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Sectorwise Assessment of Glacial Lake Outburst Flood Danger in the Indian Himalayan Region

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Climate change and associated glacier recession have led to the formation of new glacial lakes and the expansion of existing ones across the Himalayas. Many pose a potential glacial lake outburst flood (GLOF) threat to downstream communities and infrastructure. In this paper, 4418 glacial lakes in the Indian Himalayan Region and 636 transboundary lakes are analyzed. We consider hazard, exposure, and integrated danger levels using robust geographic information system-based automated approaches. The hazard level of lakes was estimated based on the potential for avalanches to strike the lake, size of the lake and its upstream watershed, and distal slope of its dam. Exposure levels were calculated by intersecting cropland, roads, hydropower projects, and the human population with potential GLOF trajectories. Then, GLOF danger was determined as a function of hazard and exposure. The study demonstrates that Jammu and Kashmir (JK) is potentially the most threatened region in terms of total number of very high and high danger lakes (n = 556), followed by Arunachal Pradesh (AP) (n = 388) and Sikkim (SK) (n = 219). Sectorwise, JK faces the greatest GLOF threat to roads and population, whereas the threat to cropland and hydropower is greatest in AP and SK, respectively. Transboundary lakes primarily threaten AP and, to a lesser extent, Himachal Pradesh (HP). For Uttarakhand (UK), the impacts of potential future glacial lakes, expected to form during rapid ongoing glacier recession because of climate change, are explored. Finally, a comparison of current results with previous studies suggests that 13 lakes in SK, 5 in HP, 4 in JK, 2 in UK, and 1 in AP are of highest priority for local investigation and potential risk reduction measures. Current results are of vital importance to policymakers, disaster management authorities, and the scientific community.

Keywords: *glacial lake outburst floods; hazard; exposure; hydropower; Indian Himalayas; transboundary threats.*

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Introduction

Glacial lakes are highly dynamic water reservoirs (Raj and Kumar 2016; Aggarwal et al 2017) that respond to climate change by expanding in number, size, and volume (Bolch et al 2019). This is particularly evident across the mountains of Asia, including in the Hindu Kush Karakoram Himalayas (HKH), Tien Shan, and Tibet (Ives et al 2010; Bolch et al 2011; Gardelle et al 2011; Nie et al 2013, 2017). As a result of climate change, and consequent accelerated glacier recession (Bolch et al 2012, 2019; Brun et al 2017; Maurer et al 2019), the number (area) of glacial lakes in HKH increased from 4549 lakes (398.9 km^2) in 1990 to 4950 lakes (455.3 km^2) in 2015 (Nie et al 2017), and similar trends are seen in the other mountain ranges (Bolch et al 2019). Several large-scale and regional assessment studies confirm the growth of glacial lakes and their hazardous potentials across Asia (Ives et al 2010; Bolch et al 2011; Worni et al 2013; Zhang et al 2015; Allen, Linsbauer, et al 2016; Aggarwal et al 2017; Prakash and Nagarajan 2017; Rounce et al 2017; Allen et al 2019; Dubey and Goyal 2020).

The first coordinated study on glacial lakes across the Indian Himalayan Region (IHR) revealed 70 potentially dangerous lakes (Ives et al 2010). By comparison, another study suggested 108 potentially critical and critical lakes in the IHR (Worni et al 2013), whereas 45 lakes were observed to be of high to very high risk by Dubey and Goyal (2020). Fujita et al (2013) revealed only 5 lakes with potentially high and very high flood volumes in the IHR. These studies applied different methods, decision criteria, and critical thresholds for defining glacial lake outburst flood (GLOF) hazard and risk and therefore are not directly comparable.

GLOFs are the sudden and high-magnitude discharge of dammed glacial lakes (Allen, Linsbauer, et al 2016), and in some cases, the release of water and entrainment of debris can lead to catastrophic floods and damage in downstream regions (Buchroithner and Bolch 2014; Kropáček et al 2015; Carrivick and Tweed 2016). Examples include Chorabari (2013) in Uttarakhand (UK), India (Allen, Rastner, et al 2016; Bhambri et al 2016); Gongbatongshacuo in China (Cook et al 2018), and the breach of moraine-dammed lakes in Nepal (1977 and 1985) (Buchroithner et al 1982; Thakuri et al 2016). Outburst floods originating from transboundary (TB) regions can be particularly dangerous, because assessment information is often incomplete. Therefore, response strategies need to be substantially strengthened between the source and the affected regions (Khanal et al 2015; Ruiz-Villanueva et al 2017).

In the HKH, the frequency of GLOFs, particularly from moraine-dammed glacial lakes, has shown periods of enhanced activity since the mid-20th century (Harrison et al 2018; Richardson and Reynolds 2000). However, despite clear trends in lake number and area, there is no long-term trend seen in the frequency of GLOFs (Hock et al 2019; Veh et al 2019). Given potential future lake development (Frey et al 2010; Linsbauer et al 2016), coupled with the rapid expansion of residential, tourism, transport, and particularly hydropower project (HPP) infrastructure higher into the alpine valleys of HKH (Sidle and Ziegler 2012; Allen, Linsbauer, et al 2016; Schwanghart et al 2016), a significant increase in future GLOF risk is anticipated. There is an urgent need for a robust scientific assessment to underpin the design of response and mitigation strategies by national- and state-level authorities (Quincey et al 2007; Allen, Linsbauer, et al 2016).

For the IHR in particular, a significant limitation in addressing the emerging GLOF risk is the lack of a homogenous inventory of glacial lakes and their associated danger level, with significant inconsistencies seen across regional studies (Ives et al 2010; Worni et al 2013; Dubey and Goyal 2020). From an applied perspective, this leads to limitations in comparing different studies from different regions. Furthermore, none of the previous studies included the entirety of the Indian Himalayan states, as recognized by the Government of India. It is, therefore, challenging to plan the allocation of resources for GLOF risk reduction measures. Hence, one of the core components of the current study addresses this crucial gap, creating the first regionwide, consistent GLOF hazard and danger inventory that draws and expands on best practices according to recent international guidelines (GAPHAZ 2017).

This study aims to fill an essential and crucial gap in our scientific understanding of the GLOF threats in the IHR. It directly responds to the needs of policymakers by highlighting critically dangerous lakes, which could be subsequently targeted for further monitoring and GLOF risk reduction measures. Specifically, the present study's aims are as follows:

1. Establish a comprehensive inventory and prioritization of potentially dangerous lakes across the IHR, including TB lakes located in neighboring territories, considering both the likelihood and the possible magnitude of an outburst event, as well as the consequences for downstream communities;
2. Identify hotspots of GLOF danger, both present and under future conditions, considering the formation of future lakes.

The study area

The present study was carried out within the glaciated IHR: Jammu and Kashmir (JK), Himachal Pradesh (HP), UK, Sikkim (SK), and Arunachal Pradesh (AP) (Figure 1). The state boundaries were adopted from the Census of India map 2011 (https://censusindia.gov.in). Other Himalayan states are highlighted in the results for cases in which potential GLOF paths extend farther downstream. The study was carried out before the formation of Jammu and Kashmir union territory and Ladakh union territory (hence, JK corresponds to both union territories). According to Randolph Glacier Inventory version 6 (RGI 2017), the IHR has 22,562 glaciers covering an area of 32,088.9 km^2. The climate of the IHR varies from a subtropical oceanic highland climate in AP to a cold desert climate in Ladakh and the eastern Karakoram region (Srivastav and Jones 2009). The temperature in the western Himalaya has increased by 1.6°C over the last century (Bhutiyani et al 2010), whereas in the eastern Himalaya, an increase of 1.98°C has been observed since 1871 (Jain et al 2013). At the same time, precipitation trends in the IHR are highly uncertain and erratic (Palazzi et al 2013). A total human population of ~77 million live in the 11 mountain states of the IHR, which is 34.4% of the HKH population (Sharma et al 2019). The population density in the IHR varies from 189 people/km^2 in UK to 17 people/km^2 in AP (Census of India 2011).

Material and methods

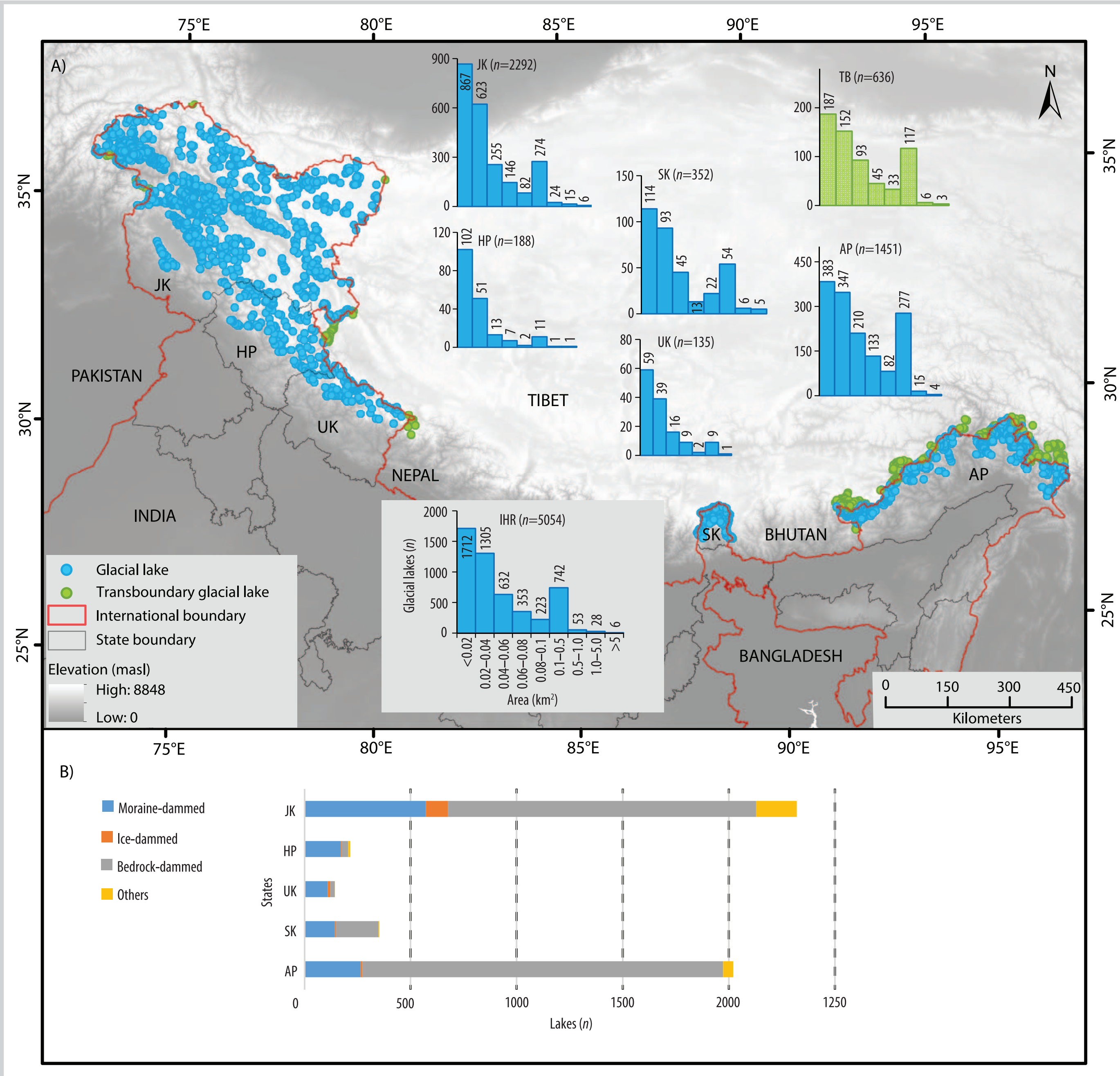
Data

For the present study, the foremost requirement was a detailed inventory of glacial lakes, which was adopted from Zheng et al (2021). The lake inventory included 5054 lakes ($>$0.01 km^2) that are located in the IHR and potentially affecting it. It was based on 51 Landsat 8 Operational Land Imager satellite images from 2014–2016 (pan-sharpened to a resolution of 15 m), acquired from the US Geological Survey (USGS) (earthexplorer.usgs.gov). Shuttle Radar Topography Mission (SRTM) version 4 digital elevation model (DEM) (90 m), also acquired from USGS, was used to generate the topographical parameters. For exposure analysis, road network information was retrieved from the OpenStreetMap (www.geofabrik.de). The raster layers defining cropland (30 m, as of 2013) and human population (100 m, as of 2019) were taken from Global Food Security Analysis support data (www.croplands.org), and WorldPop (www.worldpop.org), respectively. The HPPs for the entire IHR ($n = 198$) were obtained from Schwanghart et al (2016). An additional layer of HPPs (currently operational, under construction, and planned; $n = 228$) was generated for a case study in UK to assess current and future GLOF danger.

Methods

GLOF hazard: The GLOF hazard is considered a function of (1) the topographical potential of ice and rock avalanches, (2) the distal slope of the glacial lake dam, (3) the lake watershed area, and (4) the lake area (Allen et al 2019). Ice and rock avalanches are typical GLOF triggers in the HKH (Richardson and Reynolds 2000; Liu et al 2013). Two factors determine the likelihood of such a process chain: (1) the possibility of detachment of rock and/or ice from the slope above the glacial lake and (2) its potential to reach a glacial lake below (Allen et al 2019). These processes typically occur if there is a slope angle of 30° or more above the lake (Alean 1985) and the overall trajectory slope between the detachment zone and the lake is $>$14° (Romstad et al 2009; Allen et al 2011, 2019). The topographical potential

FIGURE 1 (A) Spatial distribution of glacial lakes in the IHR ($n = 4418$), along with transboundary glacial lakes ($n = 636$) that have potential flood trajectories draining into the IHR. (B) Glacial lake typology. Background: SRTM DEM (90 m). Red lines indicate the international border of India, whereas gray lines refer to state borders within India.



approach combines these 2 factors and quantifies the area predisposed to impact for each glacial lake (Romstad et al 2009). Higher weighting was assigned to glaciated slopes, relative to bedrock slopes, recognizing the high frequency and hence the potential of ice avalanches as a trigger of GLOFs in the HKH. To estimate the distal slope of lake dams, we extracted all slope pixels within a 1-km buffer downstream of each lake. Higher mean slope angles were considered to indicate a greater predisposition to dam failure and/or erosion of debris. The watershed area located upstream of each lake is considered essential for glacial lake hazard assessment, because meltwater and rainfall runoff can fill the glacial lakes, cause dam overtopping, and consequently, trigger a GLOF (Allen, Linsbauer, et al 2016). The area of the watershed is considered a proxy for the potential amount of runoff and water reaching a glacial lake (Allen et al 2019). Meanwhile, in the absence of direct measurements, the area of the glacial lakes is considered a proxy for lake volume (Muñoz et al 2020). All stated parameters of hazard were normalized using the percent rank function, and these values were averaged for each lake to derive a mean hazard index (Table 1).

GLOF exposure: Exposure is considered the presence of human population and infrastructure facilities that are likely to be affected by GLOF events (Allen, Linsbauer, et al 2016).

TABLE 1 Parameters for estimation of GLOF hazard in IHR.

State	Lake area	Topographical potential	Watershed area	Dam slope
JK	0.47	0.44	0.53	0.37
HP	0.36	0.46	0.44	0.53
UK	0.41	0.43	0.45	0.45
SK	0.51	0.48	0.51	0.47
AP	0.55	0.48	0.48	0.65

Note: Values are the averages of statewide standardized statistics.

The downstream GLOF trajectories were estimated until the angle of reach arrived at a minimum of 3°, corresponding to the worst-case maximum reach of destruction for hyperconcentrated GLOF flows (Haeberli 1983; Frey et al 2010; Allen et al 2019) using the modified single-flow model (Huggel et al 2003). In the next step, these GLOF trajectories were intersected with the raster layers of the human population, roads, cropland, and HPPs. The sum of the angle of reach for each pixel exposed to the lake flow path for different sectors was aggregated as a quantified measure of exposure for each glacial lake. In this way, exposed elements located farther from the lake source typically have lower levels of exposure, consistent with the rapid attenuation of GLOF intensity (Schwanghart et al 2016). The effect of GLOF on various sectors and the human population was averaged and normalized using the percent rank function.

Current lake danger: Because robust, socioeconomic-based vulnerability data for the entire IHR was unavailable, GLOF risk was not determined. Thus, to avoid possible confusion in terminology, we do not refer to "risk" but rather use the term "danger," defined as and calculated by multiplying the normalized values of hazard and sectorwise exposure for each lake. The sectorwise GLOF danger was further averaged to obtain a mean GLOF danger for each lake. A GLOF danger index (unitless) has been prepared, ranging from 0 to 4. For display and comprehension purposes, lakewise hazard, exposure, and danger values were classified into 5 classes using the natural break function in ArcGIS, which clusters the data based on natural groupings. In addition, GLOF hazard, exposure, and danger were aggregated at the state level to identify GLOF hotspots in the IHR.

Future lake danger: To demonstrate future GLOF danger, potential future glacial lakes were modeled using the GlabTop2 model (Linsbauer et al 2012, 2016; Frey et al 2014) for UK as a case study. The model estimates the ice thickness distribution based on glacier outlines and a DEM. By subtracting ice thickness values from the input surface DEM, glacier bed topography can be inferred and analyzed for overdeepened depressions. These glacier bed overdeepenings can be considered sites where existing glacial lakes can expand and new glacial lakes could develop (Frey et al 2010). For the present study, we considered bed overdeepenings with volumes of larger than 1 million m^3 as potential future sources of GLOFs (Linsbauer et al 2016). Future lake danger considers both the current and the future glacial lakes in UK; that is, we assumed all current lakes will remain in the future. This future danger only considers the future conditions of the lakes and their surroundings (future hazard conditions). Other elements, such as changes in population, roads, and croplands, were not considered. HPPs are an exception, with HPPs that were both under construction or planned considered in the study.

Results and discussion

Inventory and spatial distribution of the glacial lakes

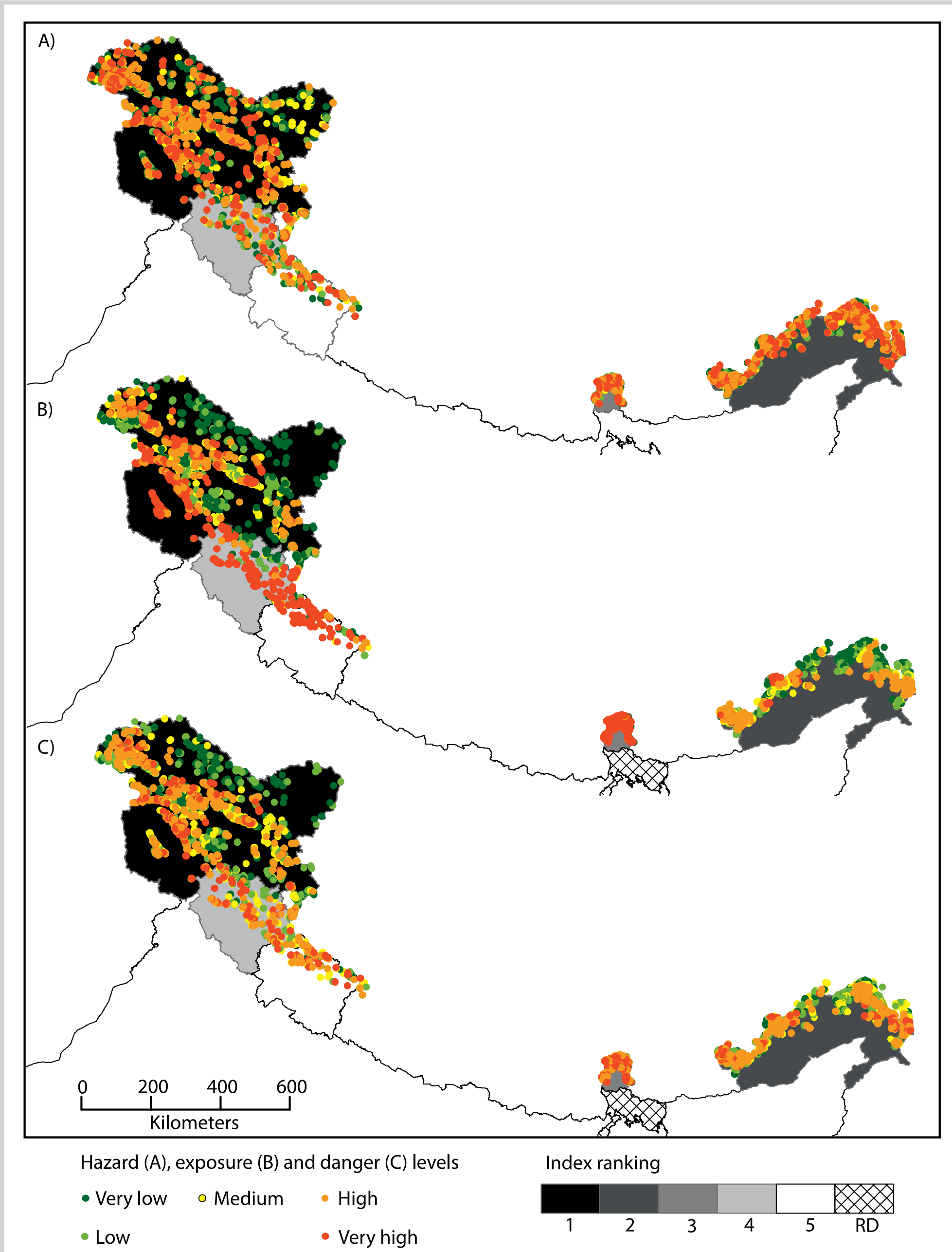
A comprehensive inventory reveals 4418 (>0.01 km^2) glacial lakes within the IHR (Figure 1A). In addition, 636 TB glacial lakes that could potentially flood the IHR were also identified. JK has 2292 glacial lakes, whereas HP, UK, SK, and AP have 188, 135, 352, and 1451 glacial lakes, respectively (Figure 1A). Glacial lakes in the IHR cover an area of 428.71 km^2 (mean = 0.10 km^2), whereas the total area of TB lakes is 49.99 km^2 (mean = 0.08 km^2). The mean glacial lake area in JK (0.12 km^2) and SK (0.09 km^2) is larger compared with AP (0.08 km^2), HP (0.05 km^2), and UK (0.04 km^2). In JK, SK, and AP, 57–84% of the lakes are bedrock-dammed, whereas in UK and HP, 76–80% are moraine-dammed. SK and JK have 41 and 25% lakes with moraine dams, respectively. Ice-dammed and other lakes are not as common as bedrock- and moraine-dammed lake types (Figure 1B). To our knowledge, this is the latest and most complete inventory of glacial lakes in the IHR and the first study to systematically include the TB lakes from which GLOFs could originate and affect downstream regions of the IHR.

Current GLOF hazard

JK has the highest aggregated GLOF hazard level, followed by AP, SK, HP, and UK (Figure 2A). The highest hazard level observed in JK results from the larger lake size (mean = 0.12 km^2) and watershed area (mean = 133.9 km^2). In AP, a higher hazard level results from high topographical potential and steep dam slopes (mean = 22.9°), because most lakes are located in steep cirques from which glaciers have significantly retreated. A moderate hazard level in SK is caused by significant topographical potential, larger lakes (mean = 0.09 km^2), moderate upstream watershed area, and steep lake dam slopes. By comparison, lower hazard levels in HP and UK result from relatively smaller lakes and upstream lake watershed areas.

A previous study (Dubey and Goyal 2020), based on the analysis of 329 lakes, indicated the highest lake hazard in SK, followed by JK, HP, and AP. UK had the lowest hazard level, according to that study. However, the study considered only the larger lakes (>0.05 km^2), sampling 7.5% of the lakes compared with the current study, and deployed a different methodological approach, making a direct comparison difficult. In the current study, the hazard assessment does not distinguish dam compositions (eg rock or moraine dams), which have vital bearings on the GLOF process. This is because in the case of massive rock or ice avalanches into a glacial lake, the resulting displacement wave can overtop the dam and flood the downstream region, even with structurally robust bedrock dams (Schneider et al 2014; Veh et al 2019; Dubey and Goyal 2020; Emmer et al 2020). Thus, the consideration of all lake types is a conservative and sensible approach for a first-order hazard assessment, particularly in a seismically active region, to avoid missing potentially catastrophic chain-reaction events. However, for the final consideration of sectorwise lake danger, including

FIGURE 2 (A) GLOF hazard based on watershed area, topographical potential, glacial lake area, and dam slope; (B) aggregated exposure of cropland, roads, HPPs, and human population; and (C) aggregated danger level for cropland, roads, HPPs, and human population (cf Figure 3 and Figure S1, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00043.1.S1, for different sectors) in IHR. Exposure, and therefore lake danger, can include areas downstream of the state in which the lake is located. The zone of residual danger (RD) contains no glacial lakes but is potentially affected by GLOF paths originating from an upstream state. The results are aggregated at the state level.

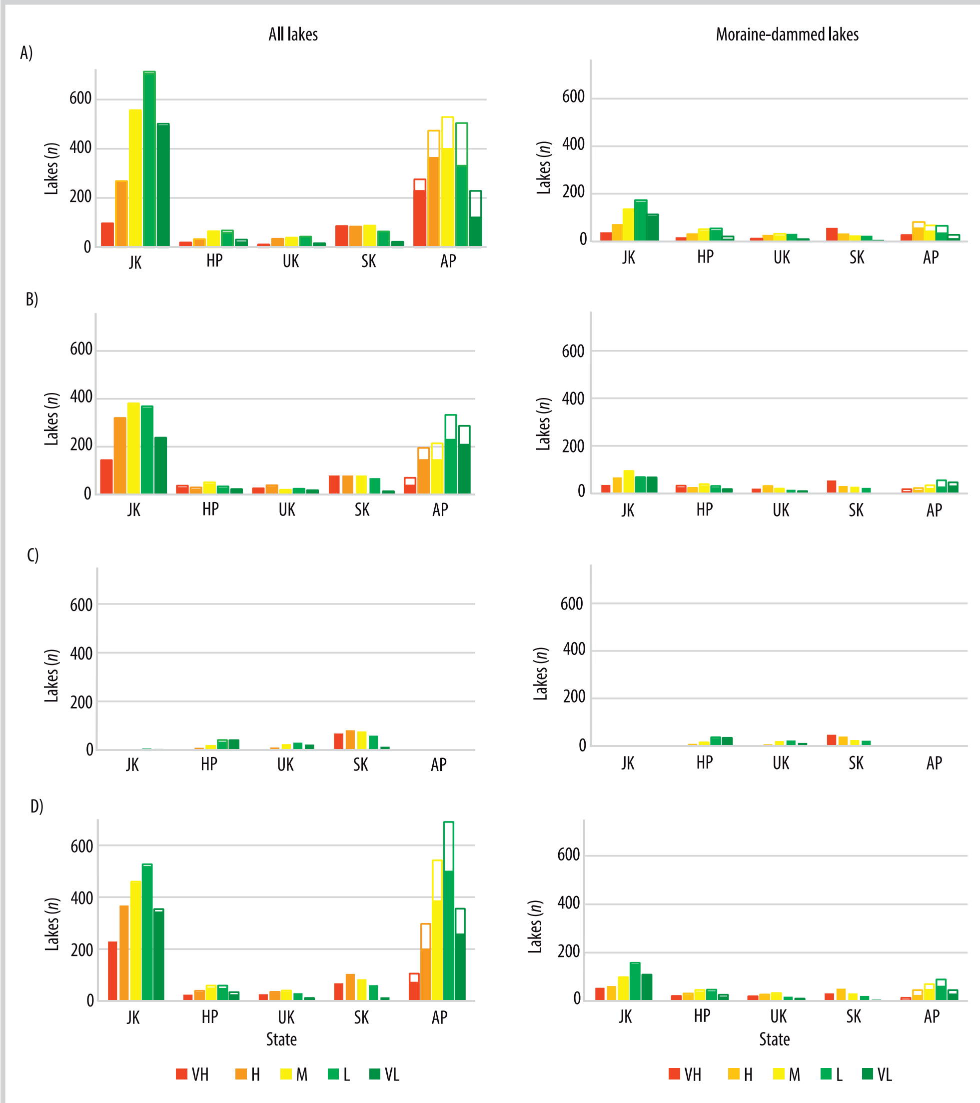


prioritization of the most dangerous lakes, moraine-dammed lakes (susceptible to a broader range of triggering processes) are distinguished from bedrock-dammed lakes (see section "Current GLOF danger").

Current GLOF exposure

In this study, we assessed the exposure of the human population, roads, cropland, and HPPs to GLOF. Furthermore, statewise aggregated exposure to these sectors is estimated for comparative purposes (Figure 2B). JK has the highest combined exposure to potential GLOFs, followed by AP, and SK, whereas HP and UK are characterized by a relatively lower level of exposure. Particularly in JK, exposure increases from remote areas in the northeast toward the southwest, where lakes can threaten densely populated areas in and around Srinagar valley. Current GLOFs also potentially affect the foothill areas of non-IHR states, for example, northern West Bengal (marked as a zone of residual danger in Figure 2B, C). The high exposure level to GLOFs in JK, AP, and SK results from intense agricultural activities, a dense road network, and a relatively high population density (SK) located high in the inner Himalayan

FIGURE 3 GLOF danger to (A) cropland, (B) roads, (C) HPPs, and (D) population. Solid and hollow bars represent IHR and TB lakes, respectively. The left panel represents all lakes, whereas the right panel indicates moraine-dammed lakes only. The *x*-axis shows the number of lakes in IHR. VH, very high; H, high; M, medium; L, low; VL, very low.



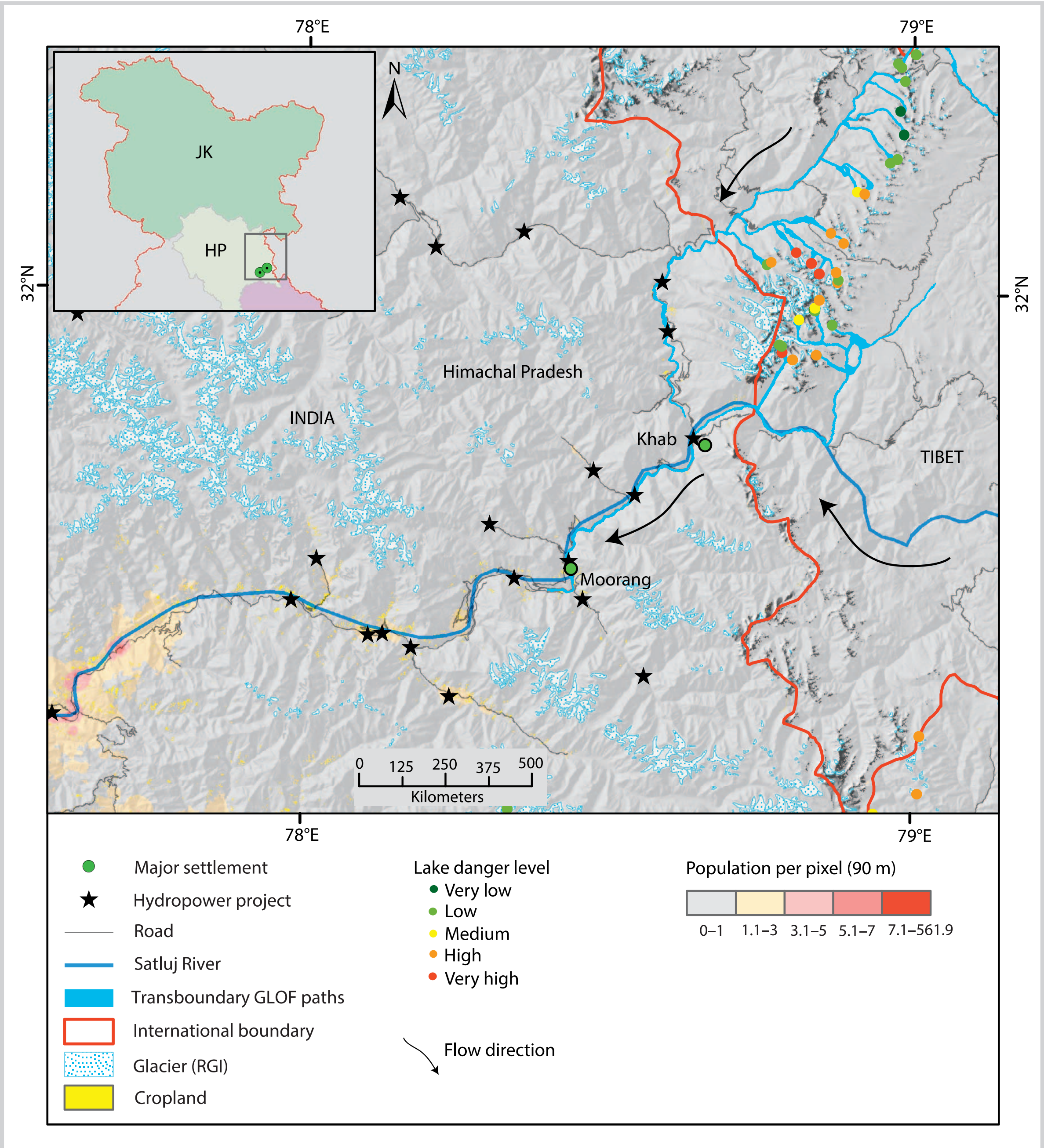
valleys (Scott et al 2019; Sharma et al 2019), all of which are within reach of GLOF trajectories. A dense network of HPPs ($n = 168$), particularly in SK, UK, and HP in the greater Himalayan regions, has led to significantly higher exposure in this sector (Schwanghart et al 2016).

Current GLOF danger

Cropland: Considering all lake types, the GLOF danger to cropland is highest in AP, followed by JK, SK, HP, and UK (see Figure 3A and Figure S1A, *Supplemental material,* https://doi.org/10.1659/MRD-JOURNAL-D-20-00043.1.S1). AP and JK have 592 (41%) and 363 (16%) glacial lakes within the very high to high danger categories. SK, by comparison, has only 170 (48%) lakes in this category. Concerning moraine-dammed lakes, 110 (5%) lakes with very high to high danger levels are located in JK, whereas 89 (25%) and 82 (6%) lakes are in SK and AP, respectively. HP and UK have relatively lower levels of GLOF danger to cropland (Figure 3A). AP emerges as an overall hotspot with regard to GLOF danger to cropland. The threat from moraine-dammed lakes is more significant in JK and SK. In HP and UK, most glacial lakes are located in areas that are not conducive to intense cultivation activities; therefore, the potential downstream damage is relatively low. Notable exceptions exist, for example, in the Kullu valley of HP (Allen, Linsbauer, et al 2016).

Roads: With regard to the overall GLOF danger to roads, JK is a hotspot, followed by AP, SK, HP, and UK (Figure S1B, *Supplemental material,* https://doi.org/10.1659/MRD-JOURNAL-D-20-00043.1.S1). JK has 462 (20%) lakes with a very high to high danger level, followed by AP with 189 (13%) lakes and SK with 160 (45%) lakes. HP and UK have relatively lower levels of GLOF threat, because only 55 (29%) and 59 (44%) lakes, respectively, affect the roads (Figure 3B). Concerning moraine-dammed lakes, JK has 102 (4%) lakes with very high to high danger levels, followed by SK with 85 (24%) lakes, whereas in other states, a lower level of danger is observed (Figure 3C). Damage and disruption of roads can result in both direct and indirect impacts, because vital trade corridors and tourism routes can be disrupted.

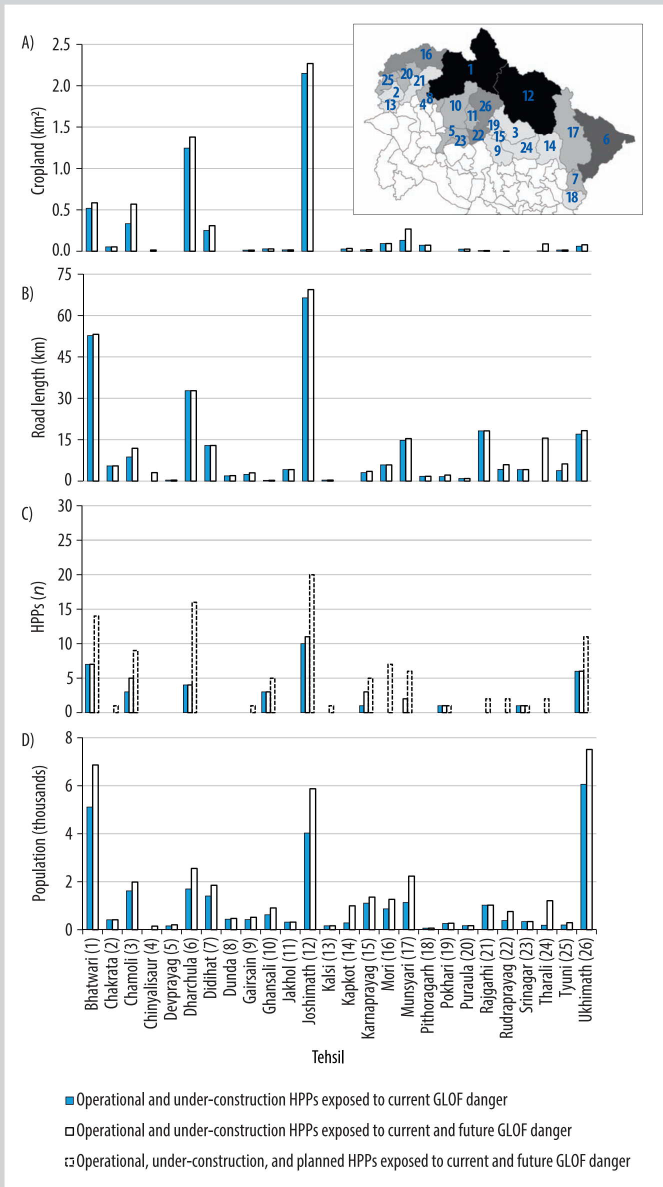
FIGURE 4 An example of TB GLOF danger in HP, originating from Tibet and affecting different sectors in India.



HPP infrastructure: SK has the highest GLOF danger level for the HPP sector regardless of lake type; therefore, it is a clear hotspot with some trans-state effects with West Bengal. HP has a comparatively moderate level of GLOF danger, followed by UK and JK (see Figure 3C and Figure S1C, *Supplemental material,* https://doi.org/10.1659/MRD-JOURNAL-D-20-00043.1.S1). AP has no HPPs within reach of GLOF trajectories; therefore, there is no GLOF danger to this sector. Moraine-dammed lakes pose a similar level of GLOF threat to HPPs, being disproportionally higher in SK and comparatively lower in other states (Figure 3C). SK has 149 (42%) lakes with very high to high danger levels for the HPP sector, whereas UK ($n = 11$, 6%) and HP ($n = 13$, 10%) have a few dangerous lakes. Notably, no glacial lake poses a very high danger level in JK (Figure 3C). The high GLOF danger may be attributed to the intense growth of HPP development in SK, UK, and HP at higher elevations close to the glacial environment (Allen, Linsbauer, et al 2016; Schwanghart et al 2016).

Human population: Overall, GLOF danger to the human population closely follows the spatial patterns for roads, where the highest and lowest GLOF danger levels are observed in JK and UK, respectively (see Figure 3D and Figure S1D, *Supplemental material,* https://doi.org/10.1659/MRD-JOURNAL-D-20-00043.1.S1). JK has 597 (26%) glacial lakes with a high to very high danger level for the human population and is therefore a GLOF danger hotspot. AP has 276 (19%) lakes and SK has 172 (49%) lakes, whereas HP and UK have a relatively lower number of lakes in these

FIGURE 5 Assessment of (A) cropland, (B) roads, (C) HPPs, and (D) human population exposed to current (solid bars) and future (hollow bars) GLOF danger in UK. The colors in the inset map of UK are taken from Figure S2A (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00043.1.S1), indicating current GLOF danger. The numbers in the inset map correspond to the tehsils on the *x*-axis of the graph.



categories. When only considering moraine-dammed lakes posing a very high to high GLOF threat, the focus again is on JK ($n = 117$, 5%), followed by SK ($n = 83$, 24%) (Figure 3D), where the Kashmir Valley and Teesta Basins, respectively, are key areas of high population exposure. Despite higher overall population densities, large communities in HP and UK appear to be little affected by GLOF danger.

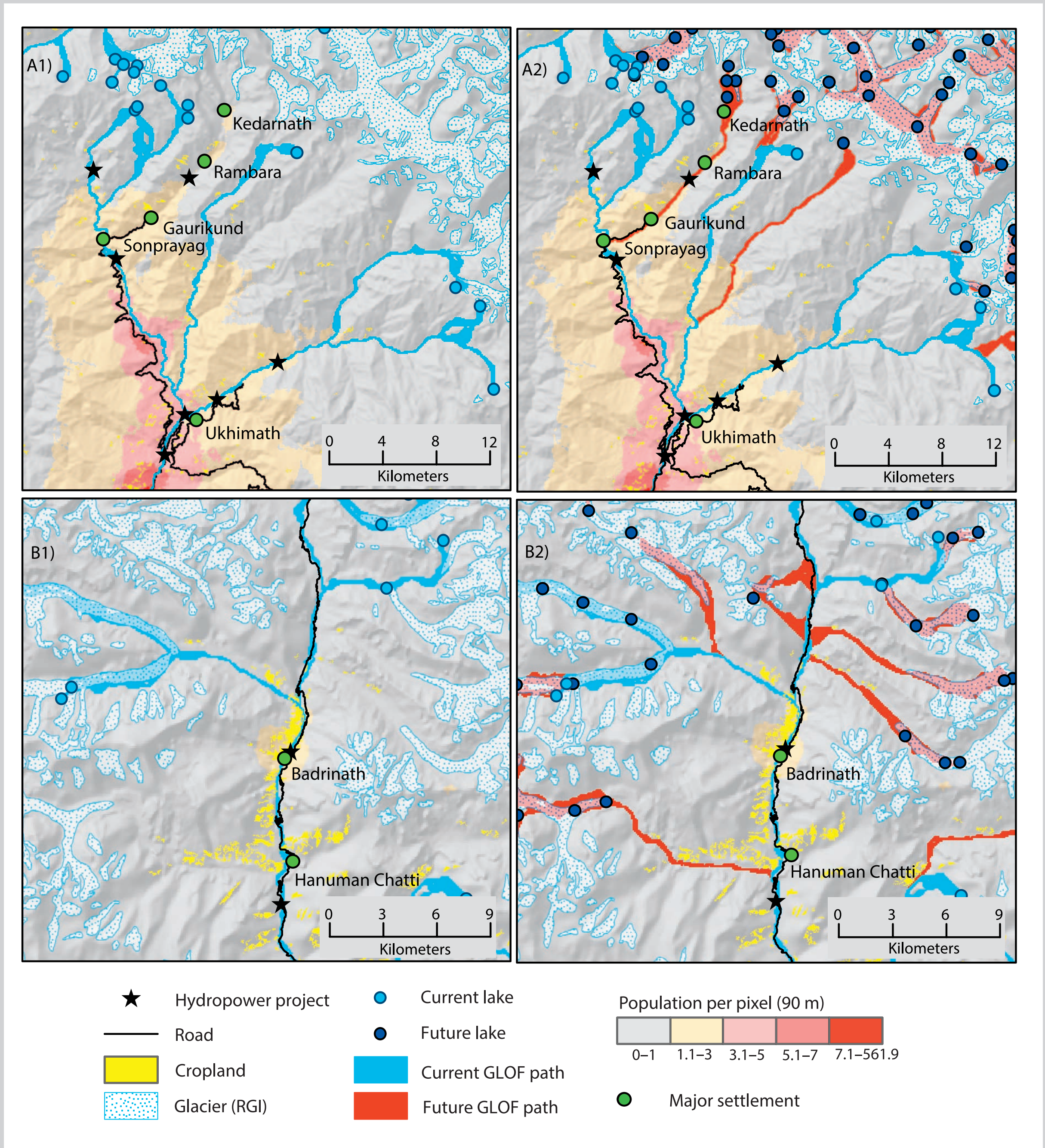
Current TB GLOF threats: The IHR has previously been affected by landslide lake outburst floods originating upstream in Tibet (Ruiz-Villanueva et al 2017; Chen et al 2020) and is threatened by numerous glacial lakes located in the same area (Figure 4). GLOFs that originate in Tibet can flow hundreds of kilometers into the IHR and potentially affect different sectors. Results show that of the total number of TB glacial lakes ($n = 636$) that could potentially affect the IHR, 570 lakes are likely to affect AP, 28 lakes are likely to affect HP and JK each, 9 lakes are likely to affect UK, and 1 lake is likely to affect SK. Because the number of TB lakes is disproportionately high in AP, the likely overall GLOF impact is expected to be very high in all sectors except for the HPP (Figure 3). The TB GLOF threat to cropland is highest in AP, which is affected by 158 TB lakes with very high to high danger levels, of which 25 lakes are moraine-dammed. Cropland in JK is affected by 3 TB lakes, in HP by 2 lakes, and in UK by 1 lake. The GLOF danger to the road network from TB lakes is highest in AP, with 76 lakes with a very high to high danger level, of which 15 lakes are moraine-dammed. This is followed by 12 (9 moraine-dammed) lakes in HP, 6 lakes in UK and 2 lakes in JK. The HPP sector does not appear to be threatened by TB lakes with very high to high danger levels in any state. For the human population, the TB GLOF threat is highest in AP, followed by HP and UK. During the emergency management of the recent landslide-dammed lake formed in the Yarlung Tsangpo Grand Canyon, upstream of AP, authorities in China and India have demonstrated the necessary coordination and collaborative response needed to effectively mitigate TB flood risk (Chen et al 2020). However, such coordinated actions can become more challenging during periods of political instability.

Changing GLOF danger: a case study in UK (Central Himalayas)

The state of UK was selected as a case study to demonstrate the future potential change in GLOF danger because of (1) the absence of a policy framework related to GLOFs in UK state disaster management plans; (2) rapid growth of the human population, agricultural activities, HPPs, and road network; and (3) recent GLOF activities (eg the 2013 Chorabari GLOF) (Ives et al 2010; Census of India 2011; Allen, Rastner, et al 2016; Raj and Kumar 2016). The study reveals that 25 of 78 tehsils (subdistrict administrative divisions) of the state are likely to be affected by current GLOFs, with one additional tehsil affected under future conditions (Figures S2A and B, *Supplemental material,* https://doi.org/10.1659/MRD-JOURNAL-D-20-00043.1.S1). Both now and in the future, the GLOF danger is highly concentrated in the glaciated northwestern region of UK (Figure S2, *Supplemental material,* https://doi.org/10.1659/MRD-JOURNAL-D-20-00043.1.S1). The study demonstrates that (1) the future GLOF danger will largely remain confined to the same valleys as those currently affected, but the abundance of new lakes will manifest in a manyfold increase in potential GLOF threats; (2) some new areas will be affected by future GLOF threats; and (3) some areas will remain devoid of GLOF threats. Our study agrees well with a previous study in the neighboring state of HP, which likewise noted a significant potential increase in GLOF danger but a more limited change in the potentially affected area (Allen, Linsbauer, et al 2016).

An increasing damage potential for all sectors is observed. HPPs and the human population will see a greater increase in damage potential compared with cropland and roads (Figure 5). In particular, the planned locations of the HPPs are in critical areas, which could be affected by future GLOFs. Recognizing the significant potential impacts on the tourism sector, we focused on 2 of the most important pilgrim centers of UK—Kedarnath and Badrinath—which

FIGURE 6 Current (A1 and B1) and future (A2 and B2) GLOF danger to Kedarnath (upper panel) and Badrinath (lower panel), the 2 most important pilgrimage centers in UK.



experienced severe damage and loss of life during the 2013 GLOF-cum-flash-floods (Allen, Rastner, et al 2016; Bhambri et al 2016). As a result of the full breach of Chorabari Lake in 2013 (Kedarnath region), there is no current GLOF threat in the valley (Figure 6A1). However, the future evolution of glacial lakes will lead to potential new GLOF threats in the upper Kedarnath region (Figure 6A2), which could have dramatic consequences for Kedarnath and other villages downstream. Although lessons have been learned from the 2013 disaster and some protection has been engineered (Ziegler et al 2014), it is unlikely that potential future GLOFs have been adequately considered in local planning. Similarly, for the Badrinath region, which is currently threatened by potential GLOFs primarily from 2 valleys (Figure 6B1), a significant additional GLOF threat will emerge from nearby valleys in the future (Figure 6B2).

Comparison with previous GLOF studies across the IHR

This study responds to the direct needs of the state disaster management authorities in India, who require a listing of the potentially most dangerous lakes. Based on our large-scale automated assessment, we extracted the 30 most dangerous lakes in each state and carefully inspected them using high-resolution Google Earth imagery. In this crucial step, 3 experts independently inspected the 30 lakes for each state

TABLE 2 Comparison of current and previous studies related to GLOF risk in IHR.

State	Latitude	Longitude	Lake area (km^2)	Standardized hazard	Standardized exposure	Standardized danger	Present study[a)]	Ives et al (2010)[a)]	Fujita et al (2013)[a)]	Worni et al (2013)[a)]	Dubey and Goyal (2020)[a)]
JK	34.067	75.475	0.18	1.991	1.892	3.767	VHD				HRL
JK	34.351	76.075	0.11	1.936	1.916	3.709	VHD				
JK	35.074	76.293	0.11	1.918	1.854	3.556	VHD	PD			
JK	35.027	75.725	0.14	1.969	1.79	3.525	VHD	PD			
HP	31.661	78.167	0.21	1.997	1.938	3.87	VDH			CL	
HP	31.915	77.526	0.12	1.936	1.97	3.812	VDH	PD		CL	
HP	32.525	77.22	0.83	1.999	1.823	3.644	VDH			CL	
HP	31.339	78.253	0.12	1.763	1.995	3.517	VDH				HRL
HP	32.762	77.195	0.05	1.865	1.736	3.238	VDH			PCL	HRL
UK	30.912	78.958	0.10	1.901	1.963	3.732	VDH			PCL	HRL
UK	30.976	79.46	0.17	1.733	1.969	3.412	VDH			PCL	VHRL
SK	27.533	88.086	0.39	1.977	1.994	3.942	VHD	PD	PHFV	PCL	
SK	28.002	88.639	0.32	1.994	1.996	3.92	VHD			CL	VHRL
SK	27.695	88.716	0.09	1.994	1.946	3.88	VHD				
SK	27.982	88.509	0.32	1.989	1.933	3.853	VHD			PCL	VHRL
SK	27.961	88.65	0.20	1.958	1.94	3.799	VHD			PCL	HRL
SK	27.993	88.546	0.67	1.941	1.952	3.789	VHD		VHPFV	CL	VHRL
SK	27.865	88.863	0.14	1.917	1.945	3.729	VHD	PD			VHRL
SK	28.008	88.572	0.26	1.91	1.948	3.721	VHD	PD		PCL	
SK	28.015	88.561	0.27	1.902	1.95	3.709	VHD	PD		CL	VHRL
SK	28.005	88.713	1.17	1.9	1.786	3.393	VHD		PHFV	CL	VHRL
SK	27.975	88.616	0.59	1.898	1.944	3.69	VHD			CL	VHRL
SK	27.873	88.638	0.10	1.671	1.972	3.295	VHD				VHRL
SK	28.008	88.699	0.94	1.936	1.256	2.432	MD	PD		CL	HRL
AP	27.774	92.315	0.13	1.997	1.704	3.403	VDH				HRL

[a)] Abbreviations, adopted from the respective studies: VDH, very high danger; PD, potentially dangerous; PHFV, potentially high flood volume; VHPFV, potentially very high flood volume; CL, critical lake; PCL, potentially critical lake; HRL, high-risk lake; VHRL, very-high-risk lake.

and judged whether the hazard and exposure levels were sufficiently high to be considered an immediate threat. Following the principle that multiple lines of evidence lead to the most robust recommendations, we compared results across recent studies and gave emphasis to lakes that have been considered dangerous by 2, 3, or even more studies (Table 2). Finally, 25 critical lakes were identified, of which 13 are in SK, 5 are in HP, 4 are in JK, 2 are in UK, and 1 is in AP. Our results are broadly consistent with previous studies in terms of the distribution of dangerous lakes (Worni et al 2013; Dubey and Goyal 2020). Of the 25 critical lakes selected, 23 have been identified as dangerous in 1 or more of the previous studies (Table 2). In this study, 2 further lakes are recognized for the first time as a threat, 1 of which has emerged rapidly over the past 5 years. This highlights the need for large-scale assessments to be regularly updated to capture potential changes in the situation and condition of some lakes. Confidence is higher for those dangerous lakes that are identified by multiple studies (Table 2). Furthermore, field-based, site-specific, in-depth assessments need to follow in all cases. We emphasize that GLOFs from even relatively small lakes can lead to large-scale damage to lives and infrastructure when combined with other hazardous processes, for example, in the case of the 2013 Chorabari GLOF combined with intense rainstorms and landslides in UK (Martha et al 2014; Allen, Linsbauer, et al 2016; Bhambri et al 2016). Many recent studies have focused more on the growth of the lake area and other lake parameters as an indication of potentially dangerous lakes (Randhawa et al 2005; Aggarwal et al 2017; Prakash and Nagarajan 2017) and do not consider the exposure level of infrastructure and human population.

Conclusion

GLOFs are of great concern to mountain communities because of their potential to cause vast damage to infrastructure and human populations in the glacierized basins of the Himalayas, even at large distances downstream from the lakes. Although several regional GLOF studies have been conducted in the IHR, pan-Himalayan studies are generally lacking. We therefore analyzed the potential impacts of 4418 glacial lakes in the IHR and 636 TB lakes on the human population and infrastructure, using a robust GLOF hazard and danger assessment approach. The study reveals that JK has the highest overall GLOF danger level. However, if we focus on the highest-priority lakes, where urgent monitoring and local site investigations are recommended, 13 lakes have been identified in SK, compared with only 1 lake in AP. Sectorwise, JK faces the greatest GLOF threat to roads and population, whereas the threat to cropland and HPPs is greatest in AP and SK, respectively. TB threats have also been identified, particularly in AP, and to a lesser extent in HP. Furthermore, the potential effects of GLOFs are expected to increase in the future, as demonstrated by an increasing potential for GLOF events in UK, with implications across all sectors, including tourism.

This study provides a first-order scientific basis for management authorities and decision-makers to prioritize adaptation and GLOF risk management planning in the currently affected GLOF regions while providing a view toward future threats. The assessment method can be adopted in other mountain regions of Asia that are currently affected by similar GLOF threats.

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Supplemental material

FIGURE S1 GLOF danger to (A) cropland, (B) roads, (C) HPPs, and (D) population in IHR, with results aggregated at the state level.
FIGURE S2 Comparison of (A) current and (B) future GLOF danger levels across tehsils in the UK, with results aggregated at the tehsil level based on current and future GLOF trajectories.

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