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Dam reoperation in an era of climate change

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Abstract. Climate change is predicted to affect the future supply and demand for water resources. Current water-management practices may not adequately cope with the impacts of climate change on the reliability of water supply, flood risk, health, agriculture, energy generation and aquatic ecosystems. Water managers can adapt to climate variability by structural change, such as increasing the size or number of dams, building desalination plants and transferring water between catchments; however, a broader set of alternatives with multiple beneficial outcomes for society and the environment should be explored. We discuss how modifying dam operations, 'dam reoperation', can assist with adaptation to climate change and help restore ecosystems. The main operating purpose of a dam (e.g. flood management, hydropower or water supply) will influence dam reoperation strategies. Reoperation may require integration across sectors or involve multiple dams, enhancing benefits such as water supply or hydropower while simultaneously achieving ecosystem restoration. We provide examples of lessons learned during extreme scenarios (e.g. floods and droughts), where operational flexibility has been demonstrated. We contrast structural climate-change adaptation strategies (e.g. building new dams) and their resulting detrimental environmental outcomes with dam reoperation, which can maximise benefits for ecosystems and society.

Additional keywords: dams, environmental flows, flood control, flow restoration, flow variability, freshwater ecosystems, hydropower, water supply.

Introduction

Climate change will affect the supply and demand for water resources, having an impact on freshwater ecosystems and ecosystem services worldwide (e.g. Milly *et al*. 2005; Bates *et al*. 2008; Palmer *et al*. 2008). Most models predict more extreme events, such as flooding and drought (Bates *et al*. 2008). By the middle of the 21st century, annual average river runoff and water availability are projected to increase at high latitudes and in some wet tropical areas, and to decrease in semiarid and arid areas (including the Mediterranean Basin, western USA, southern Africa, north-eastern Brazil, southern and eastern Australia) (Kundzewicz *et al*. 2008). Current water management may not adequately cope with the impacts of climate change on the reliability of water supply, flood risk, health, agriculture, energy generation and aquatic ecosystems (Palmer *et al*. 2008). Climate-change predictions and recent droughts and floods have increased the awareness of decision makers of the need to adapt, creating an opportunity to re-examine policies and management procedures for rivers and infrastructure (Pahl-Wostl 2007).

Adaptation measures adopted around the world include increased extraction of groundwater, improving storage capacity by building or modifying dams and reservoirs, desalination of seawater and expansion of rainwater storage and water transfer (Bates *et al*. 2008; Hirji and Davis 2009*a*, 2009*b*). Such largely structural adaptation measures can exacerbate stresses on already highly altered aquatic ecosystems. Demand-side measures and ecosystem-based adaptation measures can complement or even substitute for structural adaptation measures. Demand-side options include improving water-use efficiency by recycling water, improving seasonality of water demand by changing irrigation methods and mix of crops, improving irrigation water-use efficiency, importing agricultural products instead of growing them in water-scarce areas, using water markets to reallocate water to highly valued uses, and using water metering and other incentives to increase water conservation (Bates *et al*. 2008). Ecosystem-based adaptation uses biodiversity and ecosystem services for adapting to the adverse effects of climate change (Secretariat of the Convention of Biological Diversity 2009). In the present paper, we describe how dam reoperation can mitigate effects of climate change and increase resilience of water-management systems while contributing to ecosystem restoration.

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Dam reoperation

Most major rivers in the world have been altered by the construction of dams, impoundment of water and regulation of outflows, dramatically altering natural flow regimes (Nilsson *et al.* 2005). Dams alter the daily and seasonal flow variability, affecting the timing, magnitude and frequency of small to moderate floods and floodplain inundation (Magilligan and Nislow 2005). In general, flood-control dams replace small to medium floods with long high-flow pulses following flood peaks (Pearsall *et al.* 2005; Richter and Thomas 2007). Large hydropower dams with sizeable storage capacity generally reduce flood peaks and, if operated to provide 'peaking power', produce a rapidly fluctuating hydrological regime downstream of the dam, corresponding with power demand (Richter and Thomas 2007). Water supply dams generally reduce small and medium-sized floods, shifting seasonal discharge patterns, with extended periods of unnaturally high flows during releases and extended periods of low flows during the filling phase of dam operation.

Altered flow regimes have resulted in unintended and undesirable impacts on river ecosystems and biota (Poff *et al.* 1997; Bunn and Arthington 2002; Postel and Richter 2003). Dam reoperation can recover some environmental and social benefits of rivers lost through current dam operations. Through the application of innovative and integrative management approaches, environmental benefits can be obtained without significantly compromising other needs (e.g. water delivery, flood mitigation, power production) in regulated river systems. Dam reoperation strives to maintain (or even increase) the benefits from dam operations while simultaneously reducing the damages or costs of dam operation (Judd and McKinney 2006). Dam reoperation can restore key elements of the natural flow characteristics of the river, such as high-flow pulses, flood flows and low flows (Postel and Richter 2003; Mathews and Richter 2007). These can restore geomorphic and ecosystem processes, improve river and floodplain habitat, create opportunities for migration and recruitment, and improve in-stream and riparian biodiversity.

The assessment framework for dam reoperation outlined by Richter and Thomas (2007) can be used to evaluate and maximise the benefits restored through dam reoperation. The framework involves the following six steps: (1) assessment of dam-induced hydrological alteration; (2) description of ecological and social consequences; (3) specification of goals for dam reoperation; (4) design of dam reoperation strategies to attain goals; (5) implementation of strategies; and (6) assessment of results relative to goals. With climate change, strategies for reoperating dams will need to consider the increased risk of floods and droughts and implications for power supply and hydrological variability while seeking to maximise benefits for ecosystems and society. The opportunities, constraints and goals for dam reoperation are region- and site-specific and are strongly influenced by the main operating purpose(s) of the dam (e.g. flood mitigation, production of hydropower, water supply) (Richter and Thomas 2007).

Flood-management dams

Climate change will increase the risk of floods in many parts of the world (Bates *et al.* 2008), requiring more comprehensive and sustainable flood management, and not just a reliance on dams and levees (Opperman *et al.* 2009). Managing the increased volumes of water that will result from extreme rainfall events will require increased capacity for storage and conveyance of floodwaters. More sustainable flood management would incorporate non-structural approaches, including wetland restoration, floodplain reconnection, and improved forecasting and warning systems (Silander *et al.* 2006; Bates *et al.* 2008).

Floodplains can be used to store and convey increased flood volumes (Silander *et al.* 2006; Richter and Thomas 2007; Opperman *et al.* 2009). Water can be allowed to pass through dams and be stored and conveyed by the downstream floodplain within natural features or anthropogenic retention basins or bypasses. Part of the expected increased discharge could also be diverted through specially created fish bypasses and side channels (Silander *et al.* 2006). In some catchments, existing levees may need to be moved further back on the floodplain or new floodways established to enable floodwater to be directed around cities and towns. Reconnection of floodplains can provide significant public-safety benefits by reducing flood risks for nearby towns, cities or agricultural areas (Klijn *et al.* 2004; Opperman *et al.* 2009). Such reconnection also produces significant environmental benefits by supporting biodiversity on the floodplains (Tockner and Stanford 2002) and provision of ecosystem services such as groundwater recharge, water filtration and support for productive fisheries (Costanza *et al.* 1997).

Incorporating the floodplain in flood management can improve reservoir operation for environmental flows, increasing resilience to changing hydrological patterns. If floodplain reconnection creates additional downstream capacity to store and convey floodwaters, dam operators could reduce the reservoir volume reserved for flood control, benefiting the environment and water users. Reducing the flood reservation (i.e. allowing water levels in the reservoir to rise above the normal target level for flood control) would allow more water to be stored in the dam than what was the case under previous management. This additional water could be used to restore flood pulses in wet years and increase hydropower revenue (owing to higher hydraulic head) as well as produce more water for users in dry years. Such changes would need to ensure structural integrity of the dam and equitable reallocation of additional water.

The Yolo Bypass, a 24 000-ha floodplain in California's Central Valley, is an example of a large-scale reconnection of floodplain designed to reduce flood risk. Although not anticipated, this floodplain increased the flexibility of multipurpose reservoir operations. The Bypass was created as part of the Sacramento River Flood Control project in the 1930s when it was evident that levees alone would not sufficiently reduce flood damage in this valley (Kelley 1989). The Bypass conveys $\sim$80% of the river's floodwater during large flood events around the city of Sacramento. Two-thirds of the Bypass is privately owned productive agricultural land and incorporates extensive managed wetlands. California has flow easements allowing inundation of the Bypass, providing habitat for birds, native fish and ecosystem services, such as groundwater recharge (Sommer *et al.* 2001). In 1986, $12.5 \times 10^6\,m^3$ of water (three times the total flood-storage volume of all upstream reservoirs) was conveyed through the Bypass. The major multipurpose reservoirs (municipal and irrigation water supply) of Sacramento Valley would require more storage volume to control flooding if the Yolo Bypass and its floodplain were not available (Opperman *et al*. 2009).

In many places, current land use may limit the use of the floodplain for flood management. There are options for overcoming some land-use constraints (Richter and Thomas 2007; Opperman *et al*. 2009). Reconnected floodplains could remain privately owned but with compensation to landowners for lost productivity or occasional flood damage. Many agricultural practices are compatible with periodic inundation, such as timber production or annual cropping during the dry season where there is strong seasonal flooding. However, incorporating floodplains as part of a flood-management system is complex and should be implemented with consideration of broader implications. In Australia, where dams serve multiple uses (including water supply and flood control), water planners have been criticised for paying inadequate attention to harvesting of floodwaters through the construction of levees on private land (NWC 2009: Finding 1.7). Such levees were constructed to increase the retention of floodwater along conveyance channels to irrigation areas and to improve lake-bed farming, but have affected downstream flow and prevented floodwaters from reaching important wetlands (Steinfeld and Kingsford 2008).

Hydropower dams

Hydropower dams impound water to create hydraulic 'head' for power production resulting from the flow of water through turbines. They have two primary impacts on river flows, including production of high within-day fluctuations in flow in response to electricity demand ('load following' or 'peaking'), and capture of high flows, stored for long periods of time for energy generation. Such dams alter seasonal flow patterns and can be out of phase with the natural flow regime, reducing flow during high-flow periods and increasing flow during low-flow periods. This causes environmental degradation of the downstream ecosystems (Bunn and Arthington 2002; Postel and Richter 2003).

Reoperation of hydropower dams can release water in a pattern that is closer to the rate of natural inflow into the reservoir, reducing impacts on downstream ecosystems (Richter and Thomas 2007). Reregulation reservoirs, off-channel pumped storage, or coordinated operations within a cascade of dams can address extreme daily fluctuations in flow. Targeted release of specific types of flows or modifying operations closer to run-of-the-river conditions can restore some of the natural seasonal hydrological pattern (Richter *et al*. 2006; Mathews and Richter 2007). Moving towards run-of-river operations may change power-generation schedules and thus requires coordination of multiple dam operations (e.g. cascade of dams on a river or complex of dams within a basin). The dam that controls flows into a river reach targeted for restoration can improve the seasonality of flows through reoperation. Without changes in the turbine array, this reoperation may reduce overall power output at the target dam, necessitating compensation for lost power production at a spatial scale beyond an individual dam. For example, such restoration downstream of a target dam may require re-reoperation of non-target dams to compensate for lost power production. This requires prioritisation of the environmental and social values of different river reaches (Viers and Rheinheimer 2011) and will likely also require innovative financial mechanisms for coordinated operations among dams.

For hydropower dams producing daily peaking flows, a reregulation dam or pumped storage facility can reduce the sharp spike in the daily hydrograph. These reregulation reservoirs generally have small storage capacity but attenuate extreme fluctuations, allowing upstream dams to meet peak demands and reducing environmental impacts on the reach below the reregulation reservoir. For example, the Banimboola reregulation reservoir immediately downstream of Dartmouth Dam on the Mitta Mitta River in south-eastern Australia reregulates flows to comply with rules for rates of rise and fall to avoid damage, such as bank erosion further downstream (MDBC 2006), and provides additional capacity for electricity generation through the Banimboola power station. Pumped-storage reservoirs can replace the peaking function of a dam on a river channel. During periods of low energy demand, water can be pumped from the lower reservoir to the upper reservoir, with water flowing downhill through turbines during periods of high electricity demand. Fluctuations are contained within reservoirs rather than the downstream river channel. Pumped-storage projects are net consumers of energy so cost–benefit analysis is required to determine whether the reduced power generation and increased infrastructure costs are justified for downstream environmental benefits.

In many rivers, climate change will affect water availability for hydropower and ecosystems (Christensen *et al*. 2004). For example, the gross hydropower potential is expected to increase in northern Europe with increased river flows (Lehner *et al*. 2005), which may exceed the capacity for hydropower production. This could provide opportunities for operating dams and power stations to the benefit of riverine ecosystems, such as releasing more water to river reaches that have a reduced discharge, reintroducing key elements of the natural flow variability (Renofalt *et al*. 2010). However, the demand for hydropower will probably increase as production of electricity by fossil fuel is phased out, so some of the additional flows may be used for power production (Renofalt *et al*. 2010).

Water-supply dams

About half of the world's large dams were built exclusively or primarily for irrigation and water supply (World Commission on Dams 2000). These dams are managed to compensate for variations in natural runoff and provide a reliable supply of water. Most water-supply dams shift the seasonal hydrograph, with high flows captured during the wet season and released during the dry season. Competition for water is already intense and water-sharing arrangements are complex. For example, because of the recent prolonged drought in southern Australia, a ministerial decree was enacted to suspend water-sharing plans to safeguard 'critical human needs' (i.e. for drinking water and industry; Pittock and Finlayson 2011). Demand for water will only increase as the rates of evapotranspiration and dry periods rise.

New agreements and revised operating protocols will be needed to accommodate changing patterns of water demand (Pittock and Hartmann 2011), including the storage of water, rules for inter-annual carryover and borrowing, management and ownership of dam spills and effective delivery of environmental water from dams. Reoperation plans for water-supply dams will need to ensure consumptive water losses are minimised and water savings are maximised. For ecosystem restoration, the primary goal for reoperation of water-supply dams is to reshape the hydrograph to a more natural seasonal pattern and increase the variability of flows during release and filling modes of operation of the dam. A range of strategies can be implemented.

Improved integration of groundwater and surface storage

The operation of some water-supply dams can be altered to improve the seasonal timing of water release by using storage capacity in groundwater aquifers downstream, providing that aquifers with appropriate geology are available (Richter and Thomas 2007). Water can be released before the irrigation season to coincide with environmental needs of the ecosystems (e.g. spring spawning of fishes), and diverted and stored in groundwater aquifers for later use. Such managed aquifer recharge has been used in Australia for irrigation and urban stormwater management (Dillon *et al*. 2009), and a large-scale agricultural and urban supply is currently under consideration to reduce evaporation and improve water efficiency (Geosciences Australia 2010; NWC 2010). It is also part of the Comprehensive Everglades Restoration Plan (South Florida Water Management District 2008). Aquifer storage and recovery is particularly relevant in areas where rainfall and runoff will decrease with climate change. Transferring water to downstream aquifers during wetter months would minimise conveyance losses relative to current conveyance losses in summer, and reduce evaporative losses. The environmental and socioeconomic risks and benefits of aquifer recharge need to be assessed. Water quality may be compromised from mixing groundwater and surface water and pumping may be expensive. Governments could establish an environmental account to cover the additional pumping costs incurred by landholders if environmental benefits are realised.

Linking operations of dams

Dams arranged in series or cascades in many regulated rivers are usually managed to minimise evaporation losses by storing water in the most upstream reservoir and transferring water to reservoirs downstream for water supply when required. Typically, transfers between reservoirs are delayed for as long as possible in the irrigation season to minimise the risk of making an unnecessary transfer of water. If a transfer is required, the flows are then usually released at channel capacity to ensure timely delivery of the water. This produces sustained constant high flows during the irrigation season and extended constant minimum flows during dam filling. Reduced water availability and the imperative for water savings under climate change may increase such management.

Changes to transfer patterns between dams can alter the hydrograph without changing the volume of the releases. For example, water transfers could begin earlier in the irrigation season or be released with a more natural hydrograph instead of constant flows. This approach was trialed for the transfer of water from Dartmouth to Hume reservoirs in the Murray–Darling Basin (Allan *et al*. 2009; Watts *et al*. 2010). Such changes can improve in-stream ecological condition and simultaneously achieve some social and economic objectives. For example, the release of variable flows from Dartmouth Dam improved biodiversity, reduced the biomass of problematic biofilm on riverbed cobbles, and enhanced the ability for landholders to pump water from the river. This example demonstrates there are opportunities for managers to change river-operating rules to improve environmental benefits and meet social and economic objectives.

Changing delivery arrangements for landholders with riparian rights

In some parts of the world, landowners who occupy land on a riverbank or lakefront have a licence or right to take water for domestic purposes and stock use. In Australia, landholders with this right must be able to draw water from the river at any time, requiring the river to be managed to produce a constant base flow (‘stock and domestic’ flow). The conveyance losses for delivering this water can be extremely high. For example, Crooked Creek in the Macquarie Valley of the Murray–Darling Basin, Australia, is a regulated stream where flows of $3–7 \times 10^6\,m^3$ of water per year are required to deliver less than $0.1 \times 10^6\,m^3$ of water per year for stock and domestic use (D. Berry, State Water Corporation, pers. comm.). Water suppliers, under pressure to minimise losses during dry conditions, have considered options for piping surface water or supplying stock and domestic water users with groundwater bores. Water savings would then be converted into a licence for environmental water and the project funded by trading the water licence to the Commonwealth Environmental Water Holder, established by the Australian Government to acquire water from willing sellers to increase the share of water for the environment (Department of the Environment Water, Heritage and the Arts 2008).

Altering the timing of flows and delivering water in discrete pulses can also minimise losses. This can benefit the environment through an increased variability of flow, provided the costs and benefits of pulsed flows are considered (Watts *et al*. 2009). This strategy was implemented for irrigation-licence holders in the northern Murray–Darling Basin of Australia during periods of water scarcity. The water agency (NSW State Water Corporation) pulsed delivery, or ‘block released’, in the dry periods of 1994–1995 and in the summers of 2008–2009 and 2009–2010. Consultation with licence holders minimised disruption and allowed landholders to pump to on-farm storages to provide water for stock during periods of no flow. The reoperation of dams to minimise water losses was accepted by landholders because of the clear social benefits of water savings in extremely dry conditions. Environmental benefits were not evaluated but as the change more clearly mimicked the natural regime of flooding and drying, it was likely to be beneficial for the environment.

‘Piggy-backing’ release of environmental water on consumptive water releases or tributary inflows

‘Piggy-backing’ coincides environmental water releases with consumptive water releases from dams or inflow from unregulated tributaries to increase the magnitude of environmental flow pulses. This minimises the loss of environmental water allocation during transmission, delivering high-flow pulses for wetland inundation by overbank flow. Flow targets can be met more efficiently, with less water, if pulsed environmental releases are triggered by high-flow events in tributaries (Harman and Stewardson 2005). This requires flexible and rapid decision-making for the release of environmental water from dams to coincide with a rainfall event or unregulated flow.

Piggybacking was pioneered in the River Murray, Australia, by the Murray Wetlands Working Group (undated). It was used in three pilot trials (two on unregulated flow and one on an irrigation release) under the direction of the Murrumbidgee River Management Committee (Hardwick *et al*. 2001; Bowmer 2003). Under climate change and increasing water scarcity, 'piggy-backing' may become more important because environmental water allocations alone may not be sufficient to inundate wetlands.

Constraints and opportunities for dam reoperation

Dam reoperation requires good information, collaboration and funding. Decisions need to be based on scientific evidence, including: assessments of the key flow components to be restored downstream of a dam; potential water losses or savings; synergies among floodplain management; reservoir flood control; hydropower production and water supply; and knowledge of risks and tradeoffs. Good communication and stakeholder support for dam reoperation can enable the process to proceed smoothly, building trust among individuals, organisations, society and governments (Allan *et al*. 2009). Institutional structures are critical to support adaptive management.

Climate-change uncertainty will require new management strategies for infrastructure, including operation, design for new infrastructure and rehabilitation of aging infrastructure (Milly *et al*. 2008). Increased runoff can alter estimates of the maximum flood, requiring dam operators to improve the dam to make it compliant with standards of expert independent dam-safety committees such as ICOLD (International Commission on Large Dams). In Australia, ANCOLD (the Australian National Committee on Large Dams) requires dams to have sufficient storage capacity and release rates to cope with an increased probable maximum flood projected by the Bureau of Meteorology. Resulting upgrade of dams (e.g. wall raising and spillway modification) triggers a legal requirement for an environmental-impact assessment that can lead to the inclusion of fishways and remediation of the impacts of altered water-temperature regimes (Pittock and Hartmann 2011). Dam reoperation options should also be considered as part of infrastructure upgrades (Doyle *et al*. 2008).

Dam reoperation may be difficult to implement because of inflexible policies and operating procedures. Modelling dam reoperation and its effects on flow and implementation of flow trials should drive changes in policy and operating procedures. There may also need to be modifications of infrastructure and investment in human resources. Sufficient financial resources are usually available to increase storage capacity or to develop water-transfer schemes; however, financial support for dam reoperation is often limited. Adequate funding for implementation and monitoring is essential.

Increased appreciation of the importance of functioning ecosystems, biodiversity and the recreational and cultural values associated with more natural river flows has increased public support for dam reoperation. These values should drive change in policy and operating procedures, sometimes decades old. In the USA, relicensing of hydropower by the Federal Energy Regulatory Commission (FERC) illustrates incorporation of new policies (e.g. *Endangered Species Act* and *Clean Water Act*) and new values, through increased participation of non-government organisations, communities and resource agencies in the relicensing process (Pittock and Hartmann 2011; Viers and Rheinheimer 2011).

There is increasing understanding of potential synergies with dam reoperation. For example, floodplain reconnection reduces the need for reservoir flood-control storage, potentially increasing allocation to water supply, hydropower and environmental flows. Also, landowners can potentially receive revenue from reconnected floodplains through emerging markets for ecosystem services such as groundwater banks and carbon sequestration (Opperman *et al*. 2009). This change in land value can make dam reoperation more socioeconomically and politically feasible. Recent extreme events in many countries have highlighted the need to reconsider policy and procedures to manage reduced or increased water. Water managers are also considering management of extreme events predicted under climate change, which promotes receptiveness to dam reoperation.

Conclusion

Dam reoperation is complex because it can have an impact on water users, power production and society. Successful dam reoperations need to have an ongoing involvement of water managers, water planners, river operators and stakeholders (Richter *et al*. 2006). Many of the options for changing dam reoperations potentially have multiple benefits, and beneficiaries can provide strong support for change. Integrated assessment provides an opportunity for identifying multiple benefits of dam reoperation and will ensure that new strategies become a part of normal operations. The importance of interconnectedness of river basins and provision of public goods to society is particularly important (Molle 2009). Solutions for dam reoperations should be as broad as possible, beyond an individual dam, integrating the energy grid or other alternatives (e.g. floodplain restoration or alternative energy generation) within a catchment context.

Climate change could make environmental flows more important and more difficult to maintain (Hirji and Davis 2009*a*). Climate change will force governments and communities to choose components of ecosystems to be protected when water availability changes. Lessons learned during recent extreme events (e.g. floods and droughts) demonstrate that there can be complementary outcomes of water savings and environmental benefits from dam reoperation. Reoperation options allow water managers to 'bet hedge' and better manage future uncertainty and increased variability in river flows through more flexible infrastructure and management systems.

Dam reoperation is a climate-change adaptation measure, with benefits for the environment and society. Even with minimal change in rainfall and runoff, altering the operation of dams will maximise benefits for ecosystems and society. Multiple benefits of dam reoperation should be considered, assessed and implemented immediately.

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