

Australian Government



Assessment of environmental water requirements for the proposed Basin Plan: Edward–Wakool River System Published by Murray-Darling Basin Authority Postal Address GPO Box 1801, Canberra ACT 2601 Office location Level 4, 51 Allara Street, Canberra City Australian Capital Territory For further information contact the Murray-Darling Basin Authority office Telephone (02) 6279 0100 international + 61 2 6279 0100 Facsimile (02) 6248 8053 international + 61 2 6248 8053 E-Mail info@mdba.gov.au Internet http://www.mdba.gov.au

MDBA Publication No: 33/12

ISBN: 978-1-922068-41-5 (online)

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Murray Region

Assessment of Edward–Wakool River System environmental water requirements

1. Introduction

The Water Act 2007 (Cwlth) established the MurrayDarling Basin Authority (MDBA) and tasked it with the preparation of a Basin Plan to provide for the integrated management of the Basin's water resources. One of the key requirements of the Basin Plan is to establish environmentally sustainable limits on the quantities of surface water that may be taken for consumptive use, termed Sustainable Diversion Limits (SDLs). SDLs are the maximum long-term annual average volumes of water that can be taken from the Basin and they must represent an Environmentally Sustainable Level of Take (ESLT).

The method used to determine the ESLT is described in detail within 'The proposed "environmentally sustainable level of take" for surface water of the Murray-Darling Basin: Method and Outcomes,' (MDBA 2011). A summary of the main steps undertaken to determine the ESLT is presented in Figure 1. The assessment of environmental water requirements including specification of site-specific flow indicators at a subset of hydrologic indicator sites (Step 3 of the overall ESLT method) is the focus of this document.

The work described herein is the MDBA's current understanding of the environmental water requirements of the Edward-Wakool River System. It is not expected that the environmental water requirements assessments will remain static, rather it is intended that they will evolve over time in response to new knowledge or implementation of environmental watering actions. Within this context, feedback is sought on the material presented within this document whether that be as part of the formal draft Basin Plan consultation phase or during the environmental watering implementation phase within the framework of the Environmental Watering Plan.

1.1. Method to determine site-specific flow indicators

Assessment of environmental water requirements for different elements of the flow regime using the hydrologic indicator site approach is one of the key lines of evidence that has informed the proposed SDLs. Effort focussed on regions and parts of the flow regime with greatest sensitivity to the scale of reduction in diversions necessary to achieve environmental objectives, an ESLT and a healthy working Basin.

Within the overall framework of the ESLT method (Figure 1) the MDBA used an iterative process to assess environmental water requirements and develop site-specific flow indicators.

The hydrologic indicator site approach uses detailed eco-hydrological assessment of environmental water requirements for a subset of the key environmental assets and key ecosystem functions across the Basin. Effort focused on high flow (freshes, bankfull flows and overbank flows) requirements reflecting the prioritisation of effort on parts of the flow regime that are most sensitive to the determination of the ESLT and SDLs. The Edward-Wakool River System is one of the key environmental assets where a detailed assessment of environmental water requirements was undertaken.



Figure 1: Outline of method used to determine an Environmentally Sustainable Level of Take (Source: MDBA 2011).

Detailed environmental water requirement assessments lead to the specification of site-specific flow indicators to achieve site-specific ecological targets. Flow indicators were expressed at a hydrologic indicator site or sites. Environmental water requirements specified at hydrologic indicator sites are intended to represent the broader environmental flow needs of river valleys or reaches and thus the needs of a broader suite of ecological assets and functions.

This report provides a description of the detailed eco-hydrological assessment of environmental water requirements for the Edward-Wakool River System including information supporting the development

of site-specific flow indicators for the site (with reference to flows gauged on the Edward River at Deniliquin). More information on how the site-specific flow indicators for the Edward-Wakool River System were used within the Basin-wide modelling process to inform the ESLT (i.e. Step 5 and 6 in Figure 1) can be found in the report *'Hydrologic modelling to inform the proposed Basin Plan: Methods and results'* (MDBA 2012).

A description of the detailed eco-hydrological assessments of environmental water requirements for other indicator sites are described in other documents in the series 'Assessment of environmental water requirements for the proposed Basin Plan'.

1.2. Scope and purpose for setting site-specific flow indicators

The MDBA's assessment of environmental water requirements and associated site-specific flow indicators at hydrologic indicator sites has been used to inform the development of SDLs. This enables the MDBA to estimate the amount of water that will be required by the environment over the long-term to achieve a healthy working Basin through the use of hydrological models. Accordingly, site-specific flow indicators are not intended to stipulate future use of environmental water. MDBA expects that the body of work undertaken to establish these site-specific flow indicators will provide valuable input to environmental watering but this watering will be a flexible and adaptive process guided by the framework of the Environmental Watering Plan and natural eco-hydrological cues. It will be up to the managers of environmental water, such as the Commonwealth Environmental Water Holder, State Government agencies, and local communities to decide how best to use the available environmental water during any one year to achieve environmental outcomes.

2. Site location and extent

The Edward–Wakool River System consists of a mosaic of river, wetland and floodplain and covers an area of more than 1,000 km² between the Murray and Edward Rivers (Figure 2). The Edward River is the largest anabranch of the River Murray and breaks away from the River Murray near Mathoura, flowing north to Deniliquin and then westward. Between the Edward River and the River Murray is a complex network of interconnecting regulated streams and ephemeral creeks and wetlands; of which the Wakool River is the largest. The Wakool rejoins the Edward River, then the River Murray 500 km downstream of Deniliquin. Ephemeral wetlands include billabongs, lagoons, depressions, creeks, flood runners and lakes. The system includes a diversity of wetland and riverine habitats that are of cultural, economic and environmental significance to the Murray region (Green 2001).

The extent of the Edward-Wakool River System hydrologic indicator site has been defined using a number of data sources. The Wetlands Geographic Information System (GIS) of the Murray–Darling Basin series 2.0 dataset (Kingsford, Thomas & Knowles 1999) was used to determine the downstream extent as the junction of Wee Wee Creek and River Murray. The upstream extent of the site was determined as the junction of Tuppal Creek and Edward River based on data from A Directory of Important Wetlands in Australia (Department of the Environment, Water, Heritage and the Arts 2001). The AusHydro watercourse lines dataset was used to define the extent of the Wakool River. Spatial data used in this map is listed in Appendix A.



Figure 2: Location and extent of the Edward–Wakool River System hydrologic indicator site. Flow indicators are specified at Deniliquin on the Edward River.

3. Ecological values

The Edward–Wakool River System supports large areas of flood dependent vegetation communities dominated by river red gum (*Eucalyptus camaldulensis*), black box (*E. largiflorens*) and lignum (*Muehlenbeckia florulenta*), including Werai Forest and the Wakool Forest.

Werai Forest covers an area of about 11,000 ha and comprises the northern portion of the NSW Central Murray State Forest Ramsar site, which was Ramsar-listed in 2003 (GHD 2009). Werai Forest comprises the greatest extent of river red gum forest and woodlands in the system while also containing significant areas of reed beds and other low-lying wetlands that provide suitable waterbird breeding habitat.

The condition of Werai Forest as part of the larger Edward–Wakool River System is reported to have declined significantly under the combined impacts of drought and river regulation (GHD 2009). GHD (2009) reported that the 'droughting' of river red gums through changes to the natural wetting and drying cycles had significantly impacted on their health and vigour. In 2006, the condition of river red gum communities in Werai Forest was assessed as poor with the majority unhealthy. As an example, 92% of river red gum forests with flood-tolerant understorey were 'highly stressed, near dead and dead' (GHD 2009). This is believed to be representative of the condition of the entire Edward–Wakool River System prior to breaking of the Millennium Drought in 2010.

Irrespective of the observed decline in ecological condition, the Edward–Wakool River System still supports important habitat and species that are listed in international agreements such as the Ramsar Convention, and include vulnerable and endangered species. Appendix B provides a summary of the conservationally significant species recorded at the site.

The Edward–Wakool River System is recognised as an important area for native fish populations. Gilligan, Vey and Asmus (2009) suggest that the Edward-Wakool plays an important role in providing drought refuge for fish at a local and broader River Murray scale. The Sustainable Rivers Audit (Davies et al. 2008) indicates the fish community of these anabranches includes large populations of the vulnerable Murray cod (*Maccullochella peelii peelii;* listed under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999) and silver perch (*Bidyanus bidyanus;* listed under the NSW Fisheries Management Act 2004). Sampling at this site provided the fourth and third highest abundances for these two species across all catchment zones within the entire Murray–Darling Basin (Davies et al. 2008).

The ecological values of the Edward-Wakool River System are reflected in MDBA's assessment against the criteria used to identify key environmental assets within the Basin. The MDBA established five criteria to identify assets based on international agreements and broad alignment with the National Framework and Guidance for Describing the Ecological Character of Australian Ramsar Wetlands (Department of the Environment, Water, Heritage and the Arts 2008) and the draft criteria for identifying High Conservation Value Aquatic Ecosystems (SKM 2007).

Based on the ecological values identified within the Edward–Wakool River System, the site meets four of the five key environmental asset criteria (Table 1).

Table 1 Assessment of the Edward–Wakool River System against MDBA key environmental asset criteria.

Criterion		Ecological values that support the criterion		
1.	The water-dependent ecosystem is formally recognised in international agreements or, with environmental watering, is capable of supporting species listed in those agreements	The Edward–Wakool River System is formally recognised in, or is capable of supporting species listed in, the Japan–Australia Migratory Bird Agreement, the China–Australia Migratory Bird Agreement or the Republic of Korea – Australia Migratory Bird Agreement. The site contains Werai Forest, which is part of the NSW Central Murray State Forests Ramsar site. Species listed in international agreements that have been recorded in the Edward–Wakool River System are in Appendix B.		
3.	The water-dependent ecosystem provides vital habitat	The site provides an important breeding/spawning habitat for native birds and fish, migratory routes between in-stream and floodplain habitats, a highly significant drought refuge during dry seasons and favourable habitat during wet seasons. Gilligan, Vey and Asmus (2009) mapped drought refugia within the Edward–Wakool River System and suggested that due to the presence of large populations of conservationally significant native fish, the Edward–Wakool is an important drought refuge to aid in the post-drought recovery of the River Murray.		
4.	Water-dependent ecosystems that support Commonwealth, State or Territory listed threatened species or communities	Species and communities listed as threatened under both Commonwealth and state legislation that have been recorded at the site are in Appendix B		
5.	The water-dependent ecosystem supports, or with environmental watering is capable of supporting, significant biodiversity	The Edward–Wakool River System, including Werai Forest, has been assessed as a 'site of high biodiversity for native fish' after analysing and comparing data for sample locations across New South Wales (data sourced from freshwater fish research database, NSW Industry and Investment). Similarly, the Sustainable Rivers Audit sampling undertaken in 2005 indicates the fish community of these anabranches includes large populations of the conservationally significant Murray cod and silver perch (Davies et al. 2008).		

4. Hydrology

The hydrology of the network of interconnecting regulated streams and ephemeral creeks and wetlands that make up the Edward–Wakool River System is complex as flow can arrive from a number of locations independently or at the same time. The main watercourses that carry flow into the Edward–Wakool River System from the River Murray are the Edward River and the Gulpa Creek, which begin in the Barmah–Millewa Forest. When River Murray flow downstream of Yarrawonga Weir is greater than 10,400 ML/d, the flow exceeds the capacity of the main channel through the Barmah Choke. When this

occurs substantial volumes of water flow through the Millewa Forest and into the Edward River and ultimately to the Werai forests (GHD 2009).

The Edward–Wakool River System is supplemented with water from a number of secondary sources with the region criss-crossed with ephemeral creeks, some greater than 100 km long, that require moderate to large floods of suitable duration before they receive water. This includes Bullatale and Tuppal Creeks which flow out of the River Murray between Tocumwal and Barmah–Millewa Forest. In addition, Thule and Barbers Creeks (unregulated flow via Koondrook–Perricoota Forest) and Little Merran and Waddy Creeks (both regulated) leave the River Murray between Echuca and Swan Hill and flow into the lower Wakool River at various locations. The Poon Boon Lakes system provides another link between the Murray and Wakool Rivers during larger flood events. Billabong Creek, which flows into the Edward River at Moulamein, provides water from its own catchment as well as regulated and flood flows from the Murrumbidgee River (Green 2001).

The complex nature of flooding in the Edward–Wakool River System means that the characteristics of individual flood events vary. On average the Werai forests are flooded 3 to 4 days after the Millewa forests are flooded (GHD 2009). Due to the geography of the central Murray floodplain, the Edward–Wakool River System carries a significantly greater volume of water than the River Murray during moderate and major flooding (GHD 2009). For example, in 1993 the peak flow at Stoney Crossing on the Wakool River was 103,000 ML/d, whereas the River Murray at Swan Hill was only 34,000 ML/d. Flood waters in the Edward River at Deniliquin also expand into the broader Edward–Wakool River System, generally flowing in a north-westerly direction, before finally returning to the River Murray some 200 km to the west at Wakool Junction (GHD 2009). Large areas of floodplain, including black box depressions, become inundated during large flood events.

River regulation has been implicated in the steady decline of ecosystem health of the NSW Central Murray State Forests, including Werai Forest, over the last 75 years (GHD 2009). Inappropriate flood regimes have had the main adverse impact on the ecological character of the site (GHD 2009). The general impacts of river regulation on the hydrology of the Murray system include reduced variability of in-stream flow, reduced flood frequency, reduced flood extent, reduced flood duration, an increase in summer and autumn streamflow, and a shift in the timing of flood peaks (GHD 2009). Regulated flows in the Edward River reflect seasonal water demands for the irrigation season, with higher flows in the summer months than would have occurred naturally at that time.

In order to address changes to the flow regime due to river regulation, managed environmental watering is now a critical component of maintaining and restoring the ecological character of the NSW Central Murray State Forests (GHD 2009). Within this context, the NSW Murray Wetlands Working Group, with the assistance of Murray Irrigation Limited and the local community, has provided over 28,000 ML of water to 93 wetland sites covering more than 4,000 ha in the area bounded by the Edward–Wakool River System during the very dry period 2004-2008 (Bowen & Nias 2008).

5. Determining the site-specific flow indicators for the Edward–Wakool River System

5.1. Setting site-specific ecological targets

The objective setting framework used to determine the ESLT is outlined in the report '*The proposed* "*environmentally sustainable level of take*" for surface water of the Murray-Darling Basin: Method and Outcomes' (MDBA 2011). In summary, the MDBA developed a set of Basin-wide environmental objectives and ecological targets, which were then applied at a finer scale to develop site-specific objectives for individual key environmental assets. Using these site-specific objectives, ecological targets that relate specifically to the Edward-Wakool River System were developed (Table 2). Information underpinning site-specific ecological targets is shown in Table 2.

Site-specific ecological targets formed the basis of an assessment of environmental water requirements and the subsequent determination of site-specific flow indicators for the Edward-Wakool River System, as described below.

Site-specific ecological targets	Justification of targets
• Provide a flow regime which ensures the current extent of native vegetation of the riparian, floodplain and wetland communities is sustained in a healthy,	The site includes Werai Forest, which is part of the NSW Central Murray State Forests Ramsar site. By providing a flow regime that supports the maintenance of the current area of wetlands, as advised by GHD (2009), the ecological character of Werai Forest will be conserved. The site supports a number of different flood dependent vegetation types which are
 dynamic and resilient condition. Provide a flow regime which supports the habitat requirements of waterbirds and is conducive to successful breeding of colonial nesting waterbirds. Provide a flow regime 	important habitats for a range of biota. The NSW Central Murray State Forests are the largest complex of tree-dominated floodplain wetlands in southern Australia (GHD 2009). River red gum woodlands are productive habitats that support bird foraging and breeding after flood events. The site is formally recognised in, or is capable of supporting species listed in, the Japan–Australia Migratory Bird Agreement, the China–Australia Migratory Bird Agreement or the Republic of Korea–Australia Migratory Bird Agreement. Breeding of species listed under migratory bird agreements is supported by inundation of river red gum woodlands. Similarly, black box woodland is important habitat for a range of species.
 which supports a range of native aquatic species (e.g. fish, frogs, turtles and invertebrates). Provide a flow regime which supports key constructors 	Consistent with ecological character descriptions from other Ramsar-listed indicator sites along the River Murray (e.g. Gunbower and Barmah forests, Hattah Lakes) it is considered that a decrease in the area or a change in the distribution of wetland or floodplain vegetation communities would signal a change in the ecological character of the Edward-Wakool River System.
particularly those related to connectivity between the river and the floodplain	Werai Forest is a known area for waterbird breeding. GHD (2009) specifies a change in ecological character would be signalled by successful breeding of hundreds of colonial nesting waterbirds occurring in less than three out of ten years.
	The site supports important habitat and species that are listed in international agreements such as Ramsar. The Edward–Wakool River System is recognised as vital habitat and drought refuge for native fish populations including vulnerable and endangered species such as Murray cod (<i>Maccullochella peelii peelii</i>) and silver perch (<i>Bidyanus bidyanus</i>). Achieving the targets for floodplain wetlands and waterbirds will ensure inundation of

Table 2 Site-specific ecological targets for Edward–Wakool River System.

breeding and feeding habitats considered key for a range of fish, amphibian and water- dependent reptile and invertebrate species.
Key ecosystem functions support fish, birds and invertebrates through habitat maintenance, energy transfer and facilitating connections between rivers and floodplains. Overbank flows supply the floodplains with nutrients and sediments from the river, accelerate the breakdown of organic matter and supply water to disconnected wetlands, billabongs and oxbow lakes. As the floodwaters recede, the floodplains provide the main river channel with organic matter.
The hydrological connection between watercourses and their associated floodplain provides for the exchange of carbon and nutrients (Thoms 2003). The connections are considered essential for the functioning and integrity of floodplain-river ecosystems.

5.2. Information used to determine site-specific flow indicators

5.2.1. Vegetation

The ecological character description for the NSW Central Murray State Forest (incorporating Werai Forest) identifies hydrology as the key driver of the system, with variation in flood regime across the River Murray floodplain being the primary determinant of vegetation composition and structure (GHD 2009). There is a strong link between the frequency, timing and duration of flood events and maintaining the ecological character of the Werai Forest (GHD 2009) and in turn the broader Edward-Wakool River System.

The development of site-specific flow indicators to achieve the ecological target of providing a flow regime which ensures the current extent of native vegetation of the riparian, floodplain and wetland communities is sustained in a healthy, dynamic and resilient condition focused on assessment of the bankfull and overbank elements of the flow regime.

A number of documents were assessed to determine the flow required to achieve site-specific ecological targets, as described below. However, it was found that no single existing plan or document sets out these requirements completely. Unlike hydrologic indicator sites along the River Murray, there has not been comprehensive mapping of vegetation types and other habitat components across the large, complex Edward–Wakool River System, with information only available for Werai Forest (GHD 2009). Similarly, while floodplain inundation at different streamflow levels and forest health have both been spatially mapped for the Koondrook forests, and are in preparation for the Millewa forests, the Werai forests have not been mapped and modelled in this way (GHD 2009).

In the absence of a comprehensive assessment of the water requirements of flood dependent vegetation communities of the Edward-Wakool River System, information for this purpose has been based on the Werai Forest and drawn from nearby sites, including the NSW Central Murray State Forest, as these sites are likely to have similar water requirements to the Edward–Wakool River System. The ecological character description for the NSW Central Murray State Forest Ramsar site (GHD 2009) sets out flood frequencies and durations of selected habitat types / vegetation communities before river regulation (Table 3). This is broadly consistent with the requirements of flood dependent vegetation communities described by Roberts and Marston (2011).

Table 3Flood frequency, duration and timing before river regulation, NSW Central Murray StateForest: Edward–Wakool River System (Source: GHD 2009).

Habitat type	Flood frequency (% of years with flood)	Duration (months)	Season	
Floodplain depression marshes	75–100	7–10	winter - mid-summer	
River red gum forest	40–92	5	winter - spring	
River red gum woodland	33–46	1–2	spring	
Black box woodland	14–33	1–4	winter – spring	

Information on important flow thresholds in relation to inundation of key flood dependent vegetation communities have been compiled by assessing data contained within the River Murray Wetland Database (Green & Alexander 2006). This database was collated by the NSW Murray Wetlands Working Group and contains commence-to-flow levels for wetlands throughout the Edward-Wakool River System based on satellite image analysis, field inspection and local knowledge. Some of the ecologically relevant flow thresholds and durations and the associated expected area of key vegetation communities inundated for the Edward-Wakool River System are:

- 3,500 ML/d at Stevens Weir (generally at least 5,000 ML/d at Deniliquin) for significant flooding of reed beds and low-lying river red gums in Werai Forest (400 ha; Green & Alexander 2006);
- 18,000 ML/d at Deniliquin for more than one month to achieve significant flooding of river red gum forests and some ephemeral streams (>15,000 ha river red gum forest and woodlands in total with >9,000 ha in Werai Forest (GHD 2009) and similar, unmapped area along the rest of the system (D Green 2010, pers. comm., 12 May); >200 km of ephemeral wetlands and watercourses (Green & Alexander 2006)); and
- 30,000 ML/d at Deniliquin for more than three weeks for most ephemeral streams such as Cochrans Creek, Wee Wee Creek and Yarrien Creek and some areas of black box (>600 km of ephemeral wetlands and watercourses (Green & Alexander 2006); >2,000 ha of black box woodlands in total with >800 ha in Werai Forest (GHD 2009) and area of black box woodland along the rest of the system that is inundated at similar flow levels (D Green 2010, pers. comm., 12 May)). Such an event would also provide greater than 25,000 ML/d in the River Murray at Swan Hill, which would provide some inflow to the Poon Boon Lakes.

It is important to recognise while important flow thresholds have been identified, the duration of an event is critical in this system as many of the wetlands and vegetation communities within the Edward-Wakool River System are linked by long ephemeral streams that may require inflow for many weeks before water reaches the end.

Determination of the proposed magnitude, duration, frequency and timing of flows required to achieve the site-specific ecological targets are an amalgam of information from key resources including the River Murray Wetland Database (Green & Alexander 2006), the draft ecological character description for Werai Forest (GHD 2009), existing literature on water requirements of vegetation communities (Roberts and Marston 2011), and on-ground inundation observations.

5.2.2. Waterbirds

Waterbird breeding events, including by colonial nesting species have been recorded in the Edward-Wakool River System at Werai Forest and in the Murray Valley National Park, although the significance of the site for waterbirds in a regional context remains a knowledge gap (Hale and SKM 2011). A variety of information sources have been used to inform development of site-specific flow indicators to achieve the ecological target of providing a flow regime which supports the habitat requirements of waterbirds and is conducive to successful breeding of colonial nesting waterbirds (Scott 1997; GHD 2009; Overton et al. 2009).

Flows of approximately 5,000 ML/d at Deniliquin will inundate reed beds and low-lying river red gums that provide suitable waterbird breeding habitat in Werai Forest (Green and Alexander 2006). In addition to these flows, higher flow peaks that provide a shifting spatial and temporal mosaic of wetland inundation patterns and healthy and productive foraging and nesting habitats (Overton et al. 2009) are also likely to be important for successful waterbird breeding.

Overton et al. (2009) suggests that for successful breeding, colonial nesting waterbirds require 4–5 months of flooding in total, taking into account provision of breeding cues and time needed to lay and incubate eggs and fledge young. This is consistent with the hydrology of the area prior to regulation with flow events greater than 4 months during winter-spring associated with colonial nesting waterbird breeding (GHD 2009).

Two key factors suggest that waterbirds do not need to breed every year on the same river system (Scott 1997). Firstly, Australian waterbirds are highly mobile and their mobility over large spatial scales is a defining characteristic (Scott 1997; Overton et al. 2009). Most of the 80 odd species of (non-vagrant) Murray-Darling Basin waterbirds that use inland wetlands have broad Australia-wide distributions and it is believed that individuals of most species are capable of dispersing at the scale of the continent (Overton et al. 2009). As such, prior to river regulation at least some individuals of the more mobile waterbird species have would have been able to seek suitable conditions for successfully breeding somewhere within the Basin in most years (Scott 1997).

Secondly, it is not essential for waterbirds to breed every year to maintain sustainable populations as they are generally long-lived (Scott 1997). Waterbirds become sexually mature at the age of one to two years and have a life expectancy ranging generally from 3-4 years for ducks, up to 8 years for larger birds such as ibis (Scott 1997).

These two key factors have informed the frequency of events for site-specific flow indicators intended to support the habitat requirements of waterbirds, including provision of conditions conducive to successful breeding of colonial nesting waterbirds. Specifically, suitable flood events for successful breeding must occur within the lifespan of the species (GHD 2009) and it is desirable to provide multiple opportunities for successful waterbird breeding within the range of their life expectancy. Provision of conditions suitable for successful breeding of colonial nesting waterbirds within the Edward Wakool River System in at least three years out of ten is consistent with this rationale. However, there may be longer gaps during lengthy drought periods.

5.2.3. Native fish

The Edward–Wakool River System is recognised as an area that supports significant populations of native fish and provides important fish habitat, particularly in times of drought, not only at a local scale but also at the broader Basin scale. The importance of this area is elevated because of the widespread decline of fish populations as shown through Sustainable Rivers Audit monitoring (Davies et al. 2008). Environmental water requirements for the Edward–Wakool River System have been developed to take into account the importance of native fish populations.

The development of site-specific flow indicators focused on assessment of the in-channel baseflow element of the flow regime necessary to maintain drought refuges important for significant populations of native fish (Gilligan, Vey and Asmus 2009). Flows of 1,500 ML/d at Deniliquin and strategic use of off-take regulators are expected to maintain > 1000 km of vital fish habitats in permanent and semi-permanent regulated rivers and creeks within the Edward-Wakool River System (Green & Alexander 2006; Gilligan, Vey & Asmus 2009; Hale and SKM 2011).

Other elements of the flow regime, specifically pulses or freshes and overbank flooding, are also likely to be important for sustaining healthy native fish populations. The Murray Catchment Management Authority, the Department of Sustainability, Environment, Water, Populations and Communities, and Charles Sturt University are investigating the effects of pulse flows on native fish in the Edward-Wakool River System (Hale and SKM 2011). While this research may result in further refinement of the proposed flow indicators, as a general rule, the development of flow indicators has not sought to incorporate the variability in flow regime at the scale detailed in such studies. Rather, the flow indicators developed by the MDBA are being used to rebalance the overall volume of flow available to the environment, while finessing around variability can be addressed in real time management of environmental water.

There is still debate in the scientific literature as to the relative role of flooding to fish community dynamics, and an understanding of the nature of 'fish ecology'-'river flow' interactions is by no means clear (Humphries et al. 1999, Mallen-Cooper and Stuart 2003, Graham and Harris 2004; King et al. 2009). For example, it has been suggested that some fish species, such as the conservationally significant silver perch (*Bidyanus bidyanus*), which have been recorded in the Edward-Wakool River System require flow pulses or floods for spawning i.e. flood recruitment hypothesis (Humphries et al. 1999). This is partly supported by King et al. (2009) who suggest that flow is one environmental variable, although not always the key environmental variable, identified explaining the occurrence and abundance of spawning of golden perch, silver perch and Murray cod at the nearby Barmah-Millewa Forest. Other factors such water temperature and day length, or the interaction of a range of environmental variables including flow, are suggested to also be important for native fish recruitment (King et al. 2009).

Despite the ongoing debate regarding the link between hydrology and fish ecology, available evidence suggests that provision of flows that connect the river channel to the floodplain (e.g. Beesley et al. 2011), as well as in-channel flow variability, are important in sustaining key ecological features such as native fish populations. Flow indicators described herein for the bankfull and overbank elements of the flow regime primarily based on the water requirements of flood dependent vegetation communities and waterbirds are expected to complement flow indicators specified for in-channel baseflows targeting native fish populations. The flow regime represented by these flow indicators is expected to be

sufficient to support life-cycle and habitat requirements of native fish including provision of cues for spawning and migration and access to food sources.

5.2.4. Other biota

The understanding of flow-ecology relationships for faunal groups other than flood-dependent vegetation communities, colonial nesting waterbirds and native fish populations within the Edward-Wakool River System generally has more uncertainty owing to the reduced number of studies undertaken for these species. The MDBA is confident that the site-specific flow indicators determined to achieve the ecological targets relating to the current extent of native vegetation communities and the habitat requirements for waterbirds and fish will also have valuable beneficial effects on the life-cycle and habitat requirements of amphibians, and water-dependent reptiles and invertebrates. Key ecosystem functions associated with river and floodplain connectivity will also be enhanced.

5.3. Proposed flow indicators

A number of factors present challenges in defining the environmental water requirements of the Edward-Wakool River System (Hale and SKM 2011). Firstly, due to the vast size and complex hydrology of the Edward-Wakool River System, developing flow indicators that are representative of the needs of all areas and the different key ecological components is difficult. Secondly, further uncertainty is created by the lack of comprehensive vegetation mapping and hydraulic models linking flow with inundation. It is acknowledged that knowledge gaps remain and the proposed flow indicators should be viewed in this context.

Based on the hydrology described in Section 4 and the environmental water requirements described in Sections 5.1 and 5.2, the MDBA has proposed five flow indicators for the Edward-Wakool River System (Table 4). The site-specific flow indicators for the Edward-Wakool River System represent an amalgam of best available information from existing literature, checked against an analysis of modelled without development and baseline flow data. Site-specific flow indicators are expressed at Deniliquin on the Edward River. Flow indicators as specified for the in-channel baseflow, bankfull and overbank elements of the flow regime attempt to strike a balance between desirable flow threshold, duration and timing with desirable frequency (for example. as described in Table 3) and represent a variable flow regime that is consistent with the "without development" hydrology of the site. Where a discrepancy exists between the literature and hydrology modelling, an analysis of modelled without development flows has been used to guide the determination of site-specific flow indicators, particularly to ensure that the recommended flows are achievable and not greater than without development flows. An exception to this general approach for the lowest magnitude (baseflow) flow indicator is described below.

The site-specific flow indicators needed to achieve ecological targets for the Edward-Wakool River System should be read in their entirety to understand the environmental water requirements as multiple flow indicators will contribute to achieving each ecological target. This approach has been used because it is not possible to define a single flow threshold for each vegetation community. The flood dependent vegetation communities cover a wide range of flows and a single indicator would be misleading.

Flow indicators proposed in Table 4 are intended to represent a range of water requirements for wetland types and vegetation communities across the floodplain and network of watercourses that

comprise the Edward–Wakool River System. However, due to the vast size and complexity of this floodplain, the response will be variable across the system. The MDBA is confident that the flow regime represented by the range of flow indicators is likely to be sufficient to ensure the current extent of native vegetation of the riparian and wetland communities and the majority of floodplain communities are sustained in a healthy, dynamic and resilient condition. However, without comprehensive vegetation mapping and inundation modelling available for the Edward-Wakool River System, there is some uncertainty regarding whether the entire current extent of all floodplain vegetation communities will be maintained by the proposed flow indicators. In particular, similar to other sites along the River Murray, it is possible that the current extent of black box communities located higher on the landscape may not be sustained by the proposed flow indicators.

The current knowledge base points to black box being ecologically flexible and an opportunistic user of water (Roberts and Marston 2011). Specifically, vegetation communities such as black box located on the higher elevation floodplains may not need to be fully inundated but benefit from flooding in the lower elevation through the flushing of groundwater reserves and refreshing soil water stores (Roberts and Marston 2011). This suggests that the flood-dependence of black box at higher elevations on the Edward-Wakool River System is questionable and black box recruitment may be supported by flooding, but it is likely to be less important for tree survival. Summer rain events may also be an important factor in black box recruitment. In addition, limitations imposed by current operational constraints (see Section 6) are also likely to impede the ability to deliver flows to the higher parts of the floodplain even if this was desirable. MDBA has given consideration to these various sources of uncertainty during development of the proposed flow indicators to achieve the site-specific ecological targets.

Generally, the flow indicator metric with the greatest level of uncertainty across the Basin is the definition of the desirable frequency of inundation, expressed as the proportion of years an event is required. This uncertainty is due to a number of reasons. Firstly, it is likely that there are thresholds for many plants and animals beyond which their survival or ability to reproduce is lost, but the precise details of those thresholds are mostly unknown or where there is information (for instance river red gum communities) our knowledge is evolving. Secondly, vegetation communities are located across the floodplain and would have experienced significant variability in their inundation frequency under predevelopment conditions which subsequently makes specification of a single frequency metric deceptively certain. For many species and ecological communities the relationship between water provisions and environmental outcomes may not be threshold based, rather there could be a linear relationship between flow and the extent of environmental outcomes or the condition of a particular ecological species/community.

Recognising the degree of confidence in specifying a desirable frequency, 'lowuncertainty' and 'high-uncertainty' frequency of flow events have been specified (Table 4). For the low-uncertainty frequency, there is a high likelihood that the environmental objectives and targets will be achieved. The lower boundary of the desired range is referred to here as the high uncertainty frequency. This is effectively the best estimate of the threshold, based on current scientific understanding, which, if not met, may lead to the loss of health or resilience of ecological communities, or the inability of species to reproduce frequently enough to sustain populations. The **high**ertainty frequencies attempt to define critical ecological thresholds. The high uncertainty frequency is considered to indicate a level beyond which the ecological targets may not be achieved.

For the Edward-Wakool River System a number of key sources of information were used to inform the high and low uncertainty frequencies. Site specific information, particularly the draft *NSW Central Murray State Forest Ramsar Site Ecological Character Description* (GHD 2009) as presented in Table 3, was complemented by more generic literature on water requirements of flood dependent vegetation communities, particularly Roberts and Marston (2011). These documents express the desired frequency as a range and the high and low uncertainty frequency flow indicator metrics attempt to encapsulate the broad water requirements represented by this range. Modelled flow data was used to verify if recommended frequencies were achievable and not greater than without development flows, with the exception of the baseflow indicator.

River regulation has increased the frequency of baseflows in the Edward-Wakool River System (see Table 4) and this is likely to have contributed to sustaining native fish populations. The frequency or proportion of years specified for the lowest magnitude flow indicator (1,500 ML/d) has taken into account the modified nature of this part of the flow regime under baseline conditions, the importance of native fish populations within this system at a local and Basin scale, and the water quality risks associated with low flows in this system. As such both the high and low uncertainty frequency proposed are greater than those experienced under without development conditions. This approach differs to the general approach adopted to define environmental water requirements for other indicator sites, where modelled without development flow data is used as an upper limit to determine the water requirements.

It is recognised that periods between inundation events are an important consideration when trying to determine ecosystem resilience or thresholds of irreversible change. When investigating the environmental water requirements for the various sites, consideration was given to specifying a maximum period between events or metrics related to maximum dry. However, the literature regarding the tolerance of various floodplain ecosystems to dry periods is limited. In addition where this information exists, recommended maximum dry intervals often conflicts with the maximum dry experienced under modelled without development conditions.

Considering these issues, MDBA has not proposed a maximum dry period with the exception of a small number of sites across the Basin, which does not include the Edward-Wakool River System. Even so, the importance of maximum dry periods and their role in maintaining ecosystem resilience is recognised. Maximum dry periods between successful events are reported for hydrological modelling associated with the Edward-Wakool River System hydrologic indicator site (see MDBA 2012) despite reducing the maximum period between events not being the primary objective of the modelling process.

Table 4: Site-specific ecological targets and associated flow indicators for Edward–Wakool River System

	Site-Specific Flow Indicators					Without development and baseline event frequencies	
Site-Specific Ecological Targets	Event			Frequency – proportion of years event required		Proportion of years event	Proportion of years event
	Flow required (Edward River at Deniliquin; ML/d)	Duration ^a	Timing	Low uncertainty (%)	High uncertainty (%)	modelled without development conditions (%)	under modelled baseline conditions (%)
Provide a flow regime which ensures the current extent of native vegetation of the riparian, floodplain and wetland communities is sustained	1,500	180 days total (with 1 day minimum)	June to March	100	99	75	96
in a healthy, dynamic and resilient condition. Provide a flow regime which supports the habitat requirements of waterbirds and is conducive to	5,000	60 days total (with 7 day minimum)		70	60	82	39
successful breeding of colonial nesting waterbirds.	5,000	120 days total (with 7 day minimum)	luno to	40	35	52	22
Provide a flow regime which supports a range of native aquatic species (e.g. fish, frogs, turtles and invertebrates)	18,000	28 days total (with 5 day minimum)	December	30	25	39	15
Provide a flow regime which supports key ecosystem functions, particularly those related to connectivity between the river and the floodplain	30,000	21 days total (with 6 day minimum)		20	17	28	12

a Duration is expressed both as a total and minimum duration, allowing multiple smaller flow events that meet the minimum duration criteria to comprise a successful event. Minimum durations are therefore a subset of total duration and should not be read independently. MDBA analysis showed that if a minimum duration is not specified and individual events must meet the total duration criteria, this resulted in a significantly reduced proportion of years.

Note: Multiplication of the flow rate by the duration and frequency (proportion of years event required) does not translate into the additional volume of water the site needs to be environmentally sustainable. This is because part of the required flow is already provided under baseline conditions. Additional environmental water required is the amount over and above the baseline flows.

6. Flow delivery constraints

Basin-wide environmental objectives have been developed within the context of being deliverable in a working river system that contains public and private storages and developed floodplains. To understand and assess the implications of key constraints on the ability to achieve flow indicators specified for the Edward-Wakool River System, MDBA has drawn upon a combination of existing information (e.g. Water Sharing Plans, operating rules of water agencies, flood warning levels, Commonwealth Environment Water Holder environmental water delivery plans) and practical knowledge of river operators supported by testing using hydrological modelling.

Flows downstream of Hume Dam are typically limited to 25,000 ML/d under regulated flow conditions to minimise overbank flows and the associated inundation of agricultural land. This constraint prevents the release of flows, or adding water to augment natural flows above 25,000 ML/d.

The MDBA has a vision of a healthy working Basin that has vibrant communities, productive and resilient industries, and healthy and diverse ecosystems. The delivery of environmental flows as a managed watering event within a healthy working Basin is highly dependent on existing system constraints, accordingly the site-specific flow indicators in Table 4 have been classified into three broad types (Table 5). Consistent with this rationale, within the hydrological modelling process used by the MDBA to assess the achievement of site-specific flow indicators orders for environmental flows have been limited to be within the constraints represented by the baseline model. This limits the delivery of regulated flows to the Edward-Wakool River System.

The Commonwealth Environmental Water Holder Environmental Water Delivery Plan for the Edward-Wakool River System identify delivery triggers for the two highest flow indicators (18,000 and 30,000 ML/day) based on equivalent flows in the River Murray downstream of Yarrawonga Weir (Hale and SKM 2011). Equivalent flows are 49,500 ML/d at Yarrawonga for the 18,000 ML/d flow indicator at Deniliquin and 62,000 ML/d at Yarrawonga for the 30,000 ML/d indicator (Hale and SKM 2011). The MDBA (2012) report *Assessment of environmental water requirements for the proposed Basin Plan: Barmah-Millewa Forest* highlights flow delivery constraint issues with delivery of flows downstream of Yarrawonga in the range 50,000-60,000 ML/d, particularly the inability to support flows of this magnitude with only regulated releases from dams.

Based on information above, it is likely that the 18,000 ML/d and 30,000 ML/d flow indicators at Deniliquin (Table 4) will be not be achievable at the desirable frequency and the duration of the flows will also be difficult to obtain. Without addressing a range of constraints, the achievement of site-specific ecological targets and flow indicators will be heavily reliant on unregulated flows. There may be opportunities to supplement tributary inflows with regulated release from storage, however the duration of events will be limited to the duration of the tributary inflow.

The achievement of site-specific flow indicators in the Edward-Wakool River System is closely linked with flows in the River Murray, particularly flows at Yarrawonga, consequently environmental water delivery should be co-ordinated with flooding of the Barmah-Millewa Forest (Hale and SKM 2011).

Table 5: Site-specific flow indicators for the Edward-Wakool River System and the effect of system constraints

Site-specific ecological targets	Site-specific flow indicators
Provide a flow regime which ensures the current extent of native vegetation of the riparian,	1,500 ML/d for a total duration of 180 days (with a minimum duration of 1 consecutive day) days between June & March for 99% of years
a healthy, dynamic and resilient condition Provide a flow regime which supports the habitat requirements of waterbirds and is conducive to successful breeding of colonial nesting waterbirds	5,000 ML/d for a total duration of 60 days (with a minimum duration of 7 consecutive days) days between June & December for 60% of years
	5,000 ML/d for a total of 120 days (with a minimum duration of 7 consecutive days) between June & December for 35% of years
Provide a flow regime which supports a range of native aquatic species (e.g. fish, frogs, turtles and invertebrates)	18,000 ML/d for a total of 28 days (with a minimum duration of 5 consecutive days) between June & December for 25% of years
Provide a flow regime which supports key ecosystem functions, particularly those related to connectivity between the river and the floodplain	30,000 ML/d for a total of 21 days (with a minimum duration of 6 consecutive days) between June & December for 17% of years

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Achievable under current operating conditions Flow indicators highlighted in blue are considered deliverable as mostly regulated flows under current operating conditions.
Achievable under some conditions (constraints limit delivery at some times) Flow indicators highlighted in yellow are considered achievable when delivered in combination with tributary inflows and/or unregulated flow events. They may not be achievable in every year or in some circumstances, and the duration of flows may be limited to the duration of tributary inflows.
Difficult to influence achievement under most conditions (constraints limit delivery at most times) Flow indicators highlighted in brown require large flows that cannot be regulated by dams and it is not expected that these flows can currently be influenced by river operators due to the river operating constraints outlined above.

7. Risks associated with delivery of environmental water

According to Gilligan, Vey and Asmus (2009), risks associated with delivering environmental flows into drought-affected waterways are, the creation of hypoxic and toxic blackwater flows, the mobilisation of poor quality water that can impact on refugia with better quality water downstream, or rapid changes in water quality (such as temperature, pH or salinity) that exceed the acclimatisation capacity of fish. Fish population monitoring within the Edward–Wakool River System following watering during 2007–08 showed there were no obvious adverse effects due to declines in water quality (Gilligan, Vey & Asmus 2009). In contrast, a blackwater event and associated fish deaths were recorded in the Edward–Wakool

system in 2009. This suggests that, depending on antecedent conditions, there is potential for shortterm decline and issues associated with environmental watering events. The proposed low flow indicator (1,500 ML/d June to March for 100% of the time) is partly aimed at avoiding these water quality issues which tend to occur on rewetting after the system has dried out.

Blackwater events and acidification problems arising from exposure of acid sulfate soils are known issues for parts of the Edward-Wakool River System and further research into driving processes and their management are ongoing. Environmental water management should utilise new knowledge to minimise short-term risks in the context of an expected overall long-term improvement in ecological condition associated with implementing a more natural flow regime.

8. Summary and conclusion

The Edward-Wakool River System is a key environmental asset within the Basin and is an important site for the determination of the environmental water requirements of the Basin. MDBA has undertaken a detailed eco-hydrological assessment of the Edward-Wakool River System environmental water requirements. Specified flow indicators are indicative of a long-term flow regime that would achieve ecological targets at the Edward-Wakool River System and the broader river valley and reach. Along with other site-specific flow indicators developed across the Basin at other hydrologic indicator sites, these environmental flow requirements were integrated within hydrological models to inform the ESLT. This process, including consideration of a range of constraints such as those outlined in Section 6, is described in further detail within the companion report on the modelling process '*Hydrologic modelling to inform the proposed Basin Plan: Methods and results*' (MDBA 2012).

The flow indicators in this report are used to assess potential Basin Plan scenarios. MDBA (2012) summarises how the proposed draft Basin Plan released in November 2011 performs against flow indicators for Edward-Wakool River System.

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Appendix A

Data used in producing hydrologic indicator site maps

Data	Dataset name	Source ^a
Basin Plan regions	Draft Basin Plan Areas 25 May 2010	Murray–Darling Basin Authority (2010)
Dam walls/barrages	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia 2006
Gauges	100120 Master AWRC Gauges	
Icon sites	Living Murray Indicative Icon Site Boundaries	Murray–Darling Basin Commission (2007)
Irrigation areas	Combined Irrigation Areas of Australia Dataset	Bureau of Rural Sciences (2008)
Lakes	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
Maximum wetland extents	Wetlands GIS of the Murray–Darling Basin Series 2.0 (Kingsford)	Murray–Darling Basin Commission (1993)
National parks/nature reserves	Digital Cadastral Database	New South Wales Department of Lands (2007)
National parks/nature reserves	Collaborative Australian Protected Areas Database — CAPAD 2004	Department of the Environment, Water, Heritage and the Arts (2004)
Nationally important wetlands	Directory of Important Wetlands in Australia Spatial Database	Department of the Environment, Water, Heritage and the Arts (2001)
Ocean and landmass	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
Ramsar sites	Ramsar wetlands in Australia	Department of the Environment, Water, Heritage and the Arts (2009)
Rivers	Surface Hydrology (AUSHYDRO version 1-6)	Geoscience Australia (2010)
Roads	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
State border	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
State forests	Digital Cadastral Database	New South Wales Department of Lands (2007)
Towns	GEODATA TOPO 250K Series 3 Topographic Data	Geoscience Australia (2006)
Weirs	Murray–Darling Basin Weir Information System	Murray–Darling Basin Commission (2001)
Weirs 2	River Murray Water Main Structures	Murray–Darling Basin Authority (2008)

^a Agency listed is custodian of relevant dataset; year reflects currency of the data layer.

Appendix B

Species relevant to criteria 1 and 4: Edward–Wakool River System

Species	Recognised in international agreement(s) ¹	Environment Protection and Biodiversity Conservation Act 1999 (Cwlth)	Fisheries Management Act 2004 (NSW)	Threatened Species Conservation Act 1995 (NSW)
Amphibians and reptiles				
Southern bell or growling grass frog (Litoria raniformis) ⁴		V		E
Birds				
Australasian bittern (<i>Botaurus poiciloptilus</i>) ³				V
Barking owl (Ninox connivens)4				V
Black-chinned honeyeater (eastern subspecies) (Melithreptus				V
gularis gularis)4				
Blue-billed duck (<i>Oxyura australis</i>) ⁵				
Brown treecreeper (Climacteris picumnus)4				V
Bush stone-curlew (Burhinus grallarius) ⁴				E
Caspian tern (Sterna caspia)3	✓			
Cattle egret (Ardea ibis) ³	✓			
Diamond firetail (Stagonopleura guttata)4				V
Eastern great egret (Ardea modesta)3	✓			
Forked-tailed swift (Apus pacificus) ³	✓			
Freckled duck (Stictonetta naevosa)5				
Glossy ibis (Plegadis falcinellus) ³	✓			
Greenshank (Tringa nebularia) ³	~			
Grey-crowned babbler (eastern subspecies) (Pomatostomus				V
temporalis temporalis) ⁴				
Latham's snipe (Gallinago hardwickil)3	✓			
Marsh sandpiper (Tringa stagnatilis) ³	✓			
Painted snipe (Rostratula australis)3	✓			V
Red-necked stint (Calidris ruficollis) ³	✓			
Regent honeyeater (Xanthomyza phrygia)4				E
Regent parrot (eastern subspecies) (Polytelis anthopeplus				E
monarchoides)4				
Sharp-tailed sandpiper (Calidris acuminata) ³	✓			
Speckled warbler (Chthonicola sagittata)4				V
Superb parrot (Polytelis swainsonii) ³		V		V
Turquoise parrot (Neophema pulchella)4				V

Species	Recognised in international agreement(s) ¹	Environment Protection and Biodiversity Conservation Act 1999 (Cwlth)	Fisheries Management Act 2004 (NSW)	Threatened Species Conservation Act 1995 (NSW)
White-bellied sea-eagle (Haliaeetus leucogaster)3	~			
White-throated needletail (Hirundapus caudacutus)3	✓			
Fish				
Murray cod (<i>Maccullochella peelii peelii</i>) ^{2, 7}		V		
Murray hardyhead (Craterocephalus fluviatilis)3		V	CE	
Silver perch (<i>Bidyanus bidyanus</i>) ^{3, 7}			V	
Trout cod (Maccullochella macquariensis) ^{3, 7}		E	E	
Unspecked hardyhead (Craterocephalus stercusmuscarum fulvus)2.			E	
Mammals				
Brush-tailed phascogale (Phascogale tapoatafa)4				V
Plants				
Austrostipa metatoris ⁴		V		V
Austrostipa wakoolica4		E		E
Bitter quandong (Santalum murrayanum)4				E
Boland yellow gum (Eucalyptus leucoxylon pruinosa)4				V
Chariot wheels (Maireana cheelii)4				V
River or floating swamp wallaby-grass (Amphibromus fluitans)4				V
Silky swainson-pea (Swainsona sericea)4				V
Slender Darling pea (Swainsona murrayana)4				V
Western water-starwort (Callitriche cyclocarpa) ⁴				V
Winged peppercress (Lepidium monoplocoides)4				E
Communities				
Murray River endangered ecological community ⁶			E	

CE=critically endangered E = endangered V = vulnerable

- 1 Japan–Australia Migratory Bird Agreement, China–Australia Migratory Birds Agreement, or Republic of Korea Australia Migratory Bird Agreement
- 2 NSW Department of Environment, Climate Change and Water (2009a)
- 3 GHD (2009)
- 4 NSW Department of Environment, Climate Change and Water (2009b)
- 5 Department of the Environment, Water, Heritage and the Arts (2010)
- 6 NSW Department of Primary Industries (2007)
- 7 Gilligan, Vey & Asmus (2009)