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Role of Snow and Glacier Melt Runoff Modelling in Hydropower Projects in the Himalayan Region

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ABSTRACT: At present the installed capacity of Indian hydropower projects is about 35900 MW, which represents 25% of the total installed capacity of India (1,43,000 MW). The share of hydropower generated in the Himalayan region is about 80% of the total hydropower generated in India. The huge hydropower potential in the Himalayan region is due to the availability of water and appropriate head in the Himalayan basins. The Government of India is seriously concerned with accelerating the pace of hydropower development to accomplish exploitation of the balance of the hydropower installable capacity (about 1,00,000 MW) in a reasonable time frame. The runoff generated from the melting of snow and glaciers plays a vital role on the perennial rivers of the Himalayas and ensures the continuous availability of streamflow for hydropower projects. Rainfall contribution during the monsoon period is critical for storages in various reservoirs. The snow and glacier melt runoff is considered as highly dependable flow and used for irrigation, drinking water and generating hydropower particularly during summer period, when demand is at peak for power and irrigation. This paper presents the estimated contribution of snow and glaciers in the Himalayan rivers. It has been demonstrated that glaciers act as natural frozen reservoirs in the upper part of the basin and provide flows in a regulated manner for the operation of base load and peaking hydropower projects. This paper describes a modelling approach for snow and glacier fed basins and demonstrates its various applications for hydropower projects in Himalayan catchments including planning, design, operation and management of projects.

INTRODUCTION

The Himalayan mountain system is the source of one of the world's largest supplies of freshwater. All the major river systems in south Asia originate in the Himalayas. The presence of snow and glaciers in the upper part of the Himalayan basins form a unique reservoir of fresh water supporting rivers such as the Indus, Ganga and Brahmaputra, which are the lifeline of millions of people. The water flowing in these Himalayan rivers is a combined flow from rain, snow and glaciers. Snow and glacier runoff plays a vital role in making all these rivers perennial, whereas the rainfall contribution during monsoon period is critical for storages in various reservoirs. The summer and spring runoff, comprising mostly of snow melt and glacier melt is a source of water for irrigation, hydroelectric power production and drinking water supply. Melt water replenishes stock ponds, infiltrates the soils, and recharges the ground water. The runoff generated from the ground water storage becomes important during the lean season. The water yield of a high Himalayan basin is roughly double that from an equivalent basin area located in the Peninsular part of India. This higher water yield is mainly due to the large inputs from the snow and glaciers.

There are about 9575 glaciers in the Indian territory, occupying about 38,000 km^2 area of the Himalayas, which is about 9% of the Himalayan area. Existence of snow and glacier fields in the Himalayas is mainly because of their ultra high altitudes, which compensates for such a large glaciation extent at low latitudes. The concentration of glaciers is higher in the western Himalayas than the eastern Himalayas. Himalayas contain the largest number of glaciers in the world outside the Polar circles. The glaciation in the Himalayas is found to be more intense than the Alps and Rockies. The Himalayan glaciers have a large variation in their size. There is a lack of data and information on glaciers in India, mainly due to lack of comprehensive studies. It has resulted in poor long-term data availability regarding Himalayan glaciers as well as regarding runoff being generated from glaciers.

Glaciers are considered to be very sensitive to the climatic conditions. Retreat of glaciers and its impact on water resources is one of the current issues being debated for more than two decades. There is evidence that glaciers have retreated globally during the last century. At present deglaciation is considered to be a world-wide problem including the Himalayan region. Glaciers also preserve climatic signatures, which can be used to reconstruct past climatic records. Records available for the Himalayan glaciers also suggest retreat of glaciers.

STATUS OF HYDROPOWER DEVELOPMENT AND SUITABILITY OF HIMALAYAN RIVERS FOR HYDROPOWER GENERATION

India is endowed with economically exploitable hydropower potential in the order of 1,48,000 MW, of which only 35900 MW have been developed. Table 1 shows region wise recent generating installed capacity (MW) by generation type for different regions of India. It can be noted that on the country scale it can be seen that hydro makes up 25% of total installed capacity.

In the Himalayan region, favourable geographical location and appropriate topographical setting provide excellent conditions for hydropower development. Melting of snow and glaciers ensures the continuous availability of streamflow which in combination with appropriate head because of the topography in the mountainous areas provide a huge potential for hydropower generation. Therefore, states like Himachal Pradesh and Uttarakhand have very high hydropower potential which remains largely undeveloped. For example, Himachal Pradesh and Uttarakhand have potential of installed capacity of the order of about 19,000 and 18,000 MW respectively and they have developed about 6,100 (32%) and 3,100 MW(17%) to date. It clearly shows that the potential of hydropower generation, in Himalayas, is not exploited to the extent that it could be. There is great scope to exploit the hydropower by commissioning hydropower plants both on a large scale as well as on small scale. The hydropower initiative launched in May 2003 by the Govt. of India for an unprecedented 50,000 MW development of hydropower was the first of its kind in the country. Timely execution and completion of this initiative will depend upon prompt resolution of problems inherent and likely to be faced in hydro development. The ambitious capacity addition program for 11th Plan (2007–2012) for the country is given Table 2. It can be noted that Central, State and Private developers have to share this challenging task of adding new installed capacity in different power sectors.

Table 1: The Status of Regional Wise Installed Capacity (MW) as on 30.4.2008

Sl. No.	*Region*	*Thermal*	*Nuclear*	*Hydro (Renewable)*	*RES (MNRE)*	*Total*
1.	Northern	22436	1180	12975	1288	37879
2.	Western	31121	1840	7199	3131	43290
3.	Southern	21208	1100	10685	6350	39344
4.	Eastern	16354	0	3934	204	20491
5.	N. Eastern	969	0	1116	146	2231
6.	Island	70	0	0	6	76
	All India	92157	4120	35909	11125	143311

Source: Ministry of Power, Govt. of India.
RES- Renewable Energy Source includes Small Hydro Projects (SHP), Biomass Gas (BG), wind energy etc
MNRE- Ministry of New and Renewable Energy.

Table 2: Installed Capacity Addition (MW) Program for 11th Plan (2007–2012)

Type /sector	*Central*	*State*	*Private*	*Total*
Thermal	26800	24347	7497	58644
Hydro	9685	3605	3263	16553
Nuclear	3380	0	0	3380
Total	39865	27952	10760	78577

Source: Ministry of Power, Govt. of India.

STREAMFLOW CHARACTERISTICS OF HIMALAYAN RIVERS

The precipitation falling as snow during the winter period accumulates in the basin, and snowpack develops. The spatial distribution of runoff for the Himalayan basins shows that contribution from rain dominates in the lower part of the basins (< 2000 m). Heavy rainfall during the monsoon season contributes represents about 70% of total annual rainfall in these areas. The middle and upper parts of the basins (> 2000 m) have contribution from both rain and snowmelt and their contribution changes with altitude. As the elevation of the basin increases, the contribution from rain reduces, but snow melt contribution increases. Runoff is dominated by the snow melt runoff above 3000 m altitude. Runoff is dominated by the glacier melt for all the upper parts of the basin above 4000 m altitude. In general, snow melt during spring (March–April) provides a high proportion of the runoff. Hydrological observations carried out for the glacierized basins in the Himalayan region indicate that melting of the glaciers takes place from May to October and maximum runoff from these basins is received during July and August (Singh *et al.*, 2006). Studies indicate that maximum rainfall in the Himalayan basins takes place around 1500 m on the windward slopes of the mountains (Singh *et al.*, 1995; Singh and Kumar, 1997).

BASIN WISE DISTRIBUTION OF GLACIERS

The melt contribution in the snow and glacier fed rivers is primarily controlled by climatic conditions and the extent of basin covered by snow and glaciers. The extent of basin's glaciated area provides a higher confidence in yielding dependable river flows. A basin-wise inventory of glaciers for few selected basins is shown in Table 3. The Baspa river (a tributary of Satluj river) and Bhagirathi river have a large extent of glaciers in their basins providing a potential source of melt water runoff. The large variation in area covered by glaciers in different tributaries of the rivers is possible due to difference in orientation and precipitation pattern over the area. It is expected that during the last glacial cycle, the aggregate area occupied by glaciers, in the Himalayas, must have been much larger and the glaciers must have extended to lower altitudes as compared to their position today.

Table 3: Basin-Wise Details of Glacier Inventory of some Basins in the Himalayan Region

Basin	*Sub-Basin*	*Basin Area (km^2)*	*No. of Glaciers*	*Glacierised Area (km^2)*	*Glacierised Area (%)*	*Total Ice Volume (km^3)*
Jhelum	Shaliganga-Sookhnag	1516	5	1.8	0.12	0.02
	Sind	1142	57	39.9	3.50	1.40
	Vishav-Rembiara	1579	23	13.5	0.86	0.39
	Liddar	1283	48	38.9	3.04	1.49
Satluj	Baspa	1100	89	238.7	21.70	15.30
	Tirung	916	60	135.4	14.78	6.40
	Tagla-gyamthing	187	27	19.2	10.26	0.58
	Ropa	628	48	27.3	4.35	0.71
Bhagirathi	Bhilangna	1700	13	88.2	5.19	4.95
	Pilang	1335	23	48.5	3.63	2.96
	Jalandhri	694	64	104.9	15.13	4.65
	Jahnvi Ganga	1440	60	136.2	9.46	7.96
	Bhagirathi Ganga	1015	78	377.5	37.21	46.50
Tista	East Rathong	2351	36	58.4	2.49	3.02
	Talung	1271	61	142.9	11.25	8.65
	Changme Khangpu	1159	102	144.4	12.46	7.69
	Zemu	2392	250	359.9	15.05	20.25
Brahmaputra (Partially)	Manas	2194	4	1.5	0.07	0.02
	Kameng	12585	52	65.8	0.52	2.82
	Subansiri	8500	91	145.5	1.71	6.82
	Dibang	4725	14	10.7	0.23	0.30

Source: Geological Survey of India, 1999.

CONTRIBUTION OF SNOW AND GLACIERS IN WATER RESOURCES

Estimation of the snow and glacier contribution in the annual runoff of various Himalayan rivers is necessary for the development and efficient management of water resources, which includes flood forecasting, reservoir operation, design of hydraulic structures etc. The planning of new multi-purpose projects on the Himalayan rivers further emphasizes the need for reliable estimates of snow and glacier runoff. Despite their well recognized importance and potential, not many attempts have been made to assess the snow and glacier contributions in these rivers, although a few hydrological studies have been carried out for glacierized river basins in the western Himalayan region.

From the few studies that have been carried out to estimate snow and glacier contribution for Himalayan rivers, the following Table 4 presents snow and glacier contributions to annual flows at the gauging sites in the foothills of the Himalayas along with maximum and minimum snow covered area. These results show substantial contribution from snow melt runoff to the annual streamflows of the Himalayan rivers, which attributes to high water yield from the Himalayan river basins. It is to be noted that contribution of snow and glaciers will be higher for the hydroelectric project sites located in the upstream of the sites shown in this Table 4.

GLACIERS AS THE SOURCE OF REGULATED WATER SUPPLY

The run-of-the-river hydropower schemes, by their nature, do not have large, long term regulated storage. At the most, the water is stored for a few hours. In other words, for such schemes the generation of power is highly dependent on only the runoff available on that particular day. The runoff from snow and glacier covered basins is mostly temperature controlled and behaves similarly to regulated flow from a water storage. A good estimation of runoff from such basins is very useful for the operation of run-of-the-river hydro projects. Snow and ice storage works as a natural frozen reservoir in the basin, which gradually releases the flow.

During the summer period, in the glacier fed streams only a portion of the melt water produced each day emerges as runoff from the snout of the glacier on the same day. The remaining melt water is stored within the glacier. Thus a considerable contribution to streamflow is received from the melt water stored in the glacier. Even at diurnal cycle, the runoff also contains a part of this stored melt water. This shows that the streamflow of a glacier fed stream is controlled by storage characteristics of the glacier and determined by delayed response of the basin. The size of the glacier, extent of snow cover, depth of snow over the glacier and drainage network of the glacier are important factors which control the flow rate and volume of the water emerging as runoff. The discharge time response is also a function of the ablation and accumulation area ratio. Runoff dominated by melt water from the accumulation area has a longer time of concentration as compared to the melt water generated in the ablation area.

The melt water storage characteristics of two glaciers have been studied using continuous hourly discharge data. Daily (24 hours) streamflow records have been sub-divided into day time flow (0900–2000 hours) and night time flow (2100–0800 hours). Monthly day time and night time discharges for summer months for Dokriani Glacier and Gangotri Glacier are shown in Figures 1 and 2 respectively. The magnitude of the streamflow during day time and night time indicates that the volume of the night time flow is comparable with the day time flow. Such trends of the day time and night time flows are observed for all the years.

Table 4: Snow and Glacier Melt Contributions in Some Himalayan Rivers

River Basin	*Catchment Area (km^2)*	*Snow Cover Area (km^2)*		*Snow and Glacier Contribution in Annual Flows (%)*	*Sources*
		Max.	*Min.*		
Ganga (up to Deoprayag)	19700	9080 (40.9%)	3800 (19.3%)	29%	Singh *et al.* (1993)
Chenab (up to Akhnoor)	22200	15590 (70.2%)	5400 (24.3%)	49%	Singh *et al.* (1997)
Satluj (up to Bhakra Dam, Indian Part)	22305	14498 (65.0%)	4528 (20.3%)	60%	Singh and Jain (2002)
Beas (up to Pandoh Dam)	5278	2375 (45%)	780 (15%)	35%	Kumar *et al.* (2007)

As such, very little or no melting takes place on the glacier surface during the night period, but still a high amount of discharge is observed in the stream during the night time. It shows that melt water produced during the day time is partly stored in the glacier and released later, while such trends in the rain fed rivers do not exist. This analysis suggests that melt water storage characteristics of the glacier are much stronger in the early part of the melt season and reduces as the melt season develops. Trends of variations in the ratio of day time flow to night time flow with melt season can be explained on the basis of availability of snow cover on the glacier body and progressive development of the drainage network in the glacier. The greater extent of snow cover in the early part of the melt season along with a poorly developed drainage network amounts to a more delayed response of the melt water from the basin to the outlet, resulting in reduced difference between day time and night time streamflows. Reduction in the extent of snow cover area and progressive development of a drainage network with melt season also attribute to a faster response of melt water in mid or late melt season, which also increases the difference in the day time and night time flows.

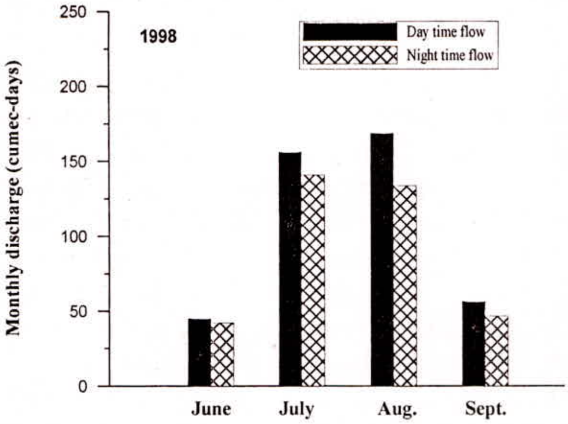

Fig. 1: Monthly distribution of day time and night time observed discharge near the snout of Dokriani Glacier (Uttarakhand) for summer 1998

The peaking power plants are generally run only when there is a high demand, known as peak demand, for electricity, whereas base load power plants operate continuously and are stopped only for maintenance or unexpected outages. The time of peak demand varies from region to region. In India, generally, peak hours correspond to morning hours (0600–0900 hours) and the evening hours (1800–2100 hours). Hydropower stations including pumped storage schemes are ideally suited for meeting peaking power requirements due to their inherent ability of almost instantaneous starting, stopping and load pickup. Their quick reaction time enables them to respond swiftly to sudden changes in consumer demand and emergencies. They also lend themselves to automation and can be operated by remote control. The regulated water supply provided by the snow and glaciers is very helpful in operation of both peaking and base load hydropower schemes.

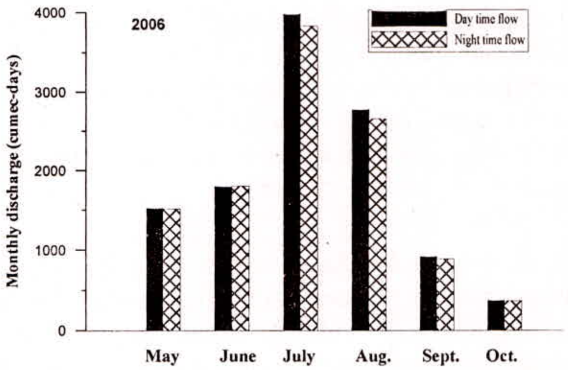

Fig 2: Monthly distribution of day time and night time observed discharge near the snout of Gangotri Glacier (Uttarakhand) for summer 2006

MODELLING OF MELT RUNOFF AND ITS APPLICATIONS

Efficient management of water resources including water availability, flood forecasting, reservoir operation and design of hydraulic and hydrologic structures requires best estimates of available resources. Keeping in view the importance of water generated from snow and glaciers in Himalayan rivers, the modelling of melt runoff becomes an important tool for various applications such as:

1. Forecasting of the volume of water to be released from snow and glaciers
2. Simulation/forecasting of streamflow including floods caused by high intensity rainfall, combination of rainfall and intense melting, and Glacier–Lake Outbursts (GLOF).
3. Better estimates of water availability and design flood for the planning and designing of hydropower projects on snow and glacier-fed rivers
4. Simulation of continuous supply of melt water for the ground water reservoirs and in turn contribution of ground water as base flow during the lean season for operation of hydropower projects.
5. Impact assessment of climate change on different hydrological variables.

The above mentioned aspects for the water resources and hydropower projects can be understood better using a modeling approach for snow and glacier fed river basins. The present status of modelling of snow and glacier melt runoff in India shows limited work has been carried out. Singh and Jain (2003) developed a conceptual Snow Melt Model (SNOWMOD), which accounts for both the snow melt and rainfall runoff, and applied this for streamflow simulation for several Himalayan rivers such as Beas river, Satluj River, Chenab river, and the upper part of Ganga river. The area of basins varied from 15–23,000 km^2 (Singh and Jain, 2003, Singh *et al*., 2006; Singh *et al*, 2008).

The model is designed primarily for mountainous basins and conceptualises the basin as a number of elevation zones depending upon the topographic relief of the mountainous basin. The basic inputs to the model are temperature, precipitation and snow covered area. The snow melt is computed using a degree-day approach and rain induced melting is also considered. For perennial rivers, like the Himalayan rivers, base flow is an important part of streamflow. During winter the major contribution to streamflow is from the base flow. Therefore, simulation of base flow also becomes essential when the streamflow is simulated for the whole year. In addition to the simulation of direct snow melt and rainfall runoff, the model also simulates base flow and a sum of these three components provides the total streamflow from the basin. The hydrological response of the water from Snow Covered Area (SCA) and Snow Free Area (SFA) is different and depends on their respective areal extents. Moreover, as both SFA and SCA change with time their hydrological response also changes with time. Such variations in hydrological response were accounted for by routing each component of runoff separately and considering the storage coefficients of snowmelt and rainfall as the function of effective SCA and SFA, respectively. The storage coefficient for the base flow routing was determined using the streamflow records of the recession period. Soil moisture index accounts for soil moisture deficit in the beginning of the simulation period.

The application of SNOWMOD for the assessment of the impact of climate change on Himalayan rivers has also been studied (Singh and Bengtsson, 2004, 2005; Singh *et al*., 2006).

RESULTS AND DISCUSSIONS

The importance of snow and glaciers, and their contribution to the streamflow of Himalayan rivers has been presented with a focus on planning and designing of hydropower projects. Snow and glaciers provide maximum water in Himalayan rivers when the demand for water for various uses is at its maximum for irrigation, hydropower and drinking water supply. Gradual increase in flow with advancement of summer, that too in a regulated manner, helps in hydropower generation both for base load and peaking power projects. The status of studies being carried out in the country shows that there is a need for a better understanding of snow and glacier melt processes as well as modelling of streamflow for Himalayan rivers. Such improvements will lead to better designing and operation of hydropower projects as well as in assessing the impact of expected climate change on water resources and hydropower projects. .

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