SNOW AND GLACIER MELT SIMULATION FOR HYDROLOGY IN A TYPICAL HIMALAYAN WATERSHED

by

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CERTIFICATE

This is to certify that the thesis entitled ***Snow and Glacier Melt Simulation for Hydrology in a Typical Himalayan Watershed*** submitted by ***Mr Anand Verdhen*** to the Indian Institute of Technology Delhi, for the award of the Degree of Doctor of Philosophy, is a record of the original bonafide research work carried out by him under our guidance and supervision. The thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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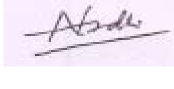

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ABSTRACT

The Himalayan watershed occupies a prime position among the water resources with naturally regulated contribution from snow and ice melt that makes its streams perennial. In spite of the great significance of the region, it lacks adequate observational network. Daily, weekly or monthly snowmelt flow in non-monsoon periods are critical for the livelihood and life of about a billion people living in the basin of the Himalayan rivers. The masses mainly depend on these rivers for water supply, irrigation, hydro-power and other water needs. The hydrology of the Himalyan rivers has been investigated extensively yet the snowmelt simulation deficiency still remains as a major issue as the existing literature indicates. Moreover, knowledge about spatiotemporal characteristics and variability of temperature, precipitation, snowpack, snow cover and snowmelt are essential to model the hydrological processes. The snow and glacier melt component analysis and simulation under varying climatic conditions could improve the predictability of snowmelt and runoff. This study is based on the observations from three snow-meteorological stations, viz., Bhang, Solang and Dhundi and discharge data from Palchan/Manali Bridge gauge station for the Beas watershed, and short term research expedition to Chhota Shigri glacier on Pir-Panjal range of the western Himalayas in Himachal Pradesh. The snowpack melt dominates the flow, after the second week of February, at the study data stations and it happens so in July at glaciers. Therefore, the springtime weekly, daily and seasonal data were analyzed to develop the physical relations and models for the ablating snow cover.

The Temperature Lapse Rate (*TLR*) is an important parameter that is a critical part for the spatial projection of temperature, which has been determined from linear

regression relation of seasonal and springtime weekly maximum, minimum, mean and mixed temperatures. Surprisingly, the *TLR* for the lower section BS (Bhang to Solang) lies between 0.6 and 1.9 °C/100 m. That means it goes up to nearly twice the adiabatic *TLR*. But the *TLR* in section BD (Bhang to Dhundi) is found to lie between 0.34 and 1.28 °C/100 m whereas in section SD (Solang to Dhundi) it remains normal (i.e. between 0.10 and 0.92 °C/100 m). The stratified *TLR* methodology has been used to identify a value 0.575 °C/100 m through simulation for the temperature projection on the base mean temperature up to 12 °C, while a value of 0.64 °C/100 m has been determined for the base mean temperature above 12 °C. The average error, range of the error and standard error of the estimates are -0.06, ±3.5 and 1.8 °C, respectively. The seasonal data indicate rise in T_{max} by 0.1 ^{o}C/yr. On the whole, the inter-station and inter-annual cross-relation signifies a rate of rise in T_{min} of the order of 0.0027 ^{o}C/100 m/yr only. However, the measurement accuracy in temperature is up to two decimal places.

Other important variables viz., weekly rainfall, precipitation (snowfall and rainfall), snowfall and snow depth have been analyzed with respect to air temperatures of Bhang to obtain spatial relations and inter-annual variability. The degree-day melt in water equivalent varies between 2 and 11.5 mm $°C^{-1}$ d^{-1} though it may rise up to 13 mm $°C^{-1}$ d^{-1} for non-zero snow condition. Temperature, snowfall, rainfall and snow depth correction per 100 m of rise in elevation have been estimated as -1.09 °C, 31.2 cm, -7.72 mm and 27.95 cm, respectively. The critical temperatures for snowfall, rainfall and equilibrium conditions have been determined. The snowfall and rainfall mixed precipitation occurs within 0.65 and 11.5 °C of weekly mean temperature for which distribution pattern has been developed. This snowmelt factor is temperature dependent so radiation based PRMS algorithm has been applied to simulate snowpack melt in three seasons at a gap of two and half decades. It has partly impacted climate variability by reducing condensation-convection component of the energy balance.

Now the most important part of the snowmelt algorithm is snowline altitude and snow cover area. The latest technology and remote sensing techniques are employed to capture this information online, but the result and dependability are however limited for the operational hydrological models. Therefore, in this study, temperature and lapse rate dependent Varying Catchment Part (VCP) has been identified through the movement of its mean Saturated Snowline Altitude (SLA). It is then coupled with a monthly simulation model albeit the Applied Basic Oscillation (ABO) of the snowline. The VCP universal parameters, *TLR* of 0.554 °C/100 m and saturated snowline mean air temperature of 5.75 °C, were designed to estimate *SLA* using weekly mean temperature and ablating snowpack at and around Solang (2485 m altitude). The VCP model for SLA uses a nomogram at Solang while the ABO application extended to produce monthly snowline and Equilibrium Line Altitude (ELA). Its inter-annual/decadal variability gives a rate of rise in ELA of 11 m/yr, which is a possible signature of climate change in the region. The Snow Cover Area (SCA) has been determined through SLA, but the distributed hydrological model works with zonal SCA depletion curves. Therefore, combining the decay and Mathieu function formulations, the simulated parameters have been determined to evaluate zonal SCA depletion with depleting snow depth at base station. However, for SCA depletion in higher altitude zones, snow depth has to be augmented with proxy data.

Further, the actual snowmelt simulation has been used in order to formulate a better algorithm (temperature index, energy balance or mixed) irrespective of data constraints. Yet, simulation deficiency could not be resolved in case of above normal wind speeds. The algorithms in different watershed models for point snowmelt successfully simulate observed snowpack ablation (R^2 up to 0.7 to 0.97) on weekly data. On the basis of performance criteria, the PRMS model results agree well with the full Energy Balance (EB) scheme on daily basis data, though SSARR is good on weekly basis. Finally, physical process based simple nomogram on temperature index has been developed in this thesis and it has been found that average condition nomogram is best suited for the varying climatic conditions. The glacier melt simulation needs more data than what is presently available. Although the relation between glacier melt and temperature may still be nonlinear yet the linear nomogram could be applicable for the temperature limits of 0.0 to 11.5 ^{o}C or more than 50% of snow cover area. The rest of the snow-free area is good for the rainfall-runoff model, which is beyond the scope of this study. Further, the performance of the nomogram has been compared with Martinec's SRM and HEC-HMS models by distributing the Beas basin (down to Manali Bridge) in three zones. The analysis of observed discharge data at Manali bridge and Palchan show reduced annual discharge and increased springtime discharge. The calibrated models have also been used to compute the variation in discharge for a unit degree rise in temperature.

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