Connectivity and floodplain infrastructure

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April 2018

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Draft Report prepared for the Murray-Darling Basin Authority by The Murray-Darling Freshwater Research Centre.

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Document history and status

Version	Date Issued	Reviewed by	Approved by	Revision type
1	3/4/2018	R Durant	D Nielsen	Internal
2	9/4/2018	P McInerney	D Nielsen	Internal
3	23/4/2018	Paul Brown	D Nielsen	Internal
4	June 2018	MDBA	D Nielsen	External

Distribution of copies

Version	Quantity	Issued to
Draft	1	Carla Tadich (MDBA)
Draft	1	Carla Tadich (MDBA) 22 June 2018

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Executive summary

Longitudinal and lateral connectivity is a fundamental process that helps to sustain healthy river-floodplain ecosystems. However, throughout the Murray-Darling Basin, connectivity has been indirectly altered by the management of water for consumptive use, both through the fragmentation effects of physical infrastructure and through alterations to the flow regime and loss of natural connection events. Successful restoration of rivers and their floodplains is reliant on the re-establishment of connectivity (both longitudinally and laterally) within the riverine network. The Murray-Darling Basin plan outlines the key objectives for the management of the Murray-Darling Basin (MDB). One of those key objectives is "to protect and restore connectivity within and between water dependant ecosystems" by ensuring that

  a) The diversity and dynamics of geomorphic structures, habitat, species, genes are protected and restored; and
  b) Ecological processes dependent on hydrologic connectivity (longitudinally, laterally and vertically are protected and restored.

In this paper we define connectivity can be defined as the ability of species and processes to move through the landscape (river channel – floodplains and floodplain - river channel), and is of primary importance to ecosystem function and to the distribution and abundance of biota (Lindenmayer *et al.* 2008; Lindenmayer & Fischer 2007; Ward *et al.* 1999). The importance of restoring connectivity is recognised as playing a key role in preserving river and floodplain biodiversity and productivity within the basin. However, there are a number of impediments to restoring lateral connectivity, such as the perceived risks of hypoxic blackwater events leading to fish kills, and social and cultural barriers to the restoration of natural inundation patterns to large floodplain areas (Baldwin et al. 2016).

Flow in the Murray-Darling system have change as a consequence of diversion,, construction of dams, weir and levees and changes in river operations (Maheshwari *et al.* 1995).While these changes have not had a major impact on the occurrence of large over bank floods, there has been a significant reduction in the small to medium floods that would have connected many floodplain channels and wetlands (Close 1990).Connectivity associated with these small to medium floods and lateral infrastructure is increasing being re-established through the use of infrastructure (e.g. regulators and pumps) to control water delivery to floodplain areas without the need for small to medium overbank flows. This provides both water-use efficiency gains, and also alleviates risks to floodplain infrastructure. Notable examples include the construction of diversion channel at Torrumbarry Weir on the Murray River, which allows extensive watering of redgum forest stands within Koondrook-Perricoota forest at river flows of between 3,500-6,000 ML/day, rather than the previous volumes of ~18,000-35,000 ML/day and the use of pumps to inundate significant areas of the Hattah Lakes complex.

However, while infrastructure based approaches can provide significant water-use efficiency gains, a number of concerns have been raised regarding the extent to which such diversions mimic natural flood events. While watering plans and event hydrographs aim to use natural cues where possible, water transferred via infrastructure during periods of in-channel flow may not provide some of the physical and chemical cues associated with natural periods of connectivity, and may not provide the same fluxes of materials (e.g. sediments, nutrients), energy (carbon) and biota (plant and animal propagules) between rivers and floodplains as natural flood events. There is as yet also a lack of information from which to evaluate whether the watering of individual fragmented sites will support broader ecosystem functions sought under the basin plan.

A number of studies undertaken by the MDFRC and other research organisations have investigated the impact of managed flows and increased connectivity on biotic responses

- McCarthy *et al.* (2009) demonstrated that pumping of water into wetlands acts as a filter on fish communities by selecting for small fish and/or larvae/eggs of fish but preventing the passage of larger sized fish.
- Stoffels *et al.* (2013) demonstrated that" managed" river-floodplain connection through a regulator did not enhance fish communities. In comparison, a "natural" connection as a result of overbank flows enhance the response of both native and non-native fish species.
- Nielsen et al (unpublished data) demonstrates that that the type of infrastructure used to deliver water into wetlands selects for different components of the plant community by selecting for either seeds drifting on the water surface or drifting sub-surface.

The likely success of infrastructure in achieving connectivity outcomes close to those of natural floods will depend on how the infrastructure is operated and managed. This will include the timing of water transfers (e.g. to coincide with natural tributary inflows and other cues), and careful management of water-residency times on the floodplain to avoid potential adverse outcomes (e.g. localised hypoxic blackwater events). The Sustainable Diversion Limits (SDL) framework and existing infrastructure will provide opportunities to conduct experiments that test these and other hypotheses, and over time to improve the design and operation of infrastructure via an adaptive management approach.

Key issues that need to be addressed are:

- How can delivery of environmental water through infrastructure be best managed to meet biotic and biogeochemical objectives?
    - How can the hydrology of the riverine-floodplain system be best managed to achieve ecological outcomes?
    - Is there sufficient knowledge to make informed trade-off decisions and compromises regarding the way that floodplain infrastructure is operated?
    - What spatial and temporal scales should be considered when using infrastructure to deliver environmental water to accommodate dispersal and other life-history characteristics of key biota?

- Informed debate to decide how much of the riverine-floodplain environment is needed to be conserved by the delivery of environmental water through infrastructure to maintain ecological integrity.
    - Identification of ecosystems that can be most readily conserved through the use of infrastructure and those that cannot.
    - Establishment of riverine-floodplain reserves that are able to be maintained via the delivery of environmental water through infrastructure.

1   Introduction

Floodplains are some of the most productive ecosystems within the landscape, supporting a diversity of ecosystems and biota (Junk *et al.* 1989; Tockner *et al.* 2008). Floodplains provide habitat for a diversity of terrestrial and aquatic biota that are reliant on periodic wetting and drying regimes. Alteration of flow regimes is an ongoing threat to the ecological sustainability of rivers and associated floodplains. Flow modification has severely altered river and floodplain ecology , with a corresponding loss of inherent resilience and resistance of floodplain and riverine systems to climate variability (e.g. drought) and other anthropogenic disturbances (Wallace *et al.* 2011).

Regulation of flows and changing climate has caused a decrease in the amount of rainfall in most arid, semi-arid and temperate regions of Australia, with climate change predicted to reduce flows in the Murray-Darling Basin (MDB) by 48% in the coming years (Pittock 2003). Reductions in flows will reduce the frequency of periods of connectivity between rivers and associated floodplains and wetlands and alter the extent and timing of connections (Dunlop & Brown 2008). Such changes influence ecosystem functioning and dynamics, causing long-term and potentially irreversible damage e.g. species extinctions.

As reduced water availability applies increasing pressure on water resources, there is a need to plan for facilitation of functioning floodplains and wetlands within the landscape that comprise a range of wetland types (Nielsen & Brock 2009). Re-establishment of natural flow regimes represents a neat theoretical objective. However, the reality is that this is likely to be impractical, since the demands of consumptive water use preclude returning our rivers to a natural state. The existing impacts of regulation combined with future impacts of climate change imply that in many river systems, overbank flows may no longer occur frequently enough to maintain ecological processes, and many wetlands and floodplains will become increasingly reliant on targeted environmental water allocations (Wallace *et al.* 2011). This has led to a range of alternative methods to optimise the benefits of environmental water.

Re-establishment of spatial connectivity is one of the major objectives of the Murray-Darling Basin Plan which aims to protect and restore connectivity within and between water dependant ecosystems (Murray-Darling Basin Authority 2007, 2010). Spatial connectivity is a major consideration in conservation planning for many systems (Cabeza 2003) and particularly relevant in freshwater applications. The success of management activities designed to restore connectivity will be influenced by longitudinal connectivity within the catchment and lateral connectivity between the river channel to its associated floodplain (Pringle 2001). Consideration of connectivity and its importance in maintaining natural ecological processes and biodiversity in fresh waters is a key for conservation planning in these systems (Grantham *et al.* 2010).

The use of environmental water is now a common river restoration technique within the MDB and other regulated rivers (Arthington *et al.* 2006). These flows aim to mimic components of the river's natural flow variability, including the magnitude, frequency, timing, duration, rate of change and predictability of flow events (Arthington *et al.* 2006). For wetlands in the MDB, watering events are often targeted at specific wetlands involving discrete parcels of environmental water (Beesley *et al.* 2011). Engineering based approaches are now commonly being used as efficient means of delivering water to floodplain wetlands. Such approaches include inundating floodplains through pumping and diversion canals, and then controlling water movement on floodplains with levees, weirs and regulators (Figure 1). The use of infrastructure is broadly designed to create or maintain local flooding that mimic natural inundation patterns.

Figure 1. Examples of infrastructure used to deliver water into wetlands in the MDB.

2   Managed flooding

As a consequence of river regulation there has been a reduction in small to medium floods resulting in reduced frequency and extent of floodplain inundation (Galat *et al.* 1998). A key goal of environmental flow programs in floodplain river systems is to restore small to medium flood events that are considered to have the greatest ecological or geomorphological benefits. To achieve this, managers within the MDB have instigated the use of three main methods of manipulating water levels onto floodplains and associated wetlands (Wallace *et al.* 2011). The construction of large regulators and pumps in areas such as Koondrook forest, Chowilla floodplain and Hattah Lakes is allowing significant areas of wetland and floodplain forest to be inundated, providing significant benefits to associated animals and plants:

Regulators: Inlet and outlet channels of many wetlands have had regulators installed. Regulators on inlet channels are being used to prevent wetlands flooding, thereby promoting a dry phase or to allow the movement of water on to the floodplain (Figure 2). Regulators on outlet channels can be used to retain water on the floodplain increasing the duration of the flood event.

Siphons: Where the commence to flow of a wetland is at or below the weir pool or river operating height, water is gravity fed by siphons into wetlands (e.g. Thegoa Lagoon).

Pumping: When the commence-to-flow for a wetland is above existing river operating height, water is delivered using pumps. The advantage of using pumps is that relatively small volumes of water can be utilised to inundate targeted sections of the floodplain during low flow periods when inundation would otherwise not be possible (Figure 2). Additionally large pumps can move large volumes of water and flood significant floodplain areas (e.g. Hattah Lakes) (Figure 2).

A primary goal of using infrastructure for environmental watering is to achieve critical environmental flow targets

Figure 2. From the top: (i) regulator at Nestron Creek, (ii) Koondrook Forest regulator, (iii) pumping wetlands in the mid-Murray, (iv) Hattah Lakes pump.

using less water (defined in terms of the timing, duration, and frequency of floodplain inundation) and to mimic inundation patterns of small to medium sized floods that would not occur under current developed conditions in the Basin. Such outcomes may be achieved either actively (e.g. pumping) or passively (e.g. diverting and holding water on floodplains) or within specific wetlands via weirs, levees, channels, and flow regulators, as opposed to relying on overbank or run-of-river floods (Bond *et al.* 2014).

3   Ecological Risks and Benefits

The ecological risks and benefits of using infrastructure for flooding can be divided into three major categories: (1) those relevant to floodplain specialist biota, (2) those affecting the fluxes of materials and energy between rivers and their floodplains, and (3) those affecting the movement of biota between river and floodplain habitats (Bond *et al.* 2014).

3.1   Floodplain specialist biota

The early use of infrastructure to artificially flood parts of the floodplain for environmental purposes, was to prevent or minimise the loss of River Red Gum (*Eucalyptus camaldulensis*) forests that were at risk during the millennium drought (2000-2010). This approach proved effective in promoting tree survival, germination and recruitment (Jensen *et al.* 2008). In addition, the inundation of wetlands enhance their persistence providing critical habitat for floodplain biota such as plants (Reid & Quinn 2004), fish (King *et al.* 2009) and waterbirds (Kingsford & Auld 2005). The use of infrastructure to artificially enhance flooding is an option in regions where vegetation condition is very poor, native fish are in decline and bird breeding has ceased or declined, and natural floods no longer occur (Bond *et al.* 2014).

The use of infrastructure for flooding has some associated risks to fish populations. Pumps and regulators may interrupt the movements of fish between lateral floodplain areas and associated river channels and hinder movements for spawning, feeding and refuge (Jones & Stuart 2008). While regulators may provide some opportunities for fish to return to the river channel, the use of pumps alone, provides no opportunity for fish to return to the river, and as water recedes they become stranded and perish (Jones 2006; Jones & Stuart 2008; Vilizzi *et al.* 2013). Pumps also appear to filter the fish communities either by exclusion or mortality (Baumgartner *et al.* 2009; McCarthy *et al.* 2009; Vilizzi *et al.* 2013).

3.2   Movement of nutrients and carbon

It is well accepted that periodic flooding events are critical for transporting significant amounts of terrestrially derived resources into the main river channel (Junk *et al.* 1989). The interaction and exchange of material between rivers and floodplains are considered to be important for the processing and delivery of carbon and nutrients for utilisation in aquatic food webs (Junk *et al.* 1989; Tockner *et al.* 2000). During flood events, water residence time increases and suspended material (sediment, carbon, nutrients) is transported from the river and deposited on the floodplain (Tockner *et al.* 1999). Floodplain inundation also mobilises nutrients (N and P) from sediments and carbon is leached from accumulated terrestrial litter (Baldwin 1999), supporting increased phytoplankton and zooplankton densities (Tockner *et al.* 1999).

As water returns to the river from the floodplain, carbon, nutrients, phytoplankton and zooplankton may be exported and made available for use in river food webs. For example, following significant flooding of Barmah-Millewa Forest, Nielsen *et al.* (2016) estimated a net export of 300 tonne of dissolved organic carbon (DOC), seven tonne of zooplankton and 0.3 tonne of phytoplankton, three tonne of phosphorus and 25 tonne of nitrogen from the floodplain immediately following the flood peak, all of which have the potential to contribute significantly to within channel productivity.

Despite the known importance of floodplains for supporting high levels of biodiversity and providing ecosystem services, floodplain-river connectivity in many catchments is limited. Flow regulation has restricted lateral movement of material both from the river to the floodplain and from the floodplain and back to the river (Tockner & Stanford 2002). The use of infrastructure that ponds water on floodplains poses an ecological and water quality risk by inducing hypoxic blackwater, driven by the leaching and subsequent microbial respiration of carbon from terrestrial leaf litter (Baldwin *et al.* 2011; Howitt *et al.* 2007; Whitworth *et al.* 2012). These risks can to be managed by timing the flood event with natural conditions (late winter - early spring); reducing the period of inundations and allowing flood waters to pass through the forest (Baldwin *et al.* 2011).

While floodplain derived inputs are an important source of carbon and nutrients to the river system, and despite the fact that many lowland fish species exhibit a high degree of tolerance to hypoxia (McMaster & Bond 2008; McNeil & Closs 2007), blackwater events if not managed, can cause mortality of fish and crayfish populations (King *et al.* 2012). Even though such events may occur naturally, the risks are greatly elevated where water is ponded behind barriers on the floodplain with limited exchange, thereby increasing the floodplain residency time (Baldwin *et al.* 2011). The negative impacts of such events can extend far downstream if sufficient hypoxic blackwater enters the river channel (Whitworth *et al.* 2013).

3.3   Dispersal of biota

Passive dispersal of propagules (seeds and fragments of plants and eggs of invertebrates and fish) can facilitate the recovery of wetland communities after disturbances such as drying and particularly are important for those species that do not persist dormant in the sediment as (Boedeltje *et al.* 2003; Vogt *et al.* 2004) or are not able to actively disperse. The ability of a propagule to float will influence its capacity to disperse longitudinally and laterally. The imposition of barriers that reduce connectivity between rivers and wetlands or modify connectivity will influence the dispersal of propagules. Furthermore, the type of artificial connection (pumps, levees etc.) is likely to select for or against propagules with specific dispersal traits. For example, the use of sub-surface pumps that increase connectivity will reduce the number of floating seeds dispersed into wetlands.

As well as passive dispersal of propagules, natural floodplain connection events provide important opportunities for active movement of some biota onto and off the floodplain. For example, in many floodplain river systems fish that are normally resident within the main channel may move into floodplain habitats to feed and to breed (Jardine *et al.* 2012; Winemiller 2014). Similarly, there are other animals (fish, amphibians) which may persist within permanent and semi-permanent floodplain wetlands, but rely on periodic reconnection events to support colonisation and movement between habitats. Recent work within the MDB suggests that artificial flooding may support different floodplain fish assemblages than natural floods (Stoffels *et al.* 2014; Stoffels *et al.* 2015). However, there is also a need to better understand the propensity for MDB fishes to utilise floodplain habitats. For example, some MDB data suggest species such as golden perch prefer main channel habitats even as larvae (Gehrke 1990; Gehrke 1991; King *et al.* 2003). However, more recent work has shown a diversity of movement patterns among species between river and floodplain habitats (Stoffels *et al.* 2015). We suggest further work is required to better understand the use of floodplain habitats by fish in the Murray-Darling Basin, and how that might influence the construction and operation of infrastructure designed to support environmental watering.

4   Making it work

The movement of biota, carbon and nutrients between habitats is vital for population persistence and riverine-floodplain productivity. This connectivity can be defined as the ability of species and processes to move through the landscape, and is of primary importance to ecosystem function and to the distribution and abundance of biota (Lindenmayer *et al.* 2008; Lindenmayer & Fischer 2007).

Connectivity is assumed to confer ecosystems with resilience, as connected populations can recover from disturbance through the linking of populations, processes or food webs (Mumby & Hastings 2008). Consequently, enhancing connectivity has emerged as an objective in many restoration projects (Hodgson *et al.* 2009).

While infrastructure can be used to deliver water onto a floodplain and associated wetlands there are however, ecological concerns around the use of infrastructure for connectivity as well as spatial and water quality issues (Humphries *et al.* 2015; Pittock *et al.* 2013; Wallace *et al.* 2011). The expectation is that sites that are fragmented in the landscape by infrastructure will still remain as sources of propagules and colonists for other areas and that biogeochemical cycles, important in the maintenance of in-channel as well as floodplain productivity will not be reduced beyond what is required to maintain overall system health (Wallace *et al.* 2011). However, infrastructure reduces transport of nutrients, biota and organic matter and may create different conditions in each wetland such that each wetland becomes a distinctive environment (Bond *et al.* 2008; Lake 2005). Methods of delivering environmental water that further restrict connectivity compromise the ability of the watering events to achieve positive ecological outcomes (Wallace *et al.* 2011). The use of pumps and regulators in areas such as Chowilla floodplain, Hattah Lakes and Koondrook forest have allowed for substantial areas of floodplain and wetlands to be inundated, providing significant improvement in the condition of many plants and animals associated with those floodplains. Management of these systems has also allowed water to return to the main river channel, transporting carbon and nutrients, that have significant benefits to the the overall wellbeing of the ecology of the river channel without any adverse water quality issues (Baldwin *et al.* 2011; Wallace & Furst 2016).

The most appropriate method for any site will vary accordingly, with a range of factors including, but not limited to; availability of environmental water, connectivity of sites to water source and management targets. The potential for the various methods outlined above to influence the different spatial components of river-floodplain systems is presented in Table 1 which demonstrates that relative to a natural large flood, few individual methods are capable of influencing the widest range of floodplain components. Methods that maximise connectivity and water exchange must be given priority (Wallace *et al.* 2011).

Reliance on infrastructure to inundate floodplains clearly carries a mix of potential benefits and risks. It is likely that some ecological processes are simply incompatible with some methods of inundation, because those processes depend either on the hydrodynamics of flooding (e.g. water residence time) or on the ways that rivers and their floodplains are connected (Table 1). For example, pumping acts as an "ecological filter" by preventing the movement of some fish and potentially limiting the dispersal of floating dormant propagules, such as seeds.

Appropriate management of infrastructure may mitigate some of the risks by replicating natural variability. For example, where hypoxic blackwater events are likely to occur they can be best managed by ensuring that water is not ponded onto floodplains for too long; floodplains are regularly inundated to prevent an accumulation of leaf litter and other organic material; flooding occurs during periods of cooler weather; and infrastructure is managed in such a way that ensures the movement of water onto and off the floodplain (Baldwin *et al.* 2011). This will only be achievable if sufficient water is available relative to what is required for the inundation event (Figure 3) (Bond *et al.* 2014; Wallace *et al.* 2011; Wood & Brown 2018).

Table 1. Relationship matrix between flow delivery method and interaction with river-floodplain components. ✓ indicates that the flow type is likely to influence the respective component, *x* indicates that the flow type is not likely to influence the respective component, ⊕ indicates that the flow type is only likely to influence the respective component in limited (i.e. specifically targeted) locations; (CTF = commence to flow) (modified from Wallace *et al.* (2011)).

Examples	Permanently inundated wetlands	Ephemeral channels/flood runners	Early CTF wetlands	Late CTF wetlands	Low elevation shedding floodplain	Low elevation retaining floodplain	High elevation shedding floodplain	High elevation retaining floodplain
Natural large flood (inundates entire floodplain)	✓	✓	✓	✓	✓	✓	✓	✓
Natural medium flood (inundates majority of floodplain)	✓	✓	✓	⊕	✓	✓	x	x
Natural small flood (spills into ephemeral channels & low wetlands)	✓	✓	✓	x	⊕	⊕	x	x
Medium flood utilising large constructed infrastructure	✓	✓	✓	⊕	✓	✓	x	x
Small flood utilising large constructed infrastructure	✓	⊕	⊕	x	⊕	⊕	x	x
Pumping water into discrete sites	⊕	✓	✓	✓	✓	✓	⊕	⊕
Constructed channels (gravity based delivery of water into discrete sites)	⊕	✓	✓	x	x	x	x	x
Retaining water from natural floods using constructed infrastructure	⊕	✓	✓	x	x	x	⊕	⊕

5   Conclusion

The delivery of water via infrastructure cannot be expected to replace all functional aspects of natural overbank flows and connectivity. In many ways, the use of infrastructure for environmental watering is at odds with the aims and objectives articulated for the Murray-Darling Basin, that often seek to achieve more ecological outcomes using less water than natural floods (Bond *et al.* 2014; Humphries *et al.* 2015). Pragmatic solutions are required to ensure that the use of infrastructure maintains those functions that are reliant on hydrological connectivity. For this to happen managed floods using infrastructure need to maintain and promote the exchange of water to maximise the benefits of connectivity and minimise risks (Wallace *et al.* 2011). However, there remain significant challenges as to how to design and manage a flow regime to ensure that the complex needs of the environment are supported in the longer term (Acreman *et al.* 2014; Arthington *et al.* 2006). The combination of environmental (e.g. connectivity), biological (e.g. movement of species) and abiotic processes (e.g. carbon and nutrients) are important determinants of the "health of riverine and floodplain systems" (Rolls & Sternberg 2015). The effectiveness of artificially creating connectivity to

meet ecological requirements needs to be quantified by targeted and rigorous designed monitoring programs that assess a broad suite of biota and associated processes to build an understanding of the linkages between them and artificially created connectivity. Such an understanding will help the prevention of undesirable and perverse outcomes and enable exploration of potential trade-offs.

6   Future needs and recommendations?

Historically, targets for floodplain inundation have been defined in terms of hydrologic characteristics (e.g. the timing, frequency, duration of flood events) rather than in terms of the physical characteristics of flooding (e.g. residency time, velocity, connectivity). In many cases these flood characteristics and the associated mosaic of inundation patterns across the floodplain, modify habitats and biological responses. Knowledge on how the physical characteristics of flooding influence physical and biotic responses to inundation is required to effectively use infrastructure to maintain the integrity of riverine-floodplain ecosystems (Table 1, Table 2).

- How can delivery of environmental water through infrastructure be best managed to meet biotic and biogeochemical objectives?
    - How can the hydrology of the riverine-floodplain system be optimised to maximise ecological outcomes?
    - Is there sufficient knowledge to optimize watering actions to achieve multiple ecological objectives?
    - What spatial and temporal scales should be considered when using infrastructure to deliver environmental water to accommodate dispersal and other life-history characteristics of key biota?
    -
- Informed debate to decide how much of the riverine-floodplain environment is needed to be conserved by the delivery of environmental water through infrastructure to maintain ecological integrity.
    - Identification of ecosystems that can be most readily conserved through the use of infrastructure.
    - Establishment of riverine-floodplain reserves that are able to be maintained via the delivery of environmental water through infrastructure.
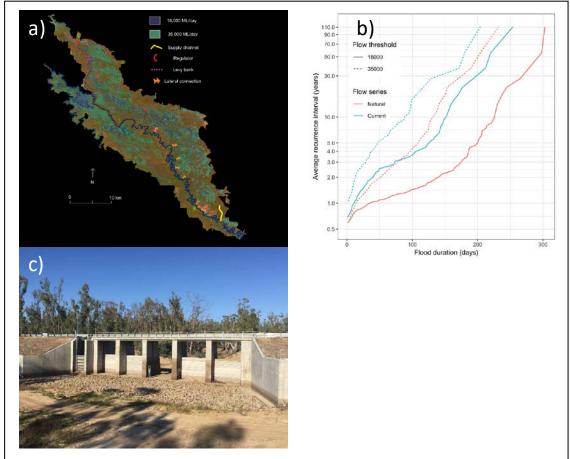
Figure 3. Koondrook–Perricoota Forest (KP) forms part of the second largest River Red Gum forest in south eastern Australia. The forest is dissected by numerous small channels, which begin to flow from the main river at a discharge of approximately 18 000 million litres per day (ML day^{-1}) in the Murray River (a). At higher flows, water flows into the forest at various points along the river; at flows between 30 000 and 35 000 ML day^{-1} the area of forest inundated rises to between 30% and 50%. The frequency and duration of forest inundation has been greatly reduced by river regulation (b). A delivery channel and a series of regulators and levee banks constructed to deliver water to areas within the forest (c). These works will allow water to enter the forest at river flows of less than 15 000 ML day^{-1}, greatly reducing water demand. However, concerns have been raised that the artificial ponding of water will lead to blackwater events in the forest and the main channel of the river (Baldwin *et al.* 2011). Connection at lower flows will also reduce lateral connectivity for species, including various fish and amphibians. Opportunities to mitigate these impacts include the modification/reoperation of downstream regulators to reduce ponding and timing flooding to coincide with cooler months (modified from Bond et al. (2014).

Table 2. Potential benefits, dis-benefits and management options for the use of infrastructure (modified from Bond *et al.* (2014)).

Type of infrastructure	Effects	Benefits	Dis-benefit	Management options
Pumping	Mimics natural flooding	Benefits vegetation (growth, germinations). Restores health of wetlands. Stimulates productivity. Provides opportunities for bird breeding. Opportunities for fish recruitment from eggs/larvae that pass through pumps.	Acts as environmental filter by acting as a barrier to dispersal of some biotic components. Loss of access to habitat. Minor lateral export of sediment and nutrients	Larger and variable depth intakes with lower velocities.
Constructed channels	Mimics overland flows	Benefit to vegetation (growth, germinations). Restores health of wetlands. Stimulates productivity. Provides opportunities for bird breeding. Potential access to floodplains by riverine biota (e.g. fish).	Reduced export of sediments, nutrients, primary and secondary production back to river.	Modify existing channels where fish may naturally occur. Include physical features to reduce velocities and turbulence. Coincide cease to flow with an in-channel flow to increase flushing to enhance export of of sediments, nutrients, primary and secondary production back to river.
Weirs and levees	Increases duration and frequency of inundation	Benefit to vegetation (growth, germinations). Restores health of wetlands. Stimulates productivity. Provides opportunities for bird breeding. Potential access to floodplains by riverine biota (e.g. fish).	Ponding may lead to adverse water quality issues. Limited return of sediments, nutrients, primary and secondary production back to river. Entrapment and mortality of fish unless fish passage is built into the structure	Inundation timed for cooler periods. Allow sufficient natural inundation to reduce the build-up of organic matter. Manipulate water levels to create mosaic of habitats.

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