RIVER RESEARCH AND APPLICATIONS

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RECONCILING HYDROPOWER AND ENVIRONMENTAL WATER USES IN THE LEISHUI RIVER BASIN

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ABSTRACT

Today's water systems require integrated water resource management to improve the water supply for conflicting water uses. This research explores alternative policies to improve the water supply for two conflicting uses, hydropower and environmental, using the Leishui River basin and Dongjiang reservoir as a case study. First, the natural flow regime prior to reservoir construction (pre-1992) was estimated by performing a statistical analysis of 41 years of daily streamflow data (March 1952–February 1993). This natural flow regime was used as a template for proposing environmental flow (e-flow) requirements. The post-reservoir flow regime (post-1992) (March 1993–February 2011) was analysed to estimate the streamflow alteration. Results show that the natural flow regime has been completely transformed; post-1992 winter normal flows are greater, and summer flows are smaller than pre-1992 conditions. Also, the occurrence of natural floods has been prevented. Second, a planning model was built of the current operation of the Dongjiang reservoir and used for comparison of four alternative water management policies that considered e-flow releases from the Dongjiang reservoir. The scenarios that considered combinations of the current operational policy and e-flow releases performed better in terms of hydropower generation than the current operation. Different volumes of e-flow requirements were tested, and an annual e-flow volume of 75% of the pre-1992 hydrograph was determined to generate the most hydropower while providing for environmental water needs. Trade-offs are essential to balance these two water management objectives, and compromises have to be made for both water uses to obtain benefits. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: environmental flows; hydropower; Dongjiang reservoir; integrated water resource management

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INTRODUCTION

Water is an essential resource for all life on the planet. The sustainable development of water resources is fundamental in promoting social and economic welfare while balancing the exploitation of natural resources, now and in the future. Because water is not distributed in the right quantity with the adequate quality in time and space for desired socioeconomic activities, water resource management is used to redistribute it to satisfy these water demands while maintaining the ecological and hydrologic integrity of a basin. Water resource management aims to optimize a basin's natural water availability to satisfy these competing demands.

To solve the problem of water resources in the long run, the concept of integrated water resource management (IWRM) was developed, defined as 'a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems' (GWP, 2000). IWRM plays a key role in implementing policies towards sustainable development; however, this process is very difficult to consolidate given the complexity of coordinating different institutions, interests and regulations, and future challenges remain in reducing the gap between theoretically agreed upon policies and implementation. Water resource sustainability depends on the effective implementation of IWRM, leading to long-term social, economic and environmental benefits (Matsuura, 2009)

A river is not only channel flow but also a set of structures, processes and interactions that can provide services to social and economic activities (Postel and Richter, 2003). Rivers provide water supply, irrigation, hydropower, recreation and food for humans, and their beauty improves the quality of life for people visiting their banks and rafting their waters. Adequate streamflow regimes protect water quality, filter and decompose pollutants, and help maintain soil fertility (Thompson *et al.*, 2012). Connected floodplains attenuate the magnitude of floods and reduce the severity of their damage (Sandoval-Solis and McKinney, 2012). Rivers interact with aquifers, storing water in the ground that can be used during drought periods (Sandoval-Solis *et al.*, 2011). Rivers reaching the coast attenuate saline intrusion in

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aquifers while providing nutrients, sediments and adequate water quality for estuarine fisheries (Kam *et al*., 2012). In summary, rivers are complex systems that can provide valuable services for society.

Riverine ecosystems depend on a variety of streamflow regimes, chemical and transportation processes, and the interaction of different geomorphic and biological components. Rivers host many plant and animal species whose variety and interactions keep the ecosystem healthy and functioning. The streamflow regime of a river transports sediments and nutrients at a certain rate to promote habitat and food abundance for native species. The interannual variability of the streamflow regime eradicates non-native species through extreme hydrologic events, such as floods and droughts. Human activities and infrastructure have altered these vital functions, degrading and in some cases destroying aquatic and riparian ecosystems.

A few examples of actions that have altered river functions required to maintain healthy ecosystems are reduction of streamflow as a result of human diversion of water (Sandoval-Solis and McKinney, 2012), disconnection of floodplains as a result of construction of levees for flood protection (Mount, 1995), and degradation of water quality as a result of disposal of untreated wastewater in rivers and lakes (IBWC, 2008). Among the most damaging alterations for the environment are dams. Dams alter the streamflow regime of rivers (Postel and Richter, 2003, Sandoval-Solis *et al*., 2010), change water temperature (Clarkson and Childs, 2000; Todd *et al*., 2005; Thompson *et al*., 2012), alter nutrient and sediment transport capacity (Williams and Wolman, 1984; Vorosmarty *et al*., 2003, Dean and Schmidt, 2011), disconnect habitat along the river (Postel and Richter, 2003, Thompson *et al*., 2012), modify upstream and downstream water quality (Ahearn *et al*., 2005), influence floodplain vegetation communities (Shafroth *et al*., 2001, Tockner and Stanford, 2002, Magilligan *et al*., 2003) and alter downstream estuaries, deltas, and coastal zones by modifying salinity, nutrient and sediment transport (Olsen *et al*., 2006, Richter and Thomas, 2007). Dams reduce the ecosystem services that a healthy river can provide (WCD, 2000; Postel and Richter, 2003; WWF, 2004; MEA, 2005), often with vast implications for the downstream river ecosystems (Collier *et al*., 1996; McCully, 1996; Willis and Griggs, 2003). Restoring the flow regimes of rivers by modifying dam operations is fundamental to recover these environmental services.

Objectives

The main objective of this study is to compare existing water management policies for hydropower with the benefits provided by an IWRM policy that considers hydropower and environmental flows (e-flows). The Dongjiang reservoir, located in the Leishui River in China, is used here as a case study. The specific objectives of this research are as follows:

(1) develop an annual e-flow hydrograph using the natural flow paradigm technique of Poff *et al*. (1997) and specifically the Indicators of Hydrologic Alteration platform,
(2) construct a simulation and planning model that represents the regional water resource system of the Leishui River basin using the C++ platform,
(3) estimate the benefits of the water management policies by testing different scenarios with the planning model: an *only hydropower* scenario, which depicts business-as-usual, and four *e-flow* scenarios, which consider the IWRM of the Dongjiang reservoir for hydropower and environmental water management,
(4) compare the benefits of alternative (e-flow oriented) policy scenarios.

The natural flow paradigm method is used to create initial e-flow estimates for the Leishui River with the assumption that the natural flow regime contained an arrangement of flow characteristics that provided functions to sustain healthy riparian and aquatic native ecosystems. Poff *et al*. (1997) and Baron *et al*. (2002) have shown that healthy river ecosystems require a natural range of variation in flow, which has been considered as an objective by several studies (Shiau and Wu, 2004; Homa *et al*., 2005). This research does not aim to prescribe e-flows; rather, the e-flows proposed here for the Dongjiang reservoir are intended to be a template to establish a more detailed e-flow policy for the Leishui River in the future. Thus, the scope of this paper is to present a framework for evaluating the benefits and disadvantages of e-flows for integrated hydropower and environmental water management.

METHODOLOGY

Leishui water system

The Leishui River, originating in the Shimen mountains of China, is the largest tributary of the Xiangjiang River, which, in turn, is a tributary of the Yangtze River (Figure 1). The river is 439 km long, with a drainage area of 11 783 km^2, an average precipitation of 1645 mm year^{-1} and an average annual discharge of 3598×10^6 m^3. Dongjiang reservoir, located in the upper Leishui basin, is a multipurpose reservoir that was built for hydropower generation, flood control and navigation with a drainage area of 4719 km^2 (40% of the total drainage area). The total storage capacity, active and dead storage are 9470×10^6 m^3, 5250×10^6 m^3 and 2870×10^6 m^3, respectively. The average annual inflow volume (1952–2010) to the reservoir is

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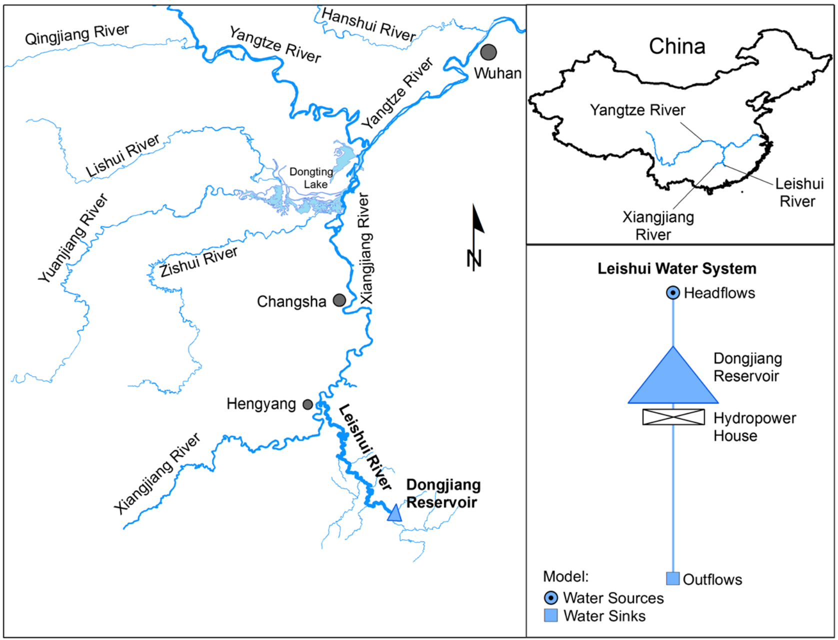

Figure 1. Leishui River system. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

3.67 km^3. Donjiang reservoir is a multiyear regulating reservoir that can store 1.4 times the average annual inflow volume. The installed capacity of the hydropower station is 500 MW, with a guaranteed turbine output of 105 MW and an average annual energy output of 1.23 billion kWh.

ENVIRONMENTAL FLOWS

Several methodologies have been developed to provide an estimation of the adequate water quantity, quality and timing required to sustain a healthy ecosystem: (i) statistical methods, such as the Tennant method (Tennant, 1976) or natural streamflow paradigm (Richter *et al.*, 1996), that analyse streamflow data to determine flow characteristics desired to prescribe e-flow recommendations; (ii) hydrogeomorphic methods, such as the near-census river assessment and rehabilitation method, that evaluate the flows and geomorphology required to provide suitable habitat for aquatic species (Pasternack, 2011); (iii) instream habitat methods, such as the Instream Flow Incremental method (Bovee, 1978), that relate different flows to habitat impacts using predetermined preferences of specific fish species; and (iv) expert-based methods, such as the building block method (Tharme and King, 1998) or the benchmark method (Brizga *et al.*, 2002), where multidisciplinary experts converge on desired environmental objectives or acceptable degrees of human intervention to prescribe restoration or conservation e-flow. Regardless of method, in the end, the initial set of e-flows should be adapted based on its capacity to meet specified environmental objectives.

One of the methods proposed to recover the environmental services provided by rivers is the natural flow paradigm (Poff *et al.*, 1997). This method considers the natural flow regime as a good template for recovering key environmental services and improving the ecological integrity of the river. The natural flow regime of a river can be integrated by six key streamflow components: variability, magnitude, frequency, duration, timing and rate of change. These components are recognized as central to sustaining biodiversity and ecosystem integrity (Poff and Ward, 1989; Richter *et al.*, 1997; Rosenberg *et al.*, 2000). Regional and/or country-specific discussions of this method have occurred for rivers throughout the world (Davies *et al.*, 1993; Contreras and Lozano, 1994; Dynesius and Nilsson, 1994; Kingsford, 2000; Pringle *et al.*, 2000; Tharme, 2003; Sandoval-Solis and McKinney, 2012).

Based on the construction of the Dongjiang reservoir in 1992, two sets of daily data were analysed: the *pre-reservoir alteration* flow regime (pre-1992), from March 1952 to February 1993, and the *post-reservoir alteration* flow regime (post-1992), from March 1993 to February 2011. The water year is defined from March to February because the rainfall season starts in March and the lowest rainfall months are January and February. The Indicators of Hydrologic Alteration platform was used to identify natural flow benchmarks in the pre-1992 period that were analysed in this study.

Determining e-flow benchmarks

Three categories were considered to determine the natural flow regime: (i) base flows; (ii) high flow pulses (hereafter called *pulses*); and (iii) floods (Postel and Richter, 2003). For each category, magnitude, frequency, duration, timing and rate of flow change were estimated. The pre-1992 period was used to determine thresholds within each category. *Base flows* were divided into two categories, *normal* and *drought flows*. *Normal flows* provide adequate habitat and water quality for aquatic species, drinking water for terrestrial species and maintain the water table height for riparian vegetation; they were estimated as the median value of the mean daily flows for each month. *Drought flows* provide sufficient water for native species to survive and purge non-native species from the ecosystem. These flows were estimated as flows below the 10th percentile of the pre-1992 daily streamflow distribution ($<29.6\,\mathrm{m^3\,s^{-1}}$). *Pulses* shape the geomorphology of the river, prevent riparian vegetation from encroaching into the channel, and restore normal water quality conditions after prolonged low flows. They were estimated as flows with peaks between the 75th percentile ($143\,\mathrm{m^3\,s^{-1}}$) and the 2-year return period (T) ($1320\,\mathrm{m^3\,s^{-1}}$). *Floods* connect the river longitudinally, from the upper regions to the outlet. They also connect the river with its floodplains, providing nursery areas for juvenile fish, recharging the water table, maintaining diverse riparian vegetation, depositing nutrients, and purging invasive species. Floods were divided into two categories, *small* and *large* floods. *Small floods* are defined as peak flows with a return period of 2 ($T=2$) ($1320\,\mathrm{m^3\,s^{-1}}$) to 10 years ($T=10$) ($2192\,\mathrm{m^3\,s^{-1}}$). *Large floods* are peak flows with a return period of greater than 10 years ($T>10$) ($>2192\,\mathrm{m^3\,s^{-1}}$).

A post-processing analysis was required to determine the typical hydrograph of pulses, small floods and large floods. For pulses, each pulse event was tagged and grouped for each month. Within each month, pulses were arranged and centred around their peak; the typical pulse hydrograph for each month is composed of the median values for each day. The pulse duration (in days) was determined as the period with flows greater than the *normal flow* for that particular month. The same procedure was applied for small floods and large floods and for pre-alteration and post-alteration periods.

Flow regime results

Pre-reservoir flow regime (pre-1992). The pre-1992 hydrograph depicting the natural flow regime is shown in Figure 2 and Table I. Prior to 1992, normal flows varied from $38\,\mathrm{m^3\,s^{-1}}$ in December to $209\,\mathrm{m^3\,s^{-1}}$ in May. From the pre-1992 hydrographs, a total of 16 pulses ($T=1$ and $2<T<3$) were identified. On average, pulses with $T=1$ occurred once per month between February and September and twice in April. Pulses with a return period of 2–3 years ($2<T<3$) occurred mainly in the months January, March, May, June, October, November and December. Small floods ($5<T<10$) typically occurred in May (peak flow $=1730\,\mathrm{m^3\,s^{-1}}$), June (peak flow $=1625\,\mathrm{m^3\,s^{-1}}$), July (peak flow $=1930\,\mathrm{m^3\,s^{-1}}$) and August (peak flow $=1400\,\mathrm{m^3\,s^{-1}}$), and large floods ($T=20$) occurred in April (peak flow $=2605\,\mathrm{m^3\,s^{-1}}$) and June (peak flow $=2740\,\mathrm{m^3\,s^{-1}}$). Figure 2 shows the total average flow volume ($3593\times10^6\,\mathrm{m^3}$) of the pre-1992 annual hydrograph, which was estimated as the sum of the volume of each benchmark component times its frequency ($\text{Frequency}=1\,T^{-1}$). The estimated volumes of normal flows, pulses and floods shown in Figure 2 are $2976\times10^6\,\mathrm{m^3}$, $393\times10^6\,\mathrm{m^3}$ and $224\times10^6\,\mathrm{m^3}$, respectively.

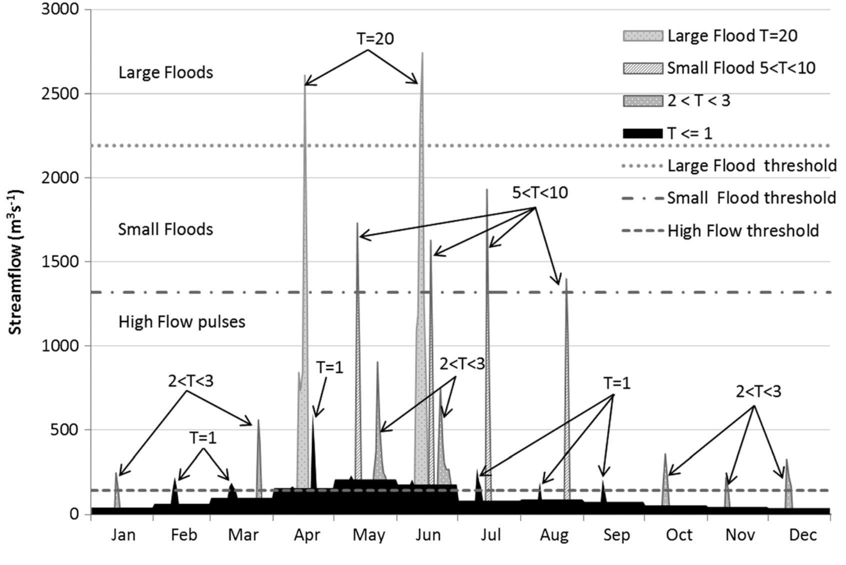

Figure 2. Natural flow regime in the Dongjiang section of Leishui River.

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Table I. Characteristics of the flow regime pre-1992 and post-1992

	Value	Unit	January	February	March	April	May	June	July	August	September	October	November	December
Pre-1992														
Drought flows	Median	$m^3 s^{-1}$	21.0	21.0	20.0	31.0	20.0	14.0	18.0	20.0	21.0	24.0	24.0	21.0
Normal flow	Median	$m^3 s^{-1}$	41.0	64.0	100.0	157.0	209.0	179.0	83.0	89.0	75.0	55.0	44.0	38.0
Pulses	Peak	$m^3 s^{-1}$	246.0	223.0	189.0	168.0	232.0	207.0	275.0	192.0	2100.	361.0	220.0	328.0
	Duration	Days	2.0	3.0	4.0	1.0	1.0	1.0	3.0	1.0	2.0	3.0	2.0	3.0
	T	years	2.4	1.2	0.8	0.8	0.7	0.7	0.9	0.6	0.7	2.0	2.3	3.4
Pulses	Peak	$m^3 s^{-1}$			560.0	603.0	903.0	750.0						
	Duration	days			2.0	2.0	7.0	7.0						
	T	years			2.4	1.2	1.8	2.2						
Small floods	Peak	$m^3 s^{-1}$					1730.0	1625.0	1930.0	1400.0				
	Duration	days					2.0	2.0	2.0	2.0				
	T*	years					13.7	5.1	10.3	10.3				
Large floods	Peak	$m^3 s^{-1}$				2605.0		2740.0						
	Duration	days				5.0		6.0						
	T*	years				20.5		20.5						
Post-1992														
Drought flows	Median	$m^3 s^{-1}$	64.0	77.0	52.0	42.0	44.0	44.0	45.0	56.0	45.0	43.0	48.0	52.0
Normal flow	Median	$m^3 s^{-1}$	191.0	180.0	135.0	98.0	77.0	75.0	152.0	164.0	101.0	99.0	108.0	141.0
Pulses	Peak	$m^3 s^{-1}$	223.0	211.0	204.0	192.0	211.0	226.0	268.0	252.0	195.0	170.0	201.0	210.0
	Duration	days	1.0	1.0	3.0	1.0	3.0	1.0	3.0	3.0	1.0	1.0	4.0	3.0
	T*	years	0.5	0.5	0.5	0.8	0.7	0.8	0.6	0.5	0.4	0.6	0.9	0.5
	Peak	$m^3 s^{-1}$	223.0	211.0	204.0		211.0		268.0	252.0	195.0	170.0		210.0
Pulses	Duration	days	1.0	1.0	3.0		3.0		3.0	3.0	1.0	1.0		3.0
	T*	years	0.5	0.5	0.5		0.7		0.6	0.5	0.4	0.6		0.5

*T denotes the *return period* of a certain flow.

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Post-reservoir flow regime (post-1992). Figure 3 and Table I show the typical post-1992 hydrograph. Normal flows varied from 75 $m^3 s^{-1}$ in June to 191 $m^3 s^{-1}$ in January. From Figure 3, two flow patterns can be distinguished for the post-reservoir flow benchmark: (i) December through March flows to generate electricity to support the power grid of Hunan province and (ii) July to August flows to generate electricity for air conditioning during the summer season. The post-1992 hydrograph showed on average a total of 21 pulses every year, almost two every month, except for April, June and November. There is also a clear absence of floods under the current reservoir operation. The total volume of the 1-year return period hydrograph is $4248 \times 10^6 m^3$. $3991 \times 10^6 m^3$ is provided by normal flows, and $257 \times 10^6 m^3$ is provided by pulses. The volume of the post-1992 hydrograph ($4248 \times 10^6 m^3$) is larger than the pre-1992 volume ($3593 \times 10^6 m^3$). This is attributed to wetter conditions in the post-1992 period (1993–2010) (average annual flow = $4476 \times 10^6 m^3$), than the pre-1992 period (1952–1992) (average annual flow = $3213 \times 10^6 m^3$).

The Dongjiang reservoir effectively captures flows occurring at all return periods, eliminating the interannual variability of flows. Floods and pulses have been converted into normal flows (median flow = 107 $m^3 s^{-1}$) by the reservoir, leading to an increase in the magnitude and timing of the normal flows compared to pre-1992. Pulses are more frequent year round.

Summary of results on flow regime alteration

The following flow alterations have been observed based on the comparison of the pre-1992 and post-1992 hydrographs:

- Normal flows have been altered in magnitude and timing. Post-1992 normal flows increased by $1263 \times 10^6 m^3$ or 39.0% compared to the pre-1992 annual quantity, and their seasonality has been reversed.
- Similarly, pulses have been altered in magnitude, timing and frequency. In the pre-1992 flow regime, pulses had a seasonal occurrence from February to September, with a frequency of one pulse per month and peak magnitudes around 240 $m^3 s^{-1}$. Pulses in the post-1992 flow regime occur year round, with an average frequency of two pulses per month and almost identical peak magnitudes around 210 $m^3 s^{-1}$.
- Small floods with return periods of 5–10 years were part of the pre-1992 flow regime and no longer occur under post-1992 conditions.
- Large floods with a return period of 20 years (T = 20) that occurred in either April or June under pre-1992 conditions are not present in the post-1992 flow regime.
- The annual variability of flows has been eliminated and modified; there is no flow variation from year to year. The lack of annual variability will prevent the river to purge non-native species.

WATER MANAGEMENT POLICIES AND SCENARIOS

The main role of the Dongjiang reservoir is to generate electricity for Hunan province. During the winter months (January through March), it increases hydropower inputs to the electricity grid when needed to ensure normal power supply. As a consequence of this operation, the runoff downstream of the Dongjiang reservoir has experienced

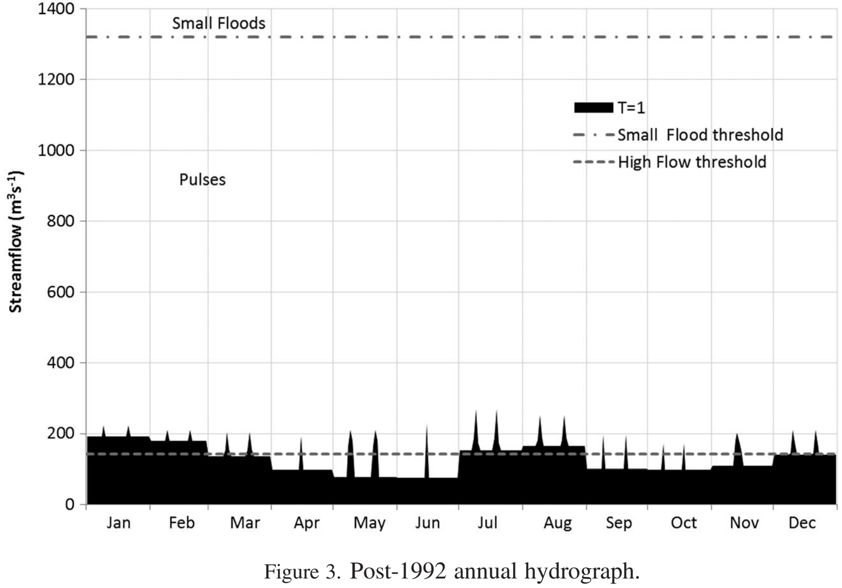

Figure 3. Post-1992 annual hydrograph.

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significant changes, including smaller summer flows and larger winter flows than normal flows under pre-1992 conditions. In order to assess the benefits of alternative policy scenarios and reservoir operation schemes, the following *baseline* and *e-flow* scenarios were considered.

Scenarios

Baseline scenario: only hydropower. The following procedure explains the rules used to operate the Dongjiang reservoir under the *only hydropower* scenario. Current reservoir release decisions are made by the reservoir's general managers and are mainly based on the rule curve (Figure 4 and Equation (1)) and empirical knowledge. First, reservoir operators determine which pool the reservoir is in (A, B, C, D or E), depending on the reservoir water level (Z_t) and the time of year. Then, water for hydropower (P_t) is released depending on the state of the storage pool as follows:

$$Q_t^T = \begin{cases} Q\left(N_f\right) & Z_t \in A \\ Q\left(1.2N_f\right) & Z_t \in B \\ Q\left(N_{exp}\right) & Z_t \in C \\ Q\left(0.8N_f\right) & Z_t \in D \\ Q\left(0.6N_f\right) & Z_t \in E \\ Q_{min} & Z_t \in Z_d \end{cases} \qquad (1)$$

where Q_t^T is the release of water for hydropower generation ($\mathrm{m^3\,s^{-1}}$); N_f is the guaranteed hydropower generation (105 MW); $Q(N_f)$ is the release required to produce the guaranteed hydropower, ($\mathrm{m^3\,s^{-1}}$); Z_t is the water level at the beginning of the time step t; $Q(N_{exp})$ is the release required for maximum hydropower generation ($\mathrm{m^3\,s^{-1}}$); Q_{min} is the minimum release required to maintain the reservoir level above the dead storage elevation (Z_d) at the end of time step t; *A*, *B*, *C*, *D*, and *E* are the storage pools that correspond to the operation rule curve of the Dongjiang reservoir.

The generated hydropower is calculated using the following equation:

$$P_t = KQ_t^T H \qquad (2)$$

where H is the net head of the hydropower (m) and K is the output coefficient (K = 8.5), a value derived from records provided by the Dongjiang hydropower operation authority.

Environmental flow scenarios. In this study, four e-flow scenarios are evaluated to investigate alternative water management policies for operating the Dongjiang reservoir. As shown in Table II, for each scenario, two parameters were altered: (i) the total volume of e-flows released and (ii) the operational policy of the Dongjiang reservoir. Two e-flow volumes were considered, the pre-1992 hydrograph with benchmarks of the following: (i) one year (T = 1) return period or (ii) one year (T = 1) and two to three year (2 < T < 3) return period. In addition, two policies for the Dongjiang reservoir were considered: (i) operation to only meet e-flow requirements or (ii) operation to meet both hydropower and e-flow requirements, while considering that the minimum reservoir release must be the maximum of the following: (i) the normal flows of the pre-1992 hydrograph and (ii) the reservoir release based on the operational rule curve.

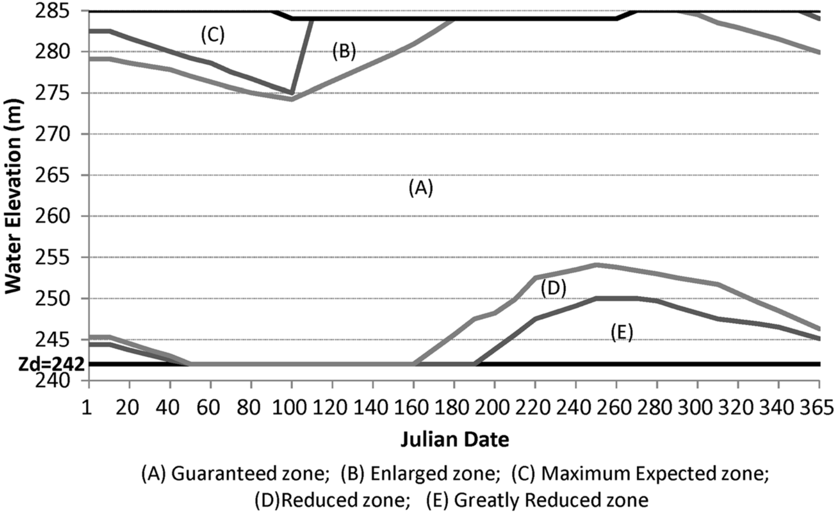

Figure 4. Operation rule curve of the Dongjiang reservoir.

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Table II. Scenarios for e-flow evaluation

	Benchmarks		Hydrograph volume	Reservoir operation	
Scenario	(T = 1)	(2 < T < 3)	(1×10^6 m^3 year^{-1})	Only e-flows	e-flows + rule curve
I	X		2976		X
II	X		2976	X	
III	X	X	3369		X
IV	X	X	3369	X	

T denotes the *return period* of a certain flow.
X denotes the type of environmental flow benchmarks and reservoir operation policy adopted for each Scenario.

Dongjiang reservoir planning model

A reservoir simulation model was built to represent the current water allocation of the Dongjiang reservoir and to evaluate the benefits of environmental water management policies. This model was constructed as a collaborative project between faculty from Wuhan University (WU) and University of California at Davis (UCD). The data (hydrologic, infrastructure and operation) and modelling platform were provided by WU while the flow regime analysis and alternative water management scenarios were recommended by UCD. The simulation model is a water planning model that calculates the balance between inflows, change of storage and evaporation in the reservoir, hydropower releases and outflows. The C++ platform was used to build the model. The period of analysis was 18 years (March 1993 to February 2011) using a daily time step. This time period was selected because there were sufficient reservoir operation data available, and it allowed for the comparison of scenarios under recent hydrologic conditions. The model was calibrated by adjusting the output coefficient parameter *K* (Equation (2)) to match the hydropower generated based on records provided by the hydropower authority. For all scenarios, an initial storage level of 270 m was used. Modelled and observed streamflow data were compared for March 1999 to February 2003, during which the operation of the Dongjiang reservoir closely followed the operational rule curve and was not very affected by the empirical operation of the managers. The per cent bias (PBIAS), index of agreement (IA), coefficient of efficiency (CE) and root mean square error–observations standard deviation ratio (RSR) for the streamflow data were satisfactory when model results were compared with historic records (Legates and McCabe, 1999; Moriasi *et al.*, 2007); PBIAS = −0.20 (desired values tend to approach 0), IA = 0.80 (desired values tend to approach 1), CE = 0.51 (desired values tend to approach 1) and RSR = 0.68 (desired values tend to approach 0). While the performance of the model is satisfactory, there are limitations to its use given that the model only accounts for the rule curve operation of the reservoir and not for the subjective operation by the reservoir managers who often base operational decisions on empirical knowledge.

Comparison of water management scenarios

Baseline and environmental flow scenarios. The baseline and four e-flows scenarios were compared using the following performance criteria: average annual hydropower generation,

Table III. Results of the comparison of the baseline (only hydropower) and the four e-flow reservoir operation scenarios

	Hydropower		Water***		
	Generation*	Reliability**	Through turbine	Spilled	Released
	(10^6 kWh year^{-1})	(%)	(1×10^6 m^3 year^{-1})	(1×10^6 m^3 year^{-1})	(1×10^6 m^3 year^{-1})
Baseline	1421	100	4356	78	4434
Scenario I	1448	100	4771	11	4482
Scenario II	1304	50	3856	657	4513
Scenario III	1421	100	4600	108	4708
Scenario IV	1317	48	3966	641	4607

*Hydropower generation (*HP*) was calculated: $HP = \sum_{y=1}^{y=Y}\left(\sum_{t=1}^{t=T}(KQ_tH \times 24)\right)/Y$; where *t* is the day of the year, *T* is the number of days in a year, *Y* are the total number of years; *K*, Q_t and *H* are explained in Equation (2).

**Reliability (*Rel*) was calculated: $Rel = [(\#\text{ of times } D_t = 0)/(Y \cdot T)] \times 100$; where D_t is the difference ($D_t = N_F - P_t$) between the guaranteed hydropower generation ($N_F = 105$ MW) and the hydropower generated (P_t) estimated through Equation (2).

***The average water through turbine (Q^T), spilled (Q^S) and released (Q^R) was calculated: $Q^i = \sum_{y=1}^{y=Y}\left(\sum_{t=1}^{t=T} Q_t^i\right)/Y$, for $i \in T, S$, or R.

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Table IV. Evaluation of Scenario III for different sets of e-flow hydrographs

		Percentage of hydrograph volume						
Criteria	Units	100%	90%	80%	75%	70%	60%	50%
Hydropower generation*	10^6 kWh year^{-1}	1421	1434	1448	1449	1446	1438	1433
Water spilled**	$1 \times 10^6\,\text{m}^3$	2139	2024	1740	1904	2230	2961	3460

*Hydropower generation (*HP*) was calculated: $HP = \sum_{y=1}^{y=Y}\left(\sum_{t=1}^{t=T}(KQ_tH \times 24)\right)/Y$; where t is the day of the year, T is the number of days in a year, Y are the total number of years; K, Q_t and H are explained in Equation (2).

**The total water spilled (Q^S) was calculated as follows: $Q^S = \sum_{y=1}^{y=Y}\left(\sum_{t=1}^{t=T}Q_t^S\right)$; where Q_t^S is the water spilled at a determined day t.

hydropower reliability, water released for hydropower and water spilled. Hydropower reliability refers to the frequency of time (expressed as a percentage) that the energy demanded is fully generated. Results for the scenarios are presented in Table III.

The results show that the hydropower generation under e-flow Scenario I and III were most similar to the baseline scenario, demonstrating that the combination of rule curve plus e-flow releases can meet the required hydropower generation while simultaneously addressing environmental needs by mimicking the natural flow regime. Scenarios II and IV (only e-flow) produced average annual power generation similar to baseline, 92% and 93% of baseline, respectively. However, both only met the hydropower generation target around 50% of the time. These results illustrate the inherent trade-offs in designing policies for both hydropower and environmental water management. Scenarios I and III demonstrated a good balance between these two conflicting uses. However, Scenario III is preferred because it generated the same hydropower as the baseline scenario while managing the system for e-flow benchmarks of $T < 3$.

Balancing hydropower and environmental water requirements. This section presents an analysis to identify water management policies that can provide the most benefits for hydropower and the environment. A set of hydrographs based on the pre-1992 natural flow hydrograph (Figure 5) are evaluated to identify which one provides the most hydropower generation. For this analysis, Scenario III (e-flows + rule curve) is used exclusively because it demonstrated adequate performance in terms of hydropower generation and e-flow provisions. Two variations of the pre-1992 natural flow regime hydrograph (Figure 5) were used in this analysis: (i) benchmarks with $T = 1$ ($2976 \times 10^6\,\text{m}^3\,\text{year}^{-1}$) or (ii) benchmarks with $T = 1$ and $2 < T < 3$ ($3369 \times 10^6\,\text{m}^3\,\text{year}^{-1}$). The authors propose that the system can be managed for hydropower and e-flows based on these flow benchmarks because flow regimes with larger return periods are expected to be naturally provided when large inflows occur into the reservoir and are released downstream for flood control and dam safety. The set of hydrographs evaluated in this section are proportional in shape and volume to the pre-1992 hydrograph (Figure 5). Essentially, normal flows shown in Figure 5 are scaled down to obtain annual

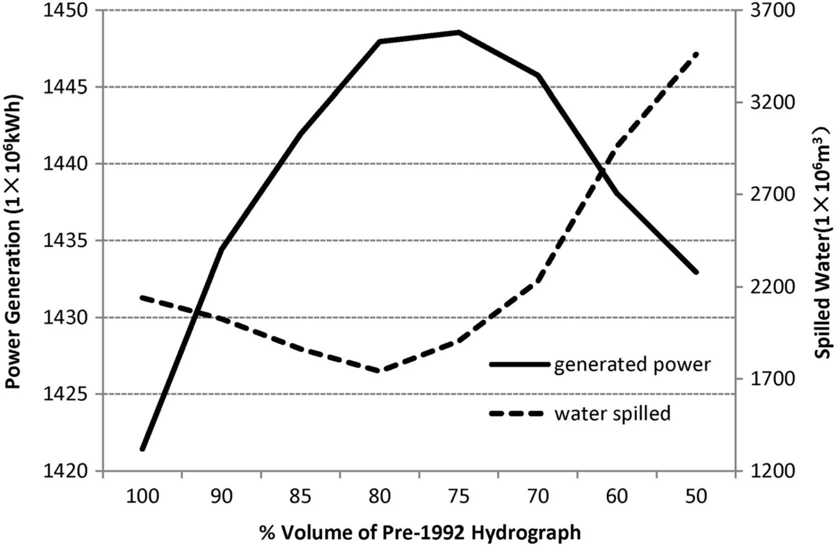

Figure 5. The relationship between power generation and the water spilled.

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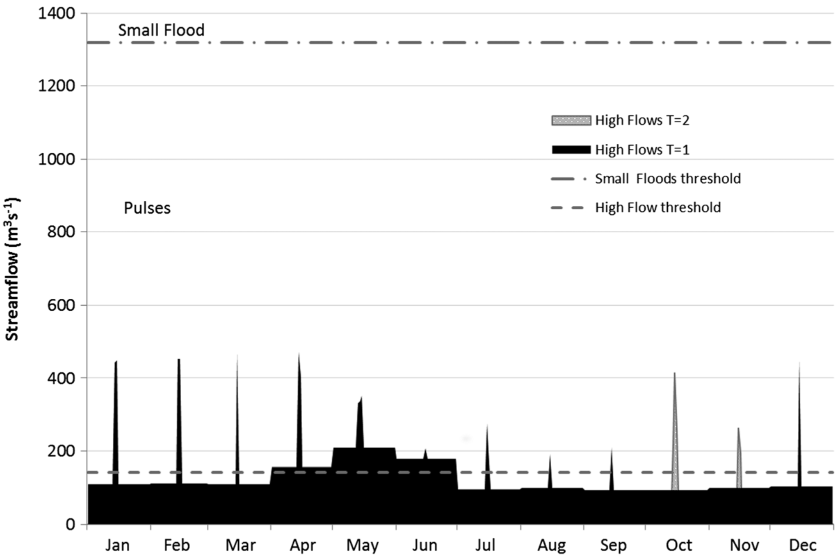

Figure 6. Annual hydrograph obtained of the combination of Scenario III and 75% of the pre-1992 hydrograph.

hydrographs of a certain percentage (e.g. 70%, 80% or 90%) of the pre-1992 hydrograph volume while maintaining the pre-1992 flow variation (i.e. pulses and flood characteristics).

Results of Scenario III and a set of scaled pre-1992 hydrographs are presented in Table IV. They show that a flow regime that releases 75% of the pre-1992 annual hydrograph volume can generate the most hydropower (1459×10^6 kWh year^{-1} or 102% compared to baseline) while at the same time meeting environmental requirements. In other words, a policy that combines the release for hydropower generation using the rule curve and that tries to meet a 75% volume of the pre-1992 natural flow regime of $T < 3$ (rule curve + 75% e-flow) is the management alternative that generates the most hydropower at 100% reliability. The least water is spilled under the 80% e-flow ratio; however, the 75% e-flow ratio spills the second least, meaning most of the water can be used for hydropower generation.

The annual hydrograph below the Dongjiang reservoir based on Scenario III (rule curve + 75% e-flow) is shown in Figure 6. This hydrograph resembles more closely the normal flows and pulses of the pre-1992 flow regime hydrograph (Figure 2) than the regulated post-1992 flow regime (Figure 3). From July to February, normal flows in Figure 6 are larger than pre-1992 conditions. This is because of the altered rule curve policy that tries to meet hydropower requirements during these months. Conversely, from March to June, normal flows in Figure 6 are larger than post-1992 normal flows in order to meet e-flow targets. These results indicate that both compromises and trade-offs can be made to balance hydropower and environmental needs. Further improvements in this policy are needed to provide pulses in May and June.

DISCUSSION

There is no simple answer or single policy when trying to reconcile reservoir operations for hydropower and environmental purposes. Trade-offs are essential to balancing these two water management objectives, and compromises have to be made for both water uses to obtain benefits. For hydropower, it must be recognized that an integrative environmental water management policy has the potential to provide environmental benefits while continuing to generate hydropower. Environmental advocates, on the other hand, need to understand that it is not economically feasible to operate the reservoir only for environmental purposes and that advocating for a scaled-down version of the natural flow regime may help incentivize hydropower users to include the environment in reservoir operations. Even if Scenario III (rule curve + 75% e-flow) is implemented, large base flows will occur in the Leishui River from July to February with potential consequences for riverine ecosystems because such large base flows were not part of the natural flow regime. Solving this problem will require physical interventions, such as the construction of artificial pools or floodplains in certain parts of the river, called sanctuaries, to recreate conditions more similar to those found under the natural flow regime. Again, balancing hydropower and environmental objectives will require managerial changes in the operation of the Dongjiang reservoir and physical changes along the river corridor to return to more natural flow conditions.

CONCLUSIONS

This research demonstrates that it is possible to integrate hydropower and environmental requirements into an IWRM

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policy, but compromises must be made. Timing for both water uses is conflicting; the policy proposed here provides the water required by both uses at all times. In some cases, water requirements for hydropower were larger than for the environment (from July to February), wherein the system was operated to meet hydropower needs. Conversely, when the environmental requirements were larger than hydropower requirements (March to June), the Dongjiang reservoir was operated to meet environmental needs. The proposed policy provides greater benefits to hydropower because it surpasses environmental base flow requirements from July to February. In order to meet the desired environmental conditions, a physical intervention must be made in the river, such as the construction of artificial pools, to provide adequate river conditions to sustain riparian and aquatic ecosystems.

This research also shows that there is no single policy that can fully meet all water use needs. Modern water resource management must integrate a mosaic of actions that balance the benefits and drawbacks that a policy causes to competing water uses. In our case, the mosaic of policies to meet competing hydropower and environmental water uses is integrated by the following: (i) a reservoir re-operation policy; (ii) an e-flow hydrograph of 75% of the natural flow regime volume; and (ii) a physical intervention in the river.

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REFERENCES

Ahearn DS, Sheibley RW, Dahlgren RA. 2005. Effects of river regulation on water quality in the lower Mokelumne River, California. *Journal of River Research and Applications* **21**: 651–670.

Baron JS, Poff NL, Angermeier PL, Dahm CN, Gleick PH, Hairston NG, Jackson RB, Johnston CA, Richter BD, Steinman AD. 2002. Meeting ecological and societal needs for freshwater. *Ecological Applications* **12**: 1247–1260.

Bovee, KD. 1978. The incremental methods of assessing habitat potential for coolwater species, with management implications. In *Selected coolwater fishes of North America*. Kendall RL (ed.), Am. Fish. Soc. Spec., Publication No. 11; 340–346.

Brizga SO, Arthington AH, Pusey BJ, Kennard MJ, Msckay SJ, Werren GL, Craigie NM, Choy SJ. 2002. Benchmarking, a 'Top-Down' methodology for assessing environmental flows for rivers, Proc., *International Conference on Environmental*

Clarkson RW, Childs MR. 2000. Temperature effects of hypolimnial-release damson early life stages of Colorado River basin big-river fishes. *Copeia* **2000**: 402–412.

Collier M, Webb RH, Schmidt RH. 1996. Dams and rivers: primer on the downstream effects of dams. U.S. Geological Survey Circular 1126, Denver, Colorado, USA.

Contreras BS, Lozano VML. 1994. Water, endangered fishes, and development perspectives in arid lands of Mexico. *Conservation Biology* **8**: 379–387.

Davies BR, O'Keeffe JH, Snaddon CD. 1993. A synthesis of the ecological functioning, conservation and management of south African river systems. Water research commission report No. TT62/93. *Water Research Commission*: Pretoria, South Africa.

Dean DJ, Schmidt JC. 2011. The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region. *Geomorphology* **126**: 333–349.

Dynesius M, Nilsson C. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. *Science* **266**: 753–762.

GWP - Global Water Partnership. 2000. Water as a social and economic good: how to put the principle into practice. Stockholm, Sweden. TAC Background Papers No. 2.

Homa ES, Vogel RM, Smith MP, Apse CD, Huber-Lee A, Seiber J. 2005. An optimization approach for balancing human and ecological flow needs. In *EWRI 2005 World Water and Environmental Resources Congress*. ASCE: Anchorage, Alaska.

IBWC - International Boundary and Water Commission. 2008. *Regional Assessment of Water Quality in the Rio Grande Basin*. Texas Cleans Rivers Program: El Paso, Texas.

Kam SP, Badjeck MC, Teh L, Teh L, Tran N. 2012. Autonomous adaptation to climate change by shrimp and catfish farmers in Vietnam's Mekong River delta. *Working paper* 2012–24. World fish.

Kingsford RT. 2000. Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25**: 109–127.

Legates DR, McCabe GJ. 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research Journal* **35**(1): 233–241.

Magilligan FJ, Nislow KH, Graber BE. 2003. Scale-independent assessment of discharge reduction and riparian disconnectivity following flow regulation by dams. *Geology* **31**:569–572.

Matsuura K. 2009. Forward to IWRM Guidelines at River Basin Level-Part 1: Principles. http://www.hydrology.nl/images/docs/ihp/IWRM_Guidelines/IWRM_Part_1_Principles.pdf

McCully P. 1996. *Silenced rivers: the ecology and politics of large dams*. Zed Books: London, UK.

MEA - Millennium Ecosystem Assessment. 2005. *Ecosystem services and human well-being: wetlands and water synthesis*. World Resources Institute: Washington, D.C., USA.

Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL. 2007. Model Evaluation guidelines for systematic quantification of Accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers* **50**(3): 885–900.

Mount JF. 1995. *California rivers and streams. The conflict between fluvial process and land use*. University of California Press: Berkeley, California, USA.

Olsen SB, Padma TV, Richter BD. 2006. A guide to managing freshwater inflows to estuaries. University of Rhode Island, Coastal Resource Center, Providence, Rhode Island, USA.

Pasternack GB. 2011. *2D modeling and ecohydraulic analysis*. Createspace: Seattle, WA.

Poff NL, Ward JV. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of stream-flow patterns. *Canadian Journal of Fisheries and Aquatic Sciences* **46**: 1805–1818.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. *BioScience* **47**: 769–784.

Postel S, Richter B. 2003. *Rivers for Life: Managing Water for People and Nature*. Island Press: Washington, D.C.

Pringle CM, Freeman MC, Freeman BJ. 2000. Regional effects of hydrologic alterations on riverine macrobiota in the New World: tropical-temperate comparisons. *BioScience* **50**(9): 807–823.

Richter BD, Thomas GA. 2007. Restoring environmental flows by modifying dam operations. *Ecology and Society* **12**(1): 12. http://www.ecologyandsociety.org/vol12/iss1/art12/

Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A method for assessing hydrological alteration within ecosystems. *Journal of Conservation Biology* **10**(4): 1163–1174.

Richter BD, Baumgartner JV, Wigington R, Braun DP. 1997. How much water does a river need? *Freshwater Biology* **37**: 231–249.

Rosenberg DM, McCully P, Pringle CM. 2000. Global-scale environmental effects of hydrological alterations: introduction. *BioScience* **50**(9): 746–751.

Sandoval-Solis S, McKinney DC. 2012. Integrated Water Management for Environmental Flows in the Rio Grande. *Water Resources Planning and Management* doi:10.1061/(ASCE)WR.1943-5452.0000331 (Nov. 8, 2012)

Sandoval-Solis S, Reith B, McKinney DC. 2010. Hydrologic analysis before and after reservoir alteration at the Big Bend reach, Rio Grande/Rio Bravo. CRWR Online Report 10–06. University of Texas at Austin <http://www.crwr.utexas.edu/reports/2010/rpt10-6.shtml> (Aug. 8, 2013)

Sandoval-Solis S, McKinney DC, Teasley RL, Patino-Gomez C. 2011. Groundwater banking in the Rio Grande basin. *Water Resources Planning and Management* **137**(1): 62–71.

Shafroth PB, Stromberg JC, Patten DT. 2001. Riparian vegetation response to altered disturbance and stress regimes. *Ecological Applications* **12**: 107–123.

Shiau JT, Wu FC. 2004. Feasible diversion and instream flow release using range of variability approach. *Journal of Water Resources Planning and Management* **130**: 395–404.

Tennant DL. 1976. Instream flow regimes for fish, wildlife, recreation and related environmental resources. *Journal of Fisheries* **1**(4): 6–10.

Tharme RE. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* **19**: 397–441.

Tharme RE, King JM. 1998. Development of the building block methodology for instream flow assessments, and supporting research on the effects of different magnitude flows on riverine ecosystems. *Water Research Commission Report* No. 576/1/98, Cape Town, South Africa

Thompson L, Escobar M, Mosser CM, Purkey DR, Yates D, Moyle PB. 2012. Water management adaptations to prevent loss of spring-run Chinook salmon in California under climate change. *Water Resources Planning and Management* **138**(5): 465–478. ISSN:0733–9496.

Tockner K, Stanford JA. 2002. Riverine floodplains: present state and future trends. *Environmental Conservation* **29**: 308–330.

Todd CR, Ryan T, Nicol SJ, Bearlin AR. 2005. The impact of cold water releases on the critical period of post-spawning survival and its implications for Murray cod (*Maccullochella peelii peelii*): a case study of the Mitta Mitta River, Southeastern Australia. *River Research and Applications* **21**(9): 1035–1052. DOI: 10.1002/rrs.873.

Vorosmarty CJ, Meybeck M, Fekete B, Sharma K, Green P, Syvitski JPM. 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change* **39**:169–190. DOI: 10.1016/S0921-8181(03)00023-7.

WCD - World Commission on Dams. 2000. *Dams and development: a new framework for decision- making*. Earthscan: London, UK.

Williams GP, Wolman MG. 1984. Downstream effects of dams on alluvial rivers. U.S. *Geological Survey Professional Paper* 1286, Denver, Colorado, USA.

Willis CM, Griggs GB. 2003. Reductions in fluvial sediment discharge by coastal dams in California and implications for beach sustainability. *The Journal of Geology* **111**: 167–182.

WWF - World Wildlife Fund. 2004. Rivers at risk: dams and the future of freshwater ecosystems. Available online at: http://assets.panda.org/downloads/riversatriskfullreport.pdf.