ESTIMATING SNOWMELT CONTRIBUTION FROM THE GANGOTRI GLACIER CATCHMENT INTO THE BHAGIRATHI RIVER, INDIA

Rodney M. Chai[1], Leigh A. Stearns[2], C. J. van der Veen[1]

ABSTRACT

The Bhagirathi River emerges from the terminus of the Gangotri Glacier at 4000 m.a.s.l., and is a major tributary of the Ganges River. The Ganges is the world's third-largest river by discharge and provides water to over 350 million people in India and Bangladesh. The discharge of the Bhagirathi, which is driven by seasonal snow cover and melt, therefore has significant impacts on the downstream water supply to a population larger than the United States. Discharge data are scarce along the Ganges River, particularly in the headwaters. The Snowmelt Runoff Model (SRM) is a simple temperature index model that uses relatively few parameters to model runoff. This makes it ideal in remote areas like the Himalayas where it is difficult to get on-the-ground data that an energy balance model would require. A digital elevation model was used to divide the basin into elevation bands, and MODIS tiles were used to determine snow-covered area for 2010 and 2011. The results show that of the three SRM parameters, SCA showed the strongest correlation with both observed and modeled discharge in 2010, with R^2 values of 0.64 and 0.56 respectively. In 2011, however, all three SRM parameters performed poorly with both observed and modeled discharge. (KEYWORDS: SRM, Gangotri glacier, snow covered areas, Ganges River)

INTRODUCTION

The Bhagirathi River emerges from the terminus of the Gangotri Glacier at 4000 m.a.s.l., and is a major tributary of the Ganges River. The Ganges is the world's third-largest river by discharge and provides water to over 350 million people in India and Bangladesh. The discharge of the Bhagirathi, which is driven by seasonal snow cover and melt, therefore has significant impacts on the downstream water supply to a population larger than the United States. Discharge data are scarce along the Ganges River, particularly in the headwaters. As a result, short- and long-term projections of water availability contain large uncertainties. Being able to quantify snowmelt allows us to better understand the implications to water security in a politically unstable region (Blaikie and Muldavin, 2004), where monsoon and snowfall patterns are already impacted by climate change (Lal, 2001).

The Snowmelt Runoff Model (SRM) is a simple temperature index model that uses relatively few parameters to model runoff. This makes it ideal in remote areas like the Himalayas where it is difficult to get on-the-ground data that an energy balance model would require. The SRM has also been successfully tested in over 100 basins in 29 different countries, mostly by independent users such as agencies and universities (Martinec, 2008).

Our objective is to investigate the validity of a simple SRM to estimate discharge from the Gangotri Glacier catchment into the Bhagirathi River in Northern India.

STUDY AREA

The Gangotri Glacier (latitudes 30°43' – 31°01'N and longitudes 79°0' – 79°17'E) is one of the largest glaciers of the Himalayas with a catchment of approximately 556 km^2 (Singh, 2008). In this study, the catchment was split into six elevation zones between 4000 and 7000 m at 500 m increments (Fig 1B) as recommended by the SRM user manual (Martinec, 2008). The headwaters of the Bhagirathi emerge from the Gangotri Glacier at 4000 m.a.s.l and there is a stream gauge three km from the glacier's terminus (Arora, 2014). It was installed in September 1999 and discharge was measured daily during the summer season (Srivastava, 2012). The daily mean discharge values range from 8 to 239 m^3/s (Srivastava, 2012).

Paper presented Western Snow Conference 2016

[1] Department of Geography and Atmospheric Science, University of Kansas, Lawrence, KS, chaimingfui@gmail.com

[2] Department of Geology, University of Kansas, Lawrence, KS

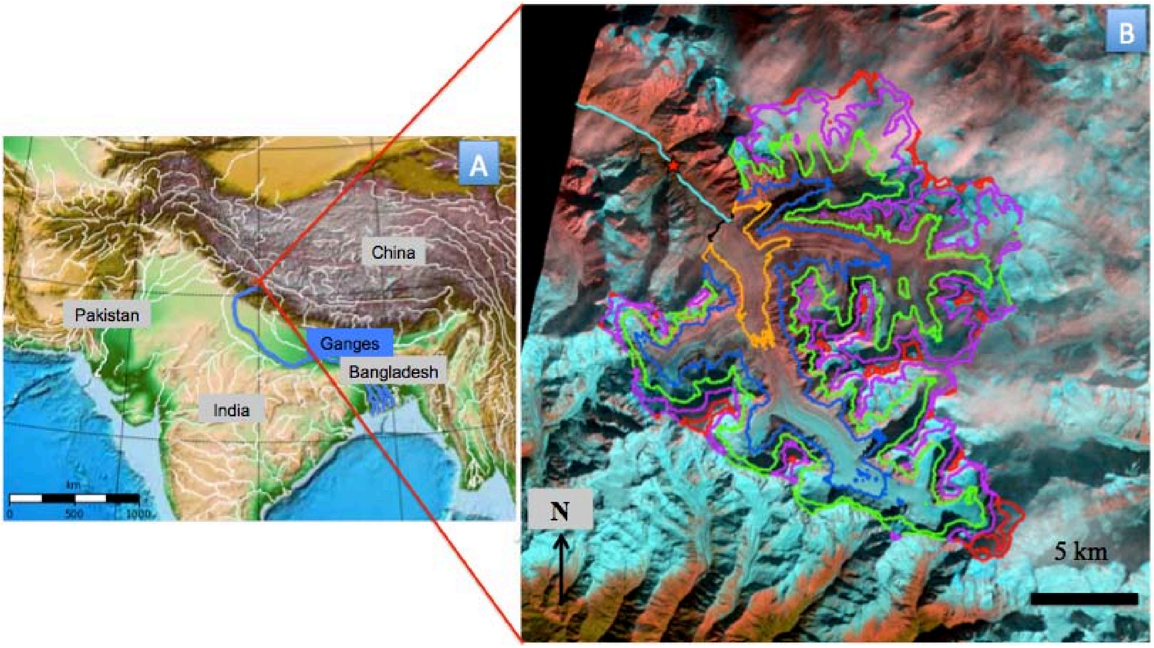

Figure 1. A). A map of South Asia, showing the location of the Gangotri Glacier catchment basin B). A Landsat 8 OLI image from 01/01/2014 with the catchment basin and elevation zones at 500m increments delineated (Black – 4000m; Orange – 4500m; Blue – 5000m; Green – 5500m; Purple – 6000 and Red – 6500m.a.s.l) The red star indicates the location of the stream gauge used to calibrate the snowmelt model.

METHODOLOGY

Due to the lack of comprehensive input data, snowmelt models in the Himalayas are often simple temperature index models that rely on relatively few parameters. We use the SRM, a temperature index model that relies on three main input parameters to calculate the discharge from snowmelt runoff, namely precipitation, temperature and changes in snow-covered area (SCA). The SRM formula is as follow:

$$Q_{n+1} = [c_{Sn} \cdot a_n (T_n + \Delta T_n) S_n + c_{Rn} P_n] \frac{A \cdot 10000}{86400} (1-k_{n+1}) + Q_n k_{n+1}$$

Equation 1: The SRM formula

Symbol	What it stands for	Value
C_S	Snow runoff coefficient	0.7
C_R	Rain runoff coefficient	0.9
a	Degree-day factor	0.9
k	Recession coefficient	0.9
Q	Discharge	
T	Temperature; ΔT – lapse rate	
A	Area of elevation zone	
S	Ratio of SCA to A	

Table 1. Explanation and the values used for the parameters in SRM

Daily values of precipitation and temperature are obtained from the weather station in the town of Gangotri at 3500 m.a.s.l and 15 km from the glacier terminus. A lapse rate of -6.5°C/1000 m is applied to estimate the temperature at the various elevation zones; precipitation is taken to be constant across the catchment basin. A degree-day factor of 0.7 cm $°C^{-1}$ day^{-1} is used to compute melt. The SRM also assumes that no melting occurs below 0°C.

The elevation zones are determined using a Digital Elevation Model (DEM) derived from 2011 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images. The areas of the elevation zones have been adjusted for slope as follow:

Zone	Slope (Degrees)
1	15
2	25
3	40
4	40
5	50
6	50

Table 2. Elevation zones and slope adjustment

The elevation accuracy of the Global DEM (GDEM) is found to be between 5-10 m and its spatial resolution is of the order of 100 m (Rees 2012). Snow Covered Area (SCA) is determined using the Level-3 (L3) Moderate Resolution Imaging Spectrometer (MODIS) product, MOD10A1, which is a tile of daily snow cover maps at 500 m spatial resolution. The categories for the MODIS L3 snow product are as follow: 200 – snow, 50 – cloud, 25 – no snow and 1 – no decision (Hall, 2006). Snow cover for each elevation zone is calculated as the proportion of snow pixels over total pixels. The most frequent errors are due to snow/cloud discrimination problems (Hall 2007. Therefore, SCA needs to be corrected for cloud cover. In our model, if there is more than 20% cloud cover on a certain day, that particular SCA is disregarded and replaced with a linearly interpolated value between two nearest dates with less than 20% cover.

Results from various studies show that the daily MODIS snow maps have an overall accuracy of about 93%, although lower accuracy is found in forested areas and complex terrain and when snow cover is thin (<1 cm thick) and ephemeral (Hall 2007). In a study conducted in the upper Rio Grande basin, the MOD10A1 MODIS snow products showed an overall accuracy of 94.2% compared with 15 SNOpackTELemetry (SNOTEL) sites for the snow season of 2000-2001 (Klein and Barnett, 2003). SNOTEL is an automated system to collect snowpack data in the western United States.

RESULTS AND DISCUSSION

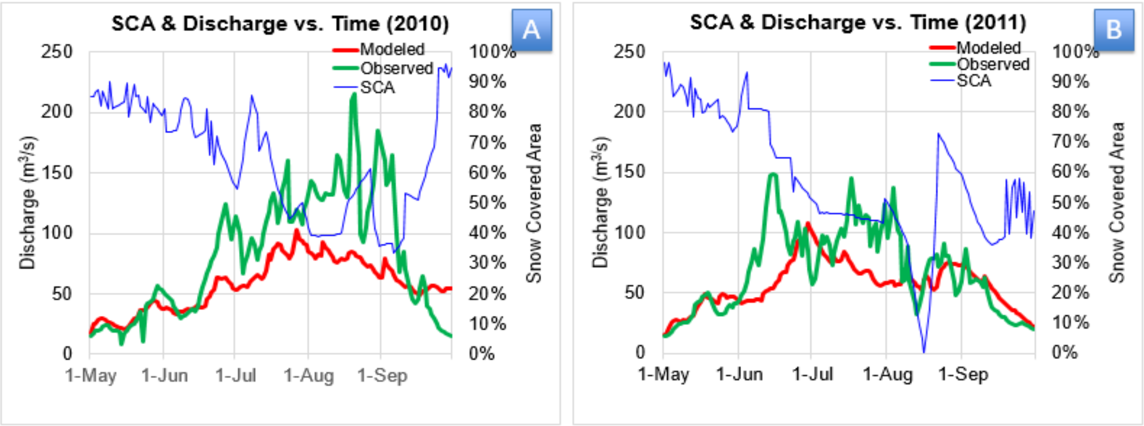

Figure 2. A) Time series of snow covered area (SCA) and stream discharge data from *in situ* observations and SRM modeled results for May to September 2010. B) May to September, 2011.

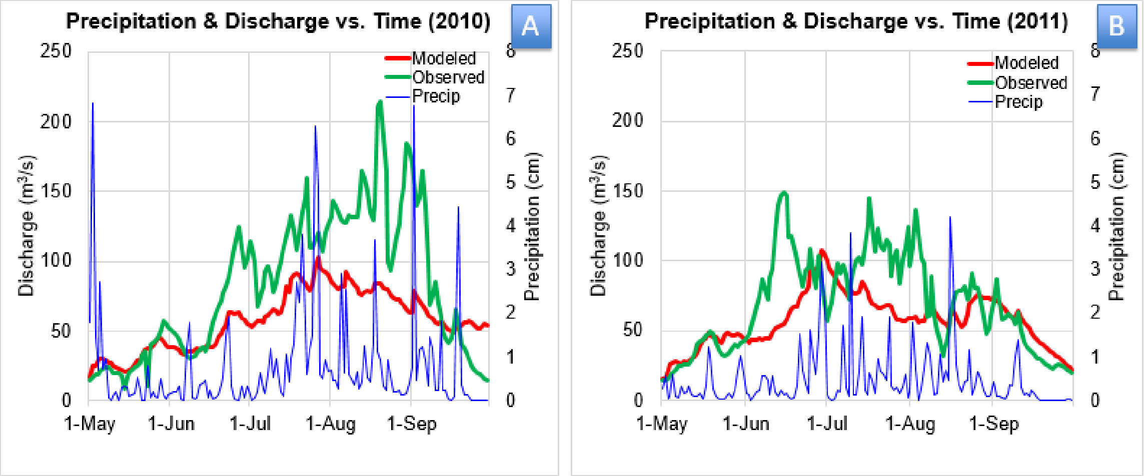

Figure 3. A) Time series of precipitation and stream discharge data from *in situ* observations and SRM modeled results for May to September 2010. B) May to September, 2011.

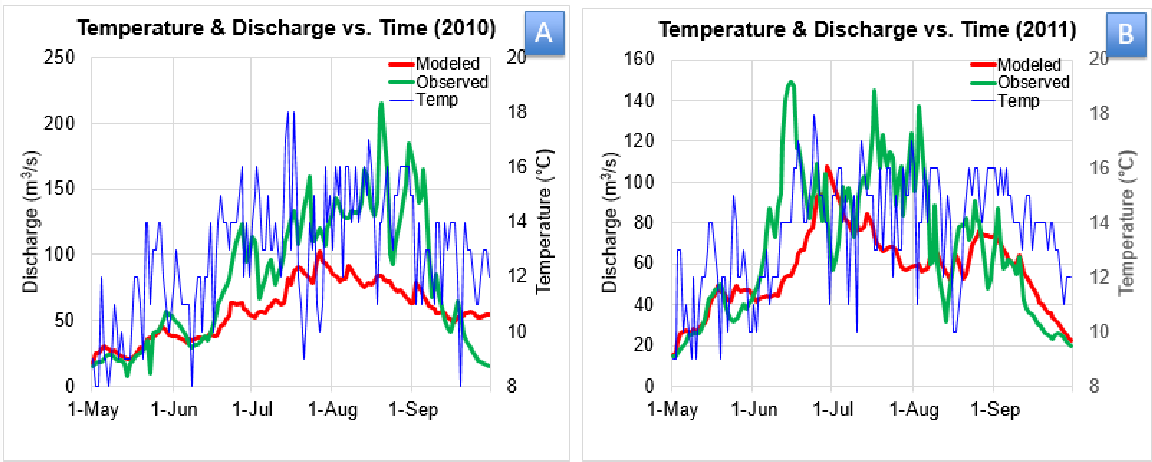

Figure 4. A) Time series of temperature and stream discharge data from *in situ* observations and SRM modeled results for May to September 2010. B) May to September, 2011.

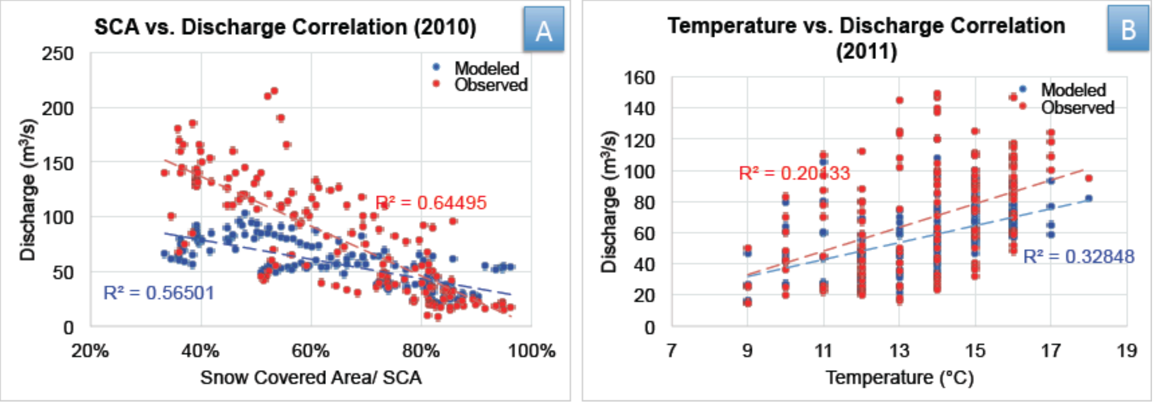

Figure 5. A) Correlation between snow-covered area (SCA) and stream discharge data from *in situ* observations and SRM modeled results for May to September 2010. B) Correlation between temperature and stream discharge data from in situ observations and SRM modeled results for May to September, 2011.

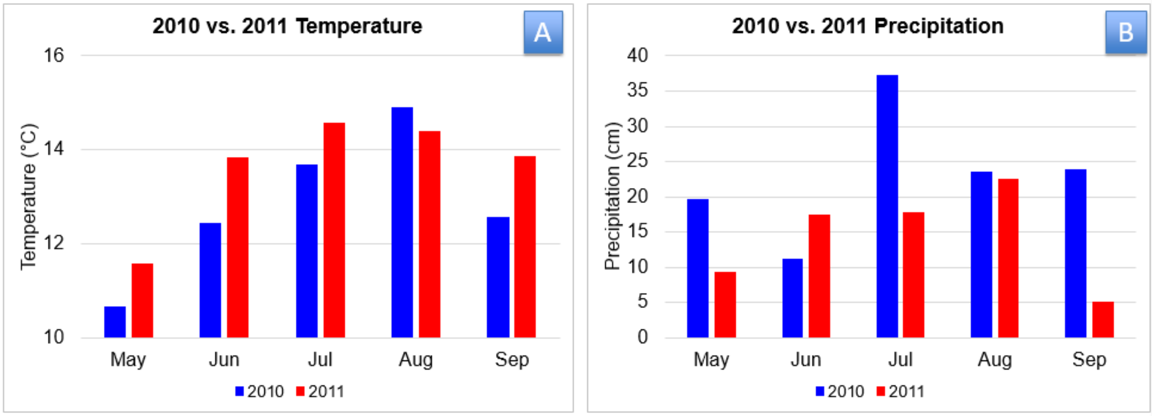

Figure 6. Comparison of mean monthly A) temperatures and B) precipitation from Gangotri weather station in 2010 and 2011.

Our modeled results underestimate the measured discharge in both 2010 and 2011, particularly at the end of the melt season, which corresponds with the onset of the Indian monsoon. In order to understand the discrepancies and improve future calibration of the snowmelt model, the three SRM parameters – namely SCA, precipitation and temperature – are plotted with measured (green), and modeled (red) discharge data in Fig 2-4 respectively.

The results show that of the three SRM parameters, SCA showed the strongest correlation with both observed and modeled discharge in 2010, with R^2 values of 0.64 and 0.56 respectively. In 2011, however, all three SRM parameters performed poorly with both observed and modeled discharge. The least worst parameter that year was temperature, with R^2 values of 0.20 and 0.33 for observed and modeled discharge respectively.

In June 2011, the SCA dropped rapidly from over 90% to less than 50% leading to a steep increase in observed discharge rose from 40 to 150 m^3/s (Fig 2B). In contrast, the SCA fell less from 80% to 60% in June 2010 and the observed discharge rose more modestly from 40 to 120 m^3/s. This was possibly caused by the higher temperatures in June 2011 than in June 2010. More snowmelt means reduced snow cover and increased discharge. As for modeled results, in June 2010, discharge rose slightly from 40 to 65 m^3/s but in June 2011, discharge rose sharply from 45 to 105 m^3/s. This is in general alignment with the rate of discharge increase in the two years, that is, the increase was sharper in 2011 than 2010.

However, later in the summer with onset of the monsoon season, precipitation takes on a more important role than temperature. In July 2010, the monthly precipitation was 37.2 cm, more than three times the amount of 11 cm in June 2010 (Fig 6B). Consequently, observed discharge rose from 67 to 160 m^3/s from July 4th to 23rd and eventually reached a peak of 215 m^3/s on Aug 20th (Fig 2A). In contrast, discharge topped out at 150 m^3/s on Jun 15, relatively early in the melt season of 2011 (Fig 2B), the year with higher temperature but lower rainfall due to a weaker than usual monsoon. Since the snow melted faster, the stream reached peak discharge earlier. But with less rainfall during the monsoon period, that early peak became the peak for the entire melt season of 2011.

Another insight we can draw from the observed discharge is the effect of monsoon precipitation. Temperature plays a bigger role in discharge earlier in the summer because of the greater snow cover. But as summer progresses and most of the snow melts away in the lower elevations, discharge would come predominantly from monsoon-enhanced rainfall instead of snowmelt. This insight can help us better calibrate snowmelt model for Himalayan basins in the future.

FUTURE WORK

We find that a simple SRM models the discharge from a small Himalayan basin rather poorly. Future model derivations will include parameters that the SRM does not currently account for. Most importantly, we need to account for snow depth. As the melt season progresses, the snowpack thins. However, this is not reflected in the current SCA methodology. Second, we need to consider Snow Water Equivalent (SWE), which is the measurement of the amount of water contained in a snowpack. Using an energy balance snowmelt model instead of a temperature index model like the SRM will incorporate the effects of a changing snowpack temperature and SWE, which impact the relationship between melt rate and air temperature. Third, the SRM only accounts for snowmelt, not glacier melt. At the end of the summer, glacier melt may contribute substantially to discharge and thus needs to be quantified. Finally, we need to consider the effect of solar radiation and terrain. The SRM assumes that no melting occurs below 0°C. However, from our experience, this is not true as snow can melt even below freezing. This is because meltwater can percolate into subfreezing snow and refreeze, releasing latent heat and warming the snowpack (Illangasekare, 1990). Eventually, the snowpack will be warmed to 0°C. As a result, air temperature is often an insufficient indicator of melting. Depending on topography, local temperature can vary greatly depending on the amount of direct solar radiation and shading.

REFERENCES

Arora, M., et al. 2014. Correlations of Stream Flow and Climatic Variables for a Large Glacierized Himalayan Basin. *Journal of Water Resource and Protection* **6**: 1326-1334.

Blaikie, P. and Muldavin, J. 2004. Upstream, downstream, China, India: the politics of environment in the Himalayan region. *Annals of the Association of American Geographers* **94**(3): 520-548.

Hall, D., et al. 2006. MODIS/Terra Snow Cover Daily L3 Global 500m Grid Version 5. National Snow and Ice Data Center, Boulder, CO.

Hall, D., et al. 2007. Accuracy assessment of the MODIS snow products. *Hydrological Processes* **21**: 1534-1547.

Illangasekare, T., et al. 1990. Modeling of meltwater infiltration in subfreezing snow. *Water Resources Research* **26**(5): 1001-1012.

Klein A. and Barnett A. 2003. Validation of daily MODIS snow maps of the Upper Rio Grande River Basin for the 2000-2001 snow year. *Remote Sensing of Environment* **86**: 162–176.

Lal, M., et al. 2001. Future climate change: Implications for Indian summer monsoon and its variability. *Current science* **81**(9): 1196-1207.

Martinec, J., et al. 2008. Snowmelt Runoff Model (SRM) User’s Manual.

Rees, W. 2012. Assessment of ASTER global digital elevation model data for Arctic research. *Polar Record* **48**(244): 31-39.

Singh, P., et al. 2007. Meteorological study for Gangotri glacier and its comparison with other high altitude meteorological stations in Central Himalayan region. *Nordic Hydrology* **38**(1): 59-77.

Singh, P., et al. 2008. Modelling and estimation of different components of streamflow for Gangotri Glacier basin, Himalayas. *Hydrological Sciences* **53**(2): 309-322.

Srivastava, D., et al. 2012. Status Report on Gangotri Glacier, Science and Engineering Research Board, Department of Science and Technology, New Delhi, Himalayan Glaciology Technical Report No.3.