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An integrated modeling system for estimating glacier and snow melt driven streamflow from remote sensing and earth system data products in the Himalayas

M.E. Brown [a,*], A.E. Racoviteanu [b], D.G. Tarboton [c], A. Sen Gupta [c], J. Nigro [a,d], F. Policelli [a], S. Habib [a], M. Tokay [d], M.S. Shrestha [e], S. Bajracharya [e], P. Hummel [f], M. Gray [f], P. Duda [f], B. Zaitchik [g], V. Mahat [h], G. Artan [i], S. Tokar [j]

[a] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[b] Laboratoire de Glaciologie et Géophysique de l'Environnement, France
[c] Utah State University, Logan, UT, USA
[d] Science Systems and Applications, Inc., Lanham, MD, USA
[e] International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal
[f] AquaTerra Consultants, Decatur, GA, USA
[g] Johns Hopkins University, Baltimore, MD, USA
[h] Colorado State University, USA
[i] U.S. Geological Survey, Sioux Falls, SD, USA
[j] U.S. Agency for International Development, Office of Foreign Disaster Assistance, Washington, DC, USA

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SUMMARY

Quantification of the contribution of the hydrologic components (snow, ice and rain) to river discharge in the Hindu Kush Himalayan (HKH) region is important for decision-making in water sensitive sectors, and for water resources management and flood risk reduction. In this area, access to and monitoring of the glaciers and their melt outflow is challenging due to difficult access, thus modeling based on remote sensing offers the potential for providing information to improve water resources management and decision making. This paper describes an integrated modeling system developed using downscaled NASA satellite based and earth system data products coupled with in-situ hydrologic data to assess the contribution of snow and glaciers to the flows of the rivers in the HKH region. Snow and glacier melt was estimated using the Utah Energy Balance (UEB) model, further enhanced to accommodate glacier ice melt over clean and debris-covered tongues, then meltwater was input into the USGS Geospatial Stream Flow Model (GeoSFM). The two model components were integrated into Better Assessment Science Integrating point and Nonpoint Sources modeling framework (BASINS) as a user-friendly open source system and was made available to countries in high Asia. Here we present a case study from the Langtang Khola watershed in the monsoon-influenced Nepal Himalaya, used to validate our energy balance approach and to test the applicability of our modeling system. The snow and glacier melt model predicts that for the eight years used for model evaluation (October 2003–September 2010), the total surface water input over the basin was 9.43 m, originating as 62% from glacier melt, 30% from snowmelt and 8% from rainfall. Measured streamflow for those years were 5.02 m, reflecting a runoff coefficient of 0.53. GeoSFM simulated streamflow was 5.31 m indicating reasonable correspondence between measured and model confirming the capability of the integrated system to provide a quantification of water availability.
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1. Introduction

The Hindu Kush Himalayan (HKH) region possesses a large resource of snow and ice, which act as a freshwater reservoir for irrigation, domestic water consumption or hydro-electric power for billions of people in Asia. Snow and glacier-melt represent a significant source of surface water and influence many aspects of hydrology including water supply, erosion and flood control (National Research Council, 2012). With projected climate-induced changes in snow and ice and population growth, the region is at risk of experiencing water stress in the coming years (Immerzeel

* Corresponding author.
E-mail address: molly.brown@nasa.gov (M.E. Brown).

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et al., 2010, 2012; Kaser et al., 2010). There are, in particular, concerns about the effect of climate change on snow water equivalent, snowmelt runoff, glacier melt runoff and total streamflow and their distribution due to mean global temperature increases.

Some recent studies published the impact of temperature increase on glacier melt runoff high altitude basins (Barnett et al., 2005; Singh and Kumar, 1997a,b), but these tend to be over-estimated or conducted on small basins (Savoskul and Smakhtin, 2013). Research has shown that there are significant differences across the HKH region with regard to the contribution of glacier and snow melt to hydrological systems, changes in the timing or amount of snowmelt due to increasing temperatures or decreasing winter precipitation due to climate change. These changes may have far-reaching societal consequences, particularly in Asia (Bookhagen and Burbank, 2010; Immerzeel et al., 2012). More information is needed to monitor and anticipate snow and glacier ice melt runoff at larger scales to improve water resources management and flood protection (Jeuland et al., 2013).

The monitoring capability of hydrologic resources in this region is challenged by the difficulty of installing and maintaining a climate and hydrologic monitoring network, due to limited transportation and communication infrastructure and difficult access to glaciers. As a result of the high, rugged topographic relief, ground observations in the region are extremely sparse (Lo et al., 2011). For example, only a few glaciers are currently monitored for mass balance measurements in the Himalaya (Dobhal et al., 2008; Wagnon et al., 2007, 2013). In the recent years, remote sensing-based modeling has helped provide has been increasingly used in recent years to estimate water resources (Thayyen and Gergan, 2010) and thus has helped improve water resources decision making and management in these data-scarce areas.

While some progress has been made in understanding the contribution of snow and ice melt to streamflow in the Himalaya using degree-day or simple ablation models (Immerzeel et al., 2010, 2012; Racoviteanu et al., 2013), a region-wide estimate of water resources is hampered by the fact that these models are not in public domain, coupled with lack of access or technical expertise of local institutions. Another significant barrier for decision makers in monitoring and understanding the impact of climate-induced changes in snow and glaciers on water resources is the scientific disciplinary divide that isolates glacier experts and hydrological analysts, as well as lack of integrated tools that allow institutional actors trusted by decision makers to conduct analyses themselves. Developing a tool that can address all these limitations by integrating snow, ice and precipitation information from both satellite and local sources is critical to allow appropriate response to natural hazards to the population (Wisner et al., 2004), and is a focus of this study.

Here we present an integrated modeling capability developed to meet the water resources planning needs of this broad, multination region taking full advantage of NASA Earth Science data and modeling products. We developed a hydrologic tool that can be used at basin or sub-basin scale in an easy-to-use graphical user interface framework accessible to most users. The modeling needs were addressed by integrating an enhanced, gridded version of the Utah Energy Balance (UEB) snowmelt model, denoted here as UEB-Grid and the Geospatial Stream Flow Model (GeoSFM) into the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) modeling system. We downscaled various NASA gridded remote sensing and climate products and combined them with higher-resolution data for use in these models.

The resulting tool, publicly available to both the hydrological and cryospheric communities online (http://hspf.com/pub/HIMALA_BASINS/) is referred here as HIMALA BASINS, and will be maintained in conjunction with the U.S. Environmental Protection Agency's (EPA) open-source BASINS tool. The HIMALA BASINS model grew out of a decade of collaborative work between USAID's Office of Foreign Disaster Assistance, USGS and ICIMOD and was initially funded through the Asia Flood Network, a project designed to produce satellite-derived rainfall data products used to drive hydrological models. Since 2003, the NOAA Climate Prediction Centre's RFE2 (Xie et al., 2002) products have been validated by ICIMOD (Shrestha, 2010) within the hydrological model GeoSFM (Artan et al., 2007). ICIMOD has been training collaborators from its member countries to use these products. Here, we address the need to augment the GeoSFM with a capability to model water melt from snow and glacier ice, which was previously not taken into account in earlier versions of this model.

The novelty of HIMALA BASINS tool consists in allowing the user to isolate various components of streamflow (rainfall, snow and glacier ice melt) in a cost-free, open-source graphical-user interface-based system that can be used for government and institutional decision-making. Given the limitations in the spatial frequency, temporal resolution and accuracy of satellite data, this study does not claim to provide the most accurate estimate of the streamflow components at large scales in the HKH region. Rather, we focus on developing and validating a tool that is capable of integrating glacier melt components as well as high-resolution climate data when available. In this paper we focus on the methodology used to integrate UEB and GeoSFM into a seamless product, illustrated for eight years of simulations. A more thorough description of the model results is presented elsewhere Sen Gupta (2014).

Our study addresses two needs: (1) to improve the understanding of the contribution of snow and ice to Himalayan water resource and (2) to assist with improved management of water resources, evaluation of projected of climate change impacts on water resources, and advanced modeling and data assimilation capability available to users in the Himalayan region. Here we present results from a very high altitude, highly glaciated region where we document the contribution of snow and ice melt to streamflow and demonstrate the importance using an integrated model for these regions. The paper is structured as follows: we first describe the integration of the two models (UEB and GeoSFM) into the BASINS modeling framework; we then describe the satellite data products, downscaling algorithms and glacier mapping methods, and finally we present model results and discussion for the Langtang Khola case study in the Nepal Himalaya.

2. Study site

The test site for the HIMALA BASINS methodology is the Langtang Khola Watershed in Nepal Himalaya, covering a surface of 360 km^2, with an elevation range of 3737 m to 7174 m (Fig. 1). Various research studies focused on the contribution of snow and ice-melt to streamflow in the Langtang Khola watershed (Immerzeel et al., 2010, 2012; Racoviteanu et al., 2013). We chose Langtang Khola as a validation site due to the availability of climate records from Nepal Department of Hydrology and Meteorology (DHM), as well as for comparison with these past studies, using different methodology. The prototype system was tested on this watershed by the HIMALA team while further evaluation of the system is being conducted by ICIMOD and the partners from regional member countries in larger basins in the HKH region (Narayani, Manas and Jhelum basins).

3. Modeling framework: HIMALA BASINS

In this study, we linked a snow melt model with a stream flow model within a version of the BASINS software developed and maintained at U.S. EPA. BASINS consists of a pre-existing suite of hydrological models and supporting tools, and was chosen for this