# ‘Natural’ versus ‘Artificial’ watering of floodplains and wetlands

The
Murray-Darling
Freshwater
Research Centre

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# ‘Natural’ versus ‘Artificial’ watering of floodplains and wetlands

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

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# Executive summary.

At a global scale, society's desire to control water for a range of purposes (e.g. irrigation, industry, stock and domestic supply, flood mitigation) has led to the regulation of a significant proportion of the world's rivers. Alteration of flow regimes is regarded as the most serious and continuing threat to ecological sustainability of rivers and their associated floodplain wetlands.  Long-term drying has severely altered the ecology of many freshwater ecosystems, causing unprecedented, long-term or potentially irreversible damage (i.e. species extinctions). It is considered that much of the natural capacity (both resistance and resilience) of aquatic ecosystems to cope with drought has been lost.

Re-establishment of natural flow regimes represents a neat theoretical objective. However, the reality is that this is impractical as the demands of society preclude returning our rivers to natural flow. 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 (EWA).

New approaches to management will be essential in order to maintain a larger active floodplain than possible under the current water sharing arrangements. However, in order for managers to be successful in achieving the stated ecological objectives of river restoration and ecological management programs, it is necessary to have an appreciation of the role of flow in natural systems and the limitations of methods of delivering EWA. Within this synthesis we:

1. Briefly summarise the role of flow in unregulated floodplain ecosystems;
2. Define key state variables that characterise the flow regime of a floodplain system;
3. Discuss the major types of EWA currently in use;
4. Summarise key ecological processes and the impact of method of EWA delivery;
5. Outline the prevailing management paradigm; and
6. Identify management considerations for progress towards sustainable river systems.

Flow is regarded as the key driver regulating processes and diversity in river systems and can be regarded as the master variable. The processes which are influenced by flow and floodplain inundation  include hydrodynamics, biogeochemistry and primary productivity. Higher order organisms respond to these habitat and primary productivity drivers. It is not just the presence of water that is important for maintenance of ecosystem function; the provision of water is a critical link in the ecology of wetland and floodplain systems but that does not automatically imply that the link is functional. Flow magnitude, frequency, timing, duration, variability, rate of change and sequence all hold major ecological significance. It is important to note that the quality of water (i.e. chemical and thermal properties) is equally as important as the quantity of water or the temporal patterns of flow. In this context, the method of maintaining inundation (i.e. ponded flood versus flowing flood) and the resultant dilution and downstream dispersal of carbon and nutrients will have a significant impact on water quality via biogeochemically mediated processes.

In unmodified catchments natural flooding regimes that are completely unaltered represent the reference condition. However, due to the extent of regulation and development throughout the MDB, there are very few sub-catchments that experience an unimpeded, natural flood. In modified catchments the closest approximation is an uncontrolled flow where the effects of storages and in-stream structures have largely been nullified. River management has skewed river channels and floodplains in opposite directions; towards an anti-drought an engineered drought scenario respectively. Regulated river systems are therefore likely to be in an extreme state of precariousness. Management needs to focus on reinstating resilience as the most pragmatic and effective way of managing ecosystems in order to withstand future droughts and provide ecosystem services.

The concept of downsizing rivers has some merit but in reality it is a process of reinstating the small floods that river regulation has removed. It also overlooks the role of the interface between the aquatic (regularly inundated) and terrestrial (never inundated) zones in subsidising terrestrial food webs. Abandonment of large sections of floodplain may create an extremely dysfunctional and potential hostile zone or 'no-man's land' that is neither aquatic or terrestrial, generating a new barrier to energy flux.

Enacted as an emergency measure, pumping water to targeted wetlands pumping water into individual sites has been highly successful in achieving a limited set of objectives. There is an emerging risk that construction and operation of new, large infrastructure specifically designed, constructed and operated for environmental outcomes is seen as an alternative to unregulated overbank floods to maintain ecosystems. It is essential to recognise that there there are a number of critical limitations associated with this approach; primarily related to spatial, connectivity and water quality issues. The expectation that fragmented sites will function as refuges that serve as the major sources of propagules and colonists for other areas and lead to improvement of the Murray-Darling Basin is unproven. Furthermore, it is critical to recognise that using a regulator to inundate large floodplains under low flow conditions has not been used as a restoration technique anywhere in the world. Consequently there is no precedence for this management activity and actual responses may differ from those expected.

Releases of large volumes of water from storages may lead to the provision of flow-associated cues and conditions otherwise absent during base flows. However, water released from an upstream storage and transferred as an EWA into an individual site during periods of in-channel flow may restrict the ecological outcomes as the productivity gains from upstream flooding are not available to be transported into the managed site. The "missing pieces" are likely to include plant and invertebrate propagules dispersed from upstream sites, increased carbon and nutrient concentrations and other chemical cues resulting from inundation of floodplain soils and plant material, eggs and larvae of fish and other organisms spawned at upstream sites.

We propose that there is a hierarchical time scale relationship between inundation events and ecological responses that is associated with all inundations. This relationship can be described as follows; Instantaneous (occur within minutes-hours of inundation), Fast (occur within hours-weeks of inundation), Slow (occur weeks-months after inundation), Delayed (processes that occur within months-years after inundation), and Cumulative (responses that may only occur/be realised after a series of events). We consider that the influence of any EWA delivery method will be related to the rate at which different processes occur. For example, chemically mediated processes occur very quickly (instantaneous) and are therefore unlikely to be affected by the method of delivery of EWA. In contrast, many biogeochemically mediated and biotic processes occur over longer time scales and are more likely to be influenced by the method of EWA delivery. This will be driven by the lag phase in ecological response providing opportunities for differences in responses/processes between natural and managed floods to cascade across multiple levels and manifest into large differences in the quality of outcomes. Methods of delivering environmental water that do not maximise (i) connectivity (i) the provision of appropriate habitat; and (ii) the development of appropriate food resources will deliver minimal benefits and compromise the ability of the EWA to achieve positive ecological outcomes.

It must be recognised that the use of EWA's is fundamentally a large-scale manipulative experiment. We currently lack sufficient ecological knowledge to predict how floodplains in different conditions will respond. This represents a major hurdle for managers as volumes of environmental water are limited and resilience is an ecosystem property that can be either created or destroyed. Investment in recovering water and construction of infrastructure for delivery of EWA's needs to be underpinned by investment in research to inform adaptive management to ensure that critical ecological processes and functions are reinstated. If this is not undertaken, there is no way that EWA's will be able to reinstate resilience.

The most appropriate method for delivery of an EWA to any site will vary accordingly with a range of factors including but not limited to; availability of water, connectivity of site to water source, and management targets. Environmental water allocations cannot replace the function of natural overbank flows and there is no ‘Silver Bullet’ for repairing water-dependant ecosystems deprived of a natural flooding regime. Consequently pragmatic solutions are required to ensure environmental watering at intervals sufficient to enable system preservation and recovery. Reinstating flows and reoperation of existing infrastructure should be actively used during wet and median conditions to build resilience at the system scale. Delivery of EWA to isolated sites should be relegated to use during dry and extreme dry conditions to avoid long-term or irreversible damage and maintain refugia. The use of these techniques as the primary tool for the long-term management of floodplains and wetlands is not recommended.

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## Introduction

At a global scale, society's desire to control water for a range of purposes (e.g. irrigation, industry, stock and domestic supply, flood mitigation) has led to the regulation of a significant proportion of the worlds rivers (Dynesius & Nilsson, 1994). The impacts of river regulation, drought and climate change have been extensively reviewed (e.g. Walker, 1985; Bunn & Arthington, 2002; Arthington & Pusey, 2003; Poff & Zimmerman, 2010). Alteration of flow regimes is regarded as the most serious and continuing threat to the ecological sustainability of rivers and their associated floodplain wetlands (see Bunn & Arthington, 2002; Arthington et al., 2010). Removing floods can have flow-on effects on the whole foodweb, not only on individual species (Lytle & Poff, 2004).

In unregulated floodplain rivers, droughts caused by seasonal or supra-seasonal rainfall deficits extend the duration of dry spells, and the movement of water, nutrients and trophic subsidies from the catchment and the riparian zone into streams becomes weakened or may cease (Bond et al., 2008). In regulated systems, the “drought-proofing” regime of large storages and in-river structures leads to an anti-drought scenario (McMahon & Finlayson, 2003) in channels used for delivery of water. Use of storages and weirs secures supply for consumptive uses but also leads to a substantial reduction in the frequency of small and medium floods (Frazier & Page, 2006) creating an “engineered-drought” for floodplains and wetlands. Seasonal or supra-seasonal rainfall deficits remove the secondary source of moisture for floodplains leading to long-term (decadal) drying of floodplains that we regard as “hyper-drought” conditions. Long-term drying has severely altered the ecology of many freshwater ecosystems, stressing and reducing/fragmenting the distribution of fauna and flora. This has caused unprecedented, long-term or potentially irreversible damage (i.e. species extinctions), and it is considered that much of the natural capacity (both resistance and resilience) of aquatic ecosystems to cope with drought has been lost (see Bond et al., 2008).

Climate change modeling predicts that the frequency and severity of droughts will increase in the southern parts of Australia (CSIRO and BOM, 2007) leading to further stress on aquatic ecosystems in the Murray–Darling Basin (MDB) (Aldous et al., 2011). The effects of climate change will be severe, but not as severe as those resulting from river regulation (Kingsford, 2011). Consequently, it is predicted that free-flowing rivers that retain natural flow variability and connectivity will be more resilient and therefore less severely affected than regulated rivers (see Kingsford, 2011; Pittock & Finlayson, 2011). The existing impacts of regulation combined with predicted future impacts of climate change imply that natural overbank flows may cease in many rivers (Aldous et al., 2011) with ecological processes in many wetlands and floodplains becoming increasingly reliant on managed floods delivered as environmental water allocations (EWA).

### *Project Scope*

New approaches to management of existing in-river structures (i.e. weirs) and new infrastructure will be essential for delivery of EWA (Aldous et al., 2011) in order to sustain a larger active floodplain than possible under the current water sharing arrangements. However, in order for managers to be successful in achieving the stated ecological objectives of river restoration and ecological management programs, it is necessary to have an appreciation of the role of flow in natural systems and the limitations of methods of delivering EWA.

The objectives of this synthesis are:

1. Briefly summarise the role of flow in unregulated floodplain ecosystems;
2. Define key state variables that characterise the flow regime of a floodplain system;
3. Discuss the major types of EWA currently in use;
4. Summarise key ecological processes and the impact of method of EWA delivery;
5. Outline the prevailing management paradigm; and
6. Identify management considerations for progress towards sustainable river systems.

The processes which are influenced by flow and floodplain inundation  include hydrodynamics, biogeochemistry and primary productivity. Higher order organisms respond to these habitat and primary productivity drivers. Bunn and Arthington (2002) suggest that there are four guiding principles for considering how changes to flow influence aquatic biodiversity and we expand on these here;

- Flow is a major determinant of physical habitat. Diversity of habitat is important as biota within river systems have evolved associations with specific habitat types
- Flow regimes influence the natural patterns of longitudinal and lateral connectivity or riverine metapopulations. This connectivity  is essential to the viability of populations of many species
- Aquatic species have evolved life history strategies tied to particular flow regimes
- Flow is a major driver of nutrient and carbon cycles in riverine ecosystems. Lateral and longitudinal transport of nutrients and carbon drive system productivity and food web structure
- The invasion and success of exotic species is facilitated by the alteration of flow regimes

Within this synthesis we have attempted to maintain a broad regional relevance. As the biotic groups present and therefore the responses observed to any EWA will regionally specific, we have focused on processes rather than biotic groups. However, we have documented some examples of potential changes to selected biota and these are presented in the supporting information section.

## The role of flow in natural systems

Flow is regarded as the key driver regulating processes and diversity in river systems and can therefore be regarded as the ‘master variable’(Power et al., 1995) or ‘maestro’ (Walker et al., 1995) of river ecology. The flow regime supports ecological functions such as nutrient spiraling, organic matter processing and food web dynamics (see Bunn & Arthington, 2002; Bond et al., 2008). Flood events are major drivers of the flux of energy and nutrients in floodplain river systems (Junk et al., 1989) that connect the channel, wetlands and woodlands as parts of one ecological system (Lytle & Poff, 2004; Walker, 2009).

Inundation of temporary wetlands creates conditions substantially more productive than those found in permanent wetlands (Junk et al. 1989) with the exchange between the river and the riparian zone regarded as a key component of riverine function (Vannote et al., 1980). During the rising limb of the hydrograph, material is transported from the river to the floodplain. In the recession phase, carbon, nutrients, plankton, propagules and fish are transported from the floodplain to the river; a fundamental process of rivers and floodplains (Junk et al. 1989). Transfer of allochthonous inputs is hypothesised to influence food-web dynamics by augmenting productivity, altering predator-prey relationships and triggering trophic cascades (see review by Ballinger & Lake, 2006). The productivity booms (Bunn et al., 2006) associated with floods provide abundant food resources for a range of higher order animals including fish (Arthington et al., 2005) and water birds (Kingsford et al., 1999), which are dependent on the provision of appropriate habitat and development of food resources (Rogers & Paton, 2008).

## State variables that characterise the flow regime of a floodplain system

It is not just the presence of water that is important for maintenance of ecosystem function (Arthington et al., 2010); the provision of water is a critical link in the ecology of wetland and floodplain systems but that does not automatically imply that the link is functional (Jenkins & Boulton, 2003). Flow magnitude, frequency, timing, duration, variability, rate of change and sequence all hold major ecological significance (Lytle & Poff, 2004; Leigh et al., 2010). These factors are particularly important in floodplain river systems that are allogenic (i.e. where the hydrological regime is determined by upstream rather than local conditions). Extreme events (floods and droughts) represent key selective processes driving mortality and recruitment (Lytle & Poff, 2004).

### *Magnitude*

The magnitude of a flow event is defined by the daily discharge (ML $d^{-1}$) recorded over a specified time. Magnitude affects physical variables including flow velocity and river height. Flow velocity reflects the energy available for basic geomorphological processes (e.g. scour, transport and deposition of sediments), rearrangement of structural (e.g. woody debris) and biotic (e.g. macrophyte community structure) habitat, and dispersal of material including biological propagules. River height alters longitudinal and lateral connectivity (extent of flooding) and therefore transfer of material between ecosystem components. Magnitude may directly or indirectly influence migration and spawning/breeding behavioral responses.

### *Frequency*

Flow frequency is defined as the number of cycles (events) of a given magnitude within a specified period and is a function of flow magnitude; small flows typically having a higher return frequency. Flow pulses occurring at different frequencies serve different biological and biogeochemical functions. Relatively frequent flows are critical for maintaining connectivity, migration, dispersal, sustaining vegetation, sediment and nutrient exchange and water quality. Less frequent large flows may also reset ecological processes (see Leigh et al., 2010).

### *Timing*

Thermal regime and day length shift with season and the consequences of seasonal timing has undergone extensive investigation (Bunn & Arthington, 2002). Temperature and day length has implications for most biotic groups through metabolic (animal energetics), endocrine (e.g. circadian rhythm), behavioural traits (Bunn & Arthington, 2002), and life history adaptations (Lytle & Poff, 2004). Thermal regime and day length also affect biogeochemical rates, shaping ecological patterns and processes in riverine ecosystems (Lytle & Poff, 2004; Arthington et al., 2010). Biota utilising behavioral adaptations (responses) to flow events are less likely to be affected by changes in timing than organisms that use life history adaptations. For example, for species that specifically avoid or capitalise on floods or dry periods, synchronisation of life history stages is linked to long-term flow regimes, not specific events (Lytle & Poff, 2004). However, the importance of any flow event is likely to be related to magnitude as rising flows combined with appropriate temperature/day length may be cues for reproductive activity (see Bunn & Arthington, 2002). Seasonal timing can have important ecological ramifications for large systems as a flood can take months to travel the course of lowland rivers (Jenkins & Boulton, 2003).

### *Duration*

Duration refers to the number of days a flow event remains at a specified magnitude. It influences the ability of biota to exploit the longitudinal and lateral connections created. Long floods increase opportunities for productivity, breeding, recruitment and access to nursery habitats and food-rich environments (see Bunn & Arthington, 2002), providing maintenance reserves that allow communities and ecological function to persist through low flow periods (see Leigh et al., 2010).

### *Variability*

Variability in frequency, timing, magnitude and duration is potentially more important than biological factors in structuring aquatic communities (see Leigh et al., 2010). Constant variations in flow combined with geomorphology (e.g. elevation, wetland commence to flow levels) function as a controlling agent of longitudinal and lateral connectivity to generate a spatially and temporally dynamic habitat mosaic with adjacent and distant areas inundated and exposed for different lengths of time leading to increased biodiversity (see King et al., 2003; Leigh et al., 2010). A dynamic, variable water regime maintains the biodiversity and ecological processes characteristic of every river and wetland ecosystem (see Arthington et al., 2010). Under any given flow scenario, a single river system will display a dynamically changing range of dry, drying, lotic, and lentic habitats. This spatio-temporal variability in habitats generates high biodiversity (Ward & Stanford, 1995; Ward et al., 1999) with the lateral expansion and connectivity of floodplain habitats during floods providing spawning, nursery and foraging areas for a variety of vertebrates (see Bunn & Arthington, 2002).

### *Rate of change*

The rate of rise or fall in water level (mm day$^{-1}$) is important for a range of biota and processes. Rates of rise are not generally important for the establishment of flood-dependent plant species as many will not germinate until water levels are drawn down and the soil is exposed to the atmosphere but retains a high moisture content (Nicol, 2004). However, established stands of low-growing and emergent amphibious macrophytes are generally more vulnerable to rapid increases in water depth than submerged and free-floating aquatic species, as many of these species  are unable to maintain sufficient rates of photosynthesis and gas exchange to survive extended periods of inundation (Siebentritt & Ganf, 2000).  Slow rates of drawdown in the range 10-30 mm day$^{-1}$ (<50mm) have the greatest benefit for amphibious and floodplain plant communities (Nicol, 2004) breeding waterbirds (Rogers & Paton, 2008), minimising the risk of stranding fish in connected wetlands (Mallen-Cooper et al., 2008) and minimising bank slumping (Gippel et al., 2008).

### *Sequence*

The ecological outcomes from any flow event will be related to the antecedent conditions; frequent small floods maintain soil moisture and water levels in wetlands that increase the potential for subsequent flows to travel further downstream and/or inundate larger areas (see Leigh et al., 2010). In addition, sequential floods have cumulative, positive effects on recruitment of native fish (Puckridge et al., 2000; Arthington et al., 2005) and waterbirds (Kingsford & Porter, 1993; Kingsford et al., 1999).

# Major types of environmental water allocations

## ***Types of floods***

Environmental flows “describe the quantity, timing and quality of water required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon these ecosystems’’ (Brisbane Declaration, 2007). In unmodified catchments natural flooding regimes that are completely unaltered represent the reference condition. However, due to the extent of regulation and development throughout the MDB, there are very few sub-catchments that actually experience an unimpeded, natural flood. In modified catchments the closest approximation is an uncontrolled flow where the effects of storages and in-stream structures have largely been nullified, either by direct removal of weirs or by water levels exceeding the crest height of structures. At the next level down are EWA that can be used either as sustaining flows, to slow the process of degradation (Lind et al., 2007), or to reinstate components of the natural flow regime in order to  provide an opportunity for ecosystem recovery through the enhancement of recruitment and growth processes (see Arthington et al., 2003; King et al., 2010). Managed flooding occurs at range of spatial scales, ranging from the river reach and/or floodplain scale down to individual wetlands or sections of ephemeral creeks.

### *Controlled releases that generate flow peaks within channel*

EWA held in storage may be released to simulate small flow peaks during base flow periods. Released at the right time of year, such flows may lead to provision of flow-associated cues and conditions otherwise absent during base flows. Such flows may also lead to enhanced ecological outcomes from processes already occurring at base flows. Anabranch channels should be a management target for this type of EWA as they typically have commence-to-flow levels below bank-full and therefore require relatively small amounts of water for connection. Pulse connections with anabranches increase the frequency and amount of allochthonous carbon subsidies to the river system with the type and amount of materials exchanged varying depending on the frequency, magnitude and duration of flow pulses. Managed, periodic connection of anabranch channels is an option that may provide significant benefits to the system at low cost compared to connecting large floodplains (McGinness and Arthur, 2011).

### *Controlled releases that engage floodplain (out of channel flows)*

There is at least one substantial rain event driven high flow period in the MDB every year. Under the current management regime water from these events is captured and stored in large reservoirs. However, these rain-driven high flows can be utilized as a base upon which to build more substantial flows by releasing accumulated EWA, thereby providing a mechanism for the restoration of small and medium floods. For example, the release of a 500 GL EWA for Barmah-Millewa Forest in 2005 is considered to have imparted resilience to sites along the river that received some proportion of that flow, reducing the level of impact resulting from the Millennium drought (King et al., 2010).

### *Hybrid floods*

Hybrid floods involve releases of EWA undertaken in conjunction with unregulated flow pulses. For example, the Barmah-Millewa Forest EWA is generally released from storage during periods of high river levels in order to maximise the delivery of water onto the floodplain (Ward, 2009). Management objectives include; (i) reducing the rate of recession of flow peaks (ii) prolonging the duration of the inundation period; and (iii) raising the magnitude of the flow peak to generate/extend lateral connectivity. This management technique has been described as “filling holes” (sensu King et al., 2010) and may be subsequently overridden by additional unregulated flows.

### *Utilisation of new structures to inundate large sections of floodplain(s)*

There is growing interest in the construction and operation of new, large infrastructure specifically designed, constructed and operated for environmental outcomes as a management tool (Windsor Report, 2011(http://www.aph.gov.au/house/committee/ra/murraydarling/report/fullreport.pdf). In theory, this approach (i) improves the capacity of river managers to distribute water to high elevation sections of the floodplain during relatively low flows when these systems would otherwise remain in a drying phase; and (ii) is likely to generate greater wetland connectivity, potentially providing improved ecological outcomes than could be achieved by pumping water into discrete/individual sites (Veltheim et al., 2009). However, there is an emerging risk that this approach is seen as an alternative to unregulated overbank floods to maintain ecosystems. It is essential to recognise that there are a number of critical limitations associated with this approach; primarily related to spatial, connectivity and water quality issues: (i) there are few sites where this approach is achievable; (ii) the expectation that fragmented sites will function as refuges that serve as the major sources of propagules and colonists for other areas (sensu Arthington & Pusey, 2003) and lead to improvement of the Murray-Darling Basin is unproven; and (iii) high rates of water exchange are essential to avoid negative outcomes. Furthermore, it is critical to recognise that using a regulator to inundate large floodplains under low flow conditions has not been used as a restoration technique anywhere in the world (Nicol, 2007). Consequently there is no precedence for this management activity (Brookes et al., 2006) and actual responses may differ from those expected (Rogers & Paton, 2008).

### *Reoperation of river infrastructure – weir pool manipulation*

Currently, weirs in the lower Murray are periodically removed, either for routine maintenance or during periods of high flow (moderate-large floods) to maintain structural integrity. However, there is little utilisation of these structures to impart variability in water levels during normal operation. The manipulation of weirs including; (i) temporarily raising weirs to maximum structural height and increase the area that can be inundated (this reduces velocity and longitudinal connectivity but increases lateral connectivity); and (ii) temporarily lowering weirs (this reduces lateral extent but increases longitudinal connectivity and velocity), needs to become a management priority.

Reoperation of existing infrastructure to instate frequent variation in weir pool levels would be beneficial for many plant species, promoting diversity by restoring a wider range of water regimes (see Bunn & Arthington, 2002). Research undertaken during weir pool raising trials in the lower Murray River has demonstrated positive outcomes for understorey vegetation (Siebentritt et al., 2004) and riparian trees (Souter et al., Submitted). We propose that this is a grossly under-utilised management technique that should become a key tool for improving condition of the riparian zone.

### *Retaining water from natural floods using constructed infrastructure to extend period of inundation*

Many wetlands have had regulators installed to allow reinstatement of wetting and drying cycles. Closure of these structures upon recession of high flows may be used to ensure flood duration is sufficient for achieving ecological outcomes.

### *Gravity based delivery of water into discrete sites*

In sites where the commence to flow level is at or below the normal weir pool or river operating height, the opening of regulators or breaching of earthern banks can be used to deliver EWA into specific sites. In some cases, very small increases in channel water level associated with flow spikes or weir pool raising can greatly increase the number of off-channel sites or the spatial area that can be inundated via this method.

### *Pumped delivery of water into discrete sites*

In sites where it is not possible to deliver water via gravity (typically because the site is elevated above the normal weir pool or river operating height) EWA are often delivered using large pumps. A key 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 due to low water availability.

Enacted as an emergency measure, pumping water into individual sites has been highly successful in achieving a limited set of objectives. However, the following factors are critical limitations; (i) the distance water can be efficiently pumped is limited; (ii) very few ecological requirements that depend on connectivity will be met from pumping; (ii) delivering EWA to wetlands via pumps and then drying them through evaporation provides extremely low connectivity to the river and provides no short-term benefit to the river channel; and (iv) there is an overwhelming number of sites to manage on an individual basis. For example, within the Murray Valley, the number of ephemeral wetlands that would have been connected to the river channel at least once every 3-4 years has fallen from 1305 under natural conditions to 657 under regulated conditions (Brookes et al., 2009a). Furthermore, repeated ponding and evaporation of water has the potential to accumulate salt in the managed sites.

## Key ecological processes and the impact of method of EWA delivery

### *Hierarchical time scales*

We propose that there is a hierarchical time scale relationship between inundation events and ecological responses that is associated with all inundations (irrespective of delivery method). This relationship can be described as follows; Instantaneous (occur within minutes-hours of inundation), Fast (occur within hours-weeks of inundation), Slow (occur weeks-months after inundation), Delayed (processes that occur within months-years after inundation), and Cumulative (responses that may only occur/be realised after a series of events). Examples of this hierarchy are provided in Table 1. We consider that the influence of any EWA delivery method will be related to the rate at which different processes occur. For example, chemically mediated processes occur very quickly (instantaneous) and are therefore unlikely to be affected by the method of delivery of EWA. In contrast, many biogeochemically mediated and biotic processes occur over longer time scales and are more likely to be influenced by the method of EWA delivery. This will be driven by the lag phase in ecological response providing opportunities for differences in responses/processes between natural and managed floods to cascade across multiple levels and manifest into large differences in the quality of outcomes.

**Table 1.** Hierarchical relationship matrix between process and temporal scale✓ indicates that the process if likely to occur within the respective time frame, ⌖ indicates that the process may occur within the respective time frame

| Examples | Instantaneous (minutes –hours) | Fast (hours-weeks) | Slow (months-years) | Delayed (months-years) | Cumulative (serial impacts) |
|---|---|---|---|---|---|
| Chemically mediated processes; release of carbon/nutrients from inundated material | ✓ | ⌖ | | | |
| Biogeochemically mediated processes; Blackwater | | ✓ | ⌖ | | |
| Biogeochemically mediated processes; Algal blooms | | ⌖ | ✓ | | |
| Fish and birds; migration to spawning/breeding locations | | ✓ | | | |
| Fish and birds; spawning/breeding | | ✓ | ✓ | | |
| Fish and birds; recruitment to young-of-year | | | | ✓ | |
| Fish and birds; recruitment to recruitment to adult | | | | ✓ | |
| Fish and birds; robust population demographic | | | | | ✓ |
| Plants; increased resource uptake | | ✓ | | | |
| Plants; increased growth/vigour | | ✓ | ✓ | | |
| Plants; germination | | ✓ | ✓ | | |
| Plants; shift in dominant functional groups | | | | ✓ | ✓ |
| Plants; shift in EVCs | | | | ✓ | ✓ |
| Soils; stimulation of microbial activity | ⌖ | ✓ | | | |
| Soils; increase in soil moisture at depth(e.g. >0.3m) | | ✓ | | | |
| Soils; soil derived salinity spikes | ✓ | ✓ | | | |
| Soils increase in soil salinity due to evapoconcentration | | | | | ✓ |
| Groundwater; freshening of saline groundwater | | ⌖ | ✓ | | |
| Groundwater; groundwater derived salinity spikes in creek/river | | | | ✓ | |
| Micro-invertebrates; hatching from seed banks | | ✓ | ⌖ | | |
| Micro-invertebrates; succession shifts | | | ✓ | | |
| Macro-invertebrates; succession shifts | | | ✓ | | |

## ***Processes that are unlikely to be influenced by method of EWA delivery***

### *Release of carbon and nutrients from inundated plant material*

When floodwater first enters a floodplain there is immediate leaching of carbon and nutrients from natural organic material (e.g. leaf litter from floodplain trees - Baldwin 1999; O'Connoll et al. 2000), coupled with a pulse of carbon and nutrients from newly inundated soil - the 'Birch effect' (Scholz et al., 2002; Kobayashi et al., 2008; Banach et al., 2009; Wilson et al., 2010). Floodplain eucalypts, particularly river red gum (*E. camaldulensis*) and to a lesser extent black box (*E. largiflorens*) generate a large standing biomass of leaf litter (approximately 2,500 $gm^{-2}$ and 600 $gm^{-2}$ respectively (Wallace, 2009)) and represent a large source of allochthonous organic matter to floodplains and wetlands (Glazebrook & Robertson, 1999; Francis & Sheldon, 2002) much of which is rapidly (within hours) released into the water column when this material is inundated (O'Connell et al., 2000; Francis & Sheldon, 2002; Wallace et al., 2008).

### *Stimulation of microbial activity in floodplain soils*

Stimulation of the resident soil microbial community is a rapid process. Wilson et al (2011) demonstrated that inundation of floodplain soils causes an immediate change in carbon turnover and rates of microbially driven processes. The activity of enzymes related to the degradation of carbohydrates (*a*-glucosidase, *b*-glucosidase and *b*-xylosidase) increased rapidly and reached a peak after 3 days, suggesting a rapid break down of large molecules for microbial utilisation leading to a rapid increase in carbon mineralization rate. In contrast, shifts in the microbial community structure were not observed until 7 days post inundation.

### *Salt mobilization from floodplain soils*

The accumulation of salt in soils is driven by evaporative discharge of groundwater during dry phases. Flood inundation has the potential to wash salt from floodplain surface soils, entraining surface salts into surface water flows. Infiltration (due to precipitation, flood events or wetland watering) transports (i.e. leaches) salt back down the soil profile. The amount of salt that can be leached from soils during flooding is influenced by flood frequency, duration and soil type (Barber et al., 2011) with accumulated salt more readily leached from sandy soils than heavy clay soils (Overton & Doody, 2008).

### *Groundwater*

In the lower Murray, regional groundwater gradients dominate groundwater discharge under low flow conditions. During high flows, bank recharge and localised vertical recharge, where the soil profile is sandy (Jolly & Walker, 1995), produce freshwater lenses that remain on top of the saline groundwater. This occurs due to limited mixing caused by density differences (Overton & Doody, 2008). Localised mounding of fresh water under the floodplain leads to the displacement of saline groundwater and discharge to connected channels and anabranches as floodwater recede (Jolly et al., 1994), contributing to groundwater-derived recession salt loads (Barber et al., 2011). During inundation, it is the spatial extent, hydraulic head and duration of inundation rather than method of EWA delivery that is likely to be important.

## ***Biogeochemically mediated processes that are likely to be influenced by method of EWA delivery***

It is important to note that the 'quality' of water (i.e. chemical and thermal properties) is equally as important as the quantity of water or the temporal patterns of flow (see Arthington et al., 2010). In this context, the method of maintaining inundation (i.e. ponded flood versus flowing flood) and the resultant dilution and downstream dispersal of carbon and nutrients will have a significant impact on water quality via biogeochemically mediated processes.

### *Cycling and metabolism of carbon and nutrients*

The carbon and nutrients released from inundated material into the overlying water column can be rapidly incorporated into microbial and algal biomass (Schemel et al. 2004). Microorganisms can use about one-third of the dissolved organic carbon (DOC) leached from litter within ten days. Within hours to a few days, nitrogen and phosphorus undergo transformation and assimilation by organisms on the floodplain. Nitrate is either taken up by microorganisms and algae, or is respired through denitrification such that floodplains act as a sink for N (Forshay & Stanley, 2005). Phosphorus is assimilated by organisms with the overall movement and uptake of phosphorus dependent on the length of time water remains on the floodplain (Schramm et al., 2009). The assimilated carbon and nutrients are subsequently cycled though the food web to higher trophic level organisms (e.g. birds and fish) via multiple pathways, including via micro- and macro-invertebrates. This process is referred to as 'trophic upsurge' (Furch & Junk, 1997; Kern & Darwich, 1997; Geraldes & Boavida, 1999; Scharf, 2002; Talbot et al., 2006; Lourantou et al., 2007).

In Australian river systems the exact role and relative importance of autochthonous and allochthonous carbon remains largely unresolved, partially confounded by the fact that high variability in flow conditions (particularly in dryland rivers and wetlands) means there is considerable overlap in $^{13}C$:$^{12}C$ signatures between terrestrial and aquatic plants (Ballinger & Lake, 2006). However, under low flow conditions, autotrophic sources of carbon are believed to dominate foodwebs (Bunn et al., 2003; Hadwen et al., 2009). Oliver and Merrick (2006) and Oliver and Lorenz (2007) demonstrated that the River Murray is energy constrained with net production close to zero. Studies in the Logan, Gwydir and Ovens Rivers (Hadwen et al., 2009) and Lachlan River (Moran, 2011) have demonstrated that respiration of the heterotrophic bacterial community and DOC consumption is limited by the quality of DOC present. This is considered to be the case for the majority of Australian rivers during low flow conditions when allochthonous DOC supply is limited (Robertson et al., 1999).

Inputs of allochthonous DOC during periods of high flow and floods are likely to provide a short-lived but significant productivity boom. For example, measures of primary productivity on the Cooper Creek floodplain found that the amount of carbon produced by benthic algae on the floodplain during a single day of a flood was equivalent to over 80 years of aquatic production under dry conditions (Bunn *et al*. 2006*b*). Robertson et al. (1999) predicted that a flood inundating 44km$^2$ would provide as much allocthonously derived carbon as produced from autochthnonous sources (i.e. phytoplankton) in one year. Gawne et al., (2007) considered that this effect could be produced by a smaller flood (34 km$^2$). A preliminary assessment has demonstrated that partial return of an EWA from a managed floodplain will return a measurable carbon and nutrient pulse (Wallace & Lenon, 2010) and a stimulation of heterotrophic activity in the receiving waters (Wallace, unpublished data).

Returning water, that contains a high biomass of prey items and increased nutrient loads, to river channels is likely to improve the recruitment success of fish inhabiting those river channels (Balcombe et al., 2007; King et al., 2009; Meredith & Beesley, 2009). A survey undertaken in 2008 revealed that 76.3% of EWA is left in wetlands to seep, evaporate or dissipate (Meredith & Beesley, 2009). This means that only a small proportion of the volume of EWA utilised is currently returned to the river. Managed floods that do not provide strong lateral and subsequent longitudinal transfer of allochthonous material minimise or even preclude the potential for transfer of productivity gains. Addressing this should be a key priority for managers.

### *Blackwater events*

Blackwater events can be described as flood events where the surface water contains enough dissolved organic carbon (DOC) to discolour the water sufficiently to resemble dark “tea” and are often associated with low dissolved oxygen (DO) concentrations (Meyer, 1990; Howitt et al., 2007) caused by heterotrophic metabolism (microbial degradation) of organic carbon leached from flooded plant material. The managed flooding of Barmah Forest in 2000 released a pulse of hypoxic (DO $<2$ mg L$^{-1}$) water back to the Murray and Edward Rivers that led to a significant fish-mortality event (Howitt et al., 2007). The 2010-11 flood in the Murray system was also characterised by a system wide blackwater event distinguished by high DOC and low DO conditions.

Hypoxia is a major concern for the ecology of wetlands and receiving waters, as tolerance to hypoxia is species and life-stage specific, therefore changes in DO concentration can have  significant impacts on biodiversity (Ekau et al., 2010). Hypoxia is associated with fish kills (Erskine et al., 2005), disruption of endocrine systems (Wu et al., 2003) embryonic development (Shang & Wu, 2004) and survival and hatch rates (Hassell et al., 2008) of fish and degradation of aquatic macroinvertebrate communities in streams (Walsh et al., 2001; Walsh, 2002; Feminella et al., 2003) and wetlands (Spieles & Mitsch, 2003). Anoxia may lead to the release of sediment bound material such as manganese, iron (Davison, 1993), ammonium (Lawrence & Breen, 1998; Boulton & Brock, 1999; Morin & Morse, 1999) and phosphorus (Mortimer, 1941; Laws, 1993; Martinova, 1993); conversion of dissolved organic nitrogen to ammonia and nitrate (Harris, 2001) and accumulation of redox sensitive compounds from anoxic sediments (e.g. Baldwin & Mitchell, 2000; Dahm et al., 2003) some of which (e.g. ammonium and sulfide) are toxic to many aquatic organisms (Vismann, 1996; Hickey & Martin, 1999).

A number of factors are critical in determining whether or not a blackwater event will result in a fish kill. The two most important factors are water temperature and carbon loading (Baldwin & Wallace, 2009). Organic loading (amount of carbon and nutrients and the stoichiometry of those nutrients) in water overlying floodplains is dependent on vegetation type and condition (Brookes et al., 2007; Wallace et al., 2008; Wallace, 2009) flood timing (Baldwin, 1999; Watkins et al., 2010a; Watkins et al., 2010b) and whether or not the accumulated litter has been flooded before (O'Connell et al., 2000). Flooding in late spring and summer is problematic as (i) peak litter fall for eucalypts occurs in summer (Briggs & Maher, 1983) and (ii) for every 10 °C increase in water temperature the rate of oxygen depletion approximately doubles (Howitt et al., 2007). Therefore, the warmer the temperature the more quickly oxygen is consumed. In addition to the factors outlined above, heat stress combined with hypoxic conditions is likely to be a lethal combination for native fish.

The risk of establishment of a blackwater event can be largely managed by (i) not utilising ponded floods for delivery of EWA; (ii) maximising water exchange when using large constructed infrastructure; and (iii) avoiding flooding during warm periods (Baldwin & Wallace, 2009). During managed inundations the volume of water and the exchange rate (turnover) are markedly lower than occurs during unregulated floods that inundate equivalent areas. Wallace and Lenon (2010) demonstrated that the rapid onset of hypoxic and anoxic conditions occurring in wetlands during ponded floods could be managed using conservative rates (<20% daily exchange) of dilution/exchange. Deep, long flooding will typically occur in low elevation areas that are flooded in order to inundate higher elevation ecological communities (i.e. black box) for relatively short periods. This type of flooding substantially increases the risk of stratification and water quality issues and is regarded as a critical risk with the potential for long-term damage. Managed floods using large infrastructure must maintain high rates of water exchange in order to maximize benefits and minimize risks (Brookes et al., 2007; Mallen-Cooper et al., 2008; Wallace & Lenon, 2010).

### *Harmful and or nuisance algal blooms*

The release of nutrients from inundated material will produce a nutrient pulse capable of supporting significant phytoplankton biomass (Brookes et al., 2007; Wallace, 2008; Wallace & Lenon, 2010). There are two scenarios where the development of cyanobacterial blooms in managed sites represent a potential hazard to public health and/or water supply; blooms restricted to the wetlands that become isolated during drawdown, and those that may be connected to the river via return flows from the wetland/floodplain. High cyanobacterial abundance in isolated wetlands may be locally significant but will have little impact on the main river channel. However, if the wetland drains into the main channel this may act as a seed source (inoculum) to the main river channel and be a significant source of toxins or taste and odour compounds (Brookes et al., 2007). The risk associated with high cyanobacteria loads in wetlands draining into the river can be mitigated by ensuring that flows in the river are relatively high and generating "wash-out" and turbulent conditions conducive to the breakdown of blooms (see Brookes et al., 2007).

## *Biotic processes that are likely to be influenced by method of EWA delivery*

The processes which are being influenced by flow manipulation and floodplain inundation include hydrodynamics, biogeochemistry and primary productivity. Higher order organisms respond to these habitat and primary productivity drivers. Detail on selected biotic groups is presented in the supporting information section. The following information is focused on the key processes; (i) connectivity; (ii) provision of food resources; (iii) influence of source water; and (iv) filling patterns.

### *Connectivity*

Beyond microbial processes, aquatic micro-invertebrates re-generating from soil egg banks and downstream transport respond quickest to inundation (Jenkins & Boulton, 2003; Boulton et al., 2006). Macro-invertebrates and macro-crustacea (shrimp, yabbies, freshwater crayfish) may need to colonise from other nearby sites or be dependent on development of appropriate habitat (e.g. macrophytes) and food resources (Nielsen et al., 1999) prior to establishment in large numbers (see Kingsford et al., 2010).

We propose that there is a hierarchical relationship between connectivity and movement:

- 1D active movement
    - longitudinal (1D) movement that is undertaken by fish and macro-crustacea (shrimps, prawns, yabbies, crayfish)
- 2D active movement;
    - lateral (2D) movement that is undertaken by fish and macro-crustacea (shrimps, prawns, yabbies, crayfish)
- 3D active movement
    - movements that are undertaken by birds and macro-invertebrates that can fly in/out in response to changing conditions
- Passive movement
    - Primarily 1D and 2D movements undertaken by carbon, nutrients, phytoplankton, micro-invertebrates, plant propagules and early life stages (egg, larval) of fish

Longitudinal barriers bisecting rivers (e.g. weirs, dams) and lateral barriers between rivers and floodplains (diversion and flood protection levees) sever connectivity and can lead to isolation of populations, failed recruitment, local extinction and loss of aquatic biodiversity (Bunn & Arthington, 2002; Arthington & Pusey, 2003). Constructed infrastructure reduces transport of nutrients, biota and organic matter, often creating different conditions in each pool, such that each may become a distinctive lentic environment (Lake, 2005) cited by (Bond et al., 2008). Methods of delivering environmental water that further restrict connectivity compromise the ability of the EWA to achieve positive ecological outcomes and this is a major challenge for the effective delivery of EWA.

### *Provision of food resources*

Factors that will influence the success (survival and recruitment) or failure of breeding events of key groups such as frog, fish and birds include the availability of appropriate food resources at the correct times via the productivity boom (Bunn et al., 2006) that occurs during floods. The productivity boom provides abundant food resources for a range of higher order animals and is therefore regarded as an ecosystem service. Invertebrates are a key food resource for breeding waterfowl as they provide the protein source required for egg and nestling development. The responses of guilds that are piscivorous, herbivorous, reliant on aquatic macro-invertebrates and terrestrial invertebrate/ insects, or utilise aquatic plants (e.g. sedges and rushes) for nesting material will depend on the provision of appropriate habitat and response/development of food resources (Rogers & Paton, 2008). It has been demonstrated (Boulton & Lloyd, 1992) that once the antecedent duration between floods exceeds 11 years, the diversity of invertebrates present in soil egg banks, and the number of animals hatching once soils are finally inundated decreases significantly. Methods and frequency of delivery of EWA that do not maximise (i) the provision of appropriate habitat; and (ii) the development of appropriate food resources will deliver minimal benefits.

### *Influence of water source*

The source of water from which EWA are comprised may influence outcomes. Water released from an upstream storage and transferred as an EWA into an individual site (i.e. wetland) during periods of in-channel flow, particularly very-low flow periods may restrict the ecological outcomes as the productivity gains from upstream flooding are not available to be transported into the managed site. The "missing pieces" are likely to include plant and invertebrate propagules dispersed from upstream sites, increased carbon and nutrient concentrations and other chemical cues resulting from inundation of floodplain soils and plant material, eggs and larvae of fish and other organisms spawned at upstream sites.

Conditions within upstream storages can range from functioning as a sink or source of nutrients, with associated changes in speciation of chemicals leading to changes in phytoplankton community structure at downstream sites (Baldwin et al., 2010). This can lead to flow-on effects on primary productivity and food webs downstream (see Burford et al., 2011). The issue of thermal pollution resulting from hypolimnetic off-takes in storages must also be taken into account when considering the ecological outcomes that can be achieved during environmental flows (Olden & Naiman, 2010). The river that water is being sourced from may also have an impact. For example, under very low flow conditions turbidity in the Darling River can be as low 16 NTU (Wallace, unpublished data) but Sherman et al., (1998) report that turbidity is usually very high (>100 NTU). When the Darling is in flood, increased turbidity can cause the euphotic depth in the lower River Murray to be less than 0.2 m (Mackay et al., 1988). If EWA are comprised of high turbidity water the potential for the growth of aquatic plants is greatly reduced (Brookes et al., 2009a). Furthermore, the microfauna of water from the Darling and Murray Rivers are markedly different and the composition of microfauna varies between storages with short (e.g. Lake Mulwala) and long (e.g. Hume Dam) retention times (see Brookes et al., 2009a).

### *Filling patterns*

During natural floods, the floodplain fills from upstream. In contrast, during floods generated by the use of large infrastructure, the floodplain is backfilled from the downstream end. The backwater curve generated leads to the maximum area inundated being located adjacent to the regulator at relatively high elevations (mAHD) compared to the area inundated at the tail end of the inundation zone where the water level will not rise as high (Nicol et al., 2010). The flow paths and deposition patterns of propagules (including larval fish) are therefore likely to be significantly altered (Mallen-Cooper et al., 2008). There will also be a lack of meteorological cues from rain events (high/low pressure systems) when high flows are generated by releases from storages.

## The prevailing management paradigm

The scale of intervention needs to expand from the management of individual wetlands and preventing loss of populations of individual species, to ecosystem management at the landscape scale. However, the recent drought across southern and eastern Australia has revealed the contention within society for delivering water to the environment during drought (when it is widely although incorrectly perceived by society that floodplain systems would not have received water). The recovery of large volumes of water for environmental purposes is intended to find a balance between extraction of water for consumptive use and the environment. However, the social tensions surrounding development of the Murray-Darling Basin Plan (http://www.mdba.gov.au/basin_plan) the cost of water recovery ($3.1 billion over 10 years) and the cost of large scale restoration projects such as *The Living Murray* (http://www.mdba.gov.au/programs/tlm) demonstrate the cost and difficulty of restoring a desired state. Furthermore, there are critical risks of institutional failure in relying entirely on environmental flow arrangements during dry periods. This has been demonstrated by the 'suspension' of environmental flow agreements by the Victorian and New South Wales Governments in 2006 (see Pittock & Finlayson, 2011) and the 'loan' of the Barmah Forest EWA to the irrigation industry during the drought which had a low (10%) likelihood of being returned when required (King et al., 2010).

In addition to the issues outlined above, a key message reported by Meredith and Beesley (2009) from managers was that they are unlikely to be able to deliver an ideal water regime (timing, volume, rate, frequency) to wetlands because of engineering (channel capacity), and the social and political (intergovernmental) constraints associated with delivery of water. The logistics of delivering water has been shown to be the single most important factor in determining which wetlands receive EWA and when. Alarmingly, ecological objectives typically play a secondary role in this decision making process (Meredith & Beesley, 2009). Consequently, the current management approach can readily be described as one of "landscape gardening" where triage decisions are made about the delivery of relatively small volumes to discrete sites that both hold significance to managers or society and that "the garden hose can reach" (i.e. it is a short distance to pump and the legislative hurdles associated with construction of banks and establishment of pump locations are surmountable).

### *Management of systems for resilience*

There is an urgently growing need to move away from maintaining stabilised conditions, where management interventions are focused on preventing irreversible damage once the system is already in an extreme level of precariousness (Scheffer et al., 2001; Scheffer & Carpenter, 2003). Instead, management needs to focus on reinstating resilience as the most pragmatic and effective way of managing ecosystems in order to withstand future droughts and provide ecosystem services (Scheffer et al., 2001; Scheffer & Carpenter, 2003; Folke et al., 2004; Bond et al., 2008). Holling (1973) defined resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables....”. Resilience has multiple attributes, but four aspects are critical (Walker et al. 2004 as cited by (Folke et al., 2004)):

- *Latitude*; the maximum amount the system can be changed and still reorganize within the same state.
- *Resistance*; how large a disturbance is required to change the current state of the system.
- *Precariousness*; how close the system is to a threshold that, if breached, makes reorganization difficult.
- *Cross-scale relations*; how the three attributes above are influenced by the states and dynamics of the system, at scales above and below the scale of interest.

Unregulated river systems are likely to have a very large degree of resilience, latitude and resistance, displaying a transient, dynamic regime (Holling, 1973) with two distinct extremes (Scheffer et al., 2001; Scheffer & Carpenter, 2003) in which wetlands are always drying or flooding (Kingsford et al., 2010). Rather than the wet and dry phase being two states with characteristic dominant biota, there is only a single state with two alternative phases interspersed by floods and droughts (Colloff & Baldwin, 2010); the system will progressively revert towards the preceding condition once the disturbance (flooding or drying ) is removed. Once a driver (i.e. permanent inundation or very long drying) exerts sufficient pressure to exceed the threshold for change a catastrophic (rather than smooth) transition to an alternate state can occur (Scheffer et al., 2001; Scheffer & Carpenter, 2003). This concept is presented in Figure 1. River management has skewed river channels towards the left of this model (anti-drought) and floodplains to the right (engineered drought). Regulated river systems are therefore likely to be in an extreme state of precariousness.

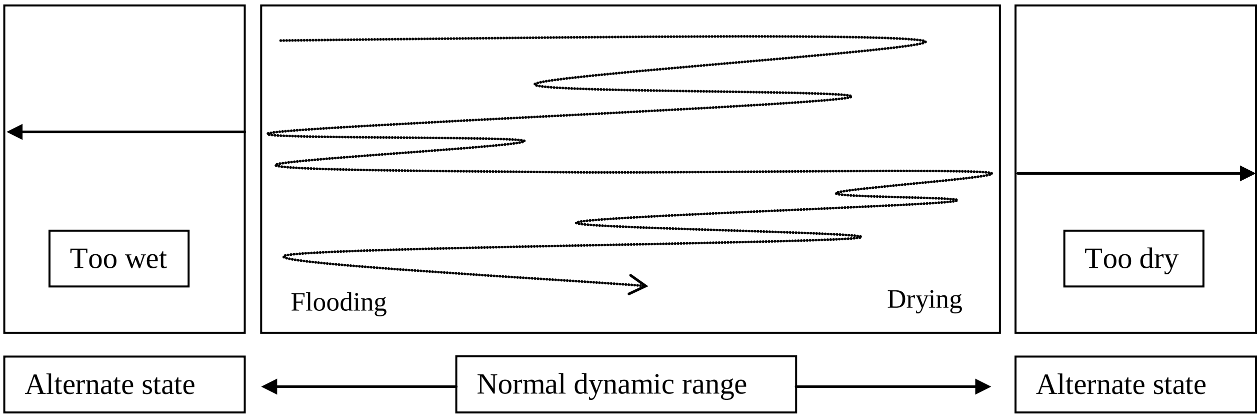

**Figure 1.** Conceptual model of the dynamic regime in which floodplains are always drying or flooding and the potential for excessive pressure to cause a transition to an alternate state.

Colloff and Baldwin (2010) suggest that the dramatic decline in condition of river red gums throughout the Murray-Darling Basin "have not yet reverted to an alternate stable state" implying that the system is approaching a tipping point. Assessments of population demographics demonstrate that in many areas there is insufficient recruitment to sustain the existing forest and woodland communities (George et al., 2005; Wallace, 2009). Furthermore the floodplain eucalypts (*E. camaldulensis* and *E. largiflorens*) retain the majority of their seed in the canopy, and trees in poor condition produce less seed than those in good condition (George et al., 2005; Jensen et al., 2008). Hence, once there is widespread loss of mature trees there is no soil seed bank for regeneration. Loss of forest/woodlands leads to increased likelihood of establishment of grassland areas (Scheffer et al., 2001); conversely, in grassland areas, droughts reduce grass cover decreasing the likelihood of fires which are a key control on the establishment of perennial shrubs (Folke et al., 2004). Once lost, costly restoration with extremely long lag phases will be required to reinstate "ecosystem engineers"  such as river red gum and black box (Colloff & Baldwin, 2010). This situation where simply restoring the original environmental conditions (i.e. natural flow regime) is not likely to be sufficient to induce a switch back to the pre-existing condition and that conditions need to be established that create a second shift, back to the “desired” condition is known as hysteresis (Scheffer et al., 2001).

## *The concept of downsizing river systems*

Re-establishment of natural flow regimes represents a neat theoretical objective. However, the reality is that this is impractical as the demands of society preclude returning our rivers to natural flow (Meredith & Beesley, 2009; Hall et al., 2011). Consequently there have been calls to downsize river systems  (see Overton & Doody, 2008; Hall et al., 2011; Pittock & Finlayson, 2011). The potential for EWA delivered according to a hydrograph mimicking natural seasonal patterns but at a smaller magnitude has been demonstrated at the Bridge River in south-western British Columbia (Hall et al., 2011). This concept holds some merit but in reality it is a process of reinstating the small floods that river regulation has removed. Frequent small floods function as the primary source of water sustaining lowland river floodplains in arid regions and maintain soil moisture and water levels in wetlands that increase the potential for subsequent flows to travel further downstream and/or inundate larger areas (see Leigh et al., 2010).

The concept of downsizing rivers also overlooks the role of the interface between the aquatic (regularly inundated) and terrestrial (never inundated) zones in subsidising terrestrial food webs. Faunal transported fluxes of energy (e.g. macrophytes grazed by herbivores; emergent aquatic insects consumed by insectivorous birds, bats, reptiles, beetles, spiders etc.) may be extremely important for terrestrial foodwebs (see review by Ballinger & Lake, 2006). Abandonment of large sections of floodplain may create an extremely dysfunctional and potential hostile (e.g. highly salinised) zone or 'no-man's land' that is neither aquatic or terrestrial (i.e. occasional floods preclude the development of terrestrial communities but are at an insufficient frequency to maintain aquatic processes) generating a new barrier to energy flux.

# Management considerations for progress towards sustainable river systems.

## *Selection of appropriate methods for delivery of EWA*

The most appropriate method for any site will vary accordingly with a range of factors including but not limited to; availability of water, connectivity of site 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 2. This 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.

**Table 2.** Relationship matrix between flow delivery method and interaction with river-floodplain components. ✓ indicates that the flow type is likely to influence the respective component, ✖ 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 (ie. specifically targeted) locations; (CTF = commence to flow).

| Examples | Main river channel | Permanently connected wetlands | Ephemeral channels/floodrunners | 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) | ✓ | ✓ | ✓ | ✓ | ⌖ | ✓ | ✓ | ✖ | ✖ |
| Natural small flood (spills into ephemeral channels and low wetlands) | ✓ | ✓ | ✓ | ✓ | ✖ | ⌖ | ⌖ | ✖ | ✖ |
| Natural in-channel flow pulse | ✓ | ⌖ | ⌖ | ⌖ | ✖ | ✖ | ✖ | ✖ | ✖ |
| Medium flood utilising large constructed infrastructure | ✓ | ✓ | ✓ | ✓ | ⌖ | ✓ | ✓ | ✖ | ✖ |
| Small flood utilising large constructed infrastructure | ✓ | ✓ | ⌖ | ⌖ | ✖ | ⌖ | ⌖ | ✖ | ✖ |
| In-channel flow pulse using large constructed infrastructure | ✓ | ⌖ | ⌖ | ⌖ | ✖ | ✖ | ✖ | ✖ | ✖ |
| Controlled releases to generate in-channel flow peaks | ✓ | ✖ | ⌖ | ⌖ | ✖ | ✖ | ✖ | ✖ | ✖ |
| Controlled releases to reinstate flow | ✓ | ✖ | ⌖ | ✖ | ✖ | ✖ | ✖ | ✖ | ✖ |
| Controlled releases to engage floodplain | ✓ | ✓ | ✓ | ⌖ | ✖ | ⌖ | ⌖ | ✖ | ✖ |
| Hybrid in-channel flow pulse (piggybacking e-water on base flows) | ✓ | ✓ | ⌖ | ⌖ | ✖ | ✖ | ✖ | ✖ | ✖ |
| Hybrid flood (controlled release that is overridden by natural flows) | ✓ | ✓ | ⌖ | ⌖ | ⌖ | ⌖ | ⌖ | ⌖ | ⌖ |
| Weir pool manipulation – lowering weir pools | ✓ | ✓ | ✖ | ✖ | ✖ | ✖ | ✖ | ✖ | ✖ |
| Weir pool manipulation – raising weir pools | ✓ | ✓ | ⌖ | ⌖ | ✖ | ⌖ | ⌖ | ✖ | ✖ |
| Pumping water into discrete sites | ⌖ | ⌖ | ✓ | ✓ | ✓ | ✓ | ✓ | ⌖ | ⌖ |
| Gravity based delivery of water into discrete sites at base flows | ⌖ | ⌖ | ✓ | ✓ | ✖ | ✖ | ✖ | ✖ | ✖ |
| Retaining water from natural floods using constructed infrastructure | ⌖ | ⌖ | ✓ | ✓ | ✓ | ✓ | ✓ | ⌖ | ⌖ |

### Severity rating criteria

We believe that the management focus must move away from defining broad taxa like fish, birds, trees, understorey vegetation, water quality and assessing the risks/benefits around these artificial groupings. The focus must become one of using EWA to create resilient, sustainable ecosystems by reinstating biophysical diversity (Walker, 2009) and ecological processes. At the site scale, the influence of contrasting delivery methods on ecological processes can be assessed using a severity rating criteria as presented in Table 3 (adapted from Arthington et al., 2003) to provide managers with a tool to determine if a specific method is likely to achieve their objectives.

**Table 3**. Severity rating criteria for assessing the effects of flow delivery method on ecological outcomes (adapted from Arthington et al., 2003)

| Severity | Criteria | Consequence |
|---|---|---|
| 1 | All natural ecological requirements/processes | Large, positive change in condition |
| 2 | Most natural ecological | Moderate positive change in condition |
| 3 | Some natural ecological | Change in condition likely to be small |
| 4 | Few natural ecological | Negative impacts may outweigh positive |
| 5 | Very few natural ecpumping water into | Increasing risk of negative impacts |
| 6 | No natural ecological requirements/processes | High risk of negative impacts dominating |

### Consideration of serial (cumulative) impacts

Serial impacts include outcomes (both positive and negative) that may not be revealed/detected until many events have occurred. Waterbirds and ground-foraging insectivorous birds are likely to respond behaviourally to inundation events rapidly but key long-term responses such as increased recruitment and strong adult survival during dry periods will occur at the highest temporal-scale of the flow-regime (Rogers & Paton, 2008). It has been demonstrated that diverse fish communities can establish in wetlands where EWA have been delivered via large pumps (McCarthy et al., 2009). In situations where the managed site is allowed to dry out via evaporation, these fish communities are denied return passage ultimately leading to fish mortality. The cumulative impact of repeated flood occurrences at a large number of managed wetlands needs to be taken into account.

### The need for pragmatic solutions

The delivery of EWA to components of river systems cannot replace the function of natural overbank flows and there is no ‘Silver Bullet’ for repairing water-dependant ecosystems deprived of a natural flooding regime. Consequently pragmatic solutions are required to ensure environmental watering at intervals sufficient to enable system preservation and recovery (Brookes et al., 2009b). Crucial functions of rivers depend on hydrological connectivity. The engineering dominated approach to river management by necessity leads to the fragmentation of river systems. Yet few would suggest this is an appropriate way to manage complex natural systems. The way to reinstate a healthy floodplain-river ecosystem is by reducing, not increasing the number of barriers. Weirs and regulators do more than merely impound water, and it is our inability to predict and control the incidental effects that gives most cause for concern (Walker, 2009). In areas that are salt affected floods at higher than normal frequencies (meaning larger volumes of water) will be required to maintain vegetation communities (Nicol et al., 2010). Given the reality of trying to achieve more with less water, using opportunities to export salt out of the floodplain, rather than using floodplains as salt stores must become a management priority.

### *Are EWA management tools or environmental experiments?*

The delivery of EWA to achieve strategic environmental outcomes is certain to become a key management tool (Windsor Report, 2011(http://www.aph.gov.au/house/committee/ra/murraydarling/report/fullreport.pdf). However, it must be recognised that the use of EWA is fundamentally a large-scale manipulative experiment. We currently lack sufficient ecological knowledge to predict how floodplains in different conditions will respond. This represents a major hurdle for managers as volumes of environmental water are limited and resilience is an ecosystem property that can be either created or destroyed (Colloff & Baldwin, 2010).

Higher order organisms respond to habitat and primary productivity drivers. Environmental flows need to focus on these key processes (Kingsford, 2011) in order to maintain ecosystems that will serve as the major sources of propagules and colonists for other areas (Arthington & Pusey, 2003). Investment in recovering water and construction of infrastructure for delivery of EWA needs to be underpinned by investment in research to inform adaptive management and to ensure that critical ecological processes and functions are reinstated. If this is not undertaken, there is no way that environmental water allocations will be able to reinstate resilience (Kingsford et al., 2010).

### *Key principles for consideration when planning the use of environmental water allocations*

Landscape scale processes, connectivity and flow regime are key drivers of ecological systems. Methods of delivering environmental water that do not maximise (i) connectivity (ii) the provision of appropriate habitat; and (iii) the development of appropriate food resources will deliver minimal benefits and compromise the ability of the EWA to achieve positive ecological outcomes. The following provides a list of key principles that must be taken into account when planning the use of environmental water in order to maximise positive outcomes.

- **It is not just the presence of water that is important for maintenance of ecosystem function**
    - The 'quality' of water is an important feature in addition to the quantity of water or the temporal patterns of flow

  - The method of achieving and maintaining inundation and the resultant dilution and downstream dispersal of carbon and nutrients will have a significant impact on water quality via biogeochemically mediated processes
  - Managed floods using infrastructure must maintain high rates of water exchange in order to maximise benefits and minimise risks
  - Ponded flooding should be avoided
  - The delivery of EWA to components of river systems cannot replace the function of natural overbank flows

- **Lateral and longitudinal connectivity drive system productivity**
  - Crucial functions of rivers depend on lateral and longitudinal hydrological connectivity
  - Movement of propagules that can colonise sites and improve condition of degraded sites is dependent on connectivity
  - Lateral and longitudinal connectivity is essential to the viability of populations of many species
  - Managed floods that do not provide strong lateral and subsequent longitudinal transfer of allochthonous material minimise or even preclude the potential for transfer of productivity gains
  - Returning water, that contains a high biomass of prey items and increased nutrient loads, to river channels is likely to improve the recruitment success of fish inhabiting those river channels

- **Habitat and primary productivity drive ecological outcomes**
    - The processes which are influenced by flow and floodplain inundation include hydrodynamics, biogeochemistry and primary productivity
    - Higher order organisms respond to these habitat and primary productivity drivers
    - Differences in the quality of outcomes between natural and managed floods will be driven by the effects of processes that cascade across multiple trophic levels
    - It is essential to manage processes to influence outcomes
    - Trying to improve the condition of only a small subset of the ecosystem without considering the consequences of the intervention on the ecosystem as a whole may cause unwanted and potentially catastrophic effects

- **Variability is essential**
    - Flow magnitude, frequency, timing, duration, rate of change and sequence all hold major ecological significance
    - Variability in these factors is potentially more important than biological factors in structuring aquatic communities
    - Ensuring EWA's are delivered with variability in all of these factors is essential to achieve positive outcomes for multiple abiotic processes and biotic groups
    - Variability is essential to minimise the possibility for negative outcomes to become dominant over cumulative events

- **Ecological outcomes will be related to the antecedent conditions**
    - Sequential floods maintain soil moisture and water levels in wetlands increasing the potential for subsequent flows to travel further downstream and/or inundate larger areas
    - Sequential floods are likely to have positive cumulative effects on biotic responses
    - Meteorological cues may be important for some ecological processes
    - Timing of flooding will have a significant impact on outcomes
    - EWA's delivered into an individual site (i.e. wetland) during periods of low flow may restrict the ecological outcomes as the productivity gains from upstream flooding are not available to be transported into the managed site

- **Reinstate resilience in order to withstand future droughts**
    - Management needs to focus on reinstating resilience as the most pragmatic and effective way of managing ecosystems in order to withstand future droughts and provide ecosystem services
    - Reducing the persistence and severity of engineered droughts will increase the ability of floodplains to withstand climate derived droughts

- EWA's should be used to capitalise on outcomes from preceding flows to (i) ensure germination/spawning/breeding leads to recruitment, and (ii) build resilience, rather than being primarily used as a management tool after long-dry periods to prevent collapse of systems
- The scale of intervention needs to expand from the management of individual wetlands and preventing loss of populations of individual species, to ecosystem management at the landscape scale

Comments on the characteristics and a severity rating score for each of the major types of EWA is presented in Table 4. Severity scores presented are generic (non-site specific) and based on the criteria outlined in Table 3. It is proposed that those management techniques that are higher in the table and shaded grey are the preferred group of management activities. These activities should be actively used during wet and median conditions to build resilience at the system scale. Activities lower in the table have higher severity ratings and are less desirable. These actions can only be applied to isolated sites and should be relegated to use during dry and extreme dry conditions to avoid long-term or irreversible damage and maintain refugia. The use of these techniques as the primary tool for the long-term management of floodplains and wetlands is not recommended.

**Table 4**. Matrix of management techniques, comments on characteristics and severity rating criteria for delivery of EWA (severity rating scores are explained in Table 3)

| Management technique | Comments | severity rating |
|---|---|---|
| natural flood in unregulated system | the reference condition | 0 |
| uncontrolled flow where effects of regulatory structures are largely nullified | closest achievable approximation of natural conditions<br>flow events are minimally attenuated by management activities<br>management of river reaches | 1 |
| controlled releases to generate flow peaks within channel and/or engage floodplain & hybrid floods | flows deliberately created or supplemented by management<br>"filling" holes in the prevailing hydrograph<br>management of river reaches | 2 |
| reoperation of existing infrastructure | weir pool manipulation<br>under-utilised technique that needs to become a management priority<br>large scale longitudinal impact<br>management of river reaches | 3 |
| retaining water from high flow events to extend period of inundation | construction and operation of additional regulatory structures<br>construction of additional barriers on floodplain<br>primary use should be to ensure breeding cycles are completed<br>exchange between wetland/floodplain and river is truncated<br>management of fragmented sites | 4 |
| utilisation of new structures to inundate large sections of floodplains | construction and operation of additional regulatory structures<br>construction of additional barriers on floodplain<br>maximising water exchange is critical to achieving positive outcomes<br>limited number of sites where this option is practicable<br>management of fragmented sites<br>meteorological cues likely to be missing<br>productivity benefits from upstream likely to be missing<br>no precedent for this activity - outcomes may differ from those expected | 4 |
| gravity based delivery of water into discrete sites | very low connectivity<br>typically no benefit to river channel<br>ponded floods generate poor water quality and soil condition<br>meteorological cues likely to be missing<br>productivity benefits from upstream likely to be missing<br>limited number of sites where this option is practicable<br>management of fragmented sites<br>construction of additional barriers on floodplain | 5 |
| pumped delivery of water into discrete sites | extremely low connectivity<br>typically no benefit to river channel<br>ponded floods generate poor water quality and soil condition<br>meteorological cues likely to be missing<br>productivity benefits from upstream likely to be missing<br>limited number of sites where this option is practicable<br>management of fragmented sites<br>construction of additional barriers on floodplain | 5 |

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