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Review Article

Modeling glacio-hydrological processes in the Himalayas: A review and future perspectives

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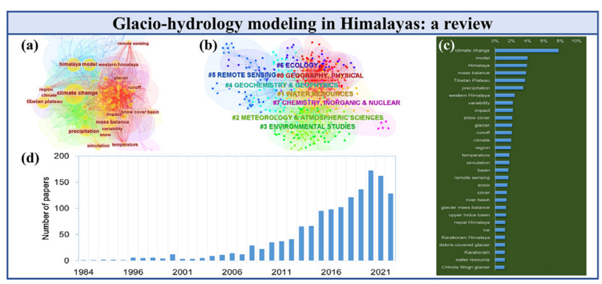
HIGHLIGHTS

- We find a publication growth in glacio-hydrology modeling in Himalayas since 2000s.
- Large uncertainties exist in the simulated runoff components in the Himalaya basins.
- Glacier melt peak time varies at Himalaya sub-basins under different CMIP scenarios.
- Precipitation error is the major source of uncertainty for Himalaya basin modeling.
- Glacio-hydrology models need to integrate glacier, snow, and permafrost processes.

GRAPHICAL ABSTRACT



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ABSTRACT

The Himalayas and their surrounding areas boast vast glaciers rivaling those in polar regions, supplying vital meltwater to the Indus, Ganges, and Brahmaputra rivers, supporting over a billion downstream inhabitants for drinking, power, and agriculture. With changing runoff patterns due to accelerated glacial melt, understanding and projecting glacio-hydrological processes in these basins is imperative. This review assesses the evolution, applications, and key challenges in diverse glacio-hydrology models across the Himalayas, varying in complexities like ablation algorithms, glacier dynamics, ice avalanches, and permafrost. Previous findings indicate higher glacial melt contributions to annual runoff in the Indus compared to the Ganges and Brahmaputra, with anticipated peak melting in the latter basins — having less glacier cover — before the mid-21st century, contrasting with the delayed peak expected in the Indus Basin due to its larger glacier area. Different modeling studies still have large uncertainties in the simulated runoff components in the Himalayan basins; and the projections of future glacier melt peak time vary at different Himalaya sub-basins under different Coupled Model Intercomparison Project (CMIP) scenarios. We also find that the lack of reliable meteorological forcing data (particularly the precipitation errors) is a major source of uncertainty for glacio-hydrological modeling in the Himalayan basins. Furthermore, permafrost degradation compounds these challenges, complicating assessments of future freshwater availability. Urgent measures include establishing comprehensive in situ observations, innovating remote-sensing technologies (especially for permafrost ice monitoring), and advancing glacio-hydrology models to integrate glacier, snow, and permafrost processes. These endeavors are crucial for informed policymaking and sustainable resource management in this pivotal, glacier-dependent ecosystem.

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1. Introduction

Extending from the rugged landscapes of Pakistan to the towering peaks of India, the Himalayan and Karakoram (H-K) region hosts one of the planet's largest ice reserves beyond the polar expanse (Dyurgerov and Meier, 2005). This area boasts 21,000 glaciers covering approximately 43,200 km^2 (Cogley, 2011), with the Himalayan glaciers spanning between 31,530 km^2 and 33,050 km^2, and the Karakoram glaciers ranging from 15,145 km^2 to 16,600 km^2. Originating from this expanse are several major rivers — Indus, Ganges, and Brahmaputra (hereinafter IGB; Fig. 1) — that sustain over a billion downstream individuals with vital resources for drinking, hydropower, and irrigation, particularly during dry periods (Bookhagen and Burbank, 2010; Moors et al., 2011; Pellicciotti et al., 2012; Biemans et al., 2019). The reliance of downstream communities on these water sources intricately intertwines with the cryospheric resources of the region. With climate change significantly impacting natural systems worldwide, the observable effects are prominently evident in the glaciers, establishing them as prominent indicators of climatic changes (Oerlemans and Hoogendoorn, 1989; Oerlemans, 1994). Consequently, in such a region characterized by dense accumulations of snow and ice, comprehending the ramifications of climate change holds exceptional significance.

The literature underscores a warming trend in the H-K region, registering a significant increase of +2.2 °C decade^{-1} (Lutz et al., 2014a). Notably, the Himalayan sector has experienced a warming rate twice that of the global average (Shrestha et al., 1999; Xu and Grumbine, 2014), exacerbating the acceleration of snow and ice melting in the area. Recent observations reveal a doubled melting rate (-0.43 ± 0.14 m w.e. yr^{-1}) in the Himalayan region within two decades post-2000, leading to an alarming surge in glacier recession (Maurer et al., 2019) and amplifying ice loss by approximately 6 Gt yr^{-1} (Chaturvedi et al., 2014). This escalated cryospheric depletion has consequently escalated the discharge of originating rivers, significantly impacting the region's hydrological cycle. Moreover, the changing climate prompts alterations in the hydrological cycle by intensifying evaporation, modifying the timing and intensity of precipitation, and reshaping existing patterns of soil moisture deficit.

In examining the impacts of climate change on the hydrology of the H-K region, hydrological models serve as indispensable tools alongside *in-situ* and satellite-based observations. Recent years have seen the development of numerous hydrological models of varying complexities, integrating glacier and snow modules with permafrost, avalanche, cliff, and supraglacial lakes, and glacier dynamics. These models aim to simulate detailed cryospheric changes and their repercussions on river flows (Ragettli et al., 2015; Singh et al., 2016). However, challenges persist, including the scarcity of quality data spanning extended periods and uncertainties linked to model parameters, glacier outlines, and spatial scales, impacting the accuracy of these simulations (Pellicciotti et al., 2012). Hence, there's a pressing need to advance hydrological models, enabling a more explicit representation of cryospheric hydrological

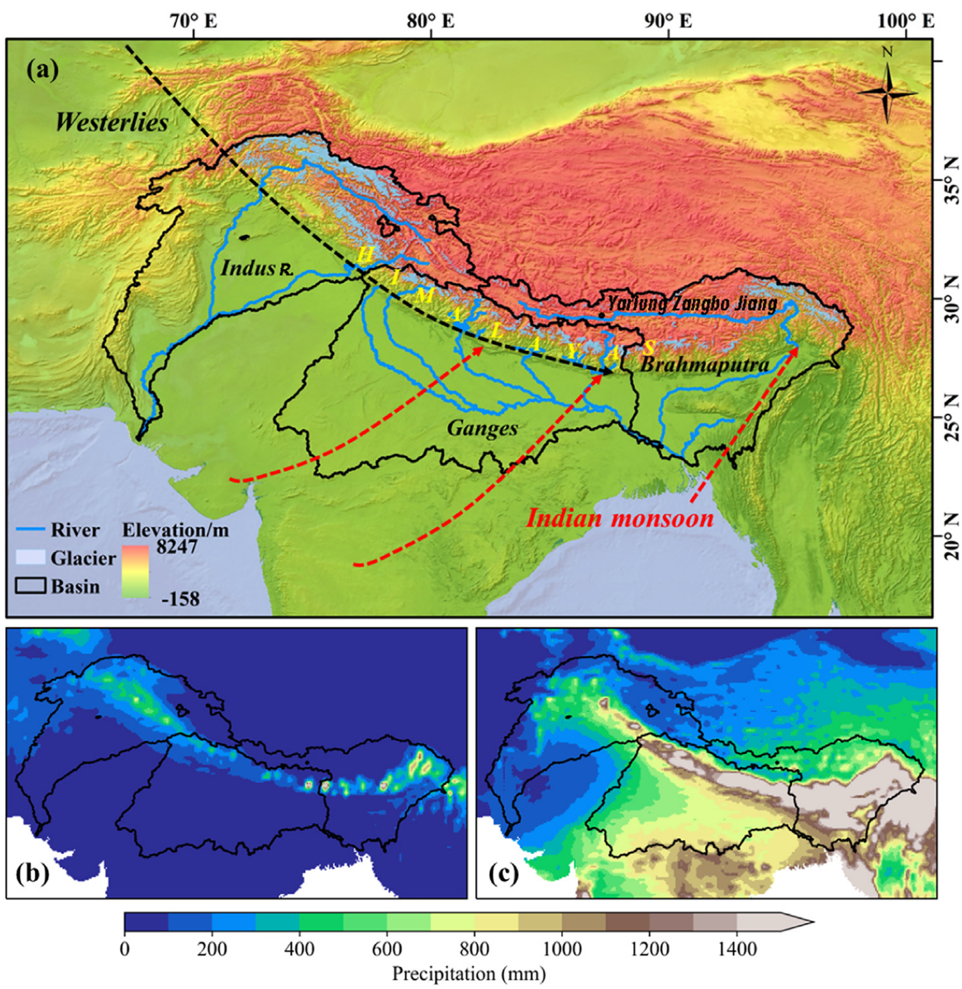

Fig. 1. (a) Depiction of the distribution of basins (Indus, Ganges, and Brahmaputra, collectively IGB) and major circulation systems (westerlies and monsoon) across the Himalayas and adjacent regions. Map showcasing the mean winter (DJF) precipitation (b) and summer (JJA) precipitation (c) within the study area. Glacier cover data sourced from RGI Consortium (2017), and precipitation data obtained from ERA5-Land.

processes to reduce uncertainties in process-based simulations. Such advancements hold promise not only in addressing future water security concerns but also in refining the management of water resources in the region.

Despite the crucial role of glacio-hydrology modeling in fostering sustainable development in the Himalayas, a comprehensive review on this specialized topic, specifically "Glacio-hydrology modeling in the Himalayas", is currently absent. This study endeavors to fill this gap by meticulously reviewing the advancements, applications, and significant challenges within glacio-hydrology modeling in the Himalayas. Leveraging detailed statistical analysis of pertinent literature, our aim is to provide a comprehensive understanding of this field.

2. Importance of glacio-hydrology in the Himalayas

A glacier, a vast accumulation of ice formed from prolonged snow buildup, gradually descends along slopes under the influence of its mass and gravitational forces. Within the high-altitude H-K region, the presence and distribution of glaciers are profoundly shaped by both the summer monsoon and westerlies (Yang et al., 2008; Yao et al., 2012; Engelhardt et al., 2017; Bandyopadhyay et al., 2019). The summer monsoon predominantly drives precipitation in over two-thirds of the southeastern area (Böhner, 2006), while the westerlies significantly impact snowfall in the Karakoram's high-altitude terrain (Bookhagen and Burbank, 2010), diminishing in influence as they extend from the west toward the southeastern regions (Benn and Owen, 1998). Consequently, glaciers exhibit spatial diversity across the H-K region (Fujita and Nuimura, 2011; Bolch et al., 2012; Kääb et al., 2012), contributing varied meltwater to different basins and sustaining river flows. Additionally, they serve as a buffering mechanism, moderating seasonal river discharge during periods of reduced regional precipitation by augmenting glacier and snowmelt (Immerzeel et al., 2010; Thayyen and Gergan, 2010; Engelhardt et al., 2017; Pritchard, 2019). This regulating capacity of glacier melting is pivotal for food production in the region, particularly amid the impacts of climate change (Biemans et al., 2019; Li et al., 2021).

3. Developments of glacio-hydrology models in the Himalayas

Glacio-hydrology models serve as a specialized hydrological framework designed to unravel the impacts of climate change on diverse cryospheric processes and their repercussions on water resources. Comprehending snow and glacier melting dynamics, glacier movement, surface and subsurface hydrology, as well as energy and mass balance mechanisms, is crucial for deciphering the complexities of glacio-hydrology within glacierized high-altitude catchments (Singh et al., 2016; Mishra et al., 2021).

In exploring recent advancements in glacio-hydrology modeling within the Himalayas, we conducted an analysis encompassing 1,403 relevant papers from the core Web of Science database (Fig. 2). This search employed keywords such as "(glacier OR snow OR permafrost) AND (model OR modeling OR models OR simulation OR projection) AND (Himalayas OR Himalaya OR Indus OR Ganges OR Brahmaputra OR Yaluzangbu)". A comprehensive frequency analysis and keyword ranking revealed prominent terms used in these publications, highlighting "climate change", "model", "Himalaya", "mass balance", "Tibetan Plateau", "precipitation", "western Himalaya", "variability", "impact", "snow cover", "glacier", and "runoff". Additionally, we observed that these studies predominantly fall within the subject categories of "Physical Geography", "Water Resources", and "Meteorology & Atmosphere Sciences". Notably, our survey uncovered a significant and consistent increase in publications, especially notable from the early 21st century, within the domain of "glacio-hydrology modeling in the Himalayas".

In recent years, a multitude of glacio-hydrological models has emerged worldwide, differing significantly in complexity, parameterization, and the incorporation of various processes. Historically, temperature index models held popularity due to their low data requirements and simplistic depiction of hydrological processes (Hock, 2003), like the TOPKAPI-ETH (Pellicciotti et al., 2012; Ragettli and Pellicciotti, 2012; Ragettli et al., 2015; Ragettli et al., 2016a), Glacio-hydrological degree-day model (GDM) (Gupta et al., 2019), Distributed Hydrology Soil Vegetation Model (DHSVM) (Mimeau et al., 2019), Spatial Process in Hydrology (SPHY) (Terink et al., 2015), and Snowmelt Runoff Model (SRM) (Khadka et al., 2014). However, these degree-day models compute melting processes without factoring in the energy budget.

In contrast, energy balance-based models like the Water and Energy Budget-based Distributed Hydrological Model (WEB-DHM) (Wang et al., 2009a, 2009b; Shrestha et al., 2010, 2012, 2015; Zhou et al., 2015; Wang et al., 2016, 2017; Qi et al., 2019; Song et al., 2020), and WRF-Hydro (Li et al., 2017) have been developed to calculate energy and mass balances in glacier basins. These models simulate snow and glacier melting processes by exchanging energy and mass among different layers of snow and glaciers, considering interactions with the atmosphere and within various layers (Shrestha et al., 2010, 2012, 2015). Moreover, these models have the capability to incorporate canopy interception, enhancing the interaction between the canopy and snow processes (Shrestha et al., 2015). While these models offer improved simulations of water phase changes and runoff during glacier and snow melting, they demand substantial high-resolution data and high-performance computing capabilities for model execution.

The complexity of glacio-hydrological models has advanced significantly by integrating the snow/glacier melting module with various physical processes like frozen ground (Wang et al., 2017; Song et al., 2020), avalanche (Ragettli et al., 2013, 2015; Mimeau et al., 2019), cliff and supraglacial lake (Ragettli et al., 2015), and glacier dynamics (Ragettli et al., 2016a). These enhancements aim to offer comprehensive insights into cryosphere changes, thereby improving the models' performance.

The frozen ground module resolves thermal diffusion, liquid-ice phase changes, and water diffusion separately. Coupled with snow processes, it captures thawing and freezing in both snow and soil, enabling the storage of liquid water as a solid form, releasing it during warmer seasons to contribute to river discharge (Wang et al., 2017). Introducing avalanche processes, Ragettli et al. (2015) distributed snow based on slope and maximum snow holding capacity. Accounting for supraglacial lakes and cliffs involves adding shallow debris to the model grid. Glacier dynamics, crucial for long-term simulations, describes glacier changes over extended periods (Shrestha et al., 2015). However, integrating glacier dynamics remains challenging due to the need for fine-resolution data and extensive cryosphere information to calculate glacier flow dynamics (Table 1).

Additionally, including reservoirs in hydrological models such as DHSVM (Zhao et al., 2016), WEB-DHM (Wang et al., 2014), and SPHY (Biemans et al., 2019) enables the regulation of river flow, particularly during floods, low flows, and for managing drinking water supply, irrigation, and hydropower (World Commission on Dams, 2000).

In a concise summary, Table 2 outlines the advantages and drawbacks of major glacier-hydrology models implemented in the Himalayas. These models vary in their treatment of physical processes and are broadly categorized based on their ablation algorithms: temperature-index models and energy-balance models. Some models incorporate glacier dynamics and debris cover effects, while others simplify these aspects. Theoretically, models with comprehensive physical mechanisms offer superior performance, yet they demand extensive data support — currently scarce in this region, particularly for precipitation and glacier data. This scarcity poses a challenge for the application of advanced energy-balance glacio-hydrology models in this area. Therefore, selecting a glacier-hydrology model should align with specific research objectives; the ideal model should fulfill all necessary criteria. Moving forward, increasing observations and the development of advanced glacio-hydrological models are essential priorities.

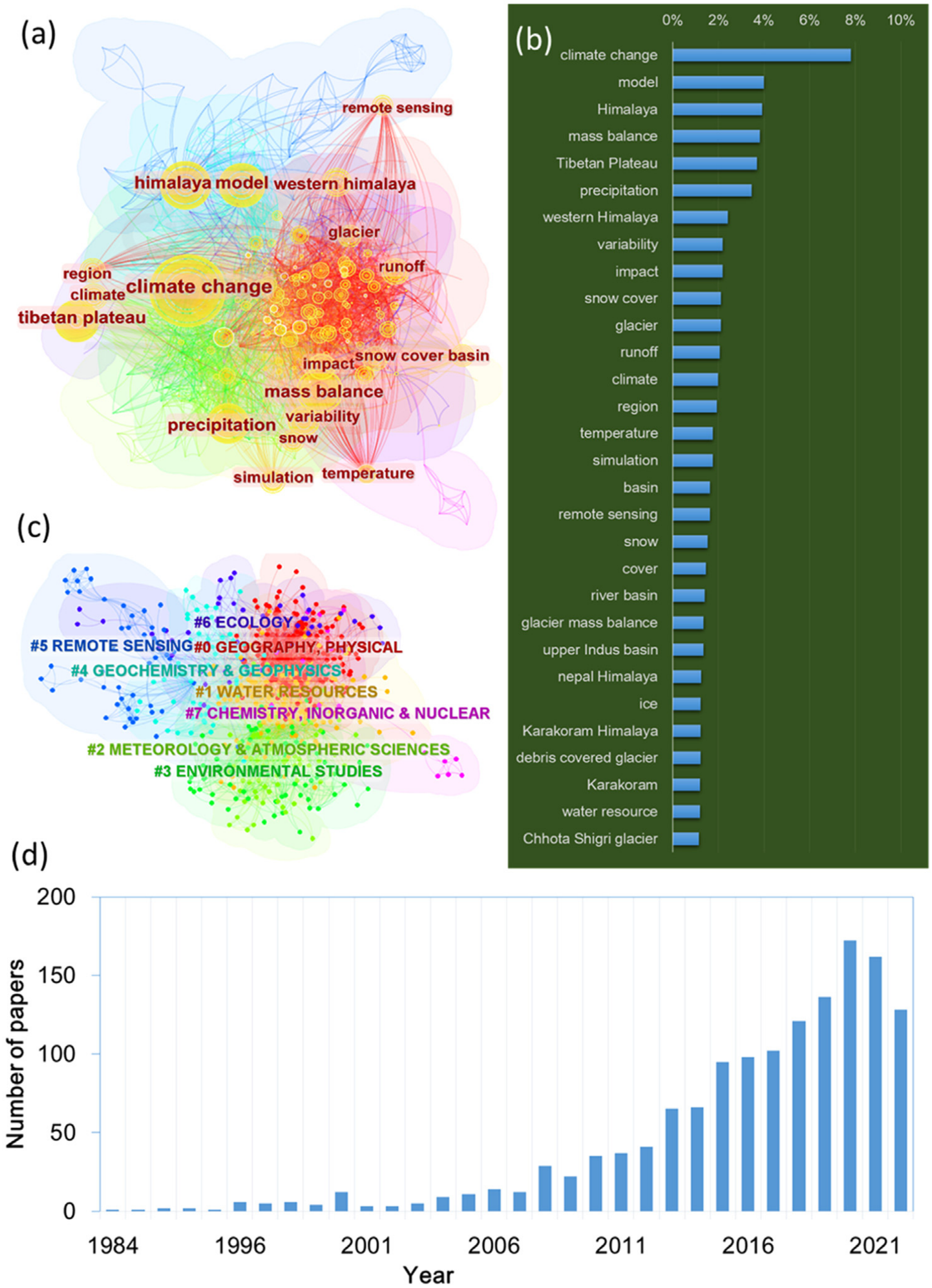

Fig. 2. (**a**) Frequency analysis, including connections among various keywords, and (**b**) ranking of the top 30 keywords observed in a dataset comprising 1,403 papers. The search query employed "(glacier OR snow OR permafrost) AND (model OR modeling OR models OR simulation OR projection) AND (Himalayas OR Himalaya OR Indus OR Ganges OR Brahmaputra OR Yaluzangbu)" within the Web of Science core database. Additionally, an examination of related subject categories (**c**) and the distribution of papers published across different years (**d**) was conducted.

4. Applications of glacio-hydrology models in the Himalayas

4.1. Studies in the IGB basins

The H-K region serves as the primary source of snow and glacier meltwater for the IGB basins. This meltwater exhibits seasonal, spatial, and downstream variations, influenced by climate change. The literature reveals significant disparities in the contribution of snow and glacier melt to the total river runoff across the IGB regions (Fig. 3).

Biemans et al. (2019) highlighted a substantial contribution of snow and ice melt, constituting approximately 60%–70% of the total runoff in the upper Indus. In contrast, the upper Ganges and Brahmaputra exhibit lower contributions, ranging from 10% to 20% of their annual streamflow. For instance, in the Hunza River Basin and Chotta Shigri Glacier, snowmelt constitutes half of the total annual runoff, followed by glacier melt (about one-third), with the remaining attributed to rainfall (Shrestha et al., 2015; Engelhardt et al., 2017).

The contribution of glacier and snow melt diminishes with decreasing altitude (Singh et al., 2008; Racoviteanu et al., 2013), indicating a greater reliance on melting water in upstream regions. The upper Indus demonstrates a glacier contribution of about 40%, surpassing the downstream regions. Similarly, the upper Ganges and Brahma-

Table 1
A summary of glacio-hydrology models in the Himalayan regions.

Models	Developed and applied methods in Glacio-hydrological model	Study area	Reference
WEB-DHM	Snow module: interphase from single-layer to three-layer on the basis of snow depth Interaction of snow with canopy Combination of snow and glacier module	Hunza River Basin	(Shrestha et al., 2015)
	Combination of snow module with frozen soil (freezing and thawing)	Qingzang Plateau (Tibetan Plateau,TP)	(Wang et al., 2017; Qi et al., 2019)
	Permafrost	TP	(Song et al., 2020)
SPHY	Snow and glacier module with degree-day approach	High Mountains	(Lutz et al., 2014b; Terink et al., 2015)
	Combination of snow and glacier with reservoirs (simple generic model)	IGB	(Biemans et al., 2019)
TOPKAPI	Snow and glacier melting driven by complex approach which is located between temperature-index model and energy-balance model	Hunza River Basin	(Pellicciotti et al., 2012)
	Enhanced temperature-index approach with addition of snow redistribution by gravity and debris-covered glacier melting	Hunza River Basin	(Ragettli et al., 2013)
	Combination of snow and glacier melt (by enhanced temperature-index approach) with avalanche (snow holding capacity)	Upper Langtang	(Ragettli et al., 2015)
	Enhanced temperature-index approach and addition of gravitational snow redistribution or topographic shading and glacier dynamics		(Ragettli et al., 2016a))
DHSVM	Addition of avalanche, debris-covered glacier melting, and snow albedo evolution for snow cover dynamics	Pheriche sub-catchment	(Mimeau et al., 2019)
Glacio-hydrological degree-day model (GDM)	Degree-day approach for glacier and snow melt	Marshyangdi River Basin and Tamor River Basin	(Gupta et al., 2019)
Snowmelt Runoff Model (SRM) (semi distributed)	Degree-day approach for snow melt	TamaKoshi River Basin	(Khadka et al., 2014)
Mass balance model	Distributed temperature-index method for snow and glacier melt		(Engelhardt et al., 2017)
Model	Introduction of basal sliding	Langtang River catchment	(Immerzeel et al., 2012)
HBV	Applied the energy-balance method, temperature-index method, combined radiation and temperature-index method for snow melt simulation	Upper Beas Basin	(Hegdahl et al., 2016)
VIC	Energy balance method	Upper Indus Basin	(Priya et al., 2020)
SWAT	Snowmelt simulation on elevation bands	Karnali River Basin Tamor River Basin Koshi River Basin	(Dhami et al., 2018) (Bhatta et al., 2019) (Devkota and Gyawali, 2015)
	Snow and ice melt, and canopy interception of precipitation	Karnali River Basin	(Dahal et al., 2020)
Temperature index model	Degree-day approach to simulate the glacier and snow melt in each elevation band. Divide the glacier melt from snow melt	High Mountain Asia	(Armstrong et al., 2019)
J2000	Glacier melt simulation is carried out using enhanced degree day method with considering slope, temperature, radiation, aspect, and debris-covered glacier factor. Calculate the contribution of glacier, snow, and rainfall in total runoff	DudhKoshi River Basin	(Nepal, 2016)
Cliff-energy balance model	Energy fluxes and mass losses calculation from cliffs	Lirung Glacier	(Steiner et al., 2015)

putra exhibit higher glacier contributions than their respective downstream areas (Immerzeel et al., 2010; Lutz et al., 2014a). Moreover, the streamflows of the upper Ganges and Brahmaputra heavily depend on rainfall, particularly during the monsoon season, while the upper Indus relies more on glacier and snow melt (Lutz et al., 2014b). This suggests that the relative glacier contribution to runoff is less significant for the Ganges and Brahmaputra, characterized as monsoon-dominated regions, but crucial for the Indus, dominated by westerlies (Immerzeel et al., 2010; Kaser et al., 2010). In terms of irrigation for agriculture, the Indus receives a higher contribution compared to the Ganges, while the Brahmaputra primarily relies on rainfall water for agricultural purposes (Biemans et al., 2019).

The glacier meltwater regulation effect is prevalent across all basins, particularly in periods of reduced precipitation and snowmelt. This phenomenon is notably observed during the summer season before the onset of the monsoon in the Indus region (Biemans et al., 2019). For instance, in the Chotta Shigri Glacier, the relative contribution of snowmelt decreased by 60% from June (80%) to September (20%). This decrease was offset by a concurrent increase in glacier melt, which rose from 10% in June to 50% in August-September, spanning the years 1955–1999 (Engelhardt et al., 2017).

In comparison to the Indus, the Ganges exhibits a utilization of meltwater primarily between March and June, with peak utilization reaching up to 20% in May (Biemans et al., 2019). The impact of climate change on the modulating effect of meltwater is significant, influencing the quantity, timing (including the shifting of peak discharge), and composition of upstream discharge within the basin.

In regions heavily dependent on meltwater, groundwater emerges as a crucial resource to compensate for reduced meltwater and low rainfall. Groundwater essentially serves as a buffer under conditions of diminished meltwater and precipitation, acting as a stabilizing factor in the hydrological dynamics of the basin.

The projected changes in total discharge for the upper Indus reveal an anticipated increase of 7%–12% and 2%–8% in the 2050s (2041–2050) compared to the reference period (1998–2007) for the RCP4.5 and RCP8.5 scenarios, respectively (Lutz et al., 2014a). Despite ongoing deglaciation in the highly glaciated basins of the Karakoram, a decrease in runoff is not expected before the close of this century (Rees and Collins, 2006). For example, a study by Ragettli et al. (2013) found no significant change in future runoff for the entire Hunza River Basin (located in the Karakoram). However, individual sub-catchments within the basin exhibited varied responses, with some showing in-

Table 2
Descriptions of different glacio-hydrology models in the Himalayan regions.

Ablation algorithm	Model	Study area	Improvements	Glacier dynamics	Reference
Temperature index	SRM	Indus, Ganges, Brahmaputra	–	V-A equation	Immerzeel et al., 2010
	SPHY	Indus, Ganges, Brahmaputra	sub-grid in glacier cover grid; considering the effect of debris cover	V-A equation considering the effect of elevation	Lutz et al., 2014a
	TOPKAPI	Indus, Ganges	considering the effect of debris cover	Weertman's sliding law	Immerzeel et al., 2013
	J2000	Dudh Koshi River Basin	considering the effect of debris cover and radiation	–	Nepal, 2016
	GSM-SOCONT	Glacier-covered basin in Himalaya	considering the effect of elevation and radiation	–	Singh et al., 2021
	SNOWMOD	Glacier-covered basin in Himalaya	–	–	Chelamallu et al., 2014
	GDM	Upper Ganges	considering the effect of debris cover	–	Kayastha et al., 2020
Energy-balance	UBC Watershed	Glacier-covered basin in Himalaya	–	–	Naeem et al., 2013
	VIC-glacier	Glacier-covered basin in Karakoram	–	V-A equation	Ren et al., 2018
	DHSVM-GDM	Glacier-covered basin in Himalaya	considering the effect of debris cover	–	Mimeau et al., 2019
	WEB-DHM-S	Hunza Basin in Karakoram	considering the effect of debris cover and the energy attenuation within the glacier	–	Shrestha et al., 2015

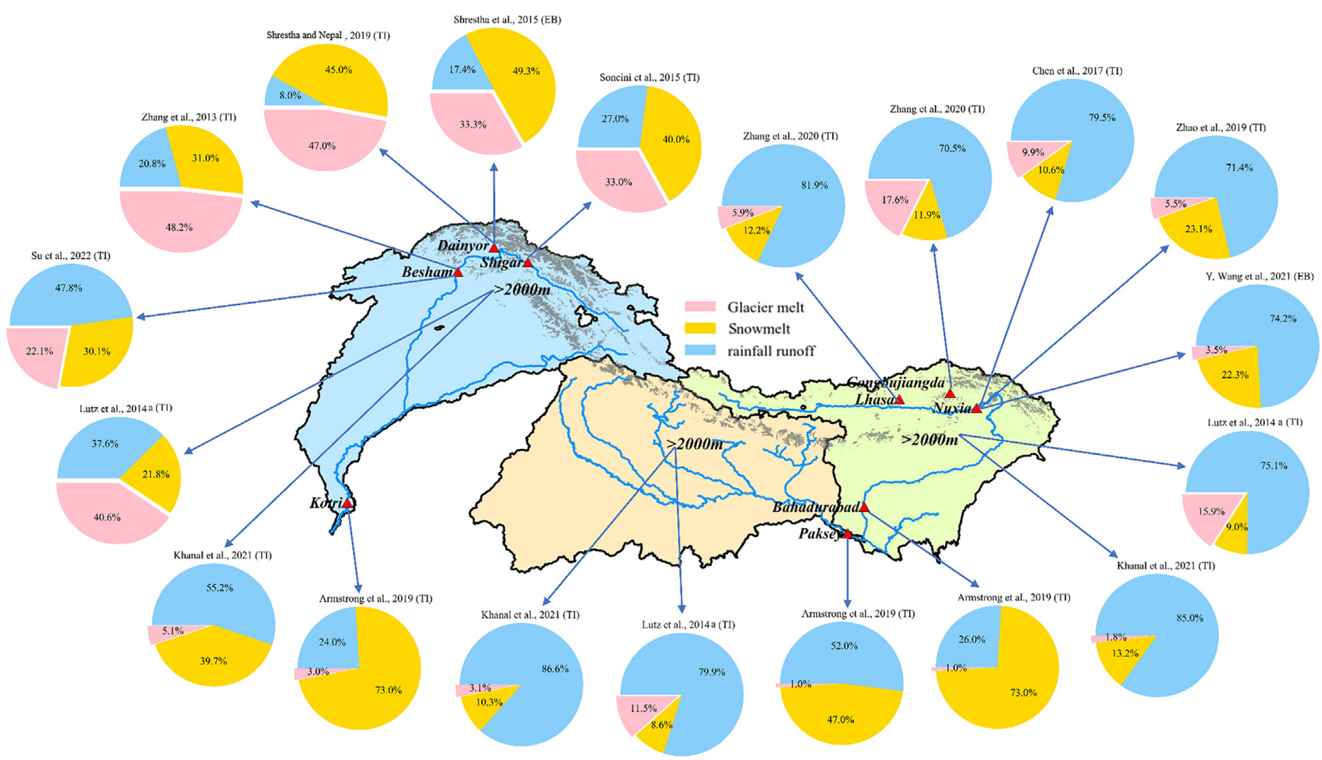

Fig. 3. Compilation of studies examining the contribution of glacial melting to the overall runoff in the IGB river basins (Chen et al., 2017; Shrestha and Nepal, 2019; Su et al., 2022; Zhang et al., 2013, 2020; Zhao et al., 2019; etc.).

creases, others reductions, and some maintaining a stable glacier mass balance.

Looking at the upper Ganges, future discharge is projected to increase by 10% and 27% under the RCP4.5 and RCP8.5 scenarios, respectively, driven by an augmentation in monsoon precipitation. Similarly, the upper Brahmaputra is expected to experience a 12% and 18% increase in precipitation for the RCP4.5 and RCP8.5 scenarios, contributing to enhanced discharge (Lutz et al., 2014a).

This increase in discharge for the upper Ganges and Brahmaputra is attributed to a rise in the rate of rainfall, while in the case of the Indus, the discharge is assumed to increase due to a higher volume of melting water (Lutz et al., 2014a).

The turning point of glacier melting, a critical juncture where glacier melt reaches its maximum before decreasing, has become a focal point in glacio-hydrology modeling studies within the IGB basins (Fig. 4). Fig. 4 provides a comprehensive

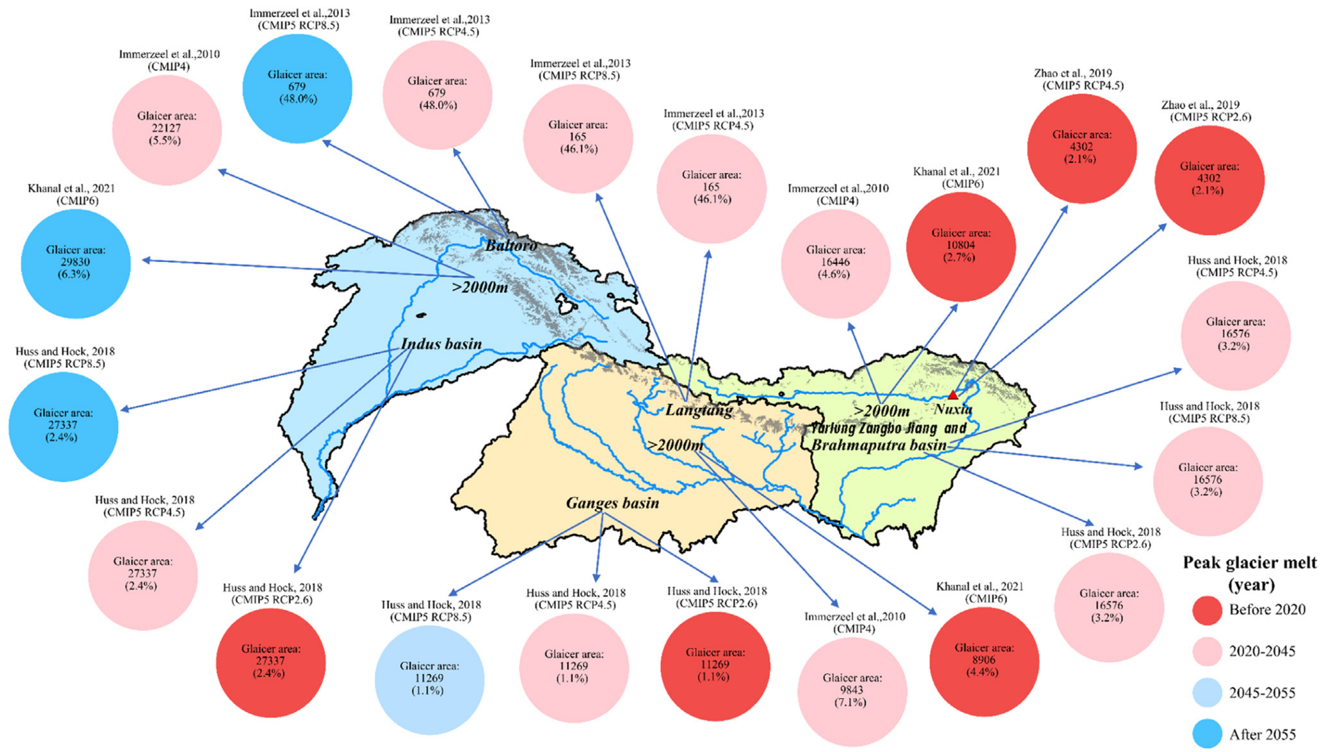

Fig. 4. Compilation of studies focusing on projecting the peak time of glacier melting in the IGB river basins (Huss and Hock, 2018; etc.).

overview of studies predicting the peak time of glacier melt in the IGB.

A synthesis of the literature indicates that, in general, the upper Ganges and Brahmaputra, characterized by a smaller glacier area, experience an earlier peak time of glacier melt. In contrast, the upper Indus, featuring a higher glacier ratio, exhibits a later peak time in ice melting. This distinction in peak timing holds significance due to its substantial impact on freshwater availability in the region.

4.2. Sub-basin studies in different countries spanning Himalayas

The Himalayas span across Pakistan, India, Nepal, China, and several other countries. Within the High Himalaya region of Nepal, there are a total of 3,808 glaciers covering an area of 3,902 km^2 (Bajracharya and Shrestha, 2011). These glaciers contribute to the formation of various river basins, including the Koshi, Gandaki, and Karnali, ultimately feeding into the Ganges Basin. Beyond glaciers and snow, temperature, and precipitation are crucial factors influencing river flow (Dahal et al., 2020).

The Nepal Himalayas are undergoing more significant warming than the global average. Over the period 1981–2020, the annual mean temperature exhibited a highly significant increase of 0.03 °C yr^{-1} ($p < 0.001$), and annual precipitation showed a significant positive trend of 3.3 mm yr^{-1} ($p < 0.05$). These findings are based on a state-of-the-art meteorological dataset from Jiang et al. (2023).

Numerous studies have utilized glacio-hydrology models to assess the impacts of climate change on river runoff in each catchment of Nepal. This comprehensive approach aims to understand the complex interplay between glacial dynamics and climatic variations, providing valuable insights into the evolving hydrological patterns in the region.

The Koshi River, a major tributary of the Ganges, traverses through Nepal and China before flowing into India. Over the period 1952–2007, the annual average maximum and minimum temperatures of the Koshi have increased by 0.06 °C and 0.01 °C, respectively. During this time frame, precipitation in the region exhibited both increasing and decreasing trends. Looking ahead, projections suggest a substantial rise in both the annual average temperature and precipitation, anticipated to be around 4 °C and 14%, respectively, until 2096 compared to the baseline period (2000–2010) (Nepal, 2016). Despite these climate changes, it is forecasted that the Koshi Basin's annual river runoff won't be significantly impacted (Devkota and Gyawali, 2015). However, specific subcatchments, such as Tamakoshi and DudhKoshi, are expected to experience an increase in future runoff (Khadka et al., 2014; Nepal, 2016). The reduction in snow-covered areas and the subsequent increase in snowmelt are likely contributors to the elevated annual discharge in these basins. The projections also indicate a heightened risk of high flow events in both basin-level and sub-basin levels, posing a potential threat of increased flood events (Khadka et al., 2014; Devkota and Gyawali, 2015; Nepal, 2016).

The Narayani Basin, situated in the central part of Nepal, witnessed a decline in average annual temperatures from 1960 to 1970, followed by a subsequent increase at a rate of 0.03 °C yr^{-1} until 2015 (Chand et al., 2021). Simultaneously, observations indicate a decrease in precipitation for all seasons except the monsoon season between 1961 and 2004 (Panthi et al., 2015). This pattern contributes to a higher frequency of heavy rainfall days and fewer rainy days, resulting in extreme floods.

The Langtang river basin, a sub-catchment of the Narayani river basin, relies significantly on snow and glacier melt, constituting about one-third of its annual runoff (Ragettli et al., 2016b). Projections for the future, under RCP4.5 and RCP8.5 scenarios, suggest an increase in both average annual temperature and precipitation from 2000 to 2100 (Ragettli et al., 2016a). Future runoff in the Langtang region is expected to rise, particularly post-monsoon, driven by increased precipitation but countered by a decrease in glacier contribution after 2040 (Immerzeel et al., 2013). This shift is attributed to a phase change in precipitation from snow to rain due to cyclonic disturbances (Collier and Immerzeel, 2015; Norris et al., 2015), potentially transforming the basin's runoff dependency from glaciers to precipitation.

Similarly, the Marsyangdi basin, another sub-basin of the Narayani river system, relies on snow and glacier melt, contributing about 9%–12% to annual discharge from 2004 to 2009 (Gupta et al., 2019). Projections indicate a decreasing trend in annual precipitation by

10.78 mm yr^{-1} until the mid-21st century (Gupta et al., 2019). Consequently, the future annual discharge reflects a declining rate in response to reduced precipitation, despite an increase in ice melt from both debris-free and debris-covered glaciers due to warming.

The Karnali, the longest river in Nepal, originates in China (Mansarovar and Rokas Lake) and flows towards India. Precipitation in this basin is influenced by both the Indian summer monsoon and westerlies (Shrestha, 2000). The monsoon period in this basin witnesses the highest rainfall, accounting for nearly 80% of the total annual precipitation. However, the entire region is undergoing warming trends, coupled with a decline in precipitation at a rate of 4.91 mm yr^{-1} during 1981–2012 (Khatiwada et al., 2016), indicative of a warm and dry climate in the Karnali Basin (Dahal et al., 2020). Projections for the Karnali Basin indicate an anticipated average annual temperature increase of 1.4–3.4 °C (RCP4.5) and 1.8–6.6 °C (RCP8.5) by the end of the 21st century (Dahal et al., 2020). Similarly, precipitation is projected to incline during pre-monsoons and monsoons, contributing to an overall increase in annual total precipitation. However, a potential concern arises with the expected decrease in precipitation during the winter season, raising the possibility of winter drought in the future. The combined impact of increasing temperature and precipitation is reflected in the projection of future annual mean discharge, expected to rise by up to 8% (RCP4.5) and 10% (RCP8.5) compared to the annual discharge during 1971–2000 (Dahal et al., 2020).

Within the Indus Basin, primarily situated in Pakistan, there are four sub-basins in the western Himalaya: Hunza, Gilgit, Shigar, and Astore. Focusing on the Hunza Basin, approximately 20% of its area is covered by glaciers, with glacier and snowmelt serving as the primary sources for runoff. According to Shrestha et al. (2015), the contribution of glacier melt and snowmelt to the total runoff in the Hunza Basin is 33.3% and 49.3%, respectively, while rainfall accounts for 17.4% of the total runoff.

Moving to the Gilgit Basin, glacier coverage is estimated at about 8.1%. Here, the runoff is predominantly driven by glacier melt (31%) and snowmelt (37%–38%), with rainfall contributing 26% (Nazeer et al., 2022). Similarly, in both the Shigar and Astore basins, glacier melt and snowmelt play a significant role, contributing more than 70% to the total runoff in each basin (Soncini et al., 2015; Farhan et al., 2015).

The upper basin of the Brahmaputra, situated in the eastern Himalaya and primarily located in China (Yarlung Zangbo), has been a focal point for numerous studies in glacio-hydrology. While these studies have yielded diverse results, a consistent finding is that rainfall plays a predominant role in controlling runoff in the upper Brahmaputra. This is particularly evident in the monsoon-dominated region, as highlighted by various studies, including those conducted by Khanal et al. (2021), Wang et al. (2021), and Cui et al. (2023) (Fig. 3).

5. Challenges in the glacio-hydrology modeling across the Himalayas

Uncertainty poses a significant challenge in hydrological simulations for high-mountain rivers. The comprehension of cryospheric processes and their implications on the H-K region is consistently hindered by a shortage of meteorological and cryospheric observations. This predicament arises from data scarcity, where issues such as precipitation underestimation are at times mitigated by hydrological models resorting to increased snow and glacier melting to ensure model consistency (Pellicciotti et al., 2012).

5.1. Lack of field data

The uncertainty surrounding the spatial and seasonal variability in ice melt, snowmelt, and precipitation impacting streamflow is attributed to several challenges (Immerzeel et al., 2010; Moors et al., 2011). These challenges include the inadequacy of quality-controlled ground observational data over an extended period (Engelhardt et al., 2017), a lack of remote sensing data, limited weather stations at high elevation regions (Lutz and Immerzeel, 2016), challenging terrain, and complex political situations (Cogley, 2011).

In the headwaters of the IGB region, approximately 40 meteorological stations exist, with only 8 stations situated above 4,000 m above sea level (a.s.l.) (Lutz and Immerzeel, 2016). The sparse distribution of these high-altitude stations poses challenges in studying the heterogeneous environment under the influence of climate change. Furthermore, this limited and uneven distribution complicates the understanding of orographic precipitation, debris glacier melting, and meteorological data variance concerning both space and time (Viviroli et al., 2011; Ragettli et al., 2013; Engelhardt et al., 2017).

Beyond data scarcity, the type, position, and measurement methods of meteorological stations are crucial for assessing data quality and accuracy. Generally, the H-K region is equipped with a few rainfall stations, such as tipping bucket stations, which solely measure rain and do not capture snowfall, thereby hindering the estimation of snowfall in the region.

Adding to the challenge of uncertainty is the utilization of low elevation meteorological data for high-altitude regions. Extrapolating point-scale meteorological data to basin-scale proves unsuitable for high-altitude catchments (Immerzeel et al., 2012) due to the pronounced verticality and elevation dependency of climate forcing (Hewitt, 2011). The meteorological forcing of temperature and precipitation introduces significant uncertainty, leading to errors in model simulations (Garen and Marks, 2005). Precipitation, in particular, carries substantial uncertainty, especially concerning the phase transformation of snow and rain (Moulin et al., 2009; Lutz et al., 2014b). To address this issue and mitigate uncertainty, Immerzeel et al. (2012, 2015) devised a straightforward method. This method involves calculating the precipitation amount from the glacier mass balance in high elevations, offering a solution to improve accuracy and reduce uncertainty in modeling.

Additionally, numerous studies have employed gridded meteorological datasets in the H-K regions, such as WRF simulations (Engelhardt et al., 2017), TRMM (Khadka et al., 2014), APHRODITE (Duncan and Biggs, 2012), ERA-Interim (Immerzeel et al., 2015), HAR (Maussion et al., 2014), and WFDEI data (Weedon et al., 2011, 2014; Lutz and Immerzeel, 2016). The APHRODITE dataset, when compared to TRMM in Nepal, demonstrates a more accurate representation of precipitation (Duncan and Biggs, 2012). However, in the upper Indus, the APHRODITE product underestimates precipitation due to an insufficient number of meteorological stations, necessitating more ground station data, particularly in high elevations, to better capture actual precipitation (Lutz et al., 2014b; Duncan and Biggs, 2012; Yatagai et al., 2012).

Among these datasets, ERA-Interim is considered more accurate for the H-K region (Lutz and Immerzeel, 2016). In the IGB basin, precipitation is observed to increase in the altitude range between 5,000 m and 6,000 m above sea level (a.s.l.), while above 6,000 m a.s.l. a decreasing trend is noted (Hewitt, 2005, 2007, 2011; Immerzeel et al., 2015; Winiger et al., 2005). To enhance precipitation data accuracy, introducing a precipitation lapse rate based on this concept can be beneficial. Subsequently, the gridded precipitation data obtained should be bias-corrected by comparing it with station data.

In this study, we conducted a comparison of various operational precipitation products in the upper Indus region, revealing a substantial variance in the mean annual precipitation amount from 1999 to 2011 across different operational datasets (Fig. 5). The range of precipitation estimates is notable, with values ranging from 312 mm according to the TRMM satellite product to 1,097 mm based on the MERRA2 reanalysis data. Specifically, the ERA5-Land provides an intermediate estimate of mean annual precipitation at the upper Indus, measuring 754 mm. This falls within a comparable range to the results obtained from the

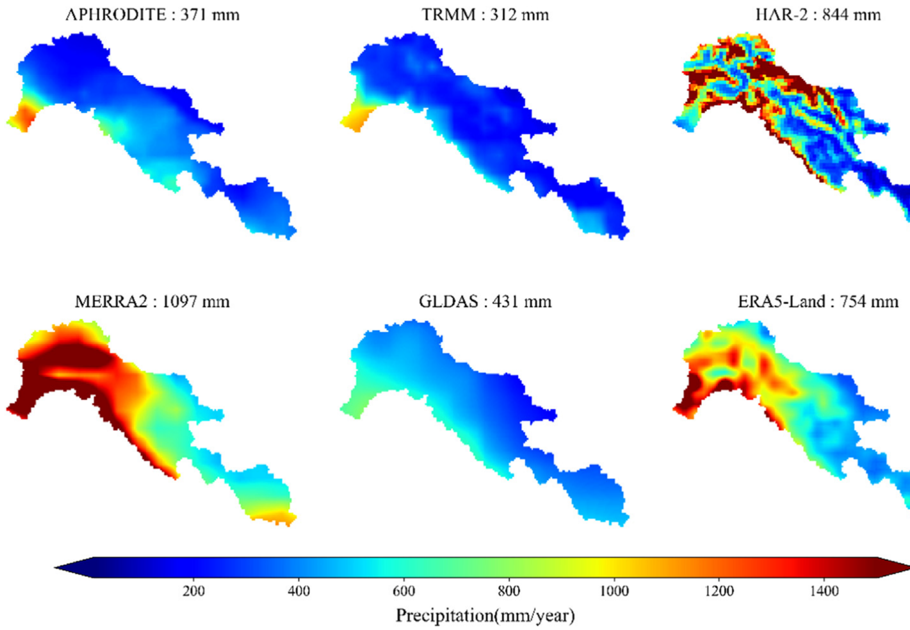

Fig. 5. Comparison of the spatial distribution of mean annual precipitation across various datasets (APHRODITE: Yatagai et al. (2012); TRMM: TRMM (2011); HAR-2: Wang et al. (2021); MERRA2: GMAO (2015); GLDAS: Beaudoing and Rodell (2020); ERA5-Land: Muñoz-Sabater et al. (2021) in the upper Indus River basin from 1999 to 2011.

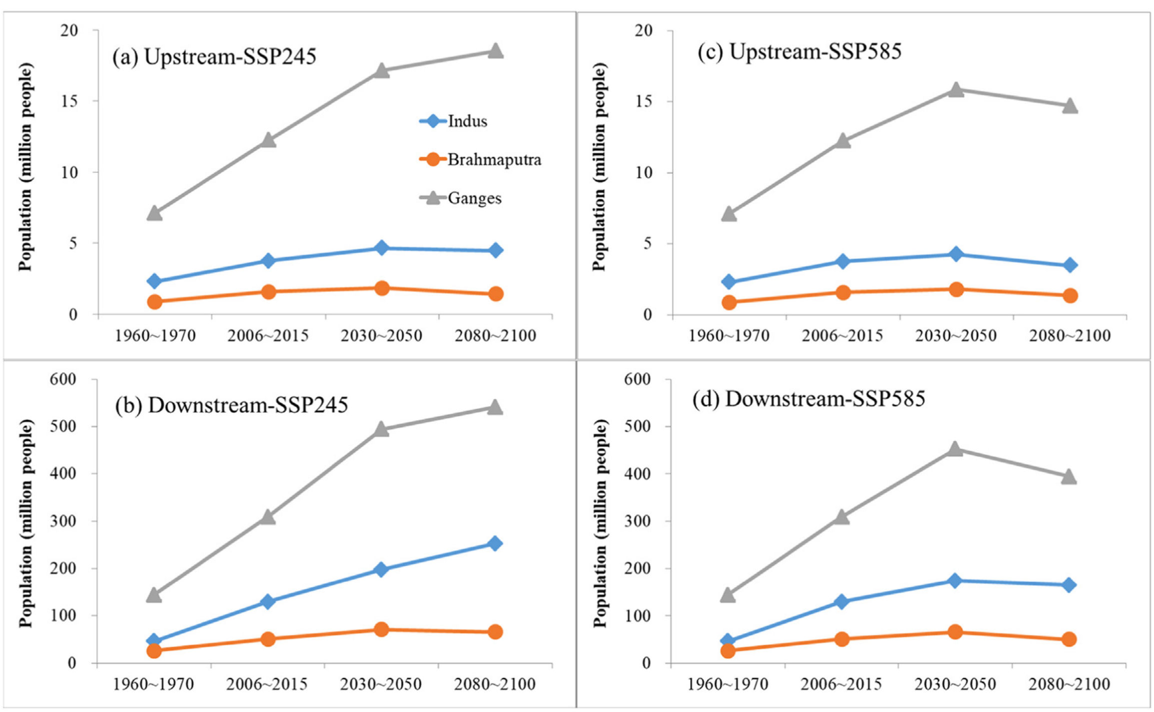

Fig. 6. Populations of the IGB river basins from 1960 to 2100 under a moderate emission scenario (SSP245; a-b) and a high emission scenario (SSP585; c-d). Here, (a) and (c) represent upstream mountain regions, while (b) and (d) represent their hydrologically-dependent downstream lower plains.

High Asia Reanalysis version 2 (HAR-2), which reported a mean annual precipitation of 844 mm.

5.2. Glacier outline uncertainty

Glacier outlines depict the area and shape of glaciers, crucial for understanding accumulation and ablation processes. The commonly used outlines in the H-K region include the Randolph Glacier Inventory and ICIMOD glacier inventory (e.g., Bajracharya et al., 2010; Racoviteanu et al., 2013). These outlines are generated from diverse satellite images captured at various times and spectral resolutions. Consequently, discrepancies emerge in the delineation of accumulation and ablation zones, particularly affecting ice and snow melting during thaw seasons and introducing uncertainty (Mimeau et al., 2019).

Some glacier outlines are established at specific periods, yet adjustments can be made by cross-referencing with satellite images from different time frames. For instance, in a study conducted by Bandyopadhyay et al. (2019), the required glacier outline was for

Table 3
A comparison to existing review papers on this topic.

Study	Topic	Contents of the review				
		Statistical analysis of the literature	Development of different glacio-hydrological model	Glacial melting component to the total runoff	Prediction of the peak glacier melt time	Challenges on the glacio-hydrological modelling
Bolch et al., 2019	Historical changes and future projections of glaciers in Hindu-Kush Himalaya Region	No	No	No	No	No
Scott et al., 2019	Status and use of water resources, and policy suggestions for water resources management	No	No	No	No	No
Farinotti et al., 2020	Manifestations of Karakoram Anomaly and its driving forces	No	No	No	No	No
Azam et al., 2021	Impact of climate change on the cryosphere (glaciers, snow, and permafrost) and water resources in the Himalayan-Karakoram region, and the challenges in modeling	No	Yes	Yes	No	Yes
Nie et al., 2021	Historical changes of the glaciers and meltwater and its driving forces, and the evolution in the future, and how they impact the water resources and water-related hazards	No	No	Yes	No	No
Yao et al., 2022	Impact of climate change on the Asian Water Tower, and its implications for downstream water resources and ecosystems	No	No	No	No	No
This paper	Developments, applications (historical changes and projections of glacio-hydrology), and major challenges of glacio-hydrology modeling in the Himalayas	Yes	Yes	Yes	Yes	Yes

the year 2000, but the applied Randolph Glacier Inventory (RGI 6.0) database was from 2001. Consequently, manual corrections were undertaken using Landsat imagery to align with the intended starting date (Table 3).

5.3. Spatial scale uncertainty

Modeling cryospheric processes like debris-covered glaciers, avalanches, wind effects on snow transport, and glacial lakes poses challenges in glacio-hydrology models due to spatial scale limitations and insufficient meteorological data at high altitudes. The spatial resolution of these models is typically determined by the coverage of the study area. Often, hydrological models exhibit lower spatial resolutions for larger-scale basins and higher resolutions for smaller-scale ones. However, when models operate at coarse resolutions, they often fail to capture critical glaciological processes such as ice dynamics (Lutz et al., 2014a), effects of supraglacial cliffs and ponds (Ragettli et al., 2015), and topographic shading (Zhang et al., 2018; Qi et al., 2019).

High-resolution modeling offers advantages in describing various intricate processes like gravity-driven snow redistribution, topographic shading, effects of supraglacial cliffs and ponds, elevation changes in small glaciers (Engelhardt et al., 2017), and even avalanches (Ragettli et al., 2016a). This detailed modeling significantly improves discharge simulations compared to low-resolution approaches. However, implementing fine spatial and temporal resolution simulations for large basins can be resource-intensive, requiring high-performance computing devices and substantial time and financial investments.

5.4. Parametric uncertainty

Parametric uncertainty, identified by Ragettli et al. (2013), arises during model calibration with observations and remains a significant source of uncertainty. Sensitive parameters crucial to this uncertainty encompass thresholds for snow/rain discrimination (Shrestha et al., 2014), snow and ice albedo (Shrestha et al., 2012; Shrestha et al., 2015), englacial layer properties like depth, porosity, and hydraulic conductivity (Mimeau et al., 2019), temperature and precipitation lapse rates (Ragettli et al., 2013; Wang et al., 2016; Lutz and Immerzeel, 2016; Shrestha et al., 2015), morphological parameters for canopy, initial conditions, and soil properties (Xue et al., 1997).

However, challenges arise due to discrepancies between observed meteorological station data and the most active hydrologic region (as indicated by studies by Hewitt (2005, 2011)) in the Karakoram region, particularly regarding vertical precipitation lapse rates. These rates vary across basins and models, complicating their accurate estimation. Investigations on parameter sensitivity involve assessing their impact on runoff by varying parameters within $a \pm 10\%$ range, ranking them based on sensitivity, revealing that the effect of parameter uncertainty on runoff decreases over time (Ragettli et al., 2013).

Strategies to mitigate parametric uncertainty involve adopting parameter ranges from previous literature to set initial conditions for model simulations (Pellicciotti et al., 2012; Ragettli et al., 2013), followed by recalibration of these parameters. However, limitations exist in utilizing parameters from earlier studies, especially when those studies lack processes like snow redistribution by gravity or glacier base melting, different from present models. In such cases, integrating ground-based observations with high-resolution satellite data (e.g., MODIS, SENTINEL) proves beneficial to substitute highly sensitive parameters (Ragettli et al., 2015).

6. Glacio-hydrology modeling for regional sustainable development

Water resources are crucial for human survival and economic progress, making it imperative to effectively manage them and alleviate supply-demand imbalances. Addressing these challenges within a sustainable framework is pivotal for regional development. In the Himalayas and downstream areas, understanding the spatiotemporal distribution of available water resources is paramount.

Changes in water resources are influenced by climatic and geographical factors. Factors like geographical latitude, atmospheric circulation, and terrain conditions determine regional precipitation and subsequent water availability. However, in alpine cold regions like the Himalayas, water resources' distribution isn't solely determined by precipitation. It also depends on the storage and regulation by solid water bodies like glaciers, snow, and permafrost under varying climatic conditions (Wang et al., 2023a, 2023b).

Accurately quantifying freshwater availability in the Himalayas, especially in the headwaters of major rivers like the Indus, Ganges, and Brahmaputra, demands improved representation of ice and snow melting and permafrost degradation in basin-scale hydrological modeling. Current models struggle to precisely estimate runoff from soil thawing/freezing due to limited knowledge about large-scale ground ice, posing challenges in satellite-based assessments. To enhance permafrost hydrological simulations and understand the impacts of permafrost degradation on freshwater availability's seasonality and long-term trends, more in-situ borehole data are necessary.

Moreover, population dynamics have significantly altered in the IGB river basins since 1960 (Fig. 6; CIESIN, 2017; Tatem, 2017; Wang et al., 2022), impacting both upstream mountain regions and their hydrologically-dependent downstream plains. Future projections suggest varying population trends across these basins, necessitating consideration to evaluate per-capita freshwater availability in the Himalayan regions. This assessment is crucial for sustainable regional economic and social development.

7. Final remarks

This study provides a distinctive focus on reviewing the evolution, applications, and key challenges of glacio-hydrology modeling specifically in the Himalayas. Over the past decade, several models of varying complexities addressing glacio-hydrological processes have emerged, encompassing aspects such as ablation, glacier dynamics, ice avalanches, and permafrost. Notably, our research marks the first attempt to conduct a statistical analysis delineating the current landscape of glacio-hydrology modeling in the Himalayas and its neighboring regions. Additionally, we systematically summarize studies pertaining to glacial melt contributions to river runoff in Himalayan basins (Indus, Ganges, and Brahmaputra) and project future peak times for glacier melting.

To enhance our understanding of glacio-hydrology processes for promoting sustainable development in the Himalayas, several recommendations are proposed. Firstly, there is an urgent need to establish comprehensive in situ observations in the Himalayas, especially in ungauged mountainous regions. Concurrently, the development of novel remote-sensing technologies, specifically for monitoring permafrost ice, is crucial. Furthermore, advancing glacio-hydrology models to comprehensively study integrated processes involving glaciers, snow, and permafrost in high-altitude regions should be prioritized in future studies.

Secondly, given the rapid pace of climate warming, the existing water resource situation in the Himalayas underscores the urgency of enhancing regional water resource management. Recognizing, quantifying, and emphasizing the value of water in decision-making processes are pivotal steps toward achieving equitable and sustainable water resource management aligned with the United Nations' Sustainable Development Goals (SDGs) outlined in the 2030 Agenda.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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