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Snow and Glacier Melt Contribution in A Himalayan Basin

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Abstract : A major source of runoff and groundwater recharge in middle and higher latitudes are contributed through snowmelt from seasonal snow covered areas of the Earth's mountain region. All the major South-Asian rivers originate in the Himalayas and their upper catchments are covered with snow and glaciers. In the present study Beas basin up to Pandoh dam has been selected located in the Western Himalayan region. The runoff in Himalaya Rivers is generated from rainfall, snow and ice. The distribution of runoff produced from these sources is such that the streamflow may be observed in these rivers throughout the year, i.e. they are perennial in nature. The average contribution of snow and glacier melt runoff in the annual flows of the Beas River at Pandoh Dam has been determined.

INTRODUCTION

Snowmelt plays a major role in seasonal runoff patterns and water supply. The Indus, Ganga and Brahmaputra river systems, originating from the Himalayan region, receive substantial amounts of snowmelt water and are considered as the lifeline of the Indian sub-continent. Few scientific evaluation is available for Himalayan water resources, firstly, due to an insufficient network of observations for both precipitation and stream discharge measurements and secondly, Himalayan terrain being most rugged and inaccessible. Nevertheless, the available estimates show that the water yield from high Himalayan basins is roughly double that of an equivalent one located in Peninsular India. This is mainly due to inputs from snow and ice melt contributions. The perennial nature of Himalayan Rivers and the suitable topographic setting of the region provide a substantial exploitable hydropower potential in this region. Therefore, near real time estimation of snow cover is of utmost importance for effective management of water resources and can serve as a guideline for reservoir operations. Moreover, planning of new hydroelectric projects on the Himalayan Rivers emphasizes the need for reliable estimation of snow and glacier runoff.

The conversion of snow and ice into water is called snowmelt, which needs input of energy (heat). Hence the process of snowmelt is linked to the flow and storage of energy into and through the snowpack (USACE, 1998). Snowmelt models have two basic approaches towards calculating the amount of snowmelt occurring from a snowpack: energy budget method and temperature index method. The energy budget approach attempts to make the process as physically based as possible. The goal is to simulate all energy fluxes occurring within the snowpack to give an accurate account of total snowmelt in response to each of these energy fluxes over time and space. This approach is extremely data intensive, requiring vast amounts of input data either to force an initial run of a model, or to calibrate it based on historical data before running a forecast. Too often, this approach suffers from inadequate data supply or simply that the level of data is unwarranted for the purpose at hand. In light of the intensive data requirements necessary for the energy budget approach, an alternative method known as the temperature index or degree day approach allows for snowmelt calculation with much less data input. The basis of the temperature index approach is that there is a high correlation between snowmelt and air temperature due to the high correlation of air temperature with the energy balance components which make up the energy budget equation (Semádeni- Davies, 1997; Hock, 2003).

STUDY AREA

The Beas River is an important river of the Indus River system. The Beas basin up to Pandoh dam has been taken for the present study. Beas River originates from the eastern slopes of Rohtang pass of Himalayas at an elevation of 3900 m and flows in nearly north-south direction up to Larji, where it takes a nearly right angle turn and flows towards west up to the Pandoh dam. The length of the river up to the Pandoh dam is 116 km. The catchment of the Beas basin up to Pandoh dam is 5278 km^2 out of which, 780 km^2 is under permanent snow. Mostly the catchment area comprises of precipitation, slopes and the rocks are mainly bare. The altitude varies from 832 m near Pandoh to more than 5000 m near Beo-Toibba. Some of the major tributaries which join the Beas River upstream of Pandoh dam are: Parvati River near Bhuntar, Tirthan and Sainj rivers near Larji, Sabari nala near Kulu and Bakhli khad near Pandoh dam. All these rivers are perennial and the flow varies considerably during different months of the year. A major portion of the catchment lies under degraded forests and cultivated land and therefore the proportion of the silt and sand are of fine, medium and coarse configuration. Steep slopes are very common but are terraced at several places in the lower ranges up to an elevation of 1982 m for agricultural purposes.

DATA AVAILABILITY

The rainfall, maximum and minimum temperature and discharge data of Beas basin have been taken for different stations. The data was collected on daily basis for the whole year from BBMB, Sudernagar. The average temperature has been computed with this data

In this study, Terra/Aqua-MODIS satellite data have been used for SCA estimation. The Moderate Resolution Imaging Spectro-radiometer (MODIS) employed by Terra and Aqua satellites provides spatial snow covered data with 500 m spatial and daily temporal resolution. It delivers raster data in public domain. The MODIS snow cover product can be ordered free of charge through the Distributed Active Archive Center (DAAC) located at the National Snow and Ice Data Center (NSIDC). The MOD10A1 (MODIS / TERRA SNOW COVER DAILY L3 GLOBAL 500m SIN GRID V005) snow product with 500m spatial resolution was obtained for both the basins for the years of 2000-2005. This data was provided in a Hierarchical Data Format (HDF). This data was re-projected to convert from HDF format into an ERDAS compatible (.img) format for visualization.

The MOD10A2 product has two SDS, namely "Maximum_Snow_Extent" and "Eight _Day_Snow_Cover". The "Maximum_ Snow_Extent" depicts the period where snow was observed on one or more days in the period. The "Eight_Day_Snow_Cover" contains the information of the numbers of days in the eight-day period when snow was observed (Riggs et al., 2006). The present study uses the "Eight_Day_Snow_Cover". The MODIS data products are final output supplied to the user communities after applying all the corrections. Hence, no corrections were needed to be performed.

The MODIS Snow data products were in sinusoidal projection and WGS84 datum. This sinusoidal projection was re-projected to Geographic Lat/Long and WGS84 datum. All the MODIS data products were found to be very accurately geo-referenced.

The Shuttle Radar Topography Mission (SRTM) is an international project led by the U.S. National Geospatial-Intelligence Agency (NGA), U.S. National Aeronautics and Space Administration (NASA), the Italian Space Agency (ASI) and the German Aerospace Center (DLR).

SRTM obtained elevation data on a near-global scale to generate the most complete high resolution digital topographic database of Earth, including three resolution products of 1 km and 90 m resolutions for the world, and a 30 m resolution for the US. The elevation data used in this study is the 90 m resolution (3-arc SRTM), which consists of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. All SRTM data are freely available at: http:// seamless.usgs.gov/Website/ Seamless/. The SRTM-DEM was downloaded from the USGS ftp site. These data are presently supplied free of cost for scientific study. The data were supplied in GeoTIFF format. These DEMs were exported to the format as unsigned 32-bit data in ERDAS Imagine platform. Sometimes variation in pixel intensity (digital numbers) may be caused by differing sensitivities or malfunctioning of the detectors, topographic effects, or/and atmospheric effects. To correct such variations, radiometric calibration were carried out. The SRTM-DEM was already projected in Geographic lat/long and WGS84 datum. A digital elevation map showing the Beas basin up to Pandoh dam is given in Figure 1.

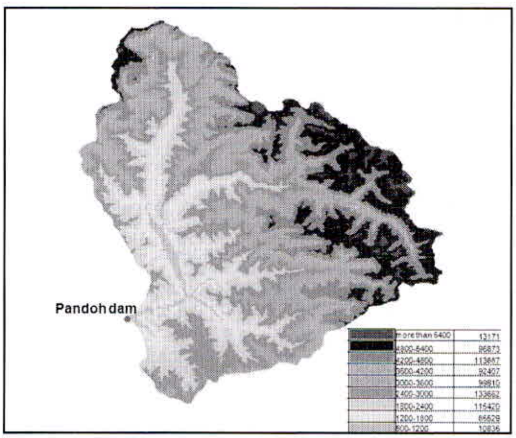

Fig. 1: Digital Elevation model of the Beas basin

METHODOLGY

There are several temperature index based snowmelt models like SNOWMOD, the SSARR Model, the HEC-1 and HEC-1F Models, the NWSRFS Model, the PRMS Model, the SRM, the GAWSER Model. In this study, snowmelt model (SNOWMOD) model (Jain, 2001, Singh and Jain, 2003) has been used for estimation of snowmelt runoff. This model is unique in this aspect as it simulates all components of runoff, i.e. snowmelt runoff, rainfall-induced runoff and base flow, using limited data. The SNOWMOD is a temperature index model, which is designed to simulate daily stream flow for mountainous basins having contribution from both snowmelt and rainfall. The generation of stream flow from such basins involves the determination of the input derived from snowmelt and rain, and its transformation into runoff. It is a semi-distributed model and for simulating the stream flow, the basin is divided into a number of elevation zones and various hydrological processes relevant to snowmelt and rainfall runoff are evaluated for each zone. The model achieves three operations at each time step. At first, the available meteorological data are extrapolated at different altitude zones. Then the rate of snowmelt is calculated at each time step. Finally, the snowmelt runoff from SCA and rainfall runoff from SFA (snow-free area) are integrated, and these components are routed separately with proper accounting of base flow to the outlet of the basin. The model optimizes the parameters used in routing of the snowmelt runoff and rainfall runoff. Details of computation of melt runoff and generation of stream flow from the basin are discussed below.

The stream flow from a snow fed river has three components namely,

- runoff from the snow-covered area,
- runoff from snow free-area and
- base flow

The runoff contributed from all the three components are computed separately for each elevation band and the output from all the bands are integrated to provide the total runoff from the basin.

Runoff contributed from snow-covered area consists of

- Snowmelt triggered by the increase in air temperature above melting temperature
- Under rainy conditions, melt caused by the heat transferred to the snow surface by the rain
- Runoff from the rain itself falling over snow covered area

The only source of surface runoff from snow-free area (SFA) is rainfall. The subsurface flow or baseflow represents the runoff from the unsaturated zone of the basin to the streamflow. After accounting for the direct surface runoff from snowmelt and rainfall, the remaining water contributes to the groundwater storage through infiltration and appears at the outlet of the basin with much delay as subsurface flow or baseflow. Depletion of this groundwater storage also results from evapo-transpiration and percolation of water to the deep groundwater zone. It is assumed that half of the water percolates down to shallow groundwater and contributes to baseflow, while the rest is accounted for by the loss from the basin in the from of evapo-transpiration and percolation to the deep groundwater aquifer, which may appear further downstream or become part of deep inactive groundwater storage. The daily total streamflow from the basin is calculated by adding the three different routed components of discharge for each day. As discussed above, the direct runoff results from overland or near surface flow, while baseflow is regarded as being a result of groundwater contribution into the stream. Infact, the contribution to baseflow starts only after the topsoil is saturated. In order to consider the soil moisture deficit, soil moisture index (SMI) has been considered in the present study.

In the present study, the Beas basin is divided into 9 elevation bands with an altitude difference of 600 m (Figure 1). Digital Elevation Model of the study area is used for the preparation of the area-elevation curve, shown in figure 2. The area covered in each elevation zone of the basin is given in Table 1.

Precipation and Temperature Data

For the present study, the daily precipitation data were available for four stations within the study area namely, Pandoh, Largi, Manali and Sainj as shown in Table 1. The rain gauge has been considered for different elevation zones (See table 1) based on its proximity to the respective elevation zones according to altitude of the station.

Snow Covered Area (SCA)

The MODIS Snow data products were in sinusoidal projection and WGS84 datum. This sinusoidal projection was re-projected to Geographic Lat/Long and WGS84 datum. All the MODIS data products were found to be very accurately geo-referenced with each other (Jain *et al.* 2008). However, it was observed that MODIS data products and SRTM-DEM are not accurately geo-referenced with respect to each other. All the MODIS images and SRTM-DEM were geo-referenced. As many as 32 Ground Control Points (GCPs) were selected in the image. The GCPs were spread throughout the image so that the rectification is more reliable. The Root

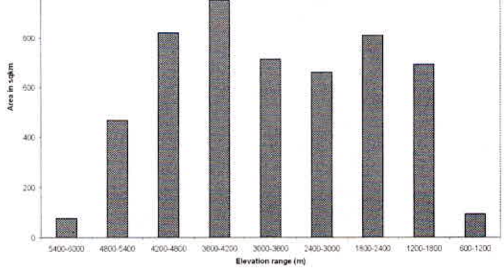

Fig. 2: Area elevation curve for the Beas basin.

Table 1: Beas basin area covered in different elevation band

Zones	Elevation range (m)	Area (km^2)	Percentage	Raingauge station	Temperature station
1	600-1200	77.34	1.46	Pandoh	Pandoh
2	1200-1800	467.56	8.84	Largi	Bhunter
3	1800-2400	823.90	15.57	Manali	Largi
4	2400-3000	954.12	18.03	Manali	Manali
5	3000-3600	713.2	13.47	Manali	Manali
6	3600-4200	659.63	12.46	Manali	Manali
7	4200-4800	811.53	15.33	Manali	Manali
8	4800-5400	691.51	13.06	Manali	Manali
9	>5400	94.10	1.78	Manali	Manali

Mean Square Error (RMSE) value was kept within a pixel (mostly 0.2). The next step was to convert the source coordinates to rectified coordinates. For this operation second-order, polynomial equation was used. The re-sampling was done using Nearest Neighbor method, which uses the value of the nearest pixel to assign to the output pixel value.

Snow exhibits high reflectance in visible band and strong absorption in SWIR (Short Wave Infrared) band. A spectral band ratio can enhance features, if there are differences in spectral slopes (e.g., Gupta *et al*, 2005). The Normalized Difference Snow Index (NDSI) uses these spectral characteristics of snow and is based on the concept of Normalized Difference Vegetation Index (NDVI) used in vegetation mapping from remote sensing data (Dozier, 1989: Hall *et al.*, 1995, Gupta *et al.*, 2005). The NDSI is defined as the difference of reflectance observed in a visible band and the short-wave infrared band divided by the sum of the two reflectance (Gupta *et al.*, 2005). The MODIS snow cover algorithm is based on the high reflectance of snow in the visible band (band 4, 0.545– 0.565 ìm) and low reflectance in the short wave infrared band (band 6, 1.628–1.652 ìm). These two bands are used to calculate the normalized difference snow index (NDSI) (Hall *et al.*, 1995).The equation is given below:

$$\text{NDSI} = \frac{\text{Visible Band} - \text{SWIR Band}}{\text{Visible Band} + \text{SWIR Band}}$$

Aqua/Terra-MODIS satellite data products are available from February 2000 till present date. The MODIS snow cover product is a classified image. For development of snow covered products, NDSI approach have been used to compute snow cover area. The images were further classified by clubbing snow and lake ice into snow category and rest of the classes into non-snow category. Thus all the images were classified into snow and non-snow category. Using the classified snow maps, the total percentage of snow cover in the study area was estimated for different dates. Further, for snowmelt runoff modeling, the SCA are required for different elevation zones. For this purpose, classified DEM and SCA maps have been processed for all the dates. The MODIS data is available from 2000 onwards, therefore, to have SCA for previous years; a method for preparation of depletion of SCA using mean air temperature has been applied. Because depletion of snow is a cumulative effect of climatic conditions in and around snow cover area, the cumulative mean air temperature (CMAT) at a nearby station should represent depletion of SCA. Using this relationship snow cover maps for the years from 1990-2002 have been generated.

The SCA in each elevation zones were plotted against the elapsed time to construct the SDC (Snow Depletion Curve) for the various elevation zones in the basin for all the years.

RESULTS

Stream flow from the study basin, basically has three components: runoff from snow covered area, runoff from snow free area and contribution from groundwater storage in terms of baseflow. The computation of runoff for each component was made for each elevation zone separately and then output from all the bands was integrated to provide the total runoff from the study basin.

The runoff from snow covered area consists of: (i) snowmelt caused due to temperature, (ii) under rainy conditions, snow melt due to heat transferred to the snow from rain, and (iii) runoff from rain itself falling over snow covered area. The source of surface runoff from the snow free area is rainfall. Like snowmelt runoff computations, runoff from snow free area was also computed for each band. The hydrological models are generally calibrated using observed and simulated results. The available data set is split into two parts; one is used for calibration purpose and the next for validation to check how affectively the model performs in simulation mode. In the present study, the Rosenbrock optimization technique was used for optimization of parameter values. The model was calibrated using a daily data set of a period of 3 years (2002-2005) for Beas basin.

The calibrated parameter values were computed considering the overall performance of the model and reproduction of the flow hydrograph. The model performance on a daily basis is commonly evaluated using the non-dimensional Nash-Sutcliffe 'R2'value (Nash and Sutcliffe, 1970). After successful calibration, the model was used for simulation for a period of twelve years 1990-1993, 1993-1996, 1996-1999 and 1999-2002 for Beas basin. The parameters estimates obtained in the calibration stage were used to simulate the runoff hydrograph for the period as mentioned above. It is observed that the volumes and peaks of streamflow were reproduced well by the model for all the years. The study shows that SNOWMOD, a temperature index based snowmelt runoff model, worked well in the study basin where limited data are available.

As discussed above the model simulate snowmelt runoff and rainfall runoff separately therefore contribution of each component to the seasonal and annual total streamflows has been calculated. The estimated contribution of snowmelt and rainfall to the abalation and annual flows is shown in Table 2 for Beas basin. The baseflow was separated into snowmelt and rainfall components using the contribution of these components to the baseflow. This study suggests that about 39% of the runoff during ablation period is generated from snowmelt runoff and the remaining 61% is from rain. The average contributions from snowmelt and rainfall to the annual runoff are estimated to be about 39% and 61%, respectively. In another study for this basin, Kumar et al. (2002) estimated the contribution of snowmelt and rainfall to the annual flows to be 35.1% and 64.9%, respectively, using the water balance approach.

CONCLUSIONS

In this study, the average contribution of snow and glacier melt runoff to the annual flows of the Beas basin at Pandoh dam site has been made. The analysis was made using the snowmelt runoff modelling. The average contribution of snow and glacier melt in the annual flow of Beas River at Pandoh was found to be about 39%, the remaining 61% being from rain. For all the sites upstream of Pandoh, the contribution of snowmelt runoff would be higher than 39 % due to higher percentage of snow-covered area in the total drainage area. The demand for water is at a peak during the summer period, when melting of seasonal snow occurs. Thus, the results of the present study also become very important for all the projects planned/under execution upstream of the Pandoh dam.

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REFERENCES

Davies, A. S., (1997), Monthly snowmelt modelling for large-scale climate change studies using the degree day approach, Ecological Modelling, Vol. 101, pp. 303-323.

Dozier J., (1989), Spectral signature of alpine snow cover from the Landsat Thematic Mapper, Remote Sensing of Environment 28, pp. 9–22.

Table 2 : Contribution of snowmelt and rainfall to the ablation and annual flows.

Season/annual	Rainfall runoff (%)		Snowmelt runoff (%)	
	Ablation	Annual	Ablation	Annual
1991	0.60	0.59	0.40	0.41
1992	0.68	0.67	0.32	0.33
1993	0.61	0.59	0.39	0.41
1994	0.55	0.53	0.45	0.47
1995	0.66	0.65	0.34	0.35
1996	0.62	0.61	0.38	0.39
1997	0.56	0.56	0.44	0.44
1998	0.64	0.64	0.36	0.36
1999	0.62	0.61	0.38	0.39
2000	0.64	0.63	0.36	0.37

Gupta R. P., Haritashya, U. K., and Singh, P., (2005), Mapping dry/wet snow cover in the Indian Himalayas using IRS multispectral images, Remote Sensing of Environment, Vol. 97, pp. 458-469.

Hall, D. K., Riggs, G. A. and Salomonson, V. V., (1995), Development of methods for mapping global snow cover using Moderate Resolution Imaging Spectrometer (MODIS) data. Remote Sensing of Environment, Vol. 4, pp. 127-140.

Hall, D. K., Riggs, G. A., and Salomonson, V. V., (2006), updated weekly. MODIS/Terra snow cover 8-day L3 global 500m grid V005, [January 01, 2001 to December 31, 2005 list the dates of the data used]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Hock, R., (2003). Temperature index melt modelling in mountain regions. *Journal of Hydrology* 282(1-4), 104-115. doi:10.1016/S0022-1694(03)00257-9.

Jain, S. K., (2001), Snowmelt runoff modeling and sedimentation studies in Satluj basin using remote sensing and GIS, PhD Theisis unpublished, University of Roorkee.

Jain, Sanjay K., Ajanata Goswami, A. K. Saraf, "Accuracy Assessment of MODIS, NOAA and IRS Data in Snow Cover Mapping Under Himalayan Condition", Vol. 29, No. 20, 10 October 2008, 5863-5878, International Journal of Remote Sensing.

Nash, J.E. and Sutcliffe, J.V., (1970), River flow forecasting through conceptual model, Part 1 a discussion of principles, Journal of Hydrology, Vol. 10, pp. 282-290.

Pandya, M. R., Singh, R. P., Murali, K. R., Babu, P. N., Kiran Kumar ,A. S., and Dadhwal, V. K., (2002), Bandpass solar exo-atmospheric irradiance and Rayleigh optical thickness of sensors onboard Indian Remote Sensing Satellites-1B, 1C, 1D, and P4; IEEE Transactions on Geoscience and Remote Sensing, Vol. 3, March 2002.

Singh, P. & Jain, S. K., (2003), Modelling of stream flow and its components for a large Himalayan basin with predominant snowmelt yields. Journal of Hydrological Sciences, 48 (2), 257-276

USACE, (1998), Engineering and Design Runoff from Snowmelt, available online at http://www.usace.army.mil/publications/eng-manuals/em1110-2-1406/toc.htm, (accessed on December 25, 2007).