Vulnerability in context of water planning*

The method detailed here is focussed on identifying the most vulnerable ecosystems in the Basin. It is just one part of the process for determining BAEWP, which requires consideration of a number of factors in addition to vulnerability (Figure 1). For example, conservation value, recreational and social values, cultural values, feasibility and management levers and constraints.

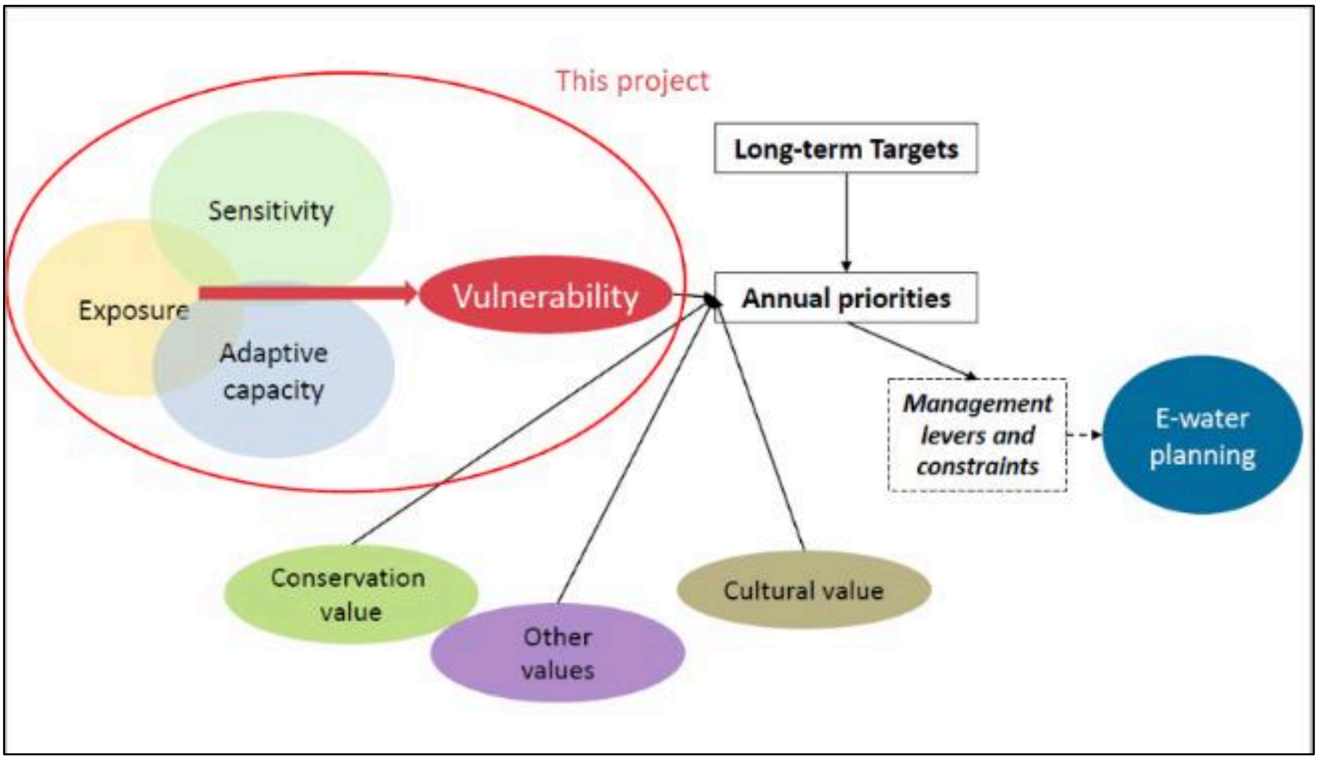


Figure 1: This project in the context of determining BAEWP

The outputs of this project are maps of vulnerability across the Basin as of 2021, together with a method to repeat annual vulnerability assessments for vegetation and waterbirds. How the results of annual vulnerability assessments are used in the identification of BAEWP is a matter for water managers, policy makers and planners. It is highly unlikely that the most vulnerable ecosystems will always equate to the highest priorities for environmental water in a given year. Factors such as water availability and the feasibility of delivering water to all aquatic ecosystems aside, there are several ecologically based issues that should be considered when assigning priorities for environmental water.

Systematic conservation planning is a process whereby ecosystems are prioritised for conservation of biodiversity (Margules and Pressey 2000, Kukkala and Moilanen 2013). Vulnerability is just one of the 12 biogeographic-economic core concepts of systematic conservation planning (adequacy, complementarity, comprehensiveness, effectiveness, efficiency, flexibility, irreplaceability, replacement cost, representation, representativeness, threat, and vulnerability). Assigning resources to the most stressed or vulnerable ecosystems does not always result in the best outcome, particularly when resources (in this case environmental water) are finite. It may be more effective to prioritise some areas that are less vulnerable to maintain habitat in good condition, or there may be instances where high ecological value or particular cultural values become the priority for environmental water allocations.

The vulnerability assessment described in this document provides a systematic data driven method for assessing vulnerability for two BWS themes across the Basin. It would require at the minimum for some remote sensing and monitoring data to be made available at an annual time-step and in a timely manner (before April of each year). When used in conjunction with other considerations and tools, it will improve the BAEWP process in terms of transparency and through evidence-based decision making.

### *Objectives*

This project aimed to develop and trial an application of a framework for assessing environmental vulnerability to contribute to the method for determining Basin annual environmental watering priorities. The specific objectives of the project were to:

- Develop a GIS based method for assessing Basin-scale vulnerability for two thematic areas of the Basin-wide environmental watering strategy (native vegetation and waterbirds). The method must be in a format that is repeatable and can be routinely updated by MDBA agency staff as part of business-as-usual operations.
- Test the method by producing outputs for the selected themes using applicable GIS/spatial analysis tools depicting (up to the most recent year that data is available):
    - indicators of stress and condition for each theme
    - an overall basin-scale assessment of vulnerability for each theme
    - vulnerability of each theme at different spatial scales applicable to water management.
- Include a consideration of confidence in the source data and outputs.
- Provide recommendations regarding data gaps and improvements to the method.

## How the vulnerability assessment was developed

The vulnerability assessment was guided by a Technical Advisory Group (TAG; Appendix A) comprised of experts in the fields of vegetation, waterbirds and geo-spatial analysis. The project team developed draft methods for discussion at on-line workshops with the TAG. Recommendations from the TAG were then used to refine the method that is presented in this report.

Geoscience Australia provided advice on earth observation indicators and provided capacity to leverage the Australian National Computational Infrastructure (NCI) to generate Wetland Insights Tool water and vegetation cover estimates for more than 270,000 wetland boundaries through the Landsat archive 1986 to 2022. This includes all wetlands and floodplains mapped in the Australian National Aquatic Ecosystems (ANAE) classification of the Basin that are in scope for water management. Geoscience Australia also developed program code to summarise the data through years enabling the project team to hind-cast vulnerability assessments back to 1986 and contrast current year assessments to known periods of severe stress during the 2000-2010 Millennium Drought.

The results of the 2021/22 application of the method were presented to the TAG and water managers for review. Input was sought from water managers on the utility of the vulnerability outputs and how they could be used in improving evidence-based environmental water management. Suggestions were incorporated, where feasible, into the final method documented in this report.

# How to use this document

This document has been structured to make the most salient information with respect to the methods and the 2021/2022 assessment of vulnerability easily accessible, while providing the technical detail for interested parties. The document is structured as follows:

- Introduction – this introduction
- Overview of the method – contains a general description of the method for assessing vulnerability and the principles upon which it is based
- Vegetation vulnerability assessment – a summary of the method development for the vegetation theme, with a worked example for 2022 of the vulnerability assessment for vegetation
- Waterbirds vulnerability assessment – a summary of the method development for the waterbirds theme, with a worked example for 2021 of the vulnerability assessment for waterbirds
- Conclusions – recommendations for future improvements to the method
- Appendix A – TAG members
- Appendix B – detailed methods and rationale for the vegetation vulnerability assessment
- Appendix C – detailed methods and rationale for the waterbird vulnerability assessment
- Appendix D – detailed methods for the spatial analysis and derivation of condition, stress and vulnerability scores (including the outcomes of sensitivity testing).

# Overview of the method

The application of the method for assessing vulnerability for waterbirds and vegetation has a number of common elements. This includes the concept and definition of vulnerability, the use of Basin-scale data sets and the calculation of condition, stress and vulnerability. A method for confidence assessment has also been included.

## What is vulnerability?

Vulnerability assessments have developed in recent years across many fields, most notably in relation to climate change. The Intergovernmental Panel on Climate Change (IPCC) has defined vulnerability as a function of exposure, sensitivity and adaptive capacity (IPCC 2007) and the ESAC framework has been adopted here (Figure 2) as the conceptual basis for assessing vulnerability. The key terms used in the vulnerability assessment are defined as follows (IPCC 2007):

- Vulnerability: a function of the sensitivity of a system to change, its exposure to those changes and its capacity to adapt to those changes.
- Exposure: the nature, magnitude and rate of environmental changes; as a function of external stressors.
- Sensitivity: the degree to which biota within a system are affected, either adversely or beneficially, by environmental change; as a function of current condition.
- Adaptive capacity: the potential, capability, or ability of biota to adjust to environmental change, to moderate potential damage, to take advantage of opportunities, or to respond to the consequences.

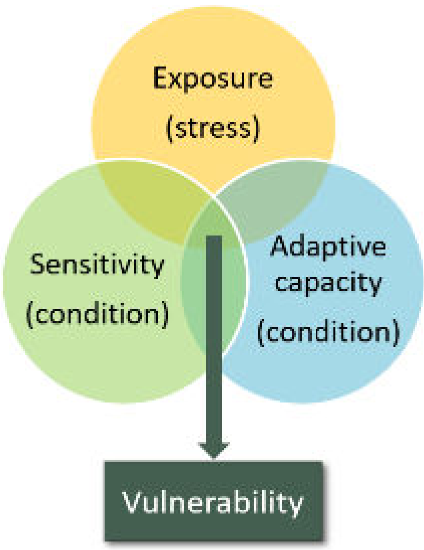


Figure 2: Conceptual framework of vulnerability assessments for BAEWP (adapted from IPCC 2007)

## How is vulnerability calculated?

### *Functional groups*

Functional groups are non-phylogenetic, aggregated units of species that share certain characteristics. With respect to the assessment of vulnerability for vegetation and waterbirds, the functional groups need to be specific enough to be represented by the same indicators of condition and stress (e.g., have similar habitat and water regime requirements) but be broad enough to allow for efficient assessment of spatial datasets (i.e., represent multiple species assemblages).

The selection of functional groups for both themes was guided by the BWS expected outcomes for vegetation and waterbirds and current ecological understanding of ecology-water regime relationships. The functional groups for each theme are provided in the vegetation functional groups section on page 16 and the waterbirds functional groups section on page 32, with more detailed justification in Appendices B and C.

## *Indicators of condition and stress*

Spatial indicators of condition and stress were based on our conceptual understanding of inundation dependent vegetation communities and waterbirds. Conceptual models of the factors that affect vulnerability were developed for each theme.

Condition indicators are *intrinsic*, that is, are direct measures of waterbirds or vegetation. They were selected from the factors that reflect the current state of waterbirds and vegetation as well as those that affect their ability to resist change and recover from potential impacts.

Indicators of stress are *extrinsic* and related to factors in the environment or habitat of waterbirds and vegetation. They were selected from factors that reflect exposure to potential impacts or stressors.

While initially a long list of potential indicators was developed for each theme (see Appendices B and C), the availability of suitable data at a Basin-scale limited the final selection. The final list comprised three indicators of condition for vegetation (tree stand condition, vegetation cover and the normalized difference vegetation index NDVI) with three indicators of stress (time since last inundation, inundation extent and soil root zone moisture) and four indicators of condition for waterbirds (abundance, species richness, breeding abundance, breeding species richness) with four indicators of stress (extent of inundation, time since last inundation, rainfall, "greenness" of vegetation) (see indicator sections on pages 16 and 33 for more details).

## *Spatial units*

The two selected themes (native vegetation and waterbirds) are largely associated with floodplain and wetland ecosystems (as opposed to in-channel, flowing systems). Basin assets are defined at different spatial scales for different purposes, ranging from individual wetlands to wetland complexes comprised of many wetlands (e.g. the Macquarie Marshes, Barmah-Millewa Forest) through to entire river valleys, the northern and southern Basin and the whole Basin as a single unit. The approach used in this project was to treat the larger spatial scales as aggregations of the many smaller wetland and floodplain units within them. The Australian National Aquatic Ecosystem (ANAE) mapping of the Murray-Darling Basin was used to define the smallest spatial units in which condition, stress and vulnerability were assessed. These wetland and floodplain polygons were then aggregated to larger spatial scales. For the wetland complex scale, four data sets were used: Ramsar Wetlands, the Directory of Important Wetland Sites (DIWA) and BWS important Basin environmental assets for waterbirds and BWS Vegetation Regions (Valleys).

## *Basin-scale data*

The method is applied across the Basin and so is limited to data sets that cover the Basin (or at least the important wetland and floodplain sites across the Basin). The data sets used comprised (see Appendix D for more detail):

- Wetland Insight Tool (WIT) - Geoscience Australia provided time series land surface cover outputs from the WIT in five categories as percentage of each ANAE polygon covered by bare ground, dry/non-green vegetation, green vegetation, wet vegetation (or water underlying vegetation) and open water for each Landsat imagery date.

- The MDBA provided tree stand condition data for river red gum, black box and coolabah as raster surfaces from 1987 to 2021.
- Normalized Difference Vegetation Index (NDVI) was used as a surrogate for productivity.
- Root zone moisture is provided by the Bureau of Meteorology Australian Water Outlook to represents the percentage of available water content in the top 1 m of the soil profile.
- Waterbird observations were sourced from the Atlas of Living Australia, MDBA aerial surveys and Coorong Lower Lakes and Murray Mouth waterbird monitoring.

### *Calculating condition, stress, and vulnerability*

The vulnerability assessment is designed to be applied across the Basin to identify those system and communities that are most vulnerable. Consistent with similar aquatic ecosystem prioritisation systems in Australia (Kennard et al. 2010, Aquatic Ecosystem Task Group 2012) indicators are not scored absolutely, but assigned to ranked categories as follows:

- Condition:
  - Better
  - Medium
  - Worse
- Stress:
  - Low
  - Medium
  - High

Each level of the ranking is assigned a numerical score (1 to 3) and overall condition and stress are calculated by summing the category scores and normalising between 0 and 1 (see Text Box 1). This produces a rank from highest to lowest of both condition and stress.

Different methods of scoring and ranking were tested on application of the method, but the overall pattern of condition and stress was robust and so the simplest method of summing individual indicators for calculating overall condition and stress is recommended (see page 37).

#### *Normalising data*

Condition (or stress):

0 is the lowest value (worst condition, highest stress)

1 is the highest value (best condition, lowest stress)

Condition and stress are each summed and rescaled from 0 to 1 using the following:

$$Score = \frac{(sum\ of\ condition\ scores - minimum\ value)}{(maximum\ possible\ value - minimum\ value)}$$

**Vulnerability** is the sum of condition and stress divided by 2 scored from 0 (most vulnerable) to 1 (least vulnerable.

Text Box 1. General calculation of condition, stress and vulnerability

## *Thresholds of condition and stress*

Assessments require standards or thresholds against which change can be measured (Kopf et al. 2015). For this vulnerability assessment we have used two different methods of establishing baselines. For most indicators, a change from baseline conditions has been used. For a small number of indicators, absolute thresholds based on known species / function group tolerances have been established.

### *Deviation from baseline*

Consistent with approaches for ecosystem condition assessment and assessments of climate change (e.g. Hansen et al. 2010, Department of the Environment and Energy 2017) a deviation from baseline approach has been adopted for several indicators of condition and stress. The majority of the spatial metrics used in this assessment are derived from the archive of Landsat imagery for the period 1986 to 2022. The baseline period was discussed with experts and the Technical Advisory Group, with a decision made to establish the baseline as the entire period of record, excluding the Millennium Drought. The exclusion of the Millennium Drought was considered appropriate as it represents a significant proportion (a little under one third) of the Landsat record. Including a large period of dry conditions in the baseline would bias the baseline towards drought conditions and reduce sensitivity to detect periods of increased water stress and associated changes in condition. The baseline period is 1986 to 2000 and 2010 to 2022 (inclusive).

To compare among wetlands and among years we calculated a standardised anomaly as the difference between annual metric values and the long-term average (baseline) for each wetland standardised by the inter-annual variability represented by the standard deviation (SD).

### *Absolute thresholds*

Thresholds for some indicators were established based on the known tolerance of the target species, communities and functional groups. These were largely related to the periods of dry conditions that functional groups were known (from the literature) to tolerate (see pages 20 and 35).

## ***Presentation of results***

The results of the condition, stress and vulnerability assessment can be presented in two ways: spatially as a map or temporally in a table. The spatial presentation allows visual comparisons of different areas in the Basin at a single point in time (e.g. Figure 3). The temporal presentation of results allows visual comparison of a single spatial unit across multiple years (e.g. Table 1).

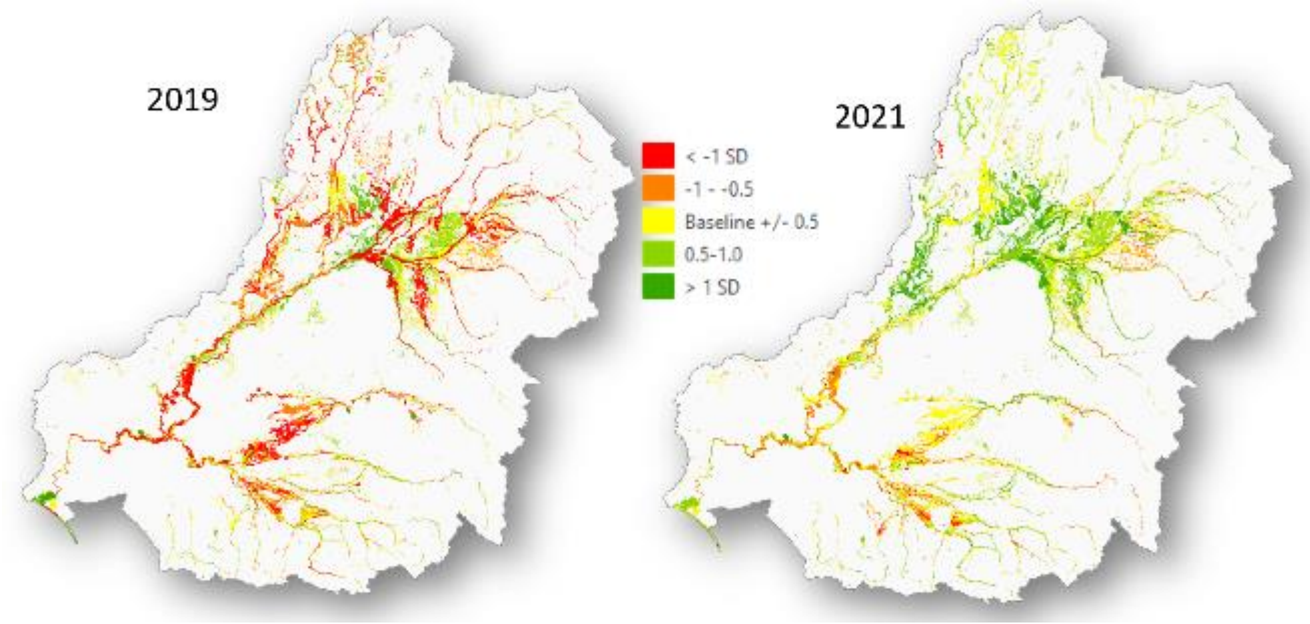


Figure 3. Example of a spatial presentation of the results for tree stand condition in two years

## Working with uncertainty

Ecological systems are complex and ecological data are characterised by many different types of uncertainty arising from both natural variability and from imperfect knowledge (Figure 4). Natural variability is a feature of ecological systems and there will be variability in ecosystems both over space and over time. Uncertainty associated with natural variability does not decrease with increased sample sizes or by having census data; but our ability to characterise the natural variability can be improved with increased data. Knowledge uncertainty is due to imperfect understanding and includes not only measurement error, but also errors associated with imperfect models and the selection of the best available model.

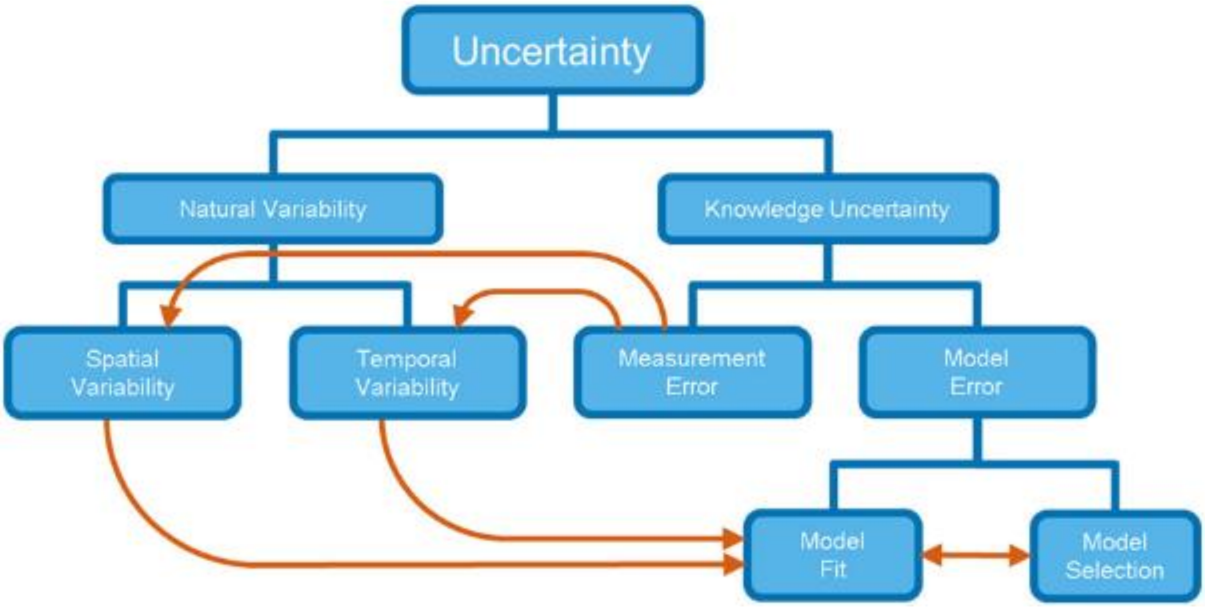


Figure 4. Sources of uncertainty in ecological studies (Yanai et al. 2018). Arrows indicate sources of uncertainty that contribute to other sources of uncertainty

Table 1. Example of a temporal presentation of the results for condition of vegetation functional groups at the scale of the whole Basin from 1991 to 2021. Numbers are relative condition (scaled 0-1) and colour highlights are percentiles from lowest condition to highest condition (red to green) with the 50th percentile yellow.

| **Group** | **1991** | **1992** | **1993** | **1994** | **1995** | **1996** | **1997** | **1998** | **1999** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| black box | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 | 0.7 | 1.0 | 0.8 | 0.5 | 0.3 | 0.7 | 0.5 | 0.3 | 0.3 | 0.5 | 0.5 | 0.3 | 0.8 | 0.7 | 0.3 | 0.8 | 0.8 | 0.8 | 1.0 | 0.7 | 0.5 | 0.3 | 0.7 | 0.7 |
| coolibah | 0.5 | 0.5 | 0.7 | 0.7 | 0.8 | 0.5 | 0.7 | 1.0 | 1.0 | 1.0 | 0.7 | 0.5 | 0.7 | 0.7 | 0.3 | 0.2 | 0.5 | 0.7 | 0.3 | 0.8 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.3 | 0.3 | 0.7 | 0.7 | 0.7 |
| river red gum swamps/forests | 0.7 | 0.7 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.5 | 0.8 | 0.8 | 0.7 | 0.3 | 0.7 | 0.8 | 0.7 | 0.5 | 0.3 | 0.5 | 0.5 | 0.7 | 0.8 | 0.7 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 0.7 | 0.7 | 0.8 | 0.8 |
| river red gum woodland | 0.5 | 0.5 | 0.7 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.5 | 0.7 | 0.7 | 0.5 | 0.3 | 0.5 | 0.7 | 0.3 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 0.8 | 0.7 | 0.8 | 0.5 | 0.7 | 0.7 | 0.7 |
| grassy meadows | 0.8 | 0.5 | 0.5 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 1.0 | 0.5 | 0.5 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| herbfield | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 | 0.5 | 0.8 | 0.5 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.8 | 0.5 | 0.5 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 | 0.5 | 0.5 | 0.8 | 0.5 |
| lignum | 0.8 | 0.5 | 0.8 | 0.8 | 1.0 | 0.5 | 1.0 | 0.8 | 1.0 | 1.0 | 0.8 | 0.5 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.8 | 0.8 | 0.5 | 1.0 | 1.0 | 1.0 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 |
| tall reed beds | 0.8 | 0.5 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

Uncertainties associated with the vulnerability assessments arise from several sources. Natural variability is a major source of uncertainty (e.g., the same vegetation community in two different parts of the Basin may react to a decline in inundation in different ways and the same vegetation community may respond to the same pattern of inundation in two different points of time differently). There is also uncertainty associated with available data representing actual conditions, with measurement errors and model errors both contributing (see Text Box 2 for an example).

To acknowledge that the vulnerability assessments provided by this framework will have associated uncertainties, confidence levels associated with both the strength of our ecological knowledge and the available data have been assigned (Table 2).

Table 2: Confidence levels for the vulnerability assessment (adapted from Overton et al. 2018)

| **Confidence level** | **Data** |
|---|---|
| Low | Anecdotal or regional level of information, providing a rough estimate of conditions. Based on low confidence in stressors and low confidence in condition. Conceptual model does not support vulnerability assessment. |
| Low/ Moderate | Remote sensing approach introduces uncertainties, condition and / or stress data missing for many spatial units. |
| Moderate | Based on moderate confidence in stressors and moderate confidence in condition. Conceptual model supports the identification of vulnerability. |
| Moderate /High | Data for both stress and condition indicators have a moderate level of uncertainty and represent relatively recent (last 2 years) conditions. Data gaps may be present but affect only a small proportion of the spatial extent being assessed. |
| High | Data for both stress and condition indicators have a low level of uncertainty and represent recent (last 12 months) conditions. There are no significant data gaps. |

## *Uncertainties associated with the Wetlands Insight Tool (WIT)*

The WIT provides a powerful tool for capturing the long-term variation in water and vegetation cover, but the outputs need to be used cautiously when interpreting specific events. The WIT is limited to clear observations of the earth surface by Landsat and therefore cannot map peak inundation that occurs on cloudy days (Figure 5). In this example, there are several instances of "truncated" peaks due to cloud cover. For example, in 2016, the maximum WIT estimation of inundated vegetation was 55% of the Barmah Forest Ramsar Site. Site Managers used a combination of field measures and modelling to estimate that 97% of the Ramsar site was inundated during those flood events.

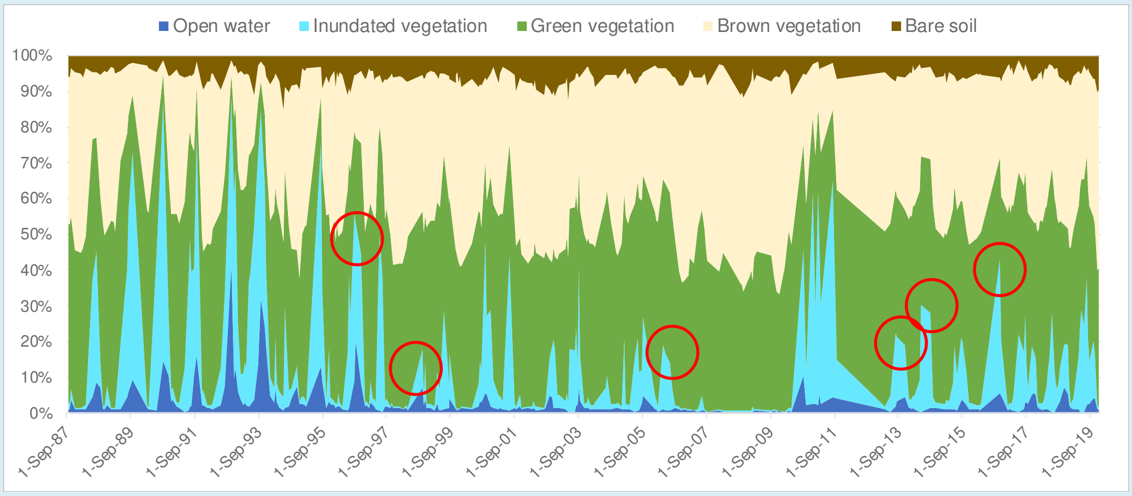


Figure 5 Complete WIT percentage inundation for Barmah Forest. Truncated peaks (circled) potentially indicate missing peak inundation on cloudy days. This "plateau" pattern was not observed in 2016 because the entire rising limb during the 4 months prior to the peak is not mapped.

The underestimation of peak inundation will be greatest at "flashy" sites where inundation recedes rapidly (before the next clear satellite view). Delivery of Commonwealth environmental water from storages may be less impacted than natural flood events with associated rain clouds. In addition, the WIT outputs are missing for a portion of the record (usually between 2011 to 2012) due to Landsat 7's failed scan line corrector (Dunn et al. 2019).

The number of observations available in a given year from the WIT is highly variable. At some sites, such as at Johnson Swamp in the Kerang Wetlands, there are generally multiple observations available each year, and an average of 19.4 observation dates annually. In contrast, at larger sites, there may be fewer than 10 observations in a year.

The number of observations is generally higher for smaller polygons and in areas of lower rainfall. This limits the utility of the WIT (and other satellite data products) with respect to calculating finer time-scale metrics. For example, in most locations, seasonal statistics (e.g., average, maximum, minimum inundation) would be highly uncertain and based on just one or two observations in a season at some sites.

Text box 2. Uncertainties associated with the WIT

# Vegetation vulnerability assessment

This section contains a summary of the vegetation theme vulnerability assessment. The complete method, prepared by Cherie Campbell is provided in Appendix B.

## Basin watering strategy expected outcomes for vegetation

Expected outcomes of the BWS for vegetation can be broadly summarised as:

- Forests and woodlands:
  - to maintain the current extent of forest and woodland vegetation
  - no decline in the condition of river red gum, black box and coolibah across the Basin
  - by 2024, improved condition of river red gum in the Lachlan, Murrumbidgee, Lower Darling, Murray, Goulburn–Broken and Wimmera–Avoca
  - by 2024, improved recruitment of trees within river red gum, black box and coolibah communities—in the long-term achieving a greater range of tree ages. (river red gum, black box and coolibah communities are presently comprised primarily of older trees which places them at risk.)
- Shrublands:
  - to maintain the current extent of the large areas of lignum shrubland within the Basin
  - by 2024, improvement in the condition of lignum shrublands.
- Non-woody vegetation:
  - to maintain the current extent of non-woody vegetation
  - by 2024, increased periods of growth for communities that:
    - closely fringe or occur within the main river corridors
    - form extensive stands within wetlands and low lying floodplains including Moira grasslands in the Barmah-Millewa Forest, common reed and cumbungi in the Great Cumbung Swamp and Macquarie Marshes, water couch on the floodplains of the Macquarie and Gwydir rivers and club-rush sedgelands in the Gwydir.
  - a sustained and adequate population of *Ruppia tuberosa* in the south lagoon of the Coorong, including:
    - *Ruppia tuberosa* to occur in at least 80% of sites across at least a 43 km extent (refer to Coorong case study)
    - by 2029, the seed bank to be sufficient for the population to be resilient to major disturbances.

# Functional groups

Functional groups for vegetation have been defined consistent with the BWS expected outcomes and ANAE types mapped across the Basin. They comprise three broad groups, with several subgroups (Table 3). In determining functional groups, consideration was given to water regime requirements, responses to stress and change in environmental variables and life history strategies. Each group represents vegetation communities for which thresholds of condition and stress have some commonalities.

Table 3: Functional groups for the vegetation theme

| Group | Description | Sub-groups |
|---|---|---|
| Forests and woodlands | Forests, woodlands and woody swamps are characterised by the presence of a woody (tree) overstory over an herbaceous or shrubby understory. | River red gum – swamp, forest<br>River red gum – woodland<br>Black box – swamp, forest, woodland<br>Coolibah – swamps, woodland |
| Shrublands | Shrublands and shrub-dominated swamps are characterised by the presence of large shrubs, with no or limited presence of trees. For the purposes of this vulnerability assessment this is restricted to lignum shrublands and swamps. | Tangled lignum – swamp, shrubland |
| Non-woody vegetation | Non-woody ecosystems are vegetation assemblages with no or limited presence of trees and large shrubs. Non-woody vegetation comprises floating plants, submerged macrophytes, herbs, grasses, sedges, sub-shrubs and tall reeds. Non-woody vegetation can form communities which are species diverse, such as lakebed herbfields, or communities which are monospecific, such as stands of Phragmites australis or species of Typha. For the purposes of this vulnerability assessment, we recognise five functional units of non-woody vegetation. | Submerged vegetation<br>Sedges / rushes<br>Grassy meadows<br>Tall reeds<br>Herbfields |

# Indicators for vegetation

## *Conceptual model*

The factors affecting vegetation vulnerability have been considered with respect to exposure (to stressors) and sensitivity / adaptive capacity (condition) and are illustrated in the conceptual model in Figure 6. This broad conceptual model provides a more comprehensive set of potential indicators of stress and condition than the vulnerability assessment can currently encompass largely due to insufficient or inappropriate data sources. They are presented here (and provided in more detail in Appendix B) as a reminder that as data availability improves, so should the vulnerability assessment of vegetation evolve to incorporate improved understanding and new data.

Potential indicators of condition and stress have been identified based on our conceptual understanding of the ecology of inundation dependent native vegetation across the Basin. While the current method and application of the vulnerability assessment is limited by the availability of Basin-scale metrics, the process is designed to be flexible and able to accommodate new sources of information as they become available.

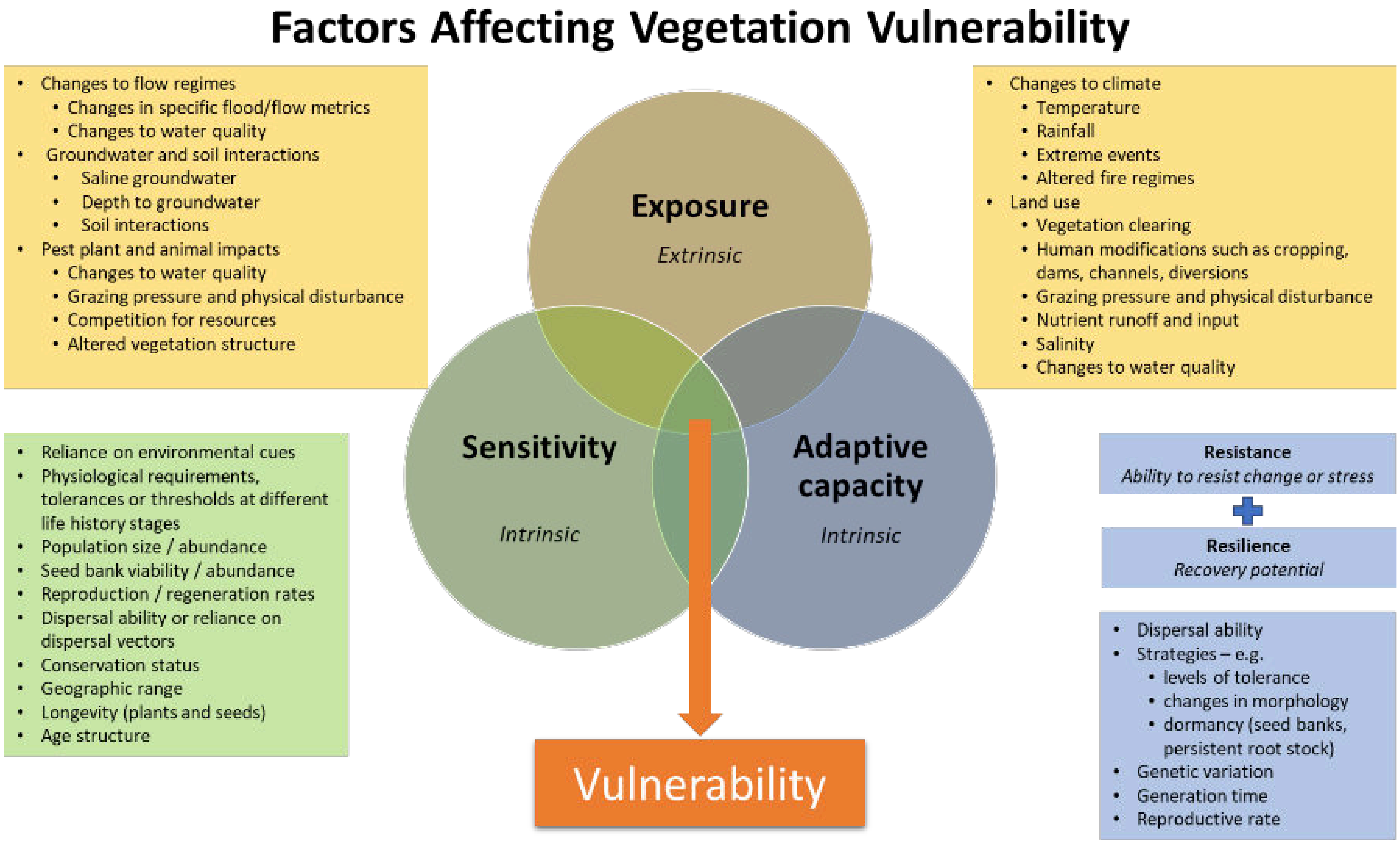


Figure 6. Conceptual diagram of factors interacting to affect native vegetation vulnerability in Australia

## *Indicators of condition*

Vegetation condition needs to consider where the plants, communities and mosaics of communities exist, that is their ***extent, distribution and spatial arrangement***. Condition also needs to consider the ***eco-physiological processes*** occurring within plants, communities and mosaics of communities that directly affect life-history stages such as germination, growth and survival and reproduction, and which impact on ecosystem services such as microclimate regulation (e.g. via tree canopy cover), erosion control or water quality. The ***structure*** and ***composition*** of plants, communities and mosaics of communities is also important in terms of the biodiversity values of vegetation and the provision of functions such as habitat and food resources.

We have also referred to the BWS outcomes when considering indicators of condition. Key aspects of the BWS outcomes for vegetation focus on the ***extent*** of functional groups (i.e. forests, woodlands, shrublands and non-woody wetland vegetation), the ***condition*** of functional groups (i.e. forests, woodlands and shrublands) as well as ***increased periods of growth*** (i.e. non-woody wetland vegetation) which can be represented at a Basin-scale as patterns of inundation and vegetation response in terms of 'greenness'.

Indicators of vegetation condition may include (See Appendix B for more detail):

- ***Extent, distribution and spatial arrangement***
  - where species / communities are in space and time
  - attributes relating to spatial arrangement (e.g. heterogeneity of community types within a region)
- ***Eco-physiological processes*** / responses of vegetation, such as:
  - water use
  - photosynthetic output
  - reproduction or regeneration rates
  - growth / biomass accumulation rates
- ***Structural*** responses of vegetation, such as:
  - extent and density of tree crowns
  - structure of lignum clumps
  - age class structure of forests and woodlands
  - density of individual species or plants within a community
  - cover of leaves
  - height of plants or vegetation strata
  - structural complexity of communities
- ***Compositional*** responses of vegetation, such as:
  - species composition and richness
  - seed bank composition and richness
  - composition of functional groups and other attributes (e.g. nativeness, rare species)
  - composition of communities within landscape mosaics.

There was sufficient data at a Bain-scale for this project to assess three condition indicators (Table 4). Thresholds for condition are assessed over multiple years as the deviation from the baseline (long-term average) and by considering the trajectory of change (whether condition is improving or declining). Condition for each indicator for each year is represented by the average deviation from the baseline in the preceding five years adjusted by the trend (trajectory slope) over the last two years.

Condition = (5-year average deviation) + (2-year trend).

This approach considering the mean and the trend recognises the different imperative for intervention comparing a wetland that is in poor condition and declining, compared to a wetland that may be still exhibiting indicators of poor condition but may be on a trajectory of rapid improvement, e.g. as happens when wetlands refill or floodplains are inundated after periods of extended dry conditions.

Condition, for each metric, is scored on a scale of 1-3:

- Better (score of 3)
  - measure of 5-year central tendency is above the 27-year baseline, and
  - sum of deviation from central tendency (5-years) and the slope of the two-year trend > 0
- Moderate (score of 2)
  - measure of 5-year central tendency is within one unit of variability (standard deviation) of the 27-year baseline, and
  - sum of deviation from central tendency (5-years) and the slope of the two-year trend is between 0 and -1
- Worse (score of 1)
  - measure of 5-year central tendency is greater than one unit of variability below the 27-year baseline, and
  - sum of deviation from central tendency (5-years) and the slope of the two-year trend is < -1.

Table 4. Indicators of condition for inundation dependent vegetation

| **Indicators of condition** | **Justification** | **Potential data sources** | **Relevant groups** |
|---|---|---|---|
| Tree stand condition | Provides an indication of the condition of three tree species based on annual assessments across the Basin from the Landsat Record combined with three field indicators: plant Area Index, Crown Extent, Live Basal Area (MDBA 2020) | MDBA Tree stand condition tool (MDBA 2020); outputs calculated for each ANAE polygon | River red gum<br>Black box<br>Coolibah |
| Photosynthetic output – 'greenness' | Provides an indication of the photosynthetic output, or condition, of vegetation | NDVI; outputs calculated for each ANAE polygon | All |
| Cover of vegetation | Provides an indication of the cover of water, vegetation (brown, green and wet) and bare soil from which to interpret condition for different vegetation functional units. | WIT time series metrics from GA; outputs calculated for each ANAE polygon<br>NPV "Dry/brown vegetation"<br>PV "green vegetation"<br>WET "wet vegetation" | All |

### *Indicators of stress*

Key sources of stress (as illustrated in Figure 6) and can be broadly grouped as changes to: i) flow regimes, ii) climate, iii) groundwater and soil interactions, iv) land use, and v) pest plant and animal impacts. Measures of stress to be used in this project are given in Table 5 and focus on changes to flow regimes.

Time since last inundation is thresholded according to known tolerances of different species and vegetation communities. Reponses of long-lived tree species to poor or favourable conditions may take multiple years to manifest so as with condition, indicators of stress for inundation extent and root zone soil moisture are scored using a moving window of five-years in which to calculate the average deviation from baseline, qualified by consideration of the trend over the two years leading to the assessment year.

Table 5. Indicators of stress for inundation dependent vegetation (Roberts and Marston 2011, Rogers and Ralph 2011; see Appendix B for more detail)

| Indicator | Functional group | Low stress | Medium stress | High stress |
|---|---|---|---|---|
| **Extent of inundation (water plus wet from WIT output)** | All | At or above the baseline.<br>Five-year average + two-year trend | Within 1 standard deviation of the baseline.<br>Five-year average + two-year trend | More than 1 standard deviation below the baseline.<br>Five-year average + two-year trend |
| **Time since last inundation** | River red gum | 1-2 years | 3-4 years | ≥ 5 years |
| | Black box | 3 – 4 years | 5 – 6 years | ≥ 7 years |
| | Coolibah | 10 years | 20 years | > 20 years |
| | Lignum | 3 years | 4 years | ≥ 5 years |
| | Submerged | < 3 months | 3 – 4 months | > 4 months |
| | Tall reed beds | < 1 year | 1 – 2 years | > 2 years |
| | Herbfields | 1 year | 2 – 4 years | > 4 years |
| **Root-zone soil moisture** | All | At or above the baseline.<br>Five-year trend | Within 1 standard deviation of the baseline.<br>Five-year trend | More than 1 standard deviation below the baseline.<br>Five-year trend |

# Spatial scales

The base scale for the vegetation vulnerability assessment is the ANAE mapped wetland and floodplain polygon scale. Indicators of condition and stress were calculated for all polygons mapping the ANAE managed floodplain. We recognise, however, that environmental watering does not target individual mapped ANAE types, which in some locations can represent very small spatial scales. For example, Barmah Forest Ramsar Site comprises over 400 ANAE polygons, with over 180 polygons that would fall into the functional group river red gum swamps and forests.

The BWS scale for assessing vegetation expected outcomes is river valley (MDBA 2019; Appendix D). For this reason, we have aggregated outputs to the valley scale in the application of the method (see page 21). The method, however, can be applied at any scale between individual ANAE polygons, to a whole of Basin, to match environmental water planning or reporting needs. Asset or wetland complex scales such as Ramsar Sites or Directory of Important Wetlands may prove to be the most useful in determining environmental watering priorities.

## Recent climatic conditions

Rainfall deciles during the recent five-year period (Figure 7) contributing to the 2021 vegetation vulnerability assessment began with a very dry period across eastern Australia in 2017-2019 (driest on record in 2019) followed by above average rainfall in much of the Basin in 2020-2021.

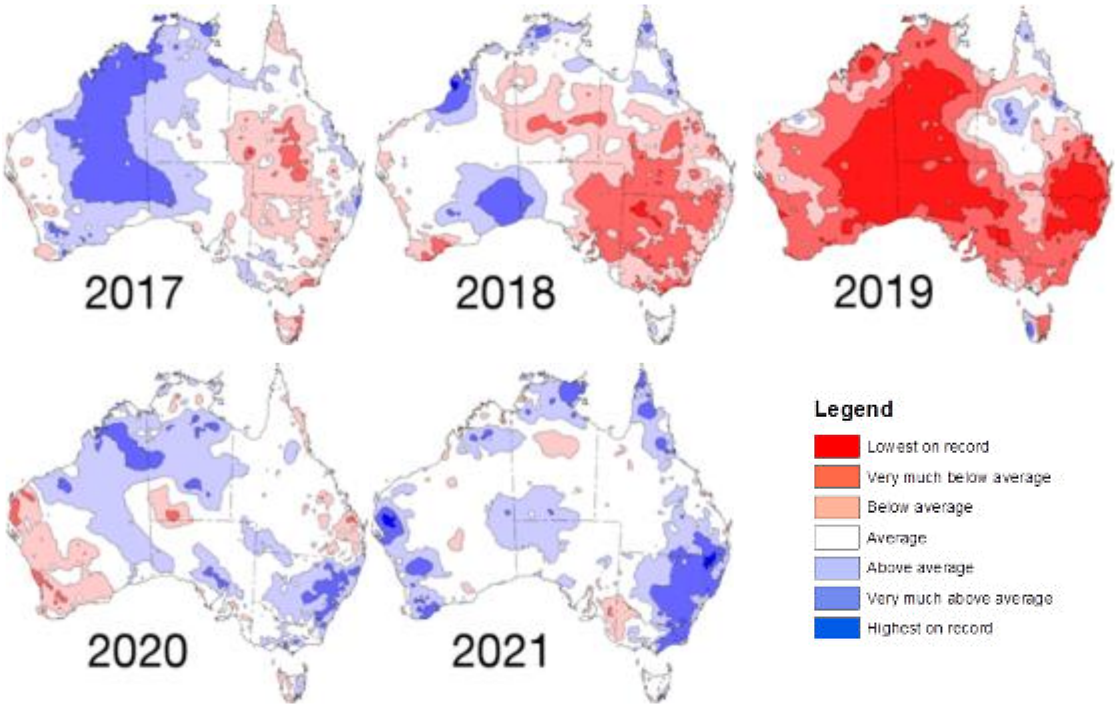


Figure 7. Rainfall deciles 2017-2021 (Bureau of Meteorology 2022a)

## Outcomes of the vulnerability assessment for vegetation

### *Condition*

Annual tree-stand condition and NDVI were measured for each ANAE wetland and floodplain polygon on the managed floodplain using Google Earth Engine. Vegetation cover was measured as the sum of the annual median of WIT non-green vegetation, green vegetation, and wet vegetation cover. Refer to Appendix D for more details of the spatial analysis. Annual NDVI mosaics and tree stand condition were available for 1987-2021, resulting in the ability to calculate condition metrics for the period 1991-2021 with each year averaging the standardised anomaly (deviation from baseline) for the preceding 5 years and trajectory of change (trend) over the last two years. Vegetation condition could not be measured for submerged vegetation that is not visible in satellite imagery used to calculate NDVI and vegetation cover.

Figure 8 shows that vegetation condition aggregated from the ANAE managed floodplain to the BWS vegetation region scale (valleys) is generally in good condition in all valleys following above average rainfall over much of the Basin in 2020 and 2021 (Figure 7). In the northern Basin, this represents a substantial increase in condition from the period leading up to 2019 (Figure 8) which includes three consecutive extremely dry years 2017-19 (Figure 7).

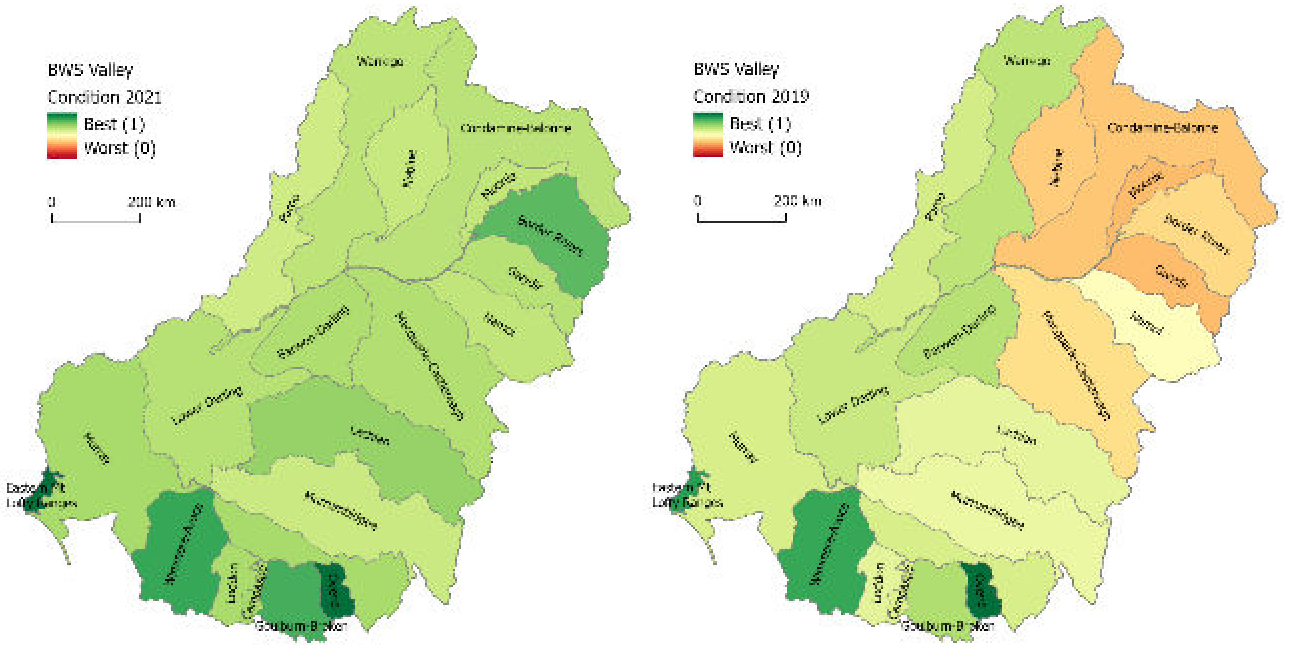


Figure 8. Vegetation condition of BWS vegetation regions at the end of 2021 and after three years of dry conditions in the northern Basin 2017–19

Figure 9 and Figure 10 map the condition of the ANAE managed floodplain within the valleys shown in Figure 8 showing how the data can be viewed at different scales to increase understanding of what is generating the pattern seen at the BWS asset scale. Figure 10 includes an example of the poorest condition in the Basin resulting from the five-years leading to 2006 during the Millennium Drought. This 5-year assessment period includes both 2002 and 2006 which were the two driest years of the drought with lowest on record rainfall over much of the Basin (Bureau of Meteorology 2022a).

Table 6 displays an example of another way to dissect the patterns in condition seen at valley scales through all years of the assessment to understand how different vegetation functional groups are contributing to the overall asset condition score. The improvement in scores at the break of drought in 2010 and wet 2016 is evident in most valleys, as is the poor condition in response to very dry conditions in 2017-2019 across much of NSW and QLD, with consistent improvement across most valleys and vegetation groups in 2020. Shallow wetlands have been slow to recover in 2021 in the Lachlan (grassy meadows, and tall reed beds which include the Great Cumbung Swamp).

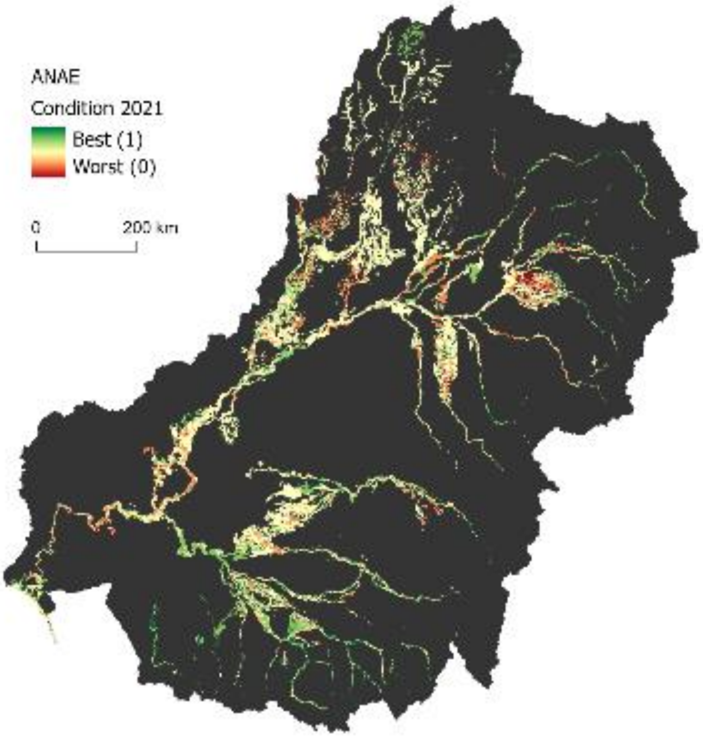


Figure 9. Vegetation condition for 2021 within ANAE wetlands and floodplains on the BWS managed floodplain

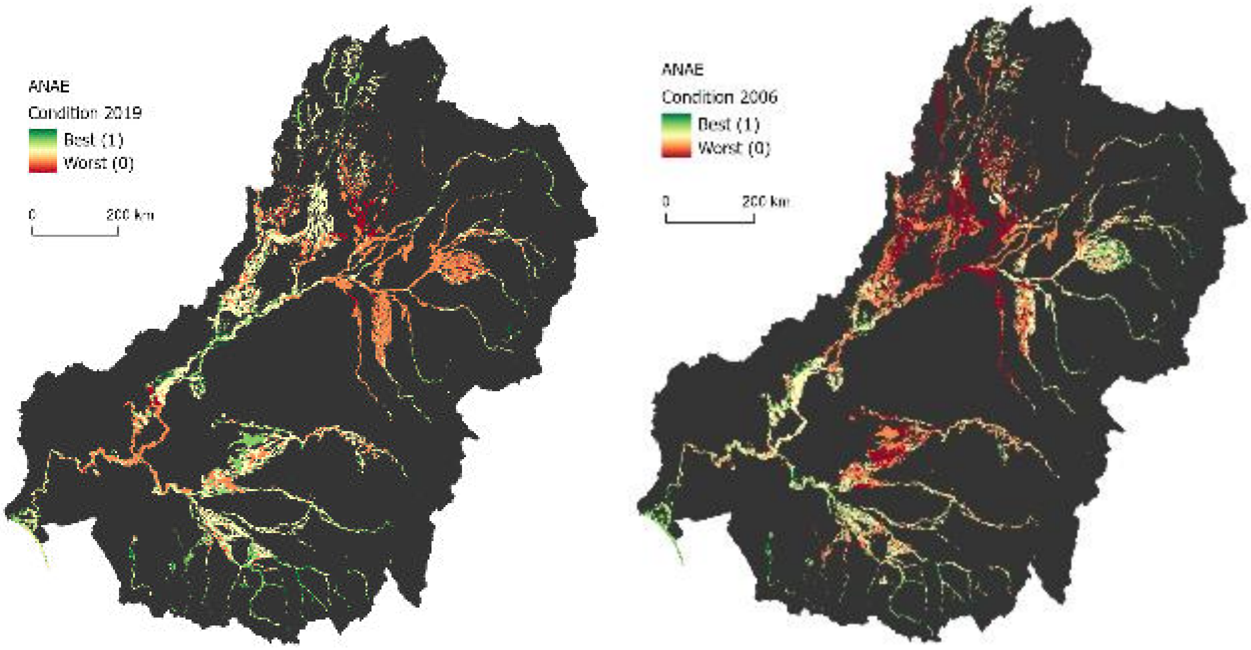


Figure 10. Vegetation condition within ANAE wetlands and floodplains on the BWS managed floodplain following three years of dry conditions in 2019 and after the driest period of the Millennium Drought in 2006

Table 6. Condition scores (re-scaled 0-1) for vegetation functional groups in six example BWS regions. The score in each year is derived from the 5 years leading up to and including the assessment year. Colour highlights are percentiles within each valley from lowest condition to highest condition (red to green) with the 50th percentile yellow.

| | Group | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Goulburn-Broken | black box | 0.5 | 0.5 | 0.7 | 0.8 | 0.7 | 0.7 | 0.8 | 0.5 | 0.5 | 0.8 | 0.5 | 0.3 | 0.7 | 0.8 | 0.5 | 0.3 | 0.5 | 0.7 | 0.7 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 1.0 | 0.8 | 1.0 | 0.8 | 0.7 | 1.0 | 0.7 |
| | grassy meadows | 0.3 | 0.5 | 0.0 | 0.5 | 0.8 | 0.5 | 0.8 | 0.8 | 1.0 | 1.0 | 0.5 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 | 0.8 | 0.5 | 0.8 | 0.5 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 |
| | herbfield | 0.5 | 0.5 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 |
| | lignum | 0.5 | 0.3 | 0.5 | 1.0 | 0.8 | 0.5 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 0.5 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 1.0 | 1.0 | 0.8 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 |
| | river red gum swamps and forests | 0.3 | 0.5 | 0.5 | 0.5 | 0.5 | 0.7 | 0.5 | 0.8 | 0.7 | 0.8 | 0.7 | 0.3 | 0.5 | 0.7 | 0.5 | 0.5 | 0.5 | 0.7 | 0.5 | 0.5 | 1.0 | 0.7 | 0.8 | 1.0 | 0.8 | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 |
| | river red gum woodland | 0.3 | 0.5 | 0.7 | 0.5 | 0.5 | 0.7 | 0.5 | 0.5 | 0.8 | 0.8 | 0.8 | 0.3 | 0.8 | 0.8 | 0.7 | 0.5 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.7 | 0.7 | 0.8 | 0.8 | 1.0 | 1.0 | 0.7 | 0.7 | 1.0 | 0.7 |
| | tall reed beds | 0.3 | 0.5 | 0.5 | 0.8 | 0.5 | 0.5 | 0.5 | 0.8 | 0.5 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Gwydir | black box | 1.0 | 0.7 | 0.8 | 0.7 | 0.8 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.5 | 0.8 | 0.5 | 0.3 | 0.3 | 0.7 | 0.3 | 0.5 | 0.7 | 0.5 | 0.5 | 0.5 | 0.5 | 0.8 | 0.2 | 0.2 | 0.3 | 0.8 | 0.7 |
| | coolibah | 0.8 | 0.7 | 0.8 | 0.7 | 1.0 | 0.8 | 0.7 | 0.8 | 1.0 | 1.0 | 0.8 | 0.5 | 0.7 | 0.8 | 0.7 | 0.3 | 0.5 | 0.8 | 0.7 | 0.7 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.2 | 0.2 | 0.3 | 0.5 | 0.7 |
| | grassy meadows | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 0.5 | 0.5 | 0.0 | 0.3 | 0.8 | 0.5 |
| | herbfield | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.5 | 0.5 | 0.5 | 1.0 | 0.5 |
| | lignum | 0.8 | 0.5 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.8 | 1.0 | 0.8 | 0.5 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 | 0.8 | 0.5 | 0.5 | 0.0 | 0.3 | 0.5 | 0.5 |
| | river red gum swamps and forests | 0.8 | 0.7 | 0.8 | 0.8 | 1.0 | 0.7 | 0.7 | 0.8 | 0.8 | 1.0 | 0.8 | 0.7 | 0.8 | 1.0 | 0.7 | 0.7 | 0.7 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.5 | 0.3 | 0.7 | 0.8 |
| | tall reed beds | 0.8 | 0.8 | 0.8 | 0.5 | 0.8 | 1.0 | 0.5 | 0.8 | 0.8 | 1.0 | 0.8 | 1.0 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.5 | 0.8 | 1.0 | 0.8 |
| Lachlan | black box | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 | 0.5 | 0.5 | 0.7 | 0.8 | 0.3 | 0.3 | 0.7 | 0.3 | 0.3 | 0.2 | 0.0 | 0.0 | 0.2 | 0.5 | 0.5 | 0.2 | 0.8 | 0.7 | 0.7 | 1.0 | 0.5 | 0.5 | 0.5 | 0.8 | 0.8 |
| | grassy meadows | 0.8 | 0.8 | 0.5 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 0.3 | 0.3 | 0.3 | 0.3 | 0.5 | 0.8 | 0.8 | 0.3 | 1.0 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.8 | 0.3 |
| | herbfield | 0.8 | 0.5 | 0.5 | 0.8 | 0.8 | 0.5 | 0.8 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 | 0.8 | 0.5 | 0.5 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 0.5 |
| | lignum | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 1.0 | 0.3 | 0.5 | 0.8 | 0.5 | 0.3 | 0.3 | 0.0 | 0.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 1.0 | 0.8 | 1.0 | 0.8 | 0.5 | 0.8 | 0.5 | 0.5 |
| | river red gum swamps and forests | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 | 0.5 | 0.5 | 0.5 | 0.8 | 0.8 | 0.5 | 0.5 | 0.7 | 0.5 | 0.5 | 0.3 | 0.3 | 0.2 | 0.3 | 0.7 | 0.5 | 0.2 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.3 | 0.5 | 0.8 | 0.8 |
| | tall reed beds | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 1.0 | 0.5 | 0.5 | 0.8 | 0.8 | 0.3 | 0.0 | 0.3 | 0.0 | 0.5 | 0.8 | 1.0 | 0.5 | 0.5 | 1.0 | 0.8 | 0.8 | 0.3 | 0.3 | 0.5 | 0.5 | 0.3 |
| Macquarie-Castlereagh | black box | 0.7 | 0.7 | 0.8 | 0.7 | 0.8 | 0.5 | 0.7 | 0.8 | 1.0 | 0.8 | 0.7 | 0.3 | 0.7 | 0.5 | 0.3 | 0.2 | 0.3 | 0.7 | 0.3 | 0.8 | 0.5 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.3 | 0.2 | 0.3 | 0.8 | 0.7 |
| | coolibah | 0.7 | 0.5 | 0.7 | 0.7 | 0.8 | 0.5 | 0.7 | 0.8 | 1.0 | 0.8 | 0.7 | 0.5 | 0.7 | 0.5 | 0.2 | 0.2 | 0.3 | 0.7 | 0.3 | 0.7 | 0.7 | 0.5 | 0.7 | 0.7 | 0.7 | 0.7 | 0.3 | 0.3 | 0.5 | 0.7 | 0.7 |
| | grassy meadows | 0.8 | 0.8 | 0.8 | 0.5 | 1.0 | 0.5 | 0.8 | 0.8 | 1.0 | 1.0 | 0.5 | 0.8 | 0.8 | 0.5 | 0.3 | 0.3 | 0.5 | 0.5 | 0.5 | 0.8 | 1.0 | 0.8 | 0.8 | 1.0 | 0.8 | 0.5 | 0.5 | 0.0 | 0.3 | 1.0 | 0.5 |
| | herbfield | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.5 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 0.8 | 0.3 | 0.5 | 0.5 | 0.8 | 0.5 | 0.8 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 | 0.3 | 0.0 | 0.3 | 1.0 | 0.5 |
| | lignum | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 0.5 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 0.5 | 0.3 | 0.3 | 0.5 | 0.5 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.3 | 0.3 | 0.3 | 0.5 | 0.5 |
| | river red gum swamps and forests | 0.7 | 0.7 | 0.8 | 0.3 | 0.7 | 0.5 | 0.5 | 0.7 | 0.8 | 1.0 | 0.7 | 0.5 | 0.7 | 0.7 | 0.7 | 0.3 | 0.3 | 0.7 | 0.5 | 0.7 | 0.7 | 0.8 | 1.0 | 0.8 | 0.8 | 1.0 | 0.8 | 0.5 | 0.3 | 1.0 | 0.8 |
| | river red gum woodland | 0.7 | 0.7 | 0.8 | 0.5 | 0.8 | 0.5 | 0.5 | 0.7 | 1.0 | 1.0 | 0.7 | 0.5 | 0.7 | 0.7 | 0.5 | 0.3 | 0.3 | 0.5 | 0.5 | 0.8 | 1.0 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.7 | 0.3 | 0.3 | 1.0 | 0.7 |
| | tall reed beds | 0.3 | 0.5 | 0.8 | 0.5 | 1.0 | 0.5 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.3 | 0.8 | 0.8 | 0.3 | 0.5 | 0.3 | 0.5 | 0.5 | 0.8 | 1.0 | 1.0 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.3 | 0.8 | 0.8 | 0.8 |
| Murray | black box | 0.7 | 0.7 | 0.8 | 1.0 | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 | 0.8 | 0.7 | 0.3 | 0.7 | 0.8 | 0.7 | 0.7 | 0.5 | 0.3 | 0.7 | 0.7 | 0.8 | 0.5 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 | 0.5 | 0.5 | 0.8 | 0.7 |
| | grassy meadows | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 | 1.0 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.8 | 1.0 | 0.5 | 0.5 | 1.0 | 1.0 | 0.8 | 1.0 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 |
| | herbfield | 0.8 | 0.5 | 0.5 | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 | 1.0 | 0.5 | 0.5 | 1.0 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 | 0.8 | 0.8 |
| | lignum | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.8 | 1.0 | 0.8 | 0.5 | 0.8 | 1.0 | 0.8 | 0.8 | 0.8 | 0.5 | 0.3 | 0.5 | 0.5 |
| | river red gum swamps and forests | 0.5 | 0.7 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.5 | 0.8 | 0.8 | 0.8 | 0.3 | 0.7 | 0.8 | 0.8 | 0.3 | 0.3 | 0.5 | 0.7 | 0.7 | 1.0 | 0.7 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 0.7 | 0.7 | 0.7 | 0.7 |
| | river red gum woodland | 0.5 | 0.3 | 0.7 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.7 | 0.5 | 0.5 | 0.8 | 0.7 | 0.5 | 0.3 | 0.3 | 0.7 | 0.7 | 0.7 | 0.7 | 1.0 | 0.8 | 1.0 | 1.0 | 1.0 | 0.8 | 0.7 | 0.8 | 0.8 |
| | tall reed beds | 0.3 | 0.3 | 0.3 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 1.0 | 0.5 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Murrumbidgee | black box | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 | 0.7 | 0.7 | 0.5 | 0.5 | 0.8 | 0.2 | 0.3 | 0.7 | 0.5 | 0.3 | 0.3 | 0.2 | 0.0 | 0.2 | 0.7 | 0.5 | 0.3 | 0.7 | 0.8 | 0.7 | 1.0 | 0.8 | 0.3 | 0.5 | 0.7 | 0.7 |
| | grassy meadows | 0.8 | 1.0 | 0.8 | 0.8 | 1.0 | 0.5 | 0.5 | 0.8 | 1.0 | 0.8 | 0.3 | 0.3 | 0.5 | 0.5 | 0.3 | 0.3 | 0.0 | 0.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 1.0 | 1.0 | 0.5 | 0.5 | 0.3 | 0.8 | 0.8 | 0.5 |
| | herbfield | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.5 | 0.8 | 1.0 | 1.0 | 0.3 | 0.5 | 0.8 | 0.5 | 0.5 | 0.3 | 0.0 | 0.0 | 0.3 | 0.5 | 0.5 | 0.3 | 0.5 | 0.8 | 0.8 | 1.0 | 0.5 | 0.5 | 0.5 | 0.8 | 0.5 |
| | lignum | 0.8 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.3 | 0.5 | 0.8 | 0.5 | 0.3 | 0.3 | 0.0 | 0.0 | 0.5 | 0.8 | 0.5 | 0.3 | 0.5 | 0.8 | 0.8 | 1.0 | 0.8 | 0.3 | 0.3 | 0.5 | 0.5 |
| | river red gum swamps and forests | 0.7 | 0.8 | 0.8 | 0.7 | 0.8 | 0.7 | 0.5 | 0.7 | 0.8 | 0.8 | 0.7 | 0.3 | 0.7 | 0.7 | 0.5 | 0.5 | 0.3 | 0.2 | 0.5 | 0.5 | 0.7 | 0.5 | 0.7 | 0.8 | 0.7 | 0.8 | 1.0 | 0.7 | 0.7 | 0.8 | 0.7 |
| | river red gum woodland | 0.5 | 0.8 | 0.8 | 0.8 | 0.7 | 0.8 | 0.7 | 0.7 | 0.5 | 0.8 | 0.5 | 0.5 | 0.7 | 0.7 | 0.5 | 0.5 | 0.5 | 0.5 | 0.7 | 0.8 | 0.3 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.8 |
| | tall reed beds | 0.8 | 0.8 | 1.0 | 0.8 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 1.0 | 0.3 | 0.5 | 0.8 | 0.8 | 0.3 | 0.0 | 0.3 | 0.0 | 0.5 | 0.8 | 1.0 | 0.5 | 0.5 | 1.0 | 0.8 | 0.8 | 0.5 | 0.3 | 0.8 | 0.5 | 0.5 |

### *Stress*

Vegetation stress is measured as a function of the inundation regime, rainfall and soils using WIT surface water extent, root zone soil moisture and the different vegetation functional groups tolerance to dry periods (measured as the time since last inundation using the WIT to characterise the duration of periods with below-median cover of surface water and wetness). With wet La Niña conditions in 2020 and 2021, the stress measured at BWS valley scales for 2021 is low in the northern Basin (Figure 11) with some highest on record rainfall in the Border Rivers area in 2021. In the same period, much of South Australia and the Victorian Murray River had below average rainfall (Figure 7) contributing to higher stress in the south of the Basin. At the valley scale, stress was estimated to be relatively low in 2019 despite three years of dry conditions because this period followed a very wet 2016 and the acute dry period did not exceed the 'medium' stress thresholds for most vegetation groups (Table 5).

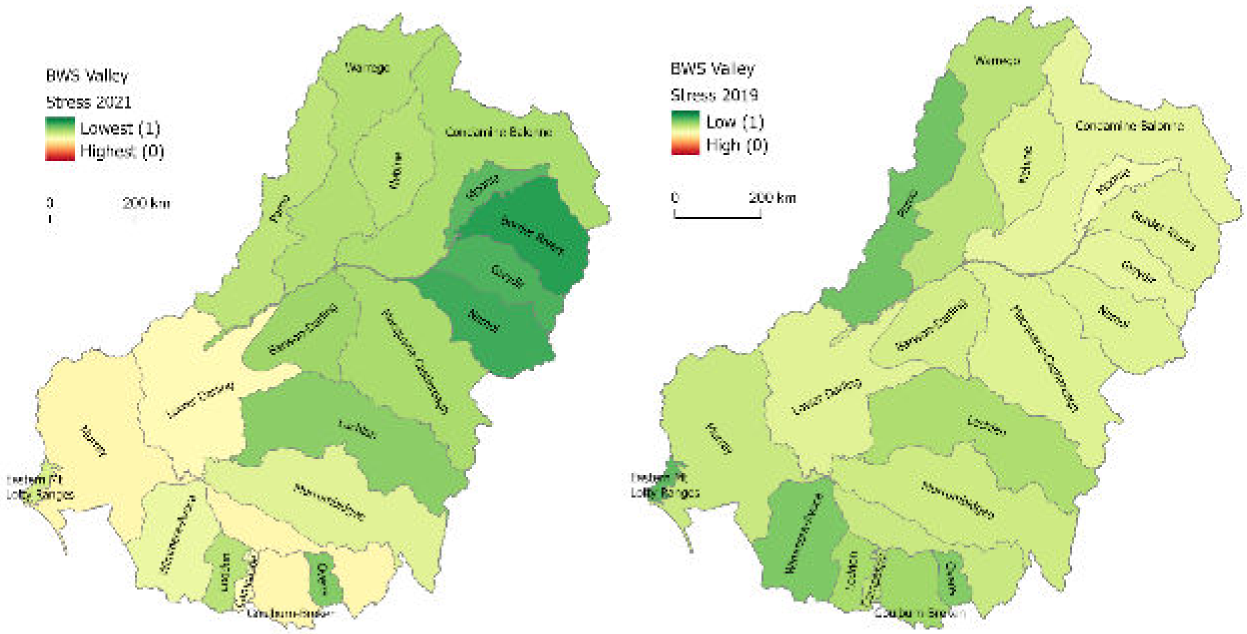


Figure 11. Vegetation stress in BWS vegetation regions 2021 and after three years of dry condition in 2019.

As for condition, the valley stress measure can be interpreted by looking at the finer spatial scale of the ANAE managed floodplain (Figure 12 and Figure 13). In 2021 there are local hotspots of higher stress visible that are not seen at the valley scales in the Wimmera-Avoca valley (Lake Hindmarsh), and the Lachlan valley (wetlands and floodplain towards the terminus of the Lachlan River at the Great Cumbung Swamp) (Figure 12). Severe stress during 2017-2019 and during the Millennium Drought (to 2006) are seen in the Figure 13 to be particularly concentrated in the lowland parts of the Basin. Headwaters in the Northern Basin are in arid landscapes for which our stress metrics during drought years are not substantively different to baseline conditions for these systems.

Table 7 shows stress for individual vegetation functional groups across all years in six of the BWS vegetation regions (valleys). Tall reed beds consistently score as highly stressed during dry conditions in the Lachlan, Murray and Murrumbidgee valleys, but less so in the Macquarie-Castlereagh (Table 7) which includes the extensive Macquarie Marshes system. This appears to be because of a combination of high inter-annual variability of inundation in the Macquarie-Castlereagh valley (lowering the stress measure when stress is standardised by the standard deviation from the baseline) but also is likely due to increased inundation frequency from annual environmental watering of the Macquarie Marshes.

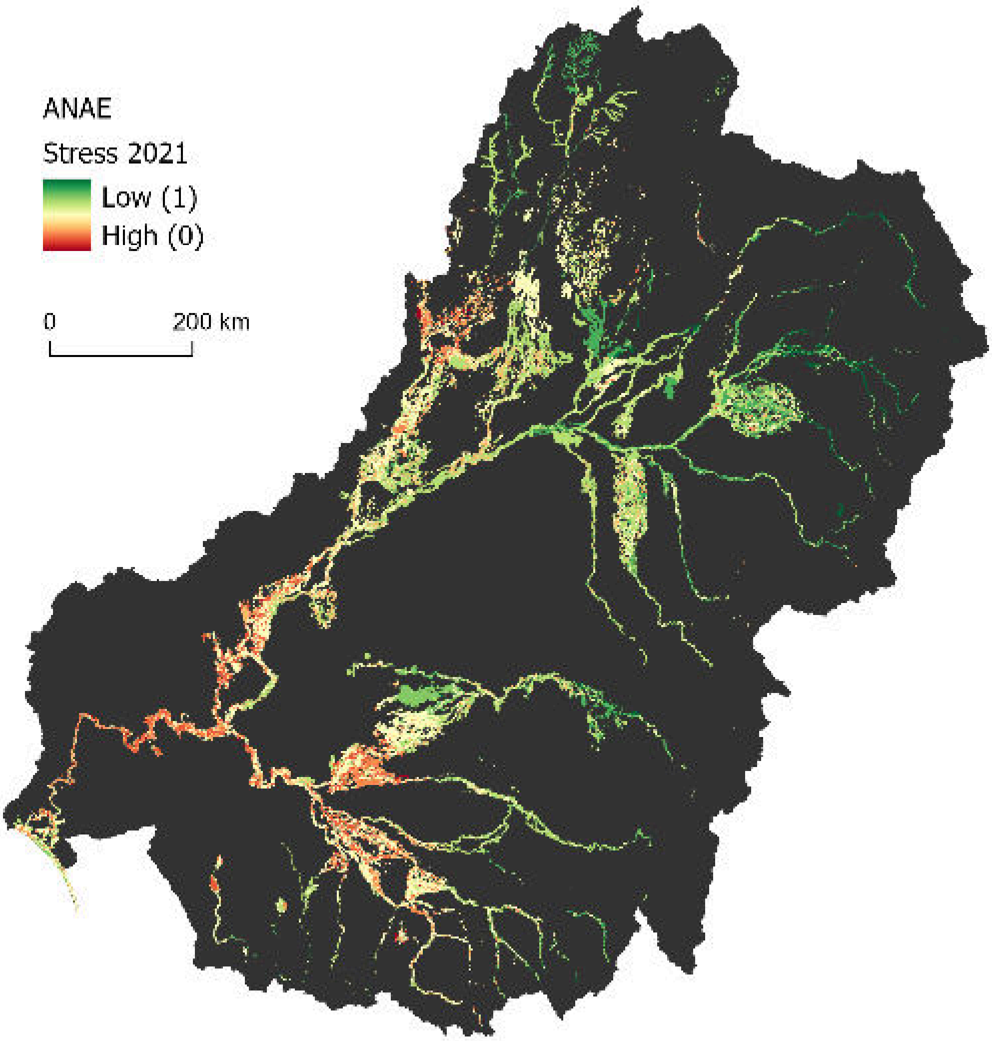


Figure 12. Vegetation stress for 2021 within ANAE wetlands and floodplains on the BWS managed floodplain

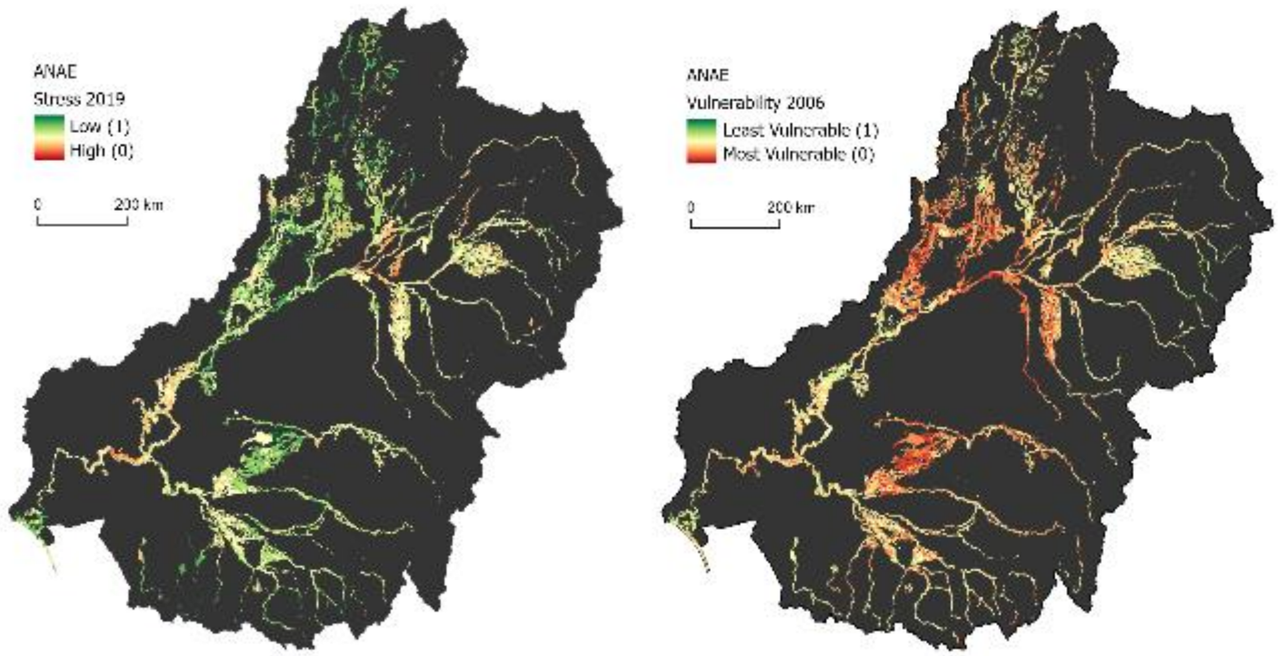


Figure 13. Vegetation stress within ANAE wetlands and floodplains on the BWS managed floodplain following three years of dry conditions in 2019 and after the driest period of the Millennium Drought in 2006

Table 7. Combined stress scores (re-scaled 0-1) for vegetation functional groups in six example BWS regions. The score in each year is derived from the 5 years leading up to and including the assessment year. Colour highlights are percentiles within each valley from lowest stress to highest stress (green to red) with the 50th percentile yellow.

| | Group | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Goulburn-Broken** | black box | 0.8 | 1.0 | 1.0 | 0.5 | 1.0 | 0.7 | 0.7 | 0.6 | 0.8 | 0.7 | 0.5 | 0.4 | 0.8 | 0.5 | 0.6 | 0.4 | 0.6 | 0.4 | 0.5 | 0.8 | 0.6 | 1.0 | 0.6 | 1.0 | 0.4 | 1.0 | 0.4 | 0.6 | 0.6 | 0.8 | 0.5 |
| | grassy meadows | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 | 1.0 | 0.8 | 0.7 | 0.8 | 0.7 | 0.4 | 0.5 | 0.8 | 0.4 | 0.6 | 0.5 | 0.7 | 0.3 | 0.5 | 0.8 | 0.8 | 0.7 | 0.7 | 0.8 | 0.4 | 0.8 | 0.7 | 0.7 | 0.6 | 0.8 | 0.5 |
| | herbfield | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 0.7 | 0.5 | 0.7 | 0.4 | 0.3 | 0.1 | 0.2 | 0.1 | 0.2 | 0.7 | 0.5 | 0.7 | 0.7 | 1.0 | 0.4 | 1.0 | 0.6 | 0.2 | 0.4 | 0.6 | 0.1 |
| | lignum | 1.0 | 1.0 | 0.8 | 0.5 | 1.0 | 1.0 | 0.7 | 0.7 | 0.8 | 1.0 | 0.5 | 0.7 | 0.8 | 0.5 | 0.5 | 0.3 | 0.7 | 0.5 | 0.3 | 0.8 | 0.7 | 0.7 | 0.7 | 0.8 | 0.3 | 0.8 | 0.7 | 0.3 | 0.5 | 1.0 | 0.3 |
| | river red gum swamps and forests | 1.0 | 1.0 | 1.0 | 0.5 | 1.0 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.5 | 0.4 | 0.8 | 0.5 | 0.7 | 0.5 | 0.6 | 0.4 | 0.4 | 0.8 | 0.8 | 0.8 | 0.7 | 1.0 | 0.5 | 1.0 | 0.5 | 0.5 | 0.7 | 0.8 | 0.5 |
| | river red gum woodland | 1.0 | 1.0 | 1.0 | 0.5 | 1.0 | 1.0 | 0.5 | 0.8 | 0.8 | 0.7 | 0.5 | 0.4 | 0.8 | 0.5 | 0.7 | 0.5 | 0.7 | 0.4 | 0.4 | 0.8 | 0.5 | 0.8 | 0.7 | 1.0 | 0.5 | 1.0 | 0.5 | 0.7 | 0.8 | 1.0 | 0.5 |
| | tall reed beds | 1.0 | 1.0 | 1.0 | 0.5 | 1.0 | 0.8 | 0.8 | 0.6 | 0.8 | 0.7 | 0.5 | 0.4 | 0.8 | 0.5 | 0.7 | 0.5 | 0.6 | 0.4 | 0.4 | 0.8 | 0.7 | 0.8 | 0.7 | 0.8 | 0.4 | 0.8 | 0.7 | 0.5 | 0.7 | 0.8 | 0.5 |
| **Gwydir** | black box | 0.8 | 1.0 | 0.8 | 0.6 | 0.8 | 1.0 | 0.7 | 1.0 | 0.8 | 1.0 | 1.0 | 0.7 | 0.8 | 1.0 | 0.8 | 0.5 | 1.0 | 0.8 | 0.6 | 1.0 | 0.7 | 0.8 | 0.5 | 0.7 | 0.8 | 0.8 | 0.5 | 0.7 | 0.5 | 1.0 | 0.8 |
| | coolibah | 0.8 | 0.9 | 0.8 | 0.6 | 0.8 | 0.8 | 0.7 | 1.0 | 0.8 | 1.0 | 1.0 | 0.6 | 0.8 | 1.0 | 0.7 | 0.5 | 0.8 | 0.8 | 0.7 | 0.8 | 0.7 | 0.8 | 0.6 | 0.6 | 0.8 | 0.8 | 0.4 | 0.6 | 0.6 | 0.8 | 0.8 |
| | grassy meadows | 0.8 | 0.8 | 0.8 | 0.4 | 0.8 | 0.8 | 0.7 | 1.0 | 0.8 | 1.0 | 1.0 | 0.8 | 1.0 | 0.8 | 0.8 | 0.4 | 0.8 | 0.8 | 0.7 | 1.0 | 0.7 | 1.0 | 0.6 | 0.6 | 0.8 | 0.8 | 0.5 | 0.6 | 0.5 | 0.8 | 0.8 |
| | herbfield | 0.9 | 0.9 | 0.8 | 0.5 | 0.8 | 0.9 | 0.7 | 1.0 | 0.8 | 1.0 | 1.0 | 0.4 | 0.9 | 1.0 | 1.0 | 0.5 | 0.8 | 0.8 | 0.6 | 0.8 | 0.7 | 1.0 | 0.6 | 0.6 | 0.9 | 0.8 | 0.5 | 0.4 | 0.6 | 0.8 | 0.8 |
| | lignum | 0.8 | 0.9 | 0.8 | 0.5 | 0.8 | 0.8 | 0.6 | 1.0 | 0.8 | 0.8 | 1.0 | 0.6 | 0.7 | 0.8 | 0.6 | 0.4 | 0.8 | 0.8 | 0.6 | 0.8 | 0.7 | 0.9 | 0.6 | 0.8 | 0.9 | 0.8 | 0.4 | 0.7 | 0.7 | 0.8 | 0.8 |
| | river red gum swamps and forests | 1.0 | 1.0 | 0.8 | 0.6 | 0.8 | 0.7 | 0.7 | 1.0 | 0.8 | 0.8 | 1.0 | 0.7 | 1.0 | 1.0 | 1.0 | 0.5 | 0.8 | 1.0 | 0.7 | 0.8 | 0.7 | 0.8 | 0.7 | 0.7 | 0.8 | 0.8 | 0.5 | 0.6 | 0.6 | 1.0 | 0.8 |
| | tall reed beds | 0.8 | 0.8 | 0.8 | 0.5 | 0.8 | 1.0 | 0.7 | 1.0 | 0.8 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 1.0 | 0.4 | 0.8 | 0.8 | 0.7 | 1.0 | 0.7 | 1.0 | 0.8 | 0.8 | 0.8 | 0.8 | 0.4 | 0.7 | 0.6 | 0.8 | 0.7 |
| **Lachlan** | black box | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.6 | 0.6 | 0.8 | 0.8 | 0.8 | 0.5 | 0.6 | 0.8 | 0.4 | 0.8 | 0.4 | 0.5 | 0.5 | 0.5 | 0.8 | 0.6 | 0.9 | 0.6 | 0.8 | 0.8 | 1.0 | 0.5 | 0.6 | 0.8 | 0.8 | 0.7 |
| | grassy meadows | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.6 | 0.6 | 0.8 | 0.7 | 0.8 | 0.6 | 0.5 | 0.8 | 0.6 | 0.8 | 0.5 | 0.8 | 0.5 | 0.6 | 0.8 | 0.6 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 0.8 | 0.6 | 0.6 | 0.8 | 0.8 |
| | herbfield | 0.8 | 1.0 | 1.0 | 0.8 | 1.0 | 0.6 | 0.6 | 0.8 | 0.8 | 1.0 | 0.6 | 0.5 | 0.8 | 0.6 | 0.7 | 0.3 | 0.5 | 0.5 | 0.5 | 0.8 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.6 | 0.6 | 1.0 | 0.8 |
| | lignum | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.6 | 0.6 | 0.8 | 0.8 | 1.0 | 0.6 | 0.6 | 0.8 | 0.4 | 0.8 | 0.4 | 0.5 | 0.6 | 0.5 | 1.0 | 0.6 | 0.9 | 0.8 | 0.8 | 0.8 | 1.0 | 0.5 | 0.6 | 0.8 | 0.8 | 0.7 |
| | river red gum swamps and forests | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 0.7 | 0.6 | 0.8 | 0.7 | 0.8 | 0.7 | 0.6 | 0.8 | 0.4 | 0.8 | 0.4 | 0.6 | 0.5 | 0.5 | 0.8 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 1.0 | 0.7 | 0.6 | 0.6 | 0.8 | 0.8 |
| | tall reed beds | 0.8 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 0.7 | 0.8 | 0.7 | 1.0 | 0.7 | 0.7 | 0.7 | 0.3 | 0.5 | 0.2 | 0.2 | 0.2 | 0.3 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.5 | 0.8 | 0.8 | 0.5 |
| **Macquarie-Castlereagh** | black box | 0.6 | 0.9 | 0.9 | 0.6 | 0.8 | 0.8 | 0.4 | 0.8 | 0.8 | 1.0 | 0.6 | 0.6 | 0.8 | 0.6 | 0.8 | 0.4 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.9 | 0.6 | 0.9 | 0.9 | 1.0 | 0.4 | 0.6 | 0.6 | 0.8 | 0.7 |
| | coolibah | 0.5 | 0.9 | 0.9 | 0.6 | 0.8 | 1.0 | 0.5 | 1.0 | 1.0 | 1.0 | 0.7 | 0.6 | 0.8 | 0.6 | 0.6 | 0.4 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 1.0 | 0.6 | 0.8 | 0.6 | 0.8 | 0.5 | 0.6 | 0.6 | 0.8 | 0.7 |
| | grassy meadows | 0.5 | 1.0 | 1.0 | 0.5 | 0.8 | 0.8 | 0.4 | 0.8 | 0.8 | 1.0 | 0.6 | 0.5 | 0.8 | 0.5 | 0.8 | 0.4 | 0.7 | 0.8 | 0.8 | 1.0 | 0.7 | 1.0 | 0.6 | 0.9 | 0.8 | 1.0 | 0.5 | 0.6 | 0.5 | 1.0 | 0.7 |
| | herbfield | 0.6 | 0.9 | 1.0 | 0.6 | 0.8 | 0.8 | 0.4 | 0.8 | 0.8 | 1.0 | 0.6 | 0.5 | 0.8 | 0.5 | 0.7 | 0.3 | 0.7 | 0.8 | 0.8 | 1.0 | 0.7 | 0.9 | 0.6 | 0.7 | 0.8 | 0.8 | 0.4 | 0.6 | 0.5 | 1.0 | 0.7 |
| | lignum | 0.5 | 0.9 | 0.9 | 0.6 | 0.8 | 1.0 | 0.3 | 0.8 | 0.8 | 0.8 | 0.6 | 0.5 | 0.8 | 0.5 | 0.6 | 0.3 | 0.7 | 0.8 | 0.7 | 0.8 | 0.6 | 0.7 | 0.5 | 0.6 | 0.7 | 0.8 | 0.3 | 0.5 | 0.5 | 0.8 | 0.7 |
| | river red gum swamps and forests | 0.7 | 1.0 | 1.0 | 0.5 | 0.8 | 0.8 | 0.5 | 0.8 | 0.8 | 1.0 | 0.7 | 0.6 | 0.8 | 0.6 | 0.8 | 0.4 | 0.8 | 0.8 | 0.8 | 1.0 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.6 | 0.6 | 1.0 | 0.8 |
| | river red gum woodland | 0.5 | 1.0 | 1.0 | 0.6 | 0.8 | 0.8 | 0.4 | 0.8 | 0.8 | 1.0 | 0.7 | 0.8 | 0.8 | 0.6 | 0.8 | 0.4 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 1.0 | 0.6 | 0.8 | 0.8 | 0.8 | 0.5 | 0.6 | 0.6 | 0.8 | 0.8 |
| | tall reed beds | 0.7 | 1.0 | 1.0 | 0.5 | 0.8 | 0.8 | 0.5 | 1.0 | 0.8 | 0.8 | 0.7 | 0.6 | 0.8 | 0.6 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 1.0 | 0.7 | 0.8 | 0.7 | 0.7 | 0.8 | 1.0 | 0.7 | 0.7 | 0.6 | 1.0 | 0.7 |
| **Murray** | black box | 0.8 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 0.6 | 0.6 | 0.8 | 0.6 | 0.5 | 0.4 | 0.8 | 0.4 | 0.8 | 0.4 | 0.8 | 0.4 | 0.5 | 0.8 | 0.8 | 0.6 | 0.8 | 1.0 | 0.8 | 1.0 | 0.7 | 0.6 | 0.6 | 0.8 | 0.5 |
| | grassy meadows | 0.8 | 1.0 | 1.0 | 0.7 | 0.8 | 0.8 | 0.6 | 0.6 | 0.7 | 0.7 | 0.4 | 0.3 | 0.7 | 0.3 | 0.7 | 0.3 | 0.5 | 0.5 | 0.5 | 0.8 | 1.0 | 0.6 | 0.8 | 0.9 | 0.7 | 0.8 | 0.6 | 0.6 | 0.5 | 0.7 | 0.4 |
| | herbfield | 1.0 | 1.0 | 0.7 | 0.7 | 0.8 | 1.0 | 0.6 | 0.6 | 0.6 | 0.8 | 0.6 | 0.4 | 0.8 | 0.6 | 0.8 | 0.4 | 0.8 | 0.5 | 0.8 | 0.8 | 0.6 | 0.7 | 0.8 | 0.7 | 0.6 | 0.8 | 0.6 | 0.5 | 0.6 | 0.8 | 0.5 |
| | lignum | 0.9 | 1.0 | 1.0 | 0.7 | 0.8 | 0.8 | 0.6 | 0.6 | 0.8 | 0.8 | 0.6 | 0.3 | 0.7 | 0.5 | 0.7 | 0.3 | 0.5 | 0.5 | 0.5 | 0.8 | 1.0 | 0.4 | 0.8 | 0.9 | 0.8 | 0.8 | 0.7 | 0.6 | 0.6 | 0.8 | 0.4 |
| | river red gum swamps and forests | 0.8 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.5 | 0.4 | 0.8 | 0.5 | 0.7 | 0.5 | 0.8 | 0.4 | 0.6 | 0.8 | 0.8 | 0.6 | 0.8 | 1.0 | 0.7 | 1.0 | 0.7 | 0.5 | 0.7 | 0.8 | 0.5 |
| | river red gum woodland | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 0.8 | 0.6 | 0.8 | 0.8 | 0.5 | 0.4 | 0.8 | 0.6 | 0.8 | 0.5 | 0.8 | 0.4 | 0.6 | 0.8 | 1.0 | 0.6 | 0.8 | 1.0 | 0.7 | 0.8 | 0.7 | 0.7 | 0.7 | 0.8 | 0.5 |
| | tall reed beds | 1.0 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 0.7 | 0.8 | 0.8 | 0.8 | 0.7 | 0.5 | 0.8 | 0.7 | 0.8 | 0.5 | 0.6 | 0.3 | 0.4 | 0.8 | 0.7 | 0.7 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.5 | 0.7 | 0.8 | 0.5 |
| **Murrumbidgee** | black box | 1.0 | 1.0 | 1.0 | 0.6 | 1.0 | 0.8 | 0.6 | 0.6 | 0.8 | 0.8 | 0.5 | 0.6 | 0.8 | 0.4 | 0.8 | 0.4 | 0.7 | 0.5 | 0.7 | 0.8 | 0.7 | 0.6 | 0.8 | 1.0 | 0.8 | 1.0 | 0.7 | 0.5 | 0.6 | 0.8 | 0.5 |
| | grassy meadows | 1.0 | 1.0 | 1.0 | 0.6 | 0.8 | 0.6 | 0.5 | 0.8 | 0.8 | 0.8 | 0.5 | 0.6 | 0.8 | 0.5 | 0.8 | 0.5 | 0.6 | 0.4 | 0.6 | 1.0 | 0.7 | 0.9 | 0.7 | 0.8 | 0.8 | 1.0 | 0.5 | 0.6 | 0.8 | 0.9 | 0.7 |
| | herbfield | 1.0 | 1.0 | 1.0 | 0.6 | 0.8 | 0.6 | 0.4 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 | 0.8 | 0.4 | 0.8 | 0.4 | 0.8 | 0.6 | 0.5 | 0.8 | 0.7 | 0.9 | 0.8 | 0.8 | 1.0 | 1.0 | 0.5 | 0.6 | 0.6 | 0.8 | 0.7 |
| | lignum | 1.0 | 1.0 | 1.0 | 0.6 | 1.0 | 0.7 | 0.6 | 0.8 | 0.8 | 0.8 | 0.5 | 0.6 | 0.8 | 0.6 | 0.8 | 0.4 | 0.7 | 0.5 | 0.6 | 1.0 | 0.7 | 0.8 | 0.8 | 0.8 | 0.7 | 0.8 | 0.7 | 0.4 | 0.6 | 0.6 | 0.5 |
| | river red gum swamps and forests | 1.0 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 0.5 | 0.8 | 0.8 | 0.8 | 0.5 | 0.6 | 0.8 | 0.5 | 0.8 | 0.5 | 0.8 | 0.5 | 0.6 | 0.8 | 0.7 | 0.8 | 0.7 | 0.8 | 0.8 | 0.8 | 0.5 | 0.7 | 0.7 | 0.8 | 0.7 |
| | river red gum woodland | 0.7 | 0.8 | 0.8 | 0.7 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.5 | 0.5 | 0.8 | 0.3 | 0.8 | 0.5 | 0.7 | 0.5 | 0.8 | 0.8 | 1.0 | 0.8 | 0.8 | 1.0 | 1.0 | 1.0 | 0.7 | 0.8 | 0.8 | 0.8 | 0.5 |
| | tall reed beds | 0.8 | 1.0 | 1.0 | 0.7 | 1.0 | 0.8 | 0.8 | 0.8 | 0.7 | 1.0 | 0.7 | 0.7 | 0.7 | 0.3 | 0.5 | 0.2 | 0.2 | 0.2 | 0.3 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.5 | 0.8 | 0.8 | 0.5 |

## *Vulnerability*

Vulnerability as the sum of condition and stress is presented at the BWS vegetation region (valley) scale in Figure 14, showing that at the end of 2021, after substantial rainfall and extensive natural flooding in the basin all BWS regions are of medium to low vulnerability. The situation was different at the end of 2019, with parts of the northern Basin exhibiting low levels of vulnerability, arising from poor vegetation condition in response to lowest on record rainfall.

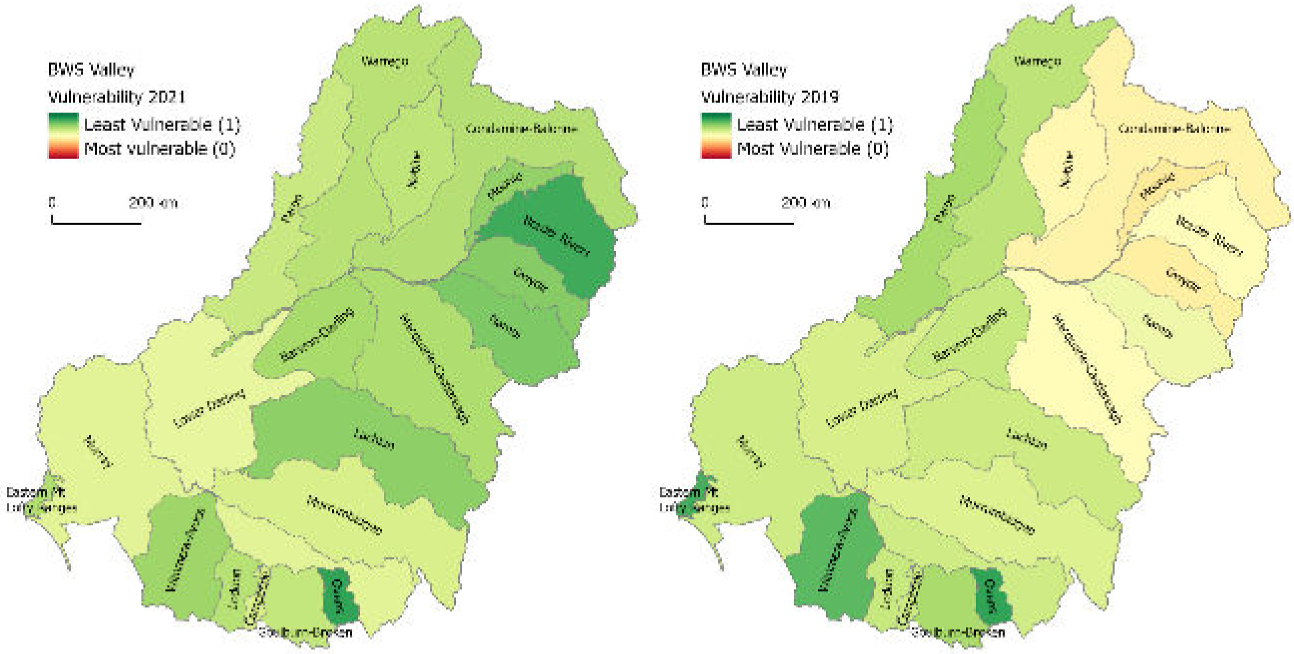


Figure 14. Vegetation vulnerability in BWS vegetation regions 2021 and after three years of dry condition in 2019.

At the scale of the ANAE managed floodplain (Figure 15) there is some indication of potentially vulnerable vegetation in the Paroo, Lower Darling, S.A. Murray and parts of the Lower Murrumbidgee at the end of 2021. Figure 16 shows the increased vulnerability of vegetation at the end of 2019 was concentrated in the Coolibah floodplains in the lowland sections of the Condamine-Balonne, Border Rivers, Gwydir, Namoi and Macquarie-Castlereagh, and river red gum and black box floodplains along the lower Darling and lower Murray River into South Australia. This approach identified that vegetation was likely to be highly vulnerable through most of the lowland floodplains of the Basin at the end of 2006 during the Millennium Drought (Figure 16).

Figure 17 is an example of how the assessment at the ANAE scale can be aggregated to the scales of wetland complexes that are closely aligned with the scales at which water is managed in the Basin. Here an area weighted sum of scores for individual ANAE polygons is used to represent the BWS important Basin environmental assets for waterbirds (Figure 17).

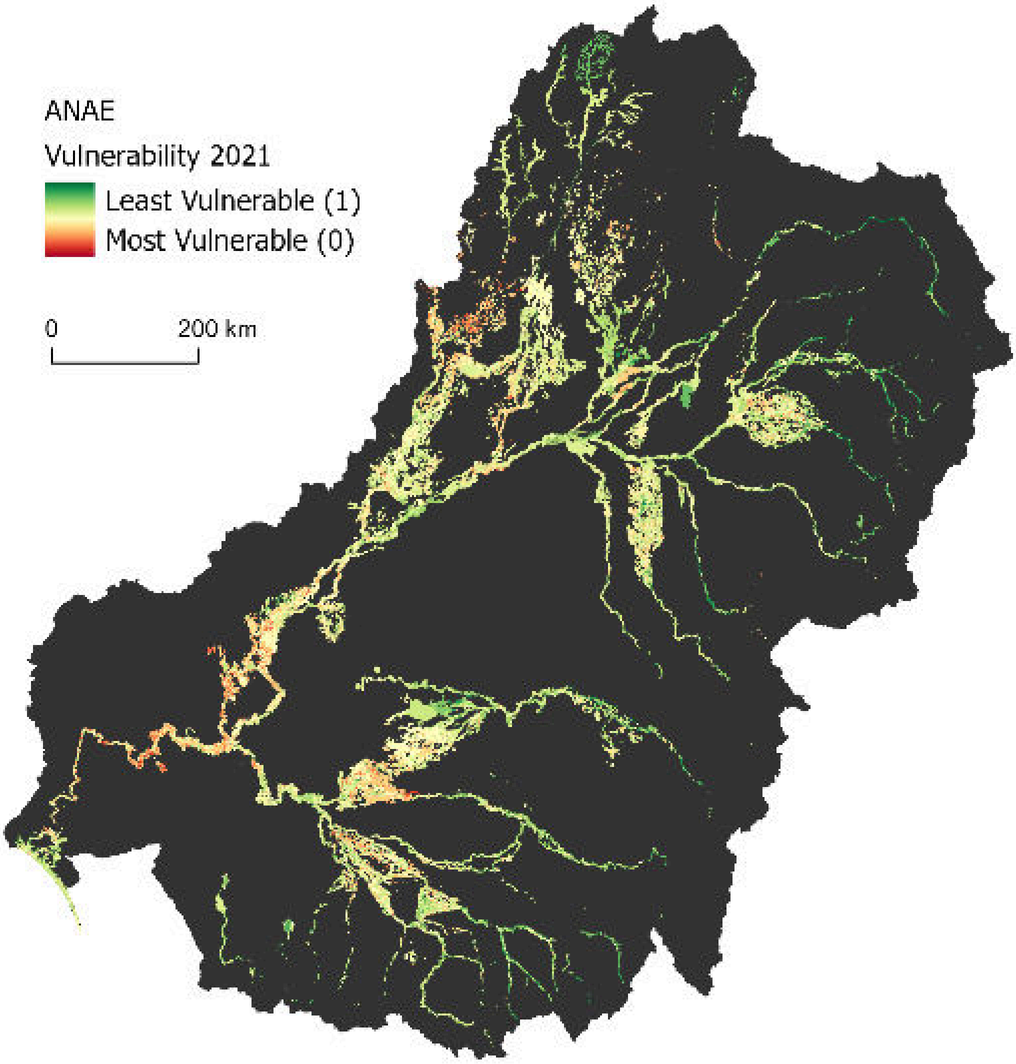


Figure 15. Vulnerability of vegetation within ANAE wetlands and floodplains on the BWS managed floodplain for 2021

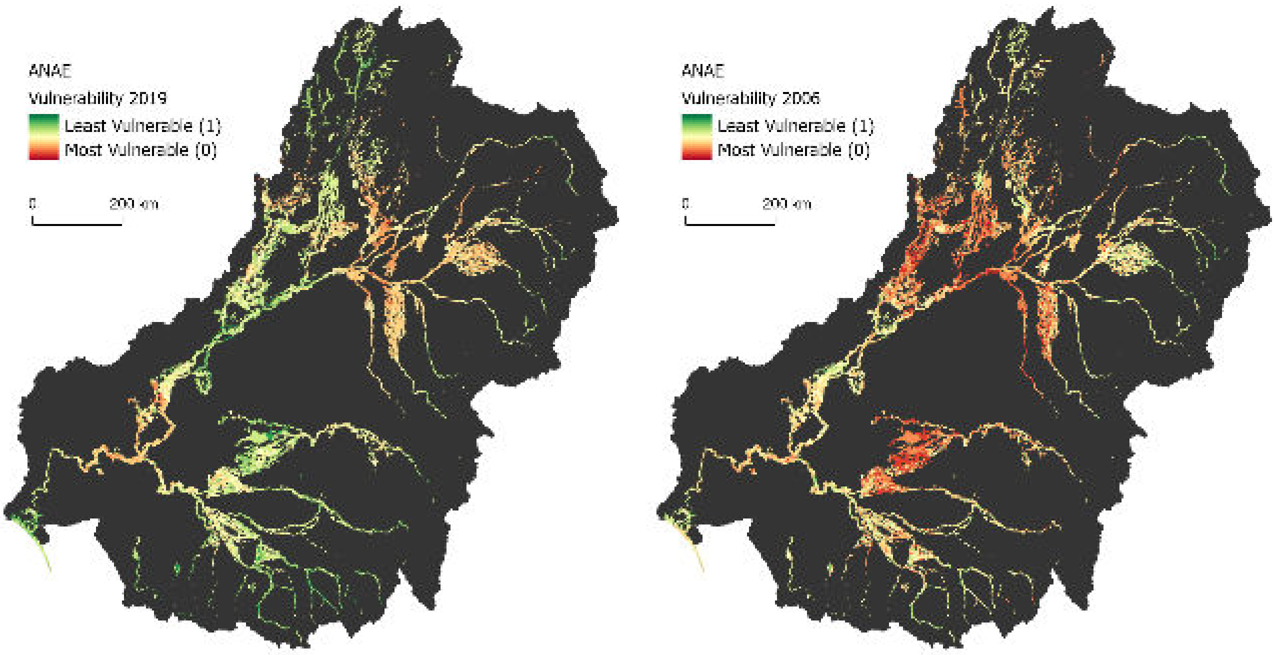


Figure 16. Vulnerability of vegetation within ANAE wetlands and floodplains on the BWS managed floodplain following three years of dry conditions in 2019 and at the end of 2006 during the Millennium Drought

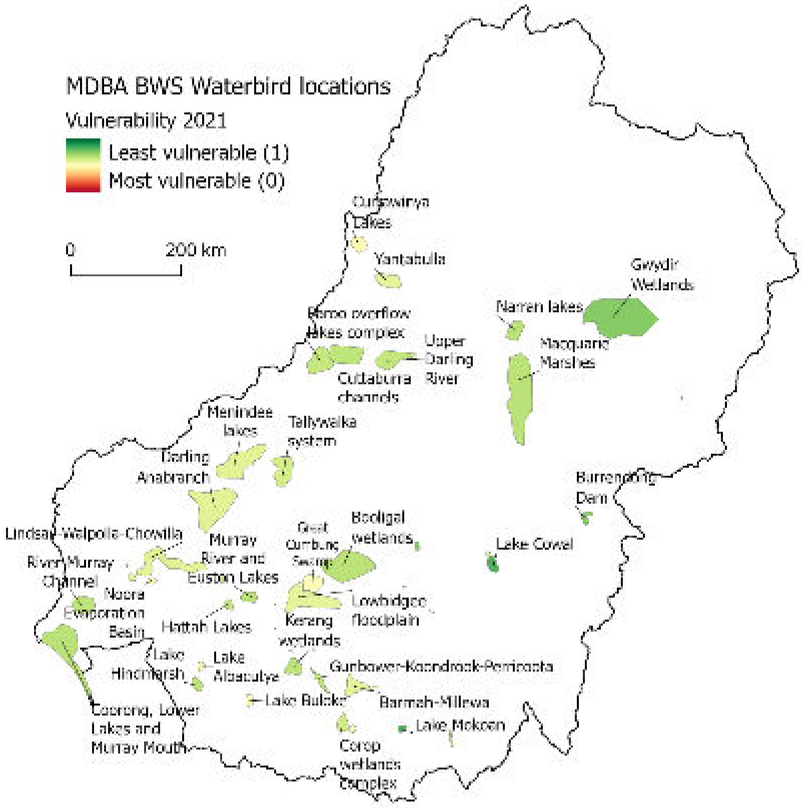


Figure 17. Vegetation vulnerability in 2021 aggregated to BWS important Basin environmental assets for waterbirds

Table 8 provides the final vulnerability score for the different vegetation functional groups in six BWS vegetation regions (valleys) through the period of record 1991 to 2021. Tall reed beds in the Lachlan valley are indicated as moderately vulnerable in 2021. The historic patterns highlight vegetation groups that are particularly vulnerable at different times and also can be interpreted to examine recovery times. This may help identify functional groups in particular regions that are slower to recover that might benefit from additional management: e.g. herbfield in the Goulburn-Broken, lignum in the Gwydir, Macquarie-Castlereagh and Murray valleys, and tall reed beds in the Lachlan and Murrumbidgee.

### *Confidence in the vulnerability assessment for vegetation*

Confidence in the outputs of the vulnerability assessment for vegetation are based both on the strength of ecological knowledge underpinning indicators and thresholds of both condition and stress as well as the robustness of the data available. Appendix B provides a review of the ecological knowledge underpinning the selection of indicators and thresholds and by and large confidence (see Table 2) was considered “moderate”.

Condition and stress metrics rely heavily on Landsat derived metrics (WIT, NDVI, Tree Stand Condition) which are limited due to cloud cover and uncertainties associated with calculation of indices (see Text Box 1 as an example). Despite this, there was good agreement between indicators, providing a multiple lines of evidence approach to stress and condition and the proportion of missing data, was relatively small, when considered at larger scales (e.g. valleys).

Using the confidence level descriptions of Table 2, the vulnerability assessment for vegetation at the valley scale would be considered moderate to high.

Table 8. Vulnerability scores (condition + stress re-scaled to 0-1) for vegetation functional groups in six BWS regions. The score in each year is derived from the 5 years leading up to and including the assessment year. Colour highlights are percentiles within each valley from lowest vulnerability to highest vulnerability (green to red) with the 50th percentile yellow.

| | Group | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Goulburn-Broken | black box | 0.7 | 0.8 | 0.8 | 0.7 | 0.8 | 0.7 | 0.8 | 0.5 | 0.6 | 0.7 | 0.5 | 0.4 | 0.7 | 0.7 | 0.6 | 0.4 | 0.6 | 0.6 | 0.6 | 0.8 | 0.7 | 0.8 | 0.7 | 0.9 | 0.7 | 0.9 | 0.7 | 0.7 | 0.7 | 0.9 | 0.6 |
| | grassy meadows | 0.6 | 0.8 | 0.5 | 0.7 | 0.9 | 0.8 | 0.8 | 0.7 | 0.9 | 0.8 | 0.4 | 0.6 | 0.8 | 0.6 | 0.5 | 0.5 | 0.7 | 0.4 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.6 | 0.9 | 0.7 | 0.7 | 0.8 | 0.9 | 0.8 |
| | herbfield | 0.8 | 0.8 | 0.8 | 0.7 | 0.9 | 0.9 | 0.8 | 0.8 | 0.9 | 0.8 | 0.7 | 0.6 | 0.7 | 0.6 | 0.5 | 0.4 | 0.5 | 0.4 | 0.5 | 0.7 | 0.5 | 0.7 | 0.7 | 0.9 | 0.6 | 0.8 | 0.7 | 0.5 | 0.6 | 0.7 | 0.5 |
| | lignum | 0.8 | 0.6 | 0.7 | 0.8 | 0.9 | 0.8 | 0.7 | 0.8 | 0.9 | 0.9 | 0.6 | 0.7 | 0.7 | 0.8 | 0.6 | 0.4 | 0.7 | 0.6 | 0.5 | 0.9 | 0.8 | 0.7 | 0.8 | 0.9 | 0.5 | 0.9 | 0.7 | 0.5 | 0.8 | 1.0 | 0.5 |
| | river red gum swamps and forests | 0.7 | 0.8 | 0.8 | 0.5 | 0.8 | 0.8 | 0.6 | 0.8 | 0.8 | 0.8 | 0.6 | 0.4 | 0.7 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.7 | 0.9 | 0.7 | 0.8 | 1.0 | 0.7 | 1.0 | 0.8 | 0.8 | 0.7 | 0.9 | 0.8 |
| | river red gum woodland | 0.7 | 0.8 | 0.8 | 0.5 | 0.8 | 0.8 | 0.5 | 0.7 | 0.8 | 0.8 | 0.7 | 0.4 | 0.8 | 0.7 | 0.7 | 0.5 | 0.7 | 0.5 | 0.6 | 0.8 | 0.7 | 0.7 | 0.7 | 0.9 | 0.7 | 1.0 | 0.8 | 0.7 | 0.8 | 1.0 | 0.6 |
| | tall reed beds | 0.6 | 0.8 | 0.8 | 0.6 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.6 | 0.5 | 0.8 | 0.6 | 0.7 | 0.6 | 0.7 | 0.6 | 0.6 | 0.9 | 0.8 | 0.9 | 0.8 | 0.9 | 0.7 | 0.9 | 0.8 | 0.7 | 0.8 | 0.9 | 0.7 |
| Gwydir | black box | 0.9 | 0.8 | 0.8 | 0.6 | 0.8 | 1.0 | 0.7 | 1.0 | 0.9 | 1.0 | 0.9 | 0.6 | 0.6 | 0.9 | 0.7 | 0.4 | 0.7 | 0.8 | 0.5 | 0.8 | 0.7 | 0.6 | 0.5 | 0.6 | 0.7 | 0.8 | 0.3 | 0.4 | 0.4 | 0.9 | 0.8 |
| | coolibah | 0.8 | 0.8 | 0.8 | 0.6 | 0.9 | 0.8 | 0.7 | 0.9 | 0.9 | 1.0 | 0.9 | 0.6 | 0.7 | 0.9 | 0.7 | 0.4 | 0.6 | 0.8 | 0.7 | 0.7 | 0.7 | 0.8 | 0.6 | 0.6 | 0.7 | 0.7 | 0.3 | 0.4 | 0.5 | 0.7 | 0.8 |
| | grassy meadows | 0.8 | 0.8 | 0.8 | 0.6 | 0.9 | 0.9 | 0.8 | 0.9 | 0.9 | 1.0 | 0.9 | 0.8 | 0.9 | 0.8 | 0.8 | 0.6 | 0.9 | 0.8 | 0.7 | 1.0 | 0.8 | 0.9 | 0.7 | 0.7 | 0.9 | 0.7 | 0.5 | 0.3 | 0.4 | 0.8 | 0.7 |
| | herbfield | 0.8 | 0.8 | 0.8 | 0.6 | 0.9 | 1.0 | 0.7 | 0.9 | 0.9 | 1.0 | 0.9 | 0.5 | 0.8 | 0.9 | 0.9 | 0.6 | 0.8 | 0.8 | 0.7 | 0.9 | 0.7 | 0.9 | 0.7 | 0.8 | 1.0 | 0.8 | 0.5 | 0.5 | 0.5 | 0.9 | 0.7 |
| | lignum | 0.8 | 0.7 | 0.8 | 0.6 | 0.9 | 0.9 | 0.7 | 1.0 | 0.9 | 0.9 | 0.9 | 0.5 | 0.7 | 0.9 | 0.7 | 0.5 | 0.8 | 0.9 | 0.8 | 0.9 | 0.8 | 1.0 | 0.7 | 0.9 | 0.8 | 0.7 | 0.5 | 0.4 | 0.5 | 0.6 | 0.7 |
| | river red gum swamps and forests | 0.9 | 0.8 | 0.8 | 0.7 | 0.9 | 0.7 | 0.7 | 0.9 | 0.8 | 0.9 | 0.9 | 0.7 | 0.9 | 1.0 | 0.8 | 0.6 | 0.7 | 1.0 | 0.8 | 0.9 | 0.8 | 0.9 | 0.7 | 0.7 | 0.8 | 0.8 | 0.6 | 0.6 | 0.5 | 0.8 | 0.8 |
| | tall reed beds | 0.8 | 0.8 | 0.8 | 0.5 | 0.8 | 1.0 | 0.6 | 0.9 | 0.8 | 1.0 | 0.9 | 0.8 | 0.9 | 0.8 | 0.9 | 0.6 | 0.9 | 0.8 | 0.7 | 1.0 | 0.7 | 0.9 | 0.9 | 0.9 | 0.9 | 0.8 | 0.5 | 0.6 | 0.7 | 0.9 | 0.7 |
| Lachlan | black box | 0.8 | 0.9 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.6 | 0.7 | 0.8 | 0.4 | 0.5 | 0.7 | 0.4 | 0.5 | 0.3 | 0.3 | 0.3 | 0.3 | 0.6 | 0.6 | 0.5 | 0.7 | 0.7 | 0.7 | 1.0 | 0.5 | 0.5 | 0.6 | 0.8 | 0.7 |
| | grassy meadows | 0.8 | 0.9 | 0.7 | 0.8 | 0.9 | 0.8 | 0.8 | 0.9 | 0.8 | 0.9 | 0.7 | 0.5 | 0.8 | 0.7 | 0.5 | 0.4 | 0.5 | 0.4 | 0.6 | 0.8 | 0.7 | 0.6 | 0.9 | 0.8 | 0.7 | 0.8 | 0.7 | 0.6 | 0.6 | 0.8 | 0.5 |
| | herbfield | 0.8 | 0.7 | 0.7 | 0.8 | 0.9 | 0.6 | 0.7 | 0.9 | 0.9 | 1.0 | 0.7 | 0.5 | 0.8 | 0.7 | 0.7 | 0.5 | 0.5 | 0.5 | 0.5 | 0.8 | 0.6 | 0.6 | 0.9 | 0.9 | 0.9 | 0.9 | 0.7 | 0.7 | 0.7 | 1.0 | 0.7 |
| | lignum | 0.8 | 0.9 | 0.9 | 0.8 | 0.6 | 0.6 | 0.6 | 0.7 | 0.6 | 1.0 | 0.4 | 0.5 | 0.8 | 0.4 | 0.5 | 0.3 | 0.3 | 0.3 | 0.5 | 0.7 | 0.6 | 0.7 | 0.6 | 0.9 | 0.8 | 1.0 | 0.6 | 0.5 | 0.8 | 0.6 | 0.6 |
| | river red gum swamps and forests | 0.8 | 0.9 | 0.9 | 0.9 | 0.8 | 0.6 | 0.6 | 0.7 | 0.7 | 0.8 | 0.6 | 0.6 | 0.7 | 0.5 | 0.6 | 0.4 | 0.5 | 0.3 | 0.4 | 0.7 | 0.6 | 0.5 | 0.7 | 0.7 | 0.7 | 0.9 | 0.8 | 0.5 | 0.6 | 0.8 | 0.8 |
| | tall reed beds | 0.8 | 0.9 | 1.0 | 0.8 | 1.0 | 0.8 | 0.6 | 0.8 | 0.7 | 1.0 | 0.6 | 0.6 | 0.7 | 0.5 | 0.4 | 0.1 | 0.2 | 0.1 | 0.4 | 0.8 | 0.8 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.5 | 0.4 | 0.7 | 0.7 | 0.4 |
| Macquarie-Castlereagh | black box | 0.6 | 0.8 | 0.9 | 0.6 | 0.8 | 0.6 | 0.5 | 0.8 | 0.9 | 0.9 | 0.6 | 0.5 | 0.7 | 0.6 | 0.5 | 0.3 | 0.5 | 0.7 | 0.5 | 0.8 | 0.6 | 0.8 | 0.6 | 0.8 | 0.8 | 0.8 | 0.4 | 0.4 | 0.5 | 0.8 | 0.7 |
| | coolibah | 0.6 | 0.7 | 0.8 | 0.6 | 0.8 | 0.7 | 0.6 | 0.9 | 1.0 | 0.9 | 0.7 | 0.5 | 0.7 | 0.6 | 0.4 | 0.3 | 0.6 | 0.7 | 0.6 | 0.8 | 0.7 | 0.7 | 0.6 | 0.7 | 0.6 | 0.8 | 0.4 | 0.5 | 0.6 | 0.7 | 0.7 |
| | grassy meadows | 0.6 | 0.9 | 0.9 | 0.5 | 0.9 | 0.7 | 0.6 | 0.8 | 0.9 | 1.0 | 0.6 | 0.6 | 0.8 | 0.5 | 0.5 | 0.3 | 0.6 | 0.7 | 0.6 | 0.9 | 0.8 | 0.9 | 0.7 | 1.0 | 0.8 | 0.8 | 0.5 | 0.3 | 0.4 | 1.0 | 0.6 |
| | herbfield | 0.7 | 0.8 | 0.9 | 0.7 | 0.9 | 0.6 | 0.6 | 0.8 | 0.9 | 1.0 | 0.7 | 0.6 | 0.8 | 0.6 | 0.5 | 0.4 | 0.6 | 0.8 | 0.6 | 0.9 | 0.8 | 0.8 | 0.7 | 0.7 | 0.9 | 0.8 | 0.3 | 0.3 | 0.4 | 1.0 | 0.6 |
| | lignum | 0.6 | 0.7 | 0.8 | 0.7 | 0.8 | 0.7 | 0.5 | 0.8 | 0.9 | 0.9 | 0.7 | 0.6 | 0.8 | 0.5 | 0.4 | 0.3 | 0.6 | 0.6 | 0.6 | 0.8 | 0.7 | 0.7 | 0.6 | 0.7 | 0.7 | 0.8 | 0.3 | 0.4 | 0.4 | 0.6 | 0.6 |
| | river red gum swamps and forests | 0.7 | 0.8 | 0.9 | 0.4 | 0.7 | 0.7 | 0.5 | 0.8 | 0.8 | 1.0 | 0.7 | 0.6 | 0.7 | 0.6 | 0.7 | 0.4 | 0.6 | 0.7 | 0.6 | 0.8 | 0.7 | 0.8 | 0.9 | 0.8 | 0.8 | 0.9 | 0.7 | 0.6 | 0.5 | 1.0 | 0.8 |
| | river red gum woodland | 0.6 | 0.8 | 0.9 | 0.6 | 0.8 | 0.7 | 0.5 | 0.8 | 0.9 | 1.0 | 0.7 | 0.6 | 0.7 | 0.6 | 0.6 | 0.4 | 0.5 | 0.7 | 0.6 | 0.8 | 0.8 | 0.9 | 0.6 | 0.8 | 0.8 | 0.8 | 0.6 | 0.5 | 0.5 | 0.9 | 0.8 |
| | tall reed beds | 0.5 | 0.7 | 0.9 | 0.5 | 0.9 | 0.7 | 0.6 | 0.9 | 0.9 | 0.9 | 0.7 | 0.4 | 0.8 | 0.7 | 0.5 | 0.5 | 0.5 | 0.7 | 0.6 | 0.9 | 0.8 | 0.9 | 0.7 | 0.9 | 0.9 | 0.9 | 0.7 | 0.5 | 0.7 | 0.9 | 0.7 |
| Murray | black box | 0.7 | 0.8 | 0.9 | 0.8 | 0.9 | 0.8 | 0.7 | 0.6 | 0.7 | 0.7 | 0.6 | 0.4 | 0.7 | 0.6 | 0.7 | 0.5 | 0.6 | 0.4 | 0.6 | 0.7 | 0.8 | 0.6 | 0.9 | 0.9 | 0.8 | 0.9 | 0.8 | 0.6 | 0.6 | 0.8 | 0.6 |
| | grassy meadows | 0.8 | 0.9 | 0.9 | 0.8 | 0.9 | 0.9 | 0.8 | 0.7 | 0.9 | 0.9 | 0.6 | 0.4 | 0.6 | 0.4 | 0.6 | 0.4 | 0.5 | 0.5 | 0.6 | 0.9 | 0.7 | 0.6 | 0.9 | 1.0 | 0.7 | 0.9 | 0.7 | 0.5 | 0.5 | 0.6 | 0.5 |
| | herbfield | 0.9 | 0.7 | 0.6 | 0.7 | 0.8 | 0.9 | 0.8 | 0.8 | 0.8 | 0.9 | 0.8 | 0.7 | 0.9 | 0.7 | 0.9 | 0.7 | 0.6 | 0.5 | 0.9 | 0.9 | 0.7 | 0.7 | 0.9 | 0.8 | 0.7 | 0.8 | 0.8 | 0.6 | 0.7 | 0.8 | 0.6 |
| | lignum | 0.8 | 0.9 | 0.9 | 0.8 | 0.9 | 0.9 | 0.8 | 0.8 | 0.9 | 0.9 | 0.7 | 0.4 | 0.6 | 0.5 | 0.6 | 0.4 | 0.5 | 0.5 | 0.6 | 0.9 | 0.9 | 0.5 | 0.8 | 1.0 | 0.8 | 0.8 | 0.7 | 0.5 | 0.4 | 0.6 | 0.5 |
| | river red gum swamps and forests | 0.7 | 0.8 | 0.9 | 0.7 | 0.8 | 0.8 | 0.7 | 0.6 | 0.8 | 0.8 | 0.7 | 0.4 | 0.7 | 0.7 | 0.7 | 0.4 | 0.5 | 0.4 | 0.6 | 0.8 | 0.9 | 0.6 | 0.8 | 1.0 | 0.8 | 1.0 | 0.8 | 0.6 | 0.7 | 0.7 | 0.6 |
| | river red gum woodland | 0.8 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.6 | 0.7 | 0.8 | 0.6 | 0.5 | 0.6 | 0.7 | 0.7 | 0.5 | 0.6 | 0.4 | 0.6 | 0.7 | 0.8 | 0.6 | 0.9 | 0.9 | 0.8 | 0.9 | 0.8 | 0.7 | 0.7 | 0.8 | 0.7 |
| | tall reed beds | 0.6 | 0.6 | 0.5 | 0.7 | 0.8 | 0.7 | 0.6 | 0.7 | 0.7 | 0.9 | 0.6 | 0.7 | 0.9 | 0.8 | 0.9 | 0.7 | 0.8 | 0.7 | 0.7 | 0.9 | 0.8 | 0.8 | 0.9 | 0.8 | 0.9 | 0.9 | 0.8 | 0.7 | 0.8 | 0.9 | 0.8 |
| Murrumbidgee | black box | 0.9 | 0.9 | 0.9 | 0.8 | 0.9 | 0.7 | 0.6 | 0.6 | 0.6 | 0.8 | 0.3 | 0.5 | 0.7 | 0.5 | 0.5 | 0.4 | 0.4 | 0.3 | 0.4 | 0.7 | 0.6 | 0.5 | 0.7 | 0.9 | 0.7 | 1.0 | 0.7 | 0.4 | 0.6 | 0.7 | 0.6 |
| | grassy meadows | 0.9 | 1.0 | 0.9 | 0.7 | 0.9 | 0.6 | 0.5 | 0.8 | 0.9 | 0.8 | 0.4 | 0.4 | 0.7 | 0.5 | 0.5 | 0.4 | 0.3 | 0.2 | 0.5 | 0.8 | 0.6 | 0.7 | 0.6 | 0.9 | 0.9 | 0.8 | 0.5 | 0.4 | 0.8 | 0.8 | 0.6 |
| | herbfield | 0.9 | 0.9 | 0.9 | 0.8 | 0.9 | 0.7 | 0.5 | 0.8 | 0.9 | 0.9 | 0.4 | 0.5 | 0.8 | 0.5 | 0.6 | 0.3 | 0.4 | 0.3 | 0.4 | 0.7 | 0.6 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 0.5 | 0.6 | 0.6 | 0.8 | 0.6 |
| | lignum | 0.9 | 0.9 | 0.9 | 0.8 | 1.0 | 0.7 | 0.7 | 0.8 | 0.8 | 0.9 | 0.4 | 0.5 | 0.8 | 0.6 | 0.5 | 0.3 | 0.4 | 0.2 | 0.6 | 0.9 | 0.6 | 0.5 | 0.6 | 0.8 | 0.7 | 0.9 | 0.7 | 0.3 | 0.4 | 0.6 | 0.5 |
| | river red gum swamps and forests | 0.8 | 0.9 | 0.9 | 0.7 | 0.9 | 0.8 | 0.5 | 0.7 | 0.8 | 0.8 | 0.6 | 0.5 | 0.7 | 0.6 | 0.6 | 0.5 | 0.5 | 0.3 | 0.5 | 0.7 | 0.7 | 0.6 | 0.7 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.7 | 0.8 | 0.7 |
| | river red gum woodland | 0.6 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 | 0.6 | 0.8 | 0.5 | 0.5 | 0.8 | 0.5 | 0.7 | 0.5 | 0.6 | 0.5 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 0.8 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.9 | 0.7 |
| | tall reed beds | 0.8 | 0.9 | 1.0 | 0.7 | 1.0 | 0.8 | 0.7 | 0.8 | 0.7 | 1.0 | 0.5 | 0.6 | 0.7 | 0.5 | 0.4 | 0.1 | 0.2 | 0.1 | 0.4 | 0.8 | 0.8 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.6 | 0.4 | 0.8 | 0.7 | 0.5 |

# Waterbird vulnerability assessment

This section contains a summary of the waterbird theme vulnerability assessment. The complete method, prepared by Dr Heather McGinness (CSIRO) is provided in Appendix C.

## Basin watering strategy expected outcomes for waterbirds

The BWS expected outcomes for waterbirds are increased abundance and the maintenance of current species diversity. From 2024 onwards, the expected outcomes are:

- that the number and type of waterbird species present in the Basin will not fall below current observations
- a significant improvement in waterbird populations in the order of 20 to 25% over the baseline scenario, with increases in all waterbird functional groups
- breeding events (the opportunities to breed rather than the magnitude of breeding per se) of colonial nesting waterbirds to increase by up to 50% compared to the baseline scenario
- breeding abundance (nests and broods) for all of the other functional groups to increase by 30–40% compared to the baseline scenario, especially in locations where the Basin Plan improves over-bank flows.

The waterbird outcomes described above are Basin-wide. However, because of the importance of the Coorong, Lakes Albert and Alexandrina for migratory shorebirds, these areas have the following additional expected outcomes:

- at a minimum maintain populations of the following four key species: curlew sandpiper, greenshank, red-necked stint and sharp-tailed sandpiper, at levels recorded between 2000 and 2014.

## Functional groups

All waterbird species are dependent on surface water to some extent for completion of their lifecycles. In general terms, an abundance of water at broad scales with some variation in inundation timing, duration, extent, and frequency can be assumed to provide benefits for most waterbirds (Jaensch 2002, Roshier et al. 2002a, Brandis et al. 2009). However, at this level, variation in life cycle requirements and traits among groups and species is ignored.

The high-level BWS expected outcomes for waterbirds provide the basis for initial selection and grouping of waterbird species for vulnerability assessment and prioritisation for environmental watering. We have used a database of waterbird species traits to develop waterbird groups combining BWS expected outcomes with two sets of dependencies: foraging behaviour and habitat dependencies; and nesting behaviour and habitat dependencies. These groups are (Table 9):

- Colonial and semi-colonial nesting waders
- Shorebirds
- Cryptic waders
- Swimmers, divers and grazers.

# Indicators for waterbirds

## *Conceptual model*

The factors affecting waterbird vulnerability have been considered within respect to exposure (to stressors) and sensitivity / adaptive capacity (condition). The conceptual model (Figure 18) provides a more comprehensive set of potential indicators of stress and condition than the vulnerability assessment can currently encompass largely due to insufficient or inappropriate data sources. They are presented here (and provided in more detail in Appendix C) as a reminder that as data availability improves, so can the vulnerability assessment of waterbirds evolve to incorporate improved understanding and new data.

Table 9: Functional groups for the waterbird theme

| Shorebirds | Swimmers, divers and grazers | Colonial nesting waders | Cryptic waders |
|---|---|---|---|
| Foraging on foot | Diving | Foraging on foot | Foraging on foot |
| Australian Pied Oystercatcher | Australasian Darter | Australian White Ibis | Australasian Bittern |
| Australian Pratincole | Australasian Grebe | Banded Stilt | Australian Little Bittern |
| Banded Lapwing | Australian Pelican | Black-winged (Pied) Stilt | Australian Painted Snipe |
| Bar-tailed Godwit | Blue-billed Duck | Cattle Egret | Australian Spotted Crake |
| Black-fronted Dotterel | Great Cormorant | Glossy Ibis | Baillon's Crake |
| Black-tailed Godwit | Great Crested Grebe | Great Egret | Buff-banded Rail |
| Broad-billed Sandpiper | Hardhead | Intermediate Egret | Latham's Snipe |
| Common Greenshank | Hoary-headed Grebe | Little Egret | Lewin's Rail |
| Common Sandpiper | Little Black Cormorant | Nankeen Night-Heron | Spotless Crake |
| Curlew Sandpiper | Little Pied Cormorant | Pied Heron | |
| Double-banded Plover | Musk Duck | Red-necked Avocet | |
| Eastern Curlew | Pied Cormorant | Royal Spoonbill | |
| Great Knot | Aerial diving | Straw-necked Ibis | |
| Grey Plover | Australian Gull-billed Tern | White-faced Heron | |
| Grey-tailed Tattler | Caspian Tern | White-necked Heron | |
| Inland Dotterel | Silver Gull | Yellow-billed Spoonbill | |
| Lesser Sand Plover | Whiskered Tern | Brolga | |
| Little Curlew | White-winged Black Tern | | |
| Long-toed Stint | Filtering/dabbling | | |
| Marsh Sandpiper | Australian Shoveler | | |
| Masked Lapwing | Chestnut Teal | | |
| Oriental Pratincole | Freckled Duck | | |
| Pacific Golden Plover | Grey Teal | | |
| Pectoral Sandpiper | Pacific Black Duck | | |
| Red Knot | Pink-eared Duck | | |
| Red-capped Plover | Grazing/foraging on foot | | |
| Red-kneed Dotterel | Australian Shelduck | | |
| Red-necked Stint | Australian Wood Duck | | |
| Ruddy Turnstone | Black Swan | | |
| Sharp-tailed Sandpiper | Dusky Moorhen | | |
| Terek Sandpiper | Eurasian Coot | | |
| Wandering Tattler | Magpie Goose | | |
| Whimbrel | Plumed Whistling-Duck | | |
| Wood Sandpiper | Wandering Whistling-Duck | | |
| | Black-tailed Native-hen | | |

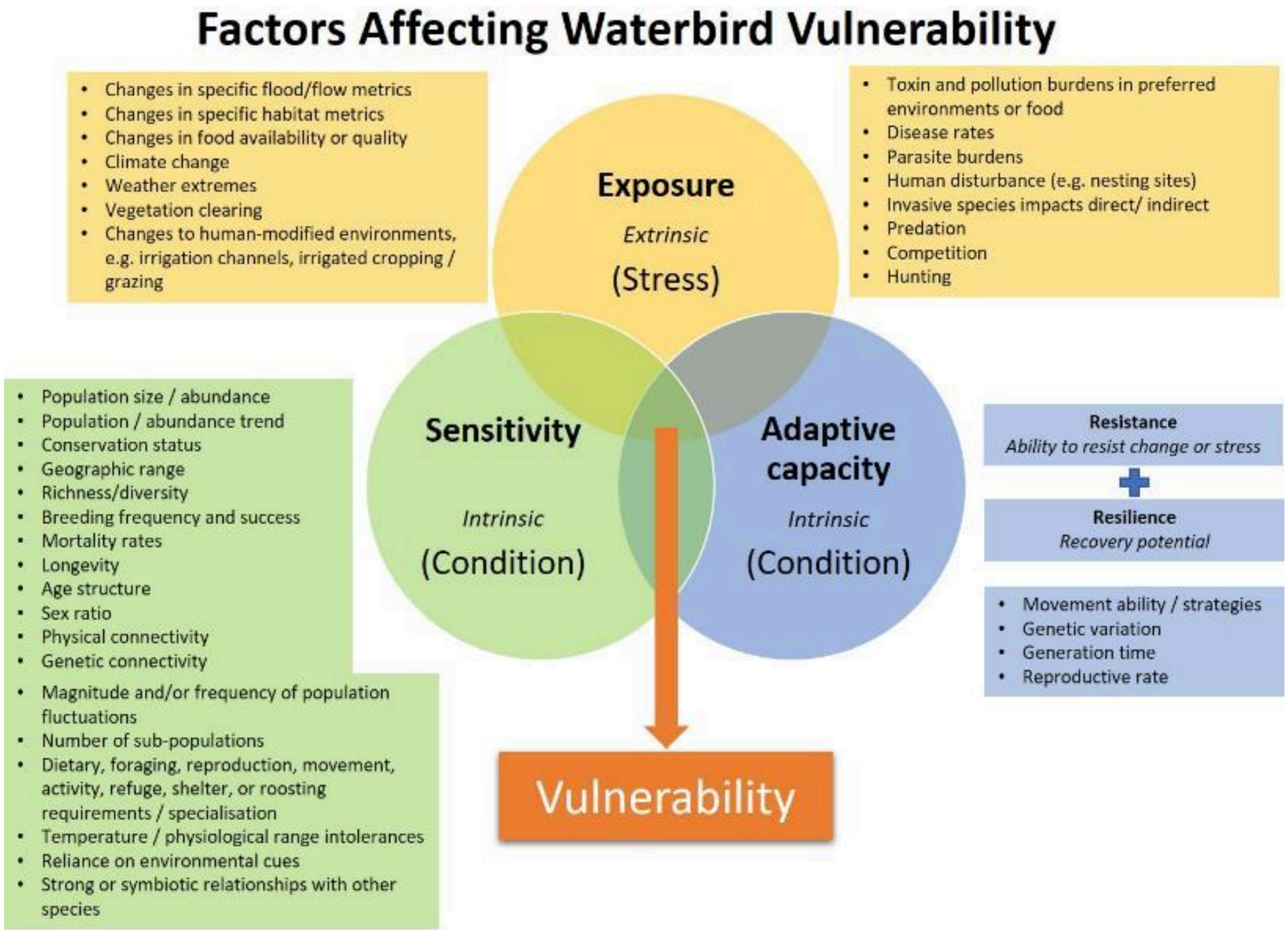


Figure 18. Conceptual diagram of factors interacting to affect waterbird vulnerability in Australia (Garnett et al. 2015, McGinness 2016, McGinness et al. 2019). For more detailed explanation, see Appendix C.

## *Indicators of condition*

There is a wide range of potential indicators of waterbird species or group condition (see Appendix C). Some of these indicators of condition for waterbirds should ideally be assessed for each species and each primary life cycle stage, e.g.: 1) Egg; 2) Chick; 3) Juvenile; 4) Sub-adult; and 4) Adult (McGinness et al. 2020). This is currently not feasible in Australia because of insufficient or inappropriate data sources. In certain situations, targeted assessment of a subset of selected indicators is appropriate and sufficient. For example, species or group presence and richness can be more confidently assessed than abundance in most locations over time given available data.

This framework is designed to be pragmatic, flexible, and able to accommodate new sources of information as they become available. There are many condition indicators for which there is no current data source available, or for which data are insufficient, but which could be accommodated were these to become available into the future.

Here, we use a subset of selected condition indicators for which reliable data are currently available at the scales required and are suitable for testing as part of an initial broad assessment of waterbird vulnerability. These are based on high-level BWS expected outcomes (Table 10). In the future, it would be wise to include additional indicators or surrogates as described above.

Condition is scored for each indicator as a deviation from baseline where (see page 10 for the method of calculating condition):

- Good / better (score of 3) – above the baseline
- Fair / moderate (score of 2) – within one unit of variability (standard deviation or mean absolute deviation) of the baseline
- Poor / worse (score of 1) – greater than one unit of variability below the baseline.

Table 10. Summary of selected condition indicators and relevant data sources for waterbird vulnerability assessment

| Condition indicators | Justification | Relevant functional groups |
|---|---|---|
| **Group species richness** | Group species richness reflects whether the quality or condition of a site is capable of supporting diversity | All |
| **Group abundance** | The abundance of birds from a certain group at a site or overall may indicate the abundance of suitable resources either just prior to the survey or at the time of the survey and aligns the indicator of condition to the BWS objectives | All |
| **Group breeding occurrence** | The occurrence of breeding by a certain group at a site or overall may indicate the availability of suitable resources for breeding either just prior to the survey or at the time of the survey and aligns the indicator of condition to the BWS objectives | Colonial nesting waders, swimmers, divers and grazers |
| **Group breeding abundance** | The number of birds recorded breeding from a certain group at a site or overall may indicate the availability of suitable resources either just prior to the survey or at the time of the survey and aligns the indicator of condition to the BWS objectives | Colonial nesting waders |

Potential data sources for all indicators includes: Atlas of Living Australia (ALA), East Australian Waterbird Surveys (EAWS), Coorong, Lower Lakes and Murray Mouth waterbird monitoring, MDBA aerial surveys, and Commonwealth Environmental Water Holder waterbird monitoring.

## *Indicators of stress*

Basic waterbird life cycle requirements include sufficient availability and quality of each species' or group's preferred breeding, foraging, roosting, movement and refuge habitats, food, drinking water and climate conditions (Reid et al. 2009, McGinness 2016, McGinness et al. 2019). When waterbird life cycle requirements are not met, waterbirds experience stress. There are a wide range of potential indicators of waterbird species / group stress, most of which we do not have adequate data to assess (see Appendix C for more detail).

Assessment of habitat stress indicators is currently the most feasible approach for vulnerability assessment for waterbirds (an approach that was recommended by the TAG at a workshop held in May 2021). Ideally, habitat stress assessment needs to be done at Basin to continental scales in a spatially explicit manner and using consistent habitat mapping and attributes that represent the complexity of topographic, hydrological, vegetative and productivity variables influencing waterbird species habitat selection throughout their life cycles. Given that this is currently not possible, at minimum, stressors associated with habitat can be described by:

- vegetation community composition and structure (e.g. black box woodland vs phragmites reed beds vs lignum shrublands)
- vegetation condition (e.g. greenness), and
- flow/inundation regimes.

Stress indicators are assessed at preferred habitat types for each species / group. An approximation of preferred habitats and their locations for each species group is derived by intersecting ANAE polygons with species presence observations from available data sources. The most common habitat type(s) for each group are then used to apply relevant indicators of stress (Table 11).

Table 11. Indicators and thresholds of stress for waterbirds
(see page 10 for method on calculating stress; Appendix C for rationale).

| Indicator | Functional group | Low stress | Medium stress | High stress |
|---|---|---|---|---|
| **Extent of inundation** | All | At or above the baseline | Within 1 standard deviation of the baseline | More than 1 standard deviation below the baseline |
| **Time since last inundation** | Colonial nesting waders cryptic waders and shorebirds | < 1 year | 1 – 5 years | > 5 years |
| | Aerial divers, grazers, filterers and swimming divers | < 1 year | 1 – 3 years | > 3 years |
| **Soil moisture (as a surrogate for rainfall)** | All | At or above the baseline | Within 1 standard deviation of the baseline | More than 1 standard deviation below the baseline |
| **Vegetation "Greenness"** | All | At or above the baseline | Within 1 standard deviation of the baseline | More than 1 standard deviation below the baseline |

# Spatial scales

Most Australian waterbirds are highly dispersive (Roshier et al. 2002b) and waterbirds that use temporary wetlands as feeding or breeding habitat must move between wetlands to survive dry periods (Kingsford and Norman 2002, Wen et al. 2016). For example, at the height of the Millennium Drought, when many of the Basin's important waterbird habitats had been dry for a prolonged period, there was an increase in waterbirds in coastal habitats (Wen et al. 2016) and using artificial wetland areas (Loyn et al. 2014). Then following large scale flooding in 2012, waterbirds dispersed across inland areas in response to increased foraging and breeding habitat (Colloff et al. 2015, Wen et al. 2016).

This pattern of movement across the landscape demonstrates the need for the assessment of condition, stress and vulnerability at large spatial scales (i.e. whole of Basin or even larger). Adapted to cycles of drought and flood, waterbirds will move from unfavourable habitat to better habitat as environmental conditions dictate (Kingsford and Norman 2002, Wen et al. 2016). A reduction in waterbirds in one wetland, does not necessarily reflect vulnerability of the species or waterbird group. For this reason, the vulnerability of waterbirds is evaluated at the whole Basin scale.

# Waterbird vulnerability

Waterbird vulnerability is the combination of condition and stress for each functional group (and species) at the Basin scale. There are many different ways of combining scores to provide an overall measure. The simplest method is to sum condition and stress and derive a combined vulnerability rank (here rescaled to between 0 and 1).

# Outcomes of the vulnerability assessment for waterbirds

The method described above for assessing vulnerability of waterbirds was applied using the most recent available data. Waterbird condition is based on measures of waterbird observations and monitoring data. There is a significant time lag between the collection of data for Basin waterbird programs (e.g. MDBA aerial surveys, Coorong, Lower Lakes and Murray Mouth waterbird monitoring) and the data becoming available. Typically, surveys conducted in spring of one year, produce data in autumn or winter of the following year (a lag of six to eight months). Similarly, it may take several months (or longer) for people to load their observations to the Atlas of Living Australia. For this reason, the most recent year for which the waterbird vulnerability assessment could be applied was 2021.

## *Condition of waterbirds*

### *Collation of data*

Waterbird records from the Basin were sourced from the following:

- Atlas of Living Australia records (https://www.ala.org.au/) which includes citizen science records (e.g. eBird as well as State based waterbird monitoring)
- MDBA aerial waterbird surveys (supplied by the MDBA)
- East Australian Aerial Waterbird Surveys (supplied by the MDBA)
- Commonwealth Environmental Water Holder staff waterbird monitoring (supplied by CEWH staff)
- Coorong, Lower Lakes and Murray Mouth Waterbird Monitoring (supplied by the MDBA).

Records were collated into a single source and records cleaned by:

- Ensuring each species was afforded a unique and consistent common name
- Removing any locations data (latitudes and longitudes) that fell outside the Basin
- Removing records that had no date fields that could be assigned to a year
- Removing records that had no location data
- Assigning each species to a functional group as per Table 9.

Breeding records were identified and cross-checked using relevant record fields including ‘Reproductive Condition’, ‘Taxon Remarks’, ‘Individual Count’, and ‘Sum of Nest’. Where coding systems such as eBird and NestWatch systems are used by observers, selected codes relevant to breeding were identified and used to filter the data. In MDBA records, the fields ‘Sum of Count’ and ‘Sum of Nest’ were used. Records with low confidence were excluded. For example, in identifying breeding sites using the ALA reproductive condition field, records tagged as ‘none’, 'F' (flying over), 'C’ (courtship or copulation), 'suggestive behaviour', 'distraction display', ‘breeding plumage’ or 'adult' only were not included, and eBird records with moderator confidence of less than C4 (confirmed) were not included.

### *Spatial attribution*

Assigning waterbird data to a location was limited by several factors. Aerial survey data is often attributed to single point locations within large wetland complexes. For example, waterbird counts from the aerial surveys of the Macquarie Marshes are attributed to a single centroid coordinate that does not reflect where the birds were observed. The waterbird data from the Coorong, Lower Lakes and Murray Mouth Waterbird Monitoring is gridded and not at a scale that was easily matched to citizen science records or the aerial survey data. As these large-scale monitoring program represented the majority of the quantitative data for both abundance and breeding abundance, all data was assigned to a wetland complex scale that allowed for their inclusion in the analysis.

There are three categories of wetland complex that are relevant to waterbirds in the Basin: Ramsar Sites, the Directory of Important Wetland Sites (DIWA) and the BWS important Basin environmental assets for waterbirds. The Ramsar and DIWA sites have defined boundaries contained within their respective spatial layers. The BWS waterbird sites, however, do not. While we initially considered using only Ramsar and DIWA sites for the waterbird vulnerability assessment, a hotspot analysis of waterbird observations indicated that several “hotspots” of waterbird abundance were not included in this list (most notably the Booligal Wetlands;

Figure 19).

As a surrogate, BWS waterbird asset polygons, that were loosely defined for aerial surveys, were provided by the MDBA and used in the vulnerability analysis. It is highly recommended that a single layer with defined boundaries of waterbird assets in the Basin be developed, based on the extent of ANAE polygons within each complex. Future applications of the vulnerability assessment for waterbirds should then be based on that set of wetland complexes.

Consistent with the vegetation vulnerability assessment and the assessment of stress indicators, standards for calculating metrics as a deviation of baseline were established based on the entire record (1986 to 2021, excluding the Millennium Drought (2000 – 2009 inclusive). Condition scores were only calculated on metrics for which there was an adequate baseline, which in this instance represented at least 10 years of data in the baseline period.

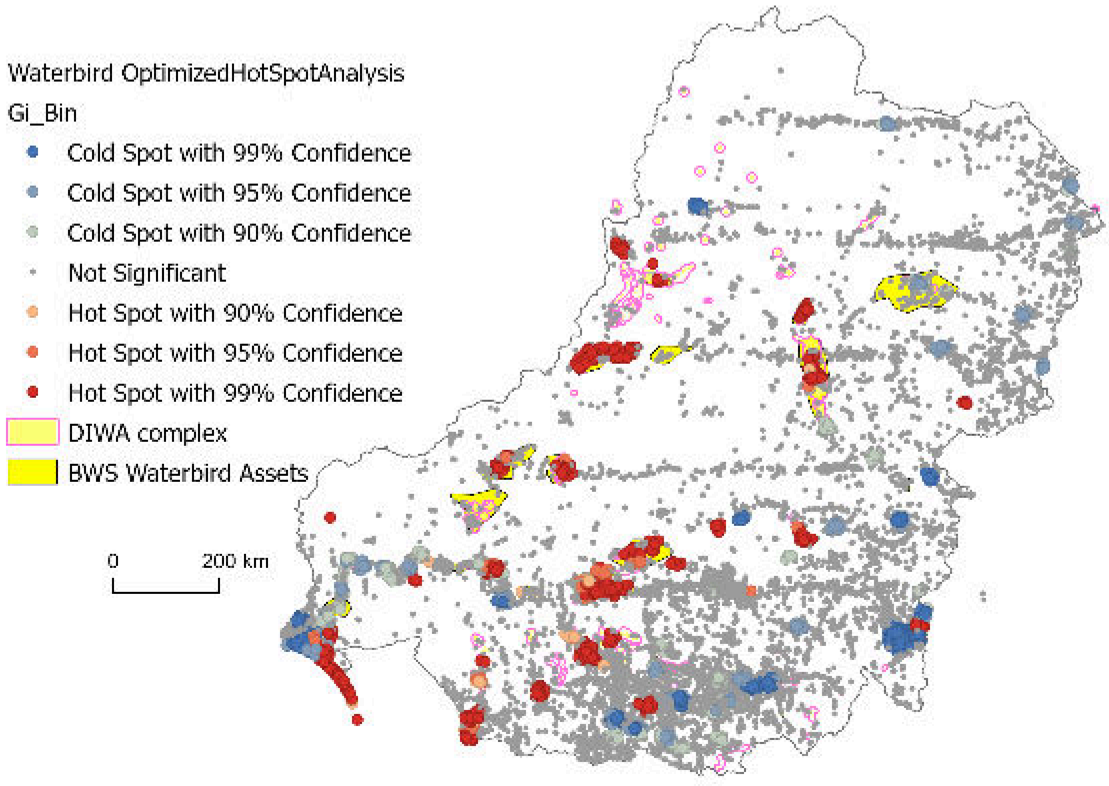


Figure 19. Waterbird hotspot analysis aligned to DIWA and BWS waterbird assets

## *Condition indicator results*

### *Waterbird abundance*

Waterbird abundance is the maximum abundance of each species of waterbird in each wetland complex in each year, regardless of source. Abundance of functional groups is the sum of the maximum abundance of each species in that group in each wetland complex in each year. The Basin abundance is the sum of the species / group across all BWS waterbird assets.

The number of waterbirds varies considerably over time, with low numbers across all groups during the Millennium Drought and maximum numbers during wet years such as 2011, 2012 and 2017 (Figure 20). There is, however, some sample effort biases in the data. All BWS asset sites have increased sample effort since around 2007, and since 2012 all have been included in the MDBA aerial surveys. For example, the Coorong, Lower Lakes and Murray Mouth (CLLM) waterbird monitoring started monitoring in the Coorong in 2000 and in the Lower Lakes in 2009 (Figure 21). The increase in waterbirds at this site from the 1990s to the 2000s, therefore does not necessarily reflect changes in waterbird usage at the site, rather the increased sample effort post 2000 and 2009.

As more data is collected and the baseline extends into more years with good quality comparable data, the limitations of uneven sample effort should be reduced at the Basin scale and at important wetland sites.

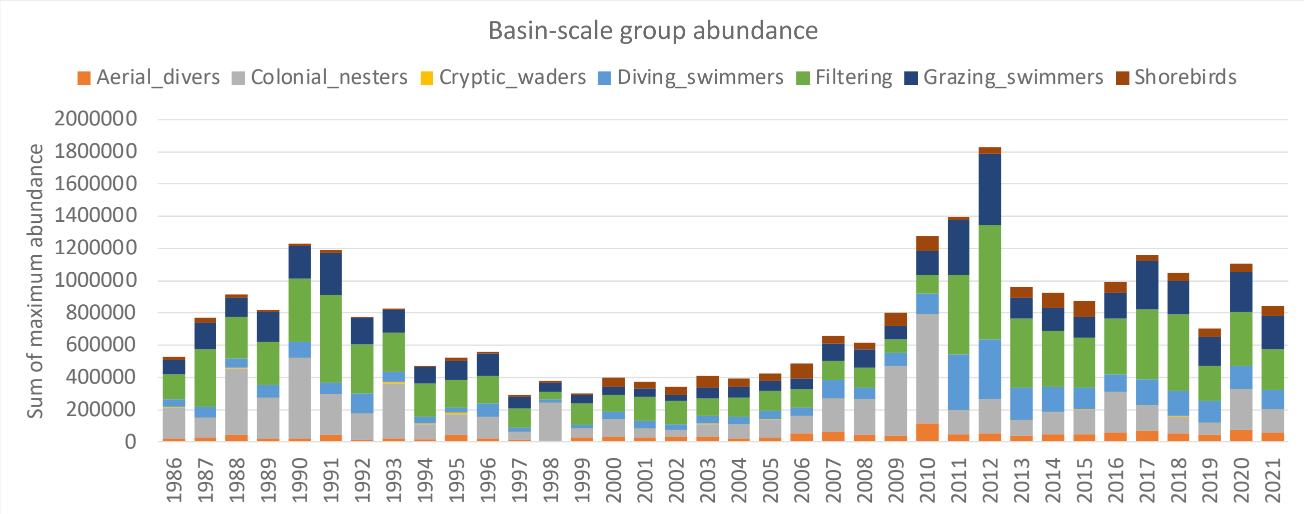


Figure 20. Sum of maximum waterbird abundance 1986 to 2022

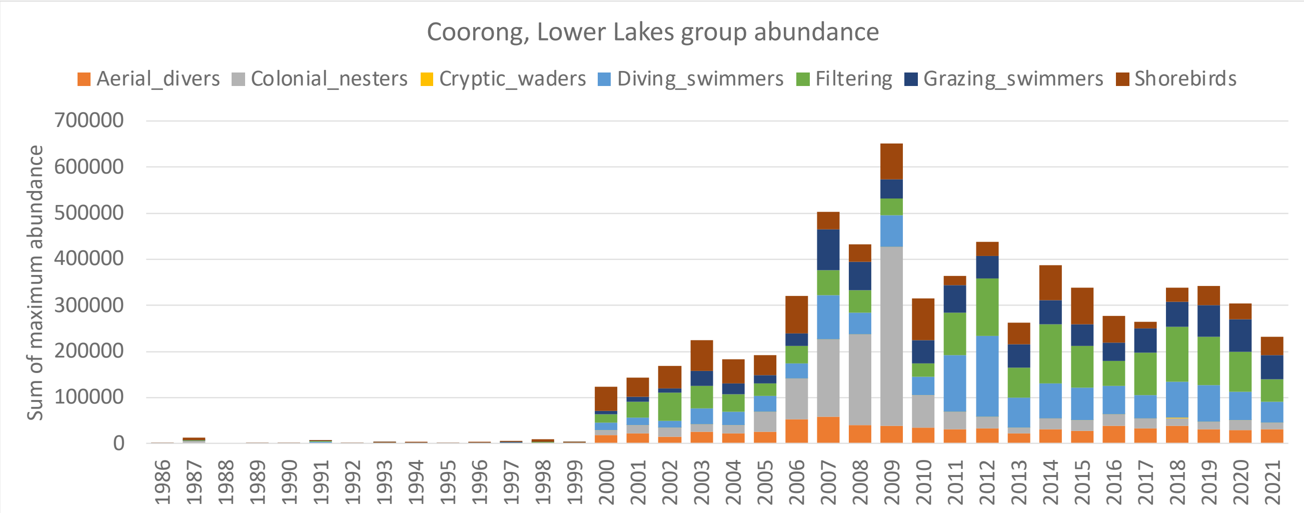


Figure 21. Sum of maximum waterbird abundance from the CLLMM BWS asset wetland complex 1986 to 2022

Condition was scored as the deviation from baseline (median standardised by the median absolute deviation (MAD)). The MAD was used as a non-parametric measure of variance instead of Standard Deviation because the waterbird data is not normally distributed due in part to sample effort and in part to flocking and aggregating behaviour of colonial breeding and feeding. This indicator was applied to all waterbird groups (Figure 22) and each individual species. All groups of waterbirds were more than one MAD below the baseline during the Millennium Drought, but in terms of abundance, most groups have recovered to above baseline conditions.

The abundance indicator can also be applied at a species scale. For example, species of filtering duck were largely below their baseline in the Millennium Drought (Figure 23). The exception was chestnut teal, for which there were high abundances recorded in the Coorong Lower Lakes during this period. Most species recovered post-drought, with the exception of Australasian shoveler, which remains below its baseline. This may reflect a continued decline in the population of this species, as recorded by other studies in south-eastern Australia (Loyn et al. 2014, Porter et al. 2014, Colloff et al. 2015).

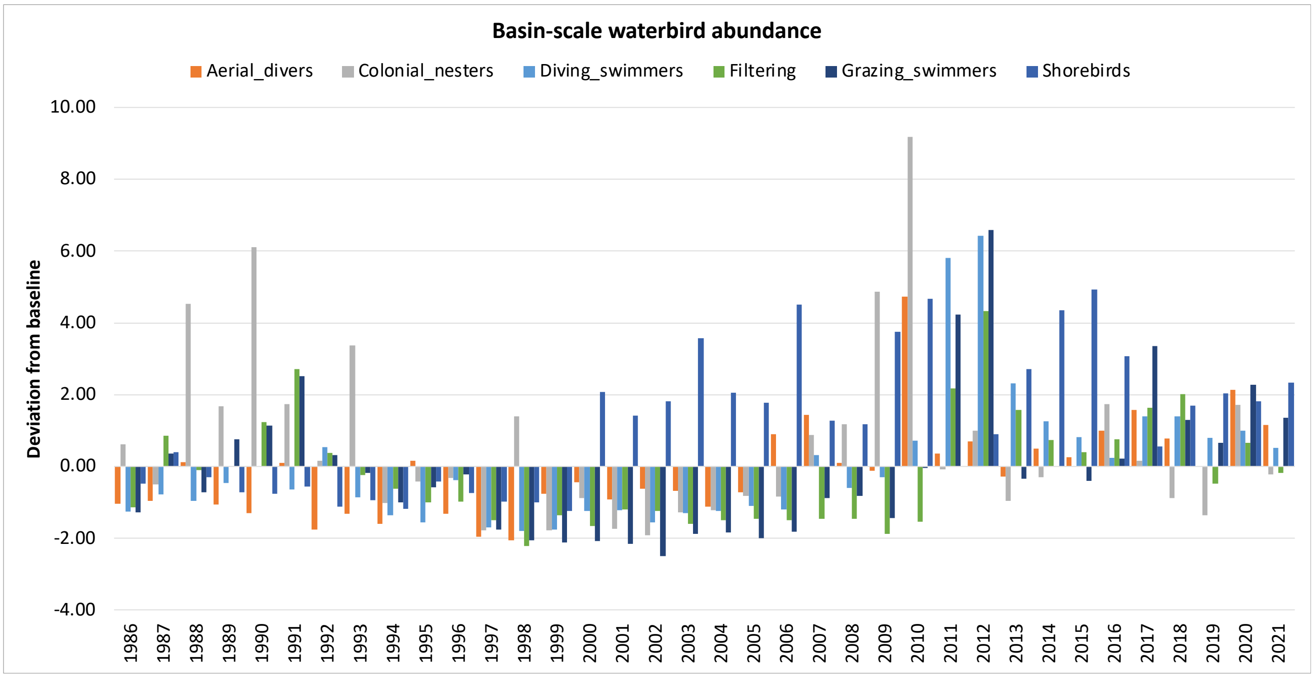


Figure 22. Condition indicator waterbird abundance, deviation from baseline (median and median absolute deviation)

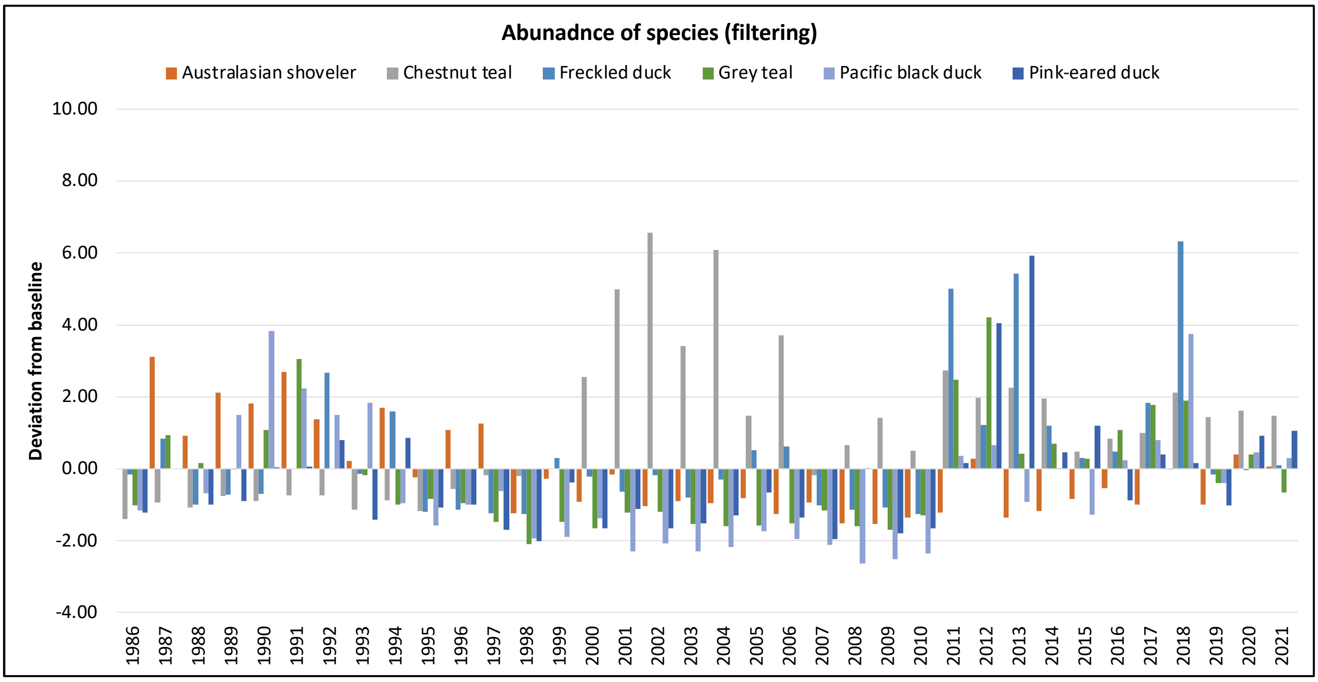


Figure 23. Condition indicator waterbird abundance, deviation from baseline for individual species in the filtering functional group

### *Waterbird group species richness*

Waterbird group species richness is the total number of species recorded within the Basin each year (also applied at the wetland complex scale). Scored as a deviation from baseline and applied to all waterbird groups. At the Basin-scale there is little variability in total species richness within a group as most species are recorded somewhere in the Basin in each year (Figure 24), reflecting the nomadic nature of most species.

While consideration was given to adding a measure of frequency of occurrence to this condition indicator to strengthen the ability to discern between good and bad condition, in the absence of a properly designed and implemented monitoring program, this was not possible. Aerial surveys do not capture all species, as small and cryptic species are difficult to detect from the air. Further, citizen science programs such as eBird result in a large number of observations of easily detected, iconic or indeed rare species as enthusiasts travel to observe birds and upload sightings to the Atlas. There are a very large number of records from different observers of the same individual and often all members of bird watching groups upload their records individually. With no object measure of true frequency, species richness was the best measure that is currently feasible.

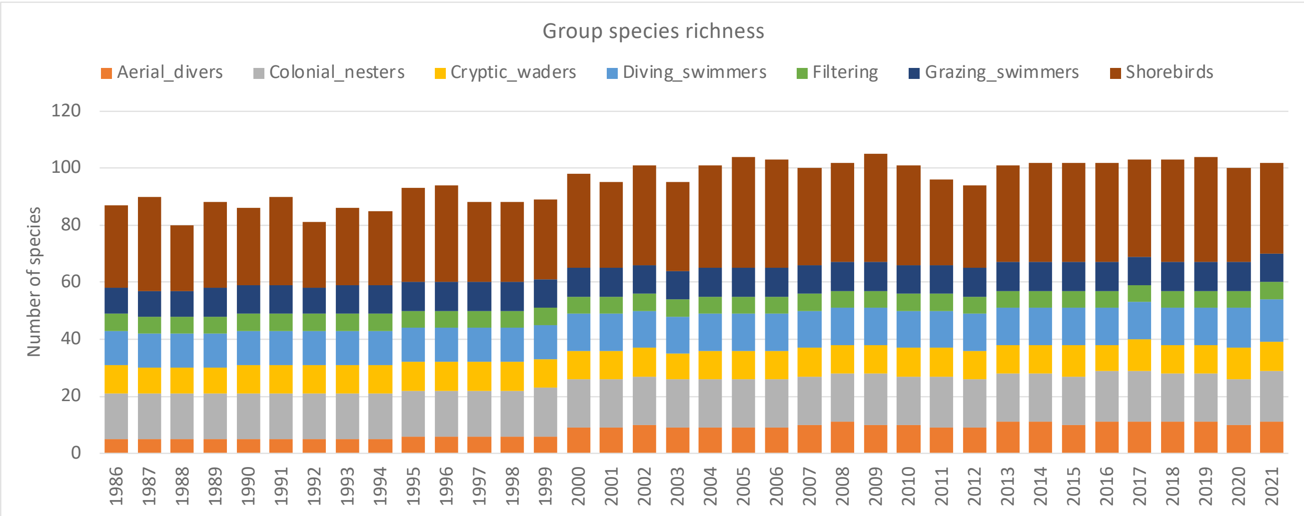


Figure 24. Species richness of each functional group 1986 to 2021

### *Waterbird breeding abundance and group breeding species richness*

Waterbird breeding records were sparse and even at the Basin scale, there was only sufficient data to calculate breeding metrics for a small number of functional groups. In terms of nest counts, there was sufficient data in the reference period (at least 10 years) for colonial nesting waders only (Figure 25). Consistent with our understanding of waterbird behaviour in the Basin, large breeding events are recorded during years of high rainfall (1990, 1998, 2010, 2016).

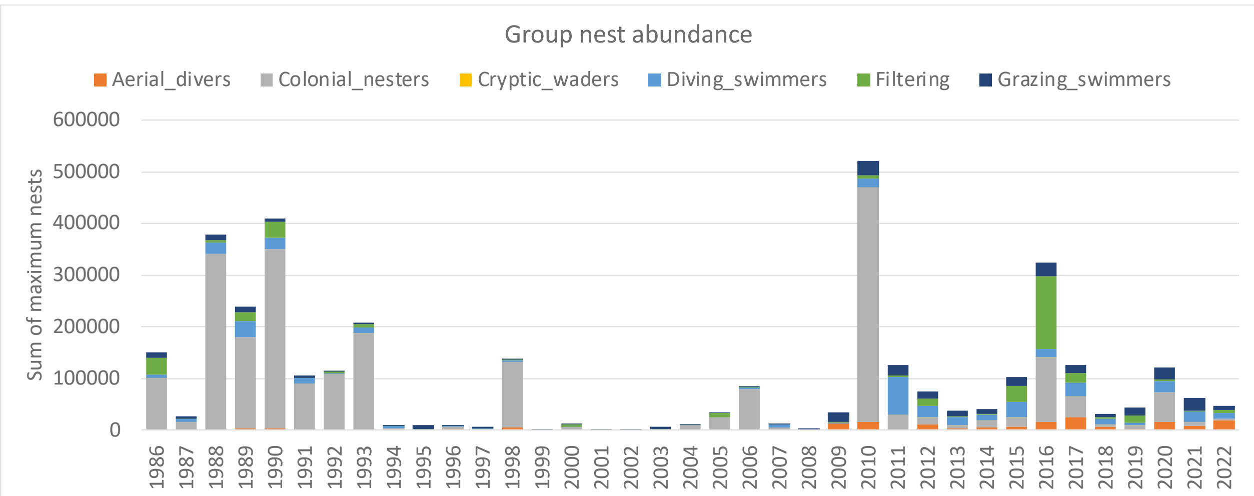


Figure 25. Waterbird breeding abundance (sum of maximum number of nests)

The number of species within a group with evidence of breeding somewhere in the Basin varies over time, from lows in 2002 (< 20 species) to over 50 species from 2015, 2016 and 2017 (Figure 26). In the assessment of vulnerability, breeding of cryptic species was not included as these species, by their nature, are easily overlooked by casual bird watchers and cannot be detected by aerial surveys. Similarly, breeding of shorebirds was not included in the assessment as many of these species breed outside Australia.

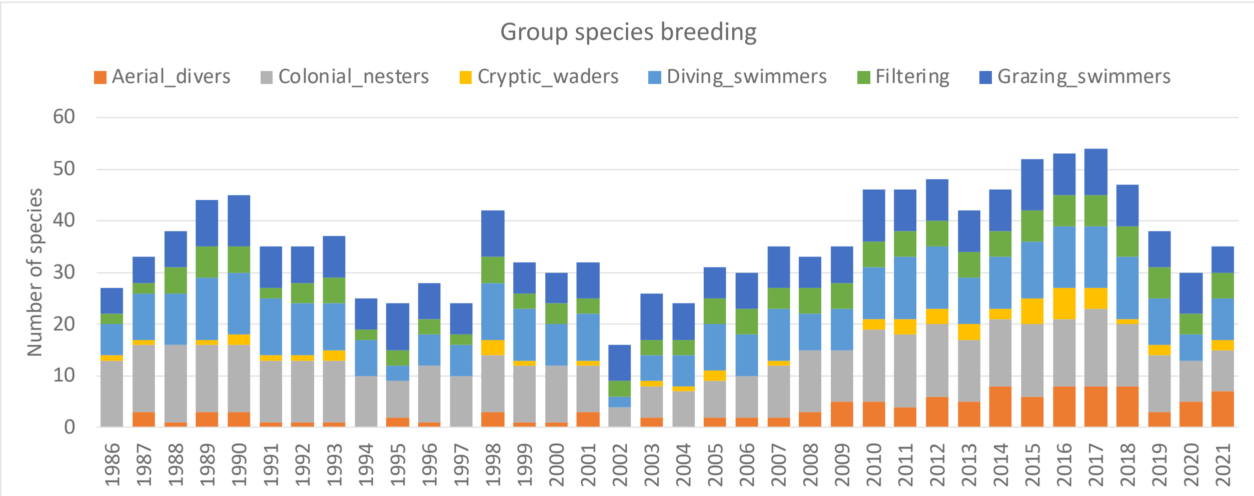


Figure 26. Number of species with observations of breeding

### *Overall condition*

Condition of waterbirds for each indicator (and combined) is shown from 1986 to 2021 in Table 1227. Overall, the pattern of worse condition in dry years and better following widescale inundation is illustrated. The exception is for shorebirds, which have remained in better condition since 2000, perhaps reflecting increased sample effort in the Coorong, which supports the greatest number and diversity of these species in the Basin.

Table 1227. Condition scores for each functional group, with overall condition in the bottom table (blanks indicate missing data)

| **C1 Species richness** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 3 |
| Colonial_nesters | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 3 |
| Cryptic_waders | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 1 | 3 | 2 | 2 | 3 | 2 |
| Diving_swimmers | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 |
| Filtering | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Grazing_swimmers | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Shorebirds | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 2 | 2 |

| **C2 Abundance** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 1 | 2 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 3 |
| Colonial_nesters | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 1 | 2 | 2 | 1 | 3 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 1 | 3 | 2 |
| Cryptic_waders | 3 | 2 | 3 | 2 | 2 | 3 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 3 | 2 | 3 | 3 | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 3 | 2 | 1 | 2 | 2 | 1 | 2 | 2 |
| Diving_swimmers | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 2 |
| Filtering | 1 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 2 |
| Grazing_swimmers | 1 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 3 | 3 |
| Shorebirds | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 |

| **C3 Breeding species** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers |  | 2 | 1 | 2 | 2 | 1 | 1 | 1 |  | 2 | 2 |  | 2 | 1 | 1 | 1 |  | 2 |  | 1 | 2 | 1 | 1 | 3 | 3 | 2 | 3 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 3 | 3 |
| Colonial_nesters | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 1 | 2 | 2 | 3 | 1 | 2 | 1 | 1 | 1 | 2 | 2 | 3 | 2 | 1 | 1 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 3 | 2 |
| Cryptic_waders | 2 | 2 |  | 1 | 1 | 2 | 2 | 2 |  |  |  |  | 2 | 1 |  | 1 |  | 1 | 1 | 2 |  | 1 |  |  | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 |  | 2 |
| Diving_swimmers | 2 | 2 | 3 | 3 | 3 | 2 | 1 | 2 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 3 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 2 |
| Filtering | 3 | 1 | 2 | 3 | 3 | 1 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 3 | 3 | 2 | 3 | 2 | 2 |
| Grazing_swimmers | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 3 |

| **C4 Breeding abun.** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Colonial_nesters | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |

| **Overall condition** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 0.0 | 0.3 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.5 | 0.3 | 0.3 | 0.3 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.3 | 0.5 | 0.5 | 0.8 | 0.8 | 0.5 | 0.8 | 0.5 | 0.5 | 0.8 | 0.8 | 0.5 | 0.8 | 1.0 | 0.8 | 0.8 | 0.8 | 1.0 |
| Colonial_nesters | 0.6 | 0.5 | 0.8 | 0.8 | 0.8 | 0.8 | 0.6 | 0.8 | 0.4 | 0.3 | 0.5 | 0.4 | 0.8 | 0.3 | 0.5 | 0.1 | 0.1 | 0.1 | 0.3 | 0.4 | 0.5 | 0.5 | 0.5 | 0.6 | 0.8 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.9 | 0.6 | 0.5 | 0.4 | 0.6 | 0.5 |
| Cryptic_waders | 0.8 | 0.3 | 0.5 | 0.3 | 0.5 | 0.8 | 0.3 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 | 0.3 | 0.3 | 0.5 | 0.3 | 0.5 | 0.5 | 0.8 | 0.8 | 0.3 | 0.5 | 0.3 | 0.3 | 0.5 | 0.5 | 0.3 | 0.8 | 0.8 | 0.0 | 0.8 | 0.5 | 0.3 | 0.8 | 0.5 |
| Diving_swimmers | 0.3 | 0.5 | 0.7 | 0.7 | 0.7 | 0.5 | 0.3 | 0.5 | 0.3 | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.5 | 0.3 | 0.5 | 0.5 | 0.8 | 0.8 | 0.7 | 0.7 | 0.7 | 0.5 | 0.8 | 0.7 | 0.5 | 0.8 | 0.7 |
| Filtering | 0.5 | 0.3 | 0.5 | 0.7 | 0.8 | 0.5 | 0.5 | 0.5 | 0.3 | 0.2 | 0.5 | 0.2 | 0.3 | 0.2 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.7 | 0.8 | 0.7 | 0.5 | 0.7 | 0.7 | 0.8 | 0.7 | 0.7 | 0.5 | 0.5 |
| Grazing_swimmers | 0.2 | 0.3 | 0.3 | 0.5 | 0.7 | 0.7 | 0.2 | 0.3 | 0.2 | 0.5 | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.2 | 0.2 | 0.2 | 0.3 | 0.5 | 0.5 | 0.7 | 0.8 | 0.7 | 0.5 | 0.5 | 0.7 | 0.7 | 0.8 | 0.7 | 0.7 | 0.8 | 0.8 |
| Shorebirds | 0.5 | 0.5 | 0.3 | 0.5 | 0.3 | 0.5 | 0.0 | 0.3 | 0.0 | 0.5 | 0.5 | 0.5 | 0.3 | 0.3 | 0.8 | 0.8 | 1.0 | 0.8 | 1.0 | 1.0 | 1.0 | 0.8 | 1.0 | 1.0 | 1.0 | 0.5 | 0.5 | 0.8 | 1.0 | 1.0 | 1.0 | 0.5 | 1.0 | 1.0 | 0.8 | 0.8 |

## Waterbird stress

The stress metrics are applied at functional group preferred habitats. These were derived from the condition data by intersecting waterbird observations with ANAE types (Table 13). This attribution is affected by uncertainties associated with the poor precision of bird location coordinates (especially for aerial surveys), the bias towards easily accessible areas, and the disparity in area among ANAE types (i.e. there are much larger areas of floodplain forest than open water lakes for example). Nevertheless, it represents a proof of concept for this first application of the method. It is recommended that the identification of important habitat types be repeated when waterbird observation data quality improves.

Table 13. Percentage of waterbird records from BWS assets and associated habitat types. Habitat types used in the assessment of stress shown highlighted

| Habitat types | Aerial divers | Colonial nesters | Cryptic waders | Diving swimmers | Filtering | Grazing swimmers | Shorebirds |
|---|---|---|---|---|---|---|---|
| Black box | 11 | 11 | 7 | 13 | 13 | 13 | 12 |
| Clay pan (shallow unvegetated wetlands) | 12 | 6 | 13 | 6 | 6 | 6 | 12 |
| Coolibah | 2 | 5 | 3 | 3 | 4 | 3 | 4 |
| Grassy meadows | 3 | 4 | 5 | 3 | 3 | 3 | 3 |
| Herbfield | 14 | 10 | 17 | 9 | 9 | 8 | 15 |
| Lakes | 22 | 15 | 15 | 19 | 16 | 17 | 18 |
| Lignum | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| River red gum swamps and forests | 8 | 26 | 15 | 25 | 28 | 27 | 11 |
| River red gum woodland | 8 | 12 | 4 | 11 | 11 | 14 | 9 |
| Tall reed beds | 15 | 8 | 16 | 7 | 6 | 6 | 11 |

The results for each stress indicator for each functional group are provided in **Error! Reference source not found.**. Again, the expected pattern of increased stress in dry years and increasing stress with prolonged dry conditions is evident.

## Waterbird vulnerability

Vulnerability is calculated by combining the stress and condition scores (**Error! Reference source not found.**). There is also sufficient data to enable a vulnerability assessment to be applied at an individual species level, for a subset of waterbirds. For example, Australasian darter, Australian shoveler and brolga are representatives of three different functional groups and three different levels of vulnerability (**Error! Reference source not found.**). While all were more vulnerable in dry years, recovery for Australasian darter was slower than for the other two species.

Table 14. Stress scores for each indicator and functional group (from 1 (high stress) to 3 (low stress), with overall stress in the bottom table (scaled from 0 (high stress) to 1 (low stress). Colours reflect ranking of stress from low stress (dark green) to high stress (red).

| **S1 Extent of inundation** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 |
| Colonial_nesters | 3 | 2 | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 1 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 3 | 3 | 2 | 2 | 1 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 3 |
| Cryptic_waders | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 |
| Diving_swimmers | 3 | 2 | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 1 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 3 | 3 | 2 | 2 | 1 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 3 |
| Filtering | 3 | 2 | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 1 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 3 | 3 | 2 | 2 | 1 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 3 |
| Grazing_swimmers | 3 | 2 | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 1 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 3 | 3 | 2 | 2 | 1 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 3 |
| Shorebirds | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 |

| **S2 Time since last inundation** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 3 | 3 | 2 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 3 |
| Colonial_nesters | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Cryptic_waders | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 |
| Diving_swimmers | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Filtering | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Grazing_swimmers | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Shorebirds | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 |

| **S3 Rainfall** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 1 | 3 | 3 | 2 | 3 | 2 | 3 | 2 | 1 | 3 | 2 | 3 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 2 | 1 | 1 | 3 | 2 |
| Colonial_nesters | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 3 | 1 | 3 | 3 | 3 | 2 | 1 | 3 | 2 | 3 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 1 | 1 | 3 | 2 |
| Cryptic_waders | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 1 | 2 | 3 | 2 | 1 | 2 | 3 | 2 | 3 | 3 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 3 |
| Diving_swimmers | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 3 | 1 | 3 | 3 | 3 | 2 | 1 | 3 | 2 | 3 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 1 | 1 | 3 | 2 |
| Filtering | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 3 | 1 | 3 | 3 | 3 | 2 | 1 | 3 | 2 | 3 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 1 | 1 | 3 | 2 |
| Grazing_swimmers | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 3 | 1 | 3 | 3 | 3 | 2 | 1 | 3 | 2 | 3 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 1 | 1 | 3 | 2 |
| Shorebirds | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 1 | 3 | 3 | 2 | 3 | 2 | 3 | 2 | 1 | 3 | 2 | 3 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 2 | 1 | 1 | 3 | 2 |

| **S4 Greeness** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Colonial_nesters | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 2 |
| Cryptic_waders | 2 | 2 | 3 | 3 | 3 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 1 | 2 | 1 | 1 | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 3 | 3 |
| Diving_swimmers | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 2 |
| Filtering | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 2 |
| Grazing_swimmers | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 2 |
| Shorebirds | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

| **Overall Stress** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.88 | 0.88 | 0.75 | 0.88 | 0.75 | 0.88 | 0.75 | 0.50 | 0.88 | 0.63 | 0.63 | 0.50 | 0.50 | 0.50 | 0.38 | 0.75 | 1.00 | 0.88 | 1.00 | 0.75 | 0.63 | 0.75 | 0.63 | 0.50 | 0.38 | 0.75 | 0.88 |
| Colonial_nesters | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.63 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.63 | 0.38 | 0.63 | 0.75 | 0.88 | 0.38 | 0.38 | 0.25 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| Cryptic_waders | 0.75 | 0.75 | 1.00 | 1.00 | 1.00 | 0.63 | 0.50 | 0.63 | 0.63 | 0.75 | 0.75 | 0.75 | 1.00 | 0.88 | 1.00 | 0.75 | 0.38 | 0.50 | 0.75 | 0.63 | 0.25 | 0.50 | 0.88 | 0.50 | 1.00 | 0.88 | 0.75 | 0.38 | 0.63 | 0.63 | 1.00 | 0.63 | 0.50 | 0.50 | 0.88 | 0.88 |
| Diving_swimmers | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.63 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.63 | 0.38 | 0.63 | 0.75 | 0.88 | 0.38 | 0.38 | 0.25 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| Filtering | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.63 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.63 | 0.38 | 0.63 | 0.75 | 0.88 | 0.38 | 0.38 | 0.25 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| Grazing_swimmers | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.63 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.63 | 0.38 | 0.63 | 0.75 | 0.88 | 0.38 | 0.38 | 0.25 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| Shorebirds | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.88 | 0.88 | 0.75 | 0.88 | 0.75 | 0.88 | 0.75 | 0.50 | 0.88 | 0.63 | 0.63 | 0.50 | 0.50 | 0.50 | 0.50 | 0.75 | 1.00 | 0.88 | 1.00 | 0.75 | 0.63 | 0.75 | 0.63 | 0.50 | 0.50 | 0.75 | 0.88 |

See page 10 for method of calculating stress.

Table 15. Overall stress, condition, and vulnerability (summing indicators) (scaled from 0 (high stress) to 1 (low stress). Colours reflect ranking of stress from low stress (dark green) to high stress (red).

| **Stress** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.88 | 0.88 | 0.75 | 0.88 | 0.75 | 0.88 | 0.75 | 0.50 | 0.88 | 0.63 | 0.63 | 0.50 | 0.50 | 0.50 | 0.38 | 0.75 | 1.00 | 0.88 | 1.00 | 0.75 | 0.63 | 0.75 | 0.63 | 0.50 | 0.38 | 0.75 | 0.88 |
| Colonial_nesters | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.63 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.63 | 0.38 | 0.63 | 0.75 | 0.88 | 0.38 | 0.38 | 0.25 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| Cryptic_waders | 0.75 | 0.75 | 1.00 | 1.00 | 1.00 | 0.63 | 0.50 | 0.63 | 0.63 | 0.75 | 0.75 | 0.75 | 1.00 | 0.88 | 1.00 | 0.75 | 0.38 | 0.50 | 0.75 | 0.63 | 0.25 | 0.50 | 0.88 | 0.50 | 1.00 | 0.88 | 0.75 | 0.38 | 0.63 | 0.63 | 1.00 | 0.63 | 0.50 | 0.50 | 0.88 | 0.88 |
| Diving_swimmers | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.63 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.63 | 0.38 | 0.63 | 0.75 | 0.88 | 0.38 | 0.38 | 0.25 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| Filtering | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.63 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.63 | 0.38 | 0.63 | 0.75 | 0.88 | 0.38 | 0.38 | 0.25 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| Grazing_swimmers | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.63 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.63 | 0.38 | 0.63 | 0.75 | 0.88 | 0.38 | 0.38 | 0.25 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| Shorebirds | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.88 | 0.88 | 0.75 | 0.88 | 0.75 | 0.88 | 0.75 | 0.50 | 0.88 | 0.63 | 0.63 | 0.50 | 0.50 | 0.50 | 0.50 | 0.75 | 1.00 | 0.88 | 1.00 | 0.75 | 0.63 | 0.75 | 0.63 | 0.50 | 0.50 | 0.75 | 0.88 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Condition** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
| Aerial_divers | 0.00 | 0.25 | 0.25 | 0.00 | 0.00 | 0.25 | 0.00 | 0.00 | 0.00 | 0.50 | 0.25 | 0.25 | 0.25 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.25 | 0.50 | 0.50 | 0.75 | 0.75 | 0.50 | 0.75 | 0.50 | 0.50 | 0.75 | 0.75 | 0.50 | 0.75 | 1.00 | 0.75 | 0.75 | 0.75 | 1.00 |
| Colonial_nesters | 0.63 | 0.50 | 0.75 | 0.75 | 0.75 | 0.75 | 0.63 | 0.75 | 0.38 | 0.25 | 0.50 | 0.38 | 0.75 | 0.25 | 0.50 | 0.13 | 0.13 | 0.13 | 0.25 | 0.38 | 0.50 | 0.50 | 0.50 | 0.63 | 0.75 | 0.63 | 0.50 | 0.50 | 0.50 | 0.50 | 0.88 | 0.63 | 0.50 | 0.38 | 0.63 | 0.50 |
| Cryptic_waders | 0.75 | 0.25 | 0.50 | 0.25 | 0.50 | 0.75 | 0.25 | 0.75 | 0.75 | 0.75 | 0.50 | 0.50 | 0.50 | 0.25 | 0.25 | 0.50 | 0.25 | 0.50 | 0.50 | 0.75 | 0.75 | 0.25 | 0.50 | 0.25 | 0.25 | 0.50 | 0.50 | 0.25 | 0.75 | 0.75 | 0.00 | 0.75 | 0.50 | 0.25 | 0.75 | 0.50 |
| Diving_swimmers | 0.33 | 0.50 | 0.67 | 0.67 | 0.67 | 0.50 | 0.33 | 0.50 | 0.33 | 0.17 | 0.33 | 0.33 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.33 | 0.50 | 0.33 | 0.50 | 0.50 | 0.83 | 0.83 | 0.67 | 0.67 | 0.67 | 0.50 | 0.83 | 0.67 | 0.50 | 0.83 | 0.67 |
| Filtering | 0.50 | 0.33 | 0.50 | 0.67 | 0.83 | 0.50 | 0.50 | 0.50 | 0.33 | 0.17 | 0.50 | 0.17 | 0.33 | 0.17 | 0.33 | 0.17 | 0.17 | 0.17 | 0.17 | 0.33 | 0.17 | 0.17 | 0.17 | 0.33 | 0.33 | 0.67 | 0.83 | 0.67 | 0.50 | 0.67 | 0.67 | 0.83 | 0.67 | 0.67 | 0.50 | 0.50 |
| Grazing_swimmers | 0.17 | 0.33 | 0.33 | 0.50 | 0.67 | 0.67 | 0.17 | 0.33 | 0.17 | 0.50 | 0.33 | 0.33 | 0.33 | 0.17 | 0.17 | 0.17 | 0.17 | 0.33 | 0.17 | 0.17 | 0.17 | 0.33 | 0.50 | 0.50 | 0.67 | 0.83 | 0.67 | 0.50 | 0.50 | 0.67 | 0.67 | 0.83 | 0.67 | 0.67 | 0.83 | 0.83 |
| Shorebirds | 0.50 | 0.50 | 0.25 | 0.50 | 0.25 | 0.50 | 0.00 | 0.25 | 0.00 | 0.50 | 0.50 | 0.50 | 0.25 | 0.25 | 0.75 | 0.75 | 1.00 | 0.75 | 1.00 | 1.00 | 1.00 | 0.75 | 1.00 | 1.00 | 1.00 | 0.50 | 0.50 | 0.75 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 1.00 | 0.75 | 0.75 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Vulnerabilty** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
| Aerial_divers | 0.44 | 0.56 | 0.56 | 0.44 | 0.44 | 0.50 | 0.44 | 0.44 | 0.25 | 0.69 | 0.56 | 0.50 | 0.56 | 0.63 | 0.69 | 0.63 | 0.50 | 0.69 | 0.44 | 0.56 | 0.50 | 0.63 | 0.63 | 0.44 | 0.75 | 0.75 | 0.69 | 0.88 | 0.75 | 0.56 | 0.75 | 0.81 | 0.63 | 0.56 | 0.75 | 0.94 |
| Colonial_nesters | 0.81 | 0.63 | 0.75 | 0.81 | 0.81 | 0.75 | 0.75 | 0.81 | 0.44 | 0.44 | 0.69 | 0.44 | 0.75 | 0.56 | 0.69 | 0.38 | 0.25 | 0.38 | 0.50 | 0.63 | 0.44 | 0.44 | 0.38 | 0.50 | 0.88 | 0.81 | 0.75 | 0.63 | 0.63 | 0.56 | 0.88 | 0.69 | 0.56 | 0.44 | 0.69 | 0.63 |
| Cryptic_waders | 0.75 | 0.50 | 0.75 | 0.63 | 0.75 | 0.69 | 0.38 | 0.69 | 0.69 | 0.75 | 0.63 | 0.63 | 0.75 | 0.56 | 0.63 | 0.63 | 0.31 | 0.50 | 0.63 | 0.69 | 0.50 | 0.38 | 0.69 | 0.38 | 0.63 | 0.69 | 0.63 | 0.31 | 0.69 | 0.69 | 0.50 | 0.69 | 0.50 | 0.38 | 0.81 | 0.69 |
| Diving_swimmers | 0.67 | 0.63 | 0.71 | 0.77 | 0.77 | 0.63 | 0.60 | 0.69 | 0.42 | 0.40 | 0.60 | 0.42 | 0.46 | 0.52 | 0.52 | 0.40 | 0.27 | 0.40 | 0.46 | 0.52 | 0.35 | 0.44 | 0.29 | 0.44 | 0.75 | 0.92 | 0.92 | 0.71 | 0.71 | 0.65 | 0.69 | 0.79 | 0.65 | 0.50 | 0.79 | 0.71 |
| Filtering | 0.75 | 0.54 | 0.63 | 0.77 | 0.85 | 0.63 | 0.69 | 0.69 | 0.42 | 0.40 | 0.69 | 0.33 | 0.54 | 0.52 | 0.60 | 0.40 | 0.27 | 0.40 | 0.46 | 0.60 | 0.27 | 0.27 | 0.21 | 0.35 | 0.67 | 0.83 | 0.92 | 0.71 | 0.63 | 0.65 | 0.77 | 0.79 | 0.65 | 0.58 | 0.63 | 0.63 |
| Grazing_swimmers | 0.58 | 0.54 | 0.54 | 0.69 | 0.77 | 0.71 | 0.52 | 0.60 | 0.33 | 0.56 | 0.60 | 0.42 | 0.54 | 0.52 | 0.52 | 0.40 | 0.27 | 0.48 | 0.46 | 0.52 | 0.27 | 0.35 | 0.38 | 0.44 | 0.83 | 0.92 | 0.83 | 0.63 | 0.63 | 0.65 | 0.77 | 0.79 | 0.65 | 0.58 | 0.79 | 0.79 |
| Shorebirds | 0.69 | 0.69 | 0.56 | 0.69 | 0.56 | 0.63 | 0.44 | 0.56 | 0.25 | 0.69 | 0.69 | 0.63 | 0.56 | 0.50 | 0.81 | 0.75 | 0.75 | 0.81 | 0.81 | 0.81 | 0.75 | 0.63 | 0.75 | 0.75 | 0.88 | 0.75 | 0.69 | 0.88 | 0.88 | 0.81 | 0.88 | 0.56 | 0.75 | 0.75 | 0.75 | 0.81 |

See page 10 for method of calculating stress, condition and vulnerability.

Table 16. Example of overall stress, condition, and vulnerability for three species: brolga, Australasian darter and Australian shelduck

| **Condition** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| brolga | 0.25 | 0 | 0.25 | 0.5 | 0.25 | 0.75 | 0.5 | 0.75 | 0.5 | 0.5 | 0.75 | 0 | 0.25 | 0 | 0.5 | 0.25 | | 0 | 0.5 | 0 | | 0.75 | 0.5 | 0.25 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.5 | 1 | 0.75 | 1 | 0.5 | 0 |
| australasian darter | 0.25 | 0.25 | 1 | 0.75 | 0.75 | 0.5 | 0.25 | 0.75 | 0.75 | 0 | 0 | | 0.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.25 | 0.75 | 0.75 | 0.25 | 0.5 | 0.5 | 0.5 | 0.75 | 0.75 | 0.5 | 0.25 | 1 |
| australian shelduck | 0.25 | 0.5 | 0.5 | 1 | 0.75 | 0.75 | 0.75 | 0.5 | 0.25 | 0.25 | 0.5 | 0.5 | 0.25 | 0 | 0 | 0.5 | 0.25 | 0.5 | 0.5 | 0.25 | 0.5 | 1 | 0.75 | 0.75 | 0.75 | 0.75 | 0.5 | 0.75 | 0.5 | 0.5 | 0.75 | 1 | 0.75 | 1 | 0.75 | 0.67 |
| **Stress** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
| brolga | 0.88 | 1.00 | 1.00 | 1.00 | 0.88 | 0.88 | 0.75 | 1.00 | 0.50 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 1.00 | 0.75 | 0.25 | 0.75 | 0.63 | 0.75 | 0.25 | 0.63 | 0.63 | 0.50 | 1.00 | 0.88 | 0.75 | 0.75 | 0.75 | 0.75 | 0.88 | 0.63 | 0.50 | 0.38 | 0.88 | 1.00 |
| australasian darter | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.75 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.75 | 0.38 | 0.88 | 0.75 | 0.88 | 0.38 | 0.38 | 0.50 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| australian shelduck | 1.00 | 0.75 | 0.75 | 0.88 | 0.88 | 0.75 | 0.88 | 0.88 | 0.50 | 0.75 | 0.88 | 0.50 | 0.75 | 0.88 | 0.88 | 0.75 | 0.38 | 0.88 | 0.75 | 0.88 | 0.38 | 0.38 | 0.50 | 0.38 | 1.00 | 1.00 | 1.00 | 0.75 | 0.75 | 0.63 | 0.88 | 0.75 | 0.63 | 0.50 | 0.75 | 0.75 |
| **Vulnerability** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
| brolga | 0.56 | 0.50 | 0.63 | 0.75 | 0.56 | 0.81 | 0.63 | 0.88 | 0.50 | 0.63 | 0.75 | 0.31 | 0.56 | 0.38 | 0.75 | 0.50 | 0.13 | 0.38 | 0.56 | 0.38 | 0.13 | 0.69 | 0.56 | 0.38 | 0.88 | 0.81 | 0.75 | 0.75 | 0.75 | 0.75 | 0.69 | 0.81 | 0.63 | 0.69 | 0.69 | 0.50 |
| australasian darter | 0.63 | 0.50 | 0.88 | 0.81 | 0.81 | 0.63 | 0.56 | 0.81 | 0.63 | 0.38 | 0.44 | 0.25 | 0.75 | 0.44 | 0.44 | 0.38 | 0.19 | 0.44 | 0.38 | 0.44 | 0.19 | 0.19 | 0.25 | 0.19 | 0.63 | 0.88 | 0.88 | 0.50 | 0.63 | 0.56 | 0.69 | 0.75 | 0.69 | 0.50 | 0.50 | 0.88 |
| australian shelduck | 0.63 | 0.63 | 0.63 | 0.94 | 0.81 | 0.75 | 0.81 | 0.69 | 0.38 | 0.50 | 0.69 | 0.50 | 0.50 | 0.44 | 0.44 | 0.63 | 0.31 | 0.69 | 0.63 | 0.56 | 0.44 | 0.69 | 0.63 | 0.56 | 0.88 | 0.88 | 0.75 | 0.75 | 0.63 | 0.56 | 0.81 | 0.88 | 0.69 | 0.75 | 0.75 | 0.71 |

### *Sensitivity testing*

In response to comments from the Technical Advisory Group, sensitivity testing included an assessment assigning the lowest condition and stress indicator score (rather than taking a normalised average; **Error! Reference source not found.**). The intent was to examine scenarios of concern without the possibility that negative indicators are being masked by positive indicators. The results showed a similar overall pattern, but perhaps with the uneven sample effort in waterbird condition data having a stronger effect on the condition results. The small differences between years are lost and overall condition is lower, stress is higher, and all groups are classed as more vulnerable.

Similarly, an assessment of using just the WIT stress metrics (i.e. excluding greenness and rainfall as stress indicators) was performed to explore if there was redundancy in stress metrics (**Error! Reference source not found.**). This indicated that there was very little difference between stress and vulnerability using the full suite of indicators and just the two derived from the WIT (extent of inundation and time since last inundation). Future applications of the method could potentially focus on using an optimised subset of indicators to reduce the dependency on many data sets.

### ***Confidence in the waterbird vulnerability assessment***

There are many uncertainties associated with the input data for both condition and stress. Stress metrics rely heavily on WIT outputs, which are limited due to cloud cover and uncertainties associated with the tassel cap index (see Text Box 1). The waterbird condition data is based on waterbird observations from a variety of sources, none of which were designed for a Basin-scale assessment of condition. Some of the data issues include:

- Missing data at wetland cluster scales – it is not possible to determine if there were no waterbirds observed at a location in a year. The aerial surveys occur one per year in spring, but do not indicate if birds were present at other times of the year. It was suggested that ALA records at wetland complex sites where terrestrial birds were recorded, but no waterbirds could be used as evidence of a “0” count. This logic, however, does not hold for all occasions. Especially at large complex sites such as the Coorong or Barmah Forest, where casual bird observers may be in bushland and not looking (or recording) waterbirds in nearby wetlands.
- Uneven sample effort at wetland complex sites is also an issue, with increased sampling in recent years. This issue will become less relevant as years with better data collection become a large component of the baseline dataset.
- Breeding data and quantitative breeding data is very patchy and highly focussed on a small number of generally colonial nesting species.
- Location of waterbird observations is also highly uncertain. The location for aerial surveys may be to a large complex site only (not the habitats within) and citizen science records in the ALA often record where the observer is standing, not where the bird was located. This makes habitat attribution for waterbird data highly uncertain.

Despite all the limitations with the data for both stress and condition indicators, at the Basin-scale, the vulnerability assessment of waterbirds is robust and provides the expected pattern with respect to wet and drought years. There is good agreement between metrics, proving a multiple lines of evidence strength to the outputs. Using the confidence level descriptions from Table 2 at the Basin scale, confidence in the waterbird vulnerability outputs would be considered “moderate”. At smaller spatial scales, the uncertainties in the WIT and missing data for waterbird condition would reduce this to “low/moderate”.

Table 17. Overall stress, condition, and vulnerability (lowest value for stress and condition indicators)

| **Stress** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 |
| Colonial_nesters | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 |
| Cryptic_waders | 2 | 2 | 3 | 3 | 3 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 3 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 3 | 2 | 2 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 2 | 2 |
| Diving_swimmers | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 |
| Filtering | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 |
| Grazing_swimmers | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 |
| Shorebirds | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 |
| **Condition** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
| Aerial_divers | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 3 |
| Colonial_nesters | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| Cryptic_waders | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 2 |
| Diving_swimmers | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Filtering | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Grazing_swimmers | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Shorebirds | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 2 | 2 |
| **Vulnerability** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
| Aerial_divers | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.0 | 0.4 | 0.2 | 0.2 | 0.2 | 0.4 | 0.4 | 0.4 | 0.2 | 0.4 | 0.2 | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.6 | 0.4 | 0.6 | 0.4 | 0.4 | 0.4 | 0.6 | 0.2 | 0.2 | 0.4 | 0.6 |
| Colonial_nesters | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.0 | 0.0 | 0.4 | 0.0 | 0.4 | 0.4 | 0.2 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.0 | 0.2 | 0.0 | 0.0 | 0.6 | 0.6 | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.0 | 0.2 | 0.2 |
| Cryptic_waders | 0.4 | 0.2 | 0.4 | 0.4 | 0.6 | 0.4 | 0.0 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.6 | 0.4 | 0.4 | 0.4 | 0.0 | 0.0 | 0.4 | 0.2 | 0.2 | 0.2 | 0.4 | 0.2 | 0.4 | 0.4 | 0.4 | 0.0 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.2 | 0.4 | 0.4 |
| Diving_swimmers | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.4 | 0.0 | 0.0 | 0.2 | 0.0 | 0.2 | 0.2 | 0.2 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.0 | 0.2 | 0.0 | 0.2 | 0.6 | 0.6 | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.4 | 0.4 |
| Filtering | 0.4 | 0.2 | 0.4 | 0.4 | 0.4 | 0.2 | 0.4 | 0.4 | 0.0 | 0.0 | 0.4 | 0.0 | 0.2 | 0.2 | 0.2 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 | 0.6 | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.4 | 0.4 |
| Grazing_swimmers | 0.4 | 0.2 | 0.2 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.0 | 0.2 | 0.2 | 0.0 | 0.2 | 0.2 | 0.2 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.0 | 0.0 | 0.2 | 0.0 | 0.6 | 0.6 | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.4 | 0.4 |
| Shorebirds | 0.4 | 0.4 | 0.2 | 0.4 | 0.2 | 0.4 | 0.2 | 0.2 | 0.0 | 0.4 | 0.4 | 0.4 | 0.2 | 0.2 | 0.4 | 0.4 | 0.4 | 0.4 | 0.6 | 0.6 | 0.4 | 0.2 | 0.4 | 0.4 | 0.4 | 0.6 | 0.4 | 0.6 | 0.6 | 0.6 | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |

Table 18. Stress and vulnerability (using WIT only stress indicators and waterbird condition indicators)

| **Stress just WIT** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerial_divers | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.67 | 0.83 | 0.67 | 0.50 | 0.67 | 0.50 | 0.50 | 0.33 | 0.67 | 1.00 | 0.83 | 1.00 | 0.83 | 0.67 | 0.67 | 0.67 | 0.67 | 0.50 | 0.67 | 1.00 |
| Colonial_nesters | 1.00 | 0.83 | 0.67 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.67 | 0.50 | 0.83 | 0.67 | 0.67 | 0.83 | 0.83 | 0.67 | 0.50 | 0.50 | 0.83 | 0.83 | 0.50 | 0.33 | 0.17 | 0.33 | 1.00 | 1.00 | 1.00 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.83 | 0.67 | 0.67 | 0.83 |
| Cryptic_waders | 0.83 | 0.83 | 1.00 | 1.00 | 1.00 | 0.67 | 0.50 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 1.00 | 0.83 | 1.00 | 0.83 | 0.50 | 0.50 | 0.67 | 0.67 | 0.33 | 0.50 | 0.83 | 0.50 | 1.00 | 0.83 | 0.67 | 0.50 | 0.67 | 0.67 | 1.00 | 0.83 | 0.67 | 0.50 | 0.83 | 0.83 |
| Diving_swimmers | 1.00 | 0.83 | 0.67 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.67 | 0.50 | 0.83 | 0.67 | 0.67 | 0.83 | 0.83 | 0.67 | 0.50 | 0.50 | 0.83 | 0.83 | 0.50 | 0.33 | 0.17 | 0.33 | 1.00 | 1.00 | 1.00 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.83 | 0.67 | 0.67 | 0.83 |
| Filtering | 1.00 | 0.83 | 0.67 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.67 | 0.50 | 0.83 | 0.67 | 0.67 | 0.83 | 0.83 | 0.67 | 0.50 | 0.50 | 0.83 | 0.83 | 0.50 | 0.33 | 0.17 | 0.33 | 1.00 | 1.00 | 1.00 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.83 | 0.67 | 0.67 | 0.83 |
| Grazing_swimmers | 1.00 | 0.83 | 0.67 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.67 | 0.50 | 0.83 | 0.67 | 0.67 | 0.83 | 0.83 | 0.67 | 0.50 | 0.50 | 0.83 | 0.83 | 0.50 | 0.33 | 0.17 | 0.33 | 1.00 | 1.00 | 1.00 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.83 | 0.67 | 0.67 | 0.83 |
| Shorebirds | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.67 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.67 | 0.83 | 0.67 | 0.50 | 0.67 | 0.50 | 0.50 | 0.50 | 0.67 | 1.00 | 0.83 | 1.00 | 0.83 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 1.00 |
| **Vulnerability just WIT** | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
| Aerial_divers | 0.42 | 0.67 | 0.67 | 0.42 | 0.42 | 0.67 | 0.42 | 0.42 | 0.33 | 0.92 | 0.67 | 0.67 | 0.67 | 0.92 | 0.92 | 0.92 | 0.83 | 0.92 | 0.58 | 0.75 | 0.83 | 1.00 | 1.00 | 0.67 | 1.08 | 1.00 | 0.92 | 1.25 | 1.17 | 0.83 | 1.08 | 1.33 | 1.08 | 1.00 | 1.08 | 1.50 |
| Colonial_nesters | 1.13 | 0.92 | 1.08 | 1.17 | 1.17 | 1.08 | 1.04 | 1.17 | 0.71 | 0.50 | 0.92 | 0.71 | 1.08 | 0.67 | 0.92 | 0.46 | 0.38 | 0.38 | 0.67 | 0.79 | 0.75 | 0.67 | 0.58 | 0.79 | 1.25 | 1.13 | 1.00 | 0.92 | 0.92 | 0.83 | 1.29 | 1.04 | 0.92 | 0.71 | 0.96 | 0.92 |
| Cryptic_waders | 1.17 | 0.67 | 1.00 | 0.75 | 1.00 | 1.08 | 0.50 | 1.08 | 1.08 | 1.08 | 0.83 | 0.83 | 1.00 | 0.67 | 0.75 | 0.92 | 0.50 | 0.75 | 0.83 | 1.08 | 0.92 | 0.50 | 0.92 | 0.50 | 0.75 | 0.92 | 0.83 | 0.50 | 1.08 | 1.08 | 0.50 | 1.17 | 0.83 | 0.50 | 1.17 | 0.92 |
| Diving_swimmers | 0.83 | 0.92 | 1.00 | 1.08 | 1.08 | 0.83 | 0.75 | 0.92 | 0.67 | 0.42 | 0.75 | 0.67 | 0.50 | 0.58 | 0.58 | 0.50 | 0.42 | 0.42 | 0.58 | 0.58 | 0.58 | 0.67 | 0.42 | 0.67 | 1.00 | 1.33 | 1.33 | 1.08 | 1.08 | 1.00 | 0.92 | 1.25 | 1.08 | 0.83 | 1.17 | 1.08 |
| Filtering | 1.00 | 0.75 | 0.83 | 1.08 | 1.25 | 0.83 | 0.92 | 0.92 | 0.67 | 0.42 | 0.92 | 0.50 | 0.67 | 0.58 | 0.75 | 0.50 | 0.42 | 0.42 | 0.58 | 0.75 | 0.42 | 0.33 | 0.25 | 0.50 | 0.83 | 1.17 | 1.33 | 1.08 | 0.92 | 1.00 | 1.08 | 1.25 | 1.08 | 1.00 | 0.83 | 0.92 |
| Grazing_swimmers | 0.67 | 0.75 | 0.67 | 0.92 | 1.08 | 1.00 | 0.58 | 0.75 | 0.50 | 0.75 | 0.75 | 0.67 | 0.67 | 0.58 | 0.58 | 0.50 | 0.42 | 0.58 | 0.58 | 0.58 | 0.42 | 0.50 | 0.58 | 0.67 | 1.17 | 1.33 | 1.17 | 0.92 | 0.92 | 1.00 | 1.08 | 1.25 | 1.08 | 1.00 | 1.17 | 1.25 |
| Shorebirds | 0.92 | 0.92 | 0.67 | 0.92 | 0.67 | 0.92 | 0.42 | 0.67 | 0.33 | 0.92 | 0.92 | 0.92 | 0.67 | 0.67 | 1.17 | 1.17 | 1.33 | 1.17 | 1.33 | 1.25 | 1.33 | 1.00 | 1.25 | 1.25 | 1.33 | 1.00 | 0.92 | 1.25 | 1.42 | 1.33 | 1.33 | 0.83 | 1.33 | 1.33 | 1.08 | 1.25 |

## From waterbird vulnerability to potential watering locations

The assessment of waterbird vulnerability is at the Basin scale. To use this information to inform watering priorities, there needs to be a spatial context to the assessment that can be related to the scales at which water management occurs. One method of moving from vulnerability to potential watering locations is to identify the locations that are important for the vulnerable group(s) of species in the Basin. The Australian Aquatic Ecosystems Toolkit has a method for identifying High Ecological Value Aquatic Ecosystems (HEVAE) (Aquatic Ecosystem Task Group 2012). By taking the principles of this method and the HEVAE criteria for "vital habitat" we can systematically identify the locations in the Basin that are important for vulnerable species or groups of waterbirds. The locations that are important for vulnerable species or groups can then be used in evidence-based decision making to inform environmental water management. A worked example for the colonial nesting waders' functional group is provided in Text Box 3.

### Important locations for colonial nesting waders

The vital habitat criteria for the HEVAE assessment have indicators related to the abundance and breeding of waterbirds. For this example, assessment, five indicators were used, each assigned a rank score as follows:

| Score | Maximum abundance | Median abundance | Species richness | Maximum breeding | Species breeding |
|---|---|---|---|---|---|
| 1 | < 1000 | < 100 | < 10 | < 1000 | < 5 |
| 2 | 1000 – 10,000 | 100 – 1000 | 10 - 14 | 1000 – 10,000 | 5 - 10 |
| 3 | 10,000 – 20,000 | > 1000 | > 14 | 10,000 – 20,000 | > 10 |
| 4 | > 20,000 | | | > 20,000 | |

Scores were applied to the BWS important waterbird wetland complexes using the same data that was used in the condition assessment (1986 – 2021). Data was pooled across years to provide a single score for importance for each wetland complex. The highest-ranking wetlands for colonial nesting waders were:

| DT_name | HEVAE_score |
|---|---|
| Lowbidgee floodplain | 17 |
| Macquarie Marshes | 17 |
| Booligal wetlands | 16 |
| Kerang wetlands | 16 |
| Lake Cowal | 16 |
| Coorong, Lower Lakes and Murray Mouth | 15 |
| Great Cumbung Swamp | 15 |
| Narran lakes | 14 |
| Fivebough Tuckerbil Swamp | 13 |
| Corop wetlands complex | 12 |
| Gwydir Wetlands | 12 |
| Barmah-Millewa | 11 |
| Lake Mokoan | 11 |
| Paroo overflow lakes complex | 11 |
| Cuttaburra channels | 10 |
| Lindsay-Walpolla-Chowilla | 10 |
| Menindee lakes | 10 |

Text Box 3. Example assessment to identify important locations for colonial nesting waders

# Conclusions

## Lessons learned from 2021 / 2022 application of the method

There are several lessons learned from the application of the vulnerability method for vegetation and waterbirds:

- The WIT represents a powerful tool for assessing vulnerability of vegetation and waterbirds – more than half the vegetation metrics and the stress metrics for waterbirds were based on the WIT outputs. The combination of extent metrics together with the derived event metrics (through linear extrapolation of the annual time series into daily data) provided a robust, Basin-scale time-series of measures for both themes. These data are expected to be updated regularly to extend the data set and so could form part of an annual assessment of vulnerability.
- Despite the problems with waterbird observation data, scoring the condition of waterbirds proved robust at the Basin-scale – the application of the method demonstrated that collation of waterbird data from varied sources represented an adequate indicator of waterbird condition at the Basin-scale.
- The outputs of condition, stress and vulnerability are relative, not absolute – for the majority of indicators a deviation from baseline approach was adopted, with the baseline represented by the duration of the Landsat record, minus the Millennium Drought. This is a relatively contemporary baseline and does not represent reference or natural condition, and there is no evidence to suggest that this period of times represents ideal conditions for vegetation or waterbirds. That is, they have been impacted to some degree by water resource use, climate change, land use changes and population growth. The outputs, therefore, are an annual relative indication of stress, condition and vulnerability and "low" vulnerability simply indicates that vulnerability is less than it has been in the past, or lower than is 'typical'.
- Measuring vulnerability at multiple scales and through time provides considerable insight to understand contemporary assessments of BWS assets in context. The method appears to provide a robust way of assessing condition, stress and vulnerability at large spatial scales despite data limitations, uncertainties and the assumptions that underpin the method. The comparisons with the Millennium Drought (when we have empirical evidence of a decline in condition and increase in stress and vulnerability) revealed expected patterns with high vulnerability suggesting the method is sensitive to revealing patterns of vulnerability to water stress that can inform management. It must be recognised, however, there will always be better, finer-scale information to inform watering requirements at the site and local scale.

## Recommendations

The method presented here is a first attempt at a Basin-scale assessment of vulnerability to inform environmental watering priorities. There are several recommendations for future applications for the method:

- Keep looking for improved indicators and metrics – the methods papers for vegetation and waterbirds (see Appendices B and C) conceptually identified a wide range of potential condition and stress metrics. The method as presented and trialled here was limited to those for which adequate Basin-scale data could be sourced. There are continual improvements in spatial data sets and tools, and it is certain that additional or alternative indicators will be possible in the future. The method should be reviewed annually to determine if more suitable datasets have become available.

- Update the baseline each year – the deviation from baseline is likely to become more robust the greater the time period it is calculated over. This is especially true for waterbird condition data, for which there is uneven sampling effort and generally increasing sample effort in recent years. Careful attention to climate change may also be required to identify whether baselines are drifting and whether establishing a defined, static baseline period that best reflects conditions against which change can be measured is required.
- Accessing waterbird survey data in a timely manner is a current issue – our experience during this project was that it took many months to access data once collected. This means that the waterbird assessment must lag at least a year, with 2021 data being used to inform 2023 watering priorities. If the data could be made available more quickly, it could be used in the subsequent year's decision making. The inclusion of data currently not accessible (e.g. The Living Murray waterbird counts) would also improve the waterbird condition assessment.
- The data assembled for this project represents a valuable resource and should be made available for others to use and build upon. This includes derived WIT outputs (e.g. event metrics, interpolated daily time series) as well as the collated and cleaned waterbird data set.
- Develop an authoritative map for important Basin assets that defines the spatial units for more consistent management and evaluation – the vulnerability assessment would have more impact and utility if Basin assets were consistently mapped at scales that were relevant to the way water is managed. Currently the BWS identifies expected outcomes for many locations for which there is no maps defining the location or extent to support the required management and evaluation. Individual ANAE polygons are too small and valleys or whole of Basin are likely too large to be informative.
- The Jupyter Python notebook developed for this project and provided to the MDBA and CEWH staff has been configured to enable annual assessment of vulnerability for these two BWS themes (waterbirds and native vegetation). While theoretically the process could be run without experience in Python code, if additional or new indicators were required, then the code would need to be updated accordingly. If the WIT data and annual waterbird counts from MDBA and CEWH programs could be made available in the first quarter of each year, then there is no reason why an assessment of vulnerability couldn't be run to inform annual watering priorities and improve evidence-based decision making. The process for annual implementation is provided in Appendix D.

# Where to from here?

Priorities for environmental water will still require consideration of a variety of factors such as cultural value, feasibility, watering history, competing priorities (see Figure 1). The principles for prioritising environmental watering locations are complex. For example:

- Should water be provided to places that are the most stressed /or vulnerable to ensure their continued survival?
- Should priority be afforded to places that have moderate to low vulnerability as a more effective, less risky use of water?
- Should priority go to places with the highest conservation value to support the maximum number of species and communities?

The vulnerability assessment cannot answer these questions, which must be based on water policy and systematic conservation planning. The vulnerability assessment as described here, however, can provide a valuable input to the prioritisation process for environmental water.

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# Appendix A: Technical Advisory Group

## Members

Sam Capon, Claire Krause, Tanya Doody, Anne Jensen, Lance Lloyd, Leo Lymburner, Ashley McQueen, Rory Nathan, Phil Papas, John Porter, Danny Rogers, Andrew Sharpe, Julian Reid, David Roshier, Rachael Thomas, Ross Thomson.

## Outcomes of the technical workshops

Two technical workshops with the TAG (and water managers) contributed significantly to the method and the outputs of this project. The major contributions from these workshops are summarised= in Table 13.

Table 19. Input from the TAG that informed the project.

| Item | Outcomes |
|---|---|
| Conceptual approach | There was general support for the conceptual approach to the project (i.e. stress, exposure and adaptive capacity = vulnerability) and the use of indicators of stress and condition.<br><br>Several participants reiterated that it will be important to continue to remind people that vulnerability does not equate to watering priorities, but that it is one of several inputs required to identify annual watering priorities. |
| Strengths and limitations of available data | Shane presented the large-scale data sets that we are accessing and some of the issues that we are grappling with.<br><br>There was a discussion around the use of WIT data to define watering events vs using the data to detect deviation from a previous state; with advocates for each approach. The key points from the discussion were:<br><br>• Some participants proposed that if we aim to maintain wetting/drying regimes then we may not need to define events (i.e. our focus can be on the distributions of reaching thresholds which may be defined as time intervals or duration periods). This allows for benchmarks to be established that are relevant to individual places on the landscape (which could be applied to every ANAE polygon). Thresholds based on deviation from ecological theory (e.g. every river red gum requires inundation 1 in 2 years) will not be applicable everywhere. In some places these trees can tolerate less frequent inundation and in others may be adapted to more frequent wetting. We can use the watering history of individual polygons to define an event or baseline against which change can be assessed.<br>• Other participants considered that "events" were important as environmental water is delivered as events and volumes of water are an important consideration.<br>• There was also a point made that if we look at water regimes in terms of deviation from "natural" or "historical" conditions, then it may help us identify the types of events to deliver through e water (i.e. where does environmental watering fit in to fill the gaps in the rest of the watering regime). |

| Item | Outcomes |
|---|---|
| | • Geoscience Australia indicated that they have gone part way down the path of writing code to assess deviations from historical conditions at an ANAE polygon scale.<br>• This conversation was continued in the vegetation break-out session (see below)<br><br>The point was made that looking at data in different ways tells you different things and there is merit in analysing data in multiple ways. |
| Vegetation method – specific comments | The point was raised that we need to recognise that we are starting from a position of highly stressed vegetation and that our starting point for satellite data (1987) in many instances will represent an already stressed state. So, deviation from conditions in 1987 may not represent a deviation from “good” or “healthy” vegetation condition. This was acknowledged by the project team (and others) and will need to be explicitly stated as a constraint / limitation of the use of satellite data.<br><br>There was a discussion about antecedent conditions and the importance of considering this in terms not only of inundation, but also of rainfall.<br><br>Several participants considered that the ecological elements modelling by Overton et al.[1] could be used to predict condition of vegetation in the absence of direct measures of condition. It was acknowledged that these models are more likely suited to the Southern Basin than the Northern Basin. There was not, however, complete agreement that these models were fit for this project, with some participants favouring the use of direct measures of condition where this was available.<br><br>There was a discussion about the WIT and the strengths and limitations of what the tool can tell us about inundation and vegetation condition. It was recognised that the “green” may indicate improved condition or may indicate weeds / exotic species. The project team have recognised this as a constraint and will ensure that this is stated as one of the limitations. We cannot detect exotic from native species in the ANAE polygons from satellite data at this stage. This led to an acknowledgement that monitoring data and time will be required to reality check outputs of the vulnerability assessment.<br><br>There was a discussion about the tree stand condition tool and how the algorithm used may assess coolibah as in “poor” condition simply because they naturally have a less green / dense canopy. The use of condition categories such as ”good” or “poor” may therefore be problematic. The project team acknowledges this and an approach that uses deviation from historic conditions will overcome this |

[1] Overton, I.C., Pollino, C.A., Grigg, N.J., Roberts, J., Reid, J.R.W., Bond, N.R., Barma, D., Freebairn, A., Stratford, D. and Evans, K., 2015. The Ecological Elements Method for adjusting the Murray–Darling Basin Plan Sustainable Diversion Limit. *Canberra: CSIRO*.

| Item | Outcomes |
|---|---|
| | problem. We will not be saying "poor" = vulnerable, but rather a decline in condition status is an indicator of vulnerability.<br><br>There was a discussion around scale and what scale may be relevant. It was suggested that the scale of an ANAE polygon is probably reasonable for the vulnerability assessment, and that the scale of application for prioritisation will be determined by the application of the tool (e.g. to assets, water management regions, etc).<br><br>There was general support for an approach that uses deviations from a baseline (rather than a standard set of thresholds based on ecological theory). |
| Waterbirds method specific comments | There was a general agreement on the approach and that as with all waterbird projects, there are limitations with respect to waterbird data. (e.g. aerial surveys are typically once a year and the atlas records are mostly ad hoc). There was also acknowledgement of the issues with the mobility of waterbirds (within the Basin and beyond) and that this is a recognised and difficult problem. No one had a solution, however, so it perhaps just needs to be stated as a known constraint / limitation.<br><br>There was a strong preference from several in the group to use direct waterbird biological indicators for condition (e.g. abundance, species richness, breeding), rather than habitat/surrogates.<br><br>The point was raised that breeding abundance and breeding species richness could be added as condition indicators, despite the issues with data availability. This was supported by the group<br><br>There was a discussion about the merits of using individual species vs functional groups. It was acknowledged that using groups could mask the trends of individual species, but that individual species approaches would lead to too many conflicting priorities that would not be fit for purpose with respect to informing watering priorities. In the end it was agreed that groups of species would be required and the functional groups proposed are robust. A suggestion was made to consider adding diet to the existing species groups.<br><br>A discussion about the use of data and thresholds concluded with a suggestion that rather than averages, deviations from maximum and minimums may be better.<br><br>Consideration was given to looking at a handful of individual species either as indicator species or to directly look at priorities for threatened waterbird species. It was recognised that there may be insufficient resources to adopt this approach, but the project team would consider it.<br><br>The discussion of habitat metrics (as indicators of stress) raised the issue of the use of habitats outside the managed floodplain by waterbirds and how important this may be. Geoscience Australia indicated that WIT outputs could be provided for non-wetland areas, but that this involves very large datasets that cannot be |

| Item | Outcomes |
|---|---|
| | stored long-term by GA. They would need to be produced, handed over then deleted from GA servers.<br><br>There was strong support for considering refuge habitats explicitly, rather than just breeding and foraging habitats. There were no suggestions, however, on how this may be achieved.<br><br>There was a discussion about scale with the suggestion that all scales will be important (site, valley, northern and southern Basins). There was support for trialling the application of the vulnerability methods at several scales to see what scale produces the best results.<br><br>There was a discussion about the possibility of using productivity measures as indicators of stress / habitat condition. This could be in terms of "greenness" of vegetation, chlorophyll-a from satellite data or NDVI. |
| Calculating stress, condition and vulnerability | Sensitivity testing of different methods of calculating scores would strengthen confidence. For example, instead of averaging the scores for each indicator, taking the lowest score could identify vulnerabilities.<br><br>Future iterations of the method could consider developing different thresholds for the northern and southern Basin (for absolute values like time since last inundation for different vegetation groups). |

# Appendix B: Vegetation method development

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# Context

## *BWS Expected outcomes for vegetation*

Expected outcomes of the BWS for vegetation can be broadly summarised as:

- Forests and woodlands:
  - to maintain the current extent of forest and woodland vegetation
  - no decline in the condition of river red gum, black box and coolibah across the Basin
  - by 2024, improved condition of river red gum in the Lachlan, Murrumbidgee, Lower Darling, Murray, Goulburn–Broken and Wimmera–Avoca
  - by 2024, improved recruitment of trees within river red gum, black box and coolibah communities—in the long-term achieving a greater range of tree ages. (river red gum, black box and coolibah communities are presently comprised primarily of older trees which places them at risk.)
- Shrublands:
  - to maintain the current extent of the large areas of lignum shrubland within the Basin
  - by 2024, improvement in the condition of lignum shrublands.
- Non-woody vegetation:
  - to maintain the current extent of non-woody vegetation
  - by 2024, increased periods of growth for communities that:
    - closely fringe or occur within the main river corridors
    - form extensive stands within wetlands and low lying floodplains including Moira grasslands in the Barmah-Millewa Forest, common reed and cumbungi in the Great Cumbung Swamp and Macquarie Marshes, water couch on the floodplains of the Macquarie and Gwydir rivers and club-rush sedgelands in the Gwydir.
  - a sustained and adequate population of *Ruppia tuberosa* in the south lagoon of the Coorong, including:
    - *Ruppia tuberosa* to occur in at least 80% of sites across at least a 43 km extent (refer to Coorong case study)
    - by 2029, the seed bank to be sufficient for the population to be resilient to major disturbances.

## *Approach*

The approach taken here comprises four primary steps:

1) Conceptual model development
2) Functional grouping of species and vegetation assemblages
3) Identifying indicators and thresholds
4) Application of the framework to vegetation functional units

In line with the expected outcomes of the BWS for vegetation the following vegetation types will be considered. For the purposes of this report, they will be referred to as vegetation functional units.

Vegetation functional units to be considered:

- Forests and woodlands
  - *Eucalyptus camaldulensis,* River Red Gum
    - Swamp (RRG-S)
    - Forest (RRG-F)
    - Woodland (RRG-W)
  - *Eucalyptus largiflorens,* Black Box
    - Swamp (BB-S)
    - Forest (BB-F)
    - Woodland (BB-W)

    - *Eucalyptus coolabah,* Coolibah
        - Swamp (C-S)
        - Woodland (C-W)
- Shrublands
    - *Duma florulenta,* Tangled Lignum
        - Swamp (L-Sw)
        - Shrubland (L-Sh)
- Non-woody vegetation (NWV)
    - Submerged vegetation
    - Sedges / rushes
    - Grassy meadows
    - Tall reeds
    - Herbfields

# Our conceptual understanding of native vegetation vulnerability

Native vegetation vulnerability in riverine ecosystems (encompassing instream, riparian bank, wetland and floodplain habitats) is a function of the character, magnitude and rate of environmental change to which the system is **exposed**, the **sensitivity** of the vegetation and its **adaptive capacity** (Intergovernmental Panel on Climate Change, 2007 in Foden, Young *et al.* 2019) (Figure 28).

**Definitions:**

These definitions are for the specific purposes of this vegetation methods document; see Foden, Young *et al.* (2019) for more general definitions; definitions given here follow Intergovernmental Panel on Climate Change, 2007 in Foden, Young *et al.* (2019):

*Exposure:* Exposure describes the nature, magnitude and rate of environmental changes experienced by native vegetation

*Sensitivity:* is the degree to which native vegetation within a system is affected, either adversely or beneficially, by environmental change

*Adaptive capacity:* The potential, capability, or ability of native vegetation to adjust to environmental change, to moderate potential damage, to take advantage of opportunities, or to respond to the consequences. For native vegetation this is considered here primarily in terms of Resistance – the ability to resist change or stress and Resilience – the recovery potential following change.

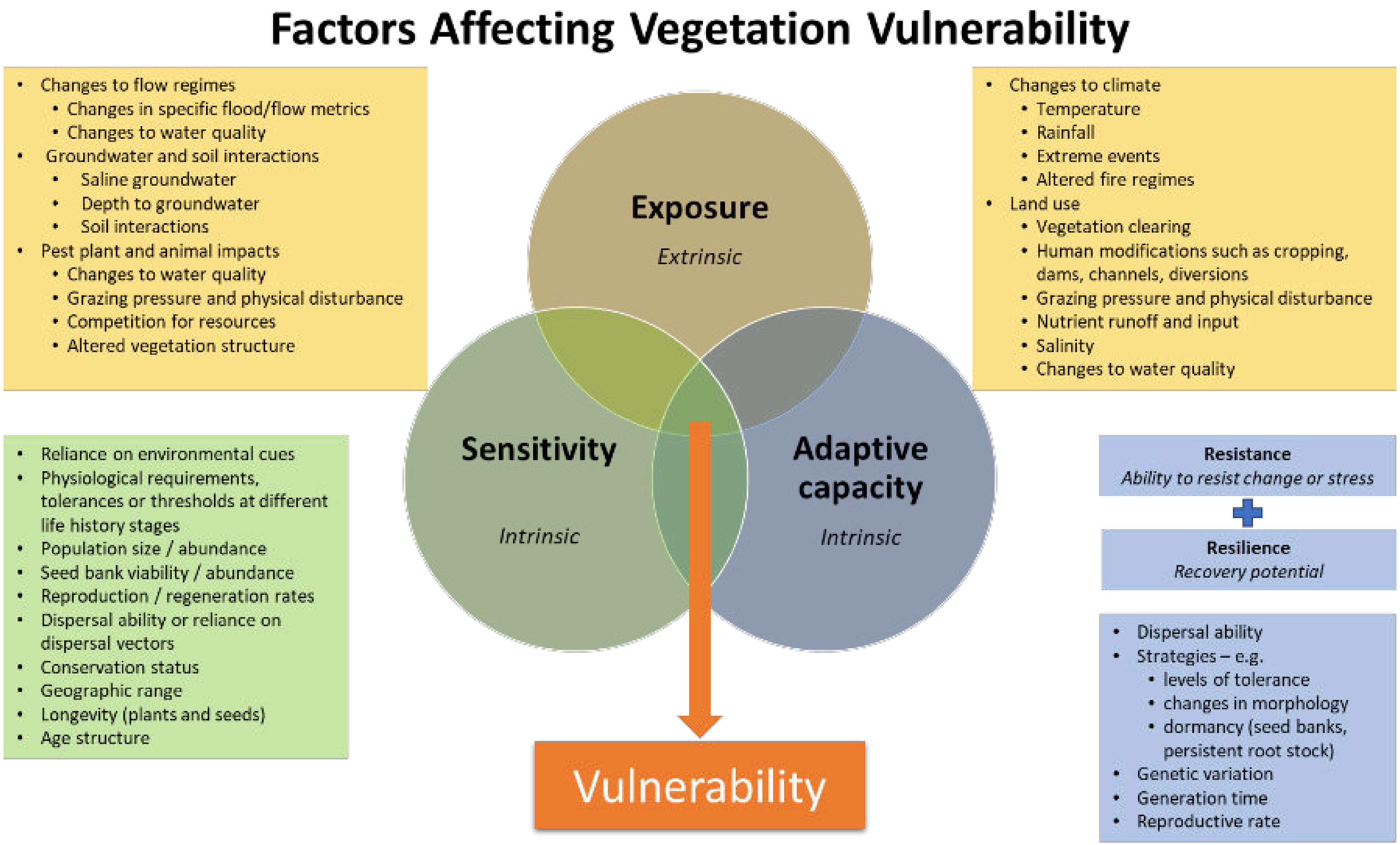


Figure 28: Conceptual diagram of factors interacting to affect native vegetation vulnerability in Australia (based on Foden, Young et al. (2019).

## *Vegetation sensitivities, adaptive capacity, and exposure*

The factors affecting vegetation vulnerability are described in more detail below in terms of:

- Exposure to environmental change, specifically changes to:
    - Flow regimes
    - Climate
    - Groundwater and soil interactions
    - Land use, and
    - Pest plant and animal interactions
- Sensitivity to environmental change
- Adaptive capacity to environmental change

## *Exposure to environmental change*

Major environmental changes affecting native vegetation in riverine ecosystems can be broadly grouped into changes to i) flow regimes; ii) climate, iii) groundwater and soil interactions, iv) land use (including vegetation clearing, human modifications, grazing, nutrient runoff and input) and v) pest plant and animal impacts. This list is not exhaustive or mutually exclusive and undoubtedly there are many other environmental changes that impact native vegetation either directly or indirectly. The primary focus for this project is vulnerability via altered flow regimes and prioritising environmental water management actions to address vulnerability. For the purposes of this study, the impacts of climate change, groundwater and soil interactions, land use, and pest plants and animals are considered in relation to their interactive effect on native vegetation vulnerability to altered flow regimes and the ability or confidence to achieve predicted mitigation outcomes through environmental water management. We focus on these five groups (though primarily flow regimes) because of the ability to implement natural resource management actions, such as environmental flows, pest plant and animal control, and land use management such as fencing, revegetation, nutrient runoff, and grazing management to mitigate the vulnerability of native vegetation caused by these environmental changes. The ability to incorporate different types of environmental changes into the vulnerability framework can be assessed as part of periodic reviews and updates to the framework.

## *Flow regimes*

The distribution and abundance of native vegetation in riverine ecosystems is strongly influenced by hydrology and the availability of water (Boulton and Brock 1999; Brock and Casanova 1997; Raulings, Morris *et al.* 2010; Rogers and Ralph 2011). Changes in flow regimes, or hydrological connectivity, are therefore likely to significantly impact the distribution and condition of vegetation in these systems (Brock and Casanova 1997; Casanova and Brock 2000; Rogers and Ralph 2011).

As a result of naturally occurring variable flow regimes riverine ecosystems are dynamic systems that are highly changeable in space and time (Bunn, Thoms *et al.* 2006; Capon 2005; Naiman, Decamps *et al.* 2010; Reid and Ogden 2006; Thoms 2006; Thorp, Thoms *et al.* 2006). Organisms, such as plants, need to have adaptations to cope with these changing environmental conditions (Brock and Casanova 1997; Brock, Nielsen *et al.* 2003; Rogers and Ralph 2011). These adaptations may take the form of levels of tolerance (e.g. RRG withstanding periods of inundation and drying) (Rogers and Ralph 2011), changes in morphology (e.g. rapid growth and morphological plasticity to survive changes in water depth) (Brock and Casanova 1997), through to stages of dormancy (e.g. dormant seed banks or persistent rhizome or root stock) (Brock 2011; Freestone, Brown *et al.* 2017). Another way to cope with changing environmental conditions is through immigration and emigration (e.g. dispersal). This enables the movement of individuals and populations as suitable habitat appears and disappears (Bullock, Moy *et al.* 2002; Damschen, Brudvig *et al.* 2008; Eriksson 1996).

While native plant species have adaptations to naturally variable flow regimes there are limits to those adaptations and plant species are still vulnerable to magnitudes of change that go beyond natural variability. Flow regimes impact all major plant life-history processes (Figure 29) and disruption to any major life-history stage contributes to the overall vulnerability of native vegetation.

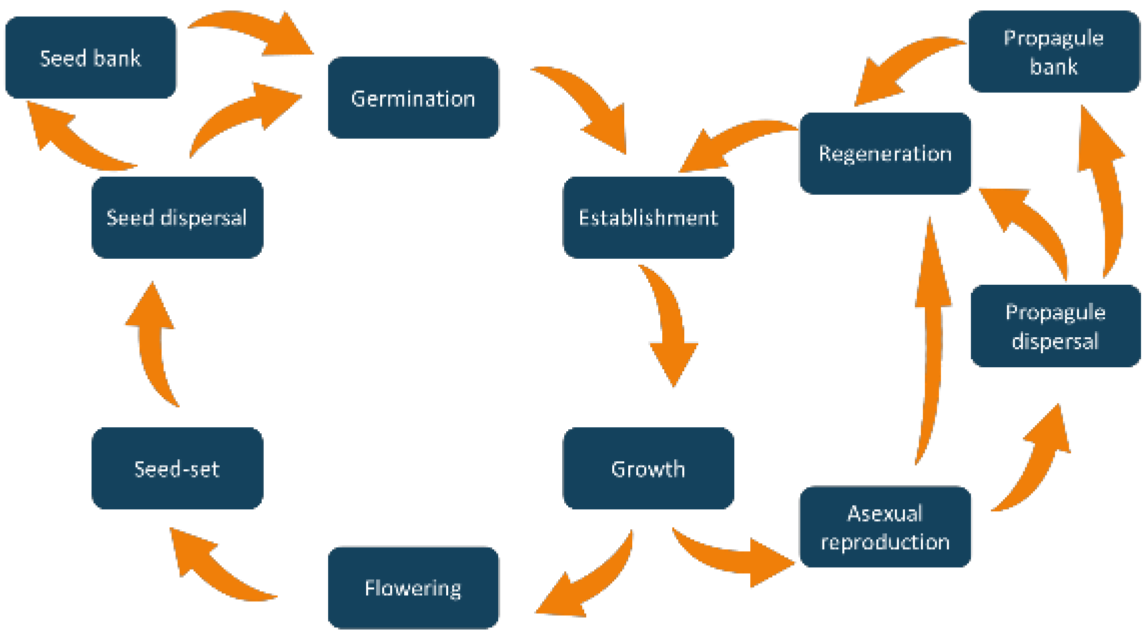


Figure 29. Conceptual model depicting major plant life-history processes that affect native vegetation vulnerability (with reference to models in Capon, James et al. 2009; Casanova 2015).

Vegetation responses to flow regimes are inherently complex, variable and dynamic in space and time and evaluating outcomes requires consideration of multiple factors (Campbell, James *et al.* 2021). The maintenance of native vegetation in riverine ecosystems involves complex interactions between the spatial arrangement of existing (e.g. extant) and potential habitat (e.g. soil seed banks), the ability to disperse between habitat patches, factors operating at regional and local scales and patch context (see Campbell and Nielsen 2014 for more information). Specifically, in relation to flow regimes, native vegetation vulnerability in riverine ecosystems needs to consider the i) temporal complexity of flow regimes, ii) interactions between hydrology, geomorphology and landscape ecology and iii) flow-ecology relationships for different species, communities or mosaics of vegetation.

Temporal complexity (see Ryo, Aguilar-Trigueros *et al.* 2019) considers the effect of flow regimes on vegetation responses across different temporal timeframes. For example, a flow pulse / the current regime or conditions influence plant responses such as growth, reproduction, germination, dispersal, quiescence or death. However, the response to a flow pulse will be influenced by short to medium term flow regimes and climatic cycles (e.g. annual to a decade) that influence the composition of plant species available to respond (e.g. viability of seedbanks) and the condition of vegetation prior to flow. The response will be further influenced by long-term flow regimes and climatic cycles (e.g. decades to centuries) which affect the structure and distribution of long-lived vegetation, which in turn has an influence on the expression of non-woody vegetation (see Campbell, Capon *et al.* 2019 for more information).

Strong interactions exist between hydrology, geomorphology and landscape ecology that affect native vegetation responses and vulnerability (Thoms, Beyer *et al.* 2006; Ward, Tockner *et al.* 2002). Flow interacts with geomorphology to determine the depth and duration of inundation and the connectivity between habitat patches such as rivers, wetlands and floodplains will influence the movement of species and nutrients.

Flow-ecology relationships for different species and communities of vegetation determine flow regime requirements in terms of flow parameters such as depth, duration, season, frequency and inter-flood dry period (Roberts and Marston 2011; Rogers and Ralph 2011).

Key hydrological metrics in relation to vegetation response and vulnerability are conceptualised for hypothetical flow regimes across three timeframes: flow pulse / event (Figure 30), short-term regime (Figure 31) and longer-term regime (Figure 32). The relationship of the hydrological metrics with native vegetation response or vulnerability is presented for a flow pulse / event (Table 20) and for short and long-term regimes combined (Table 21). The information presented here is general and may vary for different functional groups / types of vegetation. Specific indicators of condition and stress and thresholds of vulnerability for functional units used in this study are presented in Table 27.

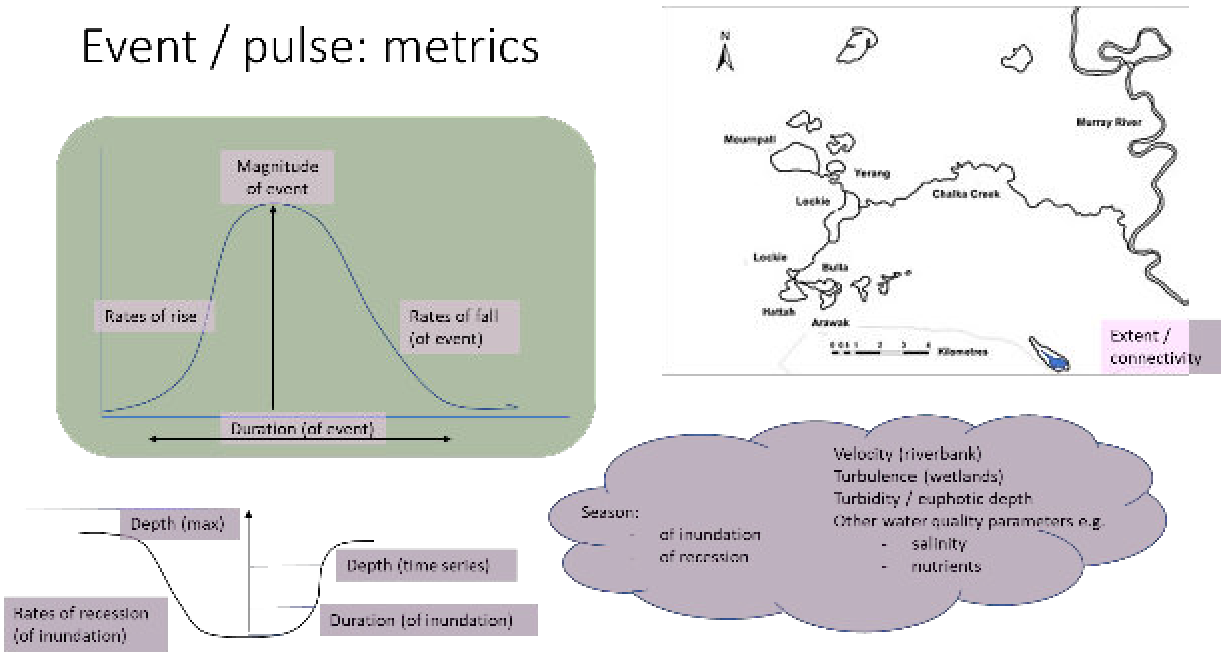


Figure 30. Conceptual representation of key hydrological metrics in relation to vegetation responses to a flow event / pulse

Table 20. Relationship between flow event / pulse hydrology metrics / flow components and generalised vegetation response

| **Metric / flow component** | **Relationship with vegetation (adapted from EWKR; (Campbell, Capon *et al.* 2019)** |
|---|---|
| Depth (max) | Individual plants have limits to the depth of inundation that they can tolerate. Their tolerance will be influenced by species characteristics, but also the condition they are in when inundated. For individuals whose tolerance is exceeded, inundation will act as a disturbance leading to declines in condition or death. |
| Depth (time series) | Provides an indication of the area of suitable habitat for different types of species over time. For some species, depth is an important habitat characteristic providing resources |
| Duration (of event) | Relevant to riverbank habitats; plants have limits to the duration of flooding that they can tolerate; also informs the relationship between event and water retention (inundation) at sites |
| Duration (of inundation) | Relevant to wetland / floodplain habitats; plants have limits to the duration of inundation that they can tolerate or that is required to complete their life-cycles or life-cycle stages (see also depth) |
| Magnitude of event | An important determinate in species dispersal patterns and transport of nutrients and sediment |
| Other water quality parameters e.g. salinity, nutrients | Affects the physiology and growth of plants |
| Rates of fall (of event) | Relevant to riverbank habitats; if the rate of drawdown is too rapid this will act as a disturbance for the plant, essentially shortening the duration of the inundation; for example species may die prior to setting seed (due to lack of soil moisture) or may not be able to colonise the receding waterline fast enough and become stranded (submerged species) |
| Rates of recession (of inundation) | Similar to rates of fall but relevant to wetland and floodplain habitats |
| Rates of rise | If the depth of inundation rises too rapidly then already established submerged vegetation may not be able to tolerate the increase in depth and may not be able to colonise higher parts of the bank rapidly enough |
| Season | River red gum, black box and lignum have aerial seed banks, with maximum seed fall timed to coincide with the greatest chance of suitable soil moisture conditions. A shift in seasonality will affect suitable conditions for germination. |
| Season (of inundation) | Relevant to submerged species and species which germinate under water; Seasonal timing is important as day length and temperature act as cues for germination and reproduction and influence productivity or the productivity of competing species |
| Season (of recession) | Relevant to amphibious species which germinate on flow recession; Seasonal timing is important as day length and temperature act as cues for germination and reproduction and influence productivity or the productivity of competing species |
| Turbidity / euphotic depth | Turbidity affects the light available to submerged plants, which will affect their productivity and growth, or limit / prevent germination |
| Turbulence (wetlands) | Relevant to wetland and floodplain habitats; Turbulence exerts a physical stress on individual plants and may dislodge plants; it may also influence the availability of nutrients and carbon dioxide in the water column; influences dispersal |
| Velocity (riverbank) | Relevant to riverbank habitats; Velocity exerts a physical stress on individual plants and may dislodge plants; it may also influence the availability of nutrients and carbon dioxide in the water column; influences dispersal |

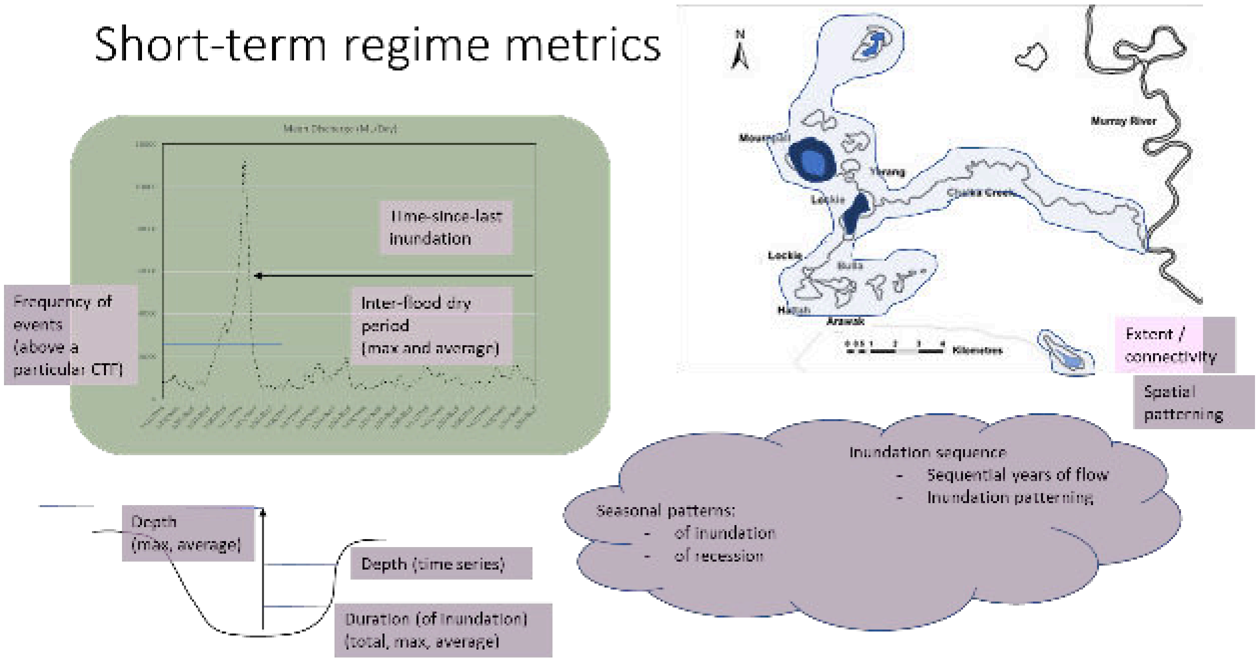


Figure 31. Conceptual representation of key hydrological metrics in relation to vegetation responses to short-term flow regimes

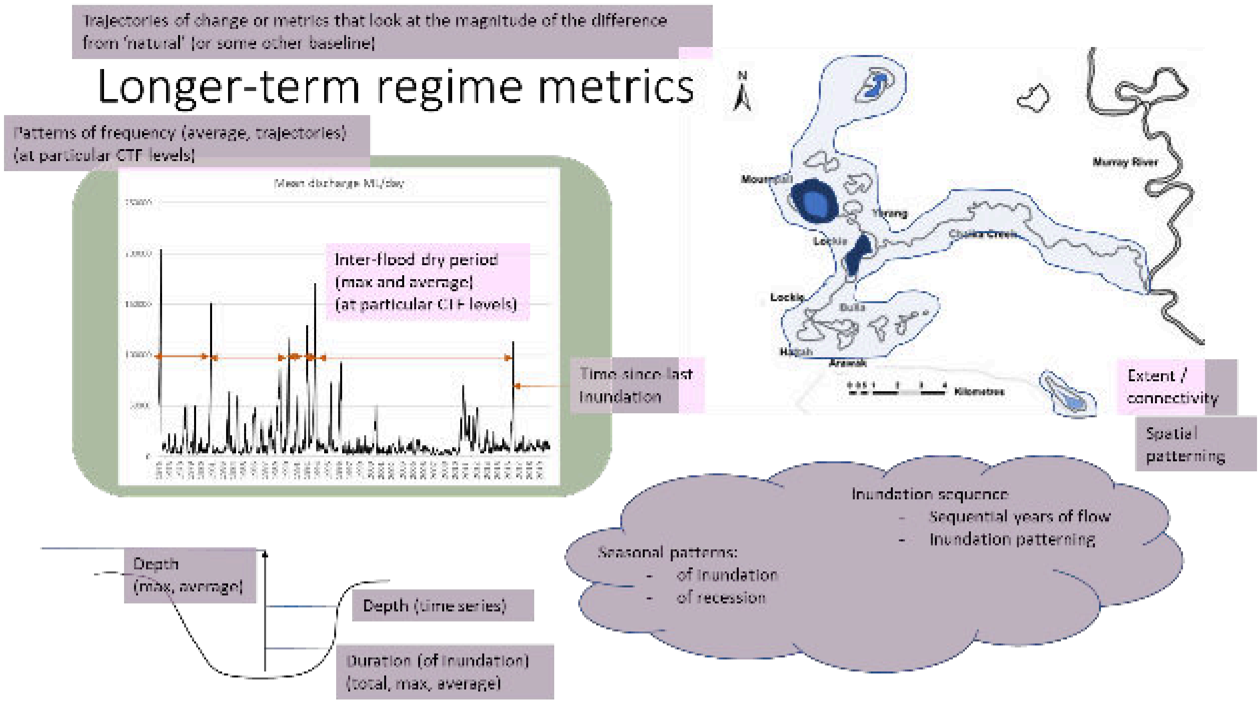


Figure 32. Conceptual representation of key hydrological metrics in relation to vegetation response to longer-term flow regimes

Table 21. Relationship between short to longer-term hydrology metrics / flow components and generalised vegetation response

| **Metric / flow component** | **Relationship with vegetation (adapted from EWKR; (Campbell, Capon *et al.* 2019)** |
|---|---|
| Depth (max and average) | Most species have limits to the depth or duration of inundation that they can tolerate and so this can act as a filter or disturbance; determinate for community distribution and condition on decadal time scales |
| Depth (time series) | Most species have limits to the depth or duration of inundation that they can tolerate and so this can act as a filter or disturbance; determinate for community distribution and condition on decadal time scales |
| Duration (of inundation) (total days, max, average) | Most species have limits to the depth or duration of inundation that they can tolerate and so this can act as a filter or disturbance; determinate for community distribution and condition on decadal time scales |
| Extent / connectivity / Spatial patterning | An important determinant in species dispersal patterns and transport of nutrients and sediment; area of influence |
| Frequency of events and patterns of frequency (at particular CTF levels) | For trees and long-lived shrubs frequency is important in meeting water requirements for persistence and recruitment opportunities; flow frequency influences seedbank and rhizome viability; determinant for community distribution and condition on decadal time scales |
| Inter-flood dry period (max and average) (at particular CTF levels) | Both prolonged inundation or prolonged drought may cause a decline in the health and persistence of trees and woody understory species and reduces seedbank and rhizome viability; determinant for community distribution and condition on decadal time scales |
| Inundation sequence (sequential years of flow, inundation patterning) | An important opportunity for forests, woodlands and shrublands to expand their distribution; will influence seed abundance and availability; influences condition and recovery trajectories |
| Seasonality | River red gum, black box and lignum have aerial seed banks, with maximum seed fall timed to coincide with the greatest chance of suitable soil moisture conditions. A shift in seasonality will affect suitable conditions for germination. |
| Seasonal patterns (of inundation) | Relevant to submerged species; Species cued to germinate and / or grow in different seasons will be influenced by seasonality in their extant distributions and abundance of propagules; determinant for community distribution and condition on decadal time scales |
| Seasonal patterns (of recession) | Relevant to amphibious species that germinate on flow recession; Species cued to germinate and / or grow in different seasons will be influenced by seasonality in their extant distributions and abundance of propagules; determinant for community distribution and condition on decadal time scales |
| Time-since-last inundation | An important determinant of vegetation condition and seedbank and rhizome viability |
| Trajectories of change or a measure of the difference from 'natural' | Assessment of the likely magnitude of the impact on above relationships |

## *Climate*

Climate interacts with flow regimes to impact native vegetation vulnerability particularly via rainfall and temperature. Rainfall includes changes to average annual volumes as well as changes to the intensity of rainfall events and changes in the interval (days) between rainfall events (where an event may need to be described as effective, i.e. 1mm of rain is not likely to be an effective event). Temperature includes changes to average minimum and maximum temperatures as well as changes to the number of 'extreme' temperature days (defined here as the number of days, particularly number of consecutive days, above 38°C). Rainfall and temperature affect surface flows, soil moisture and evapotranspiration and hence water availability for plants. Successful recruitment in both river red gum and black box trees in the Lower Murray was found to be associated with flood flows as well as average annual rainfall > 300 mm (George 2004). High intensity rainfall or hail events may also be physically disruptive to particular plants (e.g., non-woody plants and young shrub or tree seedlings) via localised ponding / flooding, scouring or physical damage. Increased number of days between rainfall events is likely to lead to greater plant water stress and potentially reduced vegetation condition. Extreme temperature events may be disruptive to physiological processes within plants, such as photosynthesis and stomatal conductance (de Dios, Loik *et al.* 2018; Loik, de Dios *et al.* 2017), though this research area is in its infancy. Additionally, extreme temperature events are likely to affect soil and surface moisture availability (via evapotranspiration) which may lead to germination 'false starts' (i.e. short-lived amphibious plants may be cued to germinate but may be unable to complete their life cycles prior to seed set which therefore has implications in terms of replenishing soil seed banks). Jensen (2008) demonstrated the effect of short-term wetting of the floodplain seed bank on species richness and survival. Short-term wetting (flooded for seven days) evoked rapid germination but all seedlings died after 49 days without additional moisture (Jensen 2008, p. 4-7). Sneezeweed (*Centipeda cunninghamii*), a common amphibious plant in river-floodplain systems, was observed to complete its life cycle in eight weeks (56 days) (Jensen 2008, p. 4-5). While acknowledging the likely differences between experimental and in-situ conditions, this highlights the potential for germination 'false starts' if adequate soil moisture (10-14%; Jensen 2008) can't be maintained beyond the initial wetting event. However, for many wetland and floodplain species in Australia, it remains a knowledge gap as to how quickly they can flower and set seed. Extreme temperature events are also likely to impact soil temperatures, particularly in areas where soil temperature is not regulated by vegetation cover, such as tree canopy cover. Low vegetation (canopy) cover may be natural (i.e. non-woody wetlands) or may reflect degraded condition (i.e. tree death or reduction in canopy density and extent). Increasing soil temperatures are likely to impact soil seed bank viability and the potential for native vegetation to respond to flow events (Dessent, Lawler *et al.* 2019; Nielsen, Jasper *et al.* 2015). Summer soil surface temperatures have been recorded as high as 50°C in Yanga National Park (J.S. Wilson, personal observation, in Baldwin, Colloff *et al.* 2013)

## *Groundwater and soil interactions*

Native vegetation, particularly long-lived vegetation such as trees, are able to access water from a range of sources, for example flooding, rainfall, sub-surface soil moisture and groundwater (Dawson and Pate 1996; Mensforth, Thorburn *et al.* 1994; Pettit and Froend 2018). The ability to utilise groundwater as a water source will depend on the salinity of the groundwater and depth to groundwater (Cunningham, Thomson *et al.* 2011; Mac Nally, Cunningham *et al.* 2011). The reliance on one or more water sources and the ability to utilise groundwater is likely to affect the vulnerability of long-lived vegetation to environmental changes such as flow alteration (Cunningham, Lindenmayer *et al.* 2014; Cunningham, Thomson *et al.* 2011). Soil conditions, such as the occurrence of sodicity and water repellence are also important considerations, where salinity percolating up from groundwater meets rainfall on grey clays, leading to loss of soil structure and repellent surfaces (A. Jensen, pers. comm. May 2021)

### *Land use*

Land use interacts with flow regimes to impact native vegetation vulnerability through a range of factors, for example, vegetation clearing, human modifications such as dams, channels and diversions, grazing pressure and other animal disturbance, and nutrient runoff and input (see Cooper, Lake *et al.* 2013; Stendera, Adrian *et al.* 2012). Vegetation clearing leads to habitat loss, fragmentation, loss of connectivity and potentially alters the type, abundance and quality of carbon and nutrient inputs to floodplain soils and in-channel productivity. Human modification such as dams, channels and diversions alter flow patterns and hydraulics and disrupt connectivity (Kingsford 2000). Grazing pressure and other animal disturbance has impacts on microhabitats for germination, plant growth and survival, and reproductive success (Jones and Vesk 2016; Nicol, Muston *et al.* 2007). Altered nutrient runoff can leads to algal blooms which has impacts on water quality and aquatic macrophyte germination, growth and survival (Anderson, Glibert *et al.* 2002; Sondergaard, Johansson *et al.* 2010).

### *Pest plants and animals*

Pest plants and animals interact with flow regimes to impact native vegetation vulnerability through a range of factors, for example, changes to water quality (Vilizzi, Thwaites *et al.* 2014), physical disturbance to individual plants (e.g. grazing, trampling, uprooting individuals) (Jones and Vesk 2016; Vilizzi, Thwaites *et al.* 2014) or seed banks (Nicol, Muston *et al.* 2007), modification of habitats (e.g. pugging, wallowing) (Felix, Orzell *et al.* 2014), and competition for resources and altered vegetation structure (e.g. invasion of non-woody wetlands by trees or shrubs, altering the availability of, and competition for, resources such as light, space and water) potentially leading to the displacement of native vegetation (Catford and Kyle 2016). Pest animal effects can occur within inundated habitats (e.g. effects of carp) (Vilizzi, Thwaites *et al.* 2014), at the wet-dry ecotone (e.g. at the edge of wetlands or rivers such as cattle pugging and pig wallowing) (Felix, Orzell *et al.* 2014) or when habitats are dry (e.g. sheep grazing and trampling) (Nicol, Muston *et al.* 2007) with pest plant invasions able to occur across all hydrological phases (Catford and Kyle 2016). Pest plants and animals can include introduced exotic species as well as the effects of native species which have become out of balance.

### ***Sensitivity to environmental change***

Sensitivity to environmental change will vary depending on the type of vegetation or individual species requirements. Sensitivity describes intrinsic attributes that are recognized to moderate and/or exacerbate the impact of external drivers and pressure (i.e. exposure to environmental change as described above) (Foden, Young et al. 2019). Sensitivity to environmental change may include attributes such as environmental tolerances, thresholds or triggers that are affected by the environmental change (e.g. flow alteration), rarity (e.g. conservation status), life history stages sensitive to the environmental change, and interactions with pressures and drivers from exposure to multiple environmental changes (Foden, Young et al. 2019). Sensitivity may also include attributes relating to mosaics of vegetation communities. For example, patch size, the heterogeneity of vegetation communities within a region, neighbouring communities, or land use. For example, non-woody wetland types such as grassy meadows may be more susceptible to woody encroachment depending on the type of neighbouring communities. Specific indicators of condition and stress and thresholds of vulnerability for functional groups used in this study are presented in Table 27.

### *Cumulative exposure and multiple interactions*

It is worth noting the likely impact of cumulative long-term exposure to stressors, such as legacy and lag effects (Thompson, King *et al.* 2018) as well as the potential effect of multiple interacting stressors (Dudgeon 2019; Lester, McGinness *et al.* 2020; Mac Nally, Cunningham *et al.* 2011). Assessment of vulnerability ideally needs to consider on-going exposure, the number of different stressors vegetation plants or communities are exposed too, as well as the way multiple stressors may interact.

### ***Adaptive capacity to environmental change***

Following the definition used by the Intergovernmental Panel on Climate Change, 2007 in Foden, Young *et al.* (2019), adaptive capacity has been defined here as 'the potential, capability, or ability of native vegetation to adjust to environmental change, to moderate potential damage, to take advantage of opportunities, or to respond to the consequences. For native vegetation this is considered here primarily in terms of ***Resistance*** – the ability to resist change or stress – and ***Resilience*** – the recovery potential following change.

Different types of vegetation functional groups will have different resistance and resilience capacity. This is an important concept underlying state-and-condition-models developed for these species (Bond, Grigg *et al.* 2018; Overton, Pollino *et al.* 2014). Recovery pathways modelled for these species (Bond, Grigg *et al.* 2018; Overton, Pollino *et al.* 2014) indicate that it may take considerable time and commitment to frequent watering to restore the condition of these species.

### *Forests and woodlands*

Long-lived woody vegetation such as RRG, BB and Coolibah has relatively high resistance to wetting and drying – with the ability to tolerate flow variability for (varying) periods of time. However, as condition is lost, and physiological damage occurs within the trees the ability to recover – the resilience – of these species is low. It takes time to rebuild physiological damage and a commitment to frequent watering to restore condition (Overton, Pollino *et al.* 2014). The loss of tree condition affects processes such as reproduction. For example, stressed RRG and BB reduce phenological cycles from annual seed fall to biennial seed fall (i.e. only once every two years) and seed volumes reduce by an order of magnitude under severe water stress (A. Jensen pers. comm., May 2021). It is also worth noting the length of time required for trees to reach maturity (i.e. seed production), which is 10-20 years for RRG and 20-30 years for BB (A. Jensen pers. comm., May 2021). Flow regimes need to be sufficient to support tree survival from germination to maturity and seed production.

### *Shrublands*

Lignum swamps and shrublands have a degree of resistance to wetting and drying regimes, with comparatively high resistance to drought (up to 17 – 20 years) but comparatively low resistance to prolonged inundation (Campbell, Freestone *et al.* 2021). Lignum plants also have high resilience with the ability to respond to favourable conditions with rapid new growth and the ability to regenerate from rootstock, layering, fragmentation, and seed (Roberts and Marston 2011). There are limits, however, to their ability to recover. For example, lignum rootstock can survive for a few years with no alive, above-ground biomass. However, the likelihood of regeneration from lignum rootstock is greatly reduced after 3 – 4 years with no alive, above-ground biomass (Freestone, Brown *et al.* 2017). It is likely condition also affects phenological cycles of lignum with flooding required for both vegetative and sexual reproduction. For example, four inundation events within a seven-year timeframe were required before mass germination of lignum seedlings were observed (S. Healy, NSW pers. comm., Nov 2020).

## *Non-woody vegetation*

There are two main strategies that non-woody plant species utilise to cope with variable wetting and drying and that is i) regeneration from below-ground structures such as rhizomes, rootstock, stolons, tubers or ii) germination from dormant seed banks.

Regeneration from below-ground structures – this strategy provides short-term resistance to wetting and drying (i.e. the ability to survive for a few years in dry soil and to survive inundation) and high resilience while the condition of below-ground structures is maintained (e.g. the ability to respond with rapid growth from resources stored in rhizomes). The ability to respond, however, is lost as soon as the below-ground structure dies. For the species to grow again in that location/situation requires a soil-stored seedbank or dispersal of seed (only relevant for species which produce seed) or other viable propagules (e.g. a viable rhizome fragment). This needs to coincide with favourable conditions in the establishment site and relies on the availability of seed / propagules within dispersal distance, a suitable dispersal vector (e.g. flowing water, wind or animals – though this will be species specific) and suitable connectivity between the source and establishment sites. Regeneration from seed / new propagules will be slower and less vigorous (see Roberts and Marston 2011). Regeneration from seed is also likely to be more vulnerable to disturbance, for example, from carp, waterbirds or wave action (e.g. small, developing roots with less secure anchorage compared with well established, healthy rhizomes). Germination from seed may also require stricter germination cues (e.g. temperature, light, season) than regeneration from below-ground structures, though this hypothesis is untested.

Regeneration from seed banks – this strategy provides little to no resistance to wetting and drying regimes (i.e. plants die when inundated and / or are typically short-lived and highly dependent on soil moisture). It does, however, provide comparatively high resilience (i.e. plant species survive as dormant seed banks until favourable conditions return). Different species have varying threshold limits in terms of seed bank viability (Brock 2011), and it is critical to ensure species are able to complete life cycles and set seed in order to replenish the seed bank. The seed bank viability of the majority of wetland and floodplain plants in Australia is unknown (but see Brock 2011 for species which are known). Once seed banks are lost or no longer viable, populations can only establish from new dispersal events, with all the limitations to dispersal as described above.

## *Vegetation functional groups for vulnerability assessment and prioritisation*

In line with the expected outcomes of the BWS for vegetation and ANAE types mapped across the Basin the following vegetation types will be considered. For the purposes of this report, they will be referred to as vegetation functional units.

Vegetation functional units to be considered:

- Forests and woodlands
  - *Eucalyptus camaldulensis,* River Red Gum
    - Swamp (RRG-S)
    - Forest (RRG-F)
    - Woodland (RRG-W)
  - *Eucalyptus largiflorens,* Black Box
    - Swamp (BB-S)
    - Forest (BB-F)
    - Woodland (BB-W)
  - *Eucalyptus coolabah,* Coolibah
    - Swamp (C-S)
    - Woodland (C-W)
- Shrublands
  - *Duma florulenta,* Tangled Lignum
    - Swamp (L-Sw)
    - Shrubland (L-Sh)
- Non-woody vegetation (NWV)
  - Submerged vegetation
  - Sedges / rushes
  - Grassy meadows
  - Tall reeds
  - Herbfields

## *Forests and woodlands*

Forests, woodlands and woody swamps are characterised by the presence of a woody (tree) overstory over an herbaceous or shrubby understory. Typically, the water requirements for these ecosystem types, within the defining woody species (e.g. RRG, BB or Coolibah), will be greatest (e.g. more frequent, longer duration) for swamps, to forests, and driest for woodlands. The dominant / defining woody species have water requirements associated with adult growth and survival, reproduction, germination, establishment and seedling survival through to reproductive maturity. Water requirements will vary between life history stages and will vary between flows to maintain vigorous growth and flows to recover vegetation from a degraded state (Bond, Grigg *et al.* 2018; Overton, Pollino *et al.* 2014). Ideally consideration should also be given to the water requirements of understory species. River red gum, black box and coolabah trees all have aerial seed banks and don't form persistent soil seed banks (Roberts and Marston 2011). Seed fall needs to be timed with suitable soil moisture conditions for germination to occur (A. Jensen, pers. comm. 2021).

### *Shrublands*

Shrublands and shrub-dominated swamps are characterised by the presence of large shrubs, with no or limited presence of trees. For the purposes of this vulnerability assessment this is restricted to lignum shrublands and swamps. Swamps are likely to have a greater requirement for water (e.g. more frequent, potentially longer duration) than shrublands. As for forests and woodlands, water requirements will vary between life history stages and will vary between flows to maintain vigorous growth and flows to recover vegetation from a degraded state (Bond, Grigg *et al.* 2018; Campbell, Freestone *et al.* 2021; Overton, Pollino *et al.* 2014). As for forests and woodlands, lignum also doesn't appear to form a soil seed bank (Roberts and Marston 2011) and seed fall needs to be timed with suitable soil moisture conditions for germination to occur (A. Jensen, pers. comm. 2021).

### *Non-woody vegetation*

Non-woody ecosystems are vegetation assemblages with no or limited presence of trees and large shrubs. Non-woody vegetation comprises floating plants, submerged macrophytes, herbs, grasses, sedges, sub-shrubs and tall reeds. Non-woody vegetation can form communities which are species diverse, such as lakebed herbfields, or communities which are monospecific, such as stands of *Phragmites australis* or species of *Typha*. For the purposes of this vulnerability assessment, we recognise five functional units of non-woody vegetation.

### *Submerged vegetation*

Vegetation assemblages that grow submerged in the water column or floating on the water surface. Submerged vegetation requires the presence of water to survive, though species can withstand dry periods as rootstock (e.g. rhizomes, stolons, tubers etc) and / or as dormant seed in soil seed banks.

### *Sedges / rushes*

Vegetation assemblages dominated by sedge or rush growth forms. These communities require regular inundation to support vegetative growth and survival and/or reproduction from seed.

### *Grassy meadows*

Vegetation assemblages dominated by aquatic / semi-aquatic grasses that require regular inundation to support vegetative growth and survival and / or reproduction from seed.

### *Tall reeds*

Vegetation assemblages dominated by tall reeds such as *Phragmites australis* or species of Typha. Tall reed beds can persist in near permanent inundation or can survive inter-flood dry periods as rootstock (e.g. rhizomes, stolons, tubers etc) and / or as dormant seed in soil seed banks.

### *Herbfields*

Vegetation assemblages dominated by forbs (herbs) that typically germinate on mud or damp soil following the recession of water. Species are dependent on soil moisture and can be relatively short-lived. Species survive inter-flood dry periods as dormant seed in soil seed banks.

### *Alignment with Australian National Aquatic Ecosystem (ANAE) types*

There are 67 ANAE types mapped across the Basin with a high proportion of these occurring on the managed floodplain (Brooks 2021). As ANAE polygons and types are the basis for mapping the condition and stress thresholds (see also Table 27), we attempted to align ANAE types to the vegetation functional units described above. There are 24 ANAE types that align with the vegetation functional units used in this vulnerability trial. There is considerable uncertainty in the alignment of non-woody vegetation functional units to ANAE types. This relates particularly to the alignment of submerged vegetation with permanent lakes or wetlands which may or may not support submerged vegetation, as well as the ability to differentiate between ANAE types supporting sedges and rushes or herbfields. There is also the additional consideration that a particular ANAE type may support submerged vegetation when inundated and herbfield vegetation on flow recession.

While the ANAE mapping layer distinguishes between swamps, forests and woodlands (or some combination thereof) for RRG, BB and Coolibah and swamps and shrublands for lignum the distinction in ecological water requirements in the literature is less refined. Therefore condition and stress metrics have only been developed for RRG swamps and forest, RRG woodlands, BB, Coolibah and lignum (see also Table 27).

The alignment of ANAE types to vegetation functional units warrants further exploration. The alignment used in this assessment is given in Table 22.

Table 22 Proposed alignment of ANAE types with vegetation functional units to be used in the vulnerability assessment

| Vulnerability functional unit | Australian National Aquatic Ecosystem (ANAE) wetland type |
|---|---|
| Forests and woodlands | |
| River red gum swamps and forest | Pt1.1.2: Temporary river red gum swamp |
| | F1.2: River red gum forest riparian zone or floodplain |
| River red gum woodland | F1.4: River red gum woodland riparian zone or floodplain |
| Black box | Pt1.2.2: Temporary black box swamp |
| | F1.6: Black box forest riparian zone or floodplain |
| | F1.8: Black box woodland riparian zone or floodplain |
| Coolibah | Pt1.3.2: Temporary coolibah swamp |
| | F1.10: Coolibah woodland and forest riparian zone or floodplain |
| Shrublands | |
| Lignum | Pt1.7.2: Temporary lignum swamp |
| | F2.2: Lignum shrubland riparian zone or floodplain |
| Non-woody vegetation | |
| Submerged vegetation or lake | Lp1.1: Permanent lake |
| | Lp1.2: Permanent lake with aquatic bed |
| | Pp4.2: Permanent wetland |
| | Lt1.2: Temporary lake with aquatic bed |
| Grassy meadows | Pp2.2.2: Permanent sedge/grass/forb marsh |
| | Pt2.2.2: Temporary sedge/grass/forb marsh |
| | Pt2.3.2: Freshwater meadow |
| | F3.2: Sedge/forb/grassland riparian zone or floodplain |
| | Pp2.3.2: Permanent grass marsh |
| Tall reed beds | Pp2.1.2: Permanent tall emergent marsh |
| | Pt2.1.2: Temporary tall emergent marsh |
| Herbfield | Pp2.4.2: Permanent forb marsh |
| | Pt4.2: Temporary wetland |
| | Lt1.1: Temporary lake |

# Identifying indicators and thresholds for assessment

## *Thresholds of vulnerability*

The framework for assessing vulnerability is based on a scoring system with inputs to this system based on three levels of stress / condition:

- Condition:
    - Better
    - Medium
    - Worse
- Stress:
    - Low
    - Medium
    - High

For levels of condition, we have chosen a ranked system (from better to worse) rather than define absolute condition states (e.g. good or poor). This highlights that the vulnerability assessment is ranking the likely vulnerability of areas rather than providing a description of the areas condition. For each identified indicator, thresholds of condition and stress have been defined. In addition, confidence levels (associated with both the strength of our ecological knowledge and the available data) have been assigned (Table 23).

Table 23: Confidence levels for thresholds of condition and stress (modified from Overton et al. 2018).

| Confidence Level | Confidence score | Data |
|---|---|---|
| **Low** | 1 | Thresholds based on anecdotal or localised level of unpublished information or conceptual understanding. Published information not (or very rarely available). Provides a rough estimate of thresholds (a best guesstimate). |
| **Low/ Moderate** | 2 | Thresholds based on a low level of ecological knowledge and understanding from a limited number of sources. |
| **Moderate** | 3 | Thresholds based on a moderate level of ecological knowledge and understanding. |
| **Moderate /High** | 4 | Thresholds based on established ecological knowledge and understanding, though studies may be limited in scale (i.e. knowledge from limited geographical regions). |
| **High** | 5 | Thresholds based on well-established ecological knowledge and understanding, with supporting data from multiple spatial and temporal scales. |

## *Indicators of vegetation 'condition'*

Potential indicators of condition and stress have been identified based on our conceptual understanding of the ecology of inundation dependent native vegetation across the Basin. The BWS prioritisation process will be applied across the Basin and as a consequence, data sources that could be used to measure condition and stress have been identified from the available Basin-scale spatial information catalogue. This framework is designed to be flexible however and be able to accommodate new sources of information as they become available. There are therefore several indicators for which there is no current data source available, but which could be accommodated were these to become available into the future.

Vegetation condition needs to consider where the plants, communities and mosaics of communities exist, that is their ***extent, distribution and spatial arrangement***. Condition also needs to consider the ***eco-physiological processes*** occurring within plants, communities and mosaics of communities that directly affect life-history stages such as germination, growth and survival and reproduction, and which impact on ecosystem services such as microclimate regulation (e.g. via tree canopy cover), erosion control or water quality. The ***structure*** and ***composition*** of plants, communities and mosaics of communities is also important in terms of the biodiversity values of vegetation and the provision of functions such as habitat and food resources.

We have also referred to the BWS outcomes when considering indicators of condition. Key aspects of the BWS outcomes for vegetation focus on the ***extent*** of functional groups (i.e. forests, woodlands, shrublands and non-woody wetland vegetation), the ***condition*** of functional groups (i.e. forests, woodlands and shrublands) as well as ***increased periods of growth*** (i.e. non-woody wetland vegetation) which can be represented at a basin-scale as patterns of inundation and vegetation response in terms of 'greenness'.

Indicators of vegetation condition may include:

- ***Extent, distribution and spatial arrangement***
  - where species / communities are in space and time

    - This is comparatively straightforward for descriptions of community types (i.e. ANAE types), it is much harder in terms of species assemblages or individual species within those community types, particularly for short-lived, non-woody vegetation
  - attributes relating to spatial arrangement
    - for example, heterogeneity of community types within a region, neighbouring community types, area of and connectivity between community types, representativeness of community types
- ***Eco-physiological processes*** / responses of vegetation, such as:
  - water use
    - as estimated from evapotranspiration models. Dr Tanya Doody from CSIRO is currently developing a Basin-scale model for RRG and BB
  - photosynthetic output
    - as determined by 'greenness'. Greenness needs to be interpreted with good underlying knowledge of the ecology of the species / communities in question as there can be natural cycles of greening and browning (e.g. seasonal)
  - reproduction or regeneration rates
    - for example, abundance of flowers, seeds, viability of seeds and seedbanks, germination rates, vegetative expansion rates
  - growth / biomass accumulation rates
- ***Structural*** responses of vegetation, such as:
  - extent and density of tree crowns
  - structure of lignum clumps (i.e. height, width, and length of clumps and gaps between clumps)
  - age class structure of forests and woodlands
  - live basal area of forest, woodlands and shrublands
  - density of individual species or plants within a community
  - cover of leaves (e.g. leaf area index), species or vegetation strata (e.g. plant area index) or communities
  - height of plants or vegetation strata
  - structural complexity of communities
  - structural arrangement of community types
- ***Compositional*** responses of vegetation, such as:
  - species composition and richness
  - seed bank composition and richness
  - composition of functional groups and other attributes (e.g. nativeness, rare species)
  - composition of communities within landscape mosaics

This list of potential indicators of vegetation condition is non-exhaustive but highlights the need to consider, where feasible and where data is available, multiple attributes and multiple scales (Campbell, James *et al.* 2021).

Measures of condition to be used as part of this project are included in Table 25. Measures of condition such as tree stand condition incorporate multiple metrics such as plant area index, crown extent and live basal area.

As the composition and structure of vegetation varies in relation to natural wetting and drying cycles, and as this project is being undertaken at a Basin-scale, the 'cover of vegetation' as a measure of condition will involve the interpretation of eight individual, remotely-sensed metrics (Table 25). We initially conceptualised the relative proportion of time different vegetation functional groups spend in different hydrological phases (Table 24) and the expected vegetation response (in terms of brown, green or wet vegetation) associated with the different hydrological phases. Four hydrological phases can be identified for wetland and floodplain vegetation, e.g. filling, inundation / water retention, drawdown/ drying and dry (Table 24). The different hydrological phases can then be associated with expected responses of WIT metrics such as bare soil, open water, "dry/brown vegetation", "green vegetation" and "wet vegetation". This in theory enables trajectories to be identified which would indicate a departure from the expected patterns of natural variability, i.e. trajectories of vulnerability. For almost all vegetation functional units (except submerged vegetation) the expected trajectory of vulnerability would be a decrease in wet and green vegetation and an increase in brown vegetation or bare soil. Changes in wet and green vegetation need to be interpreted together as a decrease in wet vegetation may lead to an increase in green vegetation prior to any subsequent increase in brown vegetation. For submerged vegetation or other ANAE types which support areas of open water the expected trajectory of vulnerability would be a decrease in water and wet vegetation and an increase in green or brown vegetation or bare ground.

Table 24: Hypothetical relative proportion of time different vegetation functional units spend in different hydrological phases (adapted from Campbell 2021)

| **Vegetation/habitat type** | Relative proportion of time in hydrological phase (conceptualised across multiple years and filling events | | | |
|---|---|---|---|---|
| Submerged vegetation | Water | WET | Green | BS |
| Sedges / rushes | Water | WET/green vegetation | Green vegetation | Green to brown |
| Grassy meadow | Water | WET/green vegetation | Green vegetation | Green to brown |
| Tall reeds | Water | WET/green vegetation | Green | Green to brown |
| Herbfields | Water | WET/green vegetation | Green vegetation | Green to brown vegetation |
| Lignum swamps and shrublands | Water/WET | WET/green | Green veg | Green to brown vegetation |
| RRG forest | Water/WET | WET/green veg | Green vegetation | Green to brown vegetation |
| RRG woodland | Water/WET | WET/green | Green vegetation | Green to brown vegetation |
| BB woodland | Water | WET | Green | Green to brown vegetation |
| Coolibah woodland | Water | WET | Green | Green to brown vegetation |

Key (from left to right): purple = filling, blue = inundation / water retention phase, green i= drawdown / drying, brown = inter-flood dry periods

Additional measures of condition should be incorporated in the future as additional data becomes available.

Table 25: Indicators of condition and relevant data sources to be included in the vulnerability assessment for inundation dependent vegetation.

| Measure of condition | Justification | Potential data sources | Relevant functional groups | Analytical approach |
|---|---|---|---|---|
| **Tree stand condition** | Provides an indication of the condition of three tree species based on annual assessments across the Basin from the Landsat Record combined with three field indicators: plant Area Index, Crown Extent, Live Basal Area (MDBA 2020) | MDBA Tree stand condition tool (MDBA 2020); outputs calculated for each ANAE polygon | River red gum<br>Black box<br>Coolibah | Deviation from baseline |
| **Photosynthetic output – 'greenness'** | Provides an indication of the photosynthetic output, or condition, of vegetation, with the assumption green vegetation is healthier than brown. | NDVI; outputs calculated for each ANAE polygon | All | Deviation from baseline |
| **Cover of vegetation** | Provides an indication of the cover of water, vegetation (brown, green and wet) and bare soil from which to interpret condition for different vegetation functional units (see also Table 24) | WIT time series metrics from GA; outputs calculated for each ANAE polygon<br>NPV "Dry/brown vegetation"<br>PV "green vegetation"<br>WET "wet vegetation" | All | Deviation from baseline |

### *Methods for calculating condition metrics*

The final three condition metrics are listed in Table 25.

For all condition metrics used in the final method, the approach is to assess the deviation from a baseline value that is specific to every ANAE polygon. The baseline was calculated using the available 36 years of landsat data (mid 1986 to April 2022), excluding the millennium drought (2001 through to 2009; so baseline based on ~27 years of data). Excluding the millennium drought prevents the baseline from being skewed to a lower value and also enables a period of validation.

Condition for each indicator for each year is represented by the average deviation from the baseline in the preceding five years adjusted by the trend (slope of the line) over the last two years.

Condition = (5-year average deviation) + (2-year trend).

This incorporates an average rolling condition as well as an indication of the trajectory of the condition or stress metrics – for example is the specific ANAE polygon in worse condition but on a trajectory of improving condition, stable or continued decline; or is the ANAE polygon in better condition and continuing to improve, stable, or on a trajectory of decline.

Condition, for each metric, is scored on a scale of 1-3:

- Better (score of 3)
    - measure of 5-year central tendency is above the 27-year baseline
    - sum of deviation from central tendency (5-years) and the slope of the two-year trend > 0
- Moderate (score of 2)
    - measure of 5-year central tendency is within one unit of variability (standard deviation) of the 27-year baseline
    - sum of deviation from central tendency (5-years) and the slope of the two-year trend is between 0 and -1
- Worse (score 1)
    - measure of 5-year central tendency is greater than one unit of variability below the 27-year baseline
    - sum of deviation from central tendency (5-years) and the slope of the two-year trend is < -1.

Scores for each individual metric are then summed (with three metrics giving a range of 3-9), and this range is then normalised (rescaled) to 0 to 1 where 0 is the worst possible score and 1 is the best possible score.

Creating a baseline for every individual ANAE polygon provides a very powerful and location specific means of assessing the trajectory away from a location-specific ‘norm’. In theory this should take into account some location-specific factors (such as saline groundwater, historic frequency and duration of inundation) which are known to affect the applicability of general water regime thresholds (for example Roberts and Marston 2011; Rogers and Ralph 2011). It also helps to accommodate the variability observed in relation to certain species and thresholds such as black box and critical duration dry intervals (see for example Overton, Coff *et al.* 2018; Overton and Doody 2008 and Section 4.4.3 in this document). While we believe this approach is very powerful we acknowledge that the calculation of the baseline is limited to the availability of landsat data (both in terms of years of available data and images not obscured by cloud). We acknowledge that there have been impacts of regulation and other stressors for decades prior to the availability of landsat data in 1987. This is likely to mean that the baseline (at least in certain locations across the MDB if not all) represents an already stressed condition. For these reasons the calculation has been referred to as a baseline (rather than a benchmark) and condition categories have been labelled ‘better, medium, worse’ (rather than ‘good or poor’). Research to support this vulnerability approach could try to determine to what extent the baseline calculated from landsat data (1987 to 2022) represents a modelled baseline from a longer time period or modelled natural.

The deviation from baseline approach was applied to all three condition metrics, however metric specific considerations are noted below.

### *Tree stand condition*

Annual tree stand condition (TSC) data covers a 16 month period from September to January therefore the available landsat data runs from September 1987 to January 2022.

As floodplain trees are long-lived and the current condition of trees is influenced by antecedent conditions, we believe the applied approach is a logical way of representing the ecologically important concepts of multiple years of condition (represented here as a five-year rolling average), judged against a longer-term ‘norm’ (e.g. either above the baseline, within the ‘natural variability’ of 1 standard deviation below, or greater than 1 standard deviation below the baseline) as well as the trajectory of any recent change in condition (represented here as the slope of the two-year trend). The trajectory of recent changes indicates whether trees are declining in condition, remaining stable, or increasing in condition while the five-year assessment against the baseline indicates the likely condition state the recent trajectory is coming from. As the approach is specific to individual ANAE types (and therefore functional groups such as river red gum) with baseline values calculated for individual ANAE polygons this avoids the issue of different species being assessed in different condition categories simply because they have less green or dense canopy (for example river red gum compared to coolibah).

### *Photosynthetic output – ‘greenness’*

Photosynthetic output, or ‘greenness’ was represented using NDVI data.

We acknowledge that photosynthetic output does not distinguish between native or exotic species and there will be no way of knowing whether the greenness response is from native or exotic plant species. We reiterate that this vulnerability assessment is one tool to be used in the prioritisation of locations for environmental watering actions. The on-ground knowledge of regional water managers will be invaluable in terms of confirming or filtering out locations identified as vulnerable based on-site knowledge and other factors affecting prioritisation (such as stakeholder values, logistical constraints).

### *Cover of vegetation (WIT time series metrics)*

The WIT metrics used to represent cover of vegetation included non-photosynthetic vegetation (brown or dry vegetation; npv), photosynthetic vegetation (green vegetation; pv), and vegetation/water (wet vegetation; wet_median).

WIT total vegetation cover = npv + pv + wet_median

As for photosynthetic output we acknowledge that the cover of vegetation based on WIT time series metrics does not distinguish between native or exotic species. Please refer to the caveats under photosynthetic output.

## *Indicators of vegetation stress*

Key sources of stress have been identified in Figure 28 and can be broadly grouped as changes to: i) flow regimes, ii) climate, iii) groundwater and soil interactions, iv) land use, and v) pest plant and animal impacts. Measures of stress to be used in this project are given in Table 26 and focus on flow regimes (extent of inundation and time-since-last-inundation) and root-zone soil moisture (which incorporates rainfall, evapotranspiration, runoff and deep drainage). For a conceptual understanding of the impact of the measures of stress on native vegetation please refer to page 66 (see Figure 30 to Figure 32, Table 20 and Table 21).

Additional measures of stress should be incorporated in the future as additional data becomes available.

Table 26: Indicators of stress and relevant data sources to be included in the vulnerability assessment for inundation dependent vegetation

| Measure of stress | Justification | Potential data sources | Relevant functional groups | Analytical approach |
|---|---|---|---|---|
| **Time-since-last inundation – extant plants** | An important determinant of the condition of extant vegetation | GA WIT metrics (WET + Water); calculated for each ANAE polygon | All | Defined ecological thresholds |
| **Extent of inundation** | An important determinant in species dispersal patterns and transport of nutrients and sediment; spatial patterning and area of influence | GA WIT metrics (WET + Water); calculated for each ANAE polygon | All | Deviation from baseline |
| **Root-zone soil moisture** | An important determinant of the likely water stress experienced by extant vegetation | BOM root-zone soil moisture data for Australia for the upper soil profile | All | Deviation from baseline |

## *Methods for calculating stress metrics*

The methods to calculate stress metrics largely follow the methods for condition metrics (page 84) and can be grouped as defined ecological thresholds or deviation from baseline (see also Table 26).

*Extent of inundation*

Stress from the extent of inundation (or lack of), using the GA WIT metric (WET + water), was calculated and scored using the deviation from baseline method as described on page 84 and 86. This provides a stress score based on the deviation and trend away from the long-term baseline extent of inundation for every individual ANAE polygon.

*Root-zone soil moisture*

Root-zone soil moisture data was extrapolated for each ANAE polygon and stress was calculated and scored using the deviation from baseline method as described in page 84 and 86. This provides a stress score based on the deviation and trend away from the long-term baseline soil moisture for every individual ANAE polygon.

*Time-since-last-inundation*

Stress related to time-since-last-inundation differs to the other two stress metrics in being based on defined ecological thresholds. Based on existing literature, thresholds of time-since-last-inundation were developed for each vegetation functional unit, for each of the three stress categories (low, medium, high). Specific thresholds are provided in Table 27 below.

## *Final indicators and thresholds for vegetation functional groups*

Table 27 Summary of final condition indicators and thresholds for vegetation functional units

| Indicator | Functional group | Low stress | Medium stress | High stress |
|---|---|---|---|---|
| **Tree stand condition** | River red gum<br>Black box<br>Coolibah | At or above the baseline + trend slope >0<br>5-year average + 2-year trend | Within 1 SD of the baseline + trend slope between 0 and -1<br>5-year average + 2-year trend | More than 1 SD below the baseline and trend slope <-1<br>5-year average + 2-year trend |
| **Photosynthetic output – 'greenness'** | All | At or above the baseline + trend slope >0<br>5-year average + 2-year trend | Within 1 SD of the baseline + trend slope between 0 and -1<br>5-year average + 2-year trend | More than 1 SD below the baseline and trend slope <-1<br>5-year average + 2-year trend |
| **Cover of vegetation** | All | At or above the baseline + trend slope >0<br>5-year average + 2-year trend | Within 1 SD of the baseline + trend slope between 0 and -1<br>5-year average + 2-year trend | More than 1 SD below the baseline and trend slope <-1<br>5-year average + 2-year trend |

Table 28 Summary of final stress indicators and thresholds for vegetation functional units

| Indicator | Functional group | Low stress | Medium stress | High stress |
|---|---|---|---|---|
| **Extent of inundation** | All | At or above the baseline + trend slope >0<br>5-year average + 2-year trend | Within 1 SD of the baseline + trend slope between 0 and -1<br>5-year average + 2-year trend | More than 1 SD below the baseline and trend slope <-1<br>5-year average + 2-year trend |
| **Time since last inundation** | RRG swamps and forests | 1-2 years | 3-4 years | ≥ 5 years |
| | RRG woodland | 1-2 years | 3-4 years | ≥ 5 years |
| | Black box | 3 – 4 years | 5 – 6 years | ≥ 7 years |
| | Coolibah | 10 years | 20 years | > 20 years |
| | Lignum | 3 years | 4 years | ≥ 5 years |
| | Submerged | < 3 months | 3 – 4 months | > 4 months |
| | Grassy meadows | < 8 months | 8 – 10 months | > 10 months |
| | Tall reed beds | < 1 year | 1 – 2 years | > 2 years |
| | Herbfields | 1 year | 2 – 4 years | > 4 years |
| **Root-zone soil moisture** | All | At or above the baseline + trend slope >0<br>5-year average + 2-year trend | Within 1 SD of the baseline + trend slope between 0 and -1<br>5-year average + 2-year trend | More than 1 SD below the baseline and trend slope <-1<br>5-year average + 2-year trend |

Because the final approach for all three condition metrics and two of the three stress metrics involves calculating a baseline specific to individual ANAE polygons the only ecological threshold values that differ between metrics are for time-since-last-inundation (Table 28).

Further details of indicators of condition and thresholds of stress specific to individual functional units, including preliminary exploration of other metrics, can be found in Appendix 1.

## Assumptions, limitations and recommendations

The following dot points should be considered when applying or reviewing the framework

- Baseline data is based on available landsat data from mid-1986. This may represent an already stressed state for some locations / vegetation functional groups. See also page 84 and 86.
- A deviation from baseline approach assumes the baseline is adequate to meet ecological requirements, with the assumption being the vegetation functional group would not occur there if the ecological requirements were not meet at some stage.

- There is no ability to distinguish native and exotic species using only basin-scale data such as photosynthetic output and WIT metrics. Incorporating site knowledge and / or on-ground data will be an important part of the overall prioritisation process.
- The vegetation vulnerability assessment has been undertaken on individual ANAE type polygons. This assumes the spatial accuracy of mapped ANAE polygons adequately represents the type and area of vegetation on the ground. The ANAE spatial layer has been periodically updated based on improved mapping inputs and on-ground verification and this process should continue.
- Inundation metrics and vegetation cover assessments have been undertaken using WIT metrics. We assume the number of available images and calculations used to distinguish metrics such as water, wet vegetation, green vegetation, brown vegetation, bare ground etc adequately reflect on-ground conditions. Ongoing field validation of WIT metrics to improve the accuracy of the tool are encouraged.
- To date, stress metrics such as time-since-last-inundation have been considered only in relation to the growth and survival of adult trees and shrubs (for long-lived trees and lignum) or extant plants (for non-woody vegetation). Where possible, future revisions should consider metrics relevant to the longevity of viable rhizomes and seed banks (for non-woody vegetation), seed production, germination, establishment and recruitment.
- This framework conceptually identified a wide range of potential condition and stress metrics but was limited in the ability to source data and/or apply many of these identified metrics. The ability to include additional condition and stress metrics should be periodically reviewed.
- Where possible the outcomes from this vulnerability assessment should be validated using on-ground data and/or the knowledge of local water managers.

# Appendix 1 Preliminary indicators and thresholds for vegetation functional units

Indicators of condition and thresholds of stress have been identified for each vegetation functional group to be used as part of this assessment. We recognise that the thresholds for condition and stress are likely to vary for different life-history stages (e.g. reproduction, germination, seedling establishment), particularly for long-lived vegetation such as RRG, BB, Coolibah and Lignum. **For the purposes of testing the vulnerability approach, thresholds for condition and stress are provided just for adult growth and survival.** Information in these tables is derived with reference to flow regime requirements given in Casanova (2015); Roberts and Marston (2011); Rogers and Ralph (2011) and other references as indicated.

### *River red gum swamps and forests*

Thresholds for condition and stress for RRG swamps and forests are currently combined. Information on the water requirements for RRG have been identified for forests and woodlands but have not been articulated for swamps. Further investigation / research is required to determine if there are different condition or stress thresholds identifiable for RRG swamps.

Table 29: Preliminary thresholds for condition for River red gum swamps and forests

| Measure of condition | Better | Medium | Worse | Confidence |
|---|---|---|---|---|
| **Extent and distribution (total area on the managed floodplain)** | >80% of RRG swamp and forest ANAE types (total area on the managed floodplain) have low vulnerability | 79 – 40% of RRG swamp and forest ANAE types have low vulnerability | < 40% of RRG swamp and forest ANAE types have low vulnerability | Low/moderate |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Tree stand condition** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Average recommended frequency of inundation for river red gum forest is once every 1 to 3 years (Roberts and Marston 2011; Rogers and Ralph 2011) for 5 to 7 (Roberts and Marston 2011) or 2 to 8 months (Rogers and Ralph 2011). Maximum inter-flood dry period is 3 to 4 years (Roberts and Marston 2011; Rogers and Ralph 2011). Timing may not be critical but more growth may occur if flooded during spring-summer (Roberts and Marston 2011), and optimal seasonality is given as winter-spring (Rogers and Ralph 2011), or late spring in the mid-Murray to early summer in the Lower Murray (A. Jensen, pers. comm. May 2021).

Table 30: Preliminary thresholds for stress for River red gum swamps and forests

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation** | 1-2 years | 3-4 years | ≥ 5 years | Moderate / high |
| **Frequency of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate / high |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Season of inundation** | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline / variability | Seasonal inversion | Moderate |
| **Duration dry** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Depth to groundwater^** | < 9 mbgl | 9-12 mbgl | > 12 mbgl | Low |
| **Groundwater salinity*** | < 10, 000 µs | 10 – 40,000 µs | > 40,000 µs | Low/moderate |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/high |
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

^River red gum trees have a taproot or sinker root that can penetrate to 9 meters or more (Horner, Baker *et al.* 2009; Roberts and Marston 2011) with multiple studies associating depths below 12 meters with a loss in condition (Jones, Stanton *et al.* 2020). However depths of 20 meters below ground level (mbgl) are used for regional GDE mapping by the QLD DNRME (Jones, Stanton *et al.* 2020). Suitable depth to groundwater will be influenced by soil type.
*Based on (Mensforth, Thorburn *et al.* 1994).

### *River red gum woodland*

Table 31: Preliminary thresholds for condition for River red gum woodland

| Measure of condition | Better | Medium | Worse | Confidence |
|---|---|---|---|---|
| **Extent and distribution (total** | >80% of RRG woodland ANAE | 79 – 40% of RRG woodland ANAE | < 40% of RRG woodland ANAE | Low/moderate |

| | | | | |
|---|---|---|---|---|
| **area on the managed floodplain)** | types have low vulnerability | types have low vulnerability | types have low vulnerability | |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Tree stand condition** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Average recommended frequency of inundation for river red gum woodland is once every 1 to 3 years (Rogers and Ralph 2011) to 2 to 4 years (Roberts and Marston 2011) for 2 to 4 (Roberts and Marston 2011) or up to 8 months (Rogers and Ralph 2011). Maximum inter-flood dry period is 3 to 4 years (Rogers and Ralph 2011) or 5 to 7 years (Roberts and Marston 2011). Timing may not be critical but more growth may occur if flooded during spring-summer (Roberts and Marston 2011), and optimal seasonality is given as winter-spring (Rogers and Ralph 2011), or late spring in the mid-Murray to early summer in the Lower Murray (A. Jensen, pers. comm. May 2021).

Table 32: Preliminary thresholds for stress for River red gum woodland

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation** | 1-2 years | 3-4 years | ≥ 5 years | Moderate / high |
| **Frequency of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate / high |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Season of inundation** | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline / variability | Seasonal inversion | Moderate |
| **Duration dry** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Depth to groundwater** | < 9 mbgl | 9-12 mbgl | > 12 mbgl | Low |
| **Groundwater salinity** | < 10, 000 µs | 10,000 – 40,000 µs | > 40,000 µs | Low/moderate |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/high |

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

### *Black box swamps, forests and woodlands*

Thresholds for condition and stress for BB swamps, forests and woodlands are currently combined. Information on the water requirements for BB have only been identified for woodlands and have not been articulated for either swamps or forests. Further investigation / research is required to determine if there are different condition or stress thresholds identifiable for BB swamps and forests.

Table 33: Preliminary thresholds for condition for Black box swamps, forests and woodlands

| Measure of condition | Better | Medium | Worse | Confidence |
|---|---|---|---|---|
| **Extent and distribution (total area on the managed floodplain)** | >80% of BB ANAE types have low vulnerability | 79 – 40% of BB ANAE types have low vulnerability | < 40% of BB ANAE types have low vulnerability | Low/moderate |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Tree stand condition** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Average recommended frequency of inundation for black box is once every 2 to 5 (Rogers and Ralph 2011) to 3 to 7 years (Roberts and Marston 2011) for 2 to 4 (Rogers and Ralph 2011) or 3 to 6 months (Roberts and Marston 2011). Maximum inter-flood dry period is 3 to 7 years to maintain good condition (Roberts and Marston 2011), though inter-flood period can be variable (Rogers and Ralph 2011) and trees are known to survive dry intervals up to 25 years (Overton, Pollino et al. 2014). Timing may not be critical (Roberts and Marston 2011; Rogers and Ralph 2011), however following natural timing is advisable (Roberts and Marston 2011) and optimal seasonality is given as late spring in the mid-Murray to early summer in the Lower Murray (A. Jensen, pers. comm. May 2021).

Table 34: Preliminary thresholds for stress for Black box swamps, forests and woodlands

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation*** | 3 – 4 years | 5 – 6 years | ≥ 7 years | High |
| **Frequency of inundation*** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate / high |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/ moderate |
| **Season of inundation** | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline / variability | Seasonal inversion | Moderate |
| **Duration dry*** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Duration dry_alt^** | ≤ the average return period | 2 – 3 x the average return period | >3 x the average return period | Moderate |
| **Depth to groundwater+** | < 6 mbgl | 6-10 mbgl | > 10 mbgl | Low/ moderate |
| **Groundwater salinity** | < 32,000 µS | 32,000 – 55,000 µS | > 55,000 µS | Moderate |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/ high |
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/ moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/ moderate |
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/ moderate |
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/ moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

* For BB, flow thresholds such as time-since-last inundation, average frequency of inundation and duration dry are likely to be strongly related to the salinity of groundwater (< 32,000 µS (Colloff, Caley *et al.* 2015) but can tolerate up to 55,000 µS (Casanova 2015)) and depth to groundwater (1.5 – 2 m (Gehrig 2013) to > 3.65 m (Colloff, Caley *et al.* 2015)). Where salinity is higher and depth to groundwater is deeper, flood inundation requirements are likely to be higher (more frequent). In addition, ^BB can potentially survive dry intervals of up to 25 years (Overton, Pollino *et al.* 2014) or may survive on rainfall alone if salinity is not a factor (Overton, Coff *et al.* 2018). Overton and Doody (2008) found that a flood interval of greater than three times the average return period resulted in poor condition (Overton, Coff *et al.* 2018). The use of baseline data calculated for every individual ANAE polygon should help to capture these location specific differences (see also page 84 and 86). + Adapted from information in Overton, Coff *et al.* (2018).

### *Coolibah swamps and woodlands*

Thresholds for condition and stress for Coolibah swamps, forests and woodlands are currently combined, with ANAE mapping combining forests and woodlands in a single ecosystem type. Information on the water requirements for Coolibah have only been identified for woodlands and have not been articulated for either swamps or forests. Less information is available regarding the water requirements for Coolibah compared with both RRG and BB. Literature indicates the average recommended flooding frequency for Coolibah is every 10 – 20 years and that the critical interval between inundation is unknown (Casanova 2015; Roberts and Marston 2011; Rogers and Ralph 2011). Further investigation / research is required to determine condition and stress thresholds for Coolibah in general.

Table 35: Preliminary thresholds for condition for Coolibah swamps and woodlands

| Measure of condition | Better | Medium | Worse | Confidence |
|---|---|---|---|---|
| **Extent and distribution (total area on the managed floodplain)** | >80% of Coolibah ANAE types have low vulnerability | 79 – 40% of Coolibah ANAE types have been low vulnerability | < 40% of Coolibah ANAE types have low vulnerability | 2 |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Tree stand condition** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Average recommended frequency of inundation for Coolibah is once every 10 to 20 years (Roberts and Marston 2011; Rogers and Ralph 2011) though more frequent inundation (e.g. once every 7 years) is likely to be tolerable (Roberts and Marston 2011). Average recommended durations of flooding are short, e.g. 2 to 5 weeks (Rogers and Ralph 2011) though optimal duration is largely unknown (Roberts and Marston 2011). Maximum inter-flood dry period is in the order or 10 to 20 years (Roberts and Marston 2011; Rogers and Ralph 2011), though falling watertables may shorten this (Roberts and Marston 2011). Timing may not be critical for adult growth (Roberts and Marston 2011) or may ideally be from summer to autumn (Rogers and Ralph 2011).

Table 36: Preliminary thresholds for stress for Coolibah swamps and woodlands

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation** | 10 years | 20 years | > 20 years | Low |
| **Frequency of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Low/moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Season of inundation** | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline / variability | Seasonal inversion | Moderate |

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Duration dry** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Depth to groundwater** | < 6 mbgl | 6-10 mbgl | > 10 mbgl | Low |
| **Groundwater salinity^** | < 32,000 µS | 32,000 – 55,000 µS | > 55,000 µS | Moderate |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/high |
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

*Groundwater depth for Black Box have been applied however additional information specific to Coolibah would be preferable in future revisions if available

^ A known salinity tolerance for Coolibah is similar to Black Box (will utilise groundwater of 20,000 mg/L which is equivalent to 31,200 µS) (Costelloe, Payne *et al.* 2008) so we have used the same groundwater salinity tolerances as for Black Box.

NB. Adult Coolibah trees may survive on rainfall or groundwater alone though, similarly to Black Box, depth to groundwater or saline groundwater may influence Coolibah thresholds such as time-since-last-inundation. It is unclear if flooding may be required to support recruitment of Coolibah seedlings or what role flooding plays in supporting the understory species in Coolibah swamps, forests or woodlands. The use of baseline data calculated for every individual ANAE polygon should help to capture location specific differences and help to determine if there have been changes in stress metrics such as time-since-last-inundation, extent of inundation and root-zone soil moisture which may be affecting Coolibah condition (see also page 84 and 86).

### *Lignum swamps and shrublands*

Thresholds for condition and stress for lignum swamps and shrublands are currently combined. Information on the water requirements for lignum have primarily been identified for shrublands and have not been clearly articulated for swamps, noting however that Roberts and Marston (2011) do distinguish between water requirements for vigorous growth and persistence of small shrubs.

Table 37: Preliminary thresholds for condition for lignum swamps and shrublands

| Measure of condition | Good | Medium | Poor | Confidence |
|---|---|---|---|---|
| **Extent and distribution (total area on the managed floodplain)** | >80% of lignum ANAE types have low vulnerability | 79 – 40% of lignum ANAE types have low vulnerability | < 40% of lignum ANAE types have low vulnerability | Low/moderate |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |

| | | | | |
|---|---|---|---|---|
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Average recommended frequency of inundation for lignum is once every 1 to 3 years to maintain large shrubs with vigorous growth, to once every 3 to 5 years for healthy shrubs (Roberts and Marston 2011) or once every to 3 to 10 years (Rogers and Ralph 2011). Average recommended durations of flooding range from 1 to 6 months (Rogers and Ralph 2011) to 3 to 7 months (Roberts and Marston 2011). Maximum inter-flood dry period is 5 to 7 years to maintain good condition (Roberts and Marston 2011), though inter-flood period can be variable and lignum shrubs are known to survive dry intervals of 17 to 20 years (Campbell, Freestone et al. 2021; Overton, Pollino et al. 2014), with rootstock persisting and able to regenerate up to 3 to 4 years after the above ground biomass has died (Freestone, Brown et al. 2017). Timing may not be critical (Roberts and Marston 2011), however following natural timing is advisable (Roberts and Marston 2011) and optimal seasonality is given as spring to early summer (Rogers and Ralph 2011), specifically late spring in the mid-Murray to early summer in the Lower Murray (A. Jensen, pers. comm. May 2021).

No literature was found about the use of groundwater or the tolerance to saline groundwater for lignum plants and this remains a knowledge gap (Campbell, Freestone et al. 2021; Roberts and Marston 2011). Based on one observation along an eroding bank, lignum roots are known to grow to a depth of at least 2 – 3 meters (Craig, Walker et al. 1991). Conservatively, values for groundwater salinity are based on river red gum tolerances and values for groundwater depth on black box. These values should be reviewed in future revisions.

Table 38: Preliminary thresholds for stress for lignum swamps and shrublands.

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation** | 3 years | 4 years | ≥ 5 years | Moderate |
| **Frequency of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Low/moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Season of inundation** | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline / variability | Seasonal inversion | Moderate |
| **Duration dry** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Rootstock longevity** | | | Individual plants have regenerated after 17 – 20 years without inundation; regeneration from rootstock is possible up to 3 – 4 years after the above ground plant has died | Moderate |

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Depth to groundwater** | < 6 mbgl | 6-10 mbgl | > 10 mbgl | Low |
| **Groundwater salinity** | < 10, 000 µs | 10,000 – 40,000 µs | > 40,000 µs | Low |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/high |
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

### *NWV – submerged vegetation*

For the purposes of identifying condition and stress thresholds, the values for submerged vegetation are based on recommended flow regime requirements for *Vallisneria australis* (Roberts and Marston 2011; Rogers and Ralph 2011).

Table 39: Preliminary thresholds for condition for submerged vegetation

| Measure of condition | Good | Medium | Poor | Confidence |
|---|---|---|---|---|
| **Extent and distribution (total area on the managed floodplain)** | >80% of submerged ANAE types have low vulnerability | 79 – 40% of submerged ANAE types have low vulnerability | < 40% of submerged ANAE types have low vulnerability | Low/ moderate |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/ moderate |
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Table 40: Preliminary thresholds for stress for submerged vegetation

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation – existing plants** | < 3 months | 3 – 4 months | > 4 months | Moderate |
| **Time-since-last inundation – seed bank** | 2 years | 5 years | >8 years | Moderate |

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Frequency of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Low/moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Season of inundation** | Late winter – spring (to grow over summer) | Summer - autumn | No water or shallow water (< 50cm) over summer | Moderate |
| | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline / variability | Seasonal inversion | Moderate |
| **Duration dry – baseline** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Duration dry – existing plants / rhizomes** | 1 – 2 months | 3 – 4 months | > 4 months | Moderate |
| **Duration dry – seed banks** | 2 years | 5 years | >8 years | Moderate |
| **Rhizome or seed bank longevity** | | | Rhizomes survive 3 – 4 months<br>Seeds survive up to 9 years | Moderate |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/high |
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

### *NWV – sedges / rushes*

For the purposes of identifying condition and stress thresholds, values for the sedge / rush vegetation functional unit are based on recommended flow regime requirements for *Bolboschoenus fluviatilis* and *Eleocharis acuta* (Roberts and Marston 2011; Rogers and Ralph 2011).

Table 41: Preliminary thresholds for condition for sedges / rushes

| Measure of condition | Good | Medium | Poor | Confidence |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| **Extent and distribution (total area on the managed floodplain)** | >80% of sedge / rush ANAE types have low vulnerability | 79 – 40% of sedge / rush ANAE types have low vulnerability | < 40% of sedge / rush ANAE types have low vulnerability | Low/moderate |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Table 42: Preliminary thresholds for stress for sedges / rushes

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation – existing plants** | 4 months | 4 – 10 months | > 10 months | Moderate |
| **Time-since-last inundation – seed bank / regeneration** | 1 – 2 years | 3 years | 5 years | Moderate |
| **Frequency of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Low/moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Season of inundation** | Dry phase should be late summer to autumn | | | Moderate |
| **Season of inundation** | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline / variability | Seasonal inversion | Moderate |
| **Duration dry – baseline** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Duration dry – existing plants** | 4 months | 4 – 10 months | > 10 months | Moderate |
| **Duration dry – seed bank / regeneration** | 1 – 2 years | 3 years | 5 years | Moderate |
| **Rhizome or seed bank longevity** | | | Rhizomes may survive 5 – 7 years | Moderate |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/high |
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

### *NWV – grassy meadows*

For the purposes of identifying condition and stress thresholds, values for the grassy meadow vegetation functional unit are based on recommended flow regime requirements for *Paspalum distichum* and *Pseudoraphis spinescens* (Roberts and Marston 2011; Rogers and Ralph 2011).

Table 43: Preliminary thresholds for condition for grass meadows

| Measure of condition | Good | Medium | Poor | Confidence |
|---|---|---|---|---|
| **Extent and distribution (total area on the managed floodplain)** | >80% of grassy meadow ANAE types have low vulnerability | 79 – 40% of grassy meadow ANAE types have low vulnerability | < 40% of grassy meadow ANAE types have low vulnerability | Low/moderate |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Table 44: Preliminary thresholds for stress for grassy meadows

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation – existing plants** | < 8 months | 8 – 10 months | > 10 months | Moderate |
| **Time-since-last inundation – seed bank / regeneration** | 1 -2 years | 3 – 5 years | > 5 years | Moderate |
| **Frequency of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Low/moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Season of inundation** | Flooding required over summer | | Avoid winter flooding unless long-lasting | Moderate |

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline / variability | Seasonal inversion | Moderate |
| **Duration dry – baseline** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Duration dry – existing plants** | < 8 months | 8 – 10 months | > 10 months | Moderate |
| **Duration dry – seed bank / regeneration** | 1 -2 years | 3 – 5 years | > 5 years | Moderate |
| **Rhizome or seed bank longevity** | | | Rootstock may persist for 5 – 7 years<br>Seeds only survive up to 2 years | Moderate |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/high |
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

### *NWV – tall reeds*

For the purposes of identifying condition and stress thresholds, values for the tall rush vegetation functional group are based on recommended flow regime requirements for *Typha* spp. and *Phragmites australis* (Roberts and Marston 2011; Rogers and Ralph 2011).

Table 45: Preliminary thresholds for condition for tall reed beds

| Measure of condition | Good | Medium | Poor | Confidence |
|---|---|---|---|---|
| **Extent and distribution (total area on the managed floodplain)** | >80% of tall reed ANAE types have low vulnerability | 79 – 40% of tall reed ANAE types have low vulnerability | < 40% of tall reed ANAE types have low vulnerability | Low/moderate |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

| | | | | |
|---|---|---|---|---|
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Table 46: Preliminary thresholds for stress for tall reed beds

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation – existing plants** | < 1 year | 1 – 2 years | > 2 years | Moderate |
| **Time-since-last inundation – seed bank / regeneration** | 1 – 2 years | 3 – 5 years | > 5 years | Moderate |
| **Frequency of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Low/moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/moderate |
| **Season of inundation** | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline | Seasonal inversion | Moderate |
| **Duration dry – baseline** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Duration dry – existing plants** | < 1 year | 1 – 2 years | > 2 years | Moderate |
| **Duration dry – seed bank / regeneration** | 1 – 2 years | 3 – 5 years | > 5 years | Moderate |
| **Rhizome or seed bank longevity** | | | Rhizomes reserves may last up to 5 (to 7) years | Moderate |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/high |
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

| | | | | |
|---|---|---|---|---|
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/moderate |

### *NWV – herbfields*

For the purposes of identifying condition and stress thresholds, values for the herbfield vegetation functional unit are based on recommended flow regime requirements for *Marsilea drummondii* (Rogers and Ralph 2011) and *Centipeda cunninghamii* (Higgisson, Doody *et al.* 2021).

Table 47: Preliminary thresholds for condition for herbfields

| Measure of condition | Good | Medium | Poor | Confidence |
|---|---|---|---|---|
| **Extent and distribution (total area on the managed floodplain)** | >80% of herbfield ANAE types have been inundated every 1 – 4 years | 79 – 40% of herbfield ANAE types have been inundated at least once in 5 years | < 40% of herbfield ANAE types have been inundated at least once in 5 years | Low/ moderate |
| **Extent and distribution (individual polygons)** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/ moderate |
| **Photosynthetic output – 'greenness'** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Cover of vegetation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |

Table 48: Preliminary thresholds for stress for herbfields

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Time-since-last inundation – extant vegetation** | 1 year | 2 – 4 years | > 4 years | Low/ moderate |
| **Time-since-last inundation – seed banks** | 1 – 2 years | 3 – 7 years | > 7 years | Low/ moderate |
| **Frequency of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate |
| **Duration of inundation** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Low/ moderate |
| **Extent of inundation** | Area of polygon inundated 1 SD > baseline | Area of polygon inundation to at least baseline | Area of polygon inundated < baseline | Low/ moderate |
| **Season of inundation** | No deviation from seasonal baseline / variability | Limited deviation from seasonal baseline / variability | Seasonal inversion | Moderate |

| Measure of stress | Low | Medium | High | Confidence |
|---|---|---|---|---|
| **Duration dry – baseline** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Moderate |
| **Duration dry – extant vegetation** | 1 year | 2 – 4 years | > 4 years | Low/ moderate |
| **Duration dry – seed banks** | 1 – 2 years | 3 – 7 years | > 7 years | Low/ moderate |
| **Seed bank longevity** | | | More than 10 years for some species but less for others | Low/ moderate |
| **Rainfall – annual average** | Deviation > baseline with the last 2 years stable or increasing | Deviation score ≥ baseline | Deviation score < baseline | Moderate/ high |
| **Rainfall – interval between events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/ moderate |
| **Rainfall – high intensity events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/ moderate |
| **Temperature – average maximum** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/ moderate |
| **Temperature – average minimum** | Deviation score within 1 SD of the baseline | Deviation score > 1 SD away from the baseline | Deviation score > 2 SD away from the baseline | Low/ moderate |
| **Temperature – extreme maximum events** | Deviation < baseline with the last 2 years stable or decreasing | Deviation score ≤ baseline | Deviation score > baseline | Low/ moderate |

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# Appendix C: Waterbird method development

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## Context

### *BWS Expected outcomes for waterbirds*

The BWS expected outcomes for waterbirds are increased abundance and the maintenance of current species diversity. From 2024 onwards, the expected outcomes are:

- that the number and type of waterbird species present in the Basin will not fall below current observations

- a significant improvement in waterbird populations in the order of 20 to 25% over the baseline scenario, with increases in all waterbird functional groups
- breeding events (the opportunities to breed rather than the magnitude of breeding per se) of colonial nesting waterbirds to increase by up to 50% compared to the baseline scenario
- breeding abundance (nests and broods) for all of the other functional groups to increase by 30–40% compared to the baseline scenario, especially in locations where the Basin Plan improves over-bank flows.

The waterbird outcomes described above are Basin-wide. However, because of the importance of the Coorong, Lakes Albert and Alexandrina for migratory shorebirds, these areas have the following additional expected outcomes:

- at a minimum maintain populations of the following four key species: curlew sandpiper, greenshank, red-necked stint and sharp-tailed sandpiper, at levels recorded between 2000 and 2014.

### *Approach*

The approach taken here comprises four primary steps:

1) Conceptual model development
2) Grouping species
3) Identifying indicators and thresholds
4) Application of the framework to species groups

Note: Multiple iterations were involved in selection of initial indicators and thresholds, with approaches and datasets originally thought likely to be suitable repeatedly found to be unfeasible at the scales required. Testing of the suitability of various datasets identified significant problems with data availability, quality, coverage and other parameters. In many cases this was due to a lack of Basin-scale, scientifically designed, on-ground research at appropriate temporal scales and resolutions.  This is important because waterbird vulnerabilities are scale dependent. This resulted in a very limited final selection of potential indicators of waterbird species or group 'condition' in particular.

It is a common perception that there are large quantities of data available for particular taxa – particularly for those taxa that are large or obvious such as birds. But the availability of certain types of data does not mean that they are fit for all purposes. The characteristics of each dataset need to be fully understood before use – which means reading and understanding exactly how the data collection was designed spatially and temporally, what it was originally designed for, the methods used and their limitations, the biases and gaps present and the caveats around use and interpretation.

## Our conceptual understanding of native waterbird vulnerabilities

A range of conceptual models exist for various aspects of waterbird ecology in Australia and the Murray-Darling Basin (e.g., LTIM cause and effect diagrams, EWKR conceptual models, Environmental Water Requirements planning, high conservation value (e.g., Ramsar) site models; McGinness et al. 2019, McGinness et al. 2020; Brandis et al. 2009). However, no conceptual model currently exists for assessment of waterbird *vulnerability* per se in the Basin.

Here we build on prior waterbird ecology conceptual models and climate change vulnerability assessment models, augmented with expert knowledge, to produce a conceptual model that is directly relevant to assessment of vulnerability of waterbirds to change and subsequent prioritisation of management actions.

Factors that adversely affect waterbirds and increase their vulnerability have been variously called strictures, stressors, pressures, hazards, limitations, constraints, or filters (Lester et al. 2020; McGinness et al. 2019; McGinness 2016). The most commonly reported of these are usually (McGinness 2016):

- habitat loss, fragmentation or change – including changes to breeding, feeding, roosting, movement and refuge habitats
- changes in food availability or quality
- climate change and weather extremes

Other factors that vary in impact by species, spatially and temporally, include:

- toxin and pollution burdens in preferred environments or food sources
- disease rates
- parasite burdens
- human disturbance (especially in nesting sites)
- vegetation clearing
- invasive species impacts, direct or indirect
- predation
- competition
- hunting
- changes to human-modified environments, e.g. irrigation channels, irrigated cropping / grazing

Vulnerability can be defined as the degree to which a system, group or species is susceptible to, and unable to cope with, adverse effects (Intergovernmental Panel on Climate Change, 2007). In conservation biology, vulnerability is typically characterised as being a function of sensitivity to change, adaptive capacity, and exposure to change (Foden et al 2019; IPCC 2007).

### *Waterbird sensitivities, adaptive capacity and exposure*

There is an extensive and rapidly evolving literature base describing approaches for assessment of species vulnerability in the context of climate change. These approaches are also useful when framing potential vulnerability of waterbirds to change in the context of environmental water and habitat management. Using the approach described by Foden et al. 2019, Figure 33 and Table 1 presented below list waterbird vulnerability factors in terms of:

1) **SENSITIVITY**: the inability of the species or group to persist, as is, under changing conditions;

2) **ADAPTIVE CAPACITY**: the ability of the species or group to respond to changes; and

3) **EXPOSURE** to change, threats, stressors, pressures etc: the extent of change and variation that the species or group encounters or is projected to encounter – which can be extreme in the Australian context.

These demonstrate the wide range of factors that should ideally be considered if an exhaustive assessment of waterbird vulnerabilities is required. However, there are significant knowledge and data gaps in Australia regarding many of these factors and therefore initial methods will be more limited.

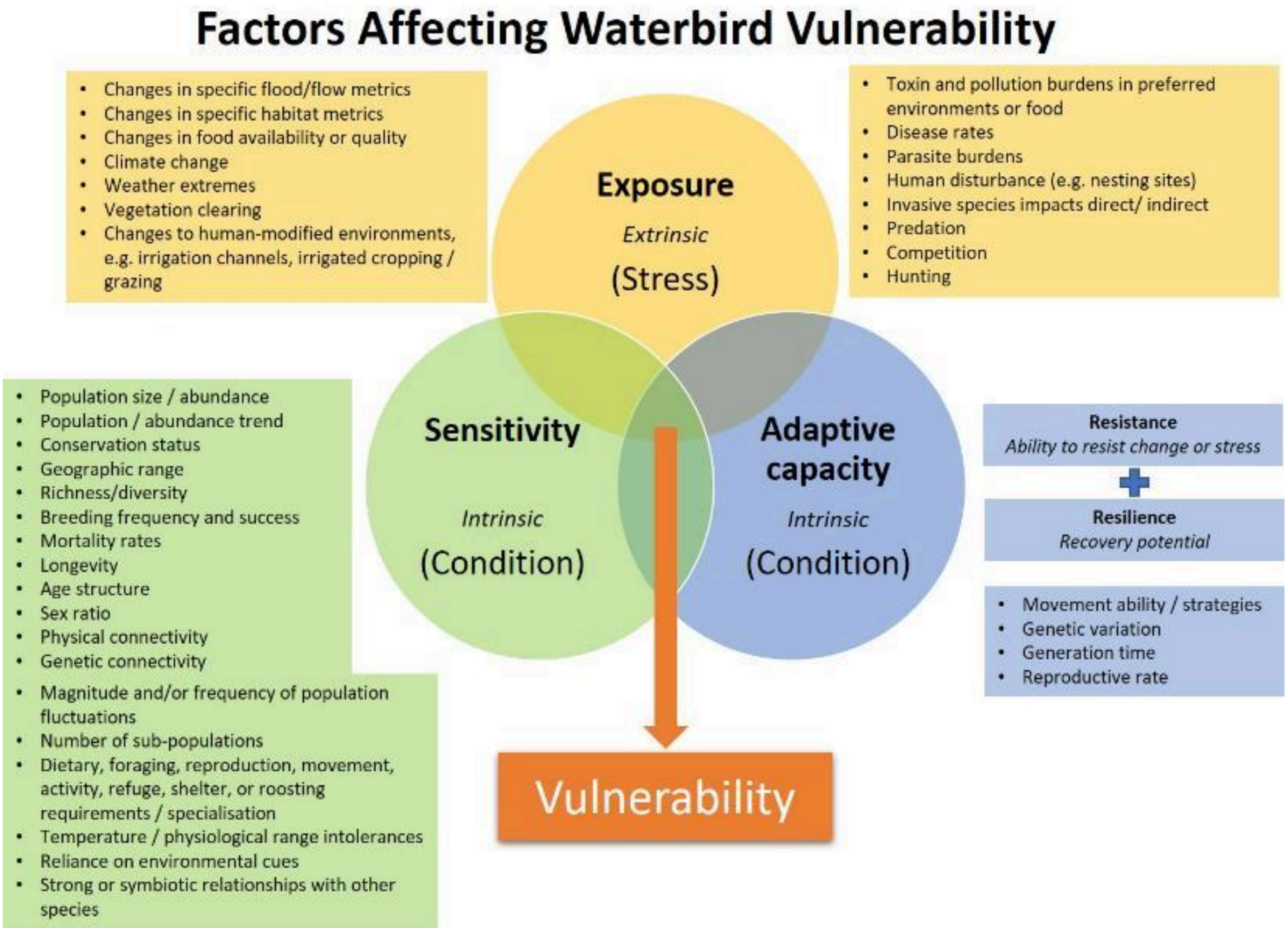


Figure 33 Conceptual diagram of factors interacting to affect waterbird vulnerability in Australia (based on Foden et al. 2019).

Table 49 Waterbird vulnerability assessment factors, following Foden et al. 2019. These tables demonstrate the wide range of factors that should ideally be considered if an exhaustive assessment of waterbird vulnerabilities is required. However, there are significant knowledge and data gaps in Australia regarding many of these factors and therefore initial methods will be more limited.

| **WATERBIRD VULNERABILITY FACTORS** | **Low vulnerability** | **Medium vulnerability** | **High vulnerability** |
|---|---|---|---|
| *SENSITIVITY: the inability of the species or group to persist, as is, under changing conditions* | | | |
| *Species / group condition* | | | |
| Abundance / population size | Large | Medium | Small |
| Abundance / population trend over time | Increasing | Maintaining | Decreasing |
| Geographic range | Large | Medium | Small |
| Richness or diversity (species, subspecies, genetic) | Large | Medium | Small |
| Breeding frequency and success | High | Medium | Low |
| Mortality rates | Low | Medium | High |
| Longevity | High | Medium | Low |
| Age structure | Normal | Skewed | Highly skewed |
| Sex ratio | Normal | Skewed | Highly skewed |
| Magnitude and/or frequency of population fluctuations | Low | Medium | High |
| Number of sub-populations | High | Medium | Low |
| Physical connectivity | High | Medium | Low |
| Genetic connectivity | High | Medium | Low |
| Conservation status (e.g. IUCN Red List Status) | LC | NT | V / E / CE |
| *Habitat loss, fragmentation or change* | | | |
| Reliance on flooding to support reproduction and breeding habitat | Low | Medium | High |
| Reliance on flooding to support feeding habitat and food | Low | Medium | High |
| Reliance on flooding to support roosting habitat / shelter | Low | Medium | High |
| Reliance on flooding to support refuge habitat | Low | Medium | High |
| Reliance on flooding to support movement and movement habitat | Low | Medium | High |
| *Sensitivity to specific habitat and flood/flow metrics:* | | | |
| Volume | Highly appropriate | Moderately appropriate | Not appropriate |
| Timing | Highly appropriate | Moderately appropriate | Not appropriate |

| WATERBIRD VULNERABILITY FACTORS | Low vulnerability | Medium vulnerability | High vulnerability |
|---|---|---|---|
| Duration | Highly appropriate | Moderately appropriate | Not appropriate |
| Depth and rate of change in depth | Highly appropriate | Moderately appropriate | Not appropriate |
| Area or extent (maximum, minimum, mean) | Highly appropriate | Moderately appropriate | Not appropriate |
| Frequency | Highly appropriate | Moderately appropriate | Not appropriate |
| Interflood period or dry duration | Highly appropriate | Moderately appropriate | Not appropriate |
| Antecedent conditions / successive flood years (e.g. prev 5 years) | Wet | Average | Dry |
| Location | Highly appropriate | Moderately appropriate | Not appropriate |
| Bare soil extent or % (min, max, mean) | Highly appropriate | Moderately appropriate | Not appropriate |
| Dry or brown vegetation extent or % (min, max, mean) | Highly appropriate | Moderately appropriate | Not appropriate |
| Green vegetation extent or % (min, max, mean) | Highly appropriate | Moderately appropriate | Not appropriate |
| Wet vegetation extent or % (min, max, mean) | Highly appropriate | Moderately appropriate | Not appropriate |
| Open water extent or % (min, max, mean) | Highly appropriate | Moderately appropriate | Not appropriate |
| Total vegetation extent or % (min, max, mean) | Highly appropriate | Moderately appropriate | Not appropriate |
| Hydrated' vegetation extent or % (wet + green veg) (min, max, mean) | Highly appropriate | Moderately appropriate | Not appropriate |
| All wet vegetation and open water combined extent or % (min, max, mean) | Highly appropriate | Moderately appropriate | Not appropriate |
| *Changes in food availability or quality* | | | |
| Dependence on freshwater for food | Low | Medium | High |
| Dependence on freshwater for drinking / hydration | Low | Medium | High |
| Food abundance | High | Medium | Low |
| Food quality | High | Medium | Low |
| | | | |
| *Climate change and weather extremes* | | | |
| Temperature or other physiological range tolerance | High | Medium | Low |

| **WATERBIRD VULNERABILITY FACTORS** | **Low vulnerability** | **Medium vulnerability** | **High vulnerability** |
|---|---|---|---|
| Reliance on environmental cues for reproduction initiation | Low | Medium | High |
| Reliance on environmental cues for reproduction completion (e.g. nest abandonment) | Low | Medium | High |
| Reliance on environmental cues for movement / migration initiation/timing | Low | Medium | High |
| Reliance on environmental cues for movement / migration routes/stops | Low | Medium | High |
| Reliance on environmental cues for circadian patterns of activity | Low | Medium | High |
| Reliance on environmental cues for other key life history traits | Low | Medium | High |
| Strong or symbiotic relationships or interactions with other species | Low | Medium | High |
| *ADAPTIVE CAPACITY: the ability of the species or group to respond to changes* | | | |
| Movement ability (dispersal, nomadism, migration, residency) | High | Medium | Low |
| Generation time | Short | Medium | Long |
| Reproductive rate | High | Medium | Low |
| Genetic variation | High | Medium | Low |
| EXPOSURE to change, threats, stressors, pressures or hazards: the extent of change and variation that the species or group encounters or is projected to encounter | | | |
| What degree of variability is the species currently exposed to? | High | Medium | Low |
| What level of change is projected across the species' range? | Low | Medium | High |
| ***Changes in habitat and flood/flow metrics:*** | ***Change from preferred is:*** | ***Change from preferred is:*** | ***Change from preferred is:*** |
| Volume | Low | Medium | High |
| Timing | Low | Medium | High |
| Duration | Low | Medium | High |
| Depth and rate of change in depth | Low | Medium | High |
| Area or extent (maximum, mean) | Low | Medium | High |
| Frequency | Low | Medium | High |
| Interflood period or dry duration | Low | Medium | High |
| Antecedent conditions / successive flood years (e.g. prev 5 years) | Low | Medium | High |

| WATERBIRD VULNERABILITY FACTORS | Low vulnerability | Medium vulnerability | High vulnerability |
|---|---|---|---|
| Location | Low | Medium | High |
| Bare soil extent or % (min, max, mean) | Low | Medium | High |
| Dry or brown vegetation extent or % (min, max, mean) | Low | Medium | High |
| Green vegetation extent or % (min, max, mean) | Low | Medium | High |
| Wet vegetation extent or % (min, max, mean) | Low | Medium | High |
| Open water extent or % (min, max, mean) | Low | Medium | High |
| Total vegetation extent or % (min, max, mean) | Low | Medium | High |
| Hydrated' vegetation extent or % (wet+green veg) (min, max, mean) | Low | Medium | High |
| All wet vegetation + open water extent or %(min, max, mean | Low | Medium | High |
| *OTHER THREATS / STRESSORS / PRESSURES / HAZARDS* | | | |
| *Changes in climate or weather* | Low | Medium | High |
| *Changes in food availability or quality* | Low | Medium | High |
| Disease rates | Low | Medium | High |
| Parasite burdens | Low | Medium | High |
| Toxin and pollution burdens in preferred environments or food | Low | Medium | High |
| Human disturbance rates (especially in nesting sites) | Low | Medium | High |
| Vegetation clearing | Low | Medium | High |
| Predation | Low | Medium | High |
| Competition | Low | Medium | High |
| Invasive species impacts, direct or indirect | Low | Medium | High |
| Hunting | Low | Medium | High |
| Changes in human-modified environments e.g. irrigation channels, irrigated cropping / grazing | Low | Medium | High |

# Grouping waterbird species for vulnerability assessment and prioritisation

All waterbird species are dependent on surface water to some extent for completion of their lifecycles. In general terms, an abundance of water at broad scales with some variation in inundation timing, duration, extent, and frequency can be assumed to provide benefits for most waterbirds. However, at this level, variation in life cycle requirements and traits among groups and species is ignored.

The high-level BWS expected outcomes for waterbirds provide the basis for initial selection and grouping of waterbird species for vulnerability assessment and prioritisation for environmental watering. We have used a database of waterbird species traits to develop waterbird groups combining BWS expectations with foraging behaviour and habitat dependencies and nesting behaviour and habitat dependencies. These groups are:

1. Colonial and semi-colonial nesting waders
2. Shorebirds
3. Cryptic waders
4. Swimmers, divers and grazers, with the sub-groups:
    a. Diving swimmers – e.g. cormorants, pelicans, grebes
    b. Aerial divers – e.g. terns, gulls
    c. Grazing simmers – e.g. swans, coots, swamphens

## *Waterbird habitat requirement groups*

**Group 1: 'Colonial and semi-colonial nesting waders'.** Colonial and semi-colonial wading species have a high level of dependence on flood timing, extent, duration, depth, vegetation type and condition for breeding. They are also dependent on specific important breeding sites. They are usually easily detectable when breeding and good datasets are available for most species. These species are typically nomadic or partially migratory.

**Group 2: 'Shorebirds'.** Shorebirds have a high level of dependence on end-of-system flows and large inland flood events that provide broad areas of shallow water and mudflat type environments. They are largely migratory or nomadic and are a group of international concern. They include Coorong and Lower Lakes migratory species listed in the BWS; the curlew sandpiper, common greenshank, red-necked stint and sharp-tailed sandpiper.

**Group 3: 'Cryptic waders'.** Cryptic wading species have a high level of dependence on shallow temporary and permanent wetland habitats with relatively dense emergent aquatic vegetation which requires regular or ongoing inundation to survive (e.g. reeds, rushes, sedges, wet grasses and lignum). These species usually nest as independent pairs though some may occasionally nest semi-colonially. They may be sedentary, nomadic, migratory or partially migratory. Few data are available however habitat requirements can be used as surrogates to assess vulnerability. This group includes two nationally listed endangered species, the Australasian bittern and the Australian painted snipe.

**Group 4 'Swimmers, divers and grazers'.** These are species with a relatively high level of dependence on semi-open, open, and deeper water environments, who commonly swim when foraging (including diving, filtering, dabbling, grazing) or when taking refuge. These species may be sedentary, nomadic, migratory or partially migratory. This group includes the nationally listed near-threatened species the blue-billed duck.

### *Waterbird group alternatives*

There have been several attempts in the past to derive practical 'functional' groups for Australian waterbirds, and such groupings generally vary depending the purpose for which they were derived and the level of simplification required. It is generally accepted that grouping species by one descriptor alone (e.g. body size, diet, foraging habitat, or breeding habit) is rarely sufficient, regardless of the purpose. If a thorough, systematic approach is taken that explicitly and consistently includes conservation status, species movements, diets, foraging methods, foraging habitats, breeding methods, and breeding habitats – including vegetation type, flood timing, frequency, duration and depth requirements – the result is a large number of groups, which can be unwieldy for practical purposes. Consequently, pragmatic simplifications have resulted in functional grouping systems in common use that can contain in the one system a group that is described by diet but not habitat, and a group described by habitat or not diet, and a group described by bird size (e.g. 'large wader') or habit (e.g. 'cryptic species').

Australian bird species have varied and adaptable diets, spatially and temporally, and the extent of this variation and adaptability affects species vulnerability. It is rare that any species eats *only* fish or *only* frogs or *only* invertebrates or *only* vegetation – most are to some extent technically omnivorous. However dietary component *preferences* and adaptations exist, which can be represented in simple terms by: 'piscivorous' (preference for aquatic vertebrate prey such as fish or frogs), 'invertivorous' (preference for invertebrate prey), 'herbivorous' (preference for vegetation), and 'omnivorous' (mixed preferences). If incorporation of dietary preferences into species groups were desired in future, **Appendix B** presents one way of grouping Australian waterbird species that includes both habitat and diet preferences. These groups are based on literature review and expert opinion, including Garnett et al. (2015) and Barker and Vestjens (1994).

In future, for waterbird vulnerability analysis it would be wise to include refined groups and indicators that are logically consistent and better reflect current species status, trends, life cycles, vulnerabilities, and associated requirements.

Finally, explicit vulnerability assessments may be desirable in future for individual species, particularly those of conservation concern. We recommend trialling this approach initially for species formally listed at a national scale (Table 51) and later expanding to assess vulnerability for species that are at risk at other scales (**Appendix** C).

Table 50 Waterbird species in groups based on foraging behaviour and habitat dependencies and nesting behaviour and habitat dependencies

| **Shorebirds** | **Swimmers, divers and grazers** | **Colonial and semi-colonial nesting waders** | **Cryptic waders** |
|---|---|---|---|
| *Foraging on foot* | *Diving* | *Foraging on foot* | *Foraging on foot* |
| Australian Pratincole | Australasian Darter | Australian White Ibis | Australasian Bittern |
| Banded Lapwing | Australasian Grebe | Banded Stilt | Australian Little Bittern |
| Bar-tailed Godwit | Australian Pelican | Black-winged (Pied) Stilt | Australian Painted Snipe |
| Black-fronted Dotterel | Blue-billed Duck | Cattle Egret | Australian Spotted Crake |
| Black-tailed Godwit | Great Cormorant | Glossy Ibis | Baillon's Crake |
| Broad-billed Sandpiper | Great Crested Grebe | Great Egret | Buff-banded Rail |
| Common Greenshank | Hardhead | Intermediate Egret | Latham's Snipe |
| Common Sandpiper | Hoary-headed Grebe | Little Egret | Lewin's Rail |
| Curlew Sandpiper | Little Black Cormorant | Nankeen Night-Heron | Spotless Crake |
| Double-banded Plover | Little Pied Cormorant | Pied Heron | |
| Eastern Curlew | Musk Duck | Red-necked Avocet | |
| Great Knot | Pied Cormorant | Royal Spoonbill | |
| Grey Plover | | Straw-necked Ibis | |
| Grey-tailed Tattler | *Aerial diving* | White-faced Heron | |
| Inland Dotterel | Australian Gull-billed Tern | White-necked Heron | |
| Lesser Sand Plover | Caspian Tern | Yellow-billed Spoonbill | |
| Little Curlew | Silver Gull | Brolga | |
| Long-toed Stint | Whiskered Tern | | |
| Marsh Sandpiper | White-winged Black Tern | | |
| Masked Lapwing | | | |
| Oriental Pratincole | *Filtering/dabbling* | | |
| Pacific Golden Plover | Australian Shoveler | | |
| Pectoral Sandpiper | Chestnut Teal | | |
| Red Knot | Freckled Duck | | |
| Red-capped Plover | Grey Teal | | |
| Red-kneed Dotterel | Pacific Black Duck | | |
| Red-necked Stint | Pink-eared Duck | | |
| Ruddy Turnstone | | | |
| Sharp-tailed Sandpiper | *Grazing/foraging on foot* | | |
| Terek Sandpiper | Australian Shelduck | | |
| Wandering Tattler | Australian Wood Duck | | |
| Whimbrel | Black Swan | | |
| Wood Sandpiper | Dusky Moorhen | | |
| | Eurasian Coot | | |
| | Magpie Goose | | |
| | Plumed Whistling-Duck | | |
| | Wandering Whistling-Duck | | |
| | Black-tailed Native-hen | | |
| | Purple Swamphen | | |

Table 51 Nationally listed water-dependent bird species

| Species name | *Species scientific name* | Family | Order | Population type | IUCN status | Australian conservation status |
|---|---|---|---|---|---|---|
| Australasian Bittern | *Botaurus poiciloptilus* | Ardeidae | Pelecaniformes | Australian | Endangered | Endangered |
| Australian Painted Snipe | *Rostratula australis* | Rostratulidae | Charadriiformes | Endemic | Endangered | Endangered |
| Bar-tailed Godwit | *Limosa lapponica* | Scolopacidae | Charadriiformes | Non-breeding migrant | Least Concern | Critically endangered |
| Black-tailed Godwit | *Limosa limosa* | Scolopacidae | Charadriiformes | Non-breeding migrant | Near Threatened | Near threatened |
| Blue-billed Duck | *Oxyura australis* | Anatidae | Anseriformes | Endemic | Near Threatened | Near threatened |
| Curlew Sandpiper | *Calidris ferruginea* | Scolopacidae | Charadriiformes | Non-breeding migrant | Vulnerable | Critically endangered |
| Eastern Curlew | *Numenius madagascariensis* | Scolopacidae | Charadriiformes | Non-breeding migrant | Vulnerable | Critically Endangered (EPBC 1999) |
| Great Knot | *Calidris tenuirostris* | Scolopacidae | Charadriiformes | Non-breeding migrant | Vulnerable | Critically Endangered (EPBC 1999) |
| Lesser Sand Plover | *Charadrius mongolus* | Charadriidae | Charadriiformes | Non-breeding migrant | Least Concern | Endangered (EPBC 1999) |
| Red Knot | *Calidris canutus* | Scolopacidae | Charadriiformes | Non-breeding migrant | Vulnerable | Endangered (EPBC 1999) |
| Red-necked Stint | *Calidris ruficollis* | Scolopacidae | Charadriiformes | Non-breeding migrant | Least Concern | Near threatened |
| Ruddy Turnstone | *Arenaria interpres* | Scolopacidae | Charadriiformes | Non-breeding migrant | Near Threatened | Near threatened |

# Identifying indicators and thresholds for assessment

## *Thresholds of vulnerability*

The framework for assessing vulnerability will be based on a scoring system (yet to be defined). Inputs to this system are likely to be based on three levels of stress / condition:

- Condition:
  - Good
  - Medium
  - Poor
- Stress:
  - Low
  - Medium
  - High

For each identified indicator, thresholds of condition and stress have been identified. In addition, confidence levels (associated with both the strength of our ecological knowledge and the available data have been assigned).

Table 52: Confidence levels for vulnerability assessment (after Overton et al. 2018).

| **Confidence Level** | **Confidence score** | **Data** |
|---|---|---|
| Low | 1 | Anecdotal or regional level of information, providing a rough estimate of site conditions. Based on low confidence in stressors and low confidence in condition. Conceptual model does not support vulnerability assessment. Vulnerability is simply classified as not-vulnerable or vulnerable |
| Low/ Moderate | 2 | Based on moderate confidence in stressors and low or moderate confidence in condition. Vulnerability based on stressors and condition only. |
| Moderate | 3 | Based on moderate confidence in stressors and moderate confidence in condition. Conceptual model supports the identification of vulnerability. Vulnerability based on stressors, condition and adaptive capacity. |
| Moderate /High | 4 | Based on moderate or high confidence in stressors and moderate or high confidence in condition. Vulnerability is based on potential impact including targeted measurements |
| High | 5 | Measured at site scale with high confidence in stressors and condition, including targeted measurements. Vulnerability is based on potential impact and resilience. |

### *Indicators of waterbird species or group 'condition'*

There is a wide range of potential indicators of waterbird species or group condition. These include:

- Richness or diversity (species, subspecies, or genetic) – including species presence
- Abundance / population size
- Abundance / population trend over time
- Breeding numbers, frequency and success
- Geographic range
- Mortality rates
- Longevity
- Age structure
- Sex ratio
- Magnitude and/or frequency of population fluctuations
- Number of sub-populations
- Physical movement and connectivity
- Genetic connectivity
- Conservation status (e.g. IUCN Red List Status)

Some of these indicators of condition for waterbirds should ideally be assessed for each species and each primary life cycle stage, e.g.: 1) Egg; 2) Chick; 3) Juvenile; 4) Sub-adult; and 4) Adult (McGinness et al 2020). This is currently not feasible in Australia because of insufficient or inappropriate data sources. In addition, measurement of all these indicators is not always practical or needed. In certain situations, targeted assessment of a subset of selected indicators is appropriate. For example, species or group presence and richness can be more confidently assessed than abundance in most locations over time given available data.

Data availability may also restrict assessment of certain indicators to particular species or groups. For example, species or group breeding opportunities and perhaps abundance can be more confidently assessed for colonial and semi-colonial waders, because they are regularly targeted by scientific surveys and have historically been frequently supported by environmental water and wetland management.

When working with species groups, caveats around interpretation of condition must be made explicit, for example:

- Species richness: If a declining or listed species is lost while a more common one is found present, species richness does not appear to change – but a negative effect has occurred, and vulnerability has increased
- Abundance: Large numbers of one or two species (e.g. grey teal) may blow out abundance numbers for an entire group, giving a false impression of positive condition that may not be applicable to the other species in the group

- Breeding and diet: Even closely related and physically similar species in the same group may have different requirements.

This framework is designed to be pragmatic, flexible, and able to accommodate new sources of information as they become available. There are many condition indicators for which there is no current data source available, or for which data are insufficient, but which could be accommodated were these to become available into the future.

**Here, we use a subset of selected condition indicators for which reliable data are currently available at the scales required and are suitable for testing as part of an initial broad assessment of waterbird vulnerability.** These are based on high-level BWS expected outcomes. In future, it would be wise to include additional indicators or surrogates as described above.

**Consistent with the recommendations from the waterbird technical workshop held in May 2021, indicators of waterbird condition were based on waterbird data (rather than habitat surrogates). Data were compiled from a variety of sources (Atlas of Living Australia, aerial waterbird surveys, LTIM / Flow-MER, Coorong and Lower Lakes waterbird monitoring) over the period 1986 to 2022. Data were consolidated into the following metrics for each spatial unit in each year:**

- C1 Abundance – the maximum abundance of each species
- C2 Species richness – the number of species in each functional group recorded
- C3 Breeding abundance – the maximum number of nests
- C4 Breeding species richness – the number of species in each functional for which there was "evidence of breeding" recorded.

Table 53 High-level summary of selected condition indicators and relevant data sources for waterbird vulnerability assessment.

| **Measure of condition** | **Justification** | **Potential data sources** |
|---|---|---|
| Group species richness | Group species richness reflects whether the quality or condition of a site is capable of supporting diversity | ALA; EAWS; MDBA aerial surveys; State Government on-ground and aerial surveys; CEWH-funded MER surveys |
| Group abundance *(Selected Groups)* | The abundance of birds from a certain group at a site or overall may indicate the abundance of suitable resources either just prior to the survey or at the time of the survey and aligns the indicator of condition to the BWS objectives | As above |
| Group breeding occurrence *(Selected Groups)* | The occurrence of breeding by a certain group at a site or overall may indicate the availability of suitable resources for breeding either just prior to the survey or at the time of the survey and aligns the indicator of condition to the BWS objectives | As above |
| Group breeding numbers / abundance *(Selected Groups)* | The number of birds recorded breeding from a certain group at a site or overall may indicate the availability of suitable resources either just prior to the survey or at the time of the survey and aligns the indicator of condition to the BWS objectives | As above |

Table 54 Thresholds for condition for waterbirds. Each threshold applies in the same way to different spatial and temporal scales.

| Waterbird | Measure of condition | Good | Medium | Poor | Confidence |
|---|---|---|---|---|---|
| Colonial and semi-colonial nesting waders | Group species richness | >75% of species present, compared to the range previously recorded | 25-75% of species present, compared to the range previously recorded | <25% of species present, compared to the range previously recorded | Moderate |
| | Group abundance | >75% abundance, compared to the range previously recorded | 25-75% abundance, compared to the range previously recorded | <25% abundance, compared to the range previously recorded | Low |
| | Group breeding occurrence | Breeding of all species recorded in the Basin AND breeding of at least 3 species of the group recorded at >5 sites in the Basin | Breeding of at least 3 species of the group recorded at >5 sites in the Basin | Breeding of at least 3 species of the group recorded at <5 sites in the Basin | Low |
| | Group breeding numbers / abundance | >75% breeding numbers, compared to the range previously recorded | 25-75% breeding numbers, compared to the range previously recorded | <25% breeding numbers, compared to the range previously recorded | Low |
| Shorebirds | Group species richness | As above | As above | As above | Moderate |
| Cryptic waders | Group species richness | As above | As above | As above | Low |
| Swimmers, divers and grazers | Group species richness | As above | As above | As above | Moderate |
| | Group abundance | As above | As above | As above | Low |

### *Indicators of stress*

Basic waterbird life cycle requirements include sufficient availability and quality of each species' or group's preferred:

- Breeding habitats – adults, eggs, chicks, juveniles
- Foraging habitats – juveniles, sub-adults, adults
- Roosting habitats – juveniles, sub-adults, adults
- Movement habitats e.g. preferred stopover sites – juveniles, sub-adults, adults
- Refuge habitats – juveniles, sub-adults, adults
- Food
- Drinking water
- Climate and weather conditions

When waterbird life cycle requirements are not met, waterbirds experience stress. There are a wide range of potential indicators of waterbird species / group stress, including:

A. *Changes in or failure to meet required thresholds in habitat metrics to meet life cycle requirements, such as:*

- Inundation timing
- Inundation duration
- Inundation area or extent
- Inundation frequency
- Interflood period or dry duration
- Antecedent conditions / successive Inundation years (e.g. previous 5 years)
- Inundation location
- Water depth and rate of change in depth
- Vegetation species / community and structure (e.g. woodland vs reed beds; ANAE)
- Vegetation condition / greenness (e.g. NDVI, WIT, Sentinel Chla outputs)
- Vegetation extent
- Proportion of vegetation community inundated

B. *Changes in or failure to meet required thresholds in other life cycle requirements or threats/stressors/pressures/hazards, such as:*

- Changes in food availability (productivity) or quality
- Changes or patterns in climate or weather including weather extremes, rainfall, ENSO etc.
- Disease rates
- Parasite burdens
- Toxin and pollution burdens in preferred environments or food
- Human disturbance rates (especially in nesting sites)

- Vegetation clearing
- Predation
- Competition
- Invasive species impacts, direct or indirect
- Hunting
- Changes in human-modified environments e.g. irrigation channels, irrigated cropping / grazing.

**It is currently not feasible to assess all these stress indicators in Australia because of insufficient data.** This is particularly the case for section 'B' above. The choice of parameters used to indicate stress on waterbirds is partly dependent on the nature of the datasets available at appropriate scales. For example, at present, data describing food availability and quality for waterbirds are generally lacking, and in most floodplain inundation situations water quality is also unknown. Data describing water depth and the rate of change in depth are also difficult to accurately assess and obtain at appropriate spatial and temporal scales. In addition, measurement of all these indicators is not always practical or needed, and in certain situations targeted assessment of a subset of selected indicators is appropriate.

**Consistent with the recommendations from the waterbird technical workshop held in May 2021, indicators of waterbird stress were based on the condition and stress of habitats. As with vegetation, only a subset of the identified indicators could be applied at the Basin-scale with the available data and tools. The indicators of stress included in the assessment are provided in Table 55. Stress is measured by applying the indicators and thresholds to the preferred habitat types (identified by frequency of records) across the Basin. The output is a score for stress for each waterbird group (and species).**

Table 55. Indicators of waterbird stress.

| Indicator | Functional group | Low stress | Medium stress | High stress |
|---|---|---|---|---|
| **Extent of inundation** | All | At or above the baseline | Within 1 standard deviation of the baseline | More than 1 standard deviation below the baseline |
| **Time since last inundation** | Colonial nesting waders cryptic waders and shorebirds | < 1 year | 1 – 5 years | > 5 years |
| | Aerial divers, grazers, filterers and swimming divers | < 1 year | 1 – 3 years | > 3 years |
| **Rainfall** | All | At or above the baseline | Within 1 standard deviation of the baseline | More than 1 standard deviation below the baseline |
| **Vegetation "Greenness"** | All | At or above the baseline | Within 1 standard deviation of the baseline | More than 1 standard deviation below the baseline |

Assessment of habitat stress indicators is currently the most feasible approach for vulnerability mapping for waterbirds. Ideally, habitat stress assessment needs to be done at Basin to continental scale in a spatially explicit manner and therefore using spatially consistent habitat mapping. In future, mapping and assessment of habitats and associated stress should include parameters that represent the complexity of topographic, hydrological, vegetative and productivity variables influencing waterbird species habitat selection through their entire life cycles and lifespans. Given that this is currently not feasible, at minimum, stressors associated with habitat can be described by:

- vegetation community composition and structure (e.g. black box woodland vs phragmites reed beds vs lignum shrublands)
- vegetation condition (e.g. greenness), and
- flow/inundation regimes (Table 9).

These can be combined to assess stress in terms of all habitat types combined, as described above, or split by foraging vs breeding habitat availability and condition. For the purposes of this initial approach, 'refuge' habitats are viewed as a subset of foraging habitats, however future iterations may characterise and target refuge habitats as a separate category.

- An approximation of preferred foraging habitats and their locations for each species group is derived by intersecting Australian National Aquatic Ecosystem Classification polygons with species presence observations from available data sources, including the Atlas of Living Australia and MDBA records (see Appendices). Similarly, preferred breeding habitats can be derived by intersecting ANAE polygons with group breeding observations. The ANAE classification integrates the best available mapping data combined with simple rules to define ecosystem types using a small number of relevant attributes (e.g. water regime, water source, salinity, landform and dominant vegetation). The classification is currently used by the Murray-Darling Basin Authority (MDBA) and Commonwealth Environmental Water Holder (CEWH) staff to support monitoring, evaluation and adaptive management of water resources in the Basin.

Breeding records are identified and cross-checked using relevant record fields including 'Reproductive Condition', 'Taxon Remarks', 'Individual Count', and 'Sum of Nest'. Where coding systems such as eBird and NestWatch systems are used by observers, selected codes relevant to breeding are identified and used to filter the data. In MDBA records, the fields 'Sum of Count' and 'Sum of Nest' are used. Records with low confidence are excluded. For example, in identifying breeding sites using the ALA reproductive condition field, records tagged as 'none', 'F' (flying over), 'C' (courtship or copulation), 'suggestive behaviour', 'distraction display', 'breeding plumage' or 'adult' only are not included, and eBird records with moderator confidence of less than C4 (confirmed) are not included.

The resulting lists of ANAE types where records of the selected group exist are ranked by the number of observations and filtered to prioritise those types where records have occurred from 1980 onward in more than one year, or more than one location, or for more than one species in the species group. The period 1980 to present represents the period of Landsat and other satellite imagery availability upon which ANAE and other environmental mapping used for the method are based.

The resulting shortlists are then used to map the availability of preferred ANAE types (breeding or foraging) under different inundation scenarios for each species group.

Inundation regimes are defined for all Australian National Aquatic Ecosystem polygons that intersect the Murray-Darling Basin 'managed floodplain', using Geoscience Australia Wetland Inundation Tool (WIT) outputs derived from satellite imagery. These outputs represent flooding / flows and their effects on habitats as represented by specific habitat metrics, including:

- Bare soil extent or % (min, max, mean)
- Dry or brown vegetation extent or % (min, max, mean)
- Green vegetation extent or % (min, max, mean)
- Wet vegetation extent or % (min, max, mean)
- Open water extent or % (min, max, mean)

- Total vegetation extent or % (min, max, mean)
- Hydrated' vegetation extent or % (wet+green veg) (min, max, mean)
- All wet vegetation + open water extent or % (min, max, mean)

### *Other considerations*

It is important to acknowledge the complexities involved in understanding and predicting population dynamics and vulnerabilities and consequently the presence, species richness or abundance of waterbirds in the Basin as targeted by the Basin Watering Strategy. In discussing vulnerability assessment in the context of conservation, Foden et al. 2019 stated:

*'Understanding the mechanisms of potential impacts on species, that is, the chain of events between the exertion of the pressure and the potential impacts at species level, is particularly valuable. Firstly, the degree of confidence associated with a projected change impact is increased if there is evidence that the impact is underpinned by a known mechanism that also has been shown to be operating. Secondly, it can help to identify appropriate targets for conservation interventions, thus allowing development of strategies to disrupt mechanisms underpinning negative impacts.* ***Individual mechanisms may act alone, or in combinations that may be synergistic, antagonistic or neutral; mechanisms may also operate in different ways and to different extents at different times and/or locations.'***

At present, for most waterbird species occurring in Australia there are insufficient data available at the required scales to satisfactorily describe population dynamics and the mechanisms behind them. For this vulnerability assessment method, multiple iterations were involved in selection of initial indicators and thresholds, with approaches and datasets originally thought likely to be suitable repeatedly found to be unfeasible. Testing of the suitability of various datasets identified significant problems with data availability, quality, coverage and other parameters. In many cases this was due to a lack of Basin-scale, scientifically designed, on-ground research at appropriate temporal scales and resolutions. This resulted in a very limited final selection of potential indicators of waterbird species or group 'condition' in particular.

Problems with data sources, and especially public citizen science data, can cause significant gaps, biases, and other issues affecting the use of those data for new specific purposes. Some of these problems include: Spatially and temporally non-random or poorly distributed observations (biased by things such as time of day or week or year, weather, and human population density), lack of coverage of areas important for species of interest, non-standardized or unstructured effort (poor design), lack of consistency in methods, pseudo-duplication of records by multiple observers, under-detection, confusion between species, and the over- or under-reporting of rare, cryptic, or elusive species (Kosmala et al. 2016; Geldman et al. 2016).

It is a common perception that there are large quantities of data available for particular taxa – particularly for those taxa that are large or obvious such as birds. But the availability of certain types of data does not mean that they are fit for all purposes. The characteristics of each dataset need to be fully understood before use – which means reading and understanding exactly how the data collection was designed spatially and temporally, what it was originally designed for, the methods used and their limitations, the biases and gaps present and the caveats around use and interpretation.

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# Appendix D: Spatial analysis

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## Spatial Units

Basin assets are defined at different spatial scales for different purposes, ranging from individual wetlands and waterbodies to wetland complexes comprised of many wetlands (e.g. the Macquarie Marshes, Barmah-Millewa Forest) to river valleys, the northern and southern Basin and the whole Basin as a single unit. The approach used in this project was to treat the larger spatial scales as aggregations of the many smaller wetland and floodplain units within them. This approach reflects the fact that water may be delivered to individual wetlands and wetland complexes, however multiple watering actions at these scales contribute outcomes towards Basin objectives that are set at larger spatial scales, or indeed for the Basin as a whole.

### *Wetlands and Floodplains (ANAEv3)*

The MDB ANAE v3 data set provided GIS mapping of polygon boundaries for all mapped wetlands and floodplains in the Murray-Darling Basin. Very small features less than 1 hectare in area were not used as they were considered too small to reliably measure using the data sets derived from Landsat satellite imagery. An objective of the vulnerability assessment was to inform priorities for environmental water management, so we focussed on the 106, 551 ANAE wetlands and floodplains that that are estimated to be in scope for water management. These were identified as occurring on the Basin-wide watering strategy managed floodplain (MDBA 2014, 2019). The managed floodplain (Figure 34) maps the area where floodplain vegetation can be influenced with the 2075 GL of environmental water under the Basin Plan (MDBA 2019). It includes actively managed areas that can receive environmental water via large headwater storages or via The Murray–Darling Basin Authority's The Living Murray 'environmental works' sites on the River Murray floodplain, and passively managed areas that receive environmental water via flow rules in water resource plans or via natural events. The managed floodplain was recently updated to include all areas that have been managed with Commonwealth environmental water since regular monitoring began in 2014 (Brooks 2022). For this project we noted that the Kerang Lakes Ramsar site was an omission from the managed floodplain, so it was added. Measured by area, the managed floodplain contains approximately 32% of the area of Basin lakes, 37% of palustrine wetlands and 25% of the Basin's floodplain area (Brooks 2021).

### *Wetland complexes and Valleys*

Four data sets mapped the extent of larger scale wetland complexes: Ramsar Wetlands, the Directory of Important Wetlands (DIWA) and BWS important Basin environmental assets for waterbirds and BWS Vegetation Regions (Valleys) (Figure 35). The various land cover estimates, condition metrics and stress metrics that were generated for ANAE polygons on the managed floodplain were aggregated within each of these larger spatial scales using an area weighted sum.

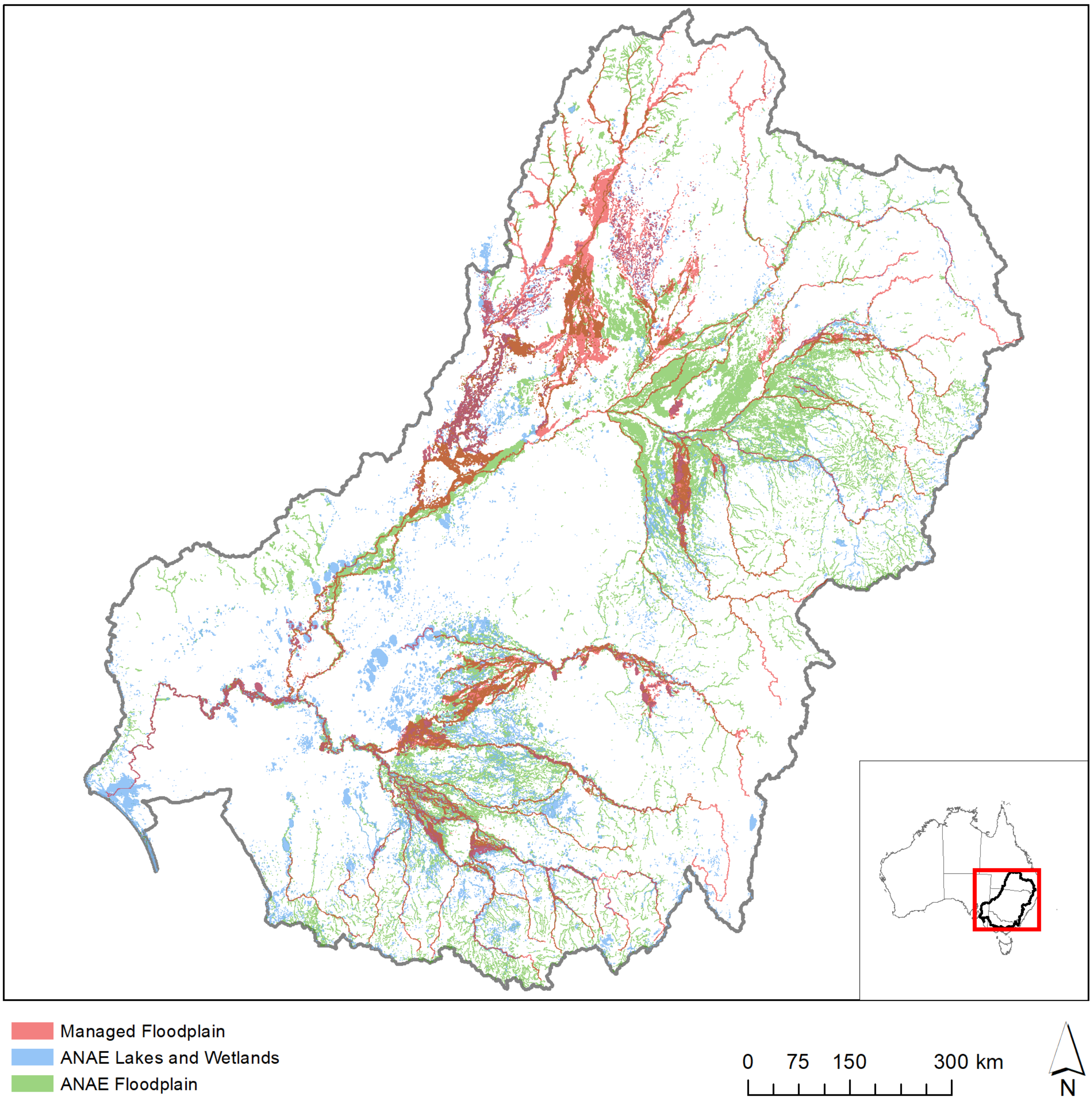


Figure 34 Spatial extent of the Basin-wide watering strategy managed floodplain compared to the extent of ANAE wetland and floodplain ecosystem types.

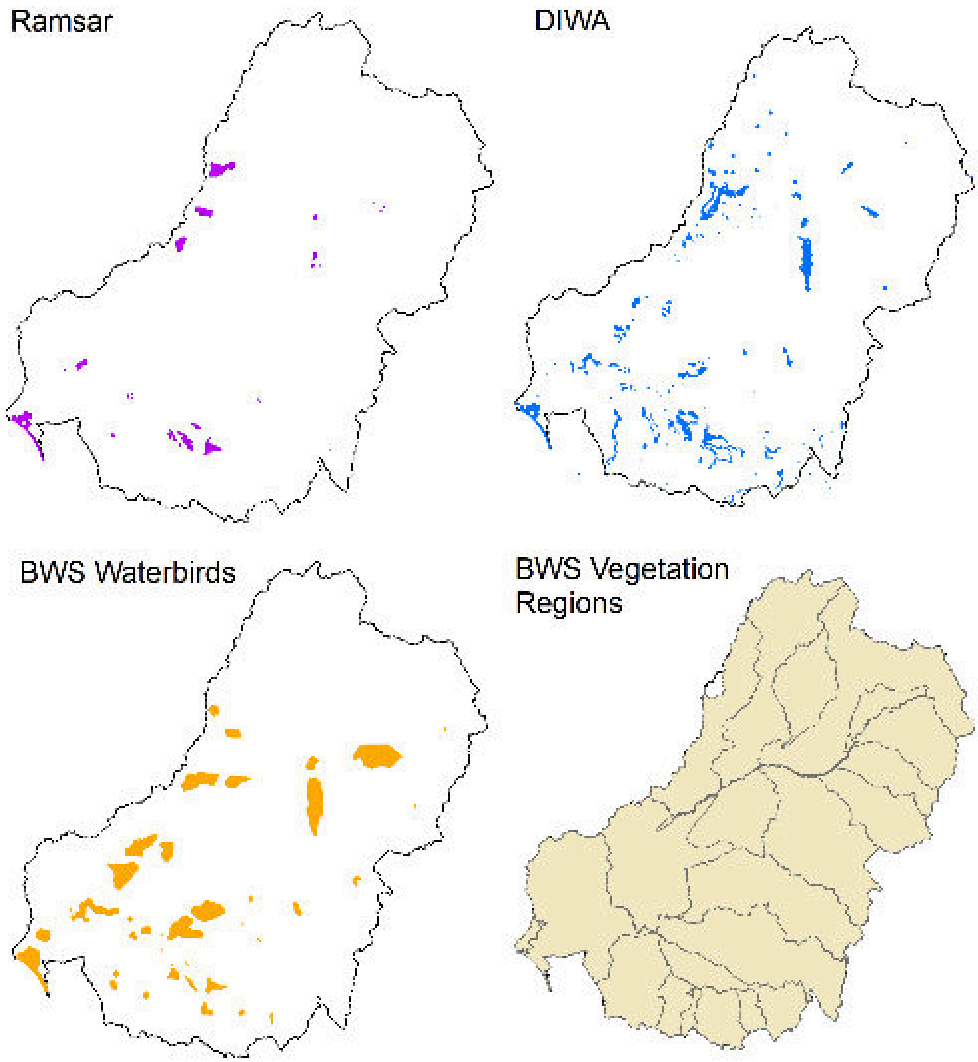


Figure 35. Wetland complexes and BWS asset scales used in the vulnerability assessment.

# Condition and Stress Metrics

## *WIT Land surface cover (water and vegetation)*

Geoscience Australia provided time series land surface cover outputs from the Wetland Insights Tool (WIT) for the 106, 551 mapped wetland and floodplains in the Murray-Darling Basin ANAE v3 data set that were greater than 1 hectare in size and located on the managed floodplain. The WIT land cover is measured in five categories presented as the percentage of the wetland area covered by bare ground, dry/non-green vegetation, green vegetation, wet vegetation (or water underlying vegetation) and open water for each Landsat imagery date (Dunn et al. 2019). The area obscured by cloud cover is also provided. Dates with less than 90% of the wetland area visible were excluded. This resulted in annual time series with between 1-127 observation dates in each calendar year (average of 32 observations per year) for a 36-year period from 1986 to April 2022. The time series proportional cover data were summarised into annual summary statistics for each wetland (minimum, mean, median and maximum extent of each cover type per year). The median extent of each metric was used to represent condition or stress and metrics were also combined (Table 56).

Table 56. Wit metrics and combinations with their interpretation

| WIT metric | Interpretation | Indicator |
|---|---|---|
| bare | % of wetland covered by bare ground | Stress (strong signal in drought years) |
| npv | % of wetland covered by dry vegetation (non-green reflectance) | |
| pv | % of wetland covered by photosynthetic vegetation (green vegetation reflectance) | |
| wet | % of wetland covered by water/vegetation mix or “wet vegetation” (thresholded tasseled-cap wetness) | |
| water | %cover of open water | |
| water+wet | Total inundation extent | Stress #1 (magnitude of inundation)<br>Stress (time since last inundation) |
| npv+pv+wet | % of wetland covered by all vegetation | Condition (total vegetation cover) |

Event statistics (e.g. inundation events from floods or water management) were characterised by first using a linear extrapolation of the annual time series into daily data. In the absence of flood inundation models or known flood thresholds for ANAE wetlands we used the median extent of open water combined with wet vegetation (median water+wet) as a trigger level to document a wet “event”. The daily time series for the 36-year period 1986-2022 was then analysed to record the starting date, duration and end date of all periods where the wetland water+wet exceeded its median. The duration of the interval between watering events was recorded as the “gap” duration between events. At the end of the sequence the final gap duration is recorded as the time since last inundation. This event analysis could also be completed for the vegetation cover fractions (e.g. to represent “greening events”) or for the bare soil fraction to identify periods of vegetation loss, however these were not explored further in this project. A copy of the python code used to analyse the WIT data is included in the Digital Earth Australia notebooks and tools repository (Krause et al. 2021).

### *Tree Stand Condition*

MDBA supplied the tree stand condition raster surfaces for 1987 and 2021. The raster surfaces represent tree condition modelled from Landsat reflectance data using machine-learning models calibrated by on-ground monitoring that have been run to hind-cast back through the Landsat data record to begin in 1987 (MDBA 2020). The resulting surfaces are calculated annually but represent overlapping 16-month epochs (September to January). The condition models are currently calibrated for river red-gum, black box and coolabah. For this project the stand condition was measured only in the ANAE wetlands and floodplains dominated by these three species using Google Earth Engine to summarise the mean tree-stand condition within each wetland polygon for each year. Condition of wetlands dominated by other species was estimated using a combination of the WIT-pv (green) and NDVI.

### *NDVI*

The Normalized Difference Vegetation Index is commonly used to estimate vegetation productivity. It is a simple ratio applied to satellite imagery that quantifies the difference in red light (absorbed by chlorophyl in actively growing healthy vegetation) and near-infrared (reflected by vegetation). NDVI was measured for each ANAE polygon in each year using Google Earth Engine from annual NDVI composite layers that combine all Landsat images within each year for the period 1986-2021.

### *Root Zone Soil Moisture*

Root Zone Soil Moisture is provided by the Bureau of Meteorology Australian Water Outlook to represent the percentage of available water content in the top 1 m of the soil profile (Bureau of Meteorology 2022b). It combines rainfall with the depth of soil and the relative soil water storage capacity. Soil properties that control the storage of water are derived from the continental scale mapping within Australian Soil Resources Information System (ASRIS; Johnston et al. 2003). Relative soil moisture was downloaded from the Australian Water Outlook for the period 1986-2022 as the relative annual anomaly and summarised for each ANAE wetland and floodplain polygon using the zonal statistics tools within ESRI ArcGIS Pro to calculate the mean decile anomaly.

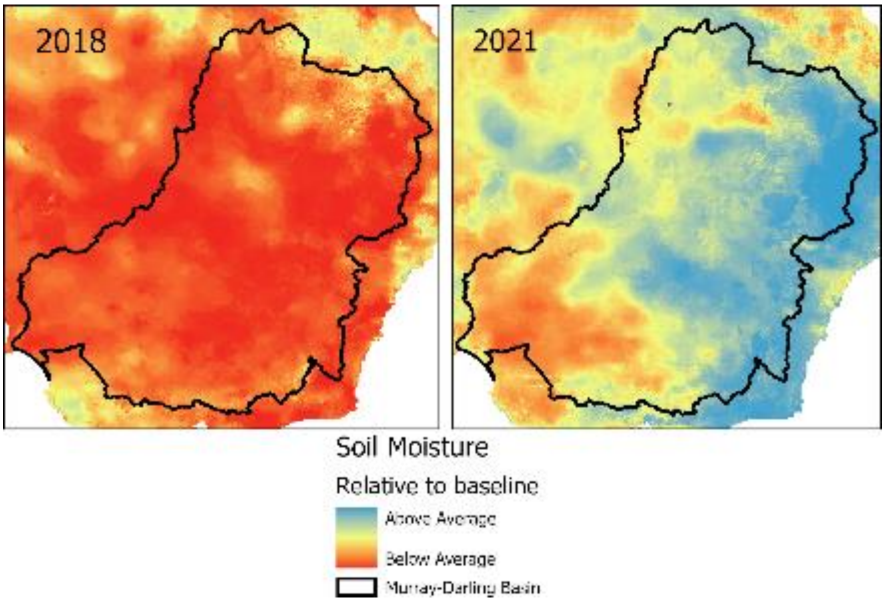


Figure 36. Australian Water Outlook relative Root Zone Soil Moisture comparing a dry year 2018 with a wetter 2021

### *Standardised anomalies*

Each wetland and floodplain area has a unique combination of waterbodies, land surface and vegetation that determine the value and variability of indicators obtained from satellite derived data sets (e.g. Figure 37). To compare among wetlands and among years we calculated a standardised anomaly as the difference between annual metric values and the long-term average (baseline) for each wetland standardised by the inter-annual variability represented by the standard deviation (SD) (Figure 38). Indicator values that are more than one SD above or below the baseline are considered 'atypical' and may indicate a period of environmental stress or uncharacteristically favourable conditions. The baseline period was defined as the duration of the Landsat data record (1986-2021/22) excluding the Millennium drought (2001-2009). The severe drought was excluded to prevent distortion of the baseline by the extreme dry years which increases the sensitivity of the method to detect similar dry conditions as an anomaly that might indicate stress. For example, short periods of atypically wet conditions (SD >1) and dry conditions (SD <1) can be detected in all three wetlands in Figure 38 outside of the millennium drought.

The root zone soil moisture was already standardised as the relative soil moisture in deciles deviating from the long-term average so was used as the mean decile value per wetland without standardising further. Likewise, time since last inundation used as an absolute threshold for different plant functional groups.

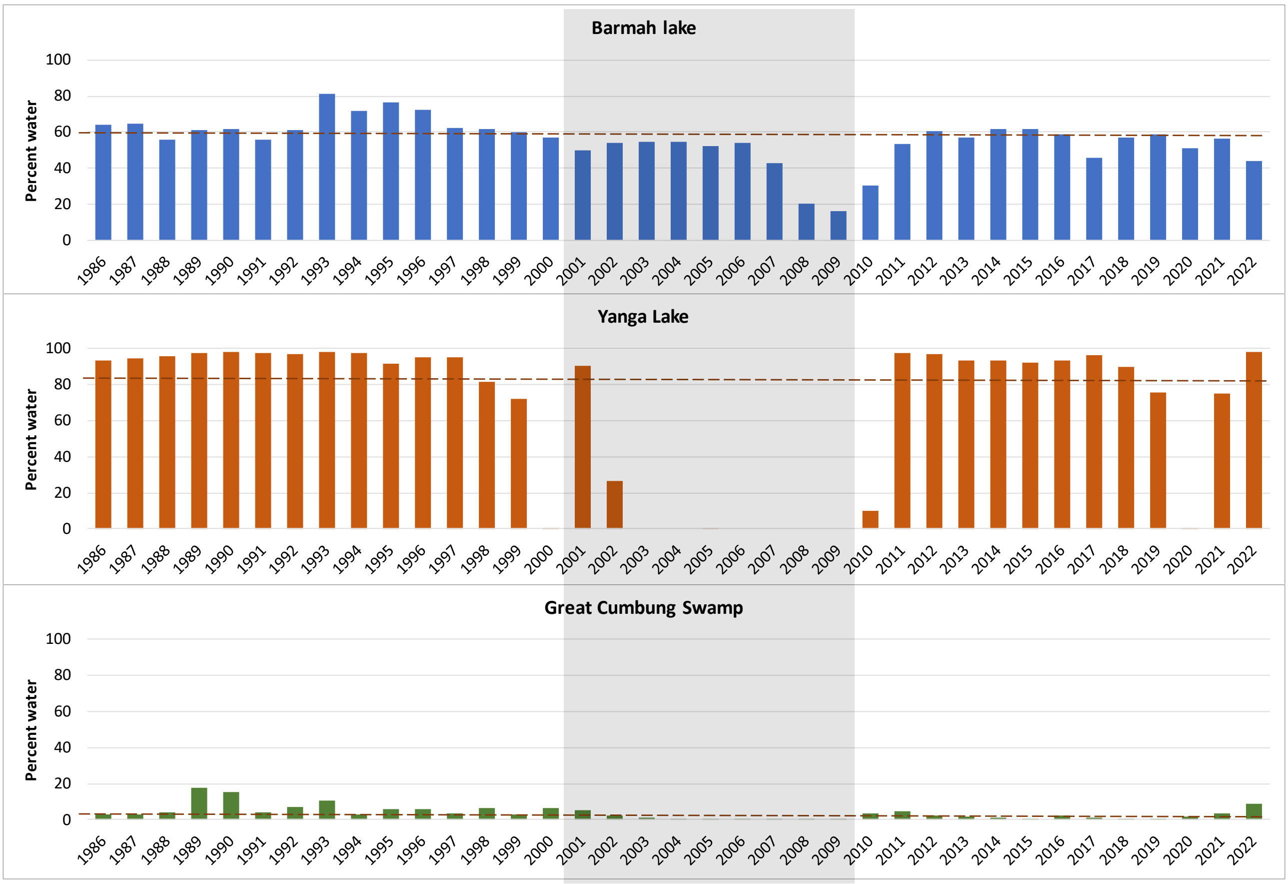


Figure 37. Plots of unstandardised annual median percent inundation (WIT water+wet metric) for three ANAE polygons on the managed floodplain. With different average baseline conditions (dashed line) and interannual variability is difficult to compare among wetlands or identify changing condition other than the obvious impact of the Millennium Drought (grey shading).

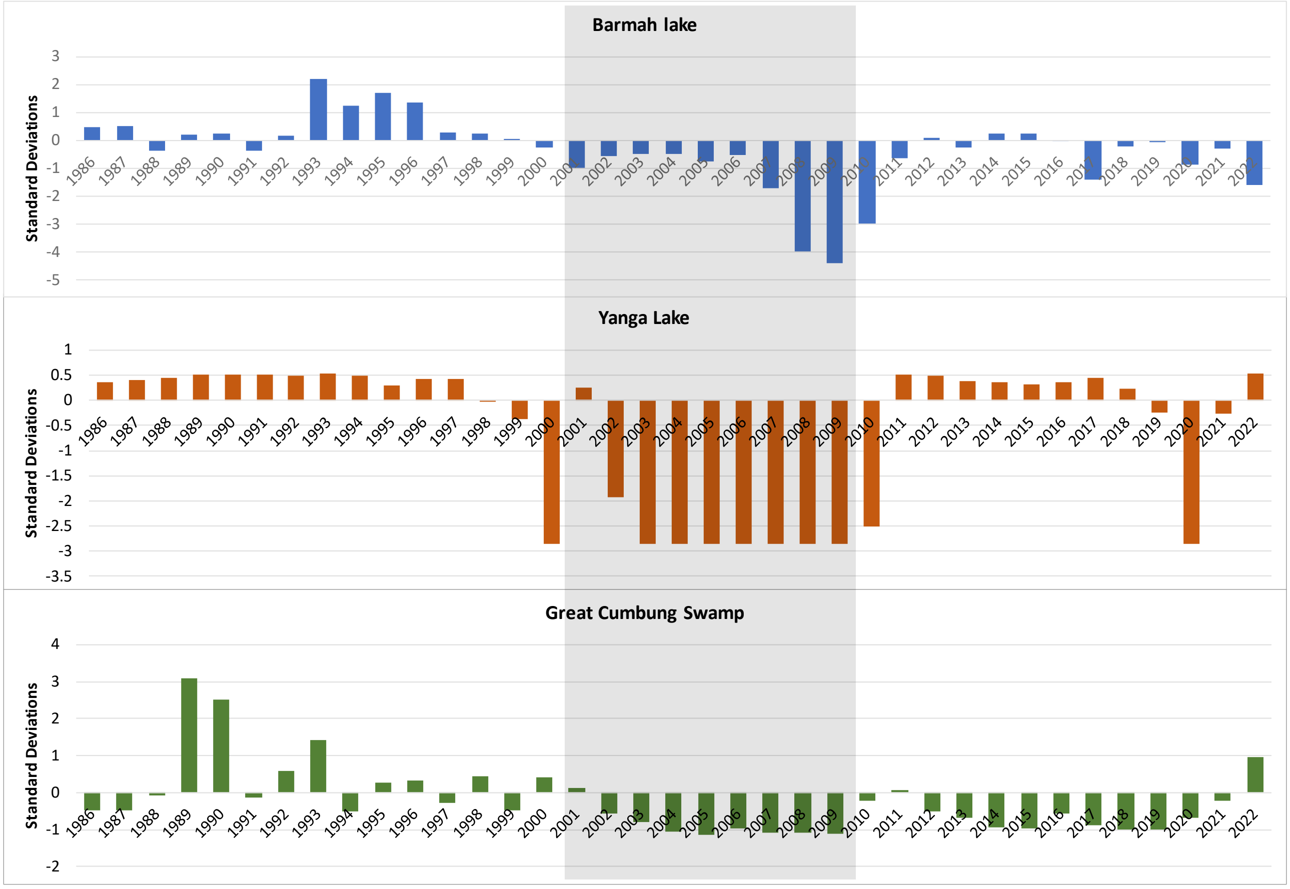


Figure 38. Standardised anomaly plots for annual median inundation (WIT water+wet metric) for three ANAE wetlands on the managed floodplain. Grey shading indicates the period of the Millennium Drought.

# Workflow and aggregation

Analyses were coded in a Jupyter Python notebook for repeatability of the analyses. Data were processed in the following steps:

1. Extraction annual metrics from time series for each individual ANAE polygon boundary.
    - Waterbird counts (number of individuals, species richness, breeding)
    - Tree stand condition
    - WIT (annual median inundation, annual median vegetation cover, time since last inundation)
    - NDVI (annual aggregate, mean per wetland)
    - Root zone soil moisture (annual decile anomaly)
2. Calculate annual anomaly as deviation from baseline standardised by the standard deviation for every ANAE wetland/floodplain polygon on the managed floodplain.
3. As long-lived vegetation respond to conditions over multiple years, each annual measure excluding time since last inundation was calculated as a five year moving average (e.g. stress in 2021 is represented by the average inundation through the 5 years (2017-21). Condition and stress metrics for waterbirds used the annual data without combining years.
4. The condition and stress measures for individual ANAE polygons were then aggregated as an area weighted sum to each of the larger spatial scales:
    - Ramsar Wetlands
    - Directory of Important Wetland Sites (DIWA)

- BWS important Basin environmental assets for waterbirds
- BWS Vegetation Regions (Valleys)
- the whole Basin

5. The individual metrics were scored at the ANAE wetland polygon scale, and again at each larger scale aggregate using the following logic:
    - Condition:
        - Better: anomaly ≥ Baseline
        - Medium: anomaly between 0 and 1 SD below baseline
        - Worse: anomaly more than 1 SD below baseline
    - Stress:
        - Low: anomaly ≥ Baseline
        - Medium: anomaly between 0 and 1 SD below baseline
        - High: anomaly more than 1SD below baseline
        - Time since last inundation applied as thresholds as noted in the vegetation (Table 5) and waterbird methods (Table 11)
6. The various condition scores are summed to provide a single overall condition score per ANAE polygon or asset-scale aggregate. There are different numbers of metrics contributing to the summed scores (only river redgum, black box and coolibah dominated locations have tree stand condition) so the overall score is re-scaled to be between 0 and 1. Overall stress is calculated the same way.
7. Vulnerability is the sum of Stress + Condition divided by 2 to give a vulnerability score scaling from 0 (most vulnerable) to 1 (least vulnerable).

# How to implement the method annually

The method is configured to be run on a two Jupyter notebooks; the BWS vulnerabilities notebook and the WIT_Metrics notebook.

## *BWS Vulnerabilty Notebook*

This Jupyter notebook is the final stage of data processing that pulls together multiple data sets to summarise and score the condition metrics, stress metrics and then add the scores to the final vulnerability metric. Multiple input data files are read in, pivoted to tabular format with years as columns. The measurement of vulnerability relies on first calculating the long-term baseline (mean of all years excluding the Millennium Drought) then scoring the deviation from the baseline. Metrics calculated for ANAE ecosystem polygons are aggregated together as an area weighted average for larger spatial units (e.g. Ramsar sites, valleys).

**Data Inputs**

1. Australian National Aquatic Ecosystem (ANAE) mapping v3 - The ANAE identifies different vegetation types and provides the spatial units used to summarise other data. Polygons < 1 Ha are removed as they are too small to meet the reliability requirements of the WIT tool and MODIS derived NDVI.
2. Geosciences Australia Wetland Insights Tool (WIT) - WIT data observations for all ANAE polygons > 1 Ha in the MDB 1986-present. Raw data supplied by Geosciences Australia for individual observation dates through the Landsat Record summarised into daily, yearly, all-time and inundation event statistics (a separate Jupyter notebook)
3. MDBA Tree Stand Condition Tool Rasters - Average condition per ANAE polygon per year 1986-present calculated using google earth engine reducer shared

code: https://code.earthengine.google.com/3b7223339c2c3cffb973b1280d5dd047 or https://code.earthengine.google.com/?scriptPath=users%2Flitepc%2FShaneGitRepo%3AeeBWS_MeanTSC_ANAEv3

4. Normalized Difference Vegetation Index (NDVI) - Average NDVI per ANAE polygon per year 1986-present calculated using google earth engine reducer: shared code: https://code.earthengine.google.com/4db0904f68e5c27fef8e8eb8fb75a375 or https://code.earthengine.google.com/?scriptPath=users%2Flitepc%2FShaneGitRepo%3AeeBWS_MODIS_NDVI_ANAEv3
5. Root Zone Soil Moisture (Australian Water Outlook) - Mean root zone soil moisture per ANAE polygon per year was generated using ArcGIS but there are many ways to calculate the annual average per polygon from the AWO netcdf https://awo.bom.gov.au/products/historical/soilMoisture-rootZone
6. Aggregated Waterbird observations (Atlas of Living Australia combined with Aerial Surveys) - Data set cleaned and manually curated by Jennifer Hale with input from Heather McGuinness
7. Stress thresholds for vegetation and waterbirds based on durations since last inundation for different functional groups that were identified by experts are coded directly into this Jupyter Notebook

**Data Outputs**

The notebook writes the various metric to the working directory in tabular format csv files (spatial units in rows, years in columns) that can be read by Microsoft Excel. Baseline values and scores are added to the tables as additional columns.

Output files follow the naming convention: {metric}*{aggregator}*{year_window_width}yr_condition.csv e.g. pv_median_DIWA_5yr_condition.csv is the median "pv" (green fractional cover) with ANAE polygons aggregated to larger DIWA wetland scales using a 5-year moving window in which to calculate rates of change.

**Processing Environment**

For the project the analysis was conducted in the python processing environment of ArcGIS Pro 3.0 but were coded to use common open-source python data processing libraries (Geopandas, Pandas, numpy) that should enable the analysis to be repeated in most environments.

## *WIT_METRICS Notebook*

**Generate metrics with WIT data**

- **Lineage**: This notebook was derived from code by Geosciences Australia and modified for:
- batch input of multiple WIT CVS in a folder (currently the ANAEv3 WIT output includes 270,653 polygons, each with its own csv file)
- multiple processor pool support to speed execution when running on a PC workstation
- linear interpolation of the observations dates to daily data to improve estimates of inundation duration
- some bug fixes in the inundation event metrics that were required when using the interpolated data
- output formatting
- Original Source: https://github.com/GeoscienceAustralia/dea-notebooks/blob/develop/Scientific_workflows/Wetlands_Insight_Tool/metrics/wit_metrics.ipynb

- **Dependencies**: This code requires two things to run (see the analysis parameters section for more information):
    - A folder containing pre-calculated WIT csv (obtained for the BWS Priorities Project from Geosciences Australia for each ANAE polygon > 1Ha)
    - A shapefile (or equivalent) that contains the area that the WIT result was run over.

**Background**

The WIT data are generated by DEA with given wetland polygons and stored in a database on NCI. The data can be dumped into a csv when required. Any statistics can be generated with WIT data. This notebook provides a way in computing temporal statistics (metrics).

**WIT Data definition**

- WIT data provides the following metrics for each polygon unit

date: time of observation

bs: percentage of bare soil

npv: percentage of non photosynthetic vegetation

pv: percentage of green/photosynthetic vegetation

wet: percentage of wetness

water: percentage of water

**Description**

This notebook uses existing WIT data to compute metrics.

- First we load the existing WIT csv data from a saved csv location
- Then we compute the metrics for all polygons and output the results to CSV files. The input CSV files are processed in "batches" that are spread across multiple CPU cores. When execution is complete the various batch outputs are merged together into single result files that contain metrics for every CSV feature ID (ANAE polygons)

The following files are created:

- **RESULT_WIT_ANAE_yearly_metrics**: min, max, mean, median of each WIT metric per calendar year
- **RESULT_WIT_ANAE_event_threshold**: for the BWS project we defined an "event" as exceeding the median [water+wet] - this file is read in to calculate the event metrics but could be replaced with user selected values if custom thresholds were wanted or the routine that generates it could be altered to change the threshold formulaically.
- **RESULT_WIT_ANAE_time_since_last_inundation**: number of days since the inundation event threshold was exceeded
- **RESULT_WIT_ANAE_event_times**: start and end time, duration, duration of preceding gap (the dry period)
- **RESULT_WIT_ANAE_event_stats**: for each event calculates the area of the polygon that was wet using the combination water+wet
- **RESULT_WIT_ANAE_inundation_metrics**: this is a join of the RESULT_WIT_ANAE_event_time and RESULT_WIT_ANAE_event_stats

- WIT metrics: refer WIT metrics

**Processing Environment**

For the project the analysis was conducted in the python processing environment of ArcGIS Pro 3.0 but were coded to use common open-source python data processing libraries (Geopandas, Pandas, numpy) that should enable the analysis to be repeated in most environments.