Cumulative biophysical impact of small and large hydropower development, Nu River, China

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Abstract:

Support for low-carbon energy and opposition to new large dams encourages global development of small hydropower facilities. This support is manifested in national and international energy and development policies designed to incentivize growth in the small hydropower sector while curtailing large dam construction. However, the preference of small to large dams assumes, without justification, that small hydropower dams entail fewer and less severe environmental and social externalities than large hydropower dams. With the objective to evaluate the validity of this assumption, we investigate cumulative biophysical effects of small (<50 MW) and large hydropower dams in China's Nu River basin, and compare effects normalized per megawatt of power produced. Results reveal that biophysical impacts of small hydropower may exceed those of large hydropower, particularly with regard to habitat and hydrologic change. These results indicate that more comprehensive standards for impact assessment and governance of small hydropower projects may be necessary to encourage low-impact energy development.

1 Introduction

The hydropower sector currently comprises eighty percent of global capacity for renewable energy generation and is considered a conduit between dependence on fossil-based energy sources and alternative energy futures [*Frey and Link*, 2002; *REN21*, 2010]. However, as dam construction often encompasses undesirable social, environmental, and political externalities [*McCully*, 1996; *WCD*, 2000; *Postel and Richter*, 2003], development of new large dams can be politically untenable. The current upsurge in construction of smaller, geographically-distributed hydrodevelopment schemes [*Painuly*, 2001] may be, in part, a result of increasing acknowledgement of and aversion to impacts of large dams.

A growing number of nations have recently highlighted development of small hydropower resources in national energy policies [China: *Li et al.*, 2009; *Zhou et al.* 2009; Nepal: *Karki*, 2007; India: *Dudhani et al.* 2006; *Purohit*, 2008; Turkey: *Yuksel*, 2007; Latin America and Caribbean: *Benstead et al.*, 1999]. New national-level regulations, as well as international energy and development policies, such as the Kyoto Protocol's Clean Development Mechanism (CDM), allow streamlined permitting processes for new hydropower facilities falling below thresholds in installed capacity, as well as other incentives designed to encourage small hydropower development in lieu of large dams [*REN21*, 2010*; UNFCCC and CCNUCC*, 2006a]. These policies are established with the intent of fostering renewable energy development, allowing realization of low-carbon energy potential in developing areas with growing demands for electricity, while avoiding the undesirable social and environmental consequences associated with large dams.

Such decisions and development strategies crafted at the national and international level have immense potential to shape both energy and hydro-ecologic landscapes. However, while the literature is replete with research and case studies documenting unintended consequences of large dams [*Abell*, 2002; *Cernea*, 1999*; Giordano et al.*, 2005; *Lerer and Scidder*, 1999; *Petts*, 1984; *Poff et al.*, 1997; *Rosenburg et al.* 2000; *Williams and Wolman*, 1984], similar investigations of small hydropower effects are scarce [but see *Gleick*, 1992]. The lack of analogous research addressing effects of small hydropower limits opportunity to recognize potential impacts and mitigate negative consequences. Adequate consideration of cumulative effects is a particularly salient issue related to small hydropower impact assessment, yet this topic has received little attention of researchers or water resources managers [but see *Irving and Bain*, 1993] and is rarely considered with sufficient rigor in impact evaluations. Given the potential for effects to accumulate under current policies encouraging development of many small facilities over fewer large facilities, the lack of comprehensive analysis regarding cumulative impact of small hydropower is a significant research gap with important policy implications.

We thus present an investigation of cumulative biophysical effects associated with large and small hydropower dams built or proposed on the mainstem and tributaries of China's Nu River in Nujiang Prefecture, Yunnan Province (Figure 1). We define large and small hydropower dams in this work according to Chinese law, which states that hydropower dams exceeding 50 MW installed capacity are large, while those falling below 50 MW installed capacity are small. Our objectives in evaluating the relative cumulative impacts of small and large hydropower are to a) augment the sparse body of evidence that currently documents effects of small hydropower, b) support discourse and policies regarding renewable energy development and mitigation of environmental effects, and c) to present new data on one of the world's last undammed, and arguably least-studied, rivers.

2 Materials and Methods:

2.1 Study site - Nujiang Prefecture

Nujiang Lisu Autonomous Prefecture (hereafter, Nujiang Prefecture) is located in Northwest Yunnan Province, China, south of the Yunnan-Tibet provincial border and east of the international border between China and Myanmar (Figure 1). From sources on the Qinghai-Tibet Plateau, the Salween River flows south through Nujiang Prefecture before entering Myanmar. China, Myanmar, and Thailand share portions of the international Salween River basin. However the headwaters of the Salween River are located in China, where it is known by its Chinese name, the Nu River. Because our analysis focuses on the reach of the Salween River within

China's borders, herein we refer to the study area as the Nu River, except in places (e.g. analysis of affected conservation lands) where analysis extends across international borders.

The upper reaches of the Nu River flow through an orogenic belt, downcutting through steep gorges, the course entrenched by constrained, high-relief valleys [*Owen*, 2006]. Intercontinental deformation associated with subduction and collision is manifested through several large, active strike-slip fault systems extending from the northwest to southeast through Yunnan Province, which trigger regular seismic events [*He and Tsukuda,* 2003*; Allen et al.*, 1991*; Zhou et al.*, 1997]. River flows in Nujiang Prefecture generate primarily through rainfall-runoff processes, with two distinct seasonal pulses of rainfall driving periods of high river flows. The first rains in Nujiang Prefecture occur each year between February and May and historically deliver between 40 to 50 percent of the yearly precipitation [*IWR*, 2006a]. A second system of precipitation, driven by the East Asian monsoon, persists from June to October and delivers a further 40 to 50 percent of annual precipitation. Snow and glacial melt contribute runoff to the Nu River mainstem during summer months, with some portions of the upper Nu River basin in Tibet contributing over 2000 mm of meltwater [*CAS*, 1990]. Conversely, snowmelt is a relatively inconsequential source of runoff in tributaries to the Nu River in Nujiang Prefecture [*YBHWR*, 2005].

Nujiang Prefecture lies within a designated hotspot of global biodiversity [*Zhou and Chen*, 2005; *UNESCO,* 2002]. A high proportion of endemic species characterize the vastly diverse organisms of Northwest Yunnan [*Xu and Wilkes*, 2003], and many species are protected at the Provincial or national level, or listed on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species [*IUCN*, 2001]. For example, of 48 species of fish known to inhabit the Nu River in Yunnan Province, 32 are endemic and several are protected [*Chu and*

Chen, 1989, 1990]. In addition to possessing rich biodiversity, Nujiang Prefecture is also one of the most ethnically diverse regions of China, with ethnic minorities comprising 92 percent of the prefectural population [*Magee*, 2006]. The three counties of Nujiang Prefecture (Gongshan, Fugong, and Lushui) are also listed amongst the most poverty-stricken counties of China, and continue to face significant challenges to economic development.

2.2 Study design and data procurement

Two distinct models of hydropower, large and small, are developing side by side in Nujiang Prefecture, driven by China's state-mandated development policies of "Western Development" and "Send Western Energy East." We distinguish large and small hydropower dams in this study based on the Chinese regulatory threshold of 50 MW, whereby stations with installed capacity not exceeding 50 MW classify as small hydropower [*MWR*, 2002]. We note that, internationally, the definition of small hydropower varies considerably across governments and agencies, and that China's definition of small hydropower is highly inclusive relative to other standards. For example, small hydropower within the United States is defined as not exceeding 25 MW, while many European countries specify standards of less than 10 MW. On the Nu River, a cascade of up to thirteen large hydropower dams has been proposed for the mainstem in Tibet and Yunnan Province, with eight projects slated to fall within Nujiang Prefecture. Small hydropower dams are already developed on tributaries throughout the Nu River basin. While the number of small hydropower dams in operation or planned for tributaries to the Nu River is unreported, our field surveys indicate that nearly one hundred small dams currently exist within Nujiang Prefecture alone.

From the population of hydropower dams proposed or constructed on the mainstem and tributaries to the Nu River in Nujiang Prefecture, we investigate samples of four large dams (totaling 10,400 MW installed capacity) and 31 small dams (totaling 417 MW installed capacity) (Table 1). The collective installed capacities of large and small hydropower stations investigated in this study indicate potential for annual certified emissions reductions of 45 million and 1.5 million metric tons of carbon dioxide (CO_2), respectively [*UNFCCC and CCNUCC*, 2006b].

In this investigation, we define potential for biophysical change according to a suite of metrics indicating absolute environmental impact (Table 2). We then normalize cumulative impacts of small and large dams by installed capacity in order to compare the cumulative impact of one megawatt of power generated by small and large dams. Impact evaluation in China's Nu River basin is challenging, primarily because access to and availability of robust and accurate information is extremely limited. Regarding data access, information pertaining to Nujiang Prefecture dams is closely guarded by the central government due to the sensitivity of the region, which is home to large proportions of Chinese ethnic minorities and potentially valuable natural resources. In addition, proposals to construct dams on the Nu River mainstem are highly controversial, both domestically and internationally. As a result, access to hydrologic, hydraulic, and geomorphic data related to the international Nu River (e.g. discharge, stage, and sediment transport), as well as plans for dam development and operations, is prohibited under the Chinese State Secrets Act. Regarding data availability, smaller catchments in Nujiang Prefecture, where small hydropower dams are sited, are ungauged, and very little research has documented the aquatic biodiversity of the remote Nu River and its tributaries.

We thus assess biophysical effects of large and small dams according to the most comprehensive and complete set of information available, compiling data from a variety of sources to inform our modeling and analyses. To obtain information related to small dams, we consult reports generated during Environmental Impact Assessment (EIA) processes [*YBHWR*, 2005; *IWR*, 2004, 2005, 2006a, 2006b, 2006c] and during certification through the Kyoto Protocol's CDM [*UNFCCC and CCNUCC*, 2007, 2008a, 2008b, 2008c, 2008d, 2009a, 2009b, 2009c]. We supplement this official reporting with information gained through our independent survey of 15 small hydropower stations. As access to analogous EIA reporting for large dams is restricted by the central government, we therefore model potential effects of large hydropower dams using publically-available information from hydropower companies, development agencies, and academic literature [*Plinston and He,* 1999*; Dore and Yu,* 2004]. Given the data-poor environment in which our analysis occurs, we characterize and report uncertainty of each parameter estimate, modeling and reporting a range of possible effects for both small and large dams.

2.3 Data analysis

2.3.1 Habitat loss

As a reservoir is filled, terrestrial and riparian habitats within the impoundment are transformed [*Lewke and Buss*, 1977; *Oliver*, 1974], and lotic aquatic habitats within the former channel become lentic environments [*Petts*, 1984], changing the habitat and resource base of local and regional ecosystems. To estimate the quantity of habitat disturbed by impoundment, we assess the area of land and length of channel inundated by reservoirs.

Due to differences in system design characterizing large and small dams of Nujiang Prefecture, the primary location of direct impact varies. Whereas the large dams create large reservoirs, the direct impacts of small dams are concentrated within the channel downstream of the dam. Because the small dams we investigate divert a majority of river flows for much of the year, we use the term "dewatered" to describe reaches below diversion dams. To evaluate alteration of riparian and aquatic habitats downstream of small diversion dams due to channel dewatering [*Smith et al.*, 1991; *Dewson et al*., 2007; *Haxton and Findlay,* 2008], we estimate the length of channel to which flows are reduced as the distance between locations of water withdrawal (from the reservoir) and return to the natural river system (at the tailrace leaving the penstock). Further, to assess the diversity of habitats disturbed by the small and large hydropower dams, we integrate areas inundated or dewatered with habitat classifications [*TNC*, 1999], determining the number of habitat types affected by each project.

2.3.2 Catchment connectivity

Dams influence the connectivity of river basins by impeding flows of energy and material from upper to lower reaches [*Ward et al.*, 1999] and by hindering passage of migrating or drifting aquatic fauna [*Northcote*, 1998]. We evaluate the fraction of catchment area contributing to each dam as an estimate of potential impact to hydraulic and ecological connectivity. To capture both localized and basinwide effects, we evaluate catchment connectivity at two scales of reference: at the scale of the international Salween River basin and at the scale of individual river catchments.

2.3.3 Priority conservation lands

To assess the potential for dams to affect areas identified as global or regional conservation priorities, we estimate areas of designated conservation lands [*UNESCO*, 2010; *TNC*, 2006; *CI*, 2004; *CI*, 2010] directly affected (inundated or dewatered) by each project. At the global scale, UNESCO designates the Three Parallel Rivers of Yunnan, including portions of the Nu River basin, as a World Heritage Site [*UNESCO*, 2003]. The Nature Conservancy (TNC) and Conservation International (CI) delineate regions of global importance for preserving biodiversity, termed Biodiversity Hotspots, within the Nu River basin. At the regional scale, comprehensive assessment and delineation of site-scale locations that possess global value as conservation priorities, termed Key Biodiversity Areas (KBAs) has been undertaken by a partnership consisting of CI, IUCN, and the Critical Ecosystems Partnerships Fund (CEPF) [*Langhammer et al.*, 2007]. The CEPF delineates KBAs according to criteria of vulnerability and/or irreplaceability of species that are supported by the specific geographic location. Finally, our analysis includes Nature Reserves, areas protected at the national, Provincial, or County level for conservation of biodiversity, where certain land uses are restricted for habitat protection.

Research indicates that, in addition to directly affecting sensitive biological resources, dams may also indirectly influence off-site habitats. For instance, at Manwan Dam on the Lancang River, China, Zhao et al. [2012] observe conversion of forest and scrubland to roads, grasslands, and farmland and demonstrate a distance-decay relationship between land conversion and proximity to a new dam. This pattern of decreasing impact with increasing distance from the reservoir is relevant to species diversity and persistence, as changes in land use and habitat fragmentation may lead to species loss [*Terborgh*, 1974; *Terborgh et al.*, 2001; *Laurance et al.*, 2000]. We therefore estimate potential indirect or off-site effects to priority areas for conservation as an index of proximity to high-priority conservation areas within the Salween River Basin, including conservation areas in China, Myanmar, and Thailand. We calculate the proximity index as:

$$P_{index}=\sum(i=1) \text{ to } n\ (1/d_i) \qquad \text{Eq.1}$$

where P_{index} is the proximity index, d_i is the minimum distance between the dam and the ith conservation area (km), given n conservation areas.

2.3.4 Landscape stability

Increasing water surface elevations in reservoirs may destabilize the base of hillslopes, and construction of hydropower infrastructure often entails expansion of power transmission routes and roads to the dam and power generation sites. Both may increase potential for land disturbance and landslides in the vicinity of dams. To assess potential for exacerbation of local landslide hazards, we integrate project footprints with landslide risk information. Landslide risk analysis is based on a spatial regression relating historic landslide occurrence in Nujiang Prefecture to the variables of slope, vegetation cover, precipitation, and proximity to roads [*Li*, 2010]. We then compute total areas characterized by high to severe risk of landslide that fall within the footprint of each reservoir.

Reservoir filling can also contribute to landscape instability through intensification of seismicity [*Gupta*, 2002; *Talwani*, 1997]. Empirical data suggest that parameters of reservoir depth, volume, and proximity to active faults are associated with increased probability of reservoir-triggered seismicity, with most documented cases occurring near reservoirs over 92 m in depth and 12E8 m^3 in volume [*Baecher and Keeney*, 1982]. However, seismic events have been triggered by much smaller reservoirs [*Chen and Talwani*, 1998]. To evaluate potential for small and large reservoirs to induce seismic events, we introduce a seismic index (S_{index}) for each project (Eq. 2) with respect to maximum reservoir depth (h_{max}), maximum reservoir volume (vol_{max}), and minimum distance ($1/d_{min}$) to active faults.

$$S_{index} = h_{max} \times vol_{max} \times 1/d_{min} \qquad \text{Eq. 2}$$

In determining distances to active faults, we apply fault data mapped by He and Tsukuda [2003].

2.3.5 Potential for modified flow and sediment regimes

Dams disrupt the natural flow of water and sediments through river systems [*Poff et al.*, 1997; *Bunn and Arthington*, 2002; *Vorosmarty et al.*, 2003], altering first-order determinants of the physical riverine environment that cascade to affect river morphology and ecology [*Poff et al.*, 2007; *Schmidt and Wilcock*, 2008; *Lytle and Poff*, 2004]. To evaluate the potential for large and small dams to modify river flows, we estimate the fraction of annual runoff controlled by each hydropower project, either through storage in reservoirs or diversion. With respect to large dams, from which water is not diverted, we assess potential for flow modification by comparing annual runoff at each dam [*Dore and Yu*, 2004] to modeled reservoir volumes.

In the case of small dams, we estimate volumes of water controlled by both reservoir storage and diversion. We model natural and modified hydrographs at each dam site, as well as reservoir volumes. We then compare annual runoff to volumes of water diverted or stored. From this analysis, we express impacts to flows downstream of small dams as the proportion of time that downstream channel flows do not exceed 5% of the mean annual flow, a standard minimum ecological flow reportedly maintained below some small dams [e.g. *UNFCCC and CCNUCC*, 2008b].

Hydrologic gauging stations record discharge on the mainstem of the Nu River, while tributaries to the Nu River are ungauged. We model flows in tributaries (Eq. 3) following standard methods of runoff prediction for small hydropower planning and design in China [*MWR*, 2002], which are based on hydrologic similarity (inferred from climatic and catchment similarity) to a nearby gauged catchment [*Falkenmark and Chapman*, 1989; *Bloschi et al.*, 2013].

$$Q_{dam} = Q_{ref} \times k_{or} \, (P_{dam}/P_{ref}) \times (A_{dam}/A_{ref}) \qquad \text{Eq. 3}$$

Within Eq. 3, Q_{dam} and Q_{ref} [*Chinese Ministry of Hydrology*, 1970, 1971, 1974, 1977, 1982a, 1982b] are the respective mean daily flows simulated at the proposed dam site and observed at a gauged reference site. In this case, Q_{ref} is recorded at the Tang Shang gauge in the 200 km^2 Yongchun River catchment, a tributary to the neighboring Lancang River. k_{or} is an orographic constant correcting for elevation-driven differences in precipitation in the modeled catchment and at the basin precipitation gauge. P_{dam} and P_{ref} are daily precipitation observed within the basin containing the dam and at the Tang Shang gauge, respectively. A_{dam} and A_{ref} are the respective basin areas contributing to the dam and the Tang Shang gauge. We model mean daily flows at each small dam over three water years known to be locally average (1972-1973), above average (1978-1979), and below average (1965-1966) with respect to runoff [*YBHWR*, 2005].

To evaluate potential effects to sediment transport, we compute the trap efficiency of each reservoir, using Eq. 4 after Brune's [1953] trapping efficiency curve, where $\Delta\tau_R$ is change in residence time of water through the reservoir as compared to the free-flowing river.

$$\text{reservoir trap efficiency} = 1-(0.05/((\Delta\tau_R)^{0.5})) \qquad \text{Eq. 4}$$

As management of reservoir sediments may moderate potential disturbance to sediment yields below dams, we also consider sediment management activities in our assessment of net reservoir trap efficiency. For example, EIAs, CDM design documents, and surveys related to small hydropower dams indicate that operators hydraulically flush sediments from behind small dams on a sub-annual to annual basis, and that this management substantially reduces the net trap efficiency of small reservoirs.

2.3.7 Water quality

Processes affecting water quality, such as biogeochemical spiraling, and mass and energy transport, may change when a river is impounded [*Stanley and Doyle*, 2002] or when river reaches below a dam are dewatered [*Meier et al.*, 2003]. To estimate potential for small and large dams to influence water quality, we evaluate the spatial and temporal extent of channel dewatering below the dam. We also evaluate potential water quality impacts as the relative (percent) change in residence time of water through the reservoir reach, calculated as the ratio of post-dam to pre-dam residence time.

2.3.8 Assessment of uncertainty

Given restrictions regarding access to and availability of information, uncertainty of data used to model biophysical effects of hydropower dams in Nujiang Prefecture is often high. To characterize bounds of uncertainty, we model upper and lower bounds of possible effects and report a range of likely potential impact. For example, uncertainty associated with an estimated reservoir surface area derives from ambiguity in true dam location, as well as variability in minimum and maximum operational pool elevations. We address both sources of uncertainty by modeling a minimum reservoir area, at the most upstream location and minimum pool, and a maximum reservoir area, modeled at the most downstream location with a maximum pool, and reporting the resulting range of possible reservoir areas.

3. Results

3.1 Habitat loss

The mean cumulative impact of land area transformed per unit of power produced is an order of magnitude greater for large than for small dams (Table 3; Figure 2). In contrast, cumulative effects to lengths of river channel inundated or dewatered by small dams exceed those associated with large dams by an order of magnitude (Table 3; Figure 2). Mean cumulative effect to habitat diversity, estimated as the number of riparian and terrestrial habitats affected, is larger for small dams than for large dams by two orders of magnitude (Table 3; Figure 2).

3.2 Catchment connectivity

At the sub-basin scale, cumulative impact to river connectivity per megawatt of power generated is two orders of magnitude greater for small dams than for large dams. In contrast, at the scale of the Salween River basin, the mean effect of large dams is eight times greater than mean effect of small dams (Table 3; Figure 2). While the greater impact of large dams at the basin scale is not surprising, our results offer new evidence that illustrates how the cumulative interruption of network connectivity by many small projects may generate sizable impacts at the sub-basin scale.

3.3 Priority conservation lands

Our results indicate that cumulative effects to protected or high priority conservation lands are greater for small dams than for large dams, according to measures of both direct and off-site impact (Table 3; Figure 2). With regard to direct effects of inundation or dewatering, the mean cumulative effect per unit power of small dams is two to six times that of large dams, while cumulative effect per unit power of indirect effects is two orders of magnitude greater for small dams than for large dams

3.4 Landscape stability

Cumulative effects to landslide risk areas affected by small and large dams are similar (Table 3; Figure 2). With respect to potential for reservoir-induced seismicity, cumulative effects of large dams exceed those associated with small by many orders of magnitude, both in terms of absolute impact and impact per unit power generated (Table 3; Figure 2.

3.5 Potential for flow modification

Small dams divert flows up to the station design flow, dewatering downstream river channels during times of low to moderate flows (Figure 3). Design flows of the investigated stations vary from 38 to 286 percent of the mean annual flow, with a mean of 145 percent. Thus, on average, flows up to 1.45 times the mean annual flow are diverted. Consequently, rivers below the small dams investigated are dewatered between 69 and 83 percent of days, with a mean of 74 percent of days (Figure 4).

Alternatively, reservoirs associated with the large dams store between 0.05 and 15 percent of the annual runoff and water is not diverted from the reservoirs. Thus, in comparing potential for modifications to the annual hydrograph, the mean cumulative impact per megawatt of power generated is three to four orders of magnitude greater for the small dams investigated than for the large dams (Table 3; Figure 2).

3.6 Potential for sediment modification

The mean cumulative effect of sediment trapping per unit power generated is greater for large dams (Table 3; Figure 2). To maintain optimal water diversion, small reservoirs are managed to hydraulically flush stored sediments at least once per year. Thus, mean cumulative effects to annual sediment yields below small dams are negligible. Large reservoirs, by contrast, store large portions of annual sediment yields, with mean reservoir trapping efficiencies ranging from 26 to 87 percent.

3.7 Water quality

As a result of water diversion for hydropower production, each small dam dewaters a mean 6.8 kilometers of river channel (Table 3) over 74 percent of days during an average water year (Figures 3 and 4). By contrast, large hydropower dams in this study do not dewater any length of river. The mean cumulative channel dewatering effect per megawatt of power produced is thus greater for small dams, with respect to both spatial and temporal parameters (Table 3; Figure 2).

Impoundments associated with small dams increase residence time of water through the inundated reach by a mean of 600 to 900 percent. Changes in residence time associated with large dams are much larger, with mean increases of 9000 to 22,000 percent. Though the percent change in residence time through small reservoirs is less than percent changes through large reservoirs, the mean cumulative impact of residence time change per unit power produced is seven to ten times greater for small dams than for large dams (Table 3; Figure 2).

4 Discussion

4.1 Cumulative biophysical effects: comparison of small and large dams

Our results illustrate that small dams in Nujiang Prefecture, defined by installed capacities less than 50 MW, often generate greater cumulative biophysical effects per megawatt of installed capacity than large dams. This trend was demonstrated for nine of fourteen investigated metrics (Figure 5), including length of river channel affected, diversity of habitats affected, catchment connectivity at the sub-basin scale, direct and indirect influence to lands designated as conservation and biodiversity priorities, potential to modify hydrologic regimes, and potential to affect water quality. In contrast, large dams produce greater effect with respect to four investigated metrics (Figure 5), including total land inundation, catchment connectivity at the basin scale, potential to affect sediment transport, and potential for reservoir-induced seismicity. With respect to landslide risk areas affected, we observed no measureable difference between large and small dams. With this exception, differences in magnitude of impact between groups of small and large dams are substantial, with mean effects often differing over several orders of magnitude.

Our observations confirm conclusions of previous work by *Gleick* [1992], who found that small hydropower dams (defined in Gleick's work according to US standards as dams with installed capacity < 25 MW) exert greater biophysical impact per unit power produced than large hydropower dams. Rather than observing biophysical effects scaling to dam size, Gleick describes segregation of effect according to project design, reporting less severe consequences from diversion hydropower dams than from projects where dam height exceeds gross static head. More recently, Ziv et al. [2012] found that cumulative effects of 78 small tributary dams resulted in greater negative impacts to fish biomass and species at extinction risk than six mainstem dams, while producing less energy and generating unaddressed transboundary impacts.

In combination with Gleick's [1992] and Ziv et al.'s [2012] work, this study illustrates that the current standard for small hydropower definition, installed capacity, may be a poor indicator of biophysical impact. Evidence from these three studies suggests that installed capacity is unlikely to convey true potential for biophysical impact, and that more comprehensive methods for differentiating high- from low-impact hydrodevelopment are necessary. The Swiss labeling of Green Hydropower [*Bratrich et al.*, 2004] or the International Hydropower Association criteria for Sustainable Hydropower [*IHP*, 2007] are examples of more complex definitions that may come closer to defining appropriate standards for policies targeting low-impact hydropower.

Further, this study highlights the need to carefully consider potential differences in absolute and power-scaled impacts of hydropower, both in definitions of low-impact hydropower as well as in planning and impact assessment. For instance, some absolute effects of an individual small dam may appear negligible as compared to absolute effects of a single large dam (Table 2). However, the comparison of absolute impact of one large dam to one small dam is subjective, as often many small dams must be built to match the power generation capacity of one large dam. Similarly, in this study, direct comparison of the absolute impact of infrastructure generating 417 MW of power (31 small dams) to infrastructure that generates 10,400 MW of power (four large dams), is arbitrary and potentially misleading. However, when effects are evaluated cumulatively over several projects and scaled to power generation, direct comparison of large and small dams is possible. Undertaking such direct comparison, we find that some cumulative, power-scaled effects of small hydropower dams exceed those of large hydropower dams. These results demonstrate the need for comprehensive planning of low-impact energy development that considers both the absolute effects of individual projects as well as the interactive and cumulative effects of multiple projects.

4.2 Differential effects of large and small Nu River dams

The large and small hydropower facilities investigated in this study segregate along a threshold of installed capacity (50 MW) determined by the Chinese government. However, other differences in design and operation better distinguish magnitudes and expression of potential environmental effects between the small and large dams. In particular, we observe pronounced differences in potential for small and large dams to modify discharge and sediment regimes. For instance, potential hydrologic alterations established by large hydropower dams relate to the extent to which reservoirs are able to capture and control flows. Large dams with storage reservoirs generally attenuate flood peaks and increase baseflows downstream [e.g. *Gregory et al.*, 2007]. On the contrary, reservoirs associated with small dams store relatively minor fractions of annual runoff. However, small dams divert large volumes of discharge from the river. Hydropower diversion from small dams predominantly affects magnitudes of low to moderate flows, as well as rates of change during transitions between low and high flows. Until the station design flow for optimal power generation is met, nearly all river flows are diverted, leaving several kilometers of river channel below the small dams dewatered for a majority of the year (Figures 3 and 4).

We observe that effects to sediment transport also diverge according to hydropower facility design. Reservoirs of small dams are hydraulically flushed on a sub-annual to annual basis, while sediment management is not planned at the large dams investigated. Flushing of stored sediments from small reservoirs substantially reduces net trapping efficiencies such that small dams do not appreciably affect annual sediment yields. However, temporary storage and pulse releases of sediments have potential to alter the timing and quality of sediments delivered to the downstream channel. Effects of periodic sediment deficit are likely to extend to the next significant sediment source downstream. The influence of periodic sediment surplus related to pulsed releases of stored sediments may be localized [*Kibler et al.*, 2011] or may propagate further downstream, with particular expression at tributary confluences [*Curtis et al.*, 2010; *Petts and Greenwood,* 1985]. In contrast, reduced sediment yield below large dams that continually trap and store sediments may lead to persistent sediment deficit downstream.

We emphasize that our observation of greater potential for sediment transport disruption at large dams is related to dominant sediment transport processes in the Nu River and its tributaries, and to management of reservoir sediments. The bedload-dominated sediment supply is stored by both large and small dams. However, because stored sediments are flushed from small reservoirs, with regard to annual sediment yields, the effect of sediment trapping by small dams is negligible. The dependence of our results on such sediment management in small reservoirs, and the lack of analogous sediment management in large reservoirs, is an important condition to our reported sediment-related impacts of large and small dams.

4.3 Differential permitting and consequential development trajectories of large and small dams

Large and small hydropower dams are often subject to divergent processes of permitting and environmental review. In China, large (> 50 MW) dams require oversight and permissions from the National Development and Reform Commission (NDRC) at two stages of project development and may require additional oversight and permissions from the State Council or National People's Congress [*Magee,* 2006]. Small dams are permitted and implemented at the Prefectural or Provincial level, requiring no collective oversight or consideration of potentially cumulative impacts. The localized effects and small number of people directly affected by each small dam allow for potential accumulations of incremental effects that are not evident at the time of decision making, nor accounted for through environmental review processes, while potential effects of large projects are investigated more thoroughly before projects are approved.

The consequences of different development and governance trajectories of small and large dams are evident in the potential for mitigation opportunities to be adequately identified, implemented, and enforced. While interviewing local personnel at the Gongshan County

(Nujiang Prefecture) Environmental Protection Board, where staff are responsible for enforcing EIA requirements of small hydropower stations, McDonald [2007] learned that mandatory monthly inspections of sites for EIA compliance were seldom completed and that mitigation requirements were often unmet. Lack of oversight at multiple levels of governance, paucity of expertise or resources at local government offices, superficial requirements for environmental assessment, and lack of enforcement creates opportunity for effects of small dams to accumulate more readily than those of large dams.

The lack of consideration toward potential environmental effects and mitigation potential is evident in engineering design and operation of small hydropower stations in Nujiang Prefecture. For example, each small station is equipped with more than one turbine, such that turbines may be selectively taken offline during times when river flows are insufficient to meet design flows. There is opportunity during times of sub-optimal flows to withdraw only the volume of water needed to power the turbines currently in use, maintaining greater instream flows through much of the year. However, as flows are not gauged at the dam site and canal intake designs are not flexible enough to control the amount of water diverted given sub-optimal hydropower generation scenarios, substantial volumes of water are diverted from the river but not utilized for hydropower production. The lack of gauging equipment at diversion sites also suggests that any minimum instream flow standards that may exist are also not monitored or strictly enforced. Indeed, we find no mention of mandatory minimum ecological flows in EIA reports, nor did we observe evidence that minimum flow standards are upheld in practice during visits to diversion sites.

While policies mandating environmental standards for design and operation of small hydropower are often created at the local level, where projects are permitted, policies encouraging development of small hydropower are often crafted at the national or international level. For instance, many of the small hydropower projects investigated in this study are partially funded by the CDM, developed as carbon-offsetting projects under the international Kyoto Protocol climate change treaty. Effects of such development policies may be global, for instance in shaping energy landscapes, or through influences to freshwater biodiversity. Despite the global scale of CDM policies, actual implementation of CDM small hydropower projects proceeds according to standards set within the host country. As regulations regarding avoidance and minimization of ecological impact may vary tremendously throughout host countries, potential for identification and mitigation of harmful effects is also variable.

4.4 Study limitations

The setting of this study within the unique morphology of the Nu River basin is important in considering the transferability of our results to other basins and policy scenarios. The Nu River flows within a narrow gorge between two steep ridges, creating a network of relatively short, low-volume tributaries with comparatively small catchments that carry runoff from basin divides to the considerably larger (in terms of length, flow, and catchment size) mainstem river. Small dams constructed on tributaries of the Nu River are almost exclusively diversion dams that route water from small reservoirs high in the catchment to high-gradient penstocks and generating stations several kilometers away. Large dams are built on the mainstem of the Nu River and do not divert water. Due to these differences in design, small and large dams both segregate discretely in space with respect to size and design and also affect the surrounding landscape in profoundly different ways, complicating the process of selecting comparable evaluation metrics.

As a consequence of the Nu River basin hydrogeology, our sample of small dams consist solely of diversion dams situated on small, steep tributaries, while the large mainstem dams investigated are comparatively very large with respect to installed capacity. A similar study set within a more dendritic river basin may have yielded a more varied selection of large dams, with the installed capacity of some facilities closer to the 50 MW policy threshold. We cannot provide conclusive evidence that our sample represents the population of dams in Nujiang Prefecture, as information regarding the total population of dams is not available. However, field visits and examination of Nu River basin hydrology indicate that our sample is likely representative of the population. With exception of one river, the Dimaluo River, tributaries large enough to support large hydropower stations are not present in this portion of the Nu River basin.

Relatedly, our definition of small hydropower, set at < 50 MW according the Chinese hydropower policy threshold, encompasses dams that would not classify as small hydropower elsewhere in the world where policies define small hydropower by lower thresholds of installed capacity. Our sample of small hydropower dams, varying between 2.5 to 49 MW, with a mean of 19 MW, covers a large range of dam sizes and impact magnitudes, as is reflected in the wide distribution of data around mean effects (Figure 2). Whether similar study utilizing a different policy definition of small hydropower would result in comparable conclusions is uncertain and should be explored.

The data environment in which this analysis is set may also influence study outcomes. While our selection of dam impacts is independent of data accessibility, our methods of evaluating magnitudes of impact are influenced by availability of information. Estimates of effect are characterized by large uncertainties in the dataset, reflected for example, in the wide ranges between estimates of minimum and maximum effects of large dams (Figure 2). Our samples of large and small dams also often encompass great variability of effect, evident in the spread of data around mean effects (Figure 2). Additionally, tributary catchments to the Nu River are ungauged, thus the runoff models we apply to estimate flows are uncalibrated and we are unable to validate results. Though uncertainty related to flows modeled by this method is unknown, this runoff model is widely applied to hydropower design in the region and is used to determine design flows of the small hydropower dams analyzed in this study. As our assessment of flow modification below small dams is relative to design flows informed by this runoff model and is not contingent upon accuracy of specific values, we are satisfied that flows simulated by this model are of sufficient quality for the purpose of our analysis.

A number of sources of uncertainty are represented in our results, including the aforementioned sources related to ambiguity in final locations of the proposed large dams and details regarding planned reservoir operations. With restricted access to dam operations data, predicting the extent and severity of effects downstream of large dams is particularly challenging. In the case of the large Nu River dams, where detailed information regarding dam operations and subsequent changes to flow magnitudes, duration, timing, and predictability are not available, detailed predictions of change to downstream channel morphology are unachievable. Channel effects related to large dams may occur far from dam sites [*Richter et al.*, 2010], yet lacking sufficient data, we are unable to account for these potential changes with a high degree of confidence.

Moreover, it is extremely difficult to predict how downstream changes to hydrology, river channels, and riparian areas may affect biodiversity. While we directly estimate the area of conservation priority land inundated by reservoirs, our use of a distance-decay function to estimate off-site impacts is inferential. However, because large and small dams in Nujiang

Prefecture are built in different locations (large dams in the valley bottom, smaller dams higher in the catchment on tributaries), there is a distinct separation of effect between the proximity of small and large dams to conservation areas, which tend to occur in the more remote upper catchments where farming is limited by slope and where portions of original vegetation remain intact.

Finally, while the objectives of this study are limited to investigation of biophysical impact, it is likely that socioeconomic consequences of small hydropower may exist, and may be similar or dissimilar to what has been reported for large dams in the Nu River [*Tullos et al.*, in press]. Further investigation of socioeconomic and geopolitical effects related to small and large dams are necessary to thoroughly inform integrative definitions of low-impact hydropower.

4.5 Conclusions

Our results indicate that small and large hydropower dams, as defined by Chinese hydropower laws, affect aquatic ecosystems in different ways. Small dams (< 50 MW) return greater impacts, per megawatt of power generated, with respect to the length of river channel affected, diversity of habitats affected, influence to lands designated as conservation and biodiversity priorities, and potential for modification of hydrologic regimes and water quality. Conversely, we report greater cumulative effects for large dams (>50 MW) related to total land inundation, potential sediment transport disruption, and potential for reservoir-induced seismicity. Effects to catchment connectivity vary according to the scale of reference, with effects of small dams exceeding those of large dams at a sub-basin scale and opposite trends observed at the international scale of the Salween Basin. Despite data uncertainties and variability, our results indicate differences in cumulative biophysical impact of large and small dams that exceed both modeling uncertainty and sample variability.

Rooted in the assumption that the biophysical consequences of small hydropower dams are fewer and less severe than those associated with large hydropower, current national and international development policies often encourage growth in the small hydropower sector while discouraging construction of large dams. These policies often define small and large hydropower dams according to a simple metric of installed capacity. Our results indicate that this definition of small hydropower is inadequate for describing the scale of potential environmental impact. Results of this study present evidence that further and more rigorous investigation of the cumulative effects of small hydropower and comparative effects of large and small hydropower are needed to develop coupled water and energy policies that more accurately define and support low-impact hydropower development.

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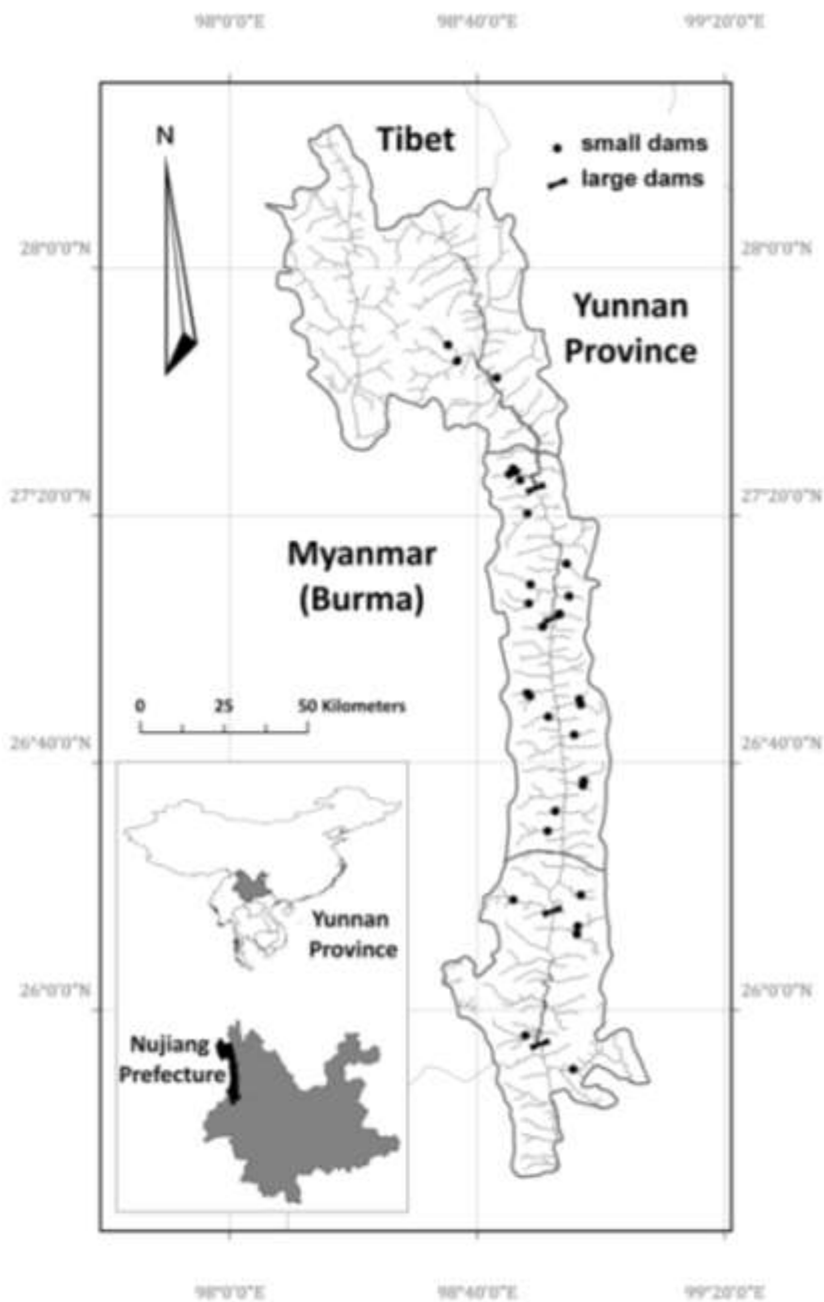

Fig. 1. Nujiang Prefecture. Study area and samples of small and large dams investigated.

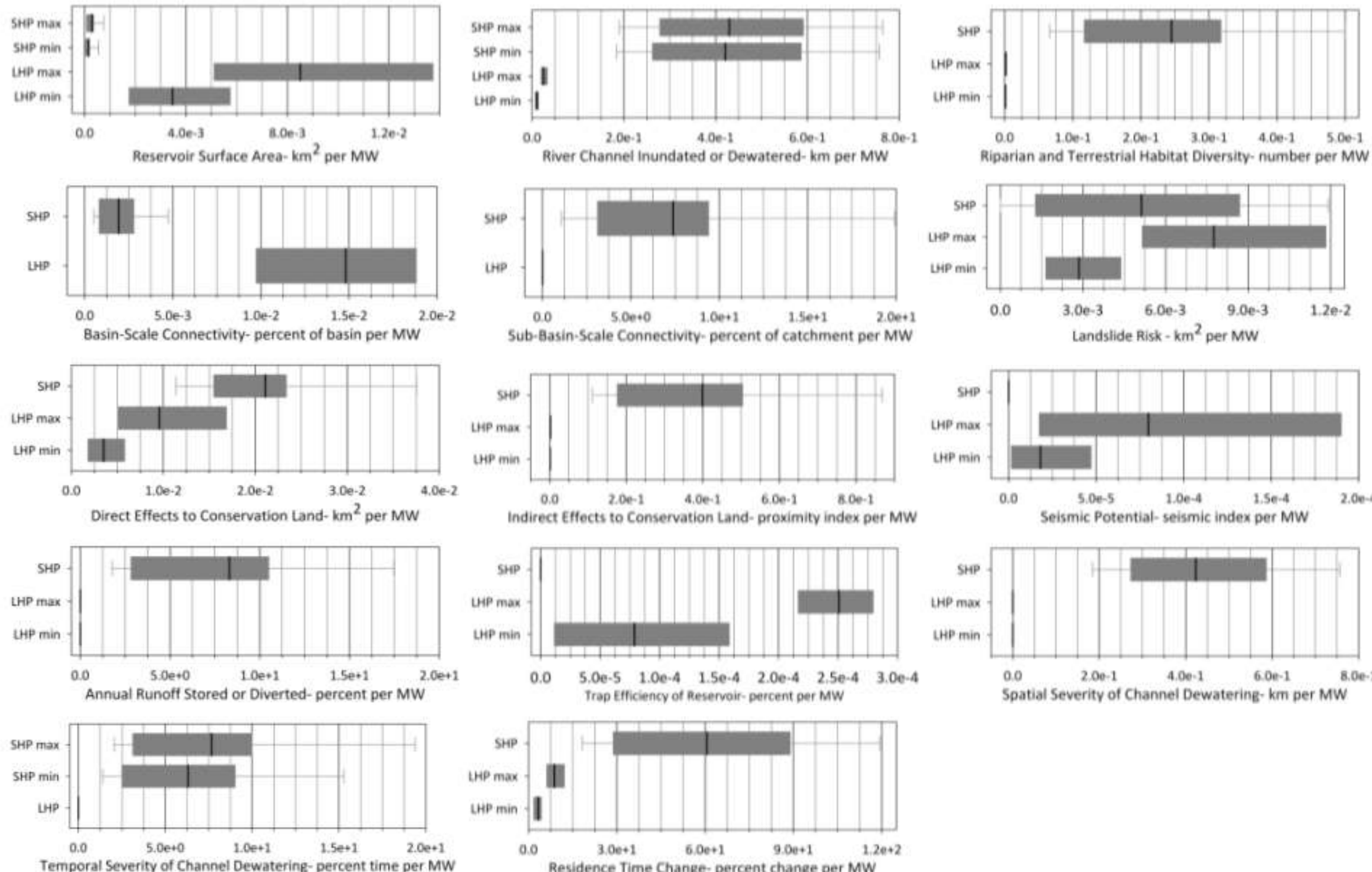

Fig. 2. Cumulative biophysical effect per MW of power produced by small (SHP) and large (LHP) dams. Bold black lines indicate sample means; boxes and whiskers indicate quartiles and 10th and 90th percentiles, respectively.

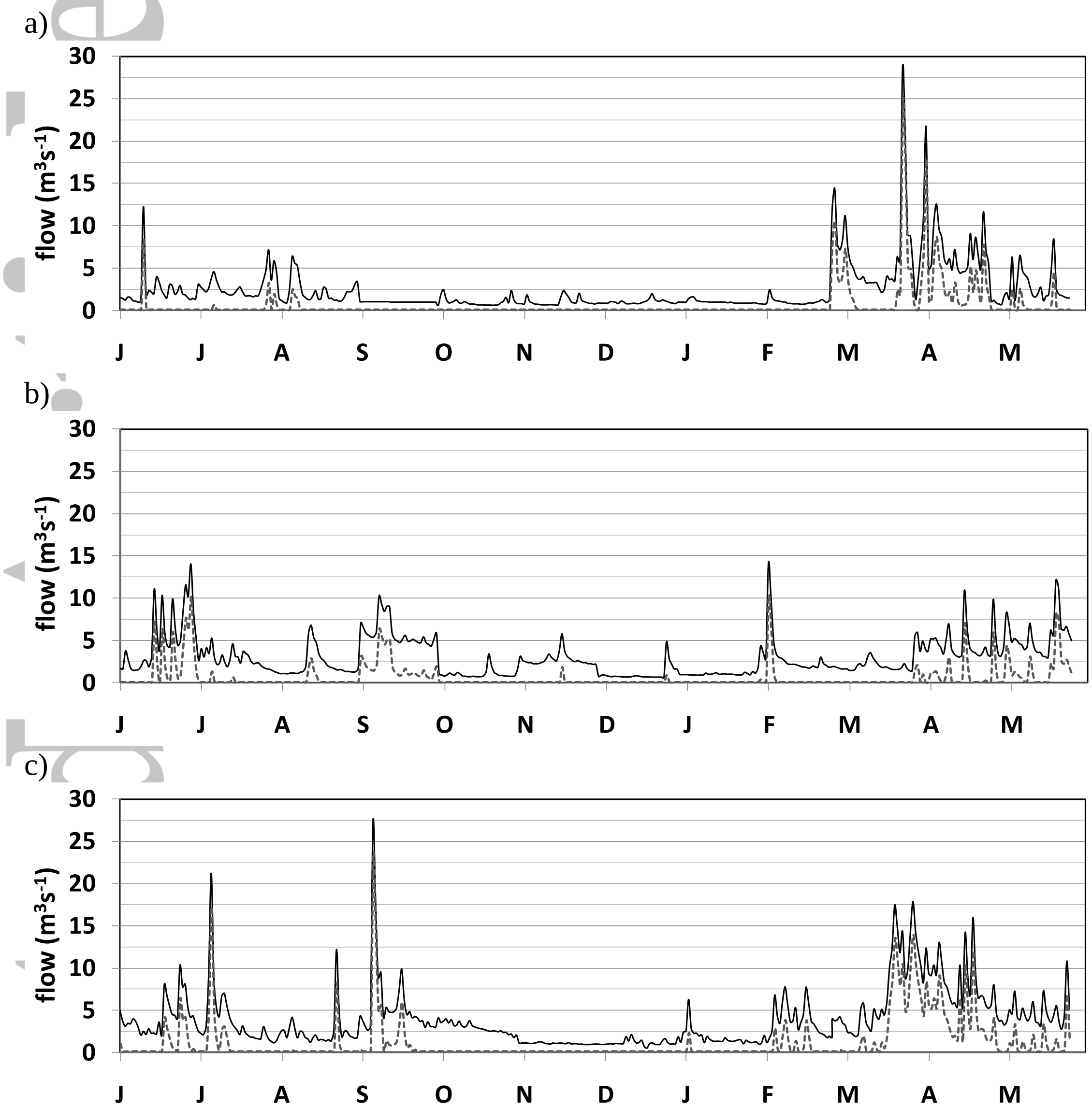

Fig. 3. Modeled natural (solid line) and modified (dashed line) flows of Gutan River, Lushui County below the small Gutan Dam (7.5 MW) for regional a) below average, b) average, and c) above average water years.

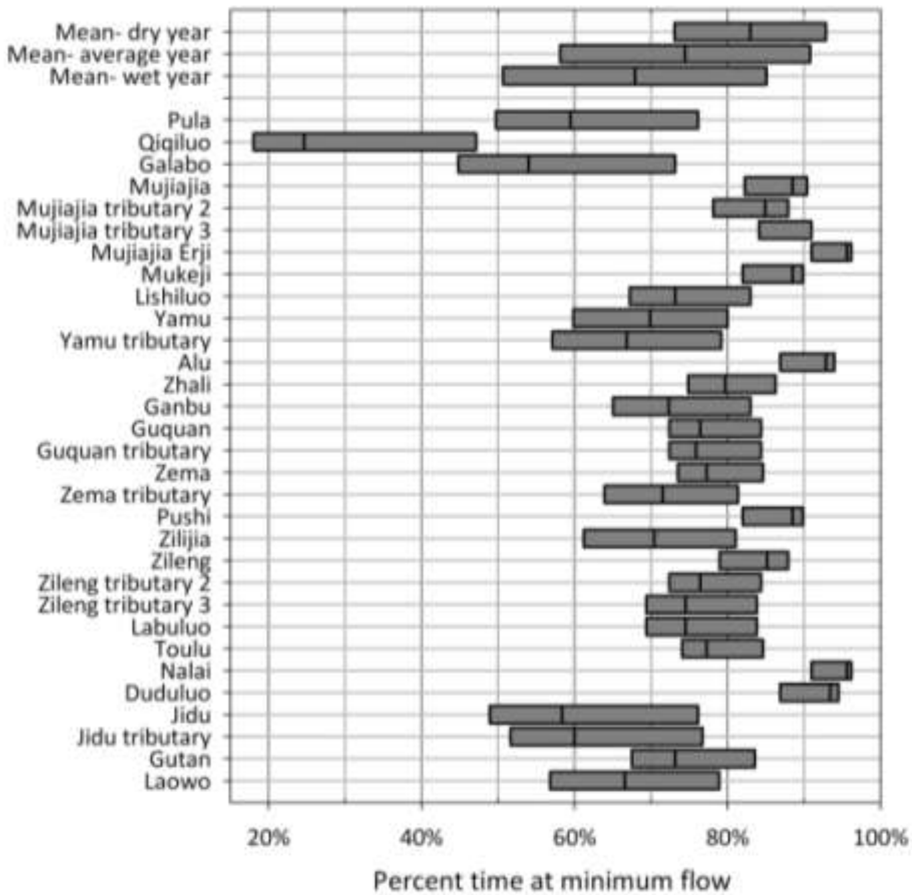

Fig. 4. Percentage of time that small dams dewater downstream river channels. Mean categories (top of figure) are mean percentages across the 31 small dams investigated, plus and minus one standard deviation. Data displayed for individual small dams (lower portion of figure) illustrates how dewatering effects vary among small dams and across typical dry, average, and wet years.

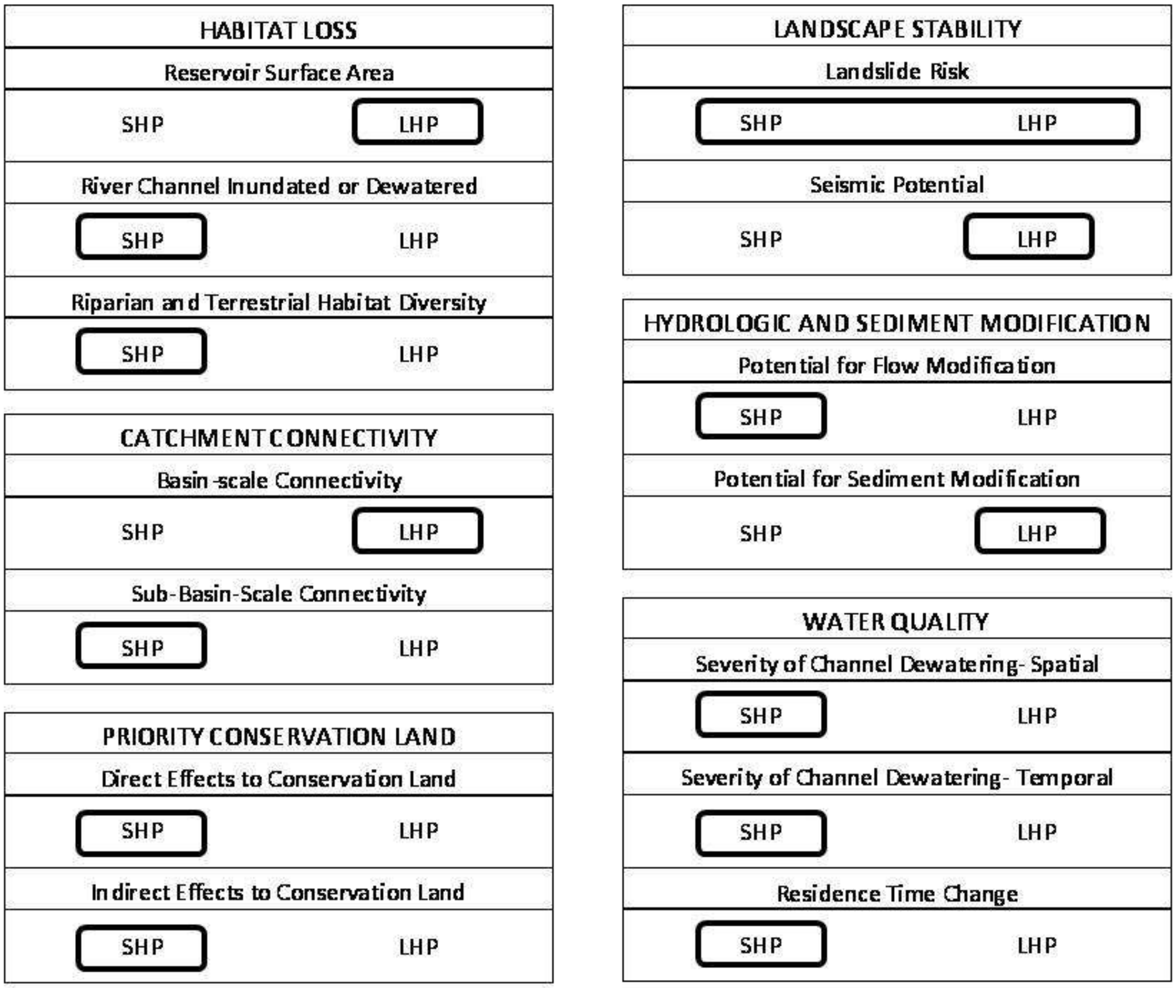

Fig. 5. Summary of study results. Figure indicates whether small hydropower dams (SHP) or large hydropower dams (LHP) have greater mean cumulative impact per megawatt of power.

Table 1. Design Characteristics of Large and Small Dams.

Dam Name	Project County	River Name	Installed Capacity (MW)	Dam Height (m)	Project Head (m)	River Gradient (mm^{-1})	Mean Flow (m^3s^{-1})
Maji	Fugong	Nu River	4200	300.0	300.0	0.001	1270.0
Lumadeng	Fugong	Nu River	2000	165.0	165.0	0.006	1330.0
Yabiluo	Lushui	Nu River	1800	133.0	133.0	0.009	1430.0
Lushui	Lushui	Nu River	2400	175.0	175.0	0.005	1500.0
Pula	Gongshan	Pula River	24.8	19.3	390.2	0.120	3.5
Qiqiluo	Gongshan	Qiluo River	20.0	18.7	80.0	0.036	13.1
Galabo	Gongshan	Galabo River	14.0	17.8	140.1	0.111	6.3
Mujiajia	Fugong	Mujiajia River	18.9	6.0	380.0	0.098	2.1
Mujiajia trib. 2	Fugong	Mujiajia tributary	NA	5.0	NA	0.182	0.8
Mujiajia trib. 3	Fugong	Mujiajia tributary	NA	6.0	NA	0.045	0.9
Mujiajia Erji	Fugong	Mujiajia River	10.0	10.0	224.0	0.143	1.9
Mukeji	Fugong	Mukeji River	31.5	10.5	640.0	0.084	3.4
Lishiluo	Fugong	Lishiluo River	6.4	14.5	338.0	0.108	1.9
Yamu	Fugong	Yamu River	49.0	8.7	367.0	0.071	3.9
Yamu trib.	Fugong	Yamu tributary	NA	8.7	NA	0.093	3.4
Alu	Fugong	Alu River	12.6	5.5	648.9	0.233	1.2
Zhali	Fugong	Zhali River	2.6	4.0	155.3	0.086	1.7
Ganbu	Fugong	Ganbu River	3.8	4.0	316.0	0.118	1.5
Guquan	Fugong	Guquan River	22.0	11.0	580.0	0.121	1.7
Guquan trib.	Fugong	Wuke River	NA	10.0	NA	0.139	1.4
Zema	Fugong	Zema River	15.0	4.0	500.0	0.064	2.6
Zema trib.	Fugong	Zema tributary	NA	3.0	NA	0.342	0.8
Pushi	Fugong	Pushi River	10.0	5.0	376.0	0.124	2.1
Zilijia	Fugong	Zilijia River	6.4	7.0	534.0	0.122	1.5
Zileng	Fugong	Zileng River	24.0	7.0	702.2	0.166	1.8
Zileng trib.	Fugong	Zileng tributary	NA	8.0	NA	0.176	1.1
Zileng trib.	Fugong	Zileng tributary	NA	5.5	NA	0.174	0.6
Labuluo	Fugong	Labuluo River	26.0	10.3	391.0	0.078	4.6
Toulu	Fugong	Toulu River	NA	10.0	NA	0.128	1.5
Nalai	Lushui	Nalai River	24.0	9.1	830.0	0.127	1.6
Duduluo	Lushui	Duduluo River	48.0	15.5	598.5	0.100	4.4
Jidu	Lushui	Jidu River	16.0	4.6	464.9	0.040	2.6
Jidu trib.	Lushui	Jidu tributary	NA	4.6	NA	0.111	2.5
Gutan	Lushui	Gutan River	7.5	4.0	300.7	0.069	3.1
Laowo	Lushui	Laowo River	25.0	17.0	177.0	0.029	15.7

Table 2. Metrics Evaluated to Characterize Biophysical Impact of Small and Large Dams.

METRIC	DESCRIPTION	UNITS
Habitat losses		
Reservoir surface area	quantity of riparian and terrestrial habitat inundated	km^2
River channel inundated or dewatered	quantity of aquatic habitat inundated or dewatered	km
Riparian and terrestrial habitat diversity	diversity (number) of riparian and terrestrial habitats inundated or dewatered	number
Catchment connectivity		
Basin-scale connectivity	percentage of Salween River basin contributing to dam	percent of basin
Sub-basin-scale connectivity	percentage of sub-basin contributing to dam	percent of basin
Priority conservation land		
Direct effects to conservation land	area of conservation land inundated or dewatered	km^2
Indirect effects to conservation land	proximity of conservation areas to project site	proximity index
Landscape stability		
Landslide risk	high and severe landslide risk areas inundated or dewatered	km^2
Seismic potential	index of reservoir depth, volume, and proximity of active faults	seismic index
Hydrologic and sediment regimes		
Potential for flow modification	percentage of annual runoff stored in reservoir or diverted from river	percent runoff
Potential for sediment modification	trap efficiency of reservoir	percent yield
Water quality		
Severity of channel dewatering (spatial)	length of dewatered channel	km
Severity of channel dewatering (temporal)	percent time channel is dewatered	percent time
Residence time change	change in residence time through impounded reach	percent change

Table 3. Cumulative Biophysical Impact, Shown as Absolute Impact and Relative to Megawatts of Power Produced by Small (SHP) and Large (LHP) Dams.

	Reservoir Surface Area		River Channel Inundated or Dewatered		Riparian and Terrestrial Habitat Diversity		Basin-Scale Connectivity		Sub-Basin-Scale Connectivity	
	Impact (km^2)	Impact Per Unit Power (km^2/MW)	Impact (km)	Impact Per Unit Power (km/MW)	Impact (number)	Impact Per Unit Power (number/MW)	Impact (percent)	Impact Per Unit Power (percent/MW)	Impact (percent)	Impact Per Unit Power (percent/MW)
SHP max	6.0E-03	2.9E-04	6.9E+00	4.3E-01	2.9E+00	2.5E-01	0.03	1.9E-03	73	7.4E+00
SHP min	3.4E-03	1.6E-04	NA	NA	NA	NA	NA	NA	NA	NA
LHP max	2.6E+01	8.5E-03	7.1E+01	2.5E-02	4.5E+00	1.8E-03	35	1.5E-02	35	1.5E-02
LHP min	1.1E+01	3.5E-03	3.0E+01	1.0E-02	3.3E+00	1.2E-03	NA	NA	NA	NA

	Direct Effect to Conservation Land		Indirect Effect to Conservation Land		Landslide Risk		Seismic Potential		Potential for Flow Modification	
	Impact (km^2)	Impact Per Unit Power (km^2/MW)	Impact (index)	Impact Per Unit Power (index/MW)	Impact (km^2)	Impact Per Unit Power (km^2/MW)	Impact (index)	Impact Per Unit Power (index/MW)	Impact (percent)	Impact Per Unit Power (percent/MW)
SHP max	0.4	2.1E-02	3.9	4.0E-01	7.6E-02	5.1E-03	7.0E-08	5.6E-09	75	8.3E+00
SHP min	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
LHP max	30.6	9.6E-03	3.6	1.5E-03	2.3E+01	7.8E-03	2.9E-01	8.0E-05	5	1.4E-03
LHP min	10.9	3.5E-03	3.0	1.2E-03	8.6E+00	2.9E-03	7.0E-02	1.8E-05	1	3.2E-04

	Potential for Sediment Modification		Severity of Channel Dewatering- Spatial		Severity of Channel Dewatering- Temporal		Residence Time Change	
	Impact (percent)	Impact Per Unit Power (percent/MW)	Impact (km)	Impact Per Unit Power (km/MW)	Impact (percent)	Impact Per Unit Power (percent/MW)	Impact (percent)	Impact Per Unit Power (percent/MW)
SHP max	0	0.E+00	4.8	4.2E-01	83	7.7E+00	8.6E+02	6.1E+01
SHP min	0	0.E+00	NA	NA	69	6.3E+00	5.6E+02	3.7E+01
LHP max	63	3.E-04	0.0	0.0E+00	0	0.0E+00	2.2E+04	8.8E+00
LHP min	26	8.E-05	0.0	0.0E+00	0	0.0E+00	8.6E+03	3.3E+00