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Differentiating rainfall, snow and glacial melt in the Sutlej Valley (western Himalaya) by distributed hydrological modeling

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Mountainous runoff from large rainfall, snow- and glacier-fed Himalayan rivers is essential for water consumption, hydropower generation, and agriculture in the densely populated Indo-Gangetic Plains. In light of steady population growth, widespread groundwater lowering, and glacial retreat, it is crucial to assess and manage the available water resources in this region. However, due to its remoteness, there is little ground-based meteorological and glacial mass-balance data available and quantitative information on the different discharge components are missing.

In this study, we quantify the water resources and discharge components for the Sutlej River ($\sim$55,000 km^2), which is the third largest river draining the Himalaya, by area. Most rain falls during the monsoon season in summer, whereas snowfall is mainly sourced by the winter westerlies. We model the hydrology at five positions of the Sutlej River and for four of its tributaries. Our model captures daily runoff derived from rainfall, snow- and glacial melts and losses due to evapotranspiration within 500x500 m grid cells. The model input is based on remote-sensing data, which we calibrated with ground measurements. We model snow and ice melting with a distributed enhanced temperature index model. We use daily MODIS (MODerate Resolution Imaging Spectroradiometer) Aqua and Terra imagery to derive fractional snow cover, surface albedo, cloud cover, mean daily surface temperature, and evapotranspiration. Rainfall is obtained by the TRMM (Tropical Rainfall Measuring Mission) product 3B42, which we calibrated with 81 weather stations distributed across our study area. We mapped glaciers using Landsat ETM+ band4/band5 ratio images and incorporated debris-covered glacier areas based on manual mapping from high-resolution imagery from Google Earth.

The modeled discharges yield high performance measures with Nash-Sutcliffe efficiency values ranking between 0.7 and 0.85. Our results indicate that the discharge of the Sutlej River at Bhakra (orogenic front) is sourced predominately by snowmelt (48%) followed by effective rainfall (rainfall – evapotranspiration) (39%) and glacial melt (13%). Average runoff per m^2 is less than 0.2 m/yr in the high-elevated, low relief Transhimalayan part of the Sutlej Valley, peaks at $\sim$1.5 m/yr in the snowmelt dominated High Himalaya, and is $\sim$0.9 m/yr at the rainfall dominated orogenic front. The average glacial ablation based on their surface area (2,004 km^2) and contribution to Sutlej River discharge between 2000 and 2007 is 0.82$\pm$0.14 m/yr. We estimate the average glacial accumulation to be 0.21$\pm$0.02 m/yr, which is based on 1 m snow water equivalent (SWE) accumulation for glacial parts with a continuous annual snow cover record. The combined glacial ablation and accumulation result in an average net mass balance of 0.61$\pm$0.16 m/yr. By incremental summation of daily snow melt amounts we can reconstruct the spatial SWE distribution for each year from 2001 to 2007. This distribution highlights the peak SWE accumulation in areas of high relief and high elevations, which amounts to a basin wide average of 0.12$\pm$0.03 m/yr in the Sutlej Valley.

Our model allows quantifying water resources and their contribution to river discharge within a large-scale watershed with reasonable accuracy, based on remote sensed imagery calibrated by ground-based observations. This basic hydrological knowledge is crucial to estimate the impact of global warming.