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Guidelines for the assessment of climate change impact on water cycle for glacierised and non-glacierised regions in India

FutureWater

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These guidelines were developed by Central Water Commission (CWC) and Swiss Agency for Development and Cooperation (SDC) for making informed decisions about water allocation, infrastructure development, and environmental regulations in Indian Himalayan Region. It presents a step-by-step guide to setting up glacio-hydrological models, i.e., spatial processes in hydrology in the Indian Himalayan region (IHR), Hindu Kush Himalayan (HKH) region and other parts of high mountain Asia (HMA). The guidelines emphasize the crucial linkages between these models and water allocation models in ensuring sustainable water management.

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Foreword

….from Minister or Secretary or Member

Message from Head of Cooperation, SDC

Message from DG-CWC

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Executive Summary

High Mountain Asia (HMA) has the world's largest ice and snow reserves outside the polar regions and is an important source of water for the major river systems in Asia, providing water for a population of more than a billion people, which is increasing rapidly (Immerzeel, 2010; Immerzeel et al., 2020; Kraaijenbrink et al., 2021; Stocker et al., 2013). The HMA region is characterized by contrasting atmospheric circulation patterns (Bookhagen and Burbank, 2006; Cannon et al., 2016). Midlatitude westerlies and Asian monsoon systems supply the most moisture as snow or rain in the western and eastern parts of HMA, respectively (Khanal et al., 2023). The variability in the climate, hypsometry and cryosphere distribution leads to characteristic glacial, nival, pluvial, and mixed hydrological regimes in HMA's rivers (Khanal et al., 2021).

Glacio-hydrological models (GHM) are important for water management as they help in understanding and predicting the complex interactions between glaciers, snowmelt, and surface and groundwater in mountainous regions. These models are especially critical in regions such as the Himalayas, where a significant proportion of the population depends on the water supply from snowmelt and glacier melt. GHMs can provide valuable information for water managers and policymakers to make informed decisions about water allocation, infrastructure development, and environmental regulations. These models can also help in assessing the impact of climate change on the water cycle, particularly in mountainous regions, where the effects of global warming are more pronounced.

This report presents a step-by-step guide to setting up a GHM, i.e., Spatial Processes in Hydrology (SPHY), in the Indian Himalayan regions (IHR) and Hindu Kush Himalayan (HKH) region. The guidelines emphasize the crucial linkages between GHMs and water allocation models in ensuring sustainable water management. GHMs estimate water availability and provide input data for water allocation models, which determine how water should be allocated to different users. These models play a vital role in making informed decisions about water allocation, infrastructure development, and environmental regulations. Effective linkages between hydrological and water allocation models are necessary to ensure sustainable water management, which is crucial for the well-being of communities and the environment.

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Abbreviations used in this document

HM – Hydrological Model

GHM – Glacio-Hydrological Model

HMA – High Mountains of Asia

IHR – Indian Himalayan Region

HKH – Hindu Kush Himalayan

SPHY – Spatial Processes in Hydrology

IWRM – Integrated Water Resources Management

DSS – Decision Support System

SDC – Swiss Agency for Development and Cooperation

CWC – Central Water Commission

ECMWF – European Centre for Medium-Range Weather Forecasts

GCM – General Circulation Model

RCM – Regional Climate Model

CMIP – Coupled Model Intercomparison Project

SSP – Shared Socioeconomic Pathways

RCP – Representative Concentration Pathways

IPCC – Intergovernmental Panel on Climate Change

NDVI – Normalized Difference Vegetation Index

DEM – Digital Elevation Model

MODIS – Moderate Resolution Imaging Spectroradiometer

GRDC – Global Runoff Data Centre

ICIMOD – International Centre for Integrated Mountain and Development

WEAP – Water Evaluation and Planning

1. Background

1.1. What is a glacio-hydrological model?

A model is a simplified replica of the real system where knowledge about a system is condensed into mathematical equations *(Beven, 2012)*. Hydro-meteorological processes are often very complicated to model due to limited information on catchment characteristics, system states, boundary conditions, governing equations, and underlying heterogeneity (Beven, 2012; Blöschl and Sivapalan, 1995). Hydrological models (HMs) represent intricate relations between input and output signals, through intermediate fluxes and states, satisfying mass, energy and momentum balances. Often hydrological fluxes and storages, such as evaporation, groundwater, soil moisture, snow, and riverine storage, are associated with memory and dependence at various spatio-temporal scales and these complex interactions are represented by HMs. A Glacio-hydrological model (GHM) typically integrates data and processes related to glaciology, hydrology, meteorology, and other relevant disciplines to simulate the behavior of glaciers and their influence on the hydrological cycle. A GHM falls under the broad category of HMs and mainly focuses on the snow and glacier processes and their influence on the overall hydrological cycle. Thus, HMs and GHMs are used interchangeably in the hydrological modeling community. GHMs can simulate various processes, such as snow accumulation and ablation, ice melt, glacier movement, and runoff generation. GHMs are valuable tools for studying glacier dynamics, hydrological processes in glacierized regions, and assessing the impacts of climate change on water resources. GHMs are often used by glaciologists, hydrologists, climatologists, and other scientists to improve our understanding of glacier behavior and its influence on hydrological systems, which can have significant implications for water management, ecosystem dynamics, and human livelihoods in glacierized regions. A well-configured and calibrated GHM serves as a robust and reliable tool to estimate the magnitude and frequency of extreme hydro-meteorological events for both current and future climate. The propagation of uncertainty, in magnitude, spatial extent, and time, from the climate driver to the hydrological response and impact can be estimated well with the GHMs.

1.2. What types of glacio-hydrological models are available?

HMs and GHMs can be defined both in terms of processes and spatial complexity across model elements (Clark et al., 2017; Hrachowitz and Clark, 2017). The HMs can be categorised into two broad categories, i.e. conceptual, and physically based models. A HM based on the understanding of processes, their interactions and overall system behaviour is a conceptual HM (Arnold et al., 1998; Bergström, 1992; Martinec and Rango, 1986). These HMs (and GHMs) require calibration and validation to comply with the purpose of use and if the model does not meet its objective the model should be revised and amended. Thus, conceptual GHMs represent a top-down approach where the uncertainty of the processes in a catchment is defined in priori. On the other hand, physically based GHMs are based on bottom-up approach which assumes overall performance is the result of a combination of all small-scale processes where each of these processes is defined based on physical laws and equations (Ragettli and Pellicciotti, 2012; Schulla, 2017). The physically based HMs incorporate the space-time variability of precipitation, radiation and variation in physiographic characteristics and also resolve the spatial heterogeneity issues *(Fatichi et al., 2016)*. In an ideal situation, physically based GHMs (and HMs) do not require any parameter calibration, however, such a model is not available. GHMs can also be categorised based on their ability to model processes at different spatial scales, i.e., lumped and distributed (also semi-distributed). Lumped HMs consider the whole system (or catchment) as a single entity. On the contrary, distributed HMs are lumped models applied at a grid scale and account for distributed forcing and catchment characteristics (Kampf and Burges, 2007). Distributed HMs provide a better understanding of the spatial variability in system behaviour and thus provide additional information on the spatio-temporal processes of the system (Reed et al., 2004; Smith et al., 2004b). Based on data availability, parameters in distributed HMs (and GHMs) can be varied spatially *(Beven, 2001)*. The lack of spatial observations mostly limits the application of distributed HMs *(Grayson et al., 2002)*. Often physically based distributed HMs have many parameters and are associated with high computational time and cost *(Koch et al., 2016)*. The choice of HMs depends on the objective of the study and it remains a matter of debate if conceptual lumped HMs models are better than physically based distributed models *(Holländer et al., 2014; Vaze et al., 2011)*.

1.3. What key processes for the glacio-hydrological model in the high mountains of Asia?

The cryosphere (water in a frozen state as snow, ice, lakes, glaciers and permafrost) plays a key role in the global water cycle and affects water availability, weather, energy, and agriculture (Hock et al., 2017; Huggel et al., 2015). Each of these components is associated with a different response and spatio-temporal scale. A change in the state of these variables affects the overall water cycle differently (both in space and time), and thus requires a proper understanding of the process and their current and future states. Followings are the key processes relevant for the IHR, HKH and HMA regions;

1.3.1. Melt modelling

Melt estimation, from snow-covered or glacierised areas, is a key element in the assessment of river runoff, flood risk, water resources and cryosphere-related changes associated with climate change in high mountains (Hock, 2003). A robust river runoff simulation, in a mountainous environment such as HKH and HMA, requires proper representation of snow and ice melting processes in GHMs (Pellicciotti et al., 2012). A degree day approach (also known as the temperature index model), based on the empirical assumption between near surface-air temperature and melt rates, is commonly used in HMs to simulate the melt (Braithwaite and Zhang, 2000; Hock, 2003). This approach has been widely used due to its simplicity and parsimony in data requirements (Pellicciotti et al., 2005). However, this method is sensitive to the time integration process of daily mean temperatures (use of different periods and time frame used to calculate the average) and is unable to capture the diurnal changes. For instance, the daily mean temperature could be zero or negative indicating no melt, but the melt conditions may fluctuate during the day *(Tobin et al., 2013)*. GHMs generally assume a constant degree day factor over the entire spatial modelling domain. The spatio-temporal variability, due to changes in seasons, topographic characteristics (slope, aspect and shading), albedo changes, and atmospheric conditions should be considered while calculating the melt rates (Hock, 2003). The other approach to calculating melt requires the estimation of all the relevant fluxes based on physical equations, which often require numerous input data at fine spatial and temporal scales (Cazorzi and Dalla Fontana, 1996; Che et al., 2019; Hock, 2005; Hock and Holmgren, 2005). Energy balance models can resolve the complex interaction between the fluxes and internal states that could not be resolved by temperature index models (Cazorzi and Dalla Fontana, 1996; Hock, 2005).

However, the implementation of an energy balance scheme in GHMs is a cumbersome process and computationally expensive task. Moreover, many variables in energy balance models are still abstract, far from being easy to identify from measurements and indirectly estimated thus increasing the uncertainty in the results (Essery et al., 2013; Günther et al., 2019; Hock, 2005).

1.3.2. Snow sublimation

Snow sublimation is found to be one of the important components of the water cycle in high-altitude regions such as HKH and HMA, and thus requires proper representation in GHMs (Lv and Pomeroy, 2020; Sexstone et al., 2018; Stigter et al., 2018; Strasser et al., 2008). Studies have reported that snow sublimation in mountainous areas is highly variable and ranges between 10–90% of winter snowfall (Groot Zwaaftink et al., 2011; Lv and Pomeroy, 2020; MacDonald et al., 2010; Montesi et al., 2004; Pomeroy and Gray, 1995; Reba et al., 2012; Sexstone et al., 2016, 2018; Stigter et al., 2018; Strasser et al., 2008). Snow sublimation is a local scale process that depends on the available energy for the turbulent flux, the vapor pressure gradient between the snow and atmosphere, wind speed and exposure *(MacDonald et al., 2010; Sexstone et al., 2018)*. Direct measurement of sublimation is a difficult task and only gives an estimate at a point scale *(Bowling et al., 2004)*. Sublimation of snow is categorised into surface sublimation (representing water vapor fluxes between the atmosphere and the snowpack surface), canopy sublimation (representing intercepted snow held within the forest canopy), and blowing sublimation (representing snow that is transported by wind) *(Groot Zwaaftink et al., 2011; Sexstone et al., 2018; Strasser et al., 2008)*. The degree day approach, often used by GHMs, is representative only when the surface melt is the only dominant ablation component as ablation represents the ensemble of the processes such as melt, evaporation, wind and gravity-driven transport and sublimation *(Litt et al., 2019; Mott et al., 2018; Saloranta et al., 2019; Stigter et al., 2018; Wagnon et al., 2013)*. The empirical relationship between sublimation and meteorological variables is generally used for scaling sublimation processes from the point level to the catchment scale *(Stigter et al., 2018)*. However, these empirical relationships are often region-specific and thus require a more sophisticated energy balance approach (Clark et al., 2015a; Knowles et al., 2012). Lack of data (for e.g. albedo decay time scale and aerodynamic roughness length) and difficulty in measurement of parameters, in reality, hinders the implementation of energy balance schemes and models in HMs *(Bowling et al., 2004; Günther et al., 2019)*.

1.3.3. Permafrost

Permafrost constitutes any type of ground (soil, sediment, or rock that extends vertically from a few feet to a few miles beneath the ground) that has been frozen (< 0 °C) continuously for a minimum of two years *(e.g., Dobinski, 2011)*. A quarter of the Northern hemisphere and 17% of the earth's land surface (exposed) is covered by permafrost *(Biskaborn et al., 2019*). The hydrological processes such as quick surface runoff, movement of water in soil layers, storage, and exchange of surface and subsurface water is affected by the low hydraulic conductivity of permafrost (Dobinski, 2011; McNamara et al., 1998; Woo and Winter, 1993). The increasing warming rates, higher at polar and high-elevation regions compared to the global average, impact permafrost and associated hydrological processes (Lafrenière and Lamoureux, 2019; Pepin et al., 2015; Quinton and Baltzer, 2013). Degradation in permafrost (or thawing), either from climate or human-induced changes, can change surface drainage patterns by generating ponding, inducing soil skin flow and gullying effects (Lafrenière and Lamoureux, 2019; Walvoord and Kurylyk, 2016). Understanding hydrologic changes and permafrost-carbon feedback mechanisms in response to permafrost degradation and climate change is critical for ecosystems (Lawrence et al., 2015; Schuur et al., 2015; Walvoord and Kurylyk, 2016). Permafrost processes are associated with diurnal changes, microclimate, physiographic characteristics and spatial heterogeneity aspects *(Gao et al., 2021)*. Permafrost processes are difficult to implement in GHMs as they require sophisticated energy balance and phase transformation schemes (Walvoord and Kurylyk, 2016).

1.3.4. Evaporation

Evaporation is an important constituent of the water and energy balance. It affects weather and climate through its influence on boundary layer dynamics and thermal dynamics (Clark et al., 2015b). Globally only 30-35% of the total inland precipitation ends up in rivers (or river systems) and the remainder is evaporated *(Rodell et al., 2015)*. Evaporation, which constitutes surface evaporation, transpiration, evaporation from interception and open water evaporation, strongly influences the hydrological conditions *(Savenije, 2004)*. Evaporation is not only affected by meteorological conditions (radiation, wind speed, atmospheric humidity and air temperature), but also depends on hydrological (soil moisture availability) and biological factors (such as type and growing stage of vegetation). Most HMs and GHMs use potential evaporation (or actual evaporation if available) to calculate the water balance (Zhao et al., 2013). Spatially distributed HMs and GHMs often require evaporation information at grid level, which is not available as it is measured at a point scale. Also, the relative contributions of various evaporation types are not well understood *(Coenders-Gerrits et al., 2014; Nelson et al., 2020; Sutanto et al., 2014)*. Thus, more data measurement efforts are required to improve the understanding of evaporation processes (Harrigan and Berghuijs, 2016). It is found that the hydrological simulations which include explicit biological processes predict lower future droughts and small evaporation changes in a warmer climate *(Prudhomme et al., 2014)*. Thus, evaporation should not be separated from the physical and biological processes it connects. There are vast arrays of methods and equations available, differing in complexity and data requirements, to estimate the potential evaporation *(Oudin et al., 2005)*. The potential evaporation estimation methods depending on the approach can be divided into energy-based, temperature-based and mass transfer-based. The energy-based implementation of evaporation processes in GHMs is cumbersome as it requires a large array of input data compared to the other two methods.

1.3.5. Groundwater

Groundwater is an essential component of GHMs and HMs and plays a critical role in the hydrological cycle and water availability *(Taylor et al., 2013)*. It acts as a vast storage reservoir, interacting with surface water bodies and influencing their flow dynamics, water quality, and ecological processes. Accurate modelling of groundwater flow is crucial for assessing sustainable pumping rates, impacts on water availability and quality, and human water use. Groundwater flow is particularly important in regions where surface water availability is limited, and where groundwater is the primary source of water for domestic, agricultural, and industrial purposes. By incorporating groundwater flow in GHMs and HMs, a comprehensive understanding of water storage and release dynamics, surface water interactions, human water use, and climate change impacts can be obtained, providing valuable insights for water resources management, planning, and adaptation strategies.

GHMs and HMs that groundwater processes may underestimate water availability, overestimate human water use, and fail to capture the impacts of climate change on water resources. Therefore, it is crucial to include groundwater flow in GHMs to obtain accurate and reliable estimates of water availability, water use, and the impacts of climate change on water resources. This information can help policymakers make informed decisions about water allocation, water management, and adaptation strategies, ensuring sustainable and equitable use of water resources for both present and future generations.

1.3.6. Flow routing

Flow routing, i.e., transport of water from upstream cells (source) to downstream cells (sink) through a river network, in physically based distributed HMs is a difficult task as it requires solving Saint-Venant equations *(Beven, 2012; Chaudhry, 2007; Te Chow, 2010)*. The physical method requires solving complex partial differential equations (i.e., continuity and momentum), and often have high data requirements related to river geometry, morphology and floodplain, which are often not available for large spatial scales (Singh and Woolhiser, 2002). Several simple numerical approximations of these complex partial differential equations have been proposed and implemented in several HMs (and GHMs) in the past *(Beven, 2012; Chanson, 2004; Cunge, 1969)*. The choice of routing scheme has a significant influence on the timing of simulated river discharge and its peak values (Hattermann et al., 2017; Zaherpour et al., 2018; Zhao et al., 2017).

1.4. What are the key challenges in setting up a glacio-hydrological model in the high mountains of Asia?

1.4.1. Data availability

The availability and quality of spatial ground-based information are crucial for the choice of HM and GHM *(Clark et al., 2017)*. In past decades, many efforts have been made to improve the technology, quantity, and quality of data required for HMs and GHMs *(Singh, 2018)*. Advancements in remote sensing technology, such as satellites and radars, made it easier to model the hydrological characteristics of ungauged or data-scarce regions such as HKH. However, for most hydrological processes, e.g. snow sublimation, avalanching, glacier melt and characteristics (debris, ponds and cliffs), permafrost, groundwater processes, and routing processes, such spatial data do not exist *(Beniston et al., 2018; Dobinski, 2011)*. The use of GHMs, especially in the high mountains where the hydrological processes vary considerably with altitude, is hampered due to the limited qualitative data availability at higher and remote regions *(Klemeš, 1990)*.

It is extremely challenging to perform reliable streamflow simulations in particular for ungauged catchments and data-scarce regions such as HMA (Immerzeel et al., 2015b; Wortmann et al., 2018). Existing hydro-meteorological stations, mostly located in valleys lower than 4000m, are sparsely and unequally distributed in the region *(Palazzi et al., 2013; Qin et al., 2009)*. The point-based station data are not representative of the complex surrounding HMA. The low quality and limited availability of data at high altitude imposes difficulty in spatial interpolation and often leads to strong underestimation of HMA precipitation (Immerzeel et al., 2015b; Li et al., 2017; Palazzi et al., 2015).

To cater to these data scarcity issues, GHMs either use a calibration parameter or an approximation based on limited data obtained from location-specific studies (e.g., glacier mass balance, snow sublimation and hydraulic conductivity). Most of the processes are often measured or modelled at a small scale (time and space). However, the real application requires estimation of these processes for long-term and large region (such as the lifetime of hydraulic structures). Conversely, some local studies use regional and global-scale coarse data and parameters. The use of these approximations makes the outcome of HMs (and GHMs) uncertain (Bierkens et al., 2001; Blöschl and Sivapalan, 1995; Peters-Lidard et al., 2017; Seyfried et al., 2009).

Remote sensing and satellite data provide better geographical coverage compared to sparse point-based station data and have been extensively used in the past decades to provide a better understanding of the states and variables related to the hydrological cycle and water resources *(Wagner et al., 2009; Xu et al., 2014)*. Integration of remote sensing information with HMs provides a better uncertainty assessment of water resources and water-related issues and therefore in-depth exploration of the accuracy of such data is required (Emery and Camps, 2017).

1.4.2. Spatio-temporal resolution

The response time of hydrological processes varies from a few minutes (snow melt, snow avalanche) to multiple decades (glacier dynamics, groundwater flow in aquifers) (Hock, 2003, 2005; Koutsoyiannis, 2005; Marshak, 2008). The choice of the appropriate modelling timestep for hydrological simulation again depends on the availability of the data (temporal resolution of the forcing), dominant hydro-meteorological processes, geophysical characteristics of the catchments and objective of the study (Bastola and Murphy, 2013; Littlewood and Croke, 2008; Ostrowski et al., 2010; Smith et al., 2004a; Syed et al., 2003). For urban drainage processes, a sub-hourly resolution time step is recommended whereas for irrigation a monthly resolution is found to be sufficient (Blöschl and Sivapalan, 1995). For the simulation of highly dynamic processes such as floods, a sub-daily time step is required to represent the high intermittency of convective precipitation and fast catchment response time which depends on basin physiographic characteristics such as the size, drainage network, steepness, and percentage of impervious area *(Ochoa-Rodriguez et al., 2015)*. The spatial resolution of GHMs can vary from less than a meter resolution (for unsaturated flow processes) to a few hundred kilometers (monsoon circulation). The coarse spatial resolution of GHMs could be an important source of error in mountainous areas, such as HKH and HMA, due to the missing interactions between the topography and atmospheric processes required for small-scale processes (Beniston et al., 2018; Blöschl and Sivapalan, 1995; Sillmann et al., 2013).

1.4.3. Computational time

The use of physically based HMs and GHMs is limited due to huge computational requirements (Huintjes et al., 2015; Koch et al., 2016; North, 1975; Paul and Kotlarski, 2010; Reid and Brock, 2010). On the other hand, conceptual HMs are becoming popular due to lower data and computation resource requirements *(Koch et al., 2016)*. The advances in computational capacity in recent decades made it possible to model the desired system and keep track of the state and fluxes of a system at any given time and spatial scale *(Fatichi et al., 2016)*. However, computing remains a present-day challenge as the expectations have also increased beyond limits *(Bierkens et al., 2015; Clark et al., 2017)*. The issues related to the trade-off between the process complexity, spatial complexity, domain size, ensemble size, the time period of simulation, single deterministic simulation and model inter-comparisons persist *(Clark et al., 2017; Wood et al., 2011)*.

1.4.4. Uncertainties

Communicating predictive uncertainties with hydrological predictions are essential for water resources and other relevant decision-making processes (Georgakakos et al., 2004; Liu and Gupta, 2007). GHMs and HMs involve many processes, and each component brings uncertainty which ultimately contributes to the total uncertainty. Uncertainties in GHMs and HMs stem from parameters, model structure, input data, initial conditions and calibration *(Lindenschmidt et al., 2007; Papacharalampous et al., 2019; Renard et al., 2010; Sudheer et al., 2011; Troin et al., 2016; Wilby, 2005)*. Parameter uncertainty in GHMs (and HMs) is a result of conceptual simplification which arises due to inadequate process understanding, over approximations, limited data, inability to measure or estimate a process (e.g. hydraulic conductivity can be measured at point scale but varies considerably for catchment scale), natural process variability, and observational errors *(Beven, 2012)*. The structural uncertainty, sometimes referred to as "model uncertainty", in GHMs and HMs mainly arises due to the simplified representation of hydrological processes *(Lindenschmidt et al., 2007; Moges et al., 2021; Troin et al., 2016)*. HMs structural uncertainty also includes alternative conceptualizations related to surface and subsurface processes *(Refsgaard et al., 2012)*. The input uncertainty in GHMs and HMs is governed by uncertainty in forcing (sampling and measurement error in rainfall and temperature, large variability among the reanalysis, satellite-derived and merged products), elevation, soil characteristics and other catchment-related information. GHMs and HMs require calibration of different parameters (including snow, glaciers, and rainfall-runoff) and states based on the availability of ground-based observations. The errors emerging from unsatisfactory calibration and imperfect observations (for e.g. systematic error in stage and runoff measurements, rating curve extrapolations and hysteresis errors) contribute to the calibration and observational uncertainty of GHMs and HMs *(Domeneghetti et al., 2012; Kiang et al., 2018)*. Parameters calibrated to a stationary climate also add uncertainty to the hydrological prediction used to assess climate change impacts *(Brigode et al., 2013; Wilby, 2005)*. Model structural uncertainty is found to be the dominant source of predictive uncertainty in GHMs and HMs under both stationary and non-stationary climate (Højberg and Refsgaard, 2005; Mendoza et al., 2015; Rojas et al., 2008). The input uncertainty, especially in data-scarce mountain environments where the data involves interpolation, scaling and derivation from other measurements, constitutes about 10–40% of the predictive uncertainty *(McMillan et al., 2018)*. To adequately assess and reduce the uncertainty from GHMs and HMs, it is important to understand and quantify it (Liu and Gupta, 2007).

2. Spatial processes in hydrology (SPHY)

SPHY is a spatially distributed leaky bucket type of model and is applied on a cell-by-cell basis. To minimize the number of input parameters, and avoid complexity and long model run-times, SPHY does not include energy balance calculations and is therefore a water-balance-based model. The main terrestrial hydrological processes are described in a physically consistent way so that changes in storage and fluxes can be assessed adequately over time and space. The model is designed for both large and small-scale cryospheric-hydrological studies and integrates different hydrological processes, including (a) rainfall-runoff, (b) cryospheric processes, (c) evapotranspiration, and (d) soil hydrological processes. SPHY can operate at flexible spatial scales (glaciers, sub-basin, basin, and regional).

Rivers originating in the high mountains of Asia are the most melt-water-dependent river systems on Earth *(Schaner et al., 2012)*. In the regions surrounding the Himalayas and the Tibetan Plateau large human populations depend on the water supplied by these rivers *(Walter W. Immerzeel, 2010)*. However, the dependency on meltwater differs strongly between river basins as a result of differences in climate and differences in basin hypsometry (Immerzeel et al., 2012). Only by using a distributed hydrological modelling approach that includes the simulation of key hydrological and cryospheric processes, and inclusion of transient changes in climate, snow cover, glaciers and runoff, appropriate adaptation and mitigation options can be developed for this region *(Sorg et al., 2014)*. The SPHY model is very suitable for such an approach and has therefore been widely applied in the region (Khanal et al., 2021).

SPHY enables the user to turn on/off modules that are not required. This concept is very useful if the user is studying hydrological processes in regions where not all hydrological processes are relevant. A user may for example be interested in studying irrigation water requirements in central Africa. For this region glacier and snow melting processes are irrelevant and can thus be switched off. Another user may only be interested in simulating moisture conditions in the first soil layer, allowing the possibility to switch off the routing and groundwater modules. The advantages of turning off irrelevant modules are two-fold: (i) decrease model run-time, and (ii) decreases the amount of required model input data.

2.1. Key processes used in the SPHY model

SPHY is suitable for a wide range of water resource management applications. Therefore, SPHY is a state-of-the-art, easy-to-use, robust tool, that can be applied for operational as well as strategic decision support. The SPHY modelling toolbox is available in the public domain and only uses open-source software. SPHY is developed by FutureWater in cooperation with national and international clients and partners (visit www.sphy.nl for more information). Following are the key cryospheric processes included in the SPHY model which make it relevant for mountainous regions such as IHR and HKH.

2.1.1. Snow

Snowmelt is an important source of runoff in the mountainous catchments. To get a realistic estimate of snowmelt several processes have to be taken into account. Processes such as snow precipitation rates, meltwater refreezing in the snowpack, and sublimation and evaporation. The SPHY model simulates dynamic snow storage at a daily time step, adopted from the model presented by *Kokkonen et al., (2006)*. The model keeps track of snow storage, which is fed by precipitation and generates runoff from snow melt. Refreezing of snowmelt and rainfall within the snowpack is simulated as well. Depending on a temperature threshold, precipitation is defined to fall in either a solid or liquid state. To simulate snow melt, the well-established and widely used degree day melt modelling approach is used *Regine Hock, (2003).* Runoff from snow is generated when the air temperature is above the melting point and no more meltwaters can be refrozen within the snowpack (for more information read the SPHY manual).

2.1.2. Glaciers

Mountain glaciers are typical features that can be found in high-mountain environments. These features, which are also mentioned as 'rivers of ice', flow from high-altitude areas to the valleys due to gravitational forces. Glaciers are typically formed when accumulated snow at higher altitudes is transformed into ice and flows down under the force of gravity. The mass balance of a glacier is thereby determined by the sum of all processes that add mass to a glacier (accumulation) and removes mass from a glacier (ablation), and can be considered to be in equilibrium when accumulation equals ablation *(Haeberli, 2011)*. When accumulation is higher than ablation, due to increased snowfall or a decrease in melt, a glacier advances/thickens, and when ablation is higher than accumulation, due to decreased snowfall or an increase in the melt, a glacier retreats/thins. Besides precipitation and temperature, variables such as sublimation, wind-blown transport of snow, and avalanching also influence the rate of ablation and accumulation on the glacier. Melting of glacier ice contributes to the river discharge by means of a slow and fast component, being (i) percolation to the groundwater reservoir that eventually becomes base flow and (ii) direct runoff. The dynamic behaviour of the glaciers can be taken into account by incorporating key processes such as accumulation, ablation and ice mass transfer from accumulation to the ablation zone. Changes in glacier fraction in response to the precipitation and temperature are considered by using a mass-conserving ice distribution approach. The accumulated snow in the accumulation zone is transformed into ice and distributed downwards to the ablation area, at the end of each melting season (1st of October). The redistribution is proportional to the initial total volume of ice so glacier parts with a larger initial ice volume will receive a large volume of accumulated ice from the accumulation zone to the ablation zone (readers are referred to Khanal et al., (2021) for further details). The ice redistribution is done once a year (1st of October) at the end of the hydrological year (1st October to 30th September next year). The SPHY model usually operates at a spatial resolution that is too large to include ice flow and dynamics of glaciers. Therefore, glaciers in SPHY are considered as melting surfaces that can completely or partly cover a grid cell (Khanal et al., 2021). Glacier melt is calculated with a degree-day modelling approach as well. Because glaciers covered with debris melt at different rates than debris-free glaciers, a distinction can be made between different degree day factors for both types. When SPHY is run for future scenarios the fractional glacier cover in a grid cell changes according to a parameterization for glacier changes at the river basin scale. This parameterization estimates the changes in a river basin's glacier extent as a function of the glacier size distribution in the basin and projected temperature and precipitation.

2.1.3. Soil

Soil water storage properties can determine the amount of rainfall-runoff and infiltration to groundwater. The soil water processes in SPHY are modelled for three soil compartments, (i) the first soil layer (rootzone), (ii) the second soil layer (sub-soil), and (iii) the third soil layer (groundwater store). The lateral flow of water in the soil between cells, the exchange of water between soil layers and the groundwater reservoir through percolation and capillary rise, as well as the release of baseflow from the groundwater reservoir, are calculated in the model.

2.1.4. Lakes

Lakes or reservoirs present within a catchment act as a natural buffer, resulting in a delayed release of water from these water bodies. SPHY allows the user to choose a more complex routing scheme if lakes/reservoirs are located in their basin of interest. The use of this more advanced routing scheme requires a known relation between lake outflow and lake level height (Q(h)-relation) or lake storage.

2.2. Glacio-hydrological study for the Bhagirathi basin project supported by SDC

This project presents a framework for IWRM and DSS for Himalayan subbasins consisting of three integrated platforms. (i) A modelling and decision support platform built around a multi-scale modelling framework for glacier-and snow-fed subbasins, based on state-of-the-art and "easy to use" modelling technology. (ii) A stakeholder engagement platform to consult key stakeholders, identify key IWRM issues and co-design a new IWRM plan for the Bhagirathi subbasin. (iii) A capacity-building platform with on-site training and e-learning modules for the key project components: glacio-hydrological modelling, IWRM and DSS, to ensure the sustainability of the approach and pave the way for upscaling to other subbasins in the Indian Himalayan Region. To this end, this project assesses the historical and future climate change impacts on the hydrological regime and water balance components of the water cycle in the Bhagirathi and Din Gad catchments.

To understand the response of climate change to the water cycle, two different model setups are used in this project, i.e., large-scale Bhagirathi (500m) and small-scale Din Gad model (50m). The Bhagirathi model, which covers the entire upstream region just before the confluence of the Alaknanda River, focused on the changes in total water availability of the entire upstream region. Whereas the Din Gad model focused on improving the understanding of the runoff contributors.

After calibrating and validating the model results for the baseline period (1991-2020), the calibrated and validated models were used to assess the future hydrological changes (2021–2100) of the selected basins. A subset (4 GCM and two SSPs) of the full ensemble of climate change scenarios provided by General Circulation Models (GCMs) in the CMIP6 multi-model ensemble was used. The downscaled and bias corrected GCM outputs are used with the calibrated hydrological models to assess the impact on streamflow in the future. This project demonstrates how runoff composition and total runoff volume are expected to change by the end of the century (2100). The results illustrate that the total water availability for the whole Bhagirathi catchment will be relatively stable for ssp245 and slightly increases for ssp370 by the end of the century. However, there are considerable changes in the timing and magnitude of peak water availability and seasonality. This may impose a threat on the livelihood of the local communities if no adaptation measures are taken. Readers are suggested to read the report on "Present-day and future changes in the hydrology of the Bhagirathi Basin" provided in

.

3. Guidelines for SPHY Model set-up

3.1. Spatial-resolution

Among many other factors, the choice of spatial resolution of the model depends on the objectives of the study, time to conduct the study, computational resources, and data availability. For instance, if the objective of the study is to assess the impact of climate change on a regional scale or large basin scale (such as the Ganges or the Brahmaputra), a spatial resolution ranging from 1km to 5km would be favourable *(Khanal et al., 2021; Lutz et al., 2014a; Wijngaard et al., 2017)*. Conversely, if the objective of the study is to assess the impact of climate change on a glacier or smaller sub-basin, a spatial resolution from 30m to 1000 m would be favourable. The choice of spatial resolution also depends on the availability of the data. If there are fewer observed stations where meteorological variables (such as snow, temperature, and precipitation) are available within the region of interest then it is advisable to use a coarser spatial resolution compared to the scenario with a dense meteorological station network. The cryospheric processes are associated with different responses and spatio-temporal scales. For instance, glacier and snow melt processes are localized and dominant processes compared in the higher mountains compared to large-scale rainfall-runoff processes which are dominant in the lower plain regions. Thus, snow and glacier melt processes require finer-scale spatial discretization compared to the large-scale rainfall-runoff processes. Since SPHY takes sub-grid variability into account, it is possible to run the glacier processes at fine resolution (50 x 50m) and downstream rainfall-runoff processes at a coarser resolution (5 x 5 km) *(Khanal et al., 2021)*. The larger the geographical extent (or the number of cells in the model), the longer it will take to simulate the hydrological characteristics. So, it is advisable to have the total number of cells less than 1 million for faster computation.

3.2. Model time-step and time-horizon

Similar to spatial resolution, the selection of appropriate temporal resolution and time horizon depends on several factors. For instance, if the objective is to simulate a particular glacier-specific extreme event then it is advisable to run the model on a sub-daily scale (sub-hourly, hourly, 3-6 hourly time step). The choice of the time step is highly dependent on the data availability. If the meteorological forcings are available only on a daily time scale then it is advisable to run the model on a daily time step. On the other hand, if the objective of the model is to understand the impact of climate change on water availability at a large scale at longer time horizons in the future (mid-century and end of century, or centennial time scale) then it is advisable to run the SPHY model on daily time steps and aggregate the outputs as per need. In the hydrological realm, it is a widely accepted practice to employ a limited set of observed discharge data for the purpose of fine-tuning GHMs *(Khanal et al., 2021; Lutz et al., 2014a; Wijngaard et al., 2017)*. However, in order to attain a comprehensive understanding of the hydrological regime and flow characteristics exhibited by a given basin, it is strongly recommended to subject the calibrated GHM to an extensive simulation period spanning 20 to 30 years. This extended duration allows for a more robust analysis of the model's performance and its ability to capture long-term hydrological patterns. It is recommended that the baseline scenario utilized for this simulation incorporates the most recent and up-to-date data.

3.3. Data requirement for SPHY model setup

SPHY requires static data as well as dynamic data. For the static data, the most relevant are topography, land use type, glacier cover, lakes/reservoirs, and soil characteristics. For the dynamic data, SPHY uses climate data, such as precipitation, temperature, vegetation, snow cover, snow depth, snow water equivalent, glacier mass balance, and streamflow. Since SPHY is a grid-based model, flexible integration of different remote sensing and global data sources can easily be done. For example, the Normalized Difference Vegetation Index (NDVI) *(Myneni and Williams, 1994)* can be used to determine the leaf-area index to estimate the growth stage of land cover. For setting up the model, streamflow data are not necessary. However, to undertake a proper calibration and validation procedure, flow data are required. The model could also be calibrated using actual evapotranspiration, soil moisture contents, and/or snow-covered area. The following data is required to set up the SPHY model:

3.3.1. Digital Elevation Model (DEM)

A DEM is a representation of the bare ground (bare earth) topographic surface of the Earth excluding trees, buildings, and any other surface objects. DEM is required to calculate the slope, aspect, flow direction, and flow accumulation in the SPHY model. The DEM can be downloaded from the following sources:

- Shuttle Radar Topography Mission (SRTM): This DEM has a spatial resolution of 30m (1-arc second global digital elevation) and covers the whole globe. This DEM is freely available in the public domain. The data can be downloaded via USGS Earth Explorer, Google Earth Engine, or any other source.
- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER): This dem has a resolution of 90m (3 arc-seconds) and also available at the global scale. The data can be downloaded via USGS Earth Explorer, Google Earth Engine, or any other source.
- HydroSHEDS: HydroSHEDS, open-source data available at 3, 15, and 30 arc-seconds as well as 5 and 6 arc-minutes, provides hydrographic information in a consistent and comprehensive format for regional and global-scale applications. It offers a suite of geo-referenced datasets (vector and raster), including stream networks, watershed boundaries, drainage directions, and ancillary data layers such as flow accumulations, distances, and river topology information. The data can be downloaded from https://www.hydrosheds.org/.

3.3.2. Soil properties

The SPHY model requires soil properties as input for the hydrological simulation. Soil information is the basis for all environmental studies. Since local soil maps of good quality are often not available, global soil maps with a low resolution are used. FutureWater has developed the HiHydroSoil v2.0, a freely available high-resolution dataset (250m), with soil properties and classes on a global scale that can be easily used for hydrological, erosion, and crop modelling. This can be downloaded from https://www.futurewater.eu/projects/hihydrosoil/. It is also possible to use the observed soil properties values or maps (read the SPHY manual for more description).

3.3.3. Land use data

Land use maps represent spatial information on different types (classes) of physical coverage of the Earth's surface, e.g., forests, grasslands, croplands, lakes, wetlands, snow and glaciers. The land use data is an important input for the SPHY model. There are several free sources to acquire land use data on a country, regional and global scale. For glacier scale studies it is recommended to generate detailed land use data using the Sentinel2 image (2015–present coverage). The raw images can be accessed via https://scihub.copernicus.eu/. Similarly, any observed land use data available can be used in the SPHY model. For large scale applications, land use data can be derived from:

- Esri Land Cover: The Esri Land Cover provides a very high resolution (10m) land cover from 2017–2022 generated using Sentinel-2. This 10m resolution data source is open source and is available on a global scale. Visit here https://livingatlas.arcgis.com/landcover/ to download and for more information.
- European Space Agency Climate Change Initiative (CCI) Land Cover V2: This data is available at 300m resolution for 1992–2018. The data can be downloaded from https://www.esa-landcover-cci.org/
- MCD12Q1 0.5 km MODIS: The Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1) Version 6 data product provides global land cover types at yearly intervals (2001–2020), derived from six different classification schemes. The MCD12Q1 Version 6 data product is derived using supervised classifications of MODIS Terra and Aqua reflectance data. The data can be downloaded fromhttps://lpdaac.usgs.gov/products/mcd12q1v006/

3.3.4. Glacier outlines

The glacier outlines are required to prepare the inputs required for simulating the glacier module in the SPHY. The observed glacier outlines, if available, can be easily used with SPHY. Otherwise, the most recent version of the Randolph Glacier Inventory (RGI 6.0) is preferred.

- The RGIv6.0 is freely available on a global scale. The dataset can be downloaded from https://www.glims.org/RGI/.
- There are some freely available regional datasets on ICIMOD's platform (visit http://rds.icimod.org/Home/DataDetail?metadataId=31029).

Moreover, the SPHY glacier module can distinguish the glacier melt into clean ice and debris-covered glaciers. However, this requires pre-distinction of glacier surface into clean ice and debris. Ablation characteristics are different on debris-covered glaciers than on clean-ice glaciers. On this type of glaciers, the amount of ablation depends on several factors, e.g. debris thickness and the presence of ice cliffs and supraglacial ponds (Pellicciotti et al., 2015; Ragettli et al., 2016; Reid and Brock, 2010; Steiner et al., 2015). The magnitude of ablation depends on the thickness of debris on the glacier. Very thin layers of debris (<2 cm) enhance melt rates due to the lower albedos, whereas thicker layers of debris reduce melt rates due to the insulation of the surface (Kraaijenbrink et al., 2017; Nicholson and Benn, 2006; Østrem, 1959; Reid and Brock, 2010; Rowan et al., 2015).

3.3.5. Glacier ice thickness

The glacier ice thickness is required to prepare the inputs required for simulating the glacier module in the SPHY. The observed glacier ice thickness, if available, can be easily used with SPHY. Otherwise, the following data sources are preferred:

- *Farinotti et al., (2019)*: The authors here use an ensemble of up to five models to provide a consensus estimate for the ice thickness distribution of 215,000 glaciers outside the Greenland and Antarctic ice sheets. The models use principles of ice flow dynamics to invert ice thickness from surface characteristics. The data set is freely available here.
- *Millan, Mouginot, Rabatel, & Morlighem, (2022)*: The authors present a comprehensive high-resolution mapping of ice motion for 98% of the world's total glacier area during the period 2017–2018. We use this mapping of glacier flow to generate an estimate of global ice volume that reconciles ice thickness distribution with glacier dynamics and surface topography. The data set is freely available here.

3.3.6. Meteorological forcings

SPHY requires spatial daily maps for precipitation and temperature (minimum, maximum and mean). The most preferred option is to use the observed station data (or gridded data) if available for the hydrological simulations. Existing hydro-meteorological stations, mostly located in valleys lower than 4000m, are sparsely distributed in the mountains. The complex topography and harsh conditions in the mountains impose difficulties in managing the ground stations. Usually, in IHR, such datasets are not available. In such cases, satellite-derived and remotely sensed products could be used. Remotely sensed satellite measurements from geostationary thermal infrared and polar-orbiting passive microwave sensors are useful for deriving precipitation measurements based on cloud-top brightness temperature and spectral scattering due to large ice particles, respectively. However, the uncertainty is high due to sensor signals' limitations in penetrating the clouds and correctly estimating the precipitation falling as snow at high altitudes *(W. W. Immerzeel et al., 2015)*. Nevertheless, remotely sensed products, in recent decades, have proven to be a cost-effective and reliable tool to understand precipitation patterns and trends at various spatial and temporal scales *(Gehne et al., 2016)*. Several reanalyses, and remotely sensed options available for IHR and HKH regions are:

- European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5: The ERA5 is an improved (atmosphere, ozone, land, and ocean waves component) and high-resolution successor of the ERA-Interim (Dee et al., 2011). The ERA5 uses observations from over 200 satellite instruments or conventional data types, including ground-based radar–gauge observations, PILOT, radiosonde, dropsonde, buoys, and aircraft measurements. The ERA5 data are available at an hourly time scale and 31 x 31 km spatial resolution for 137 vertical pressure levels. Surface or single-level data are also available, containing two-dimensional parameters such as precipitation, 2m temperature, top-of-atmosphere radiation, and vertical integrals over the entire atmosphere. ERA5 is a freely available dataset that covers the years 1950–2023 (present). The dataset can be accessed from https://cds.climate.copernicus.eu/. This data set has been extensively used for hydrological applications in the region and globally *(Khanal et al., 2021)*.

However, the data needs to be bias adjusted and downscaled for the hydrological application. The ERA-5 data have been bias-adjusted and downscaled at 1km resolution for the whole HMA using the topography-based downscaling scheme TopoSCALE (Fiddes and Gruber, 2014). TopoSCALE downscales atmospheric fields available on pressure levels to a high-resolution digital elevation model. The bias adjusted and downscaled ERA5 datasets can be accessed freely via www.shpy.nl.

- ERA5-Land: ERA5-Land is a reanalysis dataset providing a consistent view of the evolution of land variables over several decades at an enhanced resolution compared to ERA5. It is available on hourly data from 1950 to the present. The data can be accessed via https://cds.climate.copernicus.eu/.
- High Asia Refined analysis version 2 (HAR v2): The High Asia Refined analysis version 2 (HAR v2) is an atmospheric dataset generated by dynamical downscaling using the Weather Research and Forecasting model (WRF) version 4.1 and freely available for the Tibetan Plateau and surrounding mountains. It is available for the period 1980–2020 at hourly, daily, monthly, and yearly time steps.
- Other remote sensed products commonly used in HKH and HMA regions are the Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE), the Tropical Rainfall Measuring Mission (TRMM), the Climate Hazard group Infrared Precipitation (CHIRPS), the Multi-Source Weighted-Ensemble Precipitation (MSWEP), the Climate Prediction Center MORPHing product (CMORPH) and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network (PERSIANN).

The direct use of such products to derive climatological and hydrological trends often requires validation and correction based on in situ observations (Gebregiorgis and Hossain, 2015; Gehne et al., 2016). Such corrections on meteorological forcings involves adjusting meteorological data to account for the effects of terrain elevation on atmospheric variables. The process consists of several steps aimed at ensuring accurate representations of meteorological conditions in areas influenced by topography. The meteorological variables (temperature, precipitation, wind speed, and solar radiation) serve as the foundation for subsequent correction procedures. High-resolution elevation data, such as DEMs, is essential for accurately characterizing the terrain of the study area. This elevation data provides information on the elevation profile and the presence of mountains, valleys, or other topographic features. Statistical analysis, regression models, or empirical relationships could be employed to investigate and quantify the effects of elevation on temperature, precipitation, solar radiation, and other variables of interest. Based on the findings from the analysis, correction techniques could be applied to account for the topographic effects on the meteorological variables. These correction techniques may vary depending on the variable being corrected. For temperature, adjustments are made considering the lapse rate, which describes the decrease in temperature with increasing elevation. Precipitation correction involves accounting for orographic effects caused by mountains or hills, which result in increased precipitation at higher elevations. Solar radiation correction addresses shading effects caused by terrain features, incorporating models that account for shadowing and terrain slope. After the correction procedures are implemented, the corrected meteorological data is validated to ensure its accuracy and reliability. Validation involves comparing the corrected data with observed data or independent validation datasets. This step verifies the effectiveness of the topographical correction methods applied and helps assess the quality of the resulting data. It is important to note that the specific techniques and algorithms for topographical correction may vary depending on the available data, study area, and the atmospheric variables of interest.

3.4. Data required for SPHY model calibration

Datasets are used throughout model delineation, parametrization, calibration, and validation, are essential and integral parts of the glacio-hydrological modelling, which will later influence model performance and may limit model applications. Traditionally, only observed streamflow datasets are used to calibrate the GHMs. However, parameterizing the GHM alone with the stream flow would induce uncertainties (especially in the snow and glacier processes). Thus, it is a must to ensure that the snow and glacier-related processes are fairly well parameterized in the GHMs. The SPHY model can make use of a large array of observed data sources (if available). In HKH and HMA regions, where observed data are scarce, mostly streamflow data is used to calibrate the rainfall-runoff processes in the hydrological model. Here we provide the list of data that could be useful to parametrize the snow and glacier processes in a GHM.

3.4.1. Snow cover

Snow is a significant component of the ecosystem and water resources. The snow cover information is required to make sure that snow-related processes and model parameters are fairly well-calibrated in the SPHY model. Unfortunately, the snow-cover data sources are limited in this region.

- Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover data is used for this project. The most recent version of MODIS snow cover (MOD10CM006) can be downloaded from here. This is a global, 0.05° resolution monthly mean snow cover extent derived from the MODIS daily snow cover extent product (MOD10C1). The dataset is available from 2000 to the present time for the whole globe at a monthly time scale.
- International Centre for Integrated Mountain and Development (ICIMOD) has developed a new method to improve the interpretation of snow cover data in the region using Terra and Aqua MODIS snow cover data. The improved snow data for High Mountain Asia covers the MODIS observation period between 2002 and 2018. The product is available for free download on ICIMOD's Regional Database System.

3.4.2. Glacier mass balance

Region-wide observed glacier mass balance information is not available in most cases. However, for specific glaciers, some information is available in the public domain (e.g., published scientific articles, reports, and websites). SPHY is flexible enough to incorporate the data at both individual glacier and large basin level aggregation. For instance, if there is information available on glacier mass balance for multiple glaciers in a basin then different glacier mass balances could be used to parameterize the glaciers. However, If such information is not available then only one glacier-mass-balance for the whole basin can be used to parameterize the glacier processes. There are some regional databases available for HKH and HMA regions;

- *Shean et al., (2020)*: This database consists of 5,797 high-resolution digital elevation models (DEMs) from available sub-meter commercial stereo imagery (DigitalGlobe WorldView-1/2/3 and GeoEye-1) acquired over HMA glaciers from 2007 to 2018 (primarily 2013–2017). The project reprocessed 28,278 ASTER DEMs over HMA from 2000 to 2018 and combined these observations to generate robust elevation change trend maps and geodetic mass balance estimates for 99% of HMA glaciers between 2000 and 2018. The data set is freely available here.

- *Brun et al., (2017)*: This database provides the mass balance for about 92% of the glacierized area of High Mountain Asia using time series of digital elevation models derived from satellite stereo-imagery between 2000 and 2016. The data set is freely available here.
- *Wang et al., (2021)*: This database provides the recent status of HMA glaciers based on the first analysis of Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) data between 2003 and 2019. This database uses the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (FO) data to complement ICESat-1,2 data and validate them independently. The data set is freely available here.

3.4.3. Discharge

Discharge is the most crucial variable required to correctly parameterize the GHM and is important for the water resources projects, such as energy production, irrigation planning, water quality improvements or waterway transport. However, the discharge data in the HKH and HMA regions is considered to be confidential and there are many restrictions on its open use. Lack of observed data most of the time becomes a big barrier to parametrizing the qualitative GHM and its further use for estimation and prediction purposes. It is advisable to use the observed discharge data if available, but such information is not readily available in remote regions of HMA. In IHR, CWC has the mandate to monitor, collect and collate information regarding hydro-meteorological data. It is advisable to check with CWC for the location-specific discharge data. However, in some cases, the discharge data is also available with educational institutes such as universities, research institutes and agencies such as the department of forestry, hydropower/irrigation development corporation and disaster management authority. If the data are not available at the local scale, then there are few global options available. However, the quality and quantity of such global datasets are limited. The followings are the database available on global scale;

- Global Runoff Data Centre (GRDC): The GRDC is an international archive, operating under WMO, of data up to 200 years old, and fosters multinational and global long-term hydrological studies. This database consists of information on long-term daily flow data (mean daily and monthly) and catchment information from more than 10000 river gauging stations in 159 countries. This is to date the largest database of river discharge time series. The GRDC station locations are available on Google Earth Engine. The datasets are freely available here.
- Global Monthly River Discharge dataset: The Global River Discharge (RivDIS) data set contains monthly discharge measurements for 1018 stations located throughout the world. The period of record varies widely from station to station, with a mean of 21.5 years. The datasets are freely available here.

It is advisable to use the observed discharge data at daily (or sub-daily) time steps but if such information is not available then monthly (or even annual) average values could be useful to calibrate and validate the GHMs.

3.5. Data collection and available methods

Hydro-meteorological measurements in high mountains pose unique challenges due to their inaccessible terrain, harsh weather conditions, and complex environmental factors. Establishing and maintaining measurement stations in remote locations can be difficult, and extreme weather can damage instruments and hinder data collection. The significant changes in elevation and orographic effects in mountainous regions necessitate the installation of sensors at various heights. Additionally, snow and glacial processes, limited data transmission and power supply, and environmental considerations further complicate measurements. Overcoming these challenges requires specialized equipment, sensors, innovative techniques, and collaboration among multidisciplinary teams. Despite the difficulties, accurate high-mountain measurements are crucial for understanding hydrological processes, managing water resources, and mitigating natural hazards. A variety of sensors are used to collect hydro-meteorological data, capturing information about different aspects of the water cycle and meteorological variables. The choice of sensors depends on the specific research or monitoring objectives, the variables of interest, and the environmental conditions of the study area. Here are some common types of sensors used in hydro-meteorological monitoring:

- Rain Gauges: Rain gauges are used to measure precipitation, including rainfall and snowfall. They come in various designs, such as tipping bucket gauges, weighing gauges, disdrometers, pluviographs, and optical sensors, and are used to record the amount and intensity of precipitation over a specific period. Importantly, the effectiveness of rain gauge monitoring can be significantly enhanced through the integration of data from multiple gauges within a network. This approach facilitates the consideration of spatial variability in rainfall patterns, thereby enabling a comprehensive understanding of precipitation distribution across a given area.
- Temperature sensors: Thermocouples, which generate a voltage based on temperature differences, are commonly employed due to their ruggedness and wide temperature range. Resistance Temperature Detectors offer high accuracy and stability over a broad temperature span, making them suitable for mountainous regions. Thermistors, though with a limited temperature range, provide good sensitivity and accuracy. Infrared thermometers offer non-contact temperature measurements, making them useful for inaccessible or hazardous mountain locations. Data loggers integrated with temperature sensors serve as convenient solutions for continuous monitoring. Considering factors such as accuracy, temperature range, and ruggedness, along with sensor placement at different elevations, ensures comprehensive temperature measurements in high-mountain environments.
- Discharge: Traditional area-volume, rated structure, current meters, acoustic doppler current profilers, tracer methods, stage-discharge rating curves and remote sensing techniques are available to measure discharge. These methods involve the use of instruments, data analysis, and modeling techniques to estimate streamflow. Combining multiple approaches, ongoing monitoring, technological advancements, and interdisciplinary collaborations are vital for improving the precision and reliability of discharge measurements in high-mountain regions.
- Other sensors such as water level, snow depth, soil moisture, evapotranspiration and water quality sensors would help in improving our understanding of mountain hydrology, assessing water resources, and mitigating natural hazards in these critical regions.

3.6. Model parameter sensitivity analysis

In glacio-hydrological modelling, it is important to conduct a sensitivity analysis of model parameters to determine the possible values to be assigned to the parameters and the qualitative and/or quantitative variations *(McCuen, 1973)*. Model parameter sensitivity analysis is a critical step in glacio-hydrological modelling that involves evaluating how changes in model parameters influence model outputs and performance. GHMs typically have a large number of parameters (more than 100 parameters) that represent various physical and process-related characteristics of the hydrological system, such as precipitation, evapotranspiration, glaciers, snow, infiltration, runoff, and storage parameters (see Table 1).

These parameters need to be fine-tuned based on the climate and catchment characteristics *(Khanal et al., 2021; Lutz et al., 2014b; Wijngaard et al., 2017)*. Such a task is practically impossible and highly resources intensive. Sensitivity analysis quantifies the effects of parameter variations on model outputs, such as streamflow, groundwater levels, or water balance components. It helps understand how changes in parameter values affect model performance and whether the model is sensitive or robust to parameter changes. Sensitivity analysis thus reveals which parameters have a significant impact on model results and which parameters have negligible effects, allowing for prioritization of parameter estimation efforts and model calibration. So, sensitivity analysis helps identify which parameters are most influential in determining model behaviour and outputs. This is typically done through techniques such as one-at-a-time sensitivity analysis, where individual parameters are varied while others are held constant, or global sensitivity analysis methods that evaluate the combined influence of multiple parameters *(Khanal et al., 2021; Song et al., 2015; Wijngaard et al., 2017)*. The most sensitive parameters, along with the calibrated values and plausible range, identified for the SDC hydrology case study (see for more description) are presented in Table 2**Error! Reference source not found.**. Overall, parameter sensitivity analysis enhances the understanding and applicability of hydrological models, making them more reliable tools for water resources management, planning, and decision-making.

TABLE 1 OVERVIEW OF SPHY MODEL PARAMETERS. THE LAST COLUMS INDICATED WHETHER THE PARAMETER IS OBSERVABLE, OR CAN BE DETERMINED BY CALIBRATION (FREE).

Acronym	Description	Units	Parameter determination
Kc	Crop coefficient	–	Free
Kc_{max}	Maximum crop coefficient	–	Free
Kc_{min}	Minimum crop coefficient	–	Free
$NDVI_{max}$	Maximum NDVI	–	Observable
$NDVI_{min}$	Minimum NDVI	–	Observable
$FPAR_{max}$	Maximum fraction of absorbed photosynthetically active radiation	–	Free
$FPAR_{min}$	Minimum fraction of absorbed photosynthetically active radiation	–	Free
T_{crit}	Temperature threshold for precipitation to fall as snow	°C	Free
DDF_s	Degree-day factor for snow	mm °C^{-1} day^{-1}	Free
SSC	Water storage capacity of snowpack	mm mm^{-1}	Free
GlacF	Glacier fraction of grid cell	–	Observable
DDF_{CI}	Degree-day factor for debris-free glaciers	mm °C^{-1} day^{-1}	Free
DDF_{DC}	Degree-day factor for debris-covered glaciers	mm °C^{-1} day^{-1}	Free
F_{CI}	Fraction of GlacF that is debris free	–	Observable
F_{DC}	Fraction of GlacF that is covered with debris	–	Observable
GlacROF	Fraction of glacier melt that becomes glacier runoff	–	Free
$SW_{1,sat}$	Saturated soil water content of first soil layer	mm	Observable
$SW_{1,fc}$	Field capacity of first soil layer	mm	Observable
$SW_{1,pF3}$	Wilting point of first soil layer	mm	Observable
$SW_{1,pF4.2}$	Permanent wilting point of first soil layer	mm	Observable
$K_{sat,1}$	Saturated hydraulic conductivity of first soil layer	mm day^{-1}	Observable
$SW_{2,sat}$	Saturated soil water content of second soil layer	mm	Observable
$SW_{2,fc}$	Field capacity of second soil layer	mm	Observable
$K_{sat,2}$	Saturated hydraulic conductivity of second soil layer	mm day^{-1}	Observable
$SW_{3,sat}$	Saturated soil water content of groundwater layer	mm	Observable
slp	Slope of grid cell	m m^{-1}	Observable
δ_{gw}	Groundwater recharge delay time	day	Free
α_{gw}	Baseflow recession coefficient	day^{-1}	Free
BF_{tresh}	Threshold for baseflow to occur	mm	Free
kx	Flow recession coefficient	–	Free

3.7. Model calibration approach

GHM calibration can suffer from 'equifinality'. Equifinality is the phenomenon that different parameter combinations can lead to the same simulated discharge pattern. For example, a shortage in snow melt can be compensated by excess glacier melt, and underestimation of the precipitation input can be compensated for by melting extra water from the glacier but resulting in wrong melt estimates and incorrect estimations of glacier geometry changes. To avoid such internal error compensation effects and to better constrain the parameter, a multi-data or multi-signal calibration is highly recommended by several other studies (*He et al., 2018; van Tiel et al., 2020)*. To overcome equifinality problems, we suggest using a three-step modelling strategy to calibrate the snow, glaciers, and rainfall-runoff processes in the model *(Walter W. Immerzeel, 2010; Khanal et al., 2021; Lutz et al., 2014c; Francesca Pellicciotti et al., 2012)*.

3.7.1. Snow

The first step is to parameterize the snow and snow-melt-related processes. Parameters related to snow storage and melt (degree-day factor snow, water storage capacity of snowpack, minimum slope for gravitational snow transport, minimum snow holding depth and sublimation factor, etc.) can be calibrated independently by comparing observed snow flow with modeled snow flow from GHM. In most of the cases observed snow run off are difficult to obtain. So, alternative methods such as snow cover comparison as mentioned in section 3.4.1could be used to calibrate the snow module of a GHM. The remotely sensed (or observed data) could be used to calculate indicators such as snow cover area, snow seasonality and snow persistence (i.e. % of the time a pixel is covered with snow). These indicators can be simulated with a GHM and thus help to fine tune the snow parameters (see Annex 1: SDC hydrology case study in Bhagirathi Basin for more details). Depending on the need and data availability, the other snow parameters such as critical temperature, snow water equivalent, snow cover threshold and snow depth can also be parameterized.

3.7.2. Glaciers

The second step is to parameterize the glacier-related processes without altering the snow-melt-related processes. Parameters related to glacier processes are calibrated to observe (or geodetic) glacier mass balance data. To calibrate the SPHY model, the geodetic mass balance data mentioned in section 3.4.2 could be used. Users can the simulated glacier mass balance from SPHY and compare it with the observed mass balance. The parameters related to glacier mass balance in the SPHY model are the degree-day factor for clean ice, degree-day factor for debris-covered glaciers, glacier fraction, lapse rate for glaciers, and temperature and precipitation, which can be fine-tuned.

3.7.3. Rainfall-runoff and groundwater

The last step is to calibrate the rainfall-runoff-related processes without altering the snow and glacier melt-related parameters. After calibration of the model parameters related to snow and glacier melt, the remaining parameters related to soil, infiltration, groundwater, and routing (root depth, capillary rise, seepage, infiltration excess, groundwater depth, saturated water content, baseflow recession constant and routing coefficient, etc) can be calibrated to observed discharge at the existing station.

3.8. Typical outputs of the SPHY and their application

SPHY includes a large number of processes from which output can be generated. SPHY allows the user to output the variable as (a) time-series data at specified locations (b) spatial maps for the model domain. The spatial maps outputs can be aggregated for the user-specified time. In a separate csv-file, i.e. "reporting.csv", the user can decide how output should be generated for 50+ model variables (Figure 1). The csv-file has 6 columns. The first column refers to the variable name in the model, which should not be changed. In the second column, the user can decide with which frequency the map output should be generated, with Y the yearly sum, M the monthly sum, and D the daily sum. The option MS results in 12 output maps, with the long-term monthly average sum. In the third column, the average per year (Y) and month (M) can be determined, which is most suitable for storage components, such as soil water storage and groundwater storage. Here option MA results in 12 output maps, with the long-term monthly average. In the second and third columns, more than one output frequency can be selected, which should be separated with a "+" symbol. For example, when the user wants to get yearly and average monthly output the following combination should be provided: "Y+MA".In the fourth column, time series can be generated at the stations, for instance for discharge and sediment yield. In the fifth column, the user can define the filename (prefix), with a maximum of 6 characters. The sixth column provides information for each of the model variables. Furthermore, SPHY is flexible enough to output any intermediate flux or variable used in the model.

The aggregated time series and spatial map outputs from SPHY help understand hydrological cycle processes such as evapotranspiration, infiltration, snow-glaciers melt, runoff and groundwater flow, flood and drought risk assessment, environmental impact assessment, water availability and water management through water allocation planning. These outputs can provide valuable information to support Integrated Water Resources Management (IWRM) planning, which is a framework for the coordinated and sustainable development and management of water resources. For instance, the time series outputs of snow, glacier, rainfall-runoff, and baseflow could be used to understand the flow contribution of each component to the overall flow (Figure 2). Such analysis would provide the basin aggregated flow contribution analysis which helps the water manager to plan water resources in the basin. Moreover, SPHY outputs in the form of spatial maps can also be used to understand the spatial variation of the fluxes across the basin (Figure 3). The spatial maps would help the water manager to assess the sources and contribution of water, its availability, and variability (floods and droughts) across different units/subunits of the catchment. These outputs would also help to understand the trends of different components of flow across the sub-units of the basin. These outputs, together with water quality, land use, socioeconomic, institutional, and infrastructure data, further can be used to simulate various water allocation scenarios, taking into account different priorities for water use (see Section 4.7 for details). This information is essential for developing plans that balance the competing demands for water resources from various stakeholders. Therefore, the outputs of SPHY can provide valuable information for formulating an IWRM plan by assessing water availability, identifying flood and drought risks, evaluating environmental impacts, and developing water allocation plans that balance competing demands.

Name	Map	Avg	Timeseries	Filename	Description
wbal	NONE	NONE	NONE	wbal	WATER BALANCE (Can only select daily output)
# ONLY FOR LAKE AND/OR RESERVOIR MODULE					
TotStor	NONE	NONE	NONE	TotS	REPORT TOTAL STORAGE (only D or F options are logical)
RainStor	NONE	NONE	NONE	RainS	REPORT STORAGE FROM RAINFALL (only D or F options are logical)
SnowStor	NONE	NONE	NONE	SnowS	REPORT STORAGE FROM SNOW RUNOFF (only D or F options are logical)
GlacStor	NONE	NONE	NONE	GlacS	REPORT STORAGE FROM GLACIER RUNOFF (only D or F options are logical)
BaseStor	NONE	NONE	NONE	BaseS	REPORT STORAGE FROM BASEFLOW RUNOFF (only D or F options are logical)
# FLUXES IN MM					
TotPrec	Y	NONE	NONE	Prec	PREC
TotPrecF	NONE	NONE	NONE	PrecF	PREC; CORRECTED FOR FRACTION
TotPrecEF	Y	NONE	NONE	PrecEF	EFFECTIVE PRECIPITATION; CORRECTED FOR FRACTION
LAI	NONE	NONE	NONE	LAI	LEAF AREA INDEX
TotIntF	Y	NONE	NONE	IntF	INTERCEPTION; CORRECTED FOR FRACTION
TotRain	NONE	NONE	NONE	Rain	RAIN
TotRainF	NONE	NONE	NONE	RainF	RAIN; CORRECTED FOR FRACTION
TotETref	NONE	NONE	NONE	ETr	ETREF
TotETrefF	NONE	NONE	NONE	ETrF	ETREF; CORRECTED FOR FRACTION
TotETpot	Y	NONE	NONE	ETp	ETPOT
TotETpotF	NONE	NONE	NONE	ETpF	ETPOT; CORRECTED FOR FRACTION
TotETact	Y	NONE	NONE	ETa	ETACT
TotETactF	NONE	NONE	NONE	ETaF	ETACT; CORRECTED FOR FRACTION
PlantStress	NONE	MA	NONE	Pws	PLANT WATER STRESS

FIGURE 1 A SNIPPET OF THE REPORTING.CSV FILE WHICH ALLOWS THE USER TO OUTPUT THE DESIRED VARIABLES FROM SPHY

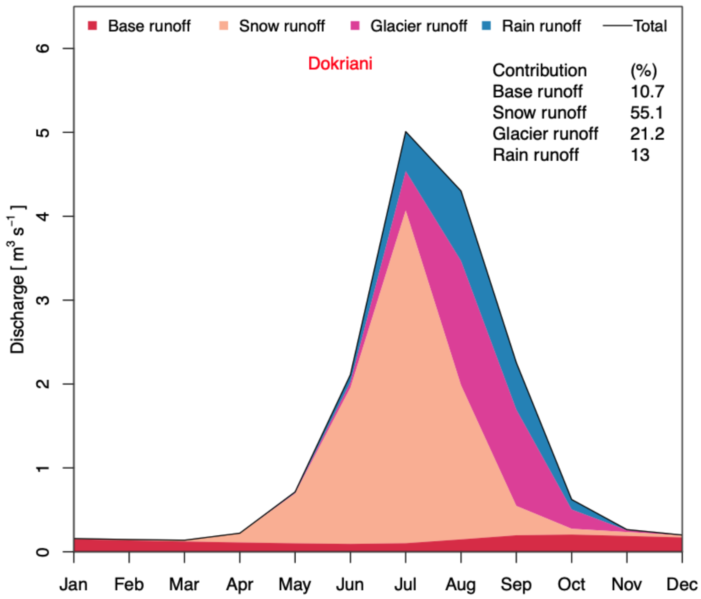

FIGURE 2 BASELINE AVERAGED MONTHLY RUNOFF WITH THE DISTINCTION OF FLOW COMPONENTS (BASE, SNOW, GLACIER, AND RAIN-RUNOFF) AT THE DOKRIANI OUTLET FOR 1991-2020. THE TOP RIGHT PART OF THE FIGURE SHOWS THE CONTRIBUTION OF STREAM FLOW CONTRIBUTORS TO THE TOTAL FLOW (EXPRESSED IN %, SEE ANNEX 1 FOR MORE DETAILS).

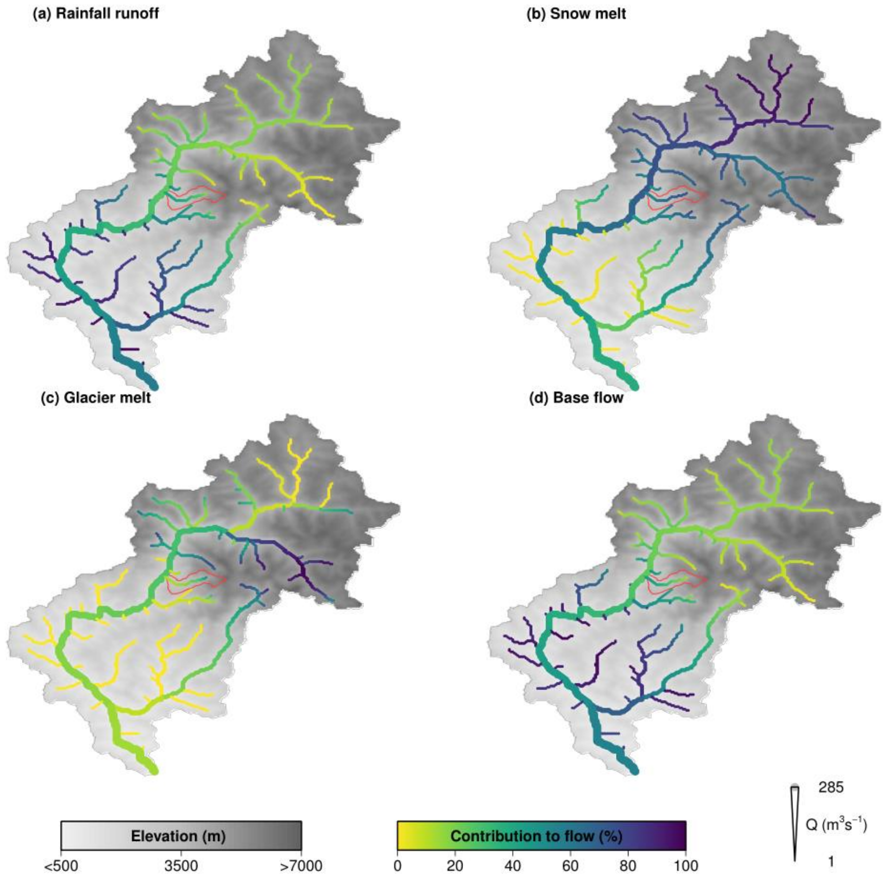

FIGURE 3 SPATIAL PATTERNS OF THE FLOW COMPONENTS (BASE, SNOW, GLACIER, AND RAIN-RUNOFF) AT THE OUTLET OF BHAGIRATHI BASIN (JUST BEFORE THE CONFLUENCE OF THE ALAKNANDA RIVER) FOR 1991-2020. THE FREY AND RED BOUNDARY REPRESENT THE BHAGIRATHI AND DIN GAD CATCHMENTS (SEE ANNEX 1 FOR MORE DETAILS).

3.9. Scaling up and application of the Model to other regions such as IHR, HKH and HMA

Scaling up GHMs refers to the process of extending or adapting existing GHMs to larger spatial and/or temporal scales. Scaling up of GHMs can be necessary to address various challenges, such as studying regional or global water resources management, understanding the impacts of climate change on hydrological processes, or supporting decision-making for water-related infrastructure projects. Scaling up hydrological models can be challenging due to the complexities and uncertainties associated with hydrological processes at larger scales, the availability and quality of data, and the computational requirements of larger models. SPHY was developed with the explicit aim to simulate terrestrial hydrology at flexible scales, under various land use and climate conditions. Since the input data require to set up the SPHY model as described in sections 3.3 and 3.4 are mostly available for the entire HMA region, the SPHY model can be easily scaled-up or applied to the different regions of IHR, HKH and HMA.

The basins adjacent to each other with similar climatic and physiographic characteristics tend to hydrologically behave in a similar manner (Merz and Blöschl, 2004; Patil and Stieglitz, 2014). Thus the calibrated parameters (see Table 2) can be transferred to a hydrologically similar basin in HKH and HMA. A "vector teams" approach, where the replica of the parameters from the gauged catchment can be transferred to the ungauged catchment, could be used for basins in the HMA region *(Bárdossy, 2007)*. This approach has been widely used for regional SPHY studies where there is a lack of available discharge data *(Khanal et al., 2021; Lutz et al., 2014b; Wijngaard et al., 2017)*. However, proper validation and verification of scaled-up and replicated models are essential to ensure their reliability and accuracy. If data is available, the key processes such as glaciers, snow, and rainfall-runoff should be validated. Either limited or no discharge data availability for the hydrological model calibration is a key issue in the data scarce HMA region. In such basins, where the discharge measurements are available, a validation of the simulated flux (e.g., simulated discharge) is essential. The replicated parameters could be re-adjusted based on the discrepancy between the simulated and the observed discharge as explained in section 3.7.

If the observed data is not available then secondary sources of information from the journal, articles, and reports should be used to validate the model. For instance, if the daily time series of observed discharge is not available, the model can still be calibrated based on the monthly/annual average values available from secondary sources. Satellite information can be highly valuable in calibrating hydrological models due to its ability to provide data on various hydrological parameters at large spatial and temporal scales. For instance, satellite-derived soil moisture data and river discharge data, such as those from radar altimetry or optical sensors, could be used to calibrate river discharge in hydrological models, helping to validate model outputs and improve their accuracy. However, it's important to carefully assess the quality and limitations of satellite data, as well as consider the uncertainties associated with hydrological processes, when using satellite information for model calibration and validation.

TABLE 2 CALIBRATED SPHY MODEL PARAMETERS ALONG WITH DESCRIPTION UNITS AND PLAUSIBLE RANGE

Parameters	Description	Units	Range	Calibrated value
DDFS	Degree day factor for snow	mm °C-1 day-1	2 – 11	6.1
DDFDG	Degree day factor for debris cover glacier	mm °C^{-1} day^{-1}	2 – 11	4.8
DDFG	Degree day factor for Snow for glacier	mm °C^{-1} day^{-1}	2 – 11	7.7
Tcrit	Critical temperature	°C^{-1}	-1 – 3	0.7
SnowSC	Water storage capacity of snow pack	-	0 – 1	0.5
Kx	Routing recession coefficient	-	0 – 1	0.9
RootDepthFlat	Thickness of root zone	Mm	50 – 1500	300
SubDepthFlat	Thickness of subsoil	Mm	50 – 1500	150
alphaGw	Baseflow recession coefficient	-	0 – 1	0.5
YieldGw	Specific aquifer yield	-	0.01 – 0.5	0.05

4. Climate change impact assessment

Mountains are highly significant regions in the context of climate change and sustainable development. In the past decades, HKH and HMA regions have experienced many climatic changes. Past climate change led to changes in the cryosphere and hydrological cycle. These changes include rapid glacier shrinkage, reduction in snow cover, permafrost degradation, changes in the area of seasonally frozen grounds, and increases in the frequency of snow and ice avalanches *(Kang et al., 2010)*. The changes in climate and cryosphere lead to shifts in the timing and magnitude of river discharge *(Walter W. Immerzeel, 2010; Khanal et al., 2021; Lutz et al., 2014b; Maurer et al., 2019)*. Furthermore, climate change has led to increases in the area and volume of glacial lakes has further exacerbated the risk of glacial lake outburst floods *(King et al., 2019)*. The impacts of climate change on the cryosphere and water resources in mountains are typically assessed by the GHM.

Climate change assessments serve as important syntheses of the science associated with the bio-physical characteristics, ecosystem, and socio-economic conditions, and they provide useful information and context for management and policy decisions. Climate change assessments usually focused on understanding the aspects such as what/why/where/how, the consequences of climate change, or the options for responding to climate change. Among others, climate change assessment usually depends on the location, context, objectives, and type of information needed.

4.1. How to assess the impacts due to climate change?

Here the focus is on climate change impact assessment on the cryosphere and water resources in the mountainous region of IHR, HKH and HMA. Usually, climate change impacts studies identify and quantify the expected impacts of climate change for decades to centuries on different sectors such as water, agriculture, energy, transportation, etc. The impact assessment begins by understanding the changes in magnitude, frequency, and patterns in hydro-meteorological variables such as temperature, rainfall, snow, streamflows, etc for the historical period. The observed station data, gridded data, and remotely sensed satellite-based information provided in Section 3.3.6 could be used to derive the changes in the historical hydroclimate of a region or sector.

For the future, climate information is obtained from 'climate projections'. Climate projections are simulations of Earth's climate in future decades (typically until 2100) based on assumed 'scenarios' for the concentrations of greenhouse gases, aerosols, and other atmospheric constituents that affect the planet's radiative balance. Climate projections are obtained by running numerical models of Earth's climate. These numerical models are used to simulate the fundamental processes driving weather and climate, which may cover either the entire globe or a specific region e.g., Asia. These models are referred to as Global Climate Models (GCMs) – also known as General Circulation Models. A GCM combines a series of models of the Earth's atmosphere, oceans, and land surface. GCMs, divide the earth into many layers and thousands of three-dimensional gridded spaces (100–400km spatial resolution and ~30–50 vertical layers between the surface and the top of the atmosphere). A Regional Climate Model (RCM) is similar to a GCM, but it is run at higher resolution over a smaller domain (e.g., Asia) to generate higher-resolution data. The RCM is used to downscale GCM information to regional or local scales, and it needs boundary information from a GCM. These models are skilled at replicating past and current climate.

Many research institutions around the world develop and maintain the GCM/RCM. There are more than 100 climate models available currently. To streamline the activities between different institutions around the world, a collaborative framework was designed to improve knowledge of climate change by the

World Climate Research Programme (WCRP) in the year 1995. This framework is known Coupled Model Intercomparison Project (CMIP). CMIP is developed in phases to foster climate model improvements but also to support national and international assessments of climate change. The objective of the CMIP is to better understand past, present and future climate changes arising from natural, unforced variability or in response to changes in radiative forcing in a multi-model context. The number of climate models in CMIP has increased over time; CMIP1-2 (1996, 18 GCMs), CMIP3 (2005-2006, 20 GCMs), CMIP5 (2010-2014, 34 GCMs) and CMIP6 (2016-present, >100 GCMs). CMIP6 is the most recent one and includes over 100 models from more than 50 modelling centers around the world.

The Intergovernmental Panel on Climate Change (IPCC) reviews and assesses the latest scientific, technical and socio-economic climate change information. These modelling groups around the world coordinate their updates around the IPCC assessment reports. The 2013 IPCC fifth assessment report (AR5) featured climate models from CMIP5, while the 2021 IPCC sixth assessment report (AR6) features the new state-of-the-art CMIP6 models. CMIP6 uses Shared Socio-economic Pathways (SSPs) scenarios which are the most complex created to date and span a range from very ambitious mitigation to ongoing growth in emissions. The SSPs use narratives about future societal development (the SSPs) in conjunction with the Representative Concentration Pathways (RPCs), which describe trajectories of change in atmospheric GHG and aerosol concentrations (and corresponding changes in radiative forcing) over time. The SSPs provide storylines regarding global societal developments and narratives about how the world might develop over the coming century in the absence of climate change or mitigation and adaptation policy. The most ambitious mitigation scenario suggested by Paris Agreement, i.e., holding the increase in global temperature to well below 2°C above pre-industrial levels, and pursuing efforts to limit the increase to 1.5°C, are included in SSPs. Five SSPs were created, with varying assumptions about human developments including: population, education, urbanization, gross domestic product (GDP), economic growth, rate of technological developments, greenhouse gas (GHG) and aerosol emissions, energy supply and demand, land-use changes, etc are as follows:

1. SSP1 - Sustainability - Taking the green road (low challenges to mitigation and adaptation)
2. SSP2 - Middle of the road - (medium challenges to mitigation and adaptation)
3. SSP3 - Regional rivalry - A rocky road (high challenges to mitigation and adaptation)
4. SSP4 - Inequality - A road divided (low challenges to mitigation, high challenges to adaptation)
5. SSP5 - Fossil-fueled development - Taking the highway (high challenges to mitigation, low challenges to adaptation)

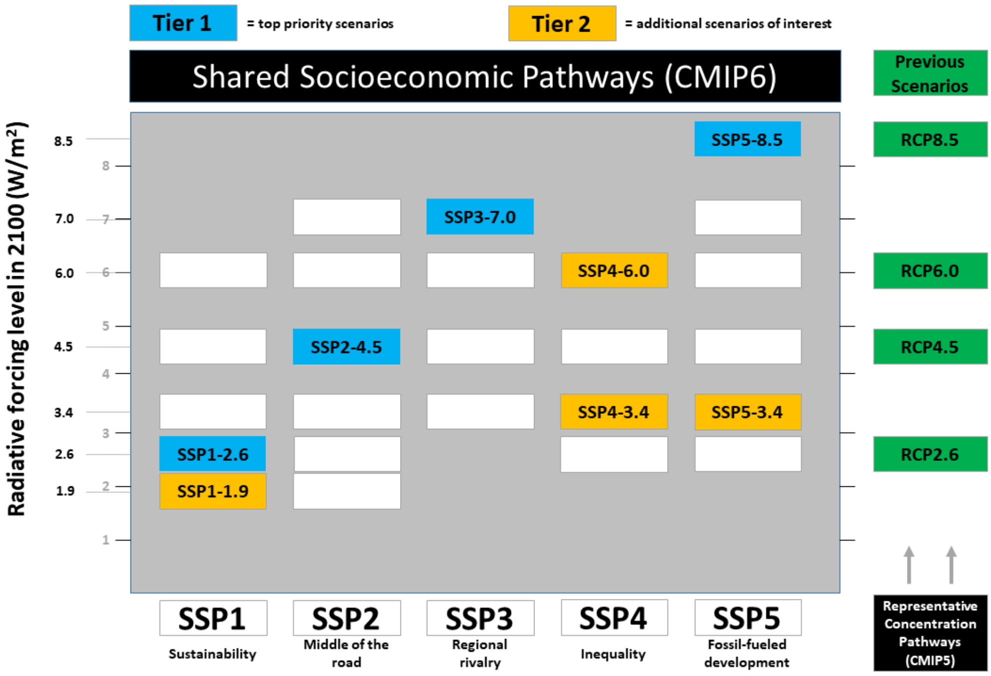

FIGURE 4 SHARED SOCIO-ECONOMIC PATHWAYS AND YEAR 2100 RADIATIVE FORCING COMBINATIONS[1]

The different levels of radiative forcing (a measure of the extent to which GHGs in the atmosphere warm or cool the climate, measured in watts per meter squared (Wm^{-2})), by the year 2100 and range from 1.9 to 8.5 Wm^{-2} with higher values representing stronger climate warming effects, are used in conjunction with SSPs (see Figure 4).

4.2. Where and how to download the projections?

Downloading and working with CMIP6 GCM data can be quite complex, and requires specialized, programming software and expertise. These data are usually available in netCDF and HDF formats. There are different ways to access the raw GCM variable and it could be downloaded from the following;

- Earth System Grid Federation (ESGF): The ESGF is a collaborative project that provides access to the world's largest collection of environmental data. You can download CMIP6 GCM data from the ESGF website.
- National Centers for Environmental Information (NCEI): The NCEI is the world's largest repository of climate and weather data. You can download CMIP6 GCM data from the NCEI website.
- PCMDI: The Program for Climate Model Diagnosis and Intercomparison (PCMDI) is a research organization that works to improve our understanding of climate variability and change. You can download CMIP6 GCM data from the PCMDI website.
- DKRZ: The DKRZ acts as a "laboratory" for all German climate researchers working with climate models. DKRZ's hardware and services are specifically tailored to complex simulations

[1] https://climate-scenarios.canada.ca/?page=cmip6-overview-notes

with numerical models of the climate system. You can download CMIP6 GCM data from the DKRZ website.

- Climate Data Store (CDS): The CDS is a service provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) that provides access to a wide range of climate data. You can download CMIP6 GCM data from the CDS website.

4.3. Selection of climate models

It is a cumbersome and resources intensive task to process all the GCM (>100 models). So, a few representative GCMs should be selected for the intended use. The selection of climate models is not straightforward and can be done by following different methods. An approach explained by *Lutz et al. (2016)* to select climate models combining the envelope approach and the past-performance approach has been widely adopted by different studies in the HKH and HMA regions. The goal is to select an ensemble consisting of a manageable number of climate model runs, which still represents all possible futures in terms of future mean air temperature and annual precipitation sums, and only includes models with acceptable performance in simulating the historical climate. So following steps are followed to sub select models;

1. Determine the research question or application: The first step in sub selecting climate models is to define the research question or application. For example, how global warming will impact a particular region, or how extreme precipitation and temperature patterns will change in the coming years?
2. Identify the relevant variables and time horizons: The second step is the identification of the climate variables, temperature, precipitation, wind patterns, or other variables, for the analysis. The time frame used for climate change impact assessment can vary depending on the specific research question or application. For example, some studies may focus on analysing climate data for a specific year or season, while others may focus on analysing decadal or centennial trends in climate data. In many cases, climate change impact assessment focuses on a baseline period, which is typically a 20 or 30-year period of time that is used as a reference for assessing changes in climate over time. The baseline period is often chosen to represent a period of relatively stable climate conditions. Climate models simulate future climate conditions by dividing the future into discrete time slices or periods, typically spanning several decades. These periods are often referred to as "time slices" or "time horizons," and they are used to assess how climate conditions may change over time. The most commonly used time slices for future climate change projections are 20-year or 30-year periods, such as 2036–2065 (mid-century) or 2071–2100 (end-of-the-century). These time slices are often used to provide projections of climate conditions that can be compared to historical data and used to assess the magnitude of climate change that is likely to occur over different periods.
3. Calculate the changes in climatic means: The initial selection is based on the range of projections of changes in the mean state of the variable. For instance, change in air temperature (ΔT) and annual precipitation sum (ΔP) between historical (1985–2014) and future time horizons (mid-century and end-of-the-century). For the model runs included in the SSP-RCP combination, low (5th or 10th) and high percentiles (95th or 90th) values for ΔT and ΔP are determined (to exclude the outliers). These values represent the four corners of the spectrum of projections for temperature and precipitation change. For instance, the 10th percentile value for ΔT and 10th

percentile value for ΔP are in the 'cold, dry' corner of the spectrum. The 10th percentile value for ΔT and 90th percentile value for ΔP are in the 'cold, wet' corner of the spectrum. The 90th percentile value for ΔT and 10th percentile value for ΔP are in the 'warm, dry' corner of the spectrum. The 90th percentile value for ΔT and 90th percentile value for ΔP are in the 'warm, wet' corner of the spectrum. The proximity of the model runs to these low/high quantiles is then calculated. Few models (5–10) in close proximity to each of these corners are selected for each SSP-RCP scenario.

4. Refine the selection by evaluating the performance of the selected models: The next step is to evaluate the performance of each model in simulating the relevant climate variables. In this step, the model runs are evaluated for their projected changes in climatic extremes with the help of extreme climate change indicators[2]. A score (from 1 to the number of initially selected models), based on the ranking (or largest change) is assigned to each climate model. Based on that final score, the few models (2-3) with the highest scores are selected.
5. Final selection based on past performance: The ability or criteria or skill of the models in reproducing historical climate conditions is assessed in this step. The skill assessment is done for the historical period from GCM and observations. These criteria might include choosing models that perform well in simulating a particular variable, models that have shown consistency across different scenarios, or models that have been widely used in previous studies. There are several skill functions available for different variables in the literature (see Lutz et al., 2016 for details). Various metrics, such as root-mean-square error or correlation coefficients, could be used to compare the model output with observations or reanalysis data as mentioned in section **Error! Reference source not found.**.

Overall, sub selecting climate models requires careful consideration of the research question, relevant variables, and model performance. It is important to keep in mind that no single model can fully capture the complexity of the Earth's climate system, and the use of multiple models can help to account for uncertainty and variability in the results.

For the SDC hydrology case study (see Annex 1 regarding the details), two scenarios– middle of the road (SSP2-RCP4.5) and a more extreme one (SSP3-RCP7.0) – are used to sub-select 4 GCMs representing 4 corners of the envelope (cold, wet / cold, dry / warm, wet / warm, dry). For this study, only GCM runs having daily mean air temperature, daily maximum air temperature, daily minimum air temperature, and daily precipitation were selected.

4.4. Bias-correction

Bias correction in climate refers to the process of adjusting climate model output or observational data to remove systematic errors or biases. These biases can arise due to various factors, such as errors in the underlying physics of the model, inadequate spatial or temporal resolution, or incomplete or inaccurate data input. In the context of climate modelling, bias correction techniques are commonly used to improve the accuracy of model simulations by matching the model output with observed data. This can help to reduce uncertainties in future climate projections and improve our understanding of how the climate system is likely to change under different scenarios.

[2] http://etccdi.pacificclimate.org/list_27_indices.shtml

Bias correction can be applied to a wide range of climate variables, including temperature, precipitation, and atmospheric circulation patterns. There are various methods for bias correction, including statistical methods such as quantile mapping and distribution-based scaling, as well as more complex techniques that involve the use of machine learning or data assimilation approaches. The choice of method and the quality of the input data can have a significant impact on the effectiveness of the correction. Careful evaluation and validation of the results are therefore essential to ensure that the corrected data is appropriate for the intended use. For more information regarding the bias-correction, readers are referred to visit the detailed climate change report of this project.

4.5. Downscaling

Downscaling is a technique used in climate science to provide more detailed and localized information on climate variables, such as temperature and precipitation, than what is typically provided by global climate models.

Global climate models (GCMs) simulate the behavior of the Earth's climate system at a coarse resolution, typically spanning hundreds of kilometers. However, for many applications, such as water resource management or agriculture, more localized and detailed information is needed.

Downscaling is the process of taking the coarse-resolution output from a global climate model and using statistical or dynamical methods to generate higher-resolution climate data that are more relevant for specific regions or locations. This can be done in two ways:

- Statistical downscaling: Statistical downscaling is a method that uses statistical relationships between large-scale climate variables (such as atmospheric pressure patterns) and local-scale climate variables (such as precipitation or temperature) to produce more detailed information. This method is typically applied when there is a strong relationship between the large-scale and local-scale climate variables.
- Dynamical downscaling: Dynamical downscaling uses regional climate models (RCMs) to simulate the behavior of the Earth's climate system at a finer resolution, typically between 10 and 50 kilometers. RCMs are driven by the boundary conditions provided by GCMs, and they can provide more detailed information on climate variables over specific regions or locations.

Downscaled climate data can be used to assess the impacts of climate change on specific regions or sectors, such as agriculture or water resources. It can also be used to develop adaptation strategies and inform decision-making in sectors that are particularly vulnerable to climate variability and change.

For the SDC hydrology case study (see Annex I regarding the details), a monthly delta change approach was used. Downscaling procedure for monthly deltas followed the following procedure:

- GCM data were resampled to the model grid (50m and 500m) using bilinear interpolation.
- Monthly climatological means (temperature) and sums (precipitation) were calculated for both the historical GCM data and the baseline series over 1991–2020.
- Monthly climatological differences, i.e., deltas, between the historical GCMs and the baseline data were determined using subtraction (temperature) and division (precipitation).
- Future GCM series were downscaled by adding (temperature) or multiplying (precipitation) the resampled daily values with the offsets and scaling factors determined under (3) on a monthly basis. That is, all daily values that correspond to a specific calendar month are multiplied by the same bias correction factor. Note that the output of the monthly delta change bias correction includes leap days.

There are several recent initiatives and projects that have focused on downscaled climate change projections for the high mountain regions of Asia. These projects utilize various climate models and observational data to provide detailed insights into the future climatic conditions of these ecologically and culturally significant regions. However, it's crucial to validate this data before application. These efforts include:

- High Mountain Asia Daily 5 km Downscaled SPEAR Precipitation and Air Temperature Projections, Version 1: The dataset provides daily projections of precipitation and air temperature for High Mountain Asia from 2015 to 2100. These projections are based on 0.5° resolution model data from the GFDL SPEAR model. It includes two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) and historical data from 01-01-1990 to 31-12-2014. The data is in netCDF-4 format, with a 5 km spatial resolution, and the spatial coverage ranges between latitudes 20.025°N to 45.975°N and longitudes 60.025°E to 110.975°E. For more information, you can access the dataset on the National Snow and Ice Data Center's website.
- NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6): The dataset comprises global downscaled climate scenarios from CMIP6 GCM runs, supporting the IPCC AR6. It includes downscaled projections for all four Tier 1 greenhouse gas emissions scenarios (SSPs). The dataset aims to provide high-resolution, bias-corrected climate change projections for evaluating impacts on local-scale climate gradients and topographic effects. Data is accessible via AWS and NCCS THREDDS, with a spatial subset feature for custom data retrieval. The dataset, in netCDF4 format, covers a global scale with a daily temporal and 25 km spatial resolution. For more details, visit the NASA NEX-GDDP-CMIP6 page.

4.6. Future hydrological impact assessment

After bias-correction and downscaling of the GCMs, the selected climate models and emission scenarios are used to generate future climate projections, such as changes in temperature, precipitation, and evapotranspiration. These future forcings are then used in conjunction with the calibrated and validated GHM. The GHM thus simulates the effects of changes in climate on variables such as river flow, groundwater recharge, and soil moisture. Evaluation of the results of the GHM to assess the potential impacts of climate change on water resources is further required. This process can involve comparing future hydrological variables to historical baseline conditions, as well as assessing the sensitivity of the results to different model assumptions and uncertainties. It is important to note that assessing future hydrological changes due to climate change involves a high degree of uncertainty, as it is not possible to predict future climate conditions with complete accuracy. Therefore, it is important to account for this uncertainty in the assessment and to use multiple models and scenarios to generate a range of possible outcomes. The results of the impact assessment are used to inform decision-making and planning for water resources management. This may involve identifying areas that are particularly vulnerable to changes in water availability, exploring different adaptation strategies, and evaluating the costs and benefits of different options.

4.7. Links to water allocation and downstream demand

Hydrological models and water allocation models are interconnected and play a crucial role in effective water management. Hydrological models estimate the amount of water available in an area by simulating the physical processes of the water cycle. Water allocation models use hydrological data to determine the amount of water that can be allocated to different users while considering factors such as water quality, environmental regulations, and competing demands. Hydrological models provide input data to water allocation models, which in turn make informed decisions about water allocation.

Linkages between these models are essential in providing critical information for sustainable water management, such as infrastructure development, dam construction, reservoirs, and irrigation systems. These models can also inform decision-making processes to ensure the social, economic, and environmental well-being of communities. Effective linkages between hydrological and water allocation models are necessary to ensure sustainable water management, which is vital for communities' well-being.

These water allocation modelling exercises should be participatory and involve stakeholders from different sectors, including government agencies, local communities, and private sector actors. This will ensure that the models reflect the diverse perspectives and needs of stakeholders and are relevant to their decision-making processes.

For water allocation assessment, it is necessary to use models that can incorporate natural hydrological processes and scenario analysis to assist decision-makers. The selection of the most suitable model for this purpose involves evaluating the strengths and weaknesses of different well-known and established models (**Error! Reference source not found.**):

- Drought
- Floods
- Allocation
- Crops

- Complexity
- Scalable
- Scenarios

	Drought	Floods	Allocation	Crops	Complexity	Scalable	Scenarios
HEC-HMS	2	3	1	1	3	3	3
HEC-RAS	1	5	2	1	4	2	2
SPHY	3	4	2	2	2	4	4
WEAP	5	4	5	5	1	5	5
SWAT	4	3	3	3	2	4	3
SOURCE	4	4	4	2	4	5	4
SWMM	2	5	2	1	2	3	2
SOBEK	1	5	2	2	3	2	2
MIKE BASIN	4	3	4	2	2	4	4
MIKE SHE	3	3	3	3	5	2	1

FIGURE 5 QUALITATIVE (EXPERT-BASED) ASSESSMENT OF SOME CATCHMENT SCALE MODELS THAT MIGHT BE USED FOR THE PROJECT. SCORES 1 (=LIMITED) TO 5 (=WELL SUITED). NOTE THAT THE COLOR SCALE FOR "COMPLEXITY" IS REVERSED TO MAINTAIN GREEN FOR "BETTER" AND RED FOR "WORSE"

The WEAP (Water Evaluation and Planning) model[3] is particularly suitable for water allocation and scenario analysis, and its scalability is a significant advantage. Despite its high level of complexity, the WEAP model has a user-friendly interface, making it accessible for training purposes as well.

Some other strengths of WEAP not covered by those seven criteria yet important for the project:

- WEAP is used in over 180 countries and has many active users in India.
- WEAP can be automated and coupled with other models. Coupling with SPHY (also used in the project) has been successfully done in many other projects.
- WEAP has excellent (and free) training modules.
- WEAP is tailored towards starting in an explorative way and gradually including other components for more detailed analysis.
- WEAP is the de-facto standard for many developing and funding agencies to make investment decisions.
- WEAP is freely available

Glacio-hydrological impacts on water allocation can also be studied using a water allocation model like WEAP (Figure 6 and Figure 7). For the Bhagarathi sub-basin, the WEAP model has been enhanced by the addition of "virtual tracers," which is an innovative approach to monitoring the various sources and reuse of water *(Simons et al., 2020)*. This involves adding user-specific virtual tracers to different sources of water in the model to assess the mixing of return flows from each water user in sources of water supply to subsequent users. Tracers have been used by hydrologists for decades by injecting harmless dyes into streams to track flow rate and movement. With tracers, it is possible to track the sources of water, such as glacial melt, snow melt, and rainfall runoff, as well as monitor the reuse of water. The assumption of complete mixing enables the use of tracer concentrations to recalculate the percentage attributed to

[3] https://www.weap21.org/

each source of water. The innovative use of virtual tracers in the WEAP model is a promising approach to better understanding water allocation and management.

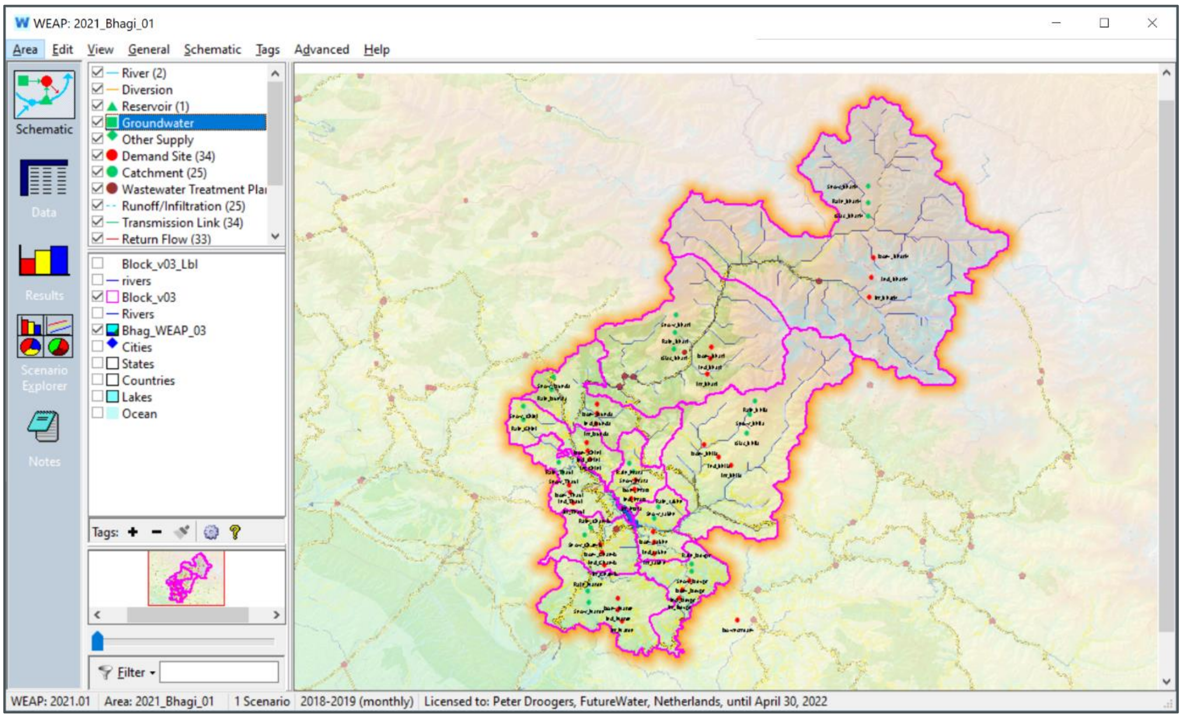

FIGURE 6 SCREENSHOT OF THE WEAP MODEL AS DEVELOPED FOR THE BHAGIRATHI BASIN TO ANALYSE WATER ALLOCATION SCENARIOS.

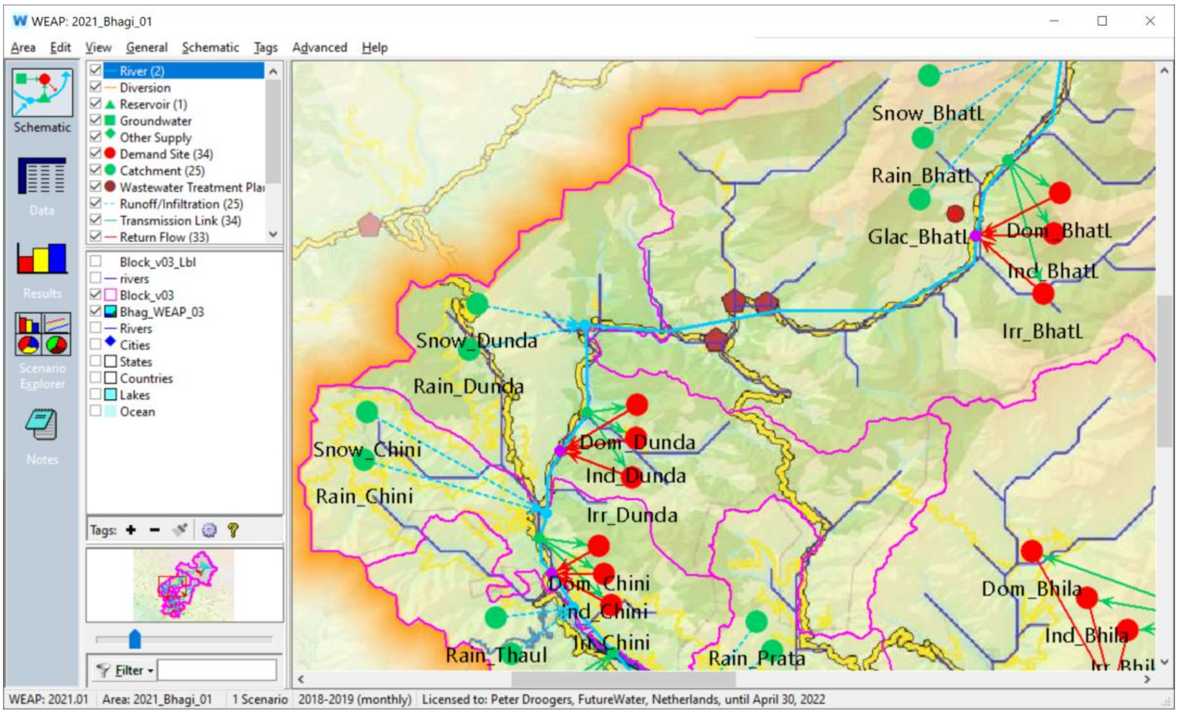

FIGURE 7 SAME AS FIGURE 6 ZOOMED AT THE WESTERN PART OF THE BHAGIRATHI BASIN.

Some typical examples of the analysis that can be done with the WEAP model in terms of tracing different water sources are presented below (Figure 8). Note that the WEAP model simulations also consider the water use and return flows to the river, while a model like SPHY does not consider water withdrawals and returns.

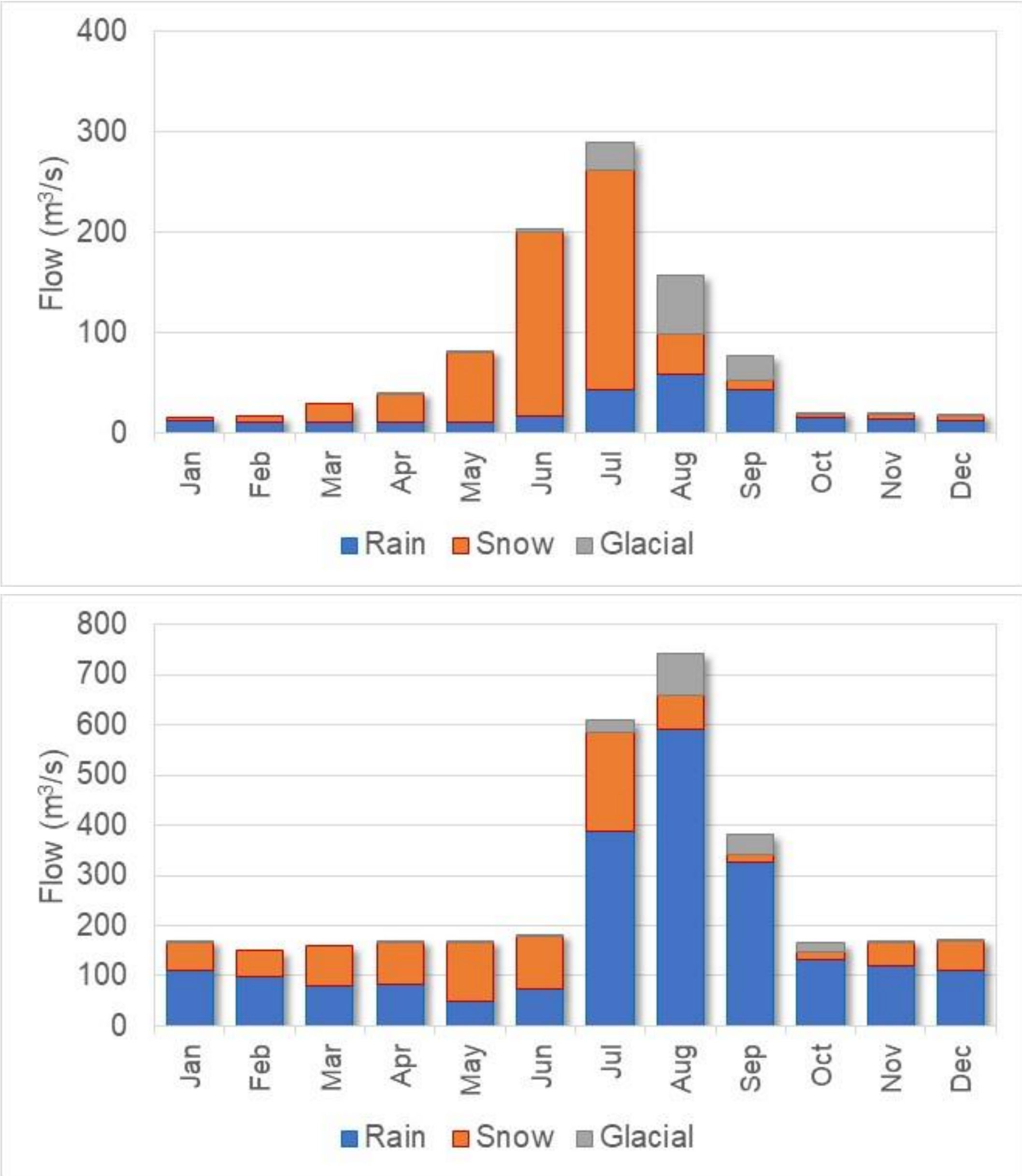

FIGURE 8 ORIGIN OF WATER. MEAN MONTHLY 2001-2020. TOP: UPSTREAM USERS BHATWARI_H; BOTTOM INFLOW TEHRI RESERVOIR.

For more details on water allocation modelling and other inputs required beyond the glacio-hydrological modelling outputs, please refer to the WEAP manual or manuals of related software.

5. References

Arnold, J. G., Srinivasan, R., Muttiah, R. S. and Williams, J. R.: LARGE AREA HYDROLOGIC MODELING AND ASSESSMENT PART I: MODEL DEVELOPMENT, J. Am. Water Resour. Assoc., 34(1), 73–89, doi:10.1111/j.1752-1688.1998.tb05961.x, 1998.

Ballesteros-Cánovas, J. A., Trappmann, D., Madrigal-González, J., Eckert, N. and Stoffel, M.: Climate warming enhances snow avalanche risk in the Western Himalayas, Proc. Natl. Acad. Sci. U. S. A., 115(13), 3410–3415, doi:10.1073/pnas.1716913115, 2018.

Bárdossy, A.: Calibration of hydrological model parameters for ungauged catchments, Hydrol. Earth Syst. Sci., 11(2), 703–710, doi:10.5194/hess-11-703-2007, 2007.

Bastola, S. and Murphy, C.: Sensitivity of the performance of a conceptual rainfall-runoff model to the temporal sampling of calibration data, Hydrol. Res., 44(3), 484–494, doi:10.2166/nh.2012.061, 2013.

Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L. M., Coppola, E., Eckert, N., Fantini, A., Giacona, F., Hauck, C., Huss, M., Huwald, H., Lehning, M., López-Moreno, J. I., Magnusson, J., Marty, C., Morán-Tejéda, E., Morin, S., Naaim, M., Provenzale, A., Rabatel, A., Six, D., Stötter, J., Strasser, U., Terzago, S. and Vincent, C.: The European mountain cryosphere: A review of its current state, trends, and future challenges, Cryosphere, 12(2), doi:10.5194/tc-12-759-2018, 2018.

Bergström, S.: The HBV model - its structure and applications, Swedish Meteorol. Hydrol. Inst. Reports Hydrol., doi:10.3368/le.88.4.685, 1992.

Beven, K.: How far can we go in distributed hydrological modelling?, Hydrol. Earth Syst. Sci., 5(1), 1–12, doi:10.5194/hess-5-1-2001, 2001.

Beven, K.: Rainfall-Runoff Modelling: The Primer., 2012.

Bierkens, M. F. P., Finke, P. and Willigen, P.: Upscaling and Downscaling Methods for Environmental Research, Dordr. etc., Kluwer, 2000. Dev. Plant Soil Sci. 88, 190 pp, 88, 2001.

Bierkens, M. F. P., Bell, V. A., Burek, P., Chaney, N., Condon, L. E., David, C. H., De Roo, A., Döll, P., Drost, N., Famiglietti, J. S., Flörke, M., Keune, J., Kollet, S., Maxwell, R. M., Reager, J. T., Samaniego, L., Sudicky, E., Sutanudjaja, E. H. and Wood, E. F.: Hyper-resolution global hydrological modelling: what is next? " Everywhere and locally relevant ", Hydrol. Process., doi:10.1002/hyp.10391, 2015.

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johannsson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J. P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A. B. K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M. and Lantuit, H.: Permafrost is warming at a global scale, Nat. Commun., 10(1), 1–11, doi:10.1038/s41467-018-08240-4, 2019.

Blöschl, G. and Sivapalan, M.: Scale issues in hydrological modelling: A review, Hydrol. Process., 9(3–4), 251–290, doi:10.1002/hyp.3360090305, 1995.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S. and Stoffel, M.: The state and fate of himalayan glaciers, Science (80-.)., 336(6079), 310–314, doi:10.1126/science.1215828, 2012.

Bookhagen, B. and Burbank, D. W.: Topography, relief, and TRMM-derived rainfall variations along the Himalaya, Geophys. Res. Lett., 33(8), 1–5, doi:10.1029/2006GL026037, 2006.

Bowling, L. C., Pomeroy, J. W. and Lettenmaier, D. P.: Parameterization of Blowing-Snow Sublimation in a Macroscale Hydrology Model, J. Hydrometeorol., doi:10.1175/1525-7541(2004)005<0745:POBSIA>2.0.CO;2, 2004.

Braithwaite, R. J. and Zhang, Y.: Sensitivity of mass balance of five Swiss glaciers to temperature changes assessed by tuning a degree-day model, J. Glaciol., doi:10.3189/172756500781833511, 2000.

Brigode, P., Oudin, L. and Perrin, C.: Hydrological model parameter instability: A source of additional uncertainty in estimating the hydrological impacts of climate change?, J. Hydrol., 476, 410–425, doi:10.1016/j.jhydrol.2012.11.012, 2013.

Brun, F., Berthier, E., Wagnon, P., Kääb, A. and Treichler, D.: A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016, Nat. Geosci., 10, 668 [online] Available from: https://doi.org/10.1038/ngeo2999, 2017.

Cannon, F., Carvalho, L. M. V., Jones, C. and Norris, J.: Winter westerly disturbance dynamics and precipitation in the western Himalaya and Karakoram: a wave-tracking approach, Theor. Appl. Climatol., 125(1–2), 27–44, doi:10.1007/s00704-015-1489-8, 2016.

Cazorzi, F. and Dalla Fontana, G.: Snowmelt modelling by combining air temperature and a distributed radiation index, J. Hydrol., 181(1–4), 169–187, doi:10.1016/0022-1694(95)02913-3, 1996.

Chanson, H.: Hydraulics of Open Channel Flow - 2nd Edition. [online] Available from: https://www.elsevier.com/books/hydraulics-of-open-channel-flow/chanson/978-0-7506-5978-9 (Accessed 19 April 2021), 2004.

Chaudhry, M. H.: Open-channel flow, Springer Science \& Business Media., 2007.

Che, Y., Zhang, M., Li, Z., Wei, Y., Nan, Z., Li, H., Wang, S. and Su, B.: Energy balance model of mass balance and its sensitivity to meteorological variability on Urumqi River Glacier No.1 in the Chinese Tien Shan, Sci. Rep., 9(1), 1–13, doi:10.1038/s41598-019-50398-4, 2019.

Te Chow, V.: Applied hydrology, Tata McGraw-Hill Education., 2010.

Clark, M. P., Nijssen, B., Lundquist, J. D., Kavetski, D., Rupp, D. E., Woods, R. A., Freer, J. E., Gutmann, E. D., Wood, A. W., Gochis, D. J., Rasmussen, R. M., Tarboton, D. G., Mahat, V., Flerchinger, G. N. and Marks, D. G.: A unified approach for process-based hydrologic modeling: 2. Model implementation and case studies, Water Resour. Res., 51(4), 2515–2542, doi:10.1002/2015WR017200, 2015a.

Clark, M. P., Fan, Y., Lawrence, D. M., Adam, J. C., Bolster, D., Gochis, D. J., Hooper, R. P., Kumar, M., Leung, L. R., Mackay, D. S., Maxwell, R. M., Shen, C., Swenson, S. C. and Zeng, X.: Improving the representation of hydrologic processes in Earth System Models, Water Resour. Res., 51(8), 5929–5956, doi:10.1002/2015WR017096, 2015b.

Clark, M. P., Bierkens, M. F. P., Samaniego, L., Woods, R. A., Uijlenhoet, R., Bennett, K. E., Pauwels, V. R. N., Cai, X., Wood, A. W. and Peters-Lidard, C. D.: The evolution of process-based hydrologic models: Historical challenges and the collective quest for physical realism, Hydrol. Earth Syst. Sci., 21(7), 3427–3440, doi:10.5194/hess-21-3427-2017, 2017.

Coenders-Gerrits, A. M. J., Van Der Ent, R. J., Bogaard, T. A., Wang-Erlandsson, L., Hrachowitz, M. and Savenije, H. H. G.: Uncertainties in transpiration estimates, Nature, 506(7487), E1–E2, doi:10.1038/nature12925, 2014.

Cunge, J. A.: On the subject of a flood propagation computation method (musklngum method), J. Hydraul. Res., 7(2), 205–230, doi:10.1080/00221686909500264, 1969.

Dobinski, W.: Permafrost, Earth-Science Rev., 108(3–4), 158–169, doi:10.1016/j.earscirev.2011.06.007, 2011.

Domeneghetti, A., Castellarin, A. and Brath, A.: Assessing rating-curve uncertainty and its effects on hydraulic model calibration, Hydrol. Earth Syst. Sci., 16(4), 1191–1202, 2012.

Emery, W. and Camps, A.: Introduction to satellite remote sensing: Atmosphere, ocean, cryosphere and land applications, Elsevier., 2017.

Essery, R., Morin, S., Lejeune, Y. and B Ménard, C.: A comparison of 1701 snow models using observations from an alpine site, Adv. Water Resour., 55, 131–148, doi:10.1016/j.advwatres.2012.07.013, 2013.

Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F. and Pandit, A.: A consensus estimate for the ice thickness distribution of all glaciers on Earth, Nat. Geosci., 12(3), 168–173, doi:10.1038/s41561-019-0300-3, 2019.

Fatichi, S., Vivoni, E. R., Ogden, F. L., Ivanov, V. Y., Mirus, B., Gochis, D., Downer, C. W., Camporese, M., Davison, J. H., Ebel, B., Jones, N., Kim, J., Mascaro, G., Niswonger, R., Restrepo, P., Rigon, R., Shen, C., Sulis, M. and Tarboton, D.: An overview of current applications, challenges, and future trends in distributed process-based models in hydrology, J. Hydrol., 537(March), 45–60, doi:10.1016/j.jhydrol.2016.03.026, 2016.

Gao, H., Wang, J., Yang, Y., Pan, X., Ding, Y. and Duan, Z.: Permafrost Hydrology of the Qinghai-Tibet Plateau: A Review of Processes and Modeling, Front. Earth Sci., 8, 535, doi:10.3389/feart.2020.576838, 2021.

Gebregiorgis, A. S. and Hossain, F.: How well can we estimate error variance of satellite precipitation data around the world?, Atmos. Res., 154, 39–59, doi:10.1016/j.atmosres.2014.11.005, 2015.

Gehne, M., Hamill, T. M., Kiladis, G. N. and Trenberth, K. E.: Comparison of global precipitation estimates across a range of temporal and spatial scales, J. Clim., 29(21), 7773–7795, doi:10.1175/JCLI-D-15-0618.1, 2016.

Georgakakos, K. P., Seo, D. J., Gupta, H., Schaake, J. and Butts, M. B.: Towards the characterization of streamflow simulation uncertainty through multimodel ensembles, in Journal of Hydrology, vol. 298, pp. 222–241, Elsevier., 2004.

Grayson, R. B., Blöschl, G., Western, A. W. and McMahon, T. A.: Advances in the use of observed spatial patterns of catchment hydrological response, Adv. Water Resour., 25(8–12), 1313–1334, doi:10.1016/S0309-1708(02)00060-X, 2002.

Groot Zwaaftink, C. D., Löwe, H., Mott, R., Bavay, M. and Lehning, M.: Drifting snow sublimation: A high-resolution 3-D model with temperature and moisture feedbacks, J. Geophys. Res. Atmos., 116(16), 1–14, doi:10.1029/2011JD015754, 2011.

Günther, D., Marke, T., Essery, R. and Strasser, U.: Uncertainties in Snowpack Simulations—Assessing the Impact of Model Structure, Parameter Choice, and Forcing Data Error on Point-Scale Energy Balance Snow Model Performance, Water Resour. Res., 55(4), 2779–2800, doi:10.1029/2018WR023403, 2019.

Haeberli, W.: Glacier mass balance, in Encyclopedia of Earth Sciences Series., 2011.

Harrigan, S. and Berghuijs, W.: The Mystery of Evaporation, Streams Thought (Young Hydrol. Soc., (July), 1–5, 2016.

Hattermann, F. F., Krysanova, V. and Gosling, S. N.: Cross - scale intercomparison of climate change impacts simulated by regional and global hydrological models in eleven large river basins, Clim. Change, 561–576, doi:10.1007/s10584-016-1829-4, 2017.

He, Z., Vorogushyn, S., Unger-Shayesteh, K., Gafurov, A., Kalashnikova, O., Omorova, E. and Merz, B.: The Value of Hydrograph Partitioning Curves for Calibrating Hydrological Models in Glacierized Basins, Water Resour. Res., 54(3), 2336–2361, doi:10.1002/2017WR021966, 2018.

Hock, R.: Temperature index melt modelling in mountain areas, J. Hydrol., 282(1–4), 104–115, doi:10.1016/S0022-1694(03)00257-9, 2003.

Hock, R.: Glacier melt: A review of processes and their modelling, Prog. Phys. Geogr., doi:10.1191/0309133305pp453ra, 2005.

Hock, R. and Holmgren, B.: A distributed surface energy-balance model for complex topography and its application to Storglaciären, Sweden, J. Glaciol., 51(172), 25–36, doi:10.3189/172756505781829566, 2005.

Hock, R., Hutchings, J. K. and Lehning, M.: Grand challenges in cryospheric sciences: Toward better predictability of glaciers, snow and sea ice, Front. Earth Sci., 5(August), 1–14, doi:10.3389/feart.2017.00064, 2017.

Højberg, A. and Refsgaard, J.: Model uncertainty - Parameter uncertainty versus conceptual models, Water Sci. Technol., 52, 177–186, doi:10.2166/wst.2005.0166, 2005.

Holländer, H. M., Bormann, H., Blume, T., Buytaert, W., Chirico, G. B., Exbrayat, J. F., Gustafsson, D., Hölzel, H., Krauße, T., Kraft, P., Stoll, S., Blöschl, G. and Flühler, H.: Impact of modellers' decisions on hydrological a priori predictions, Hydrol. Earth Syst. Sci., 18(6), 2065–2085, doi:10.5194/hess-18-2065-2014, 2014.

Hrachowitz, M. and Clark, M. P.: HESS Opinions: The complementary merits of competing modelling philosophies in hydrology, Hydrol. Earth Syst. Sci., doi:10.5194/hess-21-3953-2017, 2017.

Huggel, C., Carey, M., Clague, J. J. and Kääb, A.: The high-mountain cryosphere: Environmental changes and human risks, Cambridge University Press., 2015.

Huintjes, E., Sauter, T., Schroter, B., Maussion, F., Yang, W., Kropaček, J., Buchroithner, M., Scherer, D., Kang, S. and Schneider, C.: Evaluation of a Coupled Snow and Energy Balance Model for Zhadang Glacier, Tibetan Plateau, Using Glaciological Measurements and Time-Lapse Photography, Arctic, Antarct. Alp. Res., 47(3), 573–590, doi:10.1657/AAAR0014-073, 2015.

Immerzeel, W. W.: Climate change will effect the asian water tower, Science (80-.)., 1382, doi:10.1126/science.1183188, 2010.

Immerzeel, W. W., van Beek, L. P. H., Konz, M., Shrestha, A. B. and Bierkens, M. F. P.: Hydrological response to climate change in a glacierized catchment in the Himalayas, Clim. Change, 110(3–4), 721–736, doi:10.1007/s10584-011-0143-4, 2012.

Immerzeel, W. W., Wanders, N., Lutz, A. F., Shea, J. M. and Bierkens, M. F. P.: Reconciling high-altitude precipitation in the upper Indus basin, , 4673–4687, doi:10.5194/hess-19-4673-2015, 2015a.

Immerzeel, W. W., Wanders, N., Lutz, A. F., Shea, J. M. and Bierkens, M. F. P.: Reconciling high altitude precipitation with glacier mass balances and runoff, Hydrol. Earth Syst. Sci., 12, 4755–4784, doi:10.5194/hessd-12-4755-2015, 2015b.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T. and Baillie, J. E. M.: Importance and vulnerability of the world's water towers, Nature, 577(7790), 364–369, doi:10.1038/s41586-019-1822-y, 2020.

Kampf, S. K. and Burges, S. J.: A framework for classifying and comparing distributed hillslope and catchment hydrologic models, Water Resour. Res., 43(5), 2007.

Kang, S., Xu, Y., You, Q., Flügel, W. A., Pepin, N. and Yao, T.: Review of climate and cryospheric change in the Tibetan Plateau, Environ. Res. Lett., 5(1), doi:10.1088/1748-9326/5/1/015101, 2010.

Khanal, S., Lutz, A. F., Kraaijenbrink, P. D. A., van den Hurk, B., Yao, T. and Immerzeel, W. W.: Variable 21st Century Climate Change Response for Rivers in High Mountain Asia at Seasonal to Decadal Time Scales, Water Resour. Res., 57(5), e2020WR029266, doi:10.1029/2020wr029266, 2021.

Khanal, S., Tiwari, S., Lutz, A. F., Hurk, B. V. D. and Immerzeel, W. W.: Historical Climate Trends over High Mountain Asia Derived from ERA5 Reanalysis Data, , 263–288, doi:10.1175/JAMC-D-21-0045.1, 2023.

Kiang, J. E., Gazoorian, C., McMillan, H., Coxon, G., Le Coz, J., Westerberg, I. K., Belleville, A., Sevrez, D., Sikorska, A. E., Petersen-Øverleir, A. and others: A comparison of methods for streamflow uncertainty estimation, Water Resour. Res., 54(10), 7149–7176, 2018.

King, O., Bhattacharya, A., Bhambri, R. and Bolch, T.: Glacial lakes exacerbate Himalayan glacier mass loss, Sci. Rep., 9(1), 1–9, doi:10.1038/s41598-019-53733-x, 2019.

Klemeš, V.: The modelling of mountain hydrology: the ultimate challenge, in Hydrology of Mountainous Areas (Proceedings of the Strbské Pleso Workshop, Czechoslovakia, June 1988). IAHS Publ. no. 190., 1990.

Knowles, J. F., Blanken, P. D., Williams, M. W. and Chowanski, K. M.: Energy and surface moisture seasonally limit evaporation and sublimation from snow-free alpine tundra, Agric. For. Meteorol., 157, 106–115, doi:10.1016/j.agrformet.2012.01.017, 2012.

Koch, J., Cornelissen, T., Fang, Z., Bogena, H., Diekkrüger, B., Kollet, S. and Stisen, S.: Inter-comparison of three distributed hydrological models with respect to seasonal variability of soil moisture patterns at a small forested catchment, J. Hydrol., 533, 234–249, doi:10.1016/j.jhydrol.2015.12.002, 2016.

Kokkonen, T., Koivusalo, H., Jakeman, A. and Norton, J.: Construction of a degree–day snow model in the light of the ten iterative steps in model development, Proc. iEMSs Third Bienn. Meet. "Summit Environ. Model. Software" (July 2006), (Step 2), 12, 2006.

Koutsoyiannis, D.: Uncertainty, entropy, scaling and hydrological stochastic 2. Time dependence of hydrological processes and time scaling, Hydrol. Sci. J., 50(June), 405–426, 2005.

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F. and Immerzeel, W. W.: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers, Nature, 549, 257 [online] Available from: https://doi.org/10.1038/nature23878, 2017.

Kraaijenbrink, P. D. A., Stigter, E. E., Yao, T. and Immerzeel, W. W.: Climate change decisive for Asia's snow meltwater supply, Nat. Clim. Chang. 2021 117, 11(7), 591–597, doi:10.1038/s41558-021-01074-x, 2021.

Lafrenière, M. J. and Lamoureux, S. F.: Effects of changing permafrost conditions on hydrological processes and fluvial fluxes, Earth-Science Rev., 191, 212–223, doi:10.1016/j.earscirev.2019.02.018, 2019.

Lawrence, D. M., Koven, C. D., Swenson, S. C., Riley, W. J. and Slater, A. G.: Permafrost thaw and resulting soil moisture changes regulate projected high-latitude CO2 and CH4 emissions, Environ. Res. Lett., 10(9), doi:10.1088/1748-9326/10/9/094011, 2015.

Li, L., Gochis, D. J., Sobolowski, S. and Mesquita, M. D. S.: Evaluating the present annual water budget of a Himalayan headwater river basin using a high-resolution atmosphere-hydrology model, J. Geophys. Res. Atmos., 122(9), 4786–4807, doi:10.1002/2016JD026279, 2017.

Lindenschmidt, K.-E., Drastig, K. and Baborowski, M.: Structural Uncertainty in a River Water Quality Modelling System, Ecol. Modell., 204, 289–300, doi:10.1016/j.ecolmodel.2007.01.004, 2007.

Litt, M., Shea, J., Wagnon, P., Steiner, J., Koch, I., Stigter, E. and Immerzeel, W.: Glacier ablation and temperature indexed melt models in the Nepalese Himalaya, Sci. Rep., 9(1), 5264, doi:10.1038/s41598-019-41657-5, 2019.

Littlewood, I. G. and Croke, B. F. W.: Data time-step dependency of conceptual rainfall-streamflow model parameters: An empirical study with implications for regionalisation, Hydrol. Sci. J., 53(4), 685–695, doi:10.1623/hysj.53.4.685, 2008.

Liu, Y. and Gupta, H. V.: Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework, Water Resour. Res., 43(7), 1–18, doi:10.1029/2006WR005756, 2007.

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B. and Bierkens, M. F. P.: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation, Nat. Clim. Chang., 4(7), doi:10.1038/nclimate2237, 2014a.

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B. and Bierkens, M. F. P.: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation, Nat. Clim. Chang., 4(7), 587–592, doi:10.1038/nclimate2237, 2014b.

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B. and Bierkens, M. F. P.: Consistent increase in High Asia ' s runo due to increasing glacier melt and precipitation, Nat. Clim. Chang., (June), 1–6, doi:10.1038/NCLIMATE2237, 2014c.

Lv, Z. and Pomeroy, J. W.: Assimilating snow observations to snow interception process simulations, Hydrol. Process., 34(10), 2229–2246, doi:10.1002/hyp.13720, 2020.

MacDonald, M. K., Pomeroy, J. W. and Pietroniro, A.: On the importance of sublimation to an alpine snow mass balance in the Canadian Rocky Mountains, Hydrol. Earth Syst. Sci., 14(7), 1401–1415, doi:10.5194/hess-14-1401-2010, 2010.

Marshak, S.: Earth: Portrait of a Planet, 3rd ed., W. W. Norton & Company, Inc., 2008.

Martinec, J. and Rango, A.: Parameter values for snowmelt runoff modelling, J. Hydrol., doi:10.1016/0022-1694(86)90123-X, 1986.

Maurer, J. M., Schaefer, J. M., Rupper, S. and Corley, A.: Acceleration of ice loss across the Himalayas over the past 40 years, 2019.

McCuen, R. H.: The role of sensitivity analysis in hydrologic modeling, J. Hydrol., 18(1), 37–53, doi:10.1016/0022-1694(73)90024-3, 1973.

McMillan, H. K., Westerberg, I. K. and Krueger, T.: Hydrological data uncertainty and its implications, Wiley Interdiscip. Rev. Water, 5(6), e1319, 2018.

McNamara, J. P., Kane, D. L. and Hinzman, L. D.: An analysis of streamflow hydrology in the Kuparuk River Basin, Arctic Alaska: A nested watershed approach, J. Hydrol., 206(1–2), 39–57, doi:10.1016/S0022-1694(98)00083-3, 1998.

Mendoza, P. A., Clark, M. P., Mizukami, N., Newman, A. J., Barlage, M., Gutmann, E. D., Rasmussen, R. M., Rajagopalan, B., Brekke, L. D. and Arnold, J. R.: Effects of hydrologic model choice and calibration on the portrayal of climate change impacts, J. Hydrometeorol., 16(2), 762–780, doi:10.1175/JHM-D-14-0104.1, 2015.

Merz, R. and Blöschl, G.: Regionalisation of catchment model parameters, J. Hydrol., 287(1–4), 95–123, doi:10.1016/j.jhydrol.2003.09.028, 2004.

Millan, R., Mouginot, J., Rabatel, A. and Morlighem, M.: Ice velocity and thickness of the world's glaciers, Nat. Geosci. 2022 152, 15(2), 124–129, doi:10.1038/s41561-021-00885-z, 2022.

Moges, E., Demissie, Y., Larsen, L. and Yassin, F.: Review: Sources of hydrological model uncertainties and advances in their analysis, Water (Switzerland), 13(1), 1–23, doi:10.3390/w13010028, 2021.

Montesi, J., Elder, K., Schmidt, R. A. and Davis, R. E.: Sublimation of intercepted snow within a subalpine forest canopy at two elevations, J. Hydrometeorol., 5(5), 763–773, doi:10.1175/1525-7541(2004)005<0763:SOISWA>2.0.CO;2, 2004.

Mott, R., Vionnet, V. and Grünewald, T.: The Seasonal Snow Cover Dynamics: Review on Wind-Driven Coupling Processes, Front. Earth Sci., 6, doi:10.3389/feart.2018.00197, 2018.

Nelson, J. A., Pérez-Priego, O., Zhou, S., Poyatos, R., Zhang, Y., Blanken, P. D., Gimeno, T. E., Wohlfahrt, G., Desai, A. R., Gioli, B., Limousin, J. M., Bonal, D., Paul-Limoges, E., Scott, R. L., Varlagin, A., Fuchs, K., Montagnani, L., Wolf, S., Delpierre, N., Berveiller, D., Gharun, M., Belelli Marchesini, L., Gianelle, D., Šigut, L., Mammarella, I., Siebicke, L., Andrew Black, T., Knohl, A., Hörtnagl, L., Magliulo, V., Besnard, S., Weber, U., Carvalhais, N., Migliavacca, M., Reichstein, M. and Jung, M.: Ecosystem transpiration and evaporation: Insights from three water flux partitioning methods across FLUXNET sites, Glob. Chang. Biol., 26(12), 6916–6930, doi:10.1111/gcb.15314, 2020.

Nicholson, L. and Benn, D. I.: Calculating ice melt beneath a debris layer using meteorological data, J. Glaciol., doi:10.3189/172756506781828584, 2006.

North, G. R.: Theory of Energy-Balance Climate Models, J. Atmos. Sci., 32(11), 2033–2043, doi:10.1175/1520-0469(1975)032<2033:TOEBCM>2.0.CO;2, 1975.

Ochoa-Rodriguez, S., Wang, L. P., Gires, A., Pina, R. D., Reinoso-Rondinel, R., Bruni, G., Ichiba, A., Gaitan, S., Cristiano, E., Van Assel, J., Kroll, S., Murlà-Tuyls, D., Tisserand, B., Schertzer, D., Tchiguirinskaia, I., Onof, C., Willems, P. and Ten Veldhuis, M. C.: Impact of spatial and temporal resolution of rainfall inputs on urban hydrodynamic modelling outputs: A multi-catchment investigation, J. Hydrol., 531, 389–407, doi:10.1016/j.jhydrol.2015.05.035, 2015.

Østrem, G.: Ice Melting under a Thin Layer of Moraine, and the Existence of Ice Cores in Moraine Ridges, Geogr. Ann., doi:10.1080/20014422.1959.11907953, 1959.

Ostrowski, M., Bach, M., Desimone, S. and Gamerith, V.: Analysis of the time-step dependency of parameters in conceptual hydrological models, 2010.

Oudin, L., Michel, C. and Anctil, F.: Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 1 - Can rainfall-runoff models effectively handle detailed potential evapotranspiration inputs?, J. Hydrol., 303(1–4), 275–289, doi:10.1016/j.jhydrol.2004.08.025, 2005.

Palazzi, E., Von Hardenberg, J. and Provenzale, A.: Precipitation in the hindu-kush karakoram himalaya: Observations and future scenarios, J. Geophys. Res. Atmos., 118(1), 85–100, doi:10.1029/2012JD018697, 2013.

Palazzi, E., Von Hardenberg, J., Terzago, S. and Provenzale, A.: Precipitation in the Karakoram-Himalaya: a CMIP5 view, Clim. Dyn., 45(1–2), 21–45, doi:10.1007/s00382-014-2341-z, 2015.

Papacharalampous, G., Koutsoyiannis, D. and Montanari, A.: Quantification of predictive uncertainty in hydrological modelling by harnessing the wisdom of the crowd: Methodology development and investigationusingtoymodels, Adv. Water Resour., 136(103470), 1–63, 2019.

Patil, S. and Stieglitz, M.: Modelling daily streamflow at ungauged catchments: What information is necessary?, Hydrol. Process., 28(3), 1159–1169, doi:10.1002/hyp.9660, 2014.

Paul, F. and Kotlarski, S.: Forcing a distributed glacier mass balance model with the regional climate model REMO. Part II: Downscaling strategy and results for two swiss glaciers, J. Clim., 23(6), 1607–1620, doi:10.1175/2009JCLI3345.1, 2010.

Pellicciotti, F., Brock, B., Strasser, U., Burlando, P., Funk, M. and Corripio, J.: An enhanced temperature-index glacier melt model including the shortwave radiation balance: Development and testing for Haut Glacier d'Arolla, Switzerland, J. Glaciol., doi:10.3189/172756505781829124, 2005.

Pellicciotti, F., Buergi, C., Immerzeel, W. W., Konz, M. and Shrestha, A. B.: Challenges and uncertainties in hydrological modeling of remote hindu KushKarakoramHimalayan (HKH) Basins: Suggestions for calibration strategies, Mt. Res. Dev., 32(1), 39–50, doi:10.1659/MRD-JOURNAL-D-11-00092.1, 2012.

Pellicciotti, F., Stephan, C., Miles, E. S., Herreid, S., Immerzeel, W. W. and Bolch, T.: Mass-balance changes of the debris-covered glaciers in the Langtang Himal, Nepal, from 1974 to 1999, J. Glaciol., 61(226), 373–386, doi:10.3189/2015JoG13J237, 2015.

Pepin, N., Bradley, R. S., Diaz, H. F., Baraër, M., Caceres, E. B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M. Z., Liu, X. D. and Others: Elevation-dependent warming in mountain regions of the world, Nat. Clim. Chang., 5(5), 424–430, doi:10.1038/nclimate2563, 2015.

Peters-Lidard, C. D., Clark, M., Samaniego, L., Verhoest, N. E. C., Van Emmerik, T., Uijlenhoet, R., Achieng, K., Franz, T. E. and Woods, R.: Scaling, similarity, and the fourth paradigm for hydrology, Hydrol. Earth Syst. Sci., 21(7), 3701–3713, doi:10.5194/hess-21-3701-2017, 2017.

Pomeroy, J. W. and Gray, D. M.: Snowcover Accumulation, Relocation and Management, National Hydrology Research Institute. [online] Available from: https://books.google.nl/books?id=dS21PhlMcn8C, 1995.

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y. and Wisser, D.: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment, Proc. Natl. Acad. Sci. U. S. A., 111(9), 3262–3267, doi:10.1073/pnas.1222473110, 2014.

Qin, J., Yang, K., Liang, S. and Guo, X.: The altitudinal dependence of recent rapid warming over the Tibetan Plateau, Clim. Change, 97(1), 321–327, doi:10.1007/s10584-009-9733-9, 2009.

Quinton, W. L. and Baltzer, J. L.: The active-layer hydrology of a peat plateau with thawing permafrost (Scotty Creek, Canada), Hydrogeol. J., 21(1), 201–220, doi:10.1007/s10040-012-0935-2, 2013.

Ragettli, S. and Pellicciotti, F.: Calibration of a physically based, spatially distributed hydrological model in a glacierized basin: On the use of knowledge from glaciometeorological processes to constrain model parameters, Water Resour. Res., doi:10.1029/2011WR010559, 2012.

Ragettli, S., Bolch, T. and Pellicciotti, F.: Heterogeneous glacier thinning patterns over the last 40 years in Langtang Himal, Nepal, Cryosphere, 10(5), 2075–2097, doi:10.5194/tc-10-2075-2016, 2016.

Reba, M. L., Pomeroy, J., Marks, D. and Link, T. E.: Estimating surface sublimation losses from snowpacks in a mountain catchment using eddy covariance and turbulent transfer calculations, Hydrol. Process., 26(24), 3699–3711, doi:10.1002/hyp.8372, 2012.

Reed, S., Koren, V., Smith, M., Zhang, Z., Moreda, F. and Seo, D. J.: Overall distributed model intercomparison project results, J. Hydrol., 298(1–4), 27–60, doi:10.1016/j.jhydrol.2004.03.031, 2004.

Refsgaard, J. C., Christensen, S., Sonnenborg, T. O., Seifert, D., Højberg, A. L. and Troldborg, L.: Review of strategies for handling geological uncertainty in groundwater flow and transport modeling, Adv. Water Resour., 36, 36–50, doi:https://doi.org/10.1016/j.advwatres.2011.04.006, 2012.

Reid, T. D. and Brock, B. W.: An energy-balance model for debris-covered glaciers including heat conduction through the debris layer, J. Glaciol., 56(199), 903–916, doi:10.3189/002214310794457218, 2010.

Renard, B., Kavetski, D., Kuczera, G., Thyer, M. and Franks, S. W.: Understanding predictive uncertainty in hydrologic modeling: The challenge of identifying input and structural errors, Water Resour. Res., 46(5), 1–22, doi:10.1029/2009WR008328, 2010.

Rodell, M., Beaudoing, H. K., L'Ecuyer, T. S., Olson, W. S., Famiglietti, J. S., Houser, P. R., Adler, R., Bosilovich, M. G., Clayson, C. A., Chambers, D., Clark, E., Fetzer, E. J., Gao, X., Gu, G., Hilburn, K., Huffman, G. J., Lettenmaier, D. P., Liu, W. T., Robertson, F. R., Schlosser, C. A., Sheffield, J. and Wood, E. F.: The observed state of the water cycle in the early twenty-first century, J. Clim., 28(21), 8289–8318, doi:10.1175/JCLI-D-14-00555.1, 2015.

Rojas, R., Feyen, L. and Dassargues, A.: Conceptual model uncertainty in groundwater modeling: Combining generalized likelihood uncertainty estimation and Bayesian model averaging, Water Resour. Res., 44(12), 1–16, doi:10.1029/2008WR006908, 2008.

Rowan, A. V., Egholm, D. L., Quincey, D. J. and Glasser, N. F.: Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya, Earth Planet. Sci. Lett., 430, 427–438, doi:10.1016/j.epsl.2015.09.004, 2015.

Saloranta, T., Thapa, A., Kirkham, J. D., Koch, I., Melvold, K., Stigter, E., Litt, M. and Møen, K.: A Model Setup for Mapping Snow Conditions in High-Mountain Himalaya, Front. Earth Sci., 7, doi:10.3389/feart.2019.00129, 2019.

Savenije, H. H. G.: The importance of interception and why we should delete the term evapotranspiration from our vocabulary, Hydrol. Process., 18(8), 1507–1511, doi:10.1002/hyp.5563, 2004.

Schaner, N., Voisin, N., Nijssen, B. and Lettenmaier, D. P.: The contribution of glacier melt to streamflow, Environ. Res. Lett., 7(3), 034029, doi:10.1088/1748-9326/7/3/034029, 2012.

Schulla, J.: Model Description WaSiM, Zürich, Switzerland., 2017.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C. and Vonk, J. E.: Climate change and the permafrost carbon feedback, Nature, 520(7546), 171–179, doi:10.1038/nature14338, 2015.

Sexstone, G. A., Clow, D. W., Stannard, D. I. and Fassnacht, S. R.: Comparison of methods for quantifying surface sublimation over seasonally snow-covered terrain, Hydrol. Process., 30(19), 3373–3389, doi:10.1002/hyp.10864, 2016.

Sexstone, G. A., Clow, D. W., Fassnacht, S. R., Liston, G. E., Hiemstra, C. A., Knowles, J. F. and Penn, C. A.: Snow Sublimation in Mountain Environments and Its Sensitivity to Forest Disturbance and Climate Warming, Water Resour. Res., 54(2), 1191–1211, doi:10.1002/2017WR021172, 2018.

Seyfried, M. S., Grant, L. E., Marks, D., Winstral, A. and McNamara, J.: Simulated soil water storage effects on streamflow generation in a mountainous snowmelt environment, Idaho, USA, Hydrol. Process., 23(6), 858–873, doi:10.1002/hyp.7211, 2009.

Shean, D. E., Bhushan, S., Montesano, P. M., Rounce, D., Arendt, A. and Osmanoglu, B.: A systematic, regional assessment of High-Mountain Asia glacier mass balance, Front. Earth Sci., 7, 363: 1–19, 2020.

Sillmann, J., Kharin, V. V., Zhang, X., Zwiers, F. W. and Bronaugh, D.: Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate, J. Geophys. Res. Atmos., 118(4), 1716–1733, doi:10.1002/jgrd.50203, 2013.

Simons, G., Droogers, P., Contreras, S., Sieber, J. and Bastiaanssen, W.: Virtual tracers to detect sources ofwater and track water reuse across a river basin, Water (Switzerland), 12(8), 2315, doi:10.3390/w12082315, 2020.

Singh, V. P.: Hydrologic modeling: progress and future directions, Geosci. Lett., 5(1), doi:10.1186/s40562-018-0113-z, 2018.

Singh, V. P. and Woolhiser, D. A.: Mathematical modeling of watershed hydrology, J. Hydrol. Eng., 7(4), 270–292, 2002.

Smith, M. B., Koren, V. I., Zhang, Z., Reed, S. M., Pan, J. J. and Moreda, F.: Runoff response to spatial variability in precipitation: An analysis of observed data, in Journal of Hydrology, vol. 298, pp. 267–286, Elsevier., 2004a.

Smith, M. B., Seo, D. J., Koren, V. I., Reed, S. M., Zhang, Z., Duan, Q., Moreda, F. and Cong, S.: The distributed model intercomparison project (DMIP): Motivation and experiment design, J. Hydrol., 298(1–4), 4–26, doi:10.1016/j.jhydrol.2004.03.040, 2004b.

Song, X., Zhang, J., Zhan, C., Xuan, Y., Ye, M. and Xu, C.: Global sensitivity analysis in hydrological modeling: Review of concepts, methods, theoretical framework, and applications, J. Hydrol., 523(225), 739–757, doi:10.1016/j.jhydrol.2015.02.013, 2015.

Sorg, A., Huss, M., Rohrer, M. and Stoffel, M.: The days of plenty might soon be over in glacierized Central Asian catchments, Environ. Res. Lett., 9(10), doi:10.1088/1748-9326/9/10/104018, 2014.

Steiner, J. F., Pellicciotti, F., Buri, P., Miles, E. S., Immerzeel, W. W. and Reid, T. D.: Modelling ice-cliff backwasting on a debris-covered glacier in the Nepalese Himalaya, J. Glaciol., doi:10.3189/2015JoG14J194, 2015.

Stigter, E. E., Litt, M., Steiner, J. F. and Bonekamp, P. N. J.: The Importance of Snow Sublimation on a Himalayan Glacier, , 6(August), 1–16, doi:10.3389/feart.2018.00108, 2018.

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. M. and others: Climate change 2013: The physical science basis, Contrib. Work. Gr. I to fifth Assess. Rep. Intergov. panel Clim. Chang., 1535, 2013.

Strasser, U., Bernhardt, M., Weber, M., Liston, G. E. and Mauser, W.: Is snow sublimation important in the alpine water balance?, 2008.

Sudheer, K. P., Lakshmi, G. and Chaubey, I.: Application of a pseudo simulator to evaluate the sensitivity of parameters in complex watershed models, Environ. Model. Softw., 26(2), 135–143, doi:10.1016/j.envsoft.2010.07.007, 2011.

Sutanto, S. J., Van Den Hurk, B., Dirmeyer, P. A., Seneviratne, S. I., Röckmann, T., Trenberth, K. E., Blyth, E. M., Wenninger, J. and Hoffmann, G.: HESS Opinions "a perspective on isotope versus non-isotope approaches to determine the contribution of transpiration to total evaporation," Hydrol. Earth Syst. Sci., 18(8), 2815–2827, doi:10.5194/hess-18-2815-2014, 2014.

Syed, K. H., Goodrich, D. C., Myers, D. E. and Sorooshian, S.: Spatial characteristics of thunderstorm rainfall fields and their relation to runoff, J. Hydrol., 271(1–4), 1–21, doi:10.1016/S0022-1694(02)00311-6, 2003.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., Konikow, L., Green, T. R., Chen, J., Taniguchi, M., Bierkens, M. F. P., Macdonald, A., Fan, Y., Maxwell, R. M., Yechieli, Y., Gurdak, J. J., Allen, D. M., Shamsudduha, M., Hiscock, K., Yeh, P. J. F., Holman, I. and Treidel, H.: Ground water and climate change, Nat. Clim. Chang., 3(4), 322–329, doi:10.1038/nclimate1744, 2013.

van Tiel, M., Stahl, K., Freudiger, D. and Seibert, J.: Glacio-hydrological model calibration and evaluation, Wiley Interdiscip. Rev. Water, 7(6), doi:10.1002/wat2.1483, 2020.

Tobin, C., Schaefli, B., Nicótina, L., Simoni, S., Barrenetxea, G., Smith, R., Parlange, M. and Rinaldo, A.: Improving the degree-day method for sub-daily melt simulations with physically-based diurnal variations, Adv. Water Resour., 55, 149–164, doi:10.1016/j.advwatres.2012.08.008, 2013.

Troin, M., Poulin, A., Baraer, M. and Brissette, F.: Comparing snow models under current and future climates: Uncertainties and implications for hydrological impact studies, J. Hydrol., 540, 588–602, doi:https://doi.org/10.1016/j.jhydrol.2016.06.055, 2016.

Vaze, J., Jordan, P., Beecham, R., Frost, A. and Summerell, G.: Guidelines for rainfall-runoff modelling: towards best practice model application, 2011.

Wagner, W., C. Verhoest, N. E., Ludwig, R. and Tedesco, M.: Editorial Remote sensing in hydrological sciences, Hydrol. Earth Syst. Sci., 13(6), 813–817, doi:10.5194/hess-13-813-2009, 2009.

Wagnon, P., Vincent, C., Arnaud, Y., Berthier, E., Vuillermoz, E., Gruber, S., Ménégoz, M., Gilbert, A., Dumont, M., Shea, J. M., Stumm, D. and Pokhrel, B. K.: Seasonal and annual mass balances of Mera and Pokalde glaciers (Nepal Himalaya) since 2007, Cryosphere, 7(6), 1769–1786, doi:10.5194/tc-7-1769-2013, 2013.

Walvoord, M. A. and Kurylyk, B. L.: Hydrologic Impacts of Thawing Permafrost-A Review, Vadose Zo. J., 15(6), vzj2016.01.0010, doi:10.2136/vzj2016.01.0010, 2016.

Wang, Q., Yi, S. and Sun, W.: Continuous Estimates of Glacier Mass Balance in High Mountain Asia Based on ICESat-1,2 and GRACE/GRACE Follow-On Data, Geophys. Res. Lett., 48(2), 1–11, doi:10.1029/2020GL090954, 2021.

Wijngaard, R. R., Lutz, A. F., Nepal, S., Khanal, S., Pradhananga, S., Shrestha, A. B. and Immerzeel, W. W.: Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins, PLoS One, 12(12), 26, doi:10.1371/journal.pone.0190224, 2017.

Wilby, R. L.: Uncertainty in water resource model parameters used for climate change impact assessment, Hydrol. Process., 19(16), 3201–3219, doi:10.1002/hyp.5819, 2005.

Woo, M. K. and Winter, T. C.: The role of permafrost and seasonal frost in the hydrology of northern wetlands in North America, J. Hydrol., 141(1–4), 5–31, doi:10.1016/0022-1694(93)90043-9, 1993.

Wood, E. F., Roundy, J. K., Troy, T. J., van Beek, L. P. H., Bierkens, M. F. P., Blyth, E., de Roo, A., Döll, P., Ek, M., Famiglietti, J., Gochis, D., van de Giesen, N., Houser, P., Jaffé, P. R., Kollet, S., Lehner, B., Lettenmaier, D. P., Peters-Lidard, C., Sivapalan, M., Sheffield, J., Wade, A. and Whitehead, P.: Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water, Water Resour. Res., 47(5), doi:10.1029/2010WR010090, 2011.

Wortmann, M., Bolch, T., Menz, C., Tong, J. and Krysanova, V.: Comparison and correction of high-mountain precipitation data based on glacio-hydrological modeling in the Tarim river headwaters (High Asia), J. Hydrometeorol., 19(5), 777–801, doi:10.1175/JHM-D-17-0106.1, 2018.

Xu, X., Li, J. and Tolson, B. A.: Progress in integrating remote sensing data and hydrologic modeling, Prog. Phys. Geogr., 38(4), 464–498, doi:10.1177/0309133314536583, 2014.

Zaherpour, J., Masaki, Y., Hanasaki, N., Gosling, S. N., Mount, N., Hannes, M. and Ted, I. E.: Worldwide evaluation of mean and extreme runoff from six global-scale hydrological models that account for human impacts OPEN ACCESS Worldwide evaluation of mean and extreme runoff from six global-scale hydrological models that account for human impacts, Environ. Res. Lett., 13(6), 065015, 2018.

Zhao, F., Masaki, Y., Hanasaki, N., Biemans, H., Zaherpour, J., Gosling, S. N., Veldkamp, T. I. E., Frieler, K., Schewe, J., Ostberg, S. and Willner, S.: The critical role of the routing scheme in simulating peak river discharge in global hydrological models The critical role of the routing scheme in simulating peak river discharge in global hydrological models, Environ. Res. Lett., 12(7), 075003, 2017.

Zhao, L., Xia, J., Xu, C. yu, Wang, Z., Sobkowiak, L. and Long, C.: Evapotranspiration estimation methods in hydrological models, J. Geogr. Sci., 23(2), 359–369, doi:10.1007/s11442-013-1015-9, 2013.

6. Annex 1: SDC hydrology case study in Bhagirathi Basin