Are large-scale flow experiments informing the science and management of freshwater ecosystems?

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Greater scientific knowledge, changing societal values, and legislative mandates have emphasized the importance of implementing large-scale flow experiments (FEs) downstream of dams. We provide the first global assessment of FEs to evaluate their success in advancing science and informing management decisions. Systematic review of 113 FEs across 20 countries revealed that clear articulation of experimental objectives, while not universally practiced, was crucial for achieving management outcomes and changing dam-operating policies. Furthermore, changes to dam operations were three times less likely when FEs were conducted primarily for scientific purposes. Despite the recognized importance of riverine flow regimes, four-fifths of FEs involved only discrete flow events. Over three-quarters of FEs documented both abiotic and biotic outcomes, but only one-third examined multiple responses, thus limiting how FE results can inform dam management. Future FEs will present new opportunities to advance scientifically credible water policies.

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Rivers provide numerous ecosystem services, including a source of water for domestic, industrial, and agricultural purposes; a means of power generation and waste disposal; routes for navigation; and sites for recreation and spiritual activities (Gleick 2003). Human regulation of river flows is now ubiquitous around the globe (Lehner *et al.* 2011), and further dam construction is viewed as a promising strategy to alleviate energy and water challenges associated with climate change and human population growth (Poff *et al.* 2003; Palmer *et al.* 2008; Finer and Jenkins 2012). Policy makers face mounting pressure to guarantee the future sustainability of water resources while simultaneously minimizing societal and environmental costs of their actions.

In a nutshell:

- We present the first global review of documented outcomes from large-scale flow experiments (FEs) to evaluate their success in advancing freshwater science and management
- The efficiency and value of FEs can be improved by targeting critical knowledge gaps (eg integrated long-term monitoring of biotic–abiotic responses and societal perceptions) and emerging opportunities (eg defining explicit management-based objectives)
- The geographical, sociopolitical, and ecological context in which future FEs are conducted must be diversified, and related efforts must not be limited to pursuing scientific discovery alone

Traditional dam management often dampens or eliminates natural streamflow variability over annual to decadal timescales (Haeuber and Michener 1998), shifting the timing of what seasonal variability remains and increasing daily flow variation when hydroelectric objectives are combined with water storage. However, the associated loss of natural streamflow regimes also degrades valuable ecosystem services and threatens freshwater biodiversity (Bunn and Arthington 2002; Richter *et al.* 2003; Naiman and Dudgeon 2011). Remediating the hydrologic effects of dams is often costly or difficult to implement, yet scientific knowledge, changing societal values, and federal mandates have required dam operations to be modified in an attempt to mitigate adverse environmental impacts on downstream ecosystems (Richter and Thomas 2007; Olden and Naiman 2010; Watts *et al.* 2011; Kiernan *et al.* 2012; Konrad *et al.* 2012). Scientists continue to support an experimental approach to evaluate and develop dam operations that create a more rational basis for water-management decisions and to advance broader scientific knowledge (Souchon *et al.* 2008; Konrad *et al.* 2011).

Large-scale flow experiments (FEs) have entered the mainstream of water-resource management over the past decade and the public profile of scientists and managers seeking ways to promote ecological sustainability using systematic adaptive management (Kingsford *et al.* 2011)

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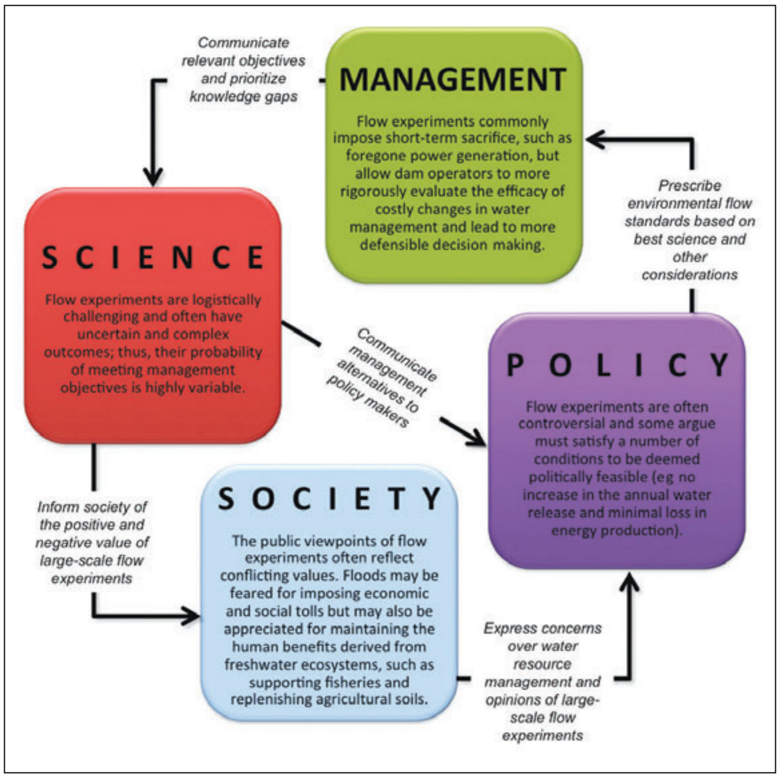

Figure 1. *Flow experiments (FEs) can often be contentious within the realms of science, management, policy, and society (boxes) but are tightly interconnected (arrows) and must work in concert to maximize their potential benefits.*

is much higher than ever before. Managing water resources for ecological outcomes is contentious (eg Cook 2013). Such actions are expensive and potentially forego other benefits; it is therefore reasonable to test and evaluate these management actions through FEs (Figure 1). For example, in the US, the four large controlled floods from Glen Canyon Dam to the Colorado River (between 1996–2012) and the deliberate spills at four Columbia River dams (McNary, John Day, Dalles, Bonneville) to allow fish passage (in 2005) were estimated to cost $12 million and $57–81 million in foregone or replaced power revenue, respectively. Similarly, multi-year flow releases from the San Joaquin River's Friant Dam to benefit Chinook salmon (*Oncorhynchus tshawytscha*) cost water users approximately $8 million annually in environmental fees, and the Low Summer Steady Flow experiment downstream of Glen Canyon Dam was estimated to result in approximately $25 million in replacement energy costs. In all of these cases, the measure of success depended on one's position, perspective, and interests (eg Schmidt *et al.* 1998; Bradford *et al.* 2011; Robinson 2012). Given their monetary costs and uncertain ecological (and economic) benefits, FEs warrant thorough evaluation individually and collectively to enhance broader scientific understanding that will increase their overall benefit to society (Acreman *et al.* 2000).

We present the first global review of documented outcomes from large-scale FEs to evaluate the performance of alternative dam operations on rivers, floodplains, and estuaries. Our objective is to initiate an evidence-based framework so that large-scale FEs may better inform future management efforts and policy decisions. To that end, we ask three fundamental questions:

(1) Why are large-scale FEs conducted and to what degree do they affect management objectives and practices?
(2) Are FEs advancing our scientific understanding and ability to inform future management and policy?
(3) What are the major challenges and emerging opportunities when considering future FEs to benefit water resource management?

Our assessment also highlights knowledge gaps and research needs relevant to advancing ecologically sustainable water management.

■ A systematic review of large-scale FEs

We systematically reviewed large-scale FEs worldwide. Conducting this review allowed us to test key hypotheses by following a strict protocol to maximize transparency and repeatability while minimizing bias (Pullin and Stewart 2006). Below we describe the review's components, including protocol formation and search strategy, data inclusion and extraction, and data analysis.

Protocol formation and search strategy

We broadly defined a large-scale FE as field observations and analysis used to test hypotheses about physical and biological responses to a deliberate manipulation of streamflow for ecological purposes (Konrad *et al.* 2011). Most FEs are performed over a defined period, with distinct streamflow characteristics (the treatment policy) and focused monitoring of abiotic and biotic responses. Generally, the experimental period encompasses a discrete event, such as a high-flow pulse (Wilcock *et al.* 1996), reduced or seasonally varied flow (Ralston 2011), reservoir drawdown (Moore *et al.* 2010), non-native fish suppression flows (Korman *et al.* 2012), or other specified flows, although experiments can span longer-term changes in dam operations that increase minimum flow (Bednarek and Hart 2005), reduce diurnal flow fluctuations (Patterson and Smokorowski 2011), or restore flow to bypassed reaches (Bradford *et al.* 2011). We used Thomson ISI's Web of Science, Science Direct, JSTOR, Digital Dissertations, and relevant gray literature sources (identified through Google Scholar) to generate a database of publications through 2011 that documented large-scale FEs. We used the search terms "flow", "experiment*", and "dam*", as well as the collective knowledge of the current authors who represented a broad range of scientific expertise in academia and water resource management from multiple geographic regions around the world.

Data inclusion and extraction

Our search screened references to include those consistent with our definition of an FE that examined ecological outcomes (Konrad *et al*. 2011); we recognize that investigations of natural flow events and investigations not intended for ecological outcomes can both provide useful information for managing water resources (eg McMullen and Lytle 2012), but they do not directly address how dam operations influence complex aquatic ecosystems. For each FE we recorded:

(1) Site attributes (eg dam height, dam release structure, reservoir area) and experiment attributes, including the primary motivation (eg recovery of threatened and endangered species, regulatory or statutory requirement, scientific knowledge).
(2) The type(s) of flow manipulation (eg high-flow pulse, minimum annual flow, seasonal variability).
(3) Type(s) of biotic responses (eg major taxonomic group) and abiotic responses (eg floodplain stage, sediment size, water temperature) assessed.
(4) Details of experimental design (eg frequency of flow treatments, type of experimental control, duration of post-FE monitoring).

In addition, we assessed management outcomes in two ways. First, we considered FEs to have a clearly articulated objective if the experiment was accompanied by an explicit statement of expectations and/or a set of hypotheses that included a measurable change – even if only qualitative (increase or decrease) – in a biophysical condition other than streamflow. We relied on documentation of outcomes and the authors' assessments of whether objectives were achieved rather than applying our own independent judgment. Second, we identified a management change resulting from an FE as either a revised dam operation (ie modified water release schedule) or continued experimentation (ie additional FEs). We allowed planned future actions to qualify as a management change, given the recent implementation of most FEs. However, recommendations for future releases did not qualify as management changes. Undocumented objectives, results, or management changes may have been present in some cases but are beyond the scope of this review. See WebPanel 1 for full details on the FE attributes.

Data analysis

We tallied counts and calculated frequency statistics (representing all reported percentages) to summarize the prevalence of a subset of experimental attributes to address our specific study objectives. Additionally, odds ratios were calculated by excluding the "uncertain" response category. In some instances, multiple categories were assigned to a FE (eg for the variables "motivation for FE", "biotic outcomes measured"); multiple assignments were treated as separate data points. We purposely focused the analysis on a subset of FE attributes, both individually and in combination. Additional data summaries are presented in WebTable 1.

■ Global patterns in large-scale FEs

Large-scale FEs have been used globally to evaluate the effects of alternative operations of water management facilities on rivers, lakes, floodplains, and estuaries (Figure 2). Our systematic literature review revealed 113 FEs, representing 102 dams and 98 river systems across 20 countries (see WebTable 2 for river systems and WebReferences for associated references). Generally, FE locations broadly correspond to global occurrence of large dams; several countries with numerous dams are also characterized by the largest number of FEs (Figure 2). For example, FEs are more common in the US (n = 56 locations), Australia (n = 15 locations), and South Africa (n = 4 locations) – countries representing the origins of many of the original flow protection methodologies and now considered leaders in progressive water policy (Arthington 2012). Exceptions to the geographic pattern include China, Japan, India, Norway, Spain, France, and Brazil, where, despite the presence of numerous large dams, there is relatively little published evidence for past FEs. Since the first documented FE in 1965 involving high pulse flows from Glen Canyon Dam, such operations have become more commonplace and have been predominantly implemented by facilities operated for power generation, water supply, and flood control (Figure 2).

The geographical, sociopolitical, and managerial context in which FEs are conducted must be diversified by focusing future efforts in data-deficient regions such as Southeast Asia, northern and western Europe, and South America. Because many of these underrepresented regions are also where the greatest numbers of large dams are planned or are currently being constructed (eg Finer and Jenkins 2012), the need for FEs is critical in helping to inform operation strategies and related policies. FEs have also involved relatively tall dams (mean height = 65 m, range = 5–216 m) as compared with the world's large dams (mean height = 46 m, range = 2–335 m; Lehner *et al*. 2011). This suggests that knowledge derived from past FEs is biased toward large dams, since > 90% of experiments were conducted below dams > 15 m in height; more than half of these are considered megadams, exceeding 50 m in height (WebFigure 1). This bias likely results from the greater perceived impact of large dams and the potential political incentives to undertake large-scale adaptive management initiatives. Large dams

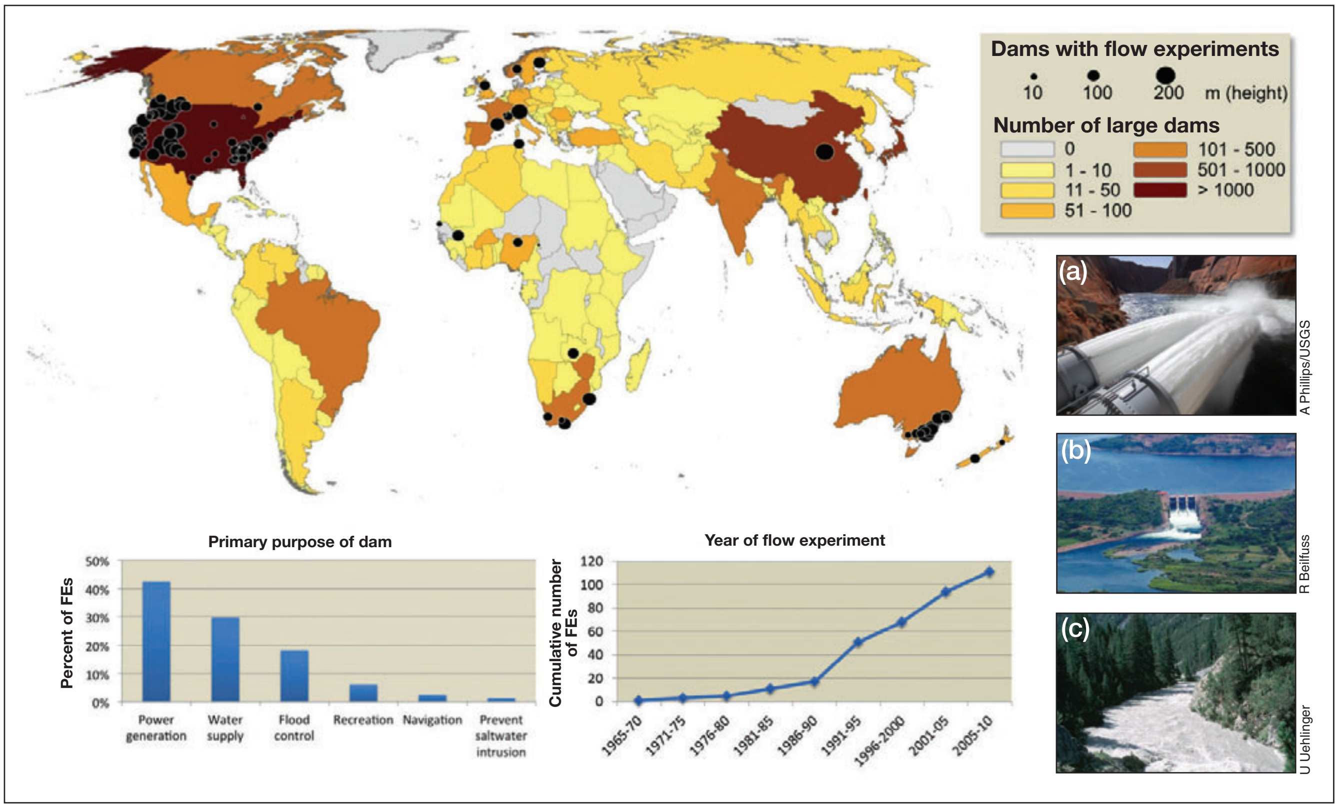

Figure 2. *Large-scale FEs (n = 113) have involved 102 dams globally to evaluate water management actions on river (83% of experiments), floodplain (10%), estuary (5%), and lake (2%) ecosystems. Country-level shading represents the number of large dams according to the Global Reservoir and Dam database (Lehner* et al. *2011). Inset charts display the primary purpose of the dam (lower left) and cumulative number of FEs over time, based on the first year of investigation (lower right). River systems and dams are listed in WebTable 1. Photographs depict the experimental floods from (a) Glen Canyon Dam, Colorado River; (b) Itezhi-tezhi Dam, Kafue River; and the (c) River Spöl downstream from the dam at Punt dal Gall.*

may also present better opportunities for conducting FEs because of greater reservoir storage capacity and greater control over releases when compared with those of small dams. The relevancy of FEs for mitigating the impacts of small dams is uncertain given that the ecological impacts of these structures are more related to habitat fragmentation than to hydrologic alteration.

■ Why are large-scale FEs conducted and were management objectives achieved and management practices changed?

Dam operations have been experimentally modified through FEs to promote a larger or more diverse set of potential ecological and social benefits from river systems than have typically been achieved by traditional operations (Panel 1). In many cases, these desired benefits are not simple, direct consequences of releasing water from a dam but are contingent on other factors. Thus, experimental approaches have been advocated as a way to inform dam operation to achieve ecological and social objectives fairly and efficiently, given constraints associated with available water, infrastructure, and applicable laws.

Large-scale FEs are multidisciplinary in their scientific foci and management objectives. The primary motivations for conducting such experiments include outcomes associated with natural resources (eg ecosystem of concern, protected area, subsistence resource), threatened and endangered species, regulatory or statutory requirements, and scientific understanding (Figure 3a). This suggests that iconic places and at-risk species (eg national parks, wildlife/fish) are important stimuli for initiating FEs. For example, Beervlei Dam (Groot River, South Africa) generally releases water at irregular intervals solely for irrigating agricultural lands, but an opportunity to conduct an FE arose when heavy rains filled its reservoir (Cambray 1991). The hypothesis underpinning this FE was whether flushing flows could decrease the salinity of pool habitats to initiate spawning of the globally endangered smallscale redfin minnow (*Pseudobarbus asper*). In another example, the federal designation of the endemic cui-ui sucker (*Chasmistes cujus*) as endangered prompted a flow restoration program on the heavily dammed Truckee River (US). Experimental releases of high spring flows were successful in promoting sucker reproduction and resulted in an unanticipated benefit of initiating extensive seedling recruitment of native Fremont cottonwood (*Populus fremontii*) and sandbar willow (*Salix exigua*) in the riparian floodplain (Rood *et al.* 2005).

Dam operation has benefited from FEs in terms of both learning and outcomes. When clear objectives were articulated prior to conducting FEs (ie objectives that included an explicit statement of expectations and/or hypotheses), experiments were twice as likely to achieve their stated objectives as compared to FEs without clearly articulated objectives (odds ratio = 2.2, confidence interval [CI] = 0.7–6.7; Figure 3b). This finding has implications for the many FEs that are rapidly designed and conducted in response to fortuitous heavy precipitation events or dam repair requirements. Objectives that consider longer term dam management issues are not always formulated for these opportunistic experiments, and measureable outcomes are often evaluated retrospectively. We therefore recommend that regional collaborative (web-based) networks be assembled to develop contingency plans that allow for managers and scientists to respond rapidly to FE opportunities.

Effective large-scale FEs were also found to depend on a broader context that includes water managers and stakeholders who can use the results in decision making. Dam management practices were three times as likely to be modified when the management objectives of FEs were considered "achieved" versus "not met" (odds ratio = 3.1, CI = 1.2–8.2; Figure 3c). Moreover, FEs intended solely for scientific purposes (ie excluding management outcomes) need only generate information to be considered "successful" but may have little impact on decision making. Indeed, FEs that failed to change dam management practices (and where management objectives were considered achieved) were approximately three times as likely to have involved experiments where scientific knowledge was the primary motivation (odds ratio = 2.8, CI = 0.8–10.6).

In summary, we found strong evidence that explicit articulation of management objectives during FE design, although not universally practiced in the past, is crucial for achieving favorable management outcomes and informing changes in dam management policies. Although meeting management objectives depends on diverse outcomes that cannot be achieved solely through single-event-based experiments, it is encouraging that past large-scale FEs are associated with identifiable changes in dam management practices. Clearly, such changes are rarely achieved when FEs are conducted solely to advance scientific knowledge without considering how that knowledge will inform dam operations, a trend shared broadly with adaptive management practices (Westgate *et al.* 2013).

■ Are large-scale FEs advancing our scientific understanding and ability to inform future management and policy?

Despite the widely reported importance of the flow regime (ie magnitude, frequency, seasonal timing, duration, and rate of change of flow) for river ecosystems (Poff *et al.* 1997; Bunn and Arthington 2002), large-scale FEs have only investigated the effects of a small range of discrete flow events. This is likely a consequence of the logistical and funding constraints to performing long-term environmental research (Konrad *et al.* 2011) and concerns from stakeholders with water use interests. To date, the majority of FEs tested the treatment effects of high pulse events and magnitude of minimum flows (56% of experiments), whereas experiments involving seasonal variability (9%) and flow regimes (8%) were much less

Panel 1. Ecological and societal benefits of large-scale flow experiments in freshwater ecosystems

Water managers use flow experiments (FEs) for specific ecological or social outcomes, and many have been successful in achieving their management objectives according to evaluations over both short- and long-term timescales. Examples of the ecological and societal benefits of FEs in freshwater ecosystems are provided below.

Improved water quality, restoration of physical habitats and native biodiversity

- Increased flows have been used to reduce salinity in the Campaspe River, Australia (State Government of Victoria 2010).
- Flushing flows released from Opuha Dam reduced filamentous green algae cover in the Opuha-Opihi River system, New Zealand (Arscott *et al.* 2007).
- High-flow pulses in the Bill Williams River, US, flushed beaver dams that were creating standing water conditions supporting non-native fishes and helped regenerate native willow/cottonwood trees on floodplains (Shafroth *et al.* 2010).
- Delivery of minimum flows below Rocklands Dam in the Glenelg River, Australia, sustained the taxonomic composition of the macroinvertebrate assemblage during drought (Lind *et al.* 2007).
- Large winter release from Sejnane Dam in the Ichkeul River, Tunisia, increased emergent wetland vegetation and nesting habitat for waterfowl (Smart 2004).

Increased economic value from natural resources

- Seasonal releases to inundate floodplain wetlands increased fisheries, agricultural, and livestock production in the River Senegal, Mauritania (Duvail and Hamerlynck 2003), and Logone River, Cameroon (Scholte *et al.* 2000).
- Flows targeting migration, spawning, and rearing life stages of Pacific salmon have increased survival and reproduction of populations in the Columbia River, US (Williams *et al.* 2005), and Gudbrandsdalslågen River, Norway (Kraabol *et al.* 2008).
- High-flow pulses following closure of Glen Canyon Dam scoured finer sediment from the tailwater of the Colorado River, US, transforming the former sand-bed channel to a gravel bed (Schmidt *et al.* 2001), improving habitat conditions that allowed establishment of a recreational trout fishery; later, re-operation of the dam to reduce hydro-peaking also allowed natural trout reproduction to occur, ending the need to stock the fishery (Korman *et al.* 2012)

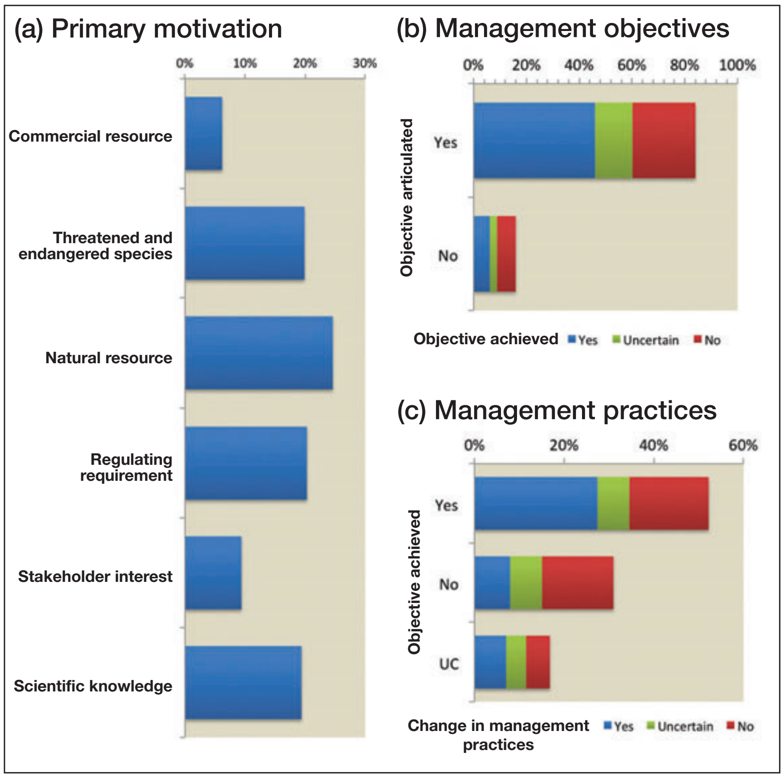

Figure 3. *The (a) primary motivation, (b) prevalence of management objectives being articulated and/or achieved, and (c) frequency of consequent changes in management practices vary among large-scale FEs. Descriptor details are in WebPanel 1.*

common (Figure 4a). The relative paucity of FEs involving flow variability conflicts with their overwhelming ecological importance (Naiman *et al.* 2008) and their role in emerging sustainable river management practices, laws, and regulations (Poff 2009; Richter *et al.* 2012). About 80% of investigated experiments focused only on discrete flow events, thereby limiting their potential to inform dam management and environmental flow policy. The time frames of FEs also vary considerably, ranging from tests of discrete flow events (eg King *et al.* 1998; Schmidt *et al.* 2001; Shafroth *et al.* 2010) to longer term monitoring policies (eg Bradford *et al.* 2011; Melis *et al.* 2012; Robinson 2012). Reconciling the knowledge gained from investigations of discrete manipulations with the need to inform longer term policies is critical for improving dam re-operation and environmental flow schemes.

Large-scale FEs have investigated a variety of abiotic outcomes (Figure 4b). Although quantifying multiple abiotic outcomes, which equally span conditions of water quality, hydrology, and geomorphology, most FEs examined only a single biological variable, with a dominant focus on freshwater fishes (Figure 4c). Perhaps this outcome is to be expected, given that simple operational rules still dominate water resource management (Jager and Smith 2008) and that these rules were typically developed at individual facilities under federal mandates (eg the US Endangered Species Act) or to promote recreational fisheries (Figure 3a). Moreover, outcomes measured in terms of socially valued resources (ie fish) are often the principal motivation for water managers to manipulate flows and may be the only acceptable justification of the costs and risks of such actions (Konrad *et al.* 2011). However, the fact that only one-third of experiments examined multiple taxonomic groups is troubling, given the shift from a simple "one size fits all" reservoir operations rule to a more flexible prescription of environmental flows to meet the needs of multiple ecosystem components (Poff 2009). Notably, very few FEs evaluated the responses of ecosystem processes (such as rates of metabolism, nutrient cycling, fluxes of nutrients and energy) or community trophic structure and food web dynamics, all of which can be strongly influenced by hydrologic variation (but see Watts *et al.* [2010] and Cross *et al.* [2011]). It is encouraging that almost 80% of FEs recorded both abiotic and biotic outcomes, thereby enhancing our understanding of the mechanisms of ecological responses to flow manipulation. But the potential for greater gains in knowledge necessitates improving FE efficiency and value. This is illustrated by the larger number of FEs resulting in changed dam management practices when both abiotic and biotic outcomes were quantified as compared to when only one response type was examined (odds ratio = 1.6, CI = 0.5–4.9).

Realizing the ecological and societal benefits of FEs requires dedicated long-term resources, including funding and personnel. Decreased monitoring and evaluation over time may appear fiscally responsible, but reduced surveillance may eventually impede the detection of longer term ecological responses and informed decision making and policy (Poff *et al.* 2003; Konrad *et al.* 2011). The variability of post-FE activity duration is striking. Short-term commitments, that involved repeated post-experiment sampling for less than a year were relatively common (72% of experiments), whereas longer term commitments, such as the establishment of monitoring programs for at least a year after the FE and the occurrence of additional flow experiments (subsequent to the focal FE), took place in only 60% and 32% of the instances, respectively (Figure 4d). Although evaluating FE success over short timescales is important (Richter *et al.* 2003), in many cases an experimental design may require years before any effects are demonstrated (Souchon *et al.* 2008); the time period is likely scaled to rates of physiochemical processes and to target species' life histories (Beechie *et al.* 2010). For instance, invertebrate community structure in the River Spöl (Switzerland) only shifted after years of repeated high-flow pulses (Robinson 2012). Similarly, multi-year monitoring was

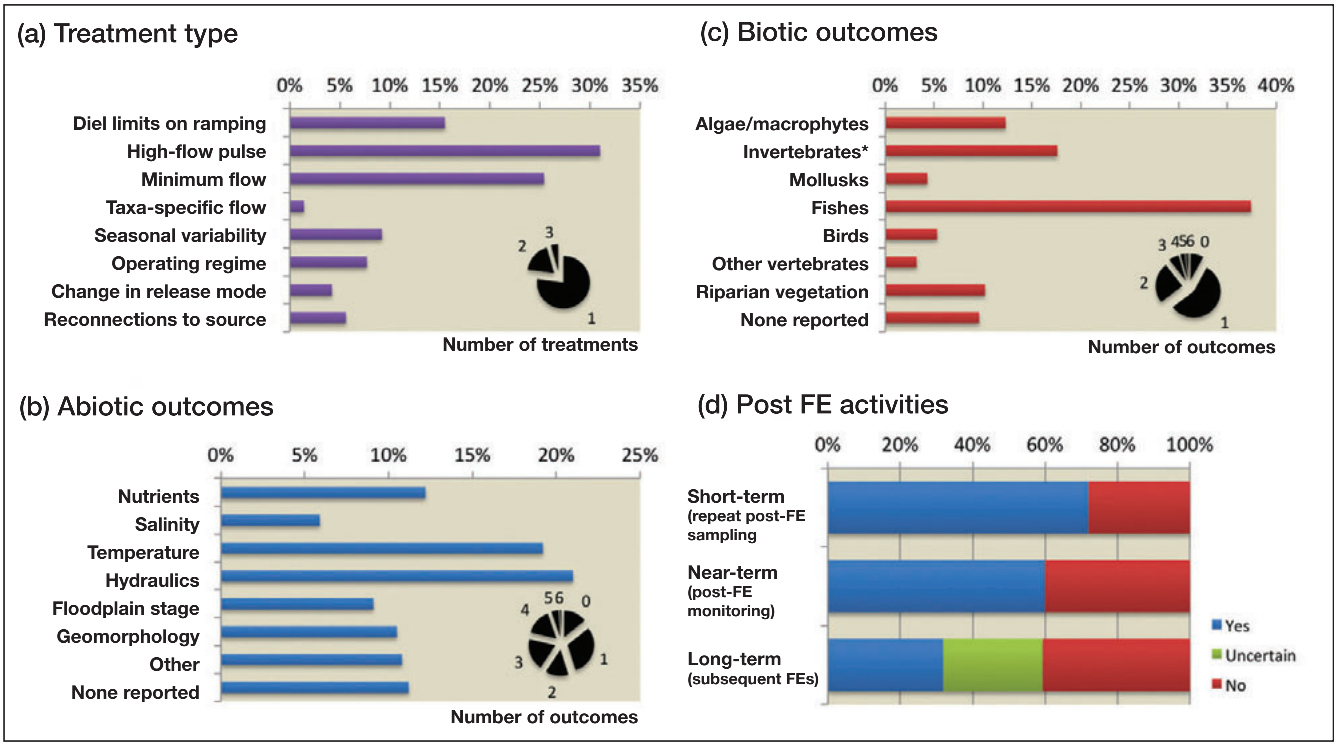

Figure 4. *(a) Large-scale FEs have involved a variety of treatments, evaluating a wide range of (b) abiotic and (c) biotic outcomes and including (d) post-FE activities operating over different timescales. Inset pie graphs report the relative proportion of experiments (wedge size) examining different numbers of treatments or outcomes. *Exclusive of mollusks. Descriptor details are in WebPanel 1.*

needed to reveal FE-induced changes in salmonid production in Bridge Creek (Canada) (Bradford *et al.* 2011), and Rood *et al.* (2005) described the sequence of flows over a period of years necessary to establish cottonwoods on the Truckee River (US). Interestingly, management objectives were more than four times as likely to be achieved when ongoing experimentation of flow regimes occurred (odds ratio = 4.4, CI = 1.7–11.0), demonstrating the critical need for continued investment in FEs in combination with regular assessment of monitoring data and modeling (King *et al.* 2010; Korman *et al.* 2012).

■ What are the major challenges and emerging opportunities for future FEs?

In an uncertain future, characterized by human population pressure and global climate change, dams will play an important role in meeting commitments such as the Millennium Development Goals to address energy and water poverty (Naiman and Dudgeon 2011; McDonald *et al.* 2012). Commitments to reduce greenhouse-gas emissions under the Kyoto Protocol provide new incentives for developing hydropower dams, whereas the mandatory relicensing of aging dams offers opportunities to renovate water-release structures and reassess operations (Pittock and Hartmann 2011). How then can dams be designed and operated so that the benefits outweigh the social and environmental costs? This cannot be answered simply through a planning process either before or after dam construction. Anticipating the full range of positive and negative consequences of dam building is complicated by substantial uncertainties about ecosystem responses. Furthermore, because societal values underlying these benefits and costs change over time, the question of trade-offs must be revisited periodically. Sustainable and equitable water resource development depends on effective adaptive management, with dams capable of releasing water in ways that mimic natural flow variability. The adoption of FEs is an integral part of informing desired release operations.

Large-scale experiments offer a practical approach to inform water policies and decisions, but they also require substantial commitment by scientists, managers, and stakeholders. Can we expect such experiments to be funded and implemented without critically evaluating ongoing and past projects? What evidence is there that FEs are providing relevant information? In an increasingly resource-limited society, how does the science of FEs remain credible and can it distinguish effective from ineffective management? In an effort to address these questions, our systematic review highlights challenges and opportunities for future FE implementation.

Practitioners of future FEs will be challenged to develop coordinated treatments and common response measures that enhance information transfer across multiple projects, while still recognizing the importance of case-specific context. Even with similar experimental designs, however, treatment strength, stressors other than flow, and the choice of ecological targets all influence the efficacy of flow manipulations to achieve specific outcomes.

For example, water temperature is often measured but rarely manipulated during large-scale FEs, despite the ecological importance of thermal regimes and the impact of dams on this parameter (Olden and Naiman 2010). The inability to simultaneously manipulate both flow and temperature during FEs has repeatedly been cited as an obstacle to achieving management goals (eg Bradford *et al.* 2011; Melis *et al.* 2012). FEs that quantify the effects of specific dam operations (eg flow versus temperature) will undoubtedly advance our mechanistic knowledge but may necessitate experiments at inconvenient times or the postponement of some management actions while others are evaluated. Furthermore, monitoring efforts should be accompanied by assessment of social responses to ecosystem change in order to identify stakeholder satisfaction with experimental outcomes. Stakeholders will value ecological outcomes in the form of goods and services they wish to sustain or improve, so their reactions to altered provision of ecosystem goods and services will provide another indicator of success (Arthington 2012).

Obtaining funding and institutional support for large-scale FEs will be crucial (Poff *et al.* 2003), yet the economic value of implementing dam operational changes to promote key ecosystem goods and services has rarely been considered. Although it is premature to expect that the economic benefits of experimental releases will completely justify their costs, FEs could facilitate documentation and valuation of ecological outcomes that support important ecosystem goods and services (Wilson and Carpenter 1999). Deriving such estimates will be challenging but not impossible, given the continued difficulty of placing monetary values on ecosystem services (Daily *et al.* 2009). With increasing market value of environmentally sound electricity production in some regions, we also expect to see potential intangible benefits associated with enhancing the environmental image of dam operators who embrace FEs. For example, the Engadin Hydroelectric Power Company recently certified its production in the River Spöl – a system that has experienced numerous FEs since 2000 (Robinson 2012) – as environmentally sound through the Swiss label "naturemade basic". In summary, FEs that provide information on economic benefits would enhance their relevancy to stakeholders (Poff *et al.* 2003) and could inform the operations of experimental releases (Duvail and Hamerlynck 2003).

Large-scale FEs provide unparalleled opportunities for interdisciplinary investigation of the full range of ecosystem goods and services impacted by reservoir management and for informing scientifically-based operating strategies that serve both ecological sustainability and social equity. Such knowledge will become increasingly important as reservoir management strategies, typically guided by only a few principal objectives, are re-examined to achieve multiple ecological and societal outcomes. Unfortunately, our findings suggest that past large-scale FEs have rarely capitalized on these opportunities. Moreover, although the number of FEs has increased in recent decades, the publication of findings in the peer-reviewed literature remains limited, and until now there was no open-access data archive of key metrics and results from these experiments to inform an evidence-based framework for future efforts (the complete FE database is available at http://dx.doi.org/10.6084/m9.figshare.761221).

In conclusion, we argue for enhancing collaboration between scientists, managers, and policy makers involved in FEs to support sustainable freshwater management. There is a clear need to diversify the geographical, sociopolitical and ecological context in which future FEs are conducted, and such efforts must not be limited to pursuing scientific discovery at the cost of managerial and policy relevance (Keith *et al.* 2011). Scientists should strive to develop FEs in the spirit of adaptive management that inform river management and advance scientific knowledge (Konrad *et al.* 2011) and refrain from using policy demands to pursue discovery goals not relevant to decision making. At the same time, managers and policy makers must embrace both the scientific uncertainty and surprise learning opportunities that inevitably arise from these experiments, and not purposely ignore uncertainty to avoid complicating their message to stakeholders, only to later invoke this issue when FEs fail to deliver expected ecological or social outcomes. By working together to embrace new thinking and effectively utilize the wealth of knowledge garnered from past experiments, we envision that future FEs will represent a critical part of strategic adaptive management efforts seeking to credibly guide water policies and decisions across the globe.

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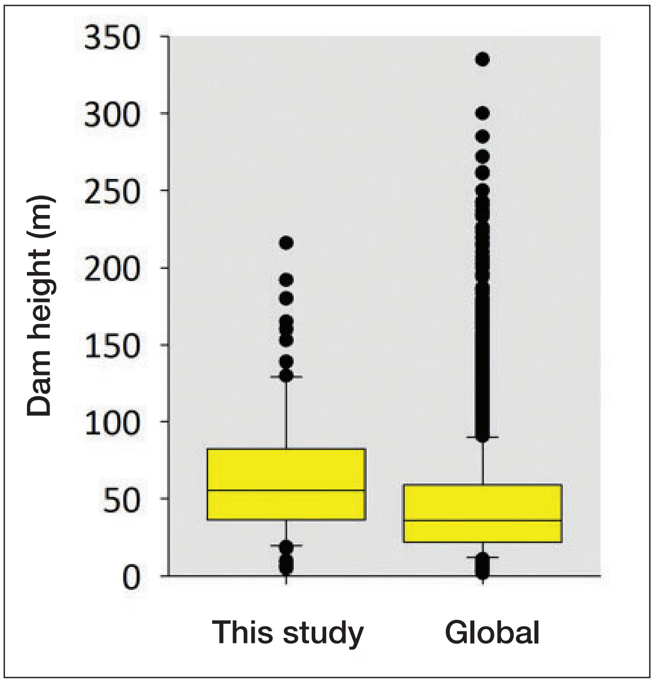

WebFigure 1. *Comparison of dam heights associated with large-scale flow experiments ("This study") versus the global database of large dams ("Global") based on Lehner* et al. *(2011).*

■ WebReference

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WebPanel 1. Attributes derived from the systematic review of 113 large-scale flow experiments

Study-site description

River system: name of river where large-scale flow experiment was conducted
Dam/facility: name of dam/facility releasing the experimental flow
System type: river; lake; floodplain; estuary

Flow treatment

Year(s) of investigation: year(s) that flow was manipulated or year(s) that flow was manipulated plus year(s) that responses were measured
Primary motivation: commercial resource; threatened and endangered species; natural resource (ecosystem of concern, national park, subsistence resource); regulatory or statutory requirement; stakeholder interest; scientific understanding
Treatment type: within-day limits on ramping rates/range; high-flow pulse; minimum flow; operating regime integrating multiple flow components; reconnection of system to sources of flow; seasonally variable flow; taxa-specific flow; change in withdrawal; mode of release rather than change in discharge (spill, multi-level withdrawal)
Treatment frequency: one trial; repeat trials; step change
Other treatments/actions applied simultaneously or during the response period: re-aeration; invasive species removal; temperature control; sediment augmentation/removal; geomorphic/structural manipulation in-channel or floodplain; hatchery, translocation, reintroduction; other flow; no other reported
Type of experimental control: pre-treatment data; modeled; paired system; upstream; none
Multiple sampling sites with variable treatment strength (longitudinal sampling) reported: yes; no

Measured responses

Abiotic responses: floodplain stage, extent of inundation, hydroperiod; geomorphology including channel form, sediment size, sediment transport; hydraulics (in-channel velocity, depth); nutrients; salinity; temperature; other; none reported
Biological responses: algae or other aquatic vegetation; birds; fish; insects and other non-mollusk aquatic invertebrates; mollusks; riparian vegetation; other vertebrates; none reported
Type of response (time scale): individual behavior (migration, passage); population abundance/recruitment/reproduction; assemblage composition/structure; food webs/trophic structure/production/nutrient spiraling; none reported
Repeat post-treatment sampling/measurement for less than a year: yes; no
Monitoring more than a year after treatment reported: yes; no
Ongoing experiments: yes; no; uncertain

Management outcomes

Management objectives clearly articulated: a clearly articulated objective with a clear statement of expectations and/or a set of hypotheses that included a measurable change, even if only qualitative (increase or decrease), in a biophysical condition other than streamflow. Yes; no; uncertain
Management objectives achieved: yes; no; uncertain
Management change in response to results: a management change resulting from an experiment as either a revised dam operation (ie modified water release schedule) or continued experimentation (ie additional FEs). We conservatively accepted planned future actions to qualify as a management change. Yes; no; uncertain

Notes: Full database is available at: http://dx.doi.org/10.6084/m9.figshare.761221.

WebTable 1. Data summaries of attributes of large-scale flow experiments

Category
- ***Attribute* (proportion of FEs)**

Study-site description
- *System type:*
  - River (0.83)
  - Lake (0.02)
  - Floodplain (0.10)
  - Estuary (0.05)

Flow treatment
- *Primary motivation:*
  - Commercial resource (0.06)
  - Threatened and endangered species (0.20)
  - Natural resource (0.25)
  - Regulatory or statutory requirement (0.20)
  - Stakeholder interest (0.09)
  - Scientific understanding (0.20)
- *Treatment type:*
  - Within-day limits on ramping rates/range (0.16)
  - High-flow pulse (0.31)
  - Minimum flow (0.25)
  - Operating regime integrating multiple flow components (0.08)
  - Reconnection of system to sources of flow (0.06)
  - Seasonally variable flow (0.09)
  - Taxa-specific flow (0.01)
  - Change in withdrawal (0.01)
  - Mode of release rather than change in discharge (0.03)
- *Treatment frequency:*
  - One trial (0.27)
  - Repeat trials (0.39)
  - Step change (0.34)
- *Other treatments/actions applied simultaneously or during the response period:*
  - Dissolved oxygen – re-aeration (0.14)
  - Invasive species removal (0.02)
  - Temperature control (0.06)
  - Sediment augmentation/removal (0.03)
  - Geomorphic/structural manipulation in-channel or floodplain (0.06)
  - Hatchery, translocation, reintroduction (0.05)
  - Other flow (0.01)
  - No other reported (0.63)
- *Type of experimental control:*
  - Pre-treatment data (0.60)
  - Modeled (0.14)
  - Paired system (0.07)
  - Upstream (0.08)
  - None (0.11)
- *Multiple sampling sites with variable treatment strength (longitudinal sampling) reported:*
  - Yes (0.68)
  - No (0.32)

continued

WebTable 1. – *continued*

Measured responses

- *Abiotic responses:*
    - Floodplain stage, extent of inundation, hydroperiod (0.09)
    - Geomorphology including channel form, sediment size, sediment transport (0.11)
    - Hydraulics (0.21)
    - Nutrients (0.12)
    - Salinity (0.06)
    - Temperature (0.19)
    - Other (0.11)
    - None reported (0.11)
- *Biological responses:*
    - Algae or other aquatic vegetation (0.12)
    - Birds (0.05)
    - Fishes (0.38)
    - Insects and other non-mollusk aquatic invertebrates (0.18)
    - Mollusks (0.04)
    - Riparian vegetation (0.10)
    - Other vertebrates (0.03)
    - None reported (0.10)
- *Type of response (timescale):*
    - Individual behavior (0.14)
    - Population abundance/recruitment/reproduction (0.40)
    - Assemblage composition/structure (0.29)
    - Food webs/trophic structure/production/nutrient spiraling (0.06)
    - None reported (0.11)
- *Repeat post-treatment sampling/measurement:*
    - Yes (0.72)
    - No (0.28)
- *Monitoring more than a year after treatment reported:*
    - Yes (0.60)
    - No (0.40)
- *Ongoing experiments:*
    - Yes (0.32)
    - No (0.41)
    - Uncertain (0.27)

Management outcomes

- *Management objectives clearly articulated:*
    - Yes (0.84)
    - No (0.16)
- *Management objectives achieved:*
    - Yes (0.52)
    - No (0.31)
    - Uncertain (0.17)
- *Management change in response to results:*
    - Yes (0.43)
    - No (0.39)
    - Uncertain (0.18)

Notes: Full database is available at: http://dx.doi.org/10.6084/m9.figshare.761221.

WebTable 2. List of 98 river systems and 102 dams/facilities from the systematic review where large-scale flow experiments have been evaluated

River name	*Facility name*	*Country*
American	Chili Bar Dam	US
Aude	St Georges Dam	France
Bafing	Manantali Dam	Mali
Big Cypress	Ferrells Bridge Dam	US
Bill Williams	Alamo Dam	US
Bregenzer Ach	Andelsbuch/Langenegg Dam	Austria
Bridge	Terzaghi Dam	Canada
Broken	Nillahcootie Dam	Australia
Campaspe	Eppalock Dam	Australia
Cheoah	Santeetlah Dam	US
Clackamas	Oak Grove Power Plant	US
Clear	Whiskeytown Dam	US
Clearwater	Dworshak Dam	US
Clinch	Norris Dam	US
Colorado	Glen Canyon Dam	US
Columbia	John Day Dam	US
	The Dalles Dam	US
	Bonneville Dam	US
Coosa	Jordan Dam	US
Cotter	Cotter Dam	Australia
Eau d'Olle	Verney Dam	France
Elk	Tims Ford Dam	US
French Broad	Douglas Dam	US
Glenelg	Rocklands Dam	Australia
Green (Kentucky)	Green River Lake Dam	US
Green (Wyoming)	Flaming Gorge Dam	US
Groot	Beervlei Dam	South Africa
Gudbrandsdalslågen	Hunderfossen Power Plant	Norway
Gunnison	Blue Mesa/Morrow Point/Crystal dams (Aspinall Unit)	US
Hadejia	Tiga and Challawa Gorge dams	Nigeria
Hiwassee	Chatuge Dam	US
Holston	Cherokee Dam	US
	South Holston Dam	US
Hunter	Glenbawn Dam	Australia
Ichkeul	Sejnane Dam	Tunisia
Jackson	Gathright Dam	US
JArperudsAlven	Lake Stor-Treen	Sweden
Kafue	Itezhi-tezhi Dam	Zambia
Kissimmee	S-65	US
Kootenai	Libby Dam	US
Kromme (Krom)	Mpofu (Impofu) Dam	South Africa
Lignon-du-Forez	Rory/St Martin Dam	France
Logone	Maga Dam	Cameroon
Macquarie	Burrendong Dam	Australia
Magpie	Steephill Falls Dam	Canada
Marias	Tiber Dam	US
Missouri	Gavins Point Dam	US
Mitta Mitta	Dartmouth Dam	Australia
Mokelumne	Camanche Dam	US
Mowamba	Mowamba River Aqueduct	Australia
Murray	Hume Dam	Australia
Murrumbidgee	Burrinjuck Dam	Australia
Narran	Multiple facilities	Australia
Neste d' Aure	Beyrede Dam	France
Nottely	Nottely Dam	US
Nueces	Wesley Seale Dam	US
Oconee	Sinclair Dam	US
Oconto	Oconto Falls Dam	US
Oldman	Oldman Dam	Canada
Olewiger Bach	Mill Race Dam	Germany
Olifants	Clanwilliam Dam	South Africa
Opuha Opihi	Opuha Dam	New Zealand

continued

WebTable 2. – *continued*

River name	*Facility name*	*Country*
Ouachita	Remmel Dam	US
Owens	Long Valley Dam	US
Paterson	Lostock Dam	Australia
Pecos	Fort Sumner Dam	US
Pongolo	Pongolapoort Dam	South Africa
Provo	Jordanelle Dam	US
Puerto Viejo	Dona Juila Hydroelectric Center - RPB	Costa Rica
Rapid	Middle Dam	US
Rhone	Pierre-Benite Dam	France
Rio Grande	Cochiti Dam	US
Roanoke	Kerr/Gaston/Roanoke Rapids Dams	US
Roizonne	Pont-Haut Dam	France
Rufus	Lake Victoria water storage	Australia
San Joaquin	Friant Dam	US
San Juan	Navajo Dam	US
Santa Ynez	Bradbury Dam	US
Santee	Wilson Dam/Lake Moultrie re-diversion canal	US
Savannah	Thurmond Dam	US
Senegal	Diama Dam	Mauritania
Shoshone	Buffalo Bill Dam	US
Silver	Camino Dam	US
Skagit	Ross/Diablo/Gorge dams	US
Snake	Ice Harbor Dam	US
Snowy	Jindabyne Dam	Australia
Spöl	Punt dal Gall Dam	Switzerland
St Lucie	Gordy Road bridge and Lake Okeechobee	US
St Mary	St Mary Dam	Canada
Strawberry	Soldier Creek Dam	US
Susquehanna	Conowingo Dam	US
Tallapoosa	Harris Dam	US
	Thurlow Dam	US
Toccoa	Blue Ridge Dam	US
Tongariro	Rangipo Dam	New Zealand
Trinity	Trinity/Lewiston dams	US
Truckee	Derby Dam	US
Tyne	Kielder Dam	UK
Ume	Stornorrfors Powerhouse/Norrfors Dam	Sweden
Willamette	Dexter/Lookout Point/Hill Creek dams	US
Wimmera	Multiple facilities	Australia
Yellow	Xiaolangdi Dam	China

Notes: Full database is available at: http://dx.doi.org/10.6084/m9.figshare.761221.

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