Reconciling Hydropower and Environmental Water Uses in the Leishui River Basin, China

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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 resources 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 (Mar/1952-Feb/1993). This natural flow regime was used as a template for proposing environmental flow (e-flow) requirements. The post-reservoir flow regime (post-1992) (Mar/1993-Feb/2011) was analyzed 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 Dongjiang reservoir and used for comparison of four alternative water management policies that considered e-flow releases from 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-flows 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. Tradeoffs are essential to balancing these two water management objectives.
and compromises have to be made for both water uses to obtain benefits.

Key Words: Environmental Flows, Hydropower, Dongjiang Reservoir, Integrated Water Resources Management
1 INTRODUCTION

Water is an essential resource for all life on the planet. The sustainable development of water resources is fundamental to 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 resources management is used to redistribute it to satisfy these water demands while maintaining the ecological and hydrologic integrity of a basin. Water resources 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-term, the concept of integrated water resources 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 resources 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 Ritcher, 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 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 inter-annual 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 due to human diversion of water (Sandoval-Solis and McKinney, 2012), disconnection of floodplains due to construction of levees for flood protection (Mount, 1995), and degradation of water quality due to 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 (Magilligan et al., 2003, Shafroth et al., 2001, Tockner and Stanford, 2002) 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.

1.1 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. The Dongjiang reservoir, located in the Leishui River in China, is used here as a case study. The specific objectives of this research are:

a) develop an annual e-flows hydrograph using the natural flow paradigm technique of Poff et al. (1997) and specifically the Indicators of Hydrologic Alteration platform;

b) construct a simulation and planning model that represents the regional water resources system of the Leishui river basin using the C++ platform;

c) 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-flows Scenarios, which consider the IWRM of Dongjiang reservoir for hydropower and environmental water management;

d) compare the benefits of alternative (E-flow-oriented) policy scenarios.

The Natural Flow Paradigm method is used to create initial e-flows 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.,
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-flows 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.

2 Methodology

2.1 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 km², an average precipitation of 1,645 mm/year and an average annual discharge of 3,598×10⁶ m³.

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 4,719 km² (40% of the total drainage area). The total storage capacity, active and dead storage are 9,470×10⁶ m³, 5,250 ×10⁶ m³ and 2,870×10⁶ m³, respectively. The average annual inflow volume (1952-2010) to the reservoir is 3.67 km³. Dongjiang reservoir is a multi-year 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.

3 Environmental Flows (E-Flows)

Several methodologies have been developed to provide an estimation of the adequate water quantity, quality and timing required to sustain a healthy ecosystem: (a) statistical methods, such as the Tennant method (Tennant, 1976) or Natural Streamflow Paradigm (Richter et al. 1996), which analyze streamflow data to determine flow characteristics desired to prescribe e-flows recommendations, (b) hydro-geomorphic methods, such as the Near-Census River Assessment and Rehabilitation method, which evaluate the flows and geomorphology required to provide suitable habitat for aquatic species (Pasternack, 2011), (c) instream habitat
methods, such as the Instream Flow Incremental method (Bovee, 1978), which relate different flows to habitat impacts using predetermined preferences of specific fish species and (d) 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; Pringle et al., 2000; Kingsford, 2000; Tharme, 2003; Sandoval-Solis and McKinney, 2012).

Based on the construction of Dongjiang reservoir in 1992, two sets of daily data were analyzed: the pre-reservoir alteration flow regime (pre-1992), from Mar/1952 to Feb/1993, and the post-reservoir alteration flow regime (post-1992), from March/1993 to Feb/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 analyzed in this study.

3.1 Determining Environmental 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 m$^3$/s). 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 m$^3$/s) and the 2-year return period (T) (1,320 m$^3$/s). 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) (1,320 m$^3$/s) to 10 years (T=10) (2,192 m$^3$/s). Large floods are peak flows with a return period of greater than 10 years (T>10) (>2,192 m$^3$/s).

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 centered 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- and post-alteration periods.

### 3.2 Flow Regime Results
3.2.1 Pre-reservoir flow regime (Pre-1992)

The pre-1992 hydrograph depicting the natural flow regime is shown in Figure 2 and Table 1. Prior to 1992, normal flows varied from 38 m$^3$/s in December to 209 m$^3$/s 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=1,730 m$^3$/s), June (peak flow=1,625 m$^3$/s), July (peak flow=1,930m$^3$/s) and August (peak flow=1,400 m$^3$/s) and large floods ($T=20$) in April (peak flow=2,605 m$^3$/s) and June (peak flow=2,740 m$^3$/s). Figure 2 shows the total average flow volume (3,593×10$^6$ m$^3$) of the pre-1992 annual hydrograph, which was estimated as the sum of the volume of each benchmark component times its frequency (Frequency=1/T). The estimated volumes of normal flows, pulses and floods shown in Figure 2 are 2,976×10$^6$ m$^3$, 393×10$^6$ m$^3$ and 224×10$^6$ m$^3$ respectively.

3.2.2 Post-reservoir flow regime (Post-1992)

Figure 3 and Table 1 show the typical post-1992 hydrograph. Normal flows varied from 75 m$^3$/s in June to 191 m$^3$/s in January. From Figure 3 two flow patterns can be distinguished for the post-reservoir flow benchmark: (1) December through March flows to generate electricity to support the power grid of Hunan province and (2) 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 current reservoir operation. The total volume of the one-year return period hydrograph is 4,248×10$^6$ m$^3$. 3,991×10$^6$ m$^3$ is provided by normal flows and 257×10$^6$ m$^3$ by pulses. The volume of the post-1992 hydrograph (4,248×10$^6$ m$^3$) is larger than the pre-1992 volume (3,593×10$^6$ m$^3$). This is attributed to wetter conditions in the post-1992 period (1993-2010) (average annual flow= 4,476×10$^6$ m$^3$),
than the pre-1992 period (1952-1992) (average annual flow=3,213×10^6 m^3).

Dongjiang reservoir effectively captures flows occurring at all return periods, eliminating the inter-annual variability of flows. Floods and pulses have been converted into normal flows (median flow = 107 m^3/s) 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.

3.3 **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 1,263×10^6 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 1 pulse per month and peak magnitudes around 240 m^3/s. 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.
- 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.

4 **WATER MANAGEMENT POLICIES AND SCENARIOS**

The main role of 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 Dongjiang reservoir has experienced 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.

4.1 Scenarios

4.1.1 Baseline Scenario: Only Hydropower

The following procedure explains the rules used to operate 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 Eq. 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:

$$Q^T_t = \begin{cases} 
Q(N_f) & Z_t \in A \\
Q(1.2N_f) & Z_t \in B \\
Q(N_{exp}) & Z_t \in C \\
Q(0.8N_f) & Z_t \in D \\
Q(0.6N_f) & Z_t \in E \\
Q_{min} & Z_t \in Z_d 
\end{cases} \quad [1]$$

Where $Q^T_t$ is the release of water for hydropower generation (m$^3$/s); $N_f$ is the guaranteed hydropower generation (105 MW); $Q(N_f)$ is the release required to produce the guaranteed hydropower, (m$^3$/s); $Z_t$ is the water level at the beginning of the time step $t$; $Q(N_{exp})$ is the release required for maximum hydropower generation (m$^3$/s); $Q_{min}$ 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 Dongjiang reservoir.

The generated hydropower is calculated using the following equation:

$$P_t = KQ^T_tH \quad [2]$$

Where $H$ is the net head of the hydropower (m) and $K$ is the output coefficient.

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(K=8.5), a value derived from records provided by the Dongjiang hydropower operation authority.

4.1.2 Environmental Flow Scenarios

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

4.2 Dongjiang Reservoir Planning Model

A reservoir simulation model was built to represent the current water allocation of 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 Davis (UCD). The data (hydrologic, infrastructure and operation) and modeling 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 was 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 $K$ (Eq. 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. Modeled and observed streamflow data were compared for March 1999 to February 2003, during which the operation of Dongjiang reservoir closely followed the operational rule curve and was not very affected by the empirical operation of managers. The percent 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 (Moriasi et al. 2007; Legates and McCabe 1999); 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.

4.3 Comparison of Water Management Scenarios

4.3.1 Baseline and Environmental Flow Scenarios

The baseline and four e-flows scenarios were compared using the following performance criteria: average annual hydropower generation, 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 3.

The results show that the hydropower generation under e-flows Scenario I and III were most similar to the Baseline Scenario, demonstrating that the combination of rule curve plus e-flows 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 tradeoffs 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 eTflows benchmarks of T<3.

4.3.2 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-flows provisions. Two variations of the pre-1992 natural flow regime hydrograph (Figure 5) were used in this analysis: (1) benchmarks with T=1 (2,976×10^6 m³/year) or (2) benchmarks with T=1 and 2<T<3 (3,369×10^6 m³/year). The authors propose that the system can be managed for hydropower and environmental flows based on these flow benchmarks, since 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 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 Figure 6. They show that a flow regime that releases 75% of the pre-1992 annual hydrograph volume can generate the most hydropower (1,459×10^6 kWh/year 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-flows) is the management alternative that generates the most hydropower at 100% reliability. The least water is spilled under the 80% e-flows ratio, however, the 75% e-flows ratio spills the second least, meaning most of the water can be used for hydropower generation.

The annual hydrograph below Dongjiang reservoir based on Scenario III (rule curve + 75% e-flows) 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 Fig. 6 are larger than pre-1992 conditions. This is due to the altered rule curve policy that tries to meet hydropower requirements during these months. Conversely, from March to June, normal flows in Fig. 6 are larger than post-1992 normal flows in order to meet environmental flow targets. These results indicate that both compromises and tradeoffs can be made to balance hydropower and environmental needs. Further improvements in this policy are needed to provide pulses in May and June.

5 DISCUSSION

There is no simple answer or single policy when trying to reconcile reservoir operations for hydropower and environmental purposes. Tradeoffs 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 Dongjiang reservoir and physical changes along the river corridor to return to more natural flow conditions.

6 Conclusions

This research demonstrates that it is possible to integrate hydropower and environmental requirements into an IWRM 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), 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 resources 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: (1) a reservoir re-operation policy, (2) an
e-flows hydrograph of 75% of the natural flow regime volume and (3) a physical intervention in the river.
7 REFERENCES


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*


London, UK.


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.


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Table 2. Scenarios for e-flows evaluation.

Table 3. Result of the five reservoir operation scenarios

Table 4. Evaluation of Scenario III for different sets of e-flows hydrographs

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*T* denotes the *Return Period* of a certain flow.
Table 2 – Scenarios for e-flows evaluation.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Benchmarks (T=1)</th>
<th>Hydrograph Volume (1×10^6 m^3/year)</th>
<th>Reservoir Operation</th>
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<td>III</td>
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<td>IV</td>
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*T denotes the *Return Period* of a certain flow.*
Table 3. Results of the comparison of the baseline (only hydropower) and the four e-flows reservoir operation scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Hydropower Generation* (10^6 kWh/year)</th>
<th>Reliability** (%)</th>
<th>Through turbine (1 × 10^6 m^3/year)</th>
<th>Spilled (1 × 10^6 m^3/year)</th>
<th>Released (1 × 10^6 m^3/year)</th>
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<tr>
<td>Baseline</td>
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<td>4,356</td>
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<td>4,771</td>
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<td>657</td>
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<td>1,317</td>
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<td>3,966</td>
<td>641</td>
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* Hydropower Generation (HP) was calculated: $HP = \sum_{t=1}^{T} (KQ_t + H \times 24))/Y$; where $t$ is the day of the year, $T$ is the number of days in a year, $Y$ are the total number of years; $K$, $Q$, and $H$ are explained in Eq. 2.

** Reliability (Rel) was calculated: $Rel = \left(\frac{\sum_d (D_t \times 0)}{(Y \cdot T)}\right) \times 100$; 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 Eq. 2.

*** The average water through turbine ($Q_T$), spilled ($Q_S$) and released ($Q_R$) was calculated: $Q_i = \sum_{t=1}^{T} (Q_{T,S,R})/T$; for $i \in T, S, or R$. 
Table 4. Evaluation of Scenario III for different sets of e-flows hydrographs.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Units</th>
<th>100%</th>
<th>90%</th>
<th>80%</th>
<th>75%</th>
<th>70%</th>
<th>60%</th>
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<td>1446</td>
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<td>Water Spilled**</td>
<td>$1 \times 10^7$ m$^3$</td>
<td>2139</td>
<td>2024</td>
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<td>1904</td>
<td>2230</td>
<td>2961</td>
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* Hydropower Generation ($HP$) was calculated: $HP = \frac{\sum_{t=1}^{\text{days}} (K_t Q_t H_t \times 24))}{Y}$; where $t$ is the day of the year, $T$ is the number of days in a year, $Y$ are the total number of years; $K$, $Q$ and $H$ are explained in Eq. 2.

** The total water spilled ($Q^s$) was calculated as follows: $Q^s = \frac{\sum_{t=1}^{\text{days}} Q^s_t}{Y}$, where $Q^s$ is the water spilled at a determined day $t$. 
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Figure 5. The relationship between power generation and the water spilled.

Figure 6. Annual Hydrograph obtained of the combination of Scenario III and 75% of the pre-1992 hydrograph.
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279x215mm (300 x 300 DPI)
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279x215mm (200 x 200 DPI)
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279x215mm (200 x 200 DPI)

(A) Guaranteed zone; (B) Enlarged zone; (C) Maximum Expected zone;
(D) Reduced zone; (E) Greatly Reduced zone
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279x215mm (200 x 200 DPI)
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279x215mm (220 x 220 DPI)