LA TROBE UNIVERSITY

Centre for Freshwater Ecosystems

CSIRO

Can we better mitigate against plant invasions through tailoring flow events in the Murray-Darling Basin?

Prepared by: Nerissa Haby, Louisa Romanin & Daryl Nielsen

Australian Government | MURRAY–DARLING BASIN AUTHORITY

Final Report

CFE Publication 214/2019

Can we better mitigate against plant invasions through tailoring flow events in the Murray-Darling Basin?

Report prepared for the Murray–Darling Basin Authority by The Centre for Freshwater Ecosystems.

Murray–Darling Basin Authority
Level 6, 33 Allara Street | GPO Box 1801
Canberra City ACT 2601

Ph: (02) 6279 0100; Fax: (02) 6248 8053

This report was prepared by the Centre for Freshwater Ecosystems (CFE). The aim of the CFE is to lead the way for healthy and sustainable freshwater ecosystems through innovation and excellence in research and education.

For further information contact:

Dr Daryl Nielsen

Centre for Freshwater Ecosystems/CSIRO
PO Box 821
Wodonga VIC 3689
Ph: (02) 6024 9650

Web: latrobe.edu.au/freshwater-ecosystems
Enquiries: cfe@latrobe.edu.au

Report Citation: Haby, N, Romanin, L, Nielsen, D. L., (2019) Can we better mitigate against weed (aquatic and terrestrial) invasions through tailoring flow events in the Murray-Darling Basin? Report prepared for the Murray–Darling Basin Authority by The Centre for Freshwater Ecosystems, CFE Publication 214/2019, June, 19pp.

Cover Image: Arrow head infestation in Broken Creek

Photographer: D. Nielsen

Contact us

Inquiries regarding the licence and any use of the document are welcome at:

Director
Communications
Murray–Darling Basin Authority
51 Allara St
Canberra ACT 2601

Email: copyright@mdba.gov.au

Document history and status

Version	Date Issued	Reviewed by	Approved by	Revision type
Draft	8/4/2019	Susan Gehrig	Daryl Nielsen	review
Draft	8/4/2019	Jason Nicol	Daryl Nielsen	review
Draft	12/4/2019	Carla Tadich/JGR	Daryl Nielsen	review

Distribution of copies

Version	Quantity	Issued to
1	Final	MDBA

Filename and path: MDFRC\Projects\MDBA\637 MDBA MDFRC Collaboration Agreement\BOC questions\2018-2019\weeds

Author(s): Nerissa Haby[1], Louisa Romanin[1], Daryl Nielsen[2],

Author affiliation(s): [1]Center for Freshwater Ecosystems, La Trobe University, Wodonga, Victoria.

[2]CSIRO, Albury, NSW

Project Manager: Daryl Nielsen

Client: MDBA

Project Title: Basin Official Committee 2018-19 questions - Weeds

Document Version: Draft

Project Number: M/BUS/637, 17/00796

Contract Number: MD3291

Acknowledgements:

The Centre for Freshwater Ecosystems offices are located on the land of the Wiradjuri peoples. We undertake work throughout the Murray–Darling Basin and acknowledge the traditional owners of this land and water. We pay respect to Elders past, present and future.

"*Project supported through the Murray–Darling Basin Joint Governments*". ***The Murray -Darling Basin Joint Governments are made up of;***

- Department of Environment, Land, Water and Planning (Victoria)
- NSW Department of Primary Industries (New South Wales)
- Department of Environment, Water and Natural Resources (South Australia)
- Department of Natural Resources and Mines (Queensland)
- ACT Environment and Sustainable Development (Australian Capital Territory)
- Department of Agriculture & Water Resources

Contents

List of Tables

List of Figures

Executive Summary

The structure and floristic composition of water dependent plant communities (riparian, riverine, floodplain and wetland) are strongly influenced by changes in the hydrological regime. Under natural hydrological regimes, flooding provides suitable conditions for flood tolerant species to flourish, then during dry periods, the abundance of these species declines and they are replaced by terrestrial species. Under natural conditions, transitions between the wet and dry phases provide opportunities for species to colonise, restructuring and shifting the extent of local communities (e.g. riparian woodlands).

In contrast, under current hydrological regimes that are defined by reduced flows, fewer floods with reversed seasonality and ponding, many plants have become stressed, mortality rates have increased and recruitment rates decreased, leading to a decline in the abundance and richness of native species. Overall, water dependent plant communities have become degraded providing the opportunity for non-native terrestrial or flood tolerant species to establish and provide seeds and propagules for new invasions downstream.

A range of plants have been introduced to Australia with traits suited to colonising habitats following changes in the wet-dry cycle as a function of the current hydrological regimes. These traits reflect specific adaptations to aquatic, amphibious or terrestrial conditions. Given the specificity of these adaptations, suitable environmental conditions may be reversed using environmental flows that may be strategically delivered to targeted areas. By their very nature, environmental flows can be designed to deliver flows at a specific time, magnitude, depth, duration, recession rate and inter-flood interval. By doing so we may be able to effectively reduce and suppress non-native species while promoting the recruitment of native species and improving our ability to manage and restore riverine, riparian, floodplain and wetland plant communities.

This review examines the potential for environmental flows to be used to mitigate the spread of non-native plants in targeted areas. We draw upon a list of more than 80 invasive (native and non-native) species compiled for the Murray-Darling Basin (Table 1), to illustrate key traits that may be used as a guide for using environmental flows to control non-native species.

(i) Terrestrial plants
  a. Typically invade during the inter-flood interval, which is well accommodated by the current hydrological regime (i.e. prolonged dry periods) and infrastructure (i.e. dehydrating large areas).
  b. Are sensitive to inundation and can be effectively controlled through prolonged inundation.

(ii) Amphibious plants
  a. Are well adapted to invading waterways, but due to their tolerance of both wet and dry conditions, may be difficult to manage using environmental flows.
  b. Effective control may require integrated approaches (e.g. extended periods of inundation to increase seedling mortality, and slashing prior to inundation, mechanical removal and herbicide treatment to increase the mortality of established plants).
  c. Partial submergence should be avoided as may promote rapid growth.

(iii) Submerged plants
  a. Typically invade during prolonged periods of stable water levels, which is well accommodated by the current hydrological regime (i.e. ponding and slow flowing irrigation channels).
  b. Are sensitive to drying and can be controlled by drawing down water levels and allowing the soil to dry (i.e. reintroducing an inter-flood interval).
  c. Effective control may require integrated approaches (e.g. herbicide application, shading or physical removal (harvesting)).

Environmental flows will also enhance conditions for native species, including plants capable of competitively excluding opportunistic non-native species, and the water quality for aquatic species that may be compromised by herbicide control of dense invasions of amphibious species.

When designing environmental flows, careful consideration should also be made of:

- The priority of weed control at a site given the risk that non-native species pose to biodiversity and the range of potential benefits of restoration (e.g. soil stability, water quality, biodiversity),
- Longitudinal and lateral connectivity between invaded sites (including the potential for environmental flows to distribute propagules),
- Designing environmental flows (e.g. duration and depth of flood, duration of dry/inter-flood interval, and timing) to take advantage of the weaknesses in traits of non-native species at different stages of their life cycle, and
- Appling integrated management techniques to support and enhance weed control (e.g. slashing or burning prior to flooding) and aid natural recruitment (e.g. erosion control).

1 Introduction

Riparian, riverine, floodplain and wetland ecosystems are some of the most altered ecosystems across the globe (Dudgeon *et al.* 2006; Nilsson & Svedmark 2002). This has principally occurred as a result of regulating flow regimes for human consumption (Lytle & Poff 2004; Poff *et al.* 1997). Increased interception by dams, regulation by weirs, and extraction of surface and groundwater has reduced flows, in some cases until rivers run dry (Dudgeon *et al.* 2006). The impact of these modifications is variable (Dudgeon *et al.* 2006), but in many cases riverine, riparian, wetland and floodplain communities have become degraded and been invaded by exotic species (D'Antonio & Meyerson 2002; Kingsford 2000; Pittock & Finlayson 2011). Once degraded, these systems can quickly deteriorate (Catford *et al.* 2011; Stokes *et al.* 2010).

Rivers within the Murray-Darling Basin once sustained a mosaic of riverine, riparian and wetland communities in a near permanent to temporary wet phase. With regulation of these rivers, many riverine, riparian, wetland and floodplain communities are being exposed to permanently wet or dry conditions, reduced and highly variable wetting frequency, and/or a reversal in the season of flows (Walker & Thoms 1993). In the future, climate change (reduced rainfall, increased temperature and an increase in extreme events) (Timbal *et al.* 2015), combined with increased demand to support a growing human population, is predicted to further reduce flows, inundation frequency and connectivity and increase salinity in most areas (Nielsen & Brock 2009; Pittock & Finlayson 2011). Native species unable to adapt to changes in the hydrological regime are likely to become locally extinct, exposing riparian, wetland and floodplain areas to colonisation by annual species capable of dispersing from upstream or terrestrial species from neighbouring drier landscapes (Nielsen & Brock 2009). Overall, this restructuring is likely to see communities become less diverse, less resilient to ongoing changes, limited in the range of biodiversity they can support and more variable in the delivery of ecosystem services (Bunn & Arthington 2002; Catford *et al.* 2011; Catford *et al.* 2013; Dudgeon *et al.* 2006; Nielsen & Brock 2009; Pittock & Finlayson 2011).

Native species have coevolved with the natural hydrological dynamics of each relatively unique riverine system (Lytle & Poff 2004; Poff 1997; Puckridge *et al.* 1998). This is demonstrated in the ability of a range of taxa to increase in response to unpredictable flood events, including the abundance of bacteria and algae, zooplankton and aquatic macrophytes, growth in floodplain shrubs, germination of riparian trees, emergence of burrowing frogs, and colonisation by fish larvae and water birds (Kingsford 2000). The individual traits that species have evolved to achieve this ability are species specific, but include modifications to an individual's life history (e.g. cues for producing seed or germination), or morphological structure (e.g. developing below-ground biomass to improve anchoring, or seeds and propagules resistant to desiccation) (Capon & Brock 2006; Lytle & Poff 2004; Riis & Biggs 2003), to improve their ability to cope with inundation or water-logging, the physical disturbance of flood events, and waterborne dispersal (Catford *et al.* 2013; Nilsson & Svedmark 2002). Overall, the development of adaptive traits is believed to be driven to the long-term average in flow dynamics (Bunn & Arthington 2002; Lytle & Poff 2004).

In some cases, species have evolved traits that make them ecosystem engineers in the development of riverine, riparian, wetland and floodplain systems. They are capable of altering river geomorphology, the hydrological regime, sedimentation patterns, physical and chemical properties of water (e.g. the availability of light, nutrients and oxygen, and temperature), and availability of habitat for other biota (Berke 2010; Caraco *et al.* 2006; Catford 2017; Gurnell 2014). Across the floodplain, dominant plants influence surface water infiltration rates, evapotranspiration rates, sedimentation rates and surface roughness (Graetz & Tongway 1986; Thompson *et al.* 2016). Given this, a turnover in the community of plants in favour of introduced species can alter the function of these systems (Gutiérrez 2017).

Wetland and riparian zones have high biodiversity value as demonstrated by their capacity to support elevated species richness (Catford *et al.* 2013; Dudgeon *et al.* 2006; Nilsson & Svedmark 2002) and act as refuges for species within the landscape (Bennett *et al.* 2014). Invasion by non-native species can be an early indicator of community degradation (Catford & Jansson 2014). Once established, non-native species can rapidly spread given the strong longitudinal and latitudinal connectivity within these systems (Ballinger & Mac Nally 2006; Bunn & Arthington 2002; Hobbs & Humphries 1995). However, the lag between initial invasion and their subsequent spread provides a window of opportunity to eradicate invasive species or to implement strategies that minimise the extent of spread or protect specific high priority locations from degradation (Hobbs & Humphries 1995). For example, by targeting geographic areas with the greatest change in hydrological regime and most at risk of invasion and loss of biodiversity (Catford *et al.* 2011). Overall, the restoration of even highly modified riparian zones can improve biodiversity values in the broader landscape (Howell & Benson 2000),

Current efforts to restore the natural function of freshwater ecosystems in the Murray-Darling Basin are focussed on delivering environmental (managed) flows. Environmental flows are designed to strategically supplement key elements of the natural flow regime at the local scale (Dudgeon *et al.* 2006). Unfortunately, environmental flows have been implicated in the spread of non-native species by watering degraded communities susceptible to invasion, and increasing the dispersal of seed and propagules longitudinally and laterally into during peak flood events or via irrigation water ways (Stokes *et al.* 2010).

Maximising the efficiency of environmental flows is a significant challenge, especially in light of our incomplete understanding of the drivers of riparian, wetland and floodplain processes (Ballinger & Mac Nally 2006; Dudgeon *et al.* 2006; Kingsford 2000). Reinstating natural flow regimes is likely to work best (Bunn & Arthington 2002), or the average conditions over which native species evolved (Bunn & Arthington 2002; Stokes *et al.* 2010). However, environmental flows can be tailored in terms of timing, depth of inundation, duration, recession rates and inter-flood interval (Stokes 2008).

This review aims to collate information on the sensitivities of non-native invasive species to hydrological changes (e.g. velocity, depth, duration of flows and quality, connectivity) to determine whether environmental flows can be a useful tool in mitigating the spread of introduced plants in targeted areas.

2 General traits of invasive species

Species that invade riverine, riparian, wetland and floodplain communities are rarely specialists with a competitive advantage (Catford *et al.* 2013). If they were, then native species with similar characteristics could invade with similar ease (Catford *et al.* 2011). Instead, non-native invaders have developed a series of traits that enhance their opportunity for colonisation, by being more readily dispersed along waterways, and capable of growing in one or more of the vegetation communities that form a mosaic at the local scale (Catford & Jansson 2014). There are a range of traits that give non-native invaders the edge over native invaders that fall under the broad categories of i) tolerating or avoiding anoxia, ii) tolerating or avoiding hydraulic disturbance, iii) enabling underwater photosynthesis and iv) water-borne dispersal (as demonstrated by the invasion of irrigated areas by C4 species, perennial graminoids and water dispersed species, through asexual reproduction) (Blom & Voesenek 1996; Catford & Jansson 2014; Juárez-Escario *et al.* 2016; Stokes *et al.* 2010).

To effectively use environmental flow cycles to manage weed infestations, it is important to understand the hydrological tolerances (sensitivities) of plants at each stage of their life cycle (Catford *et al.* 2013). Previously, our understanding of the non-native species invasion was based on land manager observations documented in reports that can be difficult to source (Blossey 1999). Since then, the majority of plants in the Murray-Darling Basin have been classified into one of eight water plant functional groups (WPFGs) based on the hydrological conditions they have adapted to grow within (Brock & Casanova 1997; Casanova 2011). These WPFGs can be broadly grouped as:

(iv) Terrestrial plants that do not tolerate flooding (Tdr), grow in damp places (Tda), or woody amphibious plants that tolerate wetting and drying (ATw).

(v) Amphibious plants that tolerate wetting and drying and have either an emergent (Ate) or low growing (ATl) growth habit, respond to flooding with different growth forms (ARp), or with floating leaves(ARf).

(vi) Submerged plants (S).

Each species have a range of traits that enable them to invade predominantly terrestrial, amphibious or aquatic environments (Figure 1). The water management strategies required to manage non-native species in each of these groups are likely to be different.

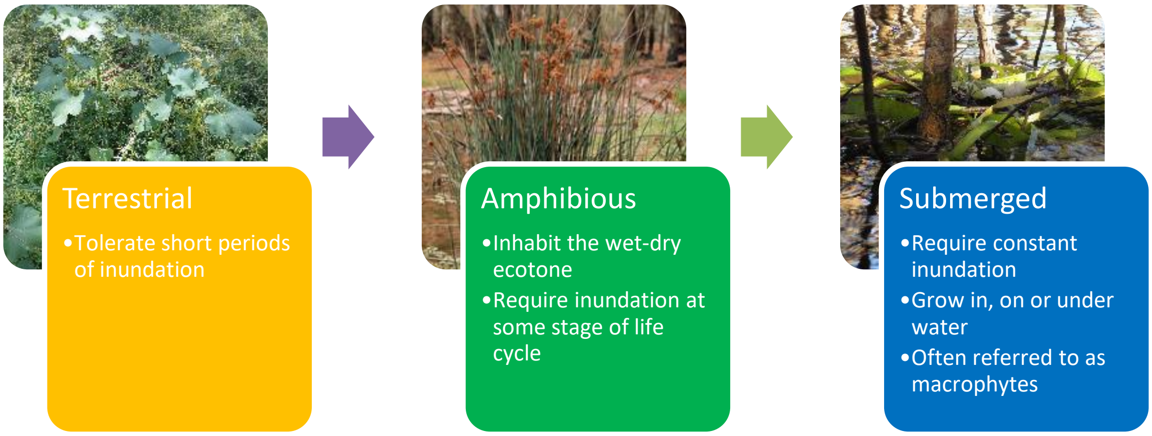

Figure 1. Functional groups used to classify non-native species based on adaptations to different hydrological conditions.

2.1 Invasive species

In the Murray-Darling Basin there are more than 100 non-native species recorded from riparian, floodplain and wetland vegetation communities (Table 1). The four species of most concern have life history traits that allow establishment from fragments. These include the submerged species are *Cabomba caroliniana* (Cabomba), *Egeria densa* (Brazilian waterweed), *Sagittaria montevidensis* (Arrowhead) and the terrestrial species *Salix* spp. (willows). These species are wide-spread and can establish in a range of conditions ranging from standing to flowing water environments.

Since their introduction, many of these species have maintained a limited distribution. However, these species may suddenly spread with a change of environmental conditions (Groves 2006). For example, *Mimosa pigra* was introduced to northern Australia in the 1890s. It remained sparse in the environment until 1952, when seeds dispersed down river to a wetter environment allowing the species to establish a dense population. From this location, regular flooding dispersed seeds downstream, quickly expanding the species' distribution (Groves 2006). Introduced species are more economical to control when they have a restricted distribution (i.e. before they become established in suitable environments for increased abundance, seed production and dispersal). If control measures are well planned, new invasions can be prevented, eradicated or contained before they become a widespread (Department of Environment and Primary Industries 2010).

Table 1 Invasive plants detected within the Murray-Darling Basin (source: Casanova unpublished data) and the water plant functional group (WPFGs) to which they have been assigned (Brock & Casanova 1997; Casanova 2011). Invasive species are indicated by an asterix and species of concern in bold.

WPFG	Species	WPFG	Species
Submerged		***Terrestrial***	
	Cabomba caroliniana*	*Grow in damp habitats (Tda)*	*Abutilon theophrasti**
	Egeria densa*		*Aster subulatus**
	*Vallisneria americana**		*Atriplex prostrata**
	*Vallisneria gigantea**		*Bromus molliformis**
Amphibious			*Centaurea calcitrapa**
Respond with different growth forms (Arp)	*Callitriche stagnalis**		*Centarium spicatum**
	*Isolepis marginata**		*Centaurium erythraea**
	*Isolepis prolifera**		*Conyza bonariensis**
	*Myriphyllum aquaticum**		*Dittrichia graveolens**
	*Ranunculus sceleratus**		*Echinochloa crus-galli**
	Sagittaria montevidensis*		*Heliotropium supinium **
	Sagittaria platyphylla*		*Holcus lanatus**
Emergent (Ate)	*Cyperus eragrostis**		*Juncus bufonius**
	Juncus acutus		*Phyla canescens**
	*Juncus articulatus**		*Oxalis pes-caprae**
	Juncus ingens		*Panicum gilvum**
	Typha domingensis		*Phalaris paradoxa**
	Typha orientalis		*Phyla canescens**
Floating (Arf)	*Eichhornia crassipes*		*Phyla nodiflora**
Low growing (Atl)	*Cotula bipinnata**		*Polypogon monospeliensis**
Terrestrial			*Rorippa palustris**
Tolerate wetting and drying (ATw)	*Eucalyptus camaldulensis*		*Rumex crispus**
	Salix spp.*		*Sisymbrium erysimoides**

WPFG	Species	WPFG	Species
<u>Terrestrial</u>		*Do not tolerate flooding (Tdr)*	*Lactuca serriola**
Grow in damp habitats (Tda)	*Soliva anthemifolia**	*(continued)*	*Leontodon taraxacoides**
(continued)	*Spergularia diandra**		*Lolium perenne**
	Trifolium spp.*		*Malva parviflora**
	*Verbena supina**		*Marrubium vulgare**
	*Xanthium*spp.*		*Medicago spp.*
Do not tolerate flooding (Tdr)	*Anagallis arvensis**		*Mesembryanthemum spp.**
	*Asperula conferta**		*Modiola caroliniana**
	*Avena spp.**		*Onopordum acanthium**
	*Bidens pilosa**		*Paronychia brasiliana**
	*Brassica tourneforti**		*Paspalum dilatatum**
	Bromus spp.		*Phalaris aquatica**
	*Cirsium vulgare**		*Picris echioides**
	*Critesion murinum**		*Polygonum arenastrum**
	*Cucumis myriocaripus**		*Polygonum arviculare**
	*Cuscuta campestris**		*Psilocaulon granulicaule**
	*Cynodon dactylon**		*Reichardia tingitana**
	*Diplotaxia muralis**		*Silybum marianum**
	*Echium plantagineum**		*Solanum nigrum**
	*Eleusine tristachia**		*Sonchus spp.**
	*Erodium cicutarium**		*Urtica urens**
	*Hordeum leporinum**		*Verbena bonariensis**
	*Hyperchaerus radicata**		*Verbena officinalis**

3 Potential to control non-native invasive species using environmental flows

Environmental flows have the potential to manage invasive plants, but their effectiveness will vary for species in different WPFGs. Invasions generally occur under two scenarios: annual species with a fast life cycle, or are terrestrial in origin, typically invade during the inter-flood period (Catford *et al.* 2011; Catford *et al.* 2013; Price *et al.* 2010), while aquatic species invade during prolonged periods of stable water levels (Dugdale *et al.* 2013b). One exception to this may occur in wetlands where species have adapted to survive in an environment that varies significantly in hydrological states, from complete inundation during flood to potentially long dry periods (Catford *et al.* 2013).

3.1 Exceeding physiological tolerances using prolonged inundation (terrestrial species)

Throughout the regulated sections of the Murray-Darling Basin, the construction of dams and levees to control the movement of water has led to a more stable water regime with many wetlands now becoming either permanently inundated or more permanently dry (Kingsford 2000; Nielsen & Brock 2009; Walker & Thoms 1993). These environmental conditions have predominantly promoted invasion by terrestrial species (Capon 2003; Catford *et al.* 2011), which are sensitive to inundation and can be effectively controlled using environmental flows (Duong *et al.* 2018; Greet *et al.* 2015; Miller *et al.* 2013).

For some woody amphibious plants, such as willow species (Salix spp.), that are generally flood-tolerant, long periods of inundation may be used to increase mortality of seedlings (Stokes 2008). However, management actions such as mechanical removal and herbicide treatment are most likely to be effective in minimising their spread (Cremer *et al.* 1999) (Figure 2).

Figure 2. Willows in the Ovens River (P. McInerney

3.2 Exceeding physiological tolerances by extending dry periods (submerged aquatic species; S)

Submerged aquatic species, such as *Cabomba caroliniana*, *Egeria densa*, and *Sagittaria montevidensis*, can be serious species of concern in rivers and wetlands of the Murray-Darling Basin. These species proliferate in standing or slow-flowing water, disperse downstream as fragments or seeds, and can form dense monocultures capable of altering the flow within irrigation channels and wetlands (Figure 3). *Cabomba caroliniana* has been effectively controlled in Lake Benalla (Victoria) by drawing down water levels and allowing the soil to dry (Dugdale *et al.* 2013a). *Egeria densa* has been effectively controlled in Lake Mulwalla (NSW) using a similar approach (Dugdale *et al.* 2012). The effectiveness of these manipulations may be improved by being used in conjunction with herbicide application, shading or physical removal (harvesting). For species requiring multiple integrated approaches for effective management it may be important to invest resources into preventing further spread (Dugdale *et al.* 2013b; Feehan *et al.* 2005).

Figure 3. Invasion of *Sagittaria montevidensis* (Arrowhead) along a flood runner associated with Broken Creek (photo D. Nielsen).

3.3 Exceeding physiological tolerances using a combined approach (amphibious emergent species; Ate)

Amphibious emergent species are well adapted to invading waterways and can have serious consequences on water flow and diversity of native aquatic species (Figure 4). In general, amphibious emergent species prefer areas that are constantly inundated at shallow depths (the preferred depth of which will vary between species), but can tolerate short periods of deeper flooding or drying. These species may be effectively managed through restoring a seasonal drought followed by a period of complete inundation. Partial submergence should be avoided as may promote rapid growth (Greet et al. 2015).

Some emergent amphibious species can grow in a variety of habitats ranging from water logged soils through to constant inundation. For example, *J. articulatus* prefers a water depth of 0.45 meters (Smith & Brock 1997). Or these species, effective control is likely to require manipulating the water regime and physical intervention through the use of herbicides, mechanical removal or cutting prior to inundation.

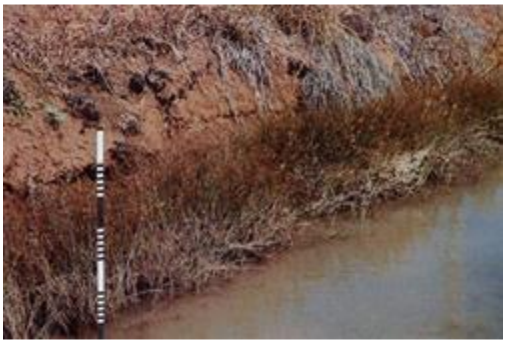

Figure 4. *Juncus articulatus* (photo Sainty and Jacobs (1981)).

3.4 Enhance competitive exclusion by native species

In some cases, the complex responses of non-native species to managed flows is sensitive to the response of native plants. For example, it is possible that prolonged floods delivered by environmental flows may control Lippia (*Phyla canescens*) by promoting the growth and competitive exclusion from dominant native species (Price *et al.* 2010). Understanding the watering requirements of native species (e.g. depth, duration and timing) may give native species a competitive advantage. For example, propagules of native species are more likely to disperse in autumn along the Hawkesbury-Nepean River (Howell & Benson 2000).

4 Connectivity in the landscape

It may be important to control populations of non-native species before implementing an environmental flow that has the potential to disperse propagules (Vivian, Ward, *et al.* 2014). For example, an infestation in an isolated wetland may show little potential to spread beyond that location. However, the delivery of environmental flows may promote the spread of propagules to nearby wetlands or floodplains. In the case of an isolated wetland, it may be preferable to allow the wetland to dry completely to control aquatic species or use chemical methods to control terrestrial weeds prior to delivering an environmental flow (Florentine and Westbrooke 2005).

5 The importance of integrated management techniques

In many cases the effective control of non-native species will require an integrated approach to weed management. This is likely to be the case for species with a complex response to environmental flows, reflecting the potential for plants to be susceptible to managed flows at different stages of their life cycle. The delivery of one type of environmental flow may have both positive and negative impacts on different stages of the life cycle and in different parts of the landscape. For example, prolonged inundation (>30 days) can reduce willow (*Salix* spp.) seedling survival, but potentially enhance recruitment along the strand line (Stokes 2008). It may then be possible to extend the inter-flood period to help reduce the survival of new recruits along the strand line, but at the cost of enhancing growth in established plants (Stokes 2008), and limiting recruitment in native species. In these instances, the effectiveness of weed control may be improved by implementing environmental flows in conjunction with additional weed control techniques (e.g. chemical control) (Holland Clift & Davies 2007). Where different life stages require different management techniques, integrated management techniques are required for cost effective weed control programs.

In situations where freshwater and riparian systems are highly modified, weed control alone may be insufficient to increase natural biodiversity and ecosystem function. Additional physical techniques may be required to increase the effectiveness of managed flows (e.g. dredging, benthic barriers, shading and nutrient inactivation) (Franklin *et al.* 2008; Madsen 2000; Wersal *et al.* 2013), or to account for non-native invasive species altering the local environmental conditions sufficiently to limit the natural regeneration of native species following weed control.

The application of herbicides may have secondary impacts on aquatic ecosystems, which may be alleviated by environmental flows. For example, herbicides can effectively control invasive species (Nichols 1991; Richardson 2008) (Figure 5). Decomposition of vegetation following broad scale herbicide use has been demonstrated to reduce dissolved oxygen concentrations, triggering hypoxic events that effect fish survival (e.g. following aerial control of dense infestations of water hyacinth, *Eichhornia crassipes*, in waterbodies occupied by barramundi) (Waltham & Fixler 2017).

Figure 5 The negative effect of herbicide control on *Sagittaria montevidensis* (Arrowhead) and a native aquatic species (*Persicaria* spp.), along Broken Creek (photos D. Nielsen)

6 Discussion

Plant invasions are a serious threat to natural and managed ecosystems worldwide (Hobbs & Humphries 1995). However, effective management strategies can be difficult to design and implement (Downey *et al.* 2010). The vast number of exotic species distributed across the Murray-Darling Basin (>100 species), highlights the importance of considering the species adaptive traits, the conditions suitable for colonisation, reproduction and dispersal, and subsequently the adverse conditions that may aid in their control. Currently many exotic species are limited in their distribution, allowing for the potential for eradication (Department of Environment and Primary Industries 2010). Management of these weeds is likely to become more difficult as more species become more widespread and new species are detected.

Identifying the traits that enable a species to colonise a new area, survive and reproduce should lead to more-effective control programs and delivery of environmental flows. We recommend assessing the biological value of particular sites and their degree of disturbance to inform management priorities. Within the Murray-Darling Basin it is likely that a triage approach may be required to manage invasive species. Environmental water is one tool that can be used to complement other activities such as mechanical, biological or herbicidal control (D'Antonio & Meyerson 2002; Hobbs & Humphries 1995). For example, multiple methods are being used to control the invasive species, water Hyacinth (*Eichhornia crassipes*) in the Gwydir wetlands, NSW (Border Rivers-Gwydir Catchment Management Authority 2008; Mawhinney 2003)

Physical management methods (i.e. where the environment is manipulated) can also be useful tools in weed control. Multiple techniques have been used successfully, including dredging, drawdown, benthic barriers, shading and nutrient inactivation (Madsen, 2000; Wersal et al., 2013). The effectiveness of environmental flows as a physical management method has so far received little attention (Ochs *et al.* 2018). Environmental flows have been successfully used to control weeds within rivers systems (Mawhinney 2003; Tena *et al.* 2013). However, their effectiveness may be species' and life cycle stage dependent (e.g. the velocity of environmental flows required to dislodge plants may only be sufficient for shallow rooted seedlings) (Bywater-Reyes *et al.* 2015), and may have negative secondary effects (e.g. through dispersing propagules longitudinally and laterally with a riverine system) (Barrat-Segretain & Bornette 2000).

Floodplains and wetlands are naturally dynamic systems that undergo periods of disturbance (flooding and drying) creating conditions suitable for a wide range of plants (Catford & Jansson 2014; Stokes 2008). In areas where the natural environment has been heavily modified or species have become naturalised, there may become a need to consider the value of novel ecosystems (Capon & Palmer 2018; Catford *et al.* 2013), and re-allocating resources for the control of invasive plants to locations where management may be more effective (Hobbs & Kristjanson 2003). However, deciding whether to allow areas to succumb (or remain in that state) should depend on a number of conditions based on the level of threat to biodiversity and potential for conservation outcomes (Downey *et al.* 2010). It is also important to note that progress has been made to restore even heavily degraded riverine, riparian, floodplain and wetland systems (e.g. Howell & Benson 1994, Howell & Benson 2000).

7 Summary

Plant invasions are a serious threat to natural and managed ecosystems worldwide and can be difficult to manage effectively. Highly modified hydrological regimes coupled with other environmental changes is likely to create suitable habitats for non-native species (Florentine & Westbrooke 2005). The use of environmental flows can promote native plant communities, that suppress terrestrial exotic species, and improve our ability to manage and restore riverine, riparian, floodplain and wetland plant communities (Duong *et al.* ; Greet *et al.* 2015). However, while environmental flows may prevent the expansion of many invasive terrestrial species it may also facilitate in the dispersal of introduced aquatic species. To maximise the effectiveness of environmental flows as a tool for weed control it is recommended that the following points be considered:

- The condition and function of the local environment,
- The potential for re-invasion from other sources,
- The timing of the natural hydrology and environmental flows to take advantage of stages in the life cycles of invasive plants sensitive to inundation,
- The applicability of complementary measures (mechanical and chemical treatment) that can be used in conjunction with environmental flows, and
- The quality of water being delivered for the environmental flow

8 Acknowledgements

Project supported through the Murray–Darling Basin Joint Governments". ***The Murray-Darling Basin Joint Governments are made up of;***

- Department of Environment, Land, Water and Planning (Victoria)
- NSW Department of Primary Industries (New South Wales)
- Department of Environment, Water and Natural Resources (South Australia)
- Department of Natural Resources and Mines (Queensland)
- ACT Environment and Sustainable Development (Australian Capital Territory)
- Department of Agriculture & Water Resources

9 References

Ballinger A, Mac Nally R (2006) The landscape context of flooding in the Murray–Darling Basin. *Advances in ecological research* **39**, 85-105.

Barrat-Segretain M-H, Bornette G (2000) Regeneration and colonization abilities of aquatic plant fragments: effect of disturbance seasonality. *Hydrobiologia* **421**, 31-39.

Bennett AF, Nimmo DG, Radford JQ (2014) Riparian vegetation has disproportionate benefits for landscape-scale conservation of woodland birds in highly modified environments. *Journal of Applied Ecology* **51**, 514-523.

Berke SK (2010) Functional groups of ecosystem engineers: a proposed classification with comments on current issues. *Integrative and Comparative Biology* **50**, 147-157.

Blom C, Voesenek L (1996) Flooding: the survival strategies of plants. *Trends in Ecology & Evolution* **11**, 290-295.

Blossey B (1999) Before, during and after: the need for long-term monitoring in invasive plant species management. *Biological Invasions* **1**, 301-311.

Border Rivers-Gwydir Catchment Management Authority (2008) Progress Report for 'Water Hyacinth Control in Gwydir Wetlands, NSW Wetland Recovery Program.

Brock MA, Casanova MT (1997) Plant life at the edge of wetlands: ecological responses to wetting and drying patterns. In: *Frontiers in Ecology: building the links* (eds. Klomp N, Lunt I), pp. 181-192. Elsevier Science Ltd., Oxford.

Bunn SE, Arthington AH (2002) Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* **30**, 0492-0507.

Bywater-Reyes S, Wilcox AC, Stella JC, Lightbody AF (2015) Flow and scour constraints on uprooting of pioneer woody seedlings. *Water Resources Research* **51**, 9190-9206.

Capon S (2003) Plant community responses to wetting and drying in a large arid floodplain. *River Research and Applications* **19**, 509-520.

Capon SJ, Brock MA (2006) Flooding, soil seed bank dynamics and vegetation resilience of a hydrologically variable desert floodplain. *Freshwater Biology* **51**, 206-223.

Capon SJ, Palmer GJ (2018) *Turning over a new leaf: the role of novel riparian ecosystems in catchment management*.

Caraco N, Cole J, Findlay S, Wigand C (2006) Vascular plants as engineers of oxygen in aquatic systems. *BioScience* **56**, 219-225.

Casanova MT (2011) Using water plant functional groups to investigate environmental water requirements. *Freshwater Biology* **56**, 2637-2652.

Catford JA (2017) Hydrological impacts of biological invasions. In: *Impact of biological invasions on ecosystem services*, pp. 63-80. Springer.

Catford JA, Downes BJ, Gippel CJ, Vesk PA (2011) Flow regulation reduces native plant cover and facilitates exotic invasion in riparian wetlands. *Journal of Applied Ecology* **48**, 432-442.

Catford JA, Jansson R (2014) Drowned, buried and carried away: effects of plant traits on the distribution of native and alien species in riparian ecosystems. *New Phytologist* **204**, 19-36.

Catford JA, Naiman RJ, Chambers LE*, et al.* (2013) Predicting novel riparian ecosystems in a changing climate. *Ecosystems* **16**, 382-400.

Cremer K, Gooey M, Houghton P (1999) Willow management for Australian rivers. *Willow management for Australian rivers.*

D'Antonio C, Meyerson LA (2002) Exotic plant species as problems and solutions in ecological restoration: a synthesis. *Restoration Ecology* **10**, 703-713.

Department of Environment and Primary Industries (2010) Invasive Plants and Animals Policy Framework. Victoria, Australia, http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/protecting-victoria/invasive-plants-and-animals/invasive-plants-and-animals-policy-framework.

Downey PO, Williams MC, Whiffen LK*, et al.* (2010) Managing alien plants for biodiversity outcomes—the need for triage. *Invasive Plant Science and Management* **3**, 1-11.

Dudgeon D, Arthington AH, Gessner MO*, et al.* (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews* **81**, 163-182.

Dugdale TM, Butler KL, Clements D, Hunt TD (2013a) Survival of cabomba (Cabomba caroliniana) during lake drawdown within mounds of stranded vegetation. *Lake and reservoir management* **29**, 61-67.

Dugdale TM, Clements D, Hunt TD, Butler KL (2012) Survival of a submerged aquatic weed (Egeria densa) during lake drawdown within mounds of stranded vegetation. *Lake and reservoir management* **28**, 153-157.

Dugdale TM, Hunt TD, Clements D (2013b) Aquatic weeds in Victoria: Where and why are they a problem, and how are they being controlled? *Plant Protection Quarterly* **28**, 35.

Duong A, Greet J, Walsh CJ, Sammonds MJ (2018) Managed flooding can augment the benefits of natural flooding for native wetland vegetation. *Restoration Ecology*.

Feehan P, Williams D, Todd C*, et al.* (2005) Protecting River Murray icon sites from invasive species– arrowhead (Sagittaria graminea). Project.
Florentine S, Westbrooke M (2005) Invasion of the noxious weed Nicotiana glauca R. Graham after an episodic flooding event in the arid zone of Australia. *Journal of Arid Environments* **60**, 531-545.
Franklin P, Dunbar M, Whitehead P (2008) Flow controls on lowland river macrophytes: A review. *Science of the Total Environment* **400**, 369-378.
Graetz R, Tongway DJ (1986) Influence of grazing management on vegetation, soil structure and nutrient distribution and the infiltration of applied rainfall in a semi-arid chenopod shrubland. *Australian Journal of Ecology* **11**, 347-360.
Greet J, Webb JA, Cousens RD (2015) Floods reduce the prevalence of exotic plant species within the riparian zone: evidence from natural floods. *Applied Vegetation Science* **18**, 503-512.
Groves R (2006) Are some weeds sleeping? Some concepts and reasons. *Euphytica* **148**, 111-120.
Gurnell A (2014) Plants as river system engineers. *Earth Surface Processes and Landforms* **39**, 4-25.
Gutiérrez JL (2017) Modification of habitat quality by non-native species. In: *Impact of biological invasions on ecosystem services*, pp. 33-47. Springer.
Hobbs RJ, Humphries SE (1995) An integrated approach to the ecology and management of plant invasions. *Conservation Biology* **9**, 761-770.
Hobbs RJ, Kristjanson LJ (2003) Triage: How do we prioritize health care for landscapes? *Ecological Management & Restoration* **4**, S39-S45.
Holland Clift S, Davies J (2007) Willows management guide: current management and control options for willows (Salix sp.) in Australia.
Howell J, Benson D (2000) Predicting potential impacts of environmental flows on weedy riparian vegetation of the Hawkesbury–Nepean River, south-eastern Australia. *Austral Ecology* **25**, 463-475.
Juárez-Escario A, Conesa JA, Solé-Senan XO (2016) Identifying alien plants linkages between irrigated orchards and adjacent riparian habitats from a trait-based approach. *Agriculture, Ecosystems & Environment* **225**, 173-183.
Kingsford RT (2000) Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25**, 109-127.
Lytle DA, Poff NL (2004) Adaptation to natural flow regimes. *Trends in Ecology & Evolution* **19**, 94-100.
Madsen JD (2000) Advantages and disadvantages of aquatic plant management techniques. ENGINEER RESEARCH AND DEVELOPMENT CENTER VICKSBURG MS ENVIRONMENTAL LAB.
Mawhinney W (2003) Restoring biodiversity in the Gwydir Wetlands through environmental flows. *Water Science and Technology* **48**, 73-81.
Miller KA, Webb JA, de Little SC, Stewardson MJ (2013) Environmental flows can reduce the encroachment of terrestrial vegetation into river channels: a systematic literature review. *Environmental Management* **52**, 1202-1212.
Nichols SA (1991) The interaction between biology and the management of aquatic macrophytes. *Aquatic Botany* **41**, 225-252.
Nielsen DL, Brock MA (2009) Modified water regime and salinity as a consequence of climate change: prospects for wetlands of Southern Australia. *Climatic Change* **95**, 523-533.
Nilsson C, Svedmark M (2002) Basic Principles and Ecological Consequences of Changing Water Regimes: Riparian Plant Communities. *Environmental Management* **30**, 468-480.
Ochs K, Rivaes RP, Ferreira T, Egger G (2018) Flow Management to Control Excessive Growth of Macrophytes–An Assessment Based on Habitat Suitability Modeling. *Frontiers in plant science* **9**, 356.
Pittock J, Finlayson CM (2011) Australia's Murray-Darling Basin: freshwater ecosystem conservation options in an era of climate change. *Marine and Freshwater Research* **62**, 232-243.

Poff NL (1997) Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. *Journal of the North American Benthological Society* **16**, 391-409.
Poff NL, Allan JD, Bain MB*, et al.* (1997) The natural flow regime. *BioScience* **47**, 769-784.
Price J, Gross C, Whalley W (2010) Prolonged summer flooding switched dominance from the invasive weed lippia (Phyla canescens) to native species in one small, ephemeral wetland. *Ecological Management & Restoration* **11**, 61-63.
Puckridge JT, Sheldon F, Walker KF, Boulton AJ (1998) Flow variability and the ecology of large rivers. *Marine and Freshwater Research* **49**, 55-72.
Richardson RJ (2008) Aquatic plant management and the impact of emerging herbicide resistance issues. *Weed Technology* **22**, 8-15.
Riis T, Biggs BJ (2003) Hydrologic and hydraulic control of macrophyte establishment and performance in streams. *Limnology and Oceanography* **48**, 1488-1497.
Sainty GR, Jacobs SWL (1981) *Waterplants of New South Wales.* Water Resources Commission, NSW.
Smith R, Brock M (1997) Germination potential, growth patterns and reproductive effort of Juncus articulatus and Glyceria australis in temporary shallow wetlands in Australia. *Wetlands Ecology and Management* **5**, 203-214.
Stokes K, Ward K, Colloff M (2010) Alterations in flood frequency increase exotic and native species richness of understorey vegetation in a temperate floodplain eucalypt forest. *Plant Ecology* **211**, 219-233.
Stokes KE (2008) Exotic invasive black willow (Salix nigra) in Australia: influence of hydrological regimes on population dynamics. *Plant Ecology* **197**, 91-105.
Tena A, Książek L, Vericat D, Batalla RJ (2013) Assessing the geomorphic effects of a flushing flow in a large regulated river. *River Research and Applications* **29**, 876-890.
Thompson C, Fryirs K, Croke J (2016) The disconnected sediment conveyor belt: patterns of longitudinal and lateral erosion and deposition during a catastrophic flood in the Lockyer Valley, South East Queensland, Australia. *River Research and Applications* **32**, 540-551.
Timbal B, Abbs D, Bhend J*, et al.* (2015) Murray Basin Cluster Report: Climate Change in Australia. Projections for Australia's Natural Resource Management Regions.'. *Ekström, Penny Whetton, Chris Gerbing, Michael Grose, Leanne Webb and James Risbey. Canberra: CSIRO and Bureau of Meteorology*.
Walker KF, Thoms MC (1993) Environmental effects of flow regulation on the lower Murray River, Australia. *Regulated Rivers: Research and Management* **8**, 103-119.
Waltham N, Fixler S (2017) Aerial herbicide spray to control invasive water hyacinth (Eichhornia crassipes): Water quality concerns fronting fish occupying a tropical floodplain wetland. *Tropical Conservation Science* **10**, 1940082917741592.
Wersal RM, Madsen JD, Cheshier JC (2013) Seasonal biomass and starch allocation of common reed (Phragmites australis)(haplotype I) in Southern Alabama, USA. *Invasive Plant Science and Management* **6**, 140-146.