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Differentiating between rain, snow, and glacier contributions to river discharge in the western Himalaya using remote-sensing data and distributed hydrological modeling

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ABSTRACT

Rivers draining the southern Himalaya provide most of the water supply for the densely populated Indo-Gangetic plains. Despite the importance of water resources in light of climate change, the relative contributions of rainfall, snow and glacier melt to discharge are not well understood, due to the scarcity of ground-based data in this complex terrain. Here, we quantify discharge sources in the Sutlej Valley, western Himalaya, from 2000 to 2012 with a distributed hydrological model that is based on daily, ground-calibrated remote-sensing observation. Based on the consistently good model performance, we analyzed the spatiotemporal distribution of hydrologic components and quantified their contribution to river discharge. Our results indicate that the Sutlej River's annual discharge at the mountain front is sourced to 55% by effective rainfall (rainfall reduced by evapotranspiration), 35% by snow melt and 10% by glacier melt. In the high-elevation orogenic interior glacial runoff contributes ~30% to annual river discharge. These glacier melt contributions are especially important during years with substantially reduced rainfall and snowmelt runoff, as during 2004, to compensate for low river discharge and ensure sustained water supply and hydropower generation. In 2004, discharge of the Sutlej River totaled only half the maximum annual discharge; with 17.3% being sourced by glacier melt. Our findings underscore the importance of calibrating remote-sensing data with ground-based data to constrain hydrological models with reasonable accuracy. For instance, we found that TRMM (Tropical Rainfall Measuring Mission) product 3B42 V7 systematically overestimates rainfall in arid regions of our study area by a factor of up to 5. By quantifying the spatiotemporal distribution of water resources we provide an important assessment of the potential impact of global warming on river discharge in the western Himalaya. Given the near-global coverage of the utilized remote-sensing datasets this hydrological modeling approach can be readily transferred to other data-sparse regions.

1. Introduction

Runoff from the Himalaya is extensively used for hydropower generation, agriculture, as well as urban and rural household use in the densely populated Indo-Gangetic Plains [7,18]. In light of recent climatic change [52], glacial retreat [15,89,98], population growth [109] and groundwater depletion [86] quantitative assessment of the available water resources in this region is a crucial task [49,113]. Although discharge generated from melting of snow and ice is generally assumed to be significant, the scarcity of detailed ground-based observations make quantification of their relative contributions to Himalayan discharge difficult.

Hydrological models are useful tools to explore and quantify fluvial discharge. Runoff from melting snow and ice is commonly estimated using either surface-energy balance [4,54] or temperature-index models [59,63,83]. In the Himalayan region, large-scale surface-energy balance approaches are currently not feasible, because of poorly validated input variables (e.g., wind speed, water-vapor pressure, humidity, radiation fluxes, etc.). In contrast, temperature-index models, which represent simplified empirically based alternatives, require less input data that are usually available for most regions on Earth. However, their simplicity may lead to lower accuracy and larger uncertainties of the results [34,78,82]. Furthermore, coefficients of temperature-index models can vary significantly within individual watersheds [42,58]. For a stronger

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physical basis of the melt water generation, the shortwave radiation balances can be included in so-called *enhanced* temperature-index models [44,78,83]. Furthermore, spatially distributed models are able to account for the high-spatial variability of meteorological parameters in mountain regions [38], but require input data that approximately match the spatial resolution of the model grid.

To achieve complete input data coverage in distributed models, previous studies have commonly extrapolated low-elevation station data to higher altitudes [e.g. [20,61,95,97]]. Extrapolation of station data for catchments with a high elevation range is problematic in mountainous regions because of the high-spatial variability of both, precipitation and temperature [9,17,62]. Alternatively, several satellite systems provide processed and gridded data products that can be used for hydrological modeling [6,90]. In the Himalaya, various MODIS and TRMM data products have been successfully integrated in hydrological models by studies that focused on mean-monthly discharges [e.g., [18]], or daily discharges in very large watersheds using MODIS [e.g., [51]]. Such approaches take advantage of temporal and/or spatial averaging, which reduces the uncertainties in the remote-sensing input data that typically contain noise, artifacts, and data gaps introduced by varying surface and atmospheric conditions, as well as specific sensor characteristics and data-processing methods [28]. Therefore, hydrological models with a high spatial and temporal resolution using remote-sensing based information on water fluxes (e.g. rainfall, evaporation) or land cover (e.g. snow cover, vegetation) need to be carefully calibrated to account for these uncertainties.

Recent hydrological modeling studies indicate high snow melt contributions to river discharge in the western Himalaya on the order of 30–60% [18,51,53,95]. In contrast, estimates of glacier melt contributions to river discharge in the Himalaya vary considerably between 2% and 30%, depending mainly on differences in glacierized catchment area, precipitation, temperature, and solar radiation [2,51,53,81].

The objective of this study is to develop a distributed hydrological model that is driven by calibrated remote-sensing data to study discharges in variably-sized catchments in steep mountainous regions, where ground-based stations are rare. As part of our modeling effort, we assess to what degree calibrated remotely sensed data change the model results, when compared to simple extrapolation of station data and uncalibrated remote-sensing data. Based on the hydrological model we analyze the spatial distribution of water resources and the temporal variations of river discharge components in the Sutlej Valley for the study period from 2000 to 2012. Furthermore, we investigate the relation of glacier snow-cover periods and glacier melt. Based on our novel approach to drive a distributed hydrological model with calibrated remote sensing data, we are able to accurately quantify the spatial and temporal variations in the release of transient water storages and investigate their impact on river discharge.

2. Study area

The Sutlej River is a tributary of the Indus River and has the third largest drainage area in the Himalaya (55,000 km^2), with two-thirds being located in China (Tibet) and one third in India (Fig. 1). Starting at the mountain front, surface elevations range from 400 m to 7200 m asl. More than 80% of the catchment area is located in the semi-arid to arid orogenic interior at elevations >4000 m asl, which results in a catchment-average elevation of 4400 m asl (Supporting material – Fig. S1). Vegetation cover is thick and dense at lower elevations at the mountain front, but decreases rapidly above an elevation of 3000 m asl and is virtually absent > 3500 m asl. Therefore, the primary land cover in the Sutlej Valley is bare ground (81.7%), as compared to trees and shrubs (7.2%), cultivated areas (6.8%), glaciers (3.2%), and lakes (1.1%) [31] (Table 1). Soil cover is present only in the lower part of the Sutlej catchment, which constitutes a small fraction (< 15%) of the entire drainage area and therefore is likely to have a low impact on overall water storages.

Precipitation in the western Himalaya has pronounced seasonal and spatial variations [18]. Snowfall occurs mostly between December and March and increases with elevation and relief [50,94,110]. During the summer months, the Indian monsoon (mid July–mid September) accounts for intense rainfall, which is mostly focused along orographic barriers of the southern Himalayan front and creates a steep SW-NE rainfall gradient, with > 2 m/yr at the fontal parts to < 0.2 m/yr over a horizontal distance of < 100 km encompassing a mean elevation range of > 4000 m [17,111]. Although most monsoonal moisture is blocked by the High Himalaya, during active monsoon phases, strong convective cells sometimes migrate across this barrier and result in cloudbursts that can mobilize enormous amounts of sediments [19,25,43,111].

3. The hydrological model

3.1. Runoff production

The newly set up distributed hydrological model calculates runoff during each time step (1 day) at each cell in the gridded model space, i.e., digital elevation model (DEM), and routes the water through the river network taking flow times and runoff storage into account. Daily runoff production, RP (mm/day), at a given location is the sum of snow melt (M_s), glacier melt (M_g), and rainfall (P_r), reduced by evapotranspiration (ET), according to:

$$RP = M_s + M_g + P_r - ET \tag{1}$$

The input data for rainfall and evapotranspiration are based on calibrated remote-sensing products, and discussed in Section 4.2 and 4.3. In contrast, snow and glacier melt are computed by processing multiple remote-sensing datasets.

3.2. Snow- and glacier melt

Similar to previous studies [22,44,45,63,78,83], we use a temperature-index model that incorporates the influences of solar radiation, snow albedo, and cloud cover. Daily snow melt (mm/day) is calculated for every snow-covered cell according to:

$$M_s = \begin{Bmatrix} (T \cdot tf_s + R_{sw} \cdot srf_s) \cdot A_s, & T > T_t \\ 0, & T \leq T_t \end{Bmatrix} \tag{2}$$

where T (°C) is the mean daily temperature, R_{sw} (W/m^2) is the mean daily net shortwave radiation, A_s (m^2) is the snow-covered area, tf_s (mm °C^{-1} day^{-1}) is an empirical *temperature factor* for snow melt, and srf_s (mm W^{-1} m^2 day^{-1}) is an empirical *shortwave radiation factor* for snow melt. T_t is a threshold temperature above which melt is assumed to occur (e.g., 0 °C). Glacier melt M_g (mm/day) is calculated similarly but occurs only if the corresponding cell is ice-covered and snow-free:

$$M_g = \begin{Bmatrix} (T \cdot tf_g + R_{sw} \cdot srf_g) \cdot (A_{ice} + df \cdot A_{debris}), & T > T_t \\ 0, & T \leq T_t \end{Bmatrix} \tag{3}$$

where A_{ice} (m^2) is the glacier area with clean ice exposure, A_{debris} (m^2) is the glacier area with debris cover, df is a dimensionless scaling factor for reduced melt rates on debris covered ice, and tf_g (mm °C^{-1} day^{-1}) and srf_g (mm W^{-1} m^2 day^{-1}) are empirical coefficients that relate temperature and shortwave radiation, respectively, to melt water production. Because supraglacial debris cover with a thickness > 2 cm, reduces ice melt due to its shielding effect on radiation and heat fluxes [20,48,64,84], we introduce a debris factor, df, that allows reducing melt rates for debris-covered ice.

Net shortwave radiation, R_{sw}, is calculated as [78]:

$$R_{sw} = R_{sky} \cdot f_{cc} \cdot (1 - \alpha) \tag{4}$$