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The role of glaciers in stream flow from the Nepal Himalaya

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Abstract

Recent concerns related to the potential impacts of the retreat of Himalayan glaciers on the hydrology of rivers originating in the catchment basins of the Himalaya have been accompanied by few analyses describing the role of glaciers in the hydrologic regime of these mountains. This is, at least in part, a result of the relative inaccessibility of the glaciers of the Himalaya, at altitudes generally between 4000–7000 m, and the extreme logistical difficulties of: 1) reaching the glaciers, and 2) conducting meaningful research once they have been reached. It is apparent that an alternative to traditional "Alpine" glaciology is required in the mountains of the Hindu Kush-Himalaya region. The objectives of the study discussed here have been to develop methodologies that will begin to quantify the role of complete glacier systems in the hydrologic regime of the Nepal Himalaya, and to develop estimates of the potential impact of a continued retreat of these glacier, based on the use of disaggregated low-altitude data bases, topography derived from satellite imagery, and simple process models of water and energy exchange in mountain regions.

While the extent of mesoscale variability has not been established by studies to date, it is clear that the dominant control on the hydrologic regime of the tributaries to the Ganges Basin from the eastern Himalaya is the interaction between the summer monsoon and the 8000 m of topographic relief represented by the Himalayan wall. All the available evidence indicates that the gradient of specific runoff with altitude resulting from this interaction is moderately to strongly curvilinear, with maximum runoff occurring at mid-altitudes, and minima at the altitudinal extremes. At the upper minimum of this gradient, Himalayan glaciers exist in what has been characterized as an "arctic desert".

The methodologies developed for this study involve the relationship between area-altitude distributions of catchment basins and glaciers, based on Shuttle Radar Topography Mission (SRTM3) data and water and energy exchange gradients. Based on these methodologies, it is estimated that the contribution of glacier annual melt water

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to annual stream flow into the Ganges Basin from the glacierized catchments of the Nepal Himalaya represents approximately 4% of the total annual stream flow volume of the rivers of Nepal, and thus, is a minor component of the annual flow of the Ganges River. The models developed for this study indicate that neither stream flow timing nor volume of the rivers flowing into the Ganges Basin from Nepal will be affected materially by a continued retreat of the glaciers of the Nepal Himalaya.

1 Introduction

The view that a significant volume of the annual flow of the Ganges River, and its principal tributaries in the Indian and Nepal portions of the Himalaya, may be derived from the melting of the glaciers of these mountains appears to be widespread. If correct, this perception has major implications for water resources supply and demand management, and for water resources development projects in south and central Asia. It is a basic premise of this study that realistic assessments of the future availability of water resources in the Himalaya region as a result of glacier retreat are not possible until the existing hydrologic regime of these mountains is better defined, the current relationship between glaciers and streamflow evaluated in at least semi-quantitative terms, and the contribution of other sources of streamflow formation examined. This report presents a description of area-altitude distributed process models developed for the study, and the most salient results of assessments of the general hydrometeorological environment of mountain catchment basins of the Nepal Himalaya and of the contribution of glaciers to streamflow formation in these basins (Alford, et al., 2009). The results obtained from these methodologies are area-altitude volumes of basin runoff and glacier ice melt.

This paper presents an assessment of the role of glaciers in the rivers of the Nepal Himalaya, based on data drawn from published sources describing the hydrometeorological and topographic environments of these mountains. Of necessity, many of these data are from low altitude sites. A principal effort has been to develop distributed process approaches to the analysis of these data, to begin development of a disaggregated data base describing the altitudinal gradients in the interactions between the glaciers and rivers of Nepal. While the subject of this paper is the role of glaciers in the hydrologic regime of the rivers draining the Nepal Himalaya, it is not, strictly speaking, a paper about Himalayan glaciology. It is, rather, an attempt to apply the concepts defining the unity of the catchment basin (e.g., Ward, 1975), to include the problems presented by the accumulation and melting of snow and glacier ice. While considerable enthusiasm is currently being expressed for expanded programs of traditional glaciological studies by governments and organizations in countries of the Himalayan region, it could be years before many of these programs begin producing useful information. In the meantime, it is possible that studies such as that described here, using existing data bases, improved topography derived from satellite imagery and simple process models, can begin to fill in the many gaps that are found in the existing understanding of the water resources, and glaciers, of the Himalaya.

This report does not deal directly with questions related to the physical interactions involved in glacier response to climate change and global warming. The complexities of mass and energy exchange in a glacier environment, and ice dynamics as it relates to the flow of ice from an area of accumulation to an area of melt are recognized, but not evaluated with the precision that might be possible from detailed mass balance studies. An attempt has been made to select values from the literature for the mass balance processes that are consistent with the spatial scale of the study. The work of Konz, et al. (2005) was particularly useful in this respect. Values used to describe the steady-state equilibrium line altitude, ELA, and ablation gradient are considered generally representative of the Nepal Himalaya, but may vary with location in these mountains, and will certainly do so within the Hindu Kush-Himalaya region.

2 Procedure

The Nepal Himalaya are characterized by a complex three-dimensional mosaic of meteorological and hydrological environments, ranging from tropical rain forests to arctic deserts, existing through an altitudinal range of more than 8000 m. There are few reliable maps of the region, and essential climate and hydrologic data are often not readily available. There are very few continuous records, other than low altitude stream flow and climatological data, for the hydrometeorological or glaciological environments of these mountains, and fewer still, models that would permit the synthesis and analysis of these data. Of necessity, much of the literature is speculative, and based upon relationships developed from other mountain regions in Asia, Europe and North America.

Results obtained from studies of the role of glaciers in mountain hydrology are sensitive to variations in scale and location. It is self-evident that stream flow immediately downstream from a glacier terminus will consist primarily of glacier melt, while at the mouth of a glacierized catchment located at some distance from the glaciers, the contribution of the glaciers may be undetectable. To a great extent, this has less to do with the mass balance of the glaciers, and more with the vertical and horizontal distance separating the glacier and the gauging station, combined with the nature of the intervening hydrometeorological environment(s). It is a basic assumption of this study that to be credible, estimates of the glacier contribution to basin discharge must be consistent with the general water budget of the catchment basin in which they exist. This estimate, combined all other estimated contributions to runoff, must be in general agreement with stream gauge measurements in the basin. At the present time, the existing stream gauge network represents the only empirical test of any efforts to assess the importance of glacier runoff from the mountain catchments to the adjacent lowlands.

The scale of this study is that of the gauged sub-basins of the major rivers of Nepal. The findings describing the role of glaciers in the stream flow of these rivers are at the scale of these sub-basins, an intermediate, or mesoscale, between that of the macro-scale Ganges Basin and of the micro-scale climate and hydrometric stations that provided data for the study. The primary locations are those of the hydrometric stations and of the glaciers that are separated horizontally by tens of kilometers and vertically by thousands of meters. The intervening hydrometeorological environment is dominated by precipitation from the summer monsoon. The relationships described here for the Nepal Himalaya can be expected to vary among mountain ranges in the Hindu Kush-Himalaya region, as the importance of the summer monsoon as the dominant source of precipitation varies.

For this study, elementary water and energy budget principles have been combined with area-altitude digital elevation models to reflect the dominant influence of altitude and surface area in determining variations in mass and energy exchange in the mountains of the region. The mesoscale models developed as a result of this study are designed to reflect a fundamental characteristic of mountain ranges or regions – virtually all properties and processes vary with altitude, and area is the most useful factor in assessing total runoff volumes. At the same time, the bulk of the data traditionally available for these mountains or regions are commonly gross aggregate means of climate and hydrology obtained from lowland stations.

Two area-altitude distributed process models were developed. An *Orographic Runoff Model* was based on the relationship between mean specific runoff, in mm and the mean altitude of each basin. The area-altitude distribution of stream flow was calculated for 1000 m belts, as the product of the specific runoff depth and the area of the belt. The *Glacier Melt Model*, based on 100 m area-altitude belts for the glacierized portion of each catchment, was designed to assess the runoff produced by melt water from the glaciers, and was based on the concept of an "ablation gradient" (Haefeli, 1962; Fig. 1). Topography was defined by digital elevation data sets acquired from the Shuttle Radar Topography Mission, SRTM, for both models (Rabus, et al., 2003). The basic topographic unit for determining the hypsometry – area-altitude distribution – is the catchment basin, or glacier (Fig. 2).

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Application of the area-altitude distributed process methodologies involves the following steps:

- Define boundary of topographic unit (catchment basin or glacier)
- Define and measure surface area of altitudinal belts within topographic unit,
- Develop orographic curves of specific process from data or theory,
- From orographic curves, select values for altitudinal belts,
- Specific process X area of altitudinal belt = volume (melt water or runoff) of belt,
- Sum of volumes for altitudinal belts = total volume for basin or glacier

3 Runoff and Stream Flow Estimates

There are three major tributaries to the Ganges River with headwaters in the Nepal Himalaya, from east to west, the Sapta Kosi, the Narayani, and the Karnali River systems, (Fig. 3). Each River basin contains gauged sub-basins, nine of which were used as the data set for this study (Table 1).

A river's discharge is the result of complex interactions between the atmosphere and the underlying topography. It is measured as either runoff, a specific depth, mm, as stream flow volume with time, m^3/s, or as volume of flow over a specified time such as a hydrologic year, million cubic meters, mcm. Mountain catchment basins present a particularly difficult problem for water budget analyses, as a result of the three-dimensional variation of all elements of the water budget equation. The use of gross aggregate means as representative for either spatial or temporal analysis, as might be possible in a lowland, relatively uniform catchment with little topographic relief, yield limited useful information concerning the hydrologic regime of the mountain basin. Contiguous mountain basins, under similar atmospheric conditions, may have widely differing hydrologic regimes as a result of differences in topography. This may be particularly true in the Himalaya Mountain, and necessitates the approximation of orographic gradients of water and energy exchange data.

Catchment basins were selected for this study on the basis of two criteria: It was necessary that they were glacierized, and that they had a hydrometric station measuring stream flow. In order to facilitate project inception, period-of-record stream flow data published in 1988 by the Nepal Department of Hydrology and Meteorology were used (DHM, 1988). Stream flow data for 28 gauged catchment basins were available. Eighteen basins contained a measureable glacierized area. Of these 18, seven had no hydrometric gauging stations, and two had hypsometric curves of glacier surface area distribution that did not look reasonable. This left nine basins that became the data set for this study (Table 1). These basins contain approximately 70% of the glacier area of Nepal. The examples presented here are considered representative of all glacierized basins in the Nepal Himalaya.

Orographic gradients of specific runoff, mm, were estimated by comparing mean period-of-record specific runoff with mean basin altitude, using DHM 1988 data. The resulting orographic gradients are shown in Fig. 3. It was found that the best correlation between calculated and measured runoff was obtained with two separate data sets, one representing the Narayani and Sapta Kosi river basins, in central and eastern Nepal, and a second plot for the Karnali river basin, in western Nepal. For the eastern basins, the maximum specific discharge value was slightly more than 2.8 m, while for the Karnali Basin; maximum specific discharge was approximately 1.3 m. It is assumed this difference is primarily caused by a weakening of the summer monsoon as it moves from east to west along the Himalayan front. In both cases, the maximum value occurred between 3000–4000 m, and decreased both above and below this altitude. Runoff values were taken by inspection from the relationships shown in Fig. 4 for 1000 m altitudinal belts in each of the nine basins. A graphical example of the spatial distribution of streamflow produced by this procedure is shown in Fig. 5.

The total volume of stream flow is calculated as the product of the area-altitude distribution in each catchment basin and the orographic runoff gradient. The resulting volume is compared with the annual stream flow volume, based on data from the Nepal Department of Hydrology and Meteorology. Examples of these calculations are shown in Table 2.

4 Glacier Mass Budget Estimates

It has been estimated that there are approximately 3250 glaciers in the Nepal Himalaya, covering an area of slightly more than 5000 km^2 and containing some 480 km^3 of ice. These glaciers cover approximately 3–4% of the total 147 000 km^2 surface area of Nepal, and are located on, or near, the crest of the Himalaya, with the bulk of the ice at altitudes generally between 4000–6000 m a.s.l. (Mool, et al., 2001).

For development of the glacier budget model used in this study, glaciers were assumed to consist of two distinct zones: an upper accumulation zone and a lower ablation zone. It was further assumed that the altitude dividing these two zones was approximately determined by the mean altitude of the summer-season (Jul–Sep) 0 °C. isotherm. This was termed the Equilibrium Line Altitude, ELA. It was assumed that little or no melt was possible at any time above the ELA, and all melt water was produced from the ablation zone. The ELA as used here is defined by the area-altitude balance ratio method, as outlined by Benn and Gemmell (1997) and Osmaston, (2005), and assumes that accumulation volume is equal to ablation volume. The approach adapted for this study is designed to be used with the very limited data generally available for the Himalayan glaciers. The assumed equality of accumulation and ablation volumes both at, and above and below the balance ratio ELA, means that the local climate can be parameterized as a first approximation in terms of accumulation and ablation-season temperatures, using statistical and analytic methods. Table 3 presents an example of the balance ratio calculations for the glaciers of the Marsyangdi Basin in the Narayani river system. In this case, a value of specific annual accumulation of 2.6 m was required to balance the annual mass loss resulting from melt in the ablation zone. It is assumed that this accumulation value represents direct precipitation, wind-blown snow

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and avalanching, and is not necessarily distributed as uniformly over the accumulation zone as suggested in Table 3.

The area-altitude hypsometry of the glaciers in each gauged catchment was determined for 100 m altitudinal belts from SRTM digital elevation models (DEMs) combined with glacier areas supplied by ICIMOD. As a first approximation, the Equilibrium Line Altitude, ELA, was set at 5400 m, the approximate mean altitude of the 0 °C. isotherm during the ablation period of June-September, and the altitude of zero net budget as measured on the Yala Glacier in the Trisuli catchment (Fujita, et al., 1998). The altitude of this isotherm was determined by extrapolation at a rate of 1 °C/160 m from the period-of-record air temperatures as measured at the network of climatological stations maintained by the Department of Irrigation, Hydrology and Meteorology (DIHM, 1976). There will be year-to-year variations in the altitude of the ELA, as well as differences among glaciers, resulting from variations in water and energy availability.

As a first approximation, it was assumed ice melt was zero at the ELA and increased down-glacier at a rate of 1.4 m/100 m to the glacier terminus, based on the general trend of this gradient with latitude as estimated by Haefeli (1962) and the field measurements of Fujita, et al., 1998 on the Yala Glacier. Values for each 100 m belt were determined from the ablation gradient, and the total ice melt was calculated:

$$Bs = bs_1 Aa_1 + bs_2 A_{a2} + bs_3 A_{a3}, \ldots + bs_n A_{an} \quad (1)$$

where:

Bs = Glacier ice melt, million cubic meters

$bs_{1,2,\ldots n}$ = Specific ice melt, m, for each altitudinal belt

$A_{a1,2,\ldots n}$ = Area of altitude belt in ablation zone, km^2

These values, summed for all the altitudinal belts on the ablating portion of the glaciers, were assumed to represent the annual ablation balance, Bs, for the combined glaciers of each catchment basin. Figure 7 shows an example of the net budget hypsometry for the Dudh Kosi glaciers. Estimates of glacier mass loss produced by

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this methodology are maximum values of snow and ice melt, and are subject to the basics of water budget considerations. The snow and ice lost by the ablation zones of the glaciers may become runoff, may be lost to evaporation or sublimation, or become groundwater or englacial storage (e.g., Konz, et al., 2006). The values determined by this study are considered to be a maximum for each glacierized basin, and the volume of ice melt that becomes measureable stream flow at the altitudes of the hydrometric stations will undoubtedly be lower. All budget vales will vary with the assumed position of the ELA.

5 The role of glaciers in the hydrologic regime of the Nepal Himalaya

Based on calculations similar to those described above for all catchment basins considered in the study, it is estimated that the contribution of glacier annual melt water to annual stream flow into the Ganges Basin from the glacierized catchments of the Nepal Himalaya represents approximately 4% of the total annual stream flow volume of the rivers of Nepal. The models developed for this study indicate that neither stream flow timing nor volume of the rivers flowing into the Ganges Basin from Nepal will be affected materially by a continued retreat of the glaciers of the Nepal Himalaya.

An analysis of the existing hydrological and glaciological data with the models developed during this study indicates that glacier melt water is not a major factor in determining the volume of rivers flowing from the Nepal Himalaya. The estimated relative contributions of: 1) total basin runoff, 2) runoff from all sources in the 4000–6000 m altitude belt, and, 3) estimated glacier melt, for the basins included in this study, are shown in Figure 8. The glaciers of the nine basins in Fig. 8 contain approximately 70% of the total glacier surface area of the Nepal Himalaya. The glacier contribution to the total measured stream flow of the basin in which they are situated varies widely among basins, from approximately 30% in the Budhi Gandaki basin to approximately 2% in the Likhu Khola Basin, averaging approximately 10%. This volume represents approximately 4% of the total mean annual estimated volume of 200 000 million cubic meters for the rivers of Nepal.

6 Discussion

The role of glaciers in the hydrology of the Nepal Himalaya is very much dependent upon the scale at which this role is assessed, as well as upon the location in the river basin for which the assessment is undertaken. At the scale of the Ganges Basin, the complete disappearance of the glaciers would most probably be undetectable from measurement of the annual streamflow at current hydrometric stations, and would have little, if any, impact on current water use practices or for existing water resources planning or management procedures. The probable impact would become progressively greater as one moved upstream in a basin, decreasing the distance to the glacier terminus.

This study has focused on the role of glaciers in the hydrologic regime of the Nepal Himalaya, only one component of a very complex, relatively unstudied, mountain hydrologic system. The study and management of mountain river basin systems has been constrained by a lack of realistic three-dimensional models for terrain of extreme relief, driven by disaggregated data bases. Neither spatial nor temporal variability in the interactions among elements of the mountain hydrologic cycle can be accurately determined by extrapolation using models developed for areas of low relief, or those driven solely by gross aggregate means from lowland gauging stations. This may be particularly true for the very high mountains of south and central Asia. A combination of a lack of topographic information, and readily available data describing the hydrometeorological environment are serious impediments to water resources development in the river basins of the region. While we believe the methodologies developed during this study may have a wide application, the results presented here are considered only applicable to the Nepal Himalaya. There is evidence in the literature that glaciers become an increasingly important source of stream flow volume in portions of the western Himalaya and the Karakoram Himalaya.

In south and central Asia, water availability is a primary problem. The study of glaciers should focus on their current and projected role in the hydrologic regime of the large river systems of the region. Since this paper was first presented at the World Bank

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Water Week in February, 2009, there has been a major shift in the general perception of aspects related to the retreat of Himalayan glaciers. It has been acknowledged that an unreviewed section of the UN Intergovernmental Panel on Climate Change (IPCC, 2007) stating that most Himalayan glaciers will have vanished by as early as 2035, was an error. It is now generally agreed that rates of glacier retreat and mountain climates vary widely in the region, with some glaciers advancing, in response to a range of hydrometeorological environments (e.g., Raina, 2009; Thayyen and Gergan, 2009). What has not yet been corrected is a statement in this same section of the IPCC report that, as a result of this retreat, the Ganga, Indus, Brahmaputra and other rivers that criss-cross the northern Indian plain could likely become seasonal rivers in the near future. The IPCC should also acknowledge that the contribution of glacier melt to flow volumes most probably varies widely among the rivers of south and central Asia, as does the dynamics of individual glaciers, and that studies of the role of glaciers in each of the major river basins is required before such sweeping generalizations can be accepted.

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Table 1. The catchment basins forming the data set for this study. Basin area, mean altitude and streamflow from DHM, 1988. Qb = streamflow volume, m^3/s, qb = specific runoff, mm, Qv = annual Streamflow volume, million cubic meters. Glacier Q estimated as described in the text. Glacier areas from Mool, et al., 2001.

River	Basin	DHM ID#	Area (Km^2)	Avg. Alt. (m)	Qb (m^3/s)	Qb mm	Qv (MCM)
Karnali	Bheri	270	13 677	4400	435	1116	13 718
Narayani	Kali Gandaki	420	6553	3200	267	1270	8420
	Marsyangdi	439	4781	4200	212	1737	6686
	Budhi Gandaki	445	3707	5400	169	1182	5048
	Trisuli	447	3623	5200	173	1382	5456
Sapta Kosi							
	Tama Kosi	647	2382	4900	145	1661	4573
	Likhu Khola	660	1297	3500	57	2184	1798
	Dudh Kosi	670	4515	4400	223	1715	7033
	Tamor	690	6330	2600	336	1879	10 596
Totals			48 164				67 081

Table 2. A comparison of calculated (calc) and measured (meas) total annual, stream flow volume, Q, mcm, based on the orographic runoff gradient , q, m, input from Fig. 3 and DEM based on SRTM imagery. Stream flow data from DHM.

Marsyangdi-439 Altitude, m	Area, km^2	q, m	Q, mcm	Trisuli-447 Area, km^2	q, m	Q, mcm
0–1000	839	0.75	628.5	861	0.75	645.75
1000–2000	722	1.5	1081.5	1121	1.5	1681.5
2000–3000	459	2	916	479	2	958
3000–4000	612	2.25	1377	401	2.25	900
4000–5000	990	1.75	1732.5	393	1.75	686
5000–6000	937	1	936	321	1	321
6000–7000	204	0	0	46	0	0
7000–8000	19	0	0	1	0	0
8000–9000	0	0	0	0	0	0
BASIN AREA	4781	calc	6671.	3623	calc	5192
GLACIERIZED AREA	617	meas	6686	248	meas	5456
% GLACIERIZED AREA	13			7		

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Table 3. Calculated steady-state budget values for the Marsyangdi glaciers, based on a 100 m area-altitude histogram of the glaciers, an ablation gradient of 1.4 m. 100 m, and an ELA at 5400 m. A steady-state balance is based on the assumption that total mass gain, Bw, is equal to total mass loss, Bs. For the Marsyangdi glaciers, this requires a mean areal value for the specific winter budget, bw, of 2.6 m water

Marsyangdi	Column1	Column2	Column3	Column4	Column5	Column6	Column7
Altitude	Area, km^2	bs, m	Bs, mcm	Alt,m	Area, km	bw, m	Bw, mcm
3250	0.02	30.1	1	5450	39	2.6	101.4
3350	0.33	28.7	9	5550	47	2.6	122.2
3450	0.28	27.3	8	5650	50	2.6	130
3550	0.87	25.9	23	5750	48	2.6	124.8
3650	0.98	24.5	24	5850	43	2.6	111.8
3750	0.87	23.1	20	5950	38	2.6	98.8
3850	1.27	21.7	28	6050	34	2.6	88.4
3950	1.75	20.3	36	6150	29	2.6	75.4
4050	3.75	18.9	71	6250	21	2.6	54.6
4150	5.33	17.5	93	6350	16	2.6	41.6
4250	6.34	16.1	98	6450	13	2.6	33.8
4350	5.95	14.7	83	6550	11	2.6	28.6
4450	5.62	13.3	71	6650	9	2.6	23.4
4550	7.01	11.9	79	6750	7	2.6	18.2
4650	6.33	10.5	62	6850	7	2.6	18.2
4750	7	9.1	59	6950	5	2.6	13
4850	9.66	7.7	68	7050	4	2.6	10.4
4950	14.52	6.3	81	7150	3	2.6	7.8
5050	19.17	4.9	81	7250	3	2.6	7.8
5150	25.87	3.5	72	7350	2	2.6	5.2
5250	28.4	2.1	40	7450	1	2.6	2.6
5350	33.92	0.7	24	7550	1	2.6	2.6
Totals	297.6		1130	7650	1	2.6	2.6
				7750	0	2.6	0
				7850	0	2.6	0
				Totals	432		1123

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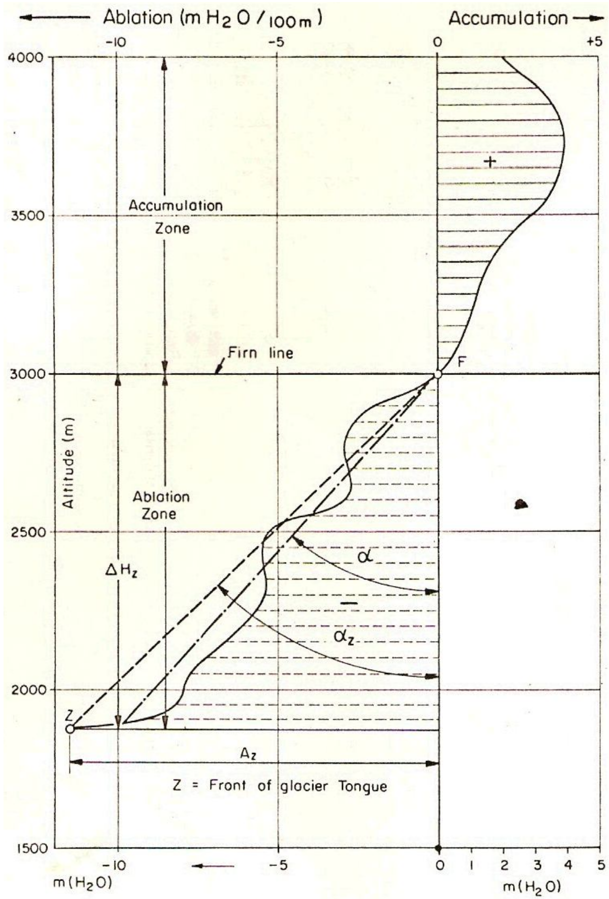

Fig. 1. The ablation gradient as defined by Haefeli (1962).

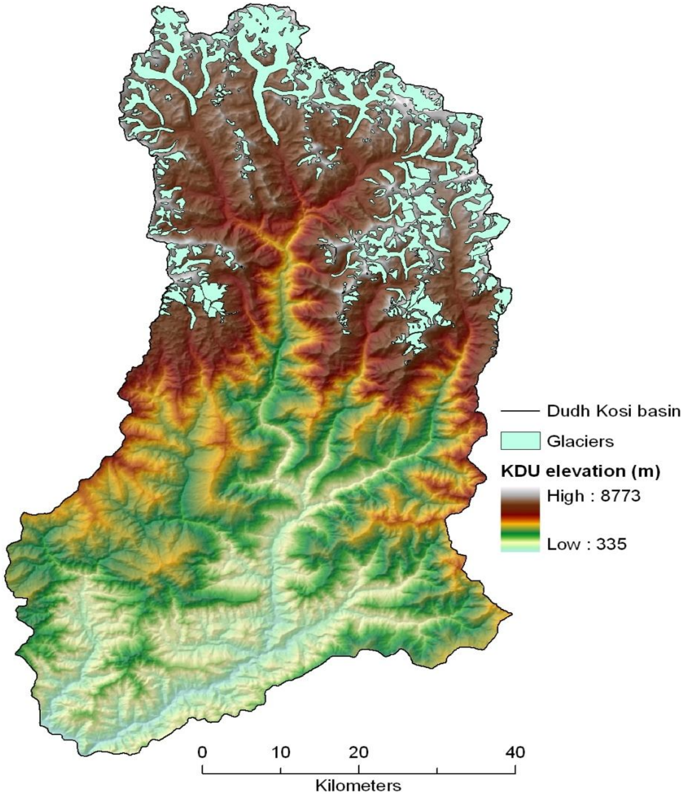

Fig. 2. The catchment basin is the basic unit for hydrologic analysis. Here, the topography and glacier-covered area of the Dudh Kosi Basin at the headwaters of the Sapta Kosi River in eastern Nepal, derived from SRTM imagery, are shown.

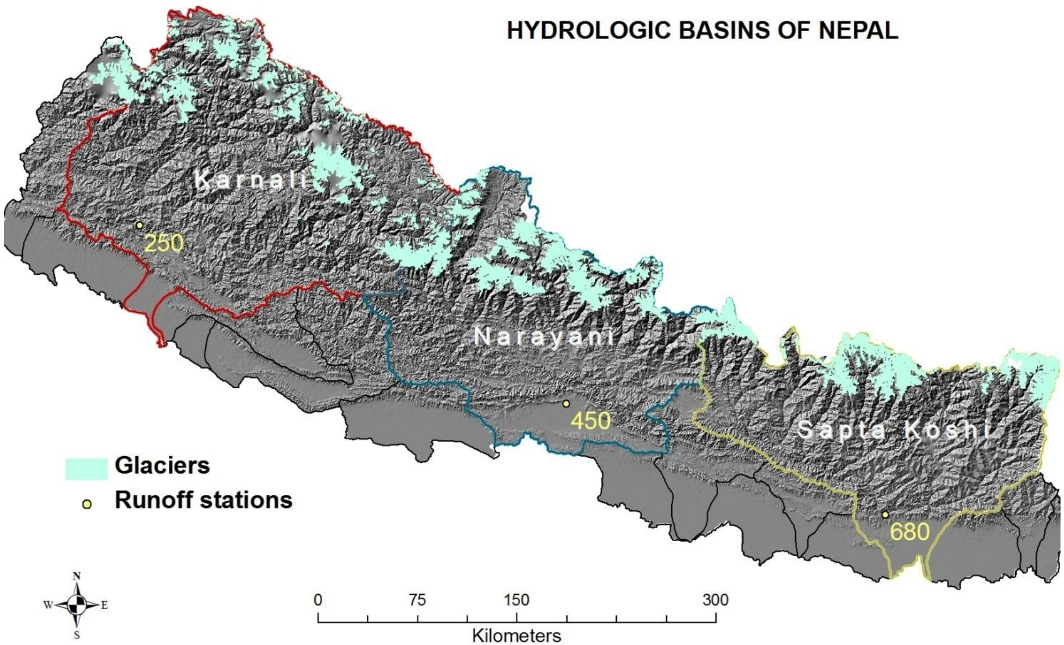

Fig. 3. The river basins of the Nepal Himalaya, showing major areas of glacierization, in blue.

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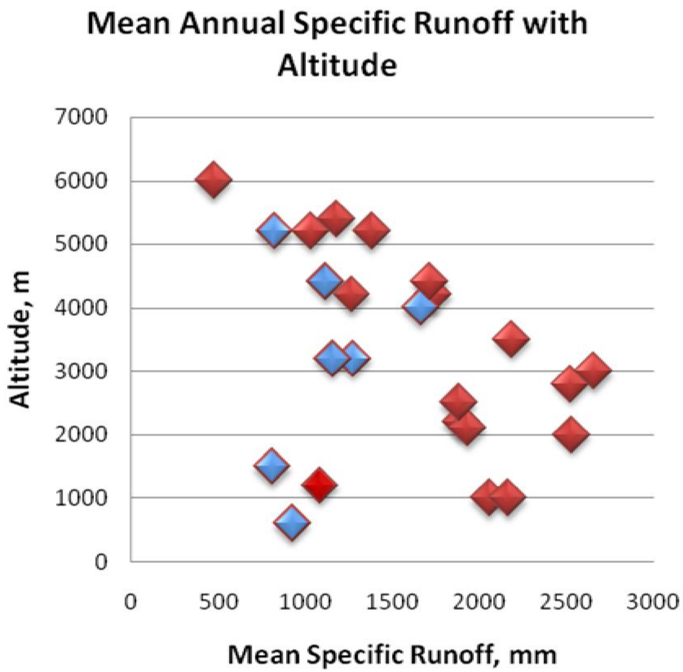

Fig. 4. The orographic trend of mean specific runoff, mm, with mean basin altitude for eastern basins (red) and western (blue) basins. These trends are based on both glacierized and non-glacierized basins. This curvilinear trend is explained a result of the altitudinal distribution of water vapor in subtropical air masses (e.g., Barry and Chorley, 1970).

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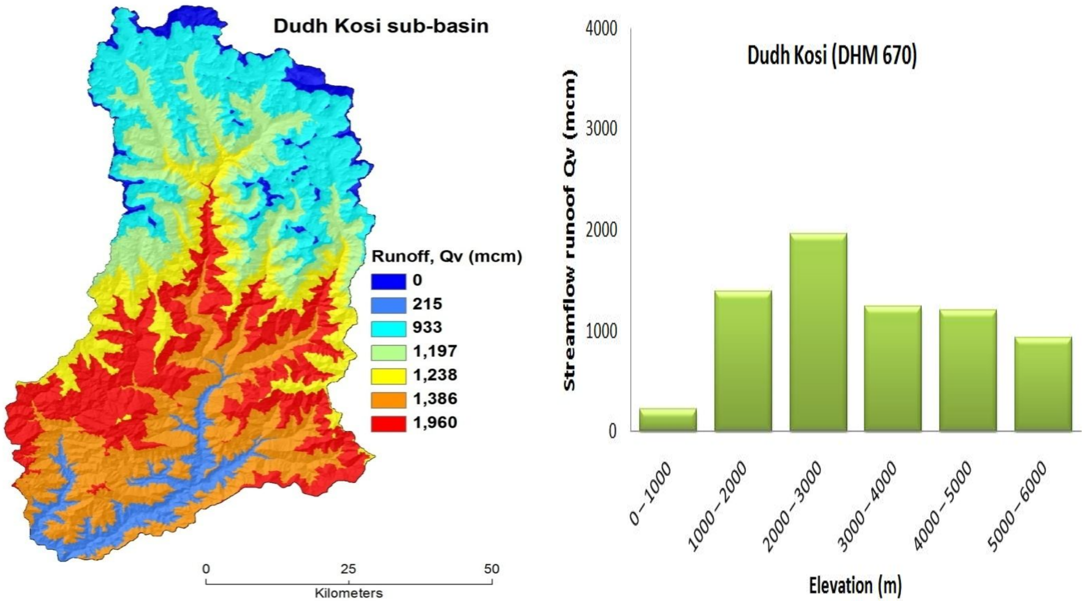

Fig. 5. The spatial pattern of annual stream flow volume, (left), and a histogram of this volume from each 1000 m altitudinal belt (right) for the Dudh Kosi Basin, eastern Nepal.

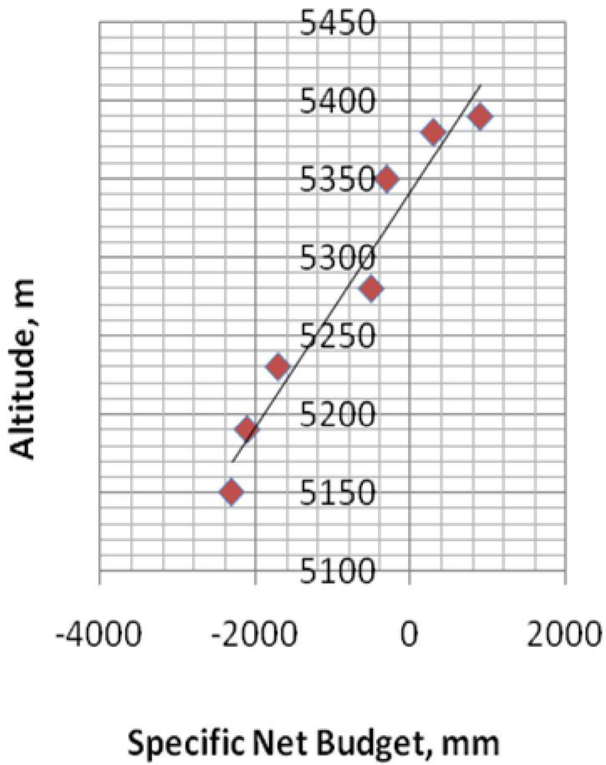

Fig. 6. The specific budget gradient , measured on the Yala Glacier, in the Trisuli Basin (Fujita, et al., 1998). The measured slope of thespecific net budget with altitude for the Yala Glacier is approximately 1.4 m/m.

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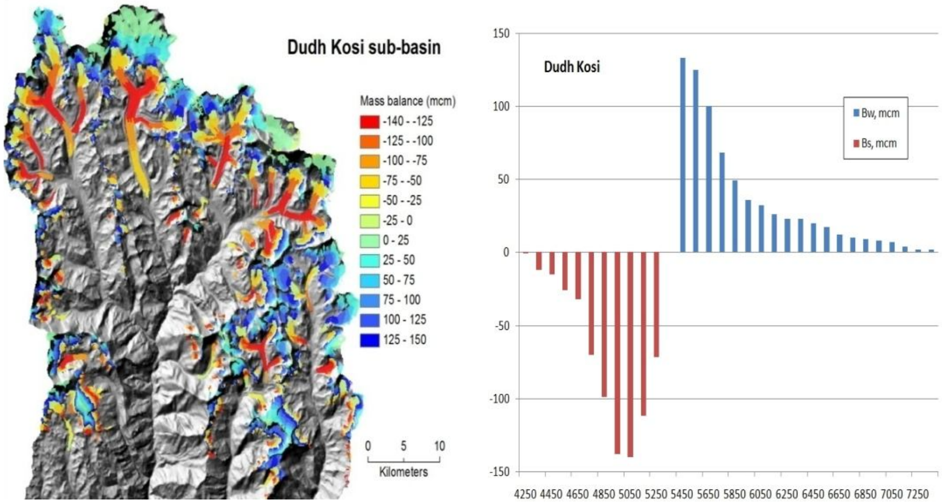
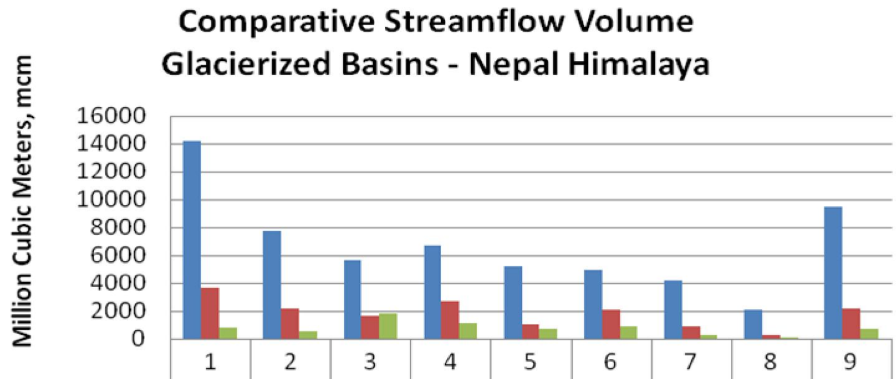


Fig. 7. The Accumulation and Ablation Zones – Dudh Kosi glaciers The mass balance volumes are the product of the specific net budget and surface area of altitudinal belts on the glacier, mcm = million cubic meters



	1	2	3	4	5	6	7	8	9
Basin	14149	7705	5624	6672	5192	4918	4153	2091	9510
4-6 K m	3618	2197	1682	2668	1007	2130	829	248	2194
Glacier Melt	747	491	1791	1106	698	869	253	81	723

Fig. 8. A histogram, showing the relative annual stream flow, mcm/yr, for Basin Total, 4000-6000 m Altitudinal Belt, and Glacier Melt, among glacierized gauged basins in the Nepal Himalaya. Catchment Basins are: 1. Bheri, 2. Kali Gandaki, 3. Budhi Gandaki, 4. Marsyangdi, 5. Trisuli, 6. Dudh Kosi, 7. Tama Kosi, 8. Likkhu, 9. Tamor.