Ecological risks and opportunities from engineered artificial flooding as a means of achieving environmental flow objectives

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Restoration of floodplain ecosystems through the reinstatement of floods is often hampered by insufficient water as a result of competing human demands. An emerging alternative approach relies on floodplain infrastructure – such as levees, weirs, regulators, and pumps – to control water levels within floodplains without requiring landscape-scale overbank floods. This technique, albeit water efficient and capable of achieving some ecological targets, does not mimic the hydraulics, hydrodynamics, and lateral connectivity of natural floods. Engineering approaches like this may risk detrimental ecological outcomes, including reductions in biotic connectivity, river–floodplain productivity, and water quality, and thus may fail to support the range of ecological processes required to sustain healthy river–floodplain systems. Here, we review the potential benefits, risks, and mitigation options associated with engineered artificial flooding. Given the growing challenge of equitable water allocation, further research on and monitoring of engineered floods as a tool to sustain floodplain ecosystems are urgently required.

Floodplain ecosystems are among the most productive landscapes on Earth, providing various direct and indirect goods and services to humans (Tockner *et al.* 2008), as well as supporting diverse ecological communities (Figure 1). In many regions, however, river regulation to support agriculture and energy production, and to prevent flood-related damage to settlements, has removed the very floods upon which these ecosystems and their biological communities depend (Nilsson *et al.* 2005; Vörösmarty *et*

In a nutshell:

- Human demand for fresh water has caused global reductions in the productivity of floodplain ecosystems
- In areas facing water stress, engineering solutions are increasingly being used to engineer artificial floods in an effort to simultaneously meet human needs and ecosystem water requirements
- These approaches may improve floodplain forest condition, but also risk failing to maintain and restore key ecosystem processes and river–floodplain connectivity that support diverse, productive riverine ecosystems
- During the planning phase, water savings from such infrastructure must be carefully weighed against restoration targets and implementation should be guided by clearly defined objectives, well-designed monitoring systems, and ongoing adaptive management

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al. 2010). The past decade has been characterized by large-scale efforts to reverse these historical impacts of flow regulation, and the concept of environmental flows is now a central component of water resource planning in most parts of the world (Tockner *et al.* 2008). Yet in a growing number of river basins, water stress means that human and environmental needs cannot both be satisfied, necessitating difficult trade-offs when allocating finite water resources (Vörösmarty *et al.* 2010).

Increasingly, alternative approaches are being sought to optimize environmental benefits while minimizing environmental water allocations. In Australia's Murray–Darling Basin (MDB), one of the world's largest floodplain ecosystems affected by large-scale river regulation (Nilsson *et al.* 2005), engineering-based approaches to supplying water to floodplain wetlands are being used as a "water-efficient" method to achieve ecological goals without needing to reinstate overbank floods (Table 1; Pittock *et al.* 2013). Such approaches include inundating floodplains through pumping and diversion canals, and then controlling water movement on floodplains with levees, weirs, and regulators (Table 1). Similar large-scale infrastructure projects are also being considered in parts of Asia, such as China's Poyang Lake on the lower Yangtze River floodplain, which has experienced prolonged low water periods since construction of the Three Gorges Dam. These engineering infrastructure programs are broadly designed to create or maintain local flooding regimes (referred to here as "engineered floods") that mimic natural floodplain inundation patterns, but without the normal prerequisite of increased river discharge. They are therefore distinct from traditional environmental flow releases, which we refer to as "augmented floods". Engineered floods require floodplain infrastructure (eg

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Figure 1. Productive floodplain environments such as those of Magela Creek in northern Australia depend on periodic flooding to deliver nutrients and sediment; such flooding also allows biota to move between the river channel and floodplain habitats.

levees and flood channels) that historically has been more widely used to prevent or limit inundation from natural floods. Such infrastructure is often aimed at protecting human assets and is now increasingly being considered for removal in some areas due to the high costs of repair, maintenance, and operation (Suddeth *et al.* 2010).

While the use of engineering infrastructure to prevent flooding may be most familiar, similar approaches have long been used to provide water to floodplains for agriculture. In Egypt, for instance, canals were used to divert floodwaters to the floodplain for irrigation as far back as the third millennium BCE (Hassan 1997), and managed inundation of "water meadows" for enhanced pasture growth in the low-lying floodplains of European rivers created productive wetlands for many centuries (Cook and Williamson 2007). However, the use of engineering structures to provide water to stressed floodplains solely for environmental benefits is a relatively new practice. For example, in the 1990s, sluice gates and channels were constructed to allow managed flooding from existing dams of the Senegal River to improve ecological and societal (eg traditional fishing and grazing) benefits (Duvail and Hamerlynck 2003). In the case of the MDB in Australia, various schemes were put in place to create engineered artificial floods (referred to locally as "environmental works and measures"), as a means of "watering" flood-dependent forests at risk of catastrophic mortality during a recent prolonged drought (Figure 2; MDBA 2011). As a result of the apparent short-term success of these efforts during the drought, the scope for delivery of engineered floods using floodplain infrastructure has now been widened. Increasingly, engineered flooding is being viewed as a potential alternative to more traditional landscape-scale, augmented flooding approaches for achieving ecological objectives in floodplain ecosystems (eg MDBA 2011). Similar examples from the Middle East, Asia, and North America have typically also been designed to provide water to support a dominant ecological value (mostly to provide waterbird habitat) rather than restoring broader floodplain ecosys-

tem processes (Table 1; eg Galat *et al.* 1998).

Although engineered artificial floods are attractive for their potential water savings, the approach has garnered some criticism. In examining infrastructure plans in the MDB, Pittock *et al.* (2013) noted four areas of concern: the potential direct negative ecological effects, the institutional challenges involved in operating infrastructure effectively, the associated opportunity costs, and the potentially maladaptive outcomes linked to climate change. Here, we seek to expand on the ecological concerns raised by Pittock *et al.* (2013) within a broader global context, while also considering possible ways to mitigate negative impacts. We review the various ecological roles played by floods in sustaining floodplain river systems, highlight the potential risks and benefits of engineered artificial floods, and discuss ways to avoid the negative outcomes that might arise from their use.

Many aspects of engineered artificial flooding are at odds with the role of connectivity as a unifying concept emerging from flow-ecology research over the past 20

A Western

Figure 2. Dying red gums (Eucalyptus camaldulensis) *due to salinization and reduced flood inundation are now commonly observed along large tracts of the lower Murray River floodplain.*

years – especially the roles of lateral and longitudinal linkages in supporting the flux of materials, energy, and biota between rivers and their floodplains (Junk *et al.* 1989; Tockner *et al.* 2000). Furthermore, it is not just the connectivity per se but the variable patterns within these connections, and hence the ecological fluxes, that largely dictate the mosaic of habitats and diversity of biota supported by healthy river–floodplain ecosystems (Ward *et al.* 1999; Naiman *et al.* 2008). Such diversity is a direct result of variability within flow regimes and the associated hydrological interactions with the landscape. While acknowledging that trade-offs are often necessary in water-stressed ecosystems, at present many indirect risks have not received sufficient attention in the planning, design, and operation of engineered artificial floods. In failing to consider these risks, the extent to which engineered floods

may fail to support the broad range of ecosystem functions driven by overbank flows has also been overlooked. It is not our intention to criticize the approach in toto, but to expand on recent evidence regarding both the benefits and risks associated with engineered artificial floods. In particular, we discuss potential risk mitigation options, and identify some of the critical research needs, design requirements, and operational knowledge requirements that will help to avoid perverse ecological outcomes potentially resulting from engineered floods.

■ The hydrologic case for engineered artificial flooding

One of the major effects of river regulation is the reduction in floodplain inundation from small-to-medium floods (Galat *et al.* 1998). This outcome results in a suite

Table 1. Examples of floodplain engineering infrastructure used to support flood inundation in different countries around the world

| Location	Engineering approach	Ecological target	Proposed or constructed	Reference
Poyang Lake, China	Dam and sluice gates	Increase seasonal wetland flooding	Proposed	www.china.org.cn/environment/2012-02/28/content_24747796.htm
Nebraska Rainwater Basin wetlands, US	Pumping of water into wetlands	Increase wetland area for migratory birds	Pumping and piping of water since 2003; clearing of sediments from wetlands and infilling drainage pits	www.fws.gov/refuge/rainwater_basin_wmd
Missouri River, US	Managed flooding; levees; combined active and passive management	Improve bird and fish breeding	Re-operation of existing structures	Galat *et al.* (1998)
Everglades Restoration, US	Canals; levees; water-control structures	Restore the South Florida ecosystem and provide for other water resource needs	Under construction (expected completion ~30 years)	www.evergladesplan.org
Gunbower–Koondrook–Perricoota Forest, Murray River, Australia	Complex system of regulators, constructed channels, weirs, and levee banks	Improve the management and timing of floodwaters to enhance colonial waterbird and native fish breeding and the health of river red gum forests	Approved	MDBA (2011)
Chowilla Floodplain, Murray River, Australia	Pumping of water into wetlands; injection of water into unconfined groundwater; regulators to enhance local flooding	Improve health of riparian and floodplain forests	Under construction (expected completion in 2014)	Holland *et al.* (2009)
Hattah Lakes, Murray River, Australia	Pumping of water into wetlands; regulators to hold environmental water	Improve health of riparian and floodplain forests; improve aquatic habitat	Some structures in place, others planned	MDBA (2011)
Lower Lakes, Murray River, Australia	Temporary levee	Limit exposure of acid sulfate soils and reduce the risk of water-body acidification	Temporary structures	Bice and Zampatti (2011)
Azraq wetlands, Jordan	Pumping of water into wetlands	Increase wetland area for migratory birds	Pumping of water into wetlands since 1994	www.rscn.org.jo/RSCN/HelpingNature/ProtectedAreas/AzraqWetlandReserve/tabid/98/Default.aspx
Arkansas "greentree reservoirs", US	Levees, locks, and weirs for impounding water around riparian hardwood forests	Increase habitat and foraging for waterbirds	Constructed	King *et al.* (1998)
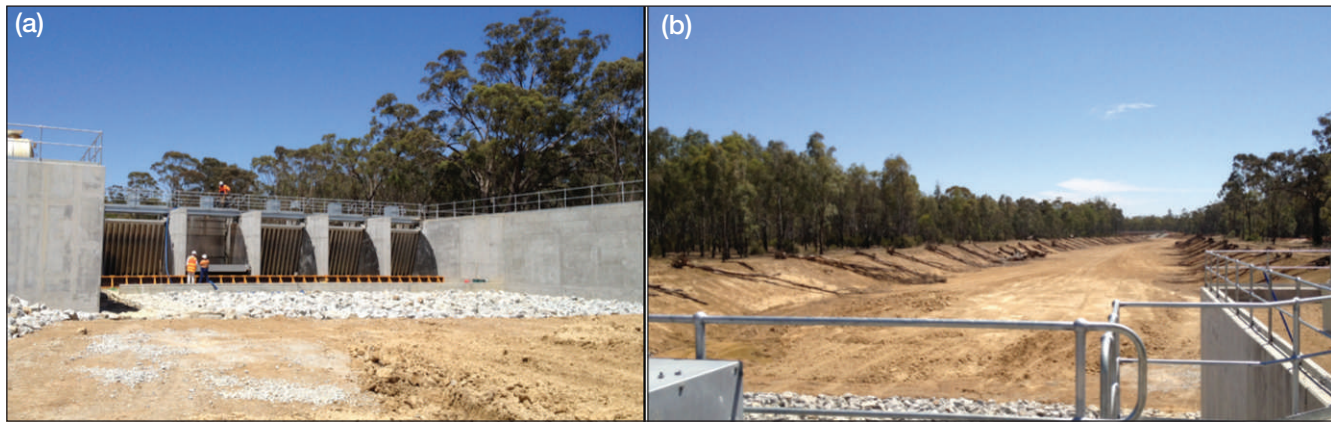
Figure 3. *Examples of large-scale works associated with the creation of artificial floods. (a) Control gates on the Edward River, an anabranch (side channel) of the Murray River, and (b) a diversion channel (Torrumbarry Cutting) in Koondrook–Perricoota Forest on the Murray River floodplain in southeastern Australia.*

of direct and indirect effects on floodplains and in rivers, including increased mortality of floodplain vegetation (Cunningham *et al.* 2009), loss of floodplain wetlands, reduced river–floodplain productivity (Bayley 1991), and loss of access to breeding and rearing habitats for fish and other riverine biota. A key goal of environmental flow programs in large river systems has thus been to restore some of the natural flood pulses that are considered to have the greatest ecological or geomorphological effects. One of the best known examples is in the Colorado River in the southwestern US, where managed floods have been used to target geomorphic processes and restore or maintain populations of key fish species (Valdez *et al.* 2001).

However, in many river systems – particularly low-gradient rivers with extensive floodplains – large reservoirs are located in the headwaters, often hundreds of kilometers from the floodplain reaches targeted by environmental flows. Therefore, augmented flooding using run-of-river environmental flows is often difficult without posing a flood risk to nearby human populations and associated infrastructure, exceeding the design capacity of outflow pipes of upstream storages, exceeding natural geomorphic flow-regulating features of the river (Holland *et al.* 2009), and exceeding volumes of available water after competing uses are taken into account. These are the systems where engineering approaches are proposed or are in use (Table 1). The key aim of engineering works is thus to achieve critical environmental flow targets (defined in terms of the timing, duration, and frequency of floodplain inundation) using less water; this can be achieved by either actively pumping or passively diverting and trapping water on floodplains or within specific wetlands through weirs, levees, channels, and flow regulators, as opposed to relying on overbank or run-of-river floods (Figure 3). Although the associated water efficiency of these engineering approaches is well recognized, they are expensive to construct, maintain, and operate, and have limited spatial coverage; furthermore, to a large extent, their ecological effectiveness has yet to be documented (Pittock *et al.* 2013).

◾ Engineered floods: risks and benefits

The ecological risks and benefits of engineered artificial 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.

Floodplain specialist biota

The initial objective of engineered flooding programs in the MDB was to prevent the mortality of floodplain river red gum (*Eucalyptus camaldulensis*) forests that were at risk as a result of prolonged drought and rising saline water tables (Figure 2; MDBA 2011). Where implemented, the approach proved extremely effective, with moist soils after re-watering helping to promote tree survival, germination, and recruitment (Jensen *et al.* 2008). Furthermore, as with natural flooding, artificially watering wetlands and floodplains increases the amount of standing water and enhances the persistence of floodplain wetlands, which are important habitats for aquatic plants, amphibians, waterbirds, and fish. Providing habitat for waterbird breeding is a major driver for managed run-of-river floods, particularly in the case of species that require long periods of flooding and semi-permanent floodplain wetlands to breed (Kingsford and Auld 2005). Globally, numerous engineered floods have been implemented primarily to increase available habitat for waterbirds (Table 1). Engineered floods are therefore likely to be an appealing option in regions where vegetation condition is very poor, bird breeding has ceased or declined, and natural floods no longer occur.

The application of engineered floods, however, is not without risk to floodplain biota. Increasing floodplain inundation in areas of shallow saline water tables provides only a partial solution to poor floodplain tree health if not accompanied by lowering of the water table (Holland *et al.* 2009). Engineering structures may even

exacerbate salinity problems by artificially maintaining high water levels in the river channel without coincident floodplain flushing, thereby preventing saline groundwater from draining into the river. In the US, the managed inundation of hardwood forests by "greentree reservoirs" to provide waterbird habitat has also driven these forests toward a more water-tolerant community that may now provide fewer food resources for key waterbird species (King *et al.* 1998).

Material and energy exchanges

For many riverine processes, the hydrodynamics of flooding are important (Steiger and Gurnell 2002; Ahearn *et al.* 2006; Howitt *et al.* 2007). These hydrodynamic characteristics clearly have a major bearing on the patterns of sediment, nutrient, energy, and biotic exchange – in terms of what leaves the river (eg deposition and erosion of sediments; Steiger and Gurnell 2002), what is exchanged on the floodplain (eg liberation and transformation of carbon [C] and nutrients; Valett *et al.* 2005; Baldwin *et al.* 2012), and what is returned to the river (Junk *et al.* 1989).

Engineered floods pose the greatest ecological risks because of the alteration or loss of these exchanges. Although there are scant data on the influence of engineered floods on the flux of sediments and most nutrients, the impacts on C fluxes have been well studied. In particular, prolonged floodplain inundation with only limited exchange of water from the river can induce hypoxic blackwater events, which are driven by the leaching and subsequent microbial respiration of C from terrestrial leaf litter (Valett *et al.* 2005; Howitt *et al.* 2007). While floodplain terrestrial inputs are an important source of C and nutrients to the river system (eg Junk *et al.* 1989), and despite the fact that many lowland fish species exhibit a high degree of tolerance to hypoxia (McNeil and Closs 2007; McMaster and Bond 2008), these blackwater events can cause fish kills that have catastrophic short- and long-term effects on fish and crayfish populations (King *et al.* 2012). Even though such events also 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 (see Figure 4; Galat *et al.* 1998; Valett *et al.* 2005; Baldwin *et al.* 2011), and where the reduced frequency of floodplain inundation events in regulated rivers allows greater litter accumulation (Howitt *et al.* 2007). The negative impacts of such events can extend far downstream if sufficient hypoxic blackwater enters the river channel (King *et al.* 2012).

In contrast to the threats from blackwater events, floodplain-derived C is also an important source of energy that supports production in floodplain rivers (Zeug and Winemiller 2008; Hladyz *et al.* 2010; Jardine *et al.* 2012). In heavily regulated rivers, the loss of floodplain inundation events can create an energy bottleneck that limits the carrying capacity of higher trophic levels (Naiman and Turner 2000), which can have strong social and economic implications in terms of lost food production (Orr *et al.* 2012). Overcoming such bottlenecks may involve restoring food webs and their associated energy pathways (Naiman *et al.* 2012), including the flux of energy back to the river, as dissolved organic C becomes incorporated into the tissue of biota that utilize floodplain nutrients (Jardine *et al.* 2012). The avoidance of blackwater events and the maintenance of energy fluxes depend on the hydrodynamics of floodplain inundation, including the duration of inundation and water residency time, and it is still unclear whether these processes can be adequately mimicked by the types of engineering works being considered and, if so, under what operating strategies.

Biotic movements and connections

In addition to floodplain processes, many in-channel ecological processes depend on flood events as a trigger. Rising river levels assist in dispersing plant propagules and triggering germination (Pettit and Froend 2001), promoting fish spawning and recruitment (King *et al.* 2009), promoting fish movement (O'Connor *et al.* 2005), and cueing some colonial waterbirds to breed (Kingsford and Auld 2005). Some species of fish also move out of the river channel to breed (Fry 2002; Barko *et al.* 2006), but such movements can be hindered or halted by water-control structures (Jones and Stuart 2008). Fish and invertebrates that survive being passed through pumps further risk becoming trapped on the floodplain and not returning to the river channel (Figure 5; Jenkins and Boulton 2003; Jones and Stuart 2008). There are similar concerns that the proposed weir between Poyang Lake and the Yangtze River will preclude movement of Yangtze finless porpoises (*Neophocaena phocaenoides*), which are highly imperiled in the wild and currently move between these habitats in search of food (Wang 2009).

As well as promoting reduced connectivity, altered hydraulic regimes may favor spawning and recruitment of exotic fish species, such as common carp (Bice and Zampatti 2011), and could also benefit introduced weed species (Catford *et al.* 2011). Consequently, assemblage structure and diversity may be substantially modified, thereby promoting dominance of exotic species and altering river–floodplain structure and function.

■ Making engineered floods work

Reliance on engineered floods 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 (eg water residence time) or on the ways that rivers and their floodplains are connected. For example, pumping is wholly incompatible with the movement of adult
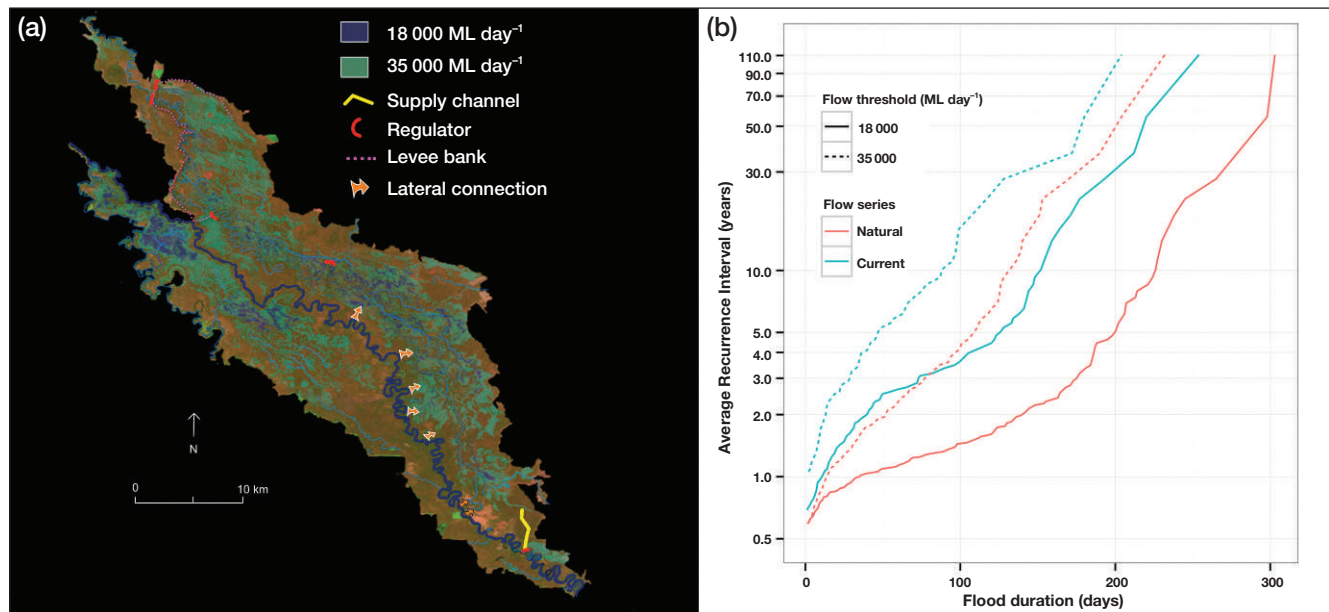
Figure 4. *Koondrook–Perricoota (KP) Forest forms part of the second largest river red gum forest in southeastern Australia and is listed as a wetland of international importance under the Ramsar Convention. It also supports several important waterbird colonies and populations of nationally threatened plants and fish. The forest is dissected by numerous small channels, which begin to flow from the main river at a discharge of approximately 18 000 million liters per day (ML day^{-1}) in the Murray River (a). At higher flows, water spills 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), causing major forest dieback along the Murray River (eg Figure 2). A program of works is presently underway to construct a delivery channel (Torrumbarry Cutting) at the head of KP Forest, and a series of downstream regulators and levee banks to maintain high water levels within the forest (a). 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. Despite considerable modeling, the extent to which long-term management objectives can be met with reduced flows remains uncertain, highlighting the need for ongoing ecosystem monitoring.*

fish onto floodplains, although this can be used to reduce the spread of exotic species and favor small-bodied fish (Vilizzi *et al.* 2012). In other cases, appropriate management of water infrastructure could mitigate some of the risks by replicating natural hydrodynamic variability (Figure 5; Table 2). For instance, blackwater events are relatively well understood, and are probably best managed by ensuring that water is not ponded onto floodplains for too long; floodplains are regularly inundated to prevent a buildup of organic material; flooding occurs during periods of cooler water temperatures (when microbial decomposition rates will be lower); or where long inundation periods are required (eg for bird breeding), an ongoing exchange of water between the river and the floodplain is established (Valett *et al.* 2005; King *et al.* 2012). If done well, this can facilitate the transfer of floodplain-derived C and nutrients back to the river channel without risks to in-channel and floodplain biota. This, of course, can be achieved only at the cost of additional water relative to that used when ponding is maintained for longer durations (Figure 4).

While effects within areas targeted for water delivery have received much attention, another major consequence of engineered floods is that higher flood frequen-

cies are restored only to isolated sections of the floodplain (MDBA 2011; Pittock *et al.* 2013). This has important consequences in terms of the extent to which such flooding contributes to increased riverine and floodplain production at large spatial scales, which can be critical in supporting the ecological and socioeconomic value of local and downstream fisheries (Bayley 1991; Opperman *et al.* 2010). Conversely, a potential benefit of engineered floods is the ability to target flooding toward high-value ecosystems while reducing the likelihood of inundating agricultural land and human infrastructure. This can have indirect benefits to ecosystems, for example by reducing the export of toxic chemicals from agriculture (Beketov *et al.* 2013). Clearly, modifying the hydraulic parameters of artificial floods (ie their velocity, magnitude, and residency) will depend on floodplain topology and priority conservation values and so may vary on a case-by-case (or even on an event-by-event) basis. This will require flexibility in delivery and managing expectations, for instance accepting that not all ecological targets may be achieved.

The effectiveness of alternative management options hinges on the specific ecosystem objectives being sought by means of floodplain reconnections. In many water-
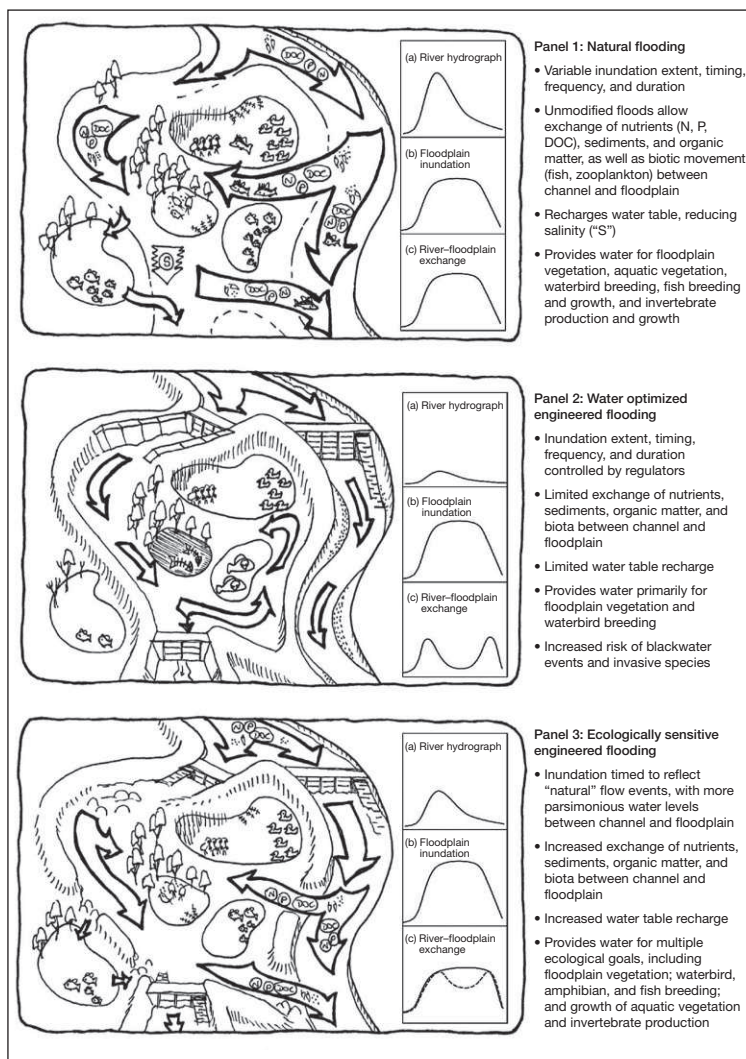
Figure 5. Key differences in the ecological processes associated with natural floods, including flow-optimized and carefully designed floodplain reconnection strategies. The inset panels illustrate variations in channel and floodplain hydrology under each scenario.

stressed regions, particularly where stresses will be exacerbated by climate change and further development pressure, engineered floods are increasingly seen as the only option once governments consider the various ecological, social, and economic values at stake. Where this is the case, it must be recognized that only a limited number of ecological objectives are likely to be achievable. These objectives need to be articulated and accepted by all stakeholders, and engineered floods must be monitored for their effectiveness and modified (in either their design or operation) when necessary. Engineered floods and their associated infrastructure requirements should also be viewed and implemented in the broader context of floodplain restoration requirements at larger spatial scales (eg catchment/basin), and their benefits considered within a temporal context (eg their role in emergency watering of valuable assets versus meeting long-term hydrological regime requirements). Artificial watering via engineering approaches should not be expected to achieve equivalent

ecological responses to those that natural floods, or indeed augmented floods, would provide.

■ A new conceptual framework for evaluating environmental flows

Engineered floods have emerged as a seemingly practical solution to achieving environmental flow targets in water-stressed systems. Historically, targets for floodplain inundation have been defined in terms of hydrologic characteristics (eg the timing, frequency, and duration of flood events) rather than in terms of hydrodynamics (eg residency time, velocity profiles, variable flow paths, and patterns of connection with the river channel). However, in many cases these hydrodynamic aspects of floods and the associated mosaic of inundation depths, durations, and flow velocities drive important physical and biological responses (Ward *et al.* 1999). The existing conceptual framework has been sufficient when floods are delivered as run-of-river events (either natural or augmented floods). Yet the growing use of engineered floods may warrant inclusion of additional hydrodynamic descriptors within the conceptual framework used to inform and set environmental flows, especially where targets require floodplain reconnection. This would facilitate more formal and thorough evaluation of the types of risks and trade-offs that we have identified (Table 2), but will also entail additional hydrodynamic modeling.

■ Conclusions

Engineered floods are a potentially efficient way of watering floodplains to achieve environmental objectives with limited volumes of water. Their use is expanding rapidly in some regions to support environmental flow delivery, and is likely to expand elsewhere in the future as a result of increasing water scarcity. Nevertheless, engineered floods pose potential ecological risks associated with the disruption of natural river–floodplain and upstream–downstream linkages, even though this approach may provide the only means of trying to mimic historical inundation patterns in some floodplains and wetlands without substantially increasing the volume of water allocated to environmental flows. Adopting engineered floods as a strategy will necessarily entail a trade-off in terms of the water savings and specific environmental benefits that environmental flows might otherwise achieve. There is a crucial need for more rigorous research on the effectiveness and risks of this approach, and the various forms of infrastructure by which engineered floods might be created, particularly focusing on the infrastructure required to optimize fluxes to *and* from the floodplain. Broader research on floodplain restoration more generally is also warranted (Lake 2012). A thorough

Table 2. Potential ecological trade-offs associated with different methods of managing water to achieve artificial floodplain inundation events

Engineering method	Effects	Benefits	Challenges	Options for mitigation
Water delivered to floodplains via pumping	Floodplain inundation to mimic natural floods	Provides water to floodplain vegetation; promotes germination; replenishes floodplain wetlands; provides opportunities for bird breeding	Mortality of fish (including larvae and eggs) via damage incurred by being passively sucked through pump; pumps represent a barrier to dispersal by fish and other large taxa; natural flow pathways lost; no access to critical habitat (eg breeding, rearing, feeding) for fish and turtles; minor lateral export of sediment and nutrients	Larger intakes for pumps to reduce water pressure and mortality of eggs, zoo-plankton, etc; screen pump intakes and/or limit extraction to non-spawning periods; limit the use of pumps to extreme dry periods and rely on natural overbank floods at other times
Water delivered to floodplains via constructed channels	Floodplain inundation to mimic overland flows	Provides water to floodplain vegetation and promotes germination; replenishes floodplain wetlands; provides opportunities for bird breeding; some access to floodplain by riverine biota	Natural flow pathways lost; reduced access to critical habitat (eg breeding, rearing, feeding) for fish and turtles; reduced lateral export of sediment and nutrients	Use existing natural entry points such as off-take channels where fish may be naturally cued to move; channel design should incorporate "rough" surfaces to reduce velocities and turbulence to aid movement both in and out during connection; plan diversions to coincide with minor (in-channel) floods to increase sediment and nutrient export
Artificial ponding of water on floodplain using down-slope infrastructure (weirs, control gates, and levees)	Increases inundation duration	Provides inundation duration sufficient for germination and breeding; increased floodplain productivity after mobilization of fine particulate organic matter and organic C	Water-quality degradation (eg hypoxic blackwater, cyano-bacterial blooms) and potential fish and crayfish kills on floodplain and in river channel; reduced energy subsidies from floodplain back to the river channel; loss of diversity of flow types (habitat types) in forest wetland systems, leading to decline in species richness and productivity of micro- and macroinvertebrates and fish; entrapment of fish and turtles	Time inundation events to occur during cooler periods (reduced risk of water-quality decline); prevent buildup of organic matter through regular inundation; manipulate water levels to promote some heterogeneity in velocities and depths; maintain sufficient returns to increase energy subsidies and biological connectivity from the floodplain to the river

assessment of the likelihood that engineered floods will achieve their intended ecological goals should be undertaken before the necessary infrastructure is constructed. This should include consideration of other floodplain interventions (eg levee removal and agricultural retirement) that may also be required (Lake 2012). The effectiveness of engineered floods in achieving ecological goals should also be further assessed using rigorous monitoring programs that take into account the difficulties of monitoring environmental flow outcomes in regulated river systems (Konrad *et al.* 2011). To this end we encourage dialogue among water managers, engineers, ecologists, and other stakeholders in examining the ecological and socio-economic risks, trade-offs, and opportunities in both the construction and operation of engineered-flood-associated infrastructure, to ensure that the range of potential trade-offs is fully understood and explored before further major investment occurs.

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