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LETTER

Uncertainty in the Himalayan energy–water nexus: estimating regional exposure to glacial lake outburst floods

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Abstract

Himalayan water resources attract a rapidly growing number of hydroelectric power projects (HPP) to satisfy Asia's soaring energy demands. Yet HPP operating or planned in steep, glacier-fed mountain rivers face hazards of glacial lake outburst floods (GLOFs) that can damage hydropower infrastructure, alter water and sediment yields, and compromise livelihoods downstream. Detailed appraisals of such GLOF hazards are limited to case studies, however, and a more comprehensive, systematic analysis remains elusive. To this end we estimate the regional exposure of 257 Himalayan HPP to GLOFs, using a flood-wave propagation model fed by Monte Carlo-derived outburst volumes of >2300 glacial lakes. We interpret the spread of thus modeled peak discharges as a predictive uncertainty that arises mainly from outburst volumes and dam-breach rates that are difficult to assess before dams fail. With 66% of sampled HPP are on potential GLOF tracks, up to one third of these HPP could experience GLOF discharges well above local design floods, as hydropower development continues to seek higher sites closer to glacial lakes. We compute that this systematic push of HPP into headwaters effectively doubles the uncertainty about GLOF peak discharge in these locations. Peak discharges farther downstream, in contrast, are easier to predict because GLOF waves attenuate rapidly. Considering this systematic pattern of regional GLOF exposure might aid the site selection of future Himalayan HPP. Our method can augment, and help to regularly update, current hazard assessments, given that global warming is likely changing the number and size of Himalayan meltwater lakes.

Introduction

Electric power demands of Himalayan nations are on a steep rise. India's energy consumption has grown by 51% between 2000 and 2010, while China's consumption has more than doubled during that time. These figures are likely to grow by another 75% by 2035 if both countries sustain their rapid economic growth (Dopazo *et al* 2014). Current strategies for satisfying demands and downsizing the risk of power shortfalls include the expansion of hydropower capacities. With abundant monsoonal river discharge along steep mountain rivers, the Himalayas (figure 1(a)) offer a seemingly ideal setting for hydroelectric power projects (HPP). Less than 20% of the ~500 GW hydropower potential of the Himalayas are currently tapped (Vaidya 2013), thus encouraging further development that is also fueled by the World Bank's program agenda of reviving hydropower (World Bank 2009), and the Kyoto Protocol's Clean Development Mechanism (CDM). With 441 HPP as registered or currently validated applicants for the CDM worldwide, the Himalayas will have by far the largest HPP growth rates in coming years (table 1) (Erlewein and Nüsser 2011). As a result, the full implementation of pending hydropower plans could make the Himalayas the mountain belt with the world's highest density of dams (Grumbine and Pandit 2013).

Despite many projected benefits, the massive development of Himalayan HPP and its anticipated

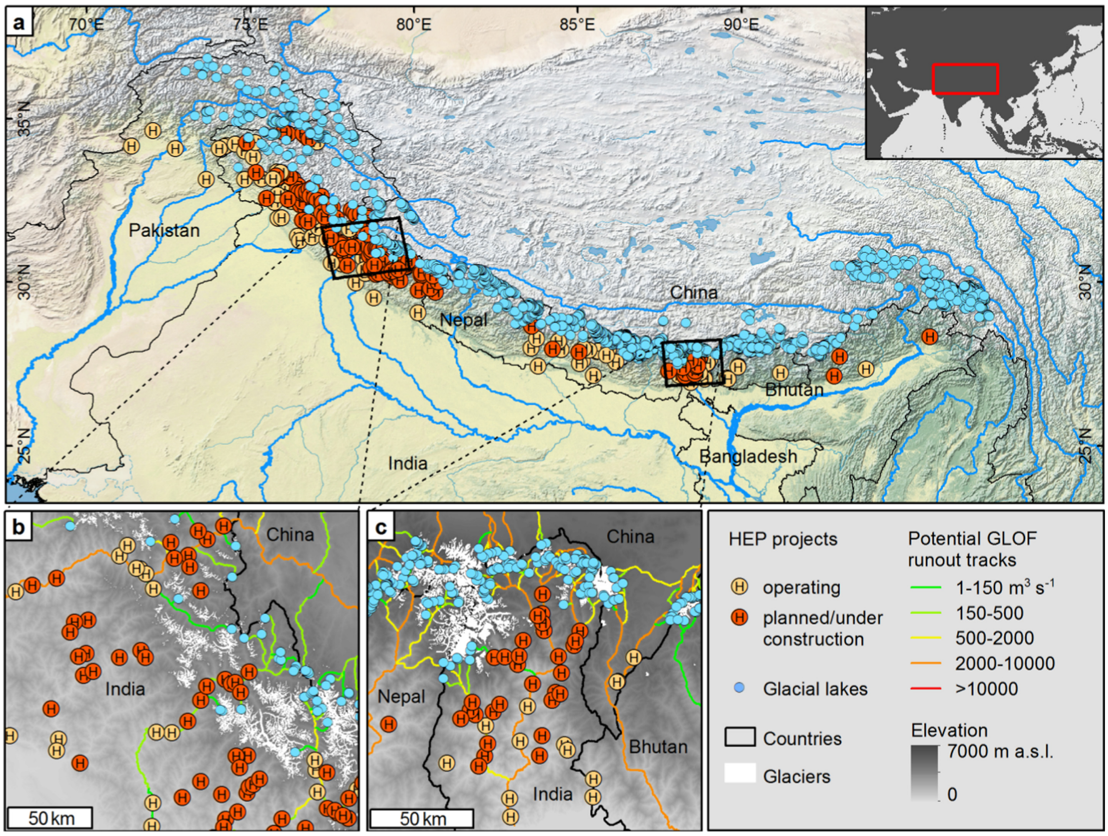

Figure 1. Distribution of 2231 Himalayan glacial lakes and studied hydropower projects. (a) Overview map of the study area. Insets (b), (c) show GLOF tracks from glacial lakes in the Indian states of Uttarakhand (b), and Sikkim (c). Color scale of GLOF tracks refers to median estimate of modeled peak discharge ($m^3\ s^{-1}$) averaged over 2 km channel segments. Where rivers accommodate multiple GLOF tracks, colors refer to the track with the highest peak discharge.

Table 1. Number of hydropower projects in the Himalayas applying for the CDM. Numbers in brackets refer to the expected power (MW). We set the breakpoint between large and small projects at 10 MW. Data is based on CDM pipeline data from 1 December, 2015 (www.cdmpipeline.org/).

	At validation		Registered		
Country	Large	Small	Large	Small	Total
Bhutan	2 (1740)		2 (1314)		4 (3054)
China[a]	2 (38)	3 (19)	230 (10 853)	70 (548)	305 (11 457)
India[b]	28 (8376)	17 (85)	36 (4800)	48 (260)	129 (13 520)
Nepal	1 (600)				1 (600)
Pakistan[c]	1 (640)		1 (84)		2 (724)
Total	34 (11 393)	20 (103)	269 (17 051)	118 (808)	441 (29 355)

[a] Yunnan province only.
[b] Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh only.
[c] Azad Kashmir only.

impacts on ecosystems, streamflow, sediment transport, and local communities have lowered the public acceptance of hydropower (Grumbine and Pandit 2013). Natural hazards are a particular concern for this sprawl of hydropower, as the Himalayas are seismically active, and prone to heavy monsoonal rainfall, landslides, and floods (Sundriyal *et al* 2015). Glacial lake outburst floods (GLOFs) in particular are a well-publicized, though insufficiently quantified, hazard to HPP (Sharma and Awal 2013, Vaidya 2013, Molden *et al* 2014, Reynolds 2014). Large amounts of meltwater from Himalayan glaciers are impounded as lakes behind moraine dams. Dozens of these natural debris dams have failed catastrophically in the 20th century, releasing destructive flash floods and debris flows. In 1985, a proglacial lake of Langmoche Glacier, Khumbu Himal, Nepal, emptied rapidly, generating a flood wave with a peak discharge Q_p of ~2000 $m^3\ s^{-1}$, and sluicing $3 \times 10^6\ m^3$ of sediment that obliterated a nearly completed HPP, along with nine years of

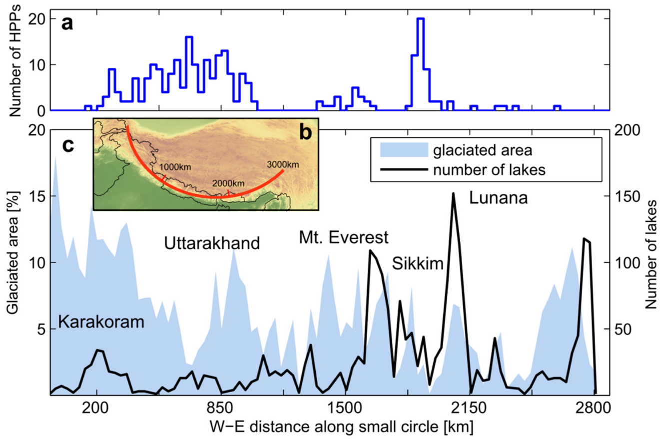

Figure 2. Distribution of Himalayan hydropower projects, glaciers, and glacial lakes. (a) Distribution of HPP sampled in this study along a small circle fitted to the axis of the Himalayan arc (inset (b)). (c) Percentage of glaciated area above 1900 m asl, and number of glacial lakes.

negotiations, planning, and construction (Ives 1986). Torrential rains rapidly raised the water level of the moraine-dammed Chorabari Lake, Uttarakhand, India, in June 2013. The dam breached and released 400 000 m^3 of water into the already flooded Mandakini River, inundating the pilgrimage city of Kedarnath (Allen *et al* 2015), and severely damaging at least two HPP sites downstream (Sandrp 2013).

The recognition that GLOFs can substantially exceed design floods of HPP at the risk of damage or complete inoperability (Richardson and Reynolds 2000) hinges on a handful of case studies, but the regional picture of GLOF exposure remains ill-defined. Most previous efforts to identify future GLOF sources from lake inventories disregard downstream impacts (Strozzi *et al* 2012, Fujita *et al* 2013). Hydrodynamic modeling of such impacts requires detailed digital elevation models (DEMs), and substantial computing power, so that simulations of potential outbursts are available for only a handful of lakes (Worni *et al* 2013). We fill this research gap by combining a new glacial lake inventory (figure 1) with both a dam-breach (Walder and O'Connor 1997) and a flood-propagation model (Ponce *et al* 2003) to estimate potential flood magnitudes for a sample of operating, planned, and currently constructed HPP in the Himalayas (figure 2(a)).

Data on the geometry of glacial lakes and the moraine dams are hard to come by, thus making regional predictions of peak discharges from GLOFs difficult. The aim of our study is to invert this problem and use the spread of simulated peak discharges at each HPP as a measure of uncertainty of GLOF exposure. We quantify this uncertainty by exploring the parameter space of the dam-breach model with a Monte Carlo simulation (figures S1–4). We use the resulting distributions of peak discharge and volume for each lake as the initial conditions for our flood-propagation model, and explore how peak discharge attenuates downstream, and varies at each HPP site.

Materials and methods

We mapped the areas of 2359 moraine-dammed lakes across the Himalayas from an unsupervised classification of high-resolution satellite images acquired between 2004 and 2015, and hosted by Google Earth and ESRI base maps (figure 1(a)). Which lakes are susceptible to draining catastrophically remains debated, and the same goes for reliably identifying moraine dams prone to imminent failure (Huggel *et al* 2004, McKillop and Clague 2007, Wang *et al* 2012). This prevents us from specifying site-specific probabilities of dam break and lake outburst. To reduce the degrees of freedom in our model, we naively assume that all dams are equally susceptible to failure, though being well aware that previous work identified ~2% of all Himalayan glacial lakes as potentially hazardous (Ives *et al* 2010). The recent destructive GLOF from the small and inconspicuous Lake Chorabari upstream of the town of Kedarnath (Allen *et al* 2015), however, clearly underscores that regional assessments of outburst probability need improving.

We used the mapped lake areas as input to a nested forward probabilistic model simulating values of outburst volume, dam-breach depth, and breach rate (see supplementary information). These parameters enter a physically based dam-breach model that predicts peak discharge at the dam (Q_0) after failure by overtopping or piping (Walder and O'Connor 1997). Determining outflow volume, breach depth, and breach rate usually requires detailed field surveys to constrain the lake bathymetry and dam properties; clearly this is impossible given the setting and number of lakes in our study. Instead, we explicitly quantify these uncertainties by sampling from probability distributions that we derived from published data (Huggel *et al* 2002, O'Connor and Beebee 2009, Sakai 2012) using a Monte-Carlo simulation (Westoby *et al* 2014b, 2015) (see supplementary information). Our probabilistic model (figures S1–3, table S1) computes for each lake 100 000 dam-breach simulations with differing values of corresponding peak discharge and outburst volume (Walder and O'Connor 1997). We obtained independent support for about 30% of our outburst volumes by cross-checking our simulations with data by Fujita *et al* (2013), who estimated potential flood volumes (PFV) of Himalayan glacial lakes by taking the geometry of moraine dams into account (see supplementary information). We repeated the Monte-Carlo simulations with breach depth and breach rate as free parameters, while keeping the outflow volume equal to PFV (figures S7–8).

We refined a semi-analytical flood-wave propagation model (Ponce *et al* 2003) that analytically approximates the kinematic wave equation for simulating downstream wave attenuation, and estimates local peak discharge Q_p mainly as a function of downstream distance, channel gradient, hydrograph volume, and flood-wave length. We calibrated this model using channel roughness (Manning's n) with observed and modeled GLOFs in the Mt Everest region (see supplementary information). We modeled the steepest-descent paths derived from a hydrologically corrected 90 m DEM using TopoToolbox 2 (Schwanghart and Scherler 2014), and tracked how Q_p attenuates downstream while capturing the propagating uncertainties in the dam-breach model.

We intersected the modeled GLOF tracks (figures 1(b) and (c)) with the locations of 95 operative, and 162 currently constructed or planned HPP from published coordinates and maps (Erlewein 2013, Sandrp 2013), and cross-checks of high-resolution satellite imagery. Most of the sampled HPP are in the Indian Himalayan states of Himachal Pradesh, Uttarakhand, and Sikkim, and some in Nepal and Bhutan (figures 1 and 2(a)). We collected data on spillway design floods (the flood magnitude that a structure can safely pass) and meteorological flood-return periods for 104 HPP from 'grey literature' such as feasibility and project reports, environmental impact assessments, and HPP company websites (see supplementary information).

Results and interpretation

Our inventory of 2359 Himalayan glacial lakes reveals that lakes cover areas from a few hectares to up to 5.6 km^2, and store an estimated 11.0 ($^{+0.7}/_{-0.6}$) km^3 (95% bootstrap confidence interval) of water between 3000 and 6000 m a.s.l. The spatial density of lakes varies regionally; lakes cluster in eastern Nepal and Bhutan, but are rare in the Karakorum despite abundant glaciers (figures 2(b) and (c)). This pattern is consistent with decadal glacier mass-balance changes in the Himalayas (Kääb *et al* 2012); lakes are prolific in the Nepal and Bhutan Himalayas, where contemporary glacial melting rates are highest (Gardelle *et al* 2011).

Estimating regional GLOF exposure

We find that 177 HPP are located along potential GLOF tracks; the remainder does not have glacial lakes in their headwaters. Half of all operating HPP are <140 km below one or several lakes, whereas planned or currently constructed HPP are much closer (<90 km) to fewer lakes on average (figure 3). This pattern documents how hydropower development pushes into higher elevations, closer to potential GLOF sources. Estimated peak discharges at potential breach sites vary by two orders of magnitude for a given lake area (figure S4), and mainly reflect uncertainties about lake bathymetry, breach depth, and breach rate (figures 4(a), S5). For smaller lake areas, lake depth and lake volume produce most of the spread in Q_0; for larger lake areas, breach depth and rate contribute most of this uncertainty (figure S5). GLOF waves attenuate rapidly downstream, whereas meteorological flood peaks grow with increasing drainage area (Cenderelli and Wohl 2001, Koike and Takenaka 2012) (figure 4(b)). Thus we define 'impact reaches' d_c, along which modeled GLOF peak discharge exceeds the estimated 100 year meteorological flood (figure 4(c)). Such impact reaches occupy the upper ~20 ($^{+35}/_{-13}$) km (90% bootstrap confidence interval) below half of all lakes mapped (figure 4(c)). Only the farthest-reaching GLOFs may surpass the estimated 100 year floods for up to 85 ($^{+45}/_{-65}$) km downstream. Particularly Sikkim stands out as a region combining abundant glacial lakes, long potential GLOF tracks, and pronounced hydropower development (figure 4(d)). Several regions in Eastern Nepal and Bhutan also host lakes that could give rise to far-reaching GLOFs.

Published design flood estimates for HPP, in contrast, derive from either unit-hydrograph or extreme-value statistics of gauging records of nearby hydrological stations. Most feasibility reports use empirical relationships between peak discharge and drainage area for a given return period, or simply extrapolate data of HPP on the same river. Our simulated GLOF peak discharges surpass the design floods of 56 HPP (90% bootstrap confidence interval; figure 5), and show potential limits of relying solely on meteorological flood peaks for establishing design floods.

Twice the uncertainty closer to glacial lakes

The distance from glacial lakes is another decisive factor in HPP exposure, and modulates the spread in simulated GLOF peak discharges at a given site. This spread becomes narrower downstream irrespective of the initial value at the breached dam (Ponce *et al* 2003).

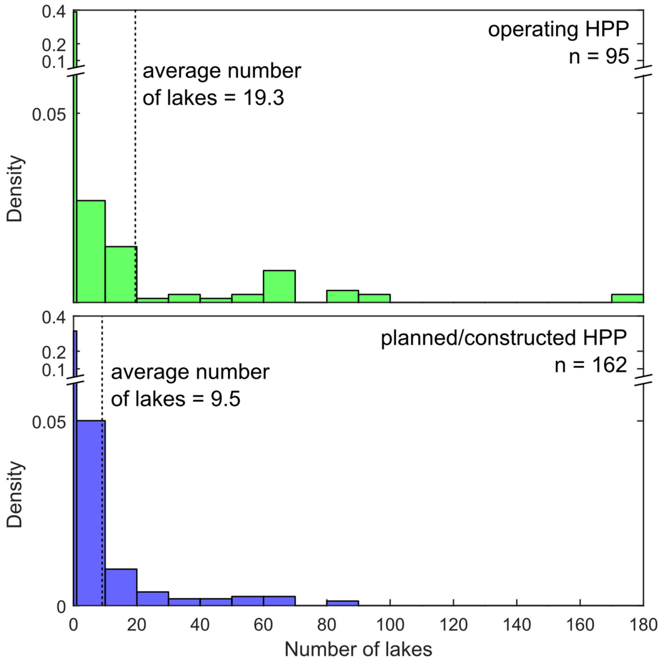

Figure 3. Distributions of the quantity of lakes upstream of operating (a) and planned/currently constructed (b) Himalayan hydropower projects.

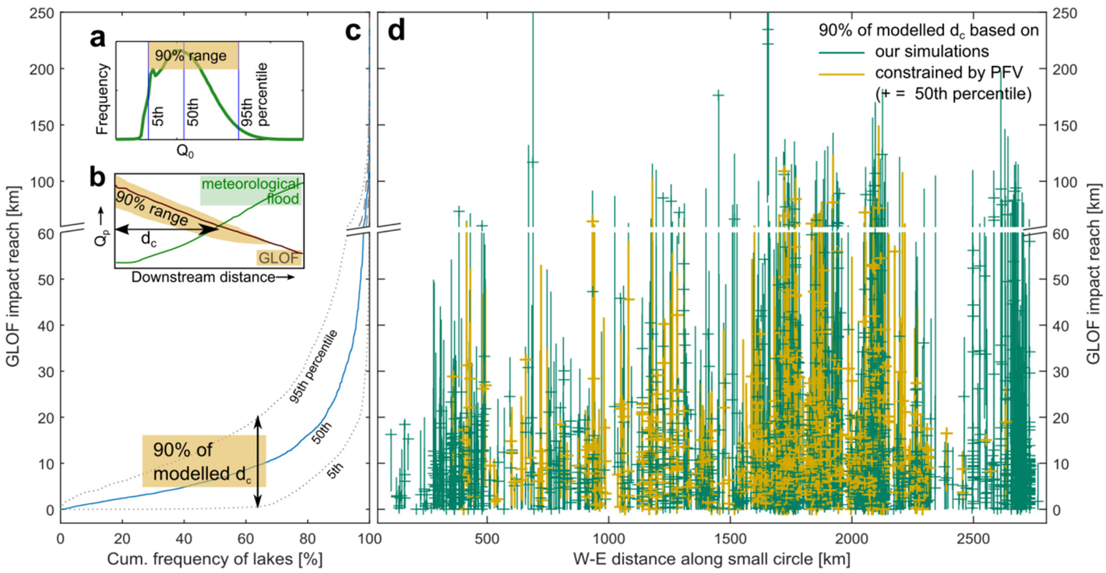

Figure 4. Distribution of GLOF impact reaches. GLOF impact reach d_c refers to those channel segments where simulated GLOF peak discharges exceed local meteorological 1-in-a-100 year flood peaks below a given glacial lake. Uncertainties about d_c derive from distributions of simulated peak discharge at the breach sites (a), and flood-attenuation modeling (b). (a) Exemplary distribution of peak discharge Q_0 simulated at the breach site of a sample lake; percentiles are used as input to the flood-propagation model. (b) Sketch of differing downstream trends in GLOF and meteorological flood peaks. (c) Simulated distribution of d_c. More than half of all potential GLOFs exceed 100-year meteorological floods at <20 km downstream from the lakes; only 1% of the lakes could theoretically release GLOFs with impact reaches of 85 km ($^{+45}/_{-65}$ km; 90% bootstrap confidence interval). (d) Distribution of GLOF impact reaches along the Himalayan arc (see figure 2(b)).

For HPP sufficiently far away from glacial lakes, the uncertainty regarding Q_p thus decreases. To identify the river reaches with the highest uncertainties, we determined the distance at which the 90% bootstrap confidence interval of our modeled Q_p narrows to <5% of that at the dam site. In more than half of all cases this distance is 80 km ($^{+100}/_{-60}$) km (figure 6(a)). Steep headwater channels stretching a few tens of kilometers below glacial lakes rarely dampen peak discharges (Ponce *et al* 2003), and are

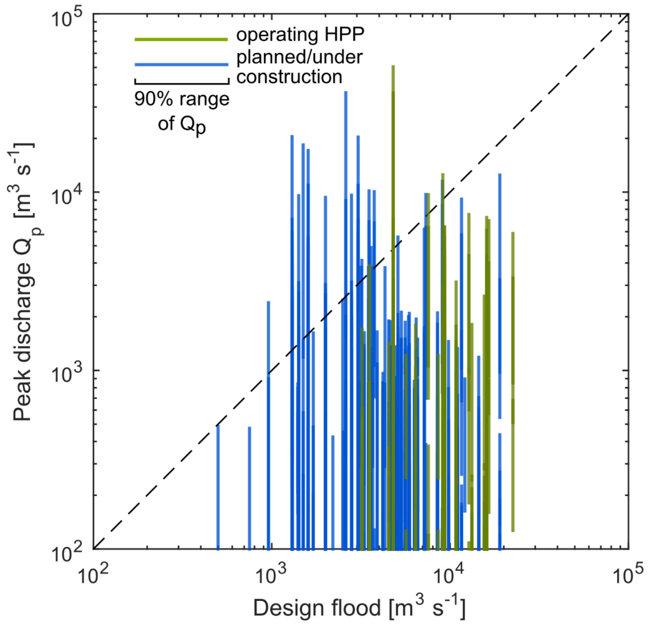

Figure 5. Reported design floods versus simulated GLOF peak discharge at selected Himalayan hydropower sites. Bars show the 90% range of simulated peak discharge from all potential GLOF tracks at a given HPP. Bars extending above the 1:1 line identify HPP with spillway design floods lower than the simulated range of GLOF peak discharge.

thus prone to more variable GLOF peaks. We compute that HPP planned or currently constructed in headwaters may have to deal with an uncertainty about Q_p that is more than twice than that in downstream reaches with already operative HPP (figure 6(b)).

Discussion

Limits to assessing regional GLOF exposure

We present a new and robust method for locating the minimum GLOF exposure of hydropower sites in the Himalayas. We refrain from determining which of the thousands of glacial lakes will drain catastrophically, because the physical setting of a lake rarely reveals unmistakable clues about GLOF probabilities (Wang *et al* 2012). The stability of moraine dams is controlled by glacier thinning and retreat, meltwater production, freeboard, and the recurrence of outburst triggers such as earthquakes, avalanches or landslides into the lake, glacier calving, or heavy rain (Watanabe *et al* 2009, Benn *et al* 2012). Whether any of these factors reliably indicates whether a lake is hazardous or not, remains largely contentious (Fujita *et al* 2009, Watanabe *et al* 2009).

Therefore, we partly invert this problem by quantifying where in the drainage network the predicted GLOF peak discharges vary the most, and where the uncertainty about GLOF exposure is highest. Our simulations emphasize how Q_0 varies up to two orders of magnitudes at a given lake without detailed information on lake volume, depth, and dam properties. Our sensitivity analysis reveals the main sources of these uncertainties, and that, for larger lakes (>0.1 km^2), data on possible breach rates and depths are more important for improving estimates of Q_0. In this context, estimating lake volumes from remote sensing data is still compromised by changing ice cover and water colors (Huggel *et al* 2002), while increasingly more detailed digital topographic data such as WorldDEM (Riegler *et al* 2015) allow capturing more accurately the geometry of moraine dams. Our simulations can hence be easily be updated, once more refined information about lake-outburst probabilities will become available. In any case, we stress that our regional analysis can augment, though in no case replace, detailed at-a-station estimates of GLOF impacts. Some HPPs have tens to up to >100 glacial lakes in their headwaters (figure 3), such that investigating each of these in the field is unrealistic. Even where lakes are selected for detailed fieldwork, site-specific estimates of Q_p are costly and compromised by scant data on past GLOFs, and predictions about future glacier dynamics and climate change (Huggel *et al* 2004, McKillop and Clague 2007).

Our hydrodynamic flood-wave propagation model attempts to go beyond empirical envelope curves for outburst floods (Bergman *et al* 2014) (figure S6) by including first-order controls such as outflow volume, channel-bed gradient, and width, while avoiding the computational burden of 2D or 3D models (Carling *et al* 2010, Westoby *et al* 2014a). Our regional focus necessitates ignoring or simplifying local effects such as hydraulic ponding or the obstruction of channels by debris or flank failures (Huggel *et al* 2004). More complex models account for such processes, but are highly sensitive to poorly constrained roughness parameters (Bajracharya *et al* 2007a), and demand

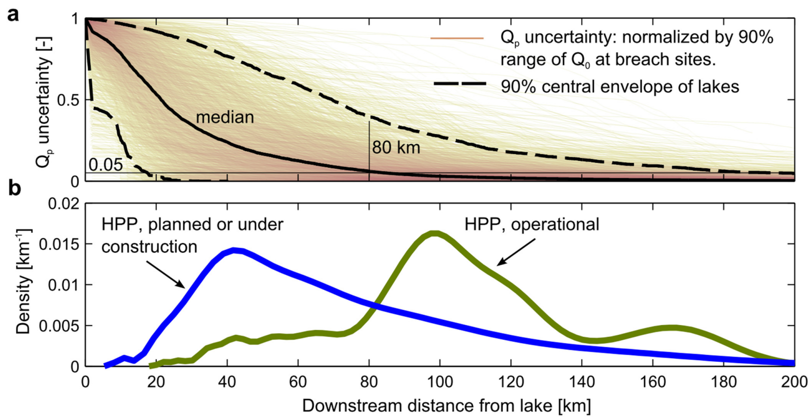

Figure 6. Downstream trend of uncertainties in GLOF simulations. (a) Uncertainty about local peak discharge Q_p expressed as the 90% range of simulated values normalized to peak discharge Q_0 at the breach site. This uncertainty decreases downstream at different rates. For 90% of all lakes, the range of normalized Q_p reduces by 2% to 90% along the first 20 km downstream of the lakes; such uncertainties decay to ⟨5%⟩ 80 km downstream. (b) Distribution of distances of HPP sites from glacial lakes. Currently planned or constructed HPP projects are in river sections with higher uncertainty (a) as compared to operational HPP.

detailed channel geometric data (Pitman *et al* 2013) that are rare for the Himalayas. Sediment concentration further alters the physical impact on HPP through bed-load transport or debris flows (Osti and Egashira 2009), and will need to see integration in future models. Detailed surveys of river bed changes by GLOFs show that erosion and reworking of coarse debris by GLOFs can be most pronounced 10–20 km downstream of the breach site (Cenderelli and Wohl 2001). However, large quantities of material can be additionally mobilized and transported further downstream by flow bulking (Breien *et al* 2008), the erosion of terraces, and undercutting and failure of valley slopes and river banks (Mool 1994), thus leading to pronounced sediment concentrations further downstream. Moreover, channel adjustment to outburst flows can last years to decades (Morche and Schmidt 2012) and compromise downstream located HPPs in the long run.

Challenges for Himalayan hydropower

HPP involve large investments, design lifetimes of ~80 years (IEA/NEA 2010) and long-term amortization. Planners of HPP have become increasingly aware of climate-change scenarios (Kääb *et al* 2012), including GLOF hazards (Molden 2015), which are likely to change as glaciers retreat and new meltwater lakes form (Bajracharya *et al* 2007b) below ice and rock slopes potentially weakened by degrading permafrost. Our results show that, even without these and other potential impacts of climate change, simulated GLOF peaks cover a broad range already, especially close to their sources. This variability will add to that tied to climate change, underlining the need for reliably (re-) assessing design floods in ungauged Himalayan catchments. The common practice of calculating extreme flood magnitudes from a portfolio of unit-hydrograph methods, empirical equations, or regionalized flood frequency largely overlooks GLOFs as a flood mechanism, and calls for regular updates of design-flood estimates. Large spillways and diversion structures are costly; yet inadequate design and subsequent overflows by GLOFs may incur substantial human and material losses (Yenigun and Erkek 2007). Further scrutinizing GLOF hazards and economic viability of HPP could be the way forward to warranting environmental security and manage risks effectively.

Those Himalayan rivers with the highest variability in predicted GLOF discharges may well include the ones to experience the largest growth rates in hydropower in coming years. Strategies for climate change mitigation and adaptation at the subnational level are currently prepared by Indian Himalayan states (i.e. State Action Plans on Climate Change), and identify GLOFs as a major climate change-related threat to hydropower development (Government of Uttarakhand 2014). At the same time, however, harnessing hydropower to higher elevations is clearly the favored effort of meeting increasing power demand and advancing low-carbon economies. Disregarding the current upstream increase of uncertainties about GLOF discharges for HPP to be located in headwaters may undermine some of the coordination between climate-change mitigation, adaption, and energy plans. The more than doubled uncertainty resulting from the upstream push of Himalayan hydropower (figure 6) is a minimum consideration. Other uncertainties will add, such as those related to Himalayan climate change and glacier dynamics (Kääb *et al* 2012), to the task of making hydropower infrastructure more adaptable and sustainable.

Conclusions

Drawing mainly on geometric data of 2359 glacial lakes in the Himalayas, we estimated the distribution of GLOF peak discharges and their downstream attenuation in a probabilistic framework. The many unknowns concerning these glacial lakes, and the stability of their dams in particular, has left researchers with few hard clues as to which lakes are likely to fail catastrophically next. Motivated by this knowledge gap, we use the spread of our modeled peak discharges as a bulk metric of uncertainty of regional GLOF exposure rather than a collection of local flood peaks. A sample of 259 HPP indicates a distinct push of development into headwaters where our GLOF simulations return a bandwidth of predictions more than twice as broad as for existing HPP sites further downstream, irrespective of any additional impacts of climate change. This move into higher uncertainty can be countered by obtaining more detailed data on lake area, depth, and volume for smaller (<0.1 km^2) lakes, and data on potential breach rate and depth for larger lakes. Even at the present level of uncertainty regarding GLOF exposure, our method offers some insights that may aid selecting locations of future HPP.

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