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Modelling and estimation of different components of streamflow for Gangotri Glacier basin, Himalayas

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Abstract The understanding of the runoff generation processes is reviewed and simulation of daily streamflow is reported for the Gangotri Glacier basin (Central Himalayas) with area of ~556 km^2, of which ~286 km^2 is occupied by the glaciers, and altitude of 4000 to 7000 m.a.s.l. A hydro-meteorological database was established by collecting meteorological and hydrological data near the snout of the glacier for four melt seasons (2000–2003) covering the period from May to October every year. Flow was simulated using a snowmelt model (SNOWMOD) based on the temperature index approach. Two years (2000 and 2001) of the four-year data set were used to calibrate the model, and the remaining two years (2002 and 2003) were used for verification. The study was carried out during the ablation period, as the availability of data was restricted to that period, responsible for a major part of the runoff. The model performed well for both calibration and verification periods. The overall efficiency of the model, R^2, was 0.96 and the difference in volume of computed and observed streamflow was –2.5%, indicating a good model performance. Simulation of different components of streamflow clearly indicates that almost all the high peaks are attributed to melt. The model was also used to estimate the respective contributions by melt and rainfall to the total seasonal flow: for summer runoff, these were estimated to be about 97% and 3%. Such studies are very useful for the planning and management of water resources in high-altitude areas and for designing hydropower projects.

Key words streamflow modelling; SNOWMOD; temperature index; Gangotri Glacier; Himalayas

Modélisation et estimation des différentes composantes de l'écoulement fluviatile du bassin du Glacier Gangotri, Himalaya

Résumé La compréhension des processus de génération de l'écoulement est synthétisée et une simulation de l'écoulement journalier est présentée pour le bassin du Glacier Gangotri (Himalaya Central) d'une superficie de ~556 km^2, dont ~286 km^2 sont englacés, et d'une altitude variant entre 4000 et 7000 m au dessus du niveau de la mer. Une base de données hydro-météorologiques a été établie suite à la collecte de données météorologiques et hydrologiques à proximité du front du glacier pendant quatre saisons de fonte (2000–2003) couvrant chaque année la période Mai–Octobre. L'écoulement fluviatile a été simulé à l'aide d'un modèle de fonte nivale (SNOWMOD) basé sur l'approche de l'indice de température. Deux années (2000 et 2001) parmi le jeu de données de quatre ans ont été utilisées pour caler le modèle, et les deux autres années (2002 et 2003) ont été utilisées pour la vérification. L'étude a été menée lors de la période d'ablation, dans la mesure où la disponibilité des données est limitée à cette période, responsable de la plupart de l'écoulement. Le modèle donne de bons résultats pour les périodes de calage et de vérification. L'efficience globale du modèle, R^2, est de 0.96 et la différence entre les volumes simulés et observés est de –2.5%, ce qui indique une bonne performance du modèle. La simulation des différentes composantes de l'écoulement indique clairement que presque tous les forts pics sont attribués à la fonte. Le modèle est également utilisé pour estimer les contributions respectives de la fonte et des précipitations aux écoulements saisonniers totaux: pour l'écoulement estival, elles ont été estimées à 97% et 3%. De telles études sont très utiles pour la planification et la gestion des ressources en eau dans les régions de haute altitude et pour le dimensionnement de projets hydroélectriques.

Mots clefs modélisation de l'écoulement fluviatile; SNOWMOD; indice de température; Glacier Gangotri; Himalaya

INTRODUCTION

Himalayan rivers receive substantial contributions from snow and glacier melt runoff to annual streamflows (Singh & Jain, 2002). The water yield from a high Himalayan basin is about double that of an equivalent basin located in the south of the plains region (peninsular part) of India. Higher water yields in the summer season from the rivers originating from Himalayan basins are mainly due to large inputs from melting snow and glaciers. Glacier melt is an important component of runoff from the high mountainous catchment, particularly during summer months.

The melting of snow and ice can be computed using either an energy balance approach or a temperature index (degree-day) approach. Energy balance models provide the best estimate of the energy transfer to the snow/glacier surface, but these models require information on the radiative energy, sensible and latent heat, energy transferred through the rainfall over the snow/glacier surface and heat conduction from the ground (Singh & Singh, 2001). Several meteorological parameters have to be monitored to obtain such information over the glacier. In contrast, index models use simple empirical expressions to parameterise the energy exchange over the glacier surface. Air temperature correlates well with several energy balance components, hence it is the most commonly used index, but other variables such as net radiation, wind speed, vapour pressure and solar radiation are also used. Studies have shown that temperature index or degree-day models are the most widely used approaches for runoff computation from glacierized basins (Aizen *et al.*, 1995; Rango & Martinec, 1995; Semadeni-Davies, 1997; Hock, 2003).

The hydrological response of a glacier changes throughout the ablation period, resulting in changes in the magnitude and the pattern of melt runoff with time. The simulation of streamflow from a glacierized basin requires the proper concepts of meltwater generation, storage and routing. The storage characteristics and routing pattern of a glacier are responsible for the delayed response of runoff to meltwater generated over the glacier surface. Storage controls the magnitude of the water runoff and depends on the dynamics, size, drainage network, seasonal snow cover and firn cover, and size of the bare ice area, which generally grows during the ablation season (Singh *et al.*, 2006). Water can be stored in a glacier in a number of ways: in surface snow and firn, crevasses, surface pools, englacial pockets, subglacial cavities, englacial and subglacial drainage networks, and in basal sediments (Jansson, 2003). The glacier storage peaks in the early part of the melt season because of the seasonal snow/firn cover over the glacier and poorly developed drainage system, and water is gradually released during the later part of the summer period when the efficiency of the glacier drainage system increases and runoff occurs more quickly (Stenborg, 1970; Tangborn *et al.*, 1975; Ostling & Hooke, 1986; Seaberg *et al.*, 1988; Singh *et al.*, 2006).

STREAMFLOW CHARACTERISTICS OF HIMALAYAN RIVERS

All the large Himalayan basins have contributions from three sources, i.e. rain, snow and glaciers. The spatial distribution of runoff for the large Himalayan basins shows that, as the elevation of the basin increases, the rain contribution to streamflow decreases while that of melt increases. Runoff is dominated by glacier melt for all the upper parts of the basin above 4000 m altitude. The melt contribution in the pro-glacier stream is primarily controlled by climatic conditions and the extent of basin covered by glaciers and, therefore, it varies from year to year. Hydrological observations carried out for glacierized basins in the Himalayan region indicate that melting from the glaciers takes place between May and October and maximum runoff from these basins is received during July and August (Singh *et al.*, 2006).

OBJECTIVES

Limited efforts are made to understand the melting pattern of Himalayan glaciers and to simulate the runoff generated from them. Such studies are hampered due to non-availability of required data because of harsh weather conditions and difficult terrain, as well as difficulty in maintaining the instruments at high altitudes. In order to carry out this study, a database was acquired for four melt seasons for the Gangotri Glacier basin and used for modelling of streamflow. Since a specific type of data required for the energy budget method could not be collected, a temperature index approach was adopted for melt computation. In other basins, the most commonly available data are also restricted to daily maximum and minimum temperatures. In the present study, the snowmelt model (SNOWMOD) based on the temperature index approach was applied to simulate the daily flows for the Gangotri Glacier basin. Application of the model was extended to estimate the melt and rainfall contributions to summer season flows.

STUDY AREA AND DATA AVAILABILITY

The present study was carried out for the Gangotri Glacier (latitudes 30°43′–31°01′N and longitudes 79°0′–79°17′E), which is one of the largest glaciers of the Himalayas (Fig. 1). The pro-glacial meltwater stream, Bhagirathi River, emerges from the snout of the Gangotri Glacier—known as "Gaumukh"—at an elevation of ~4000 m. The name Gangotri Glacier refers to the Gangotri Glacier system—a cluster of many glaciers of which the main Gangotri Glacier (length: 30.20 km; width: 0.20–2.35 km; area: 86.32 km^2) is the trunk. The total glacierized area of the valley-type Gangotri Glacier is about 286 km^2. The total catchment area up to the discharge-gauging site established downstream of the snout is about 556 km^2. The data used in the computation of this study are daily values of air temperature, precipitation and streamflow collected during the ablation period in four consecutive years, 2000–2003. These data sets were collected by establishing a meteorological observatory and a gauging site at the same location near the snout of the glacier. Singh *et al.* (2006, 2005) and Haritashya *et al.* (2006b) have described the detailed procedure involved in obtaining these observations.

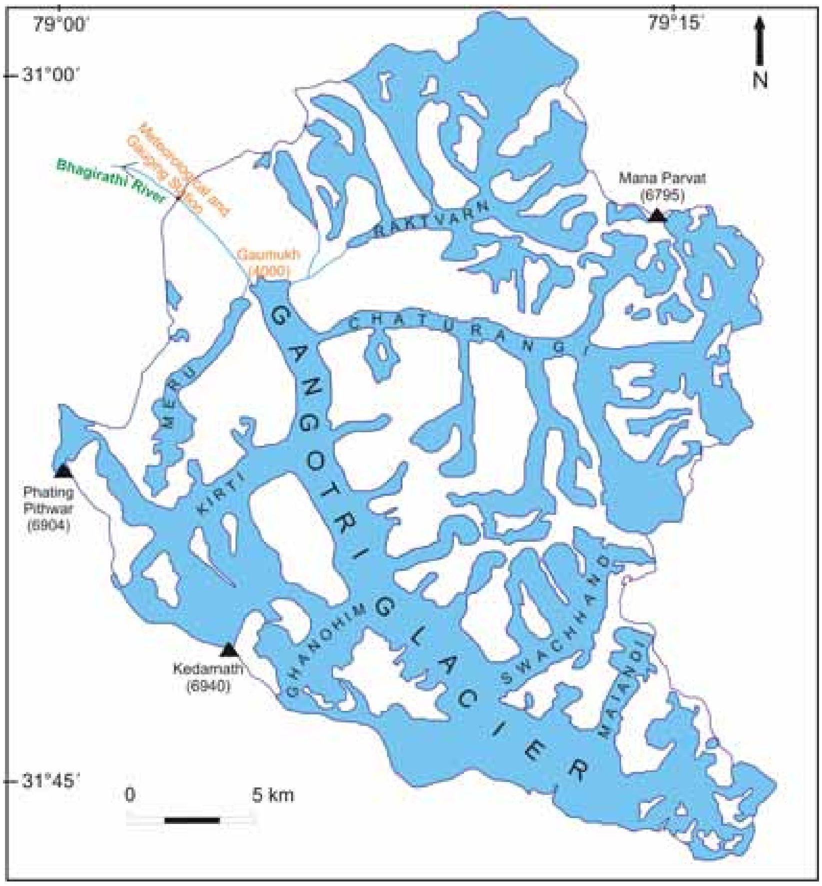

Fig. 1 Location map of the study area showing major tributaries of the Gangotri Glacier.

SPECIAL FEATURES OF THE SNOWMELT MODEL (SNOWMOD)

The process of generation of streamflow from snow- and glacier-covered areas primarily involves determination of the amount of basin input derived from the melt, along with the contribution from rain. The snowmelt model (SNOWMOD) has been designed to simulate daily streamflow in a mountainous basin where melt is the major runoff component. As discussed above, for the Himalayan basins, the most important factor influencing model choice is the limited availability of

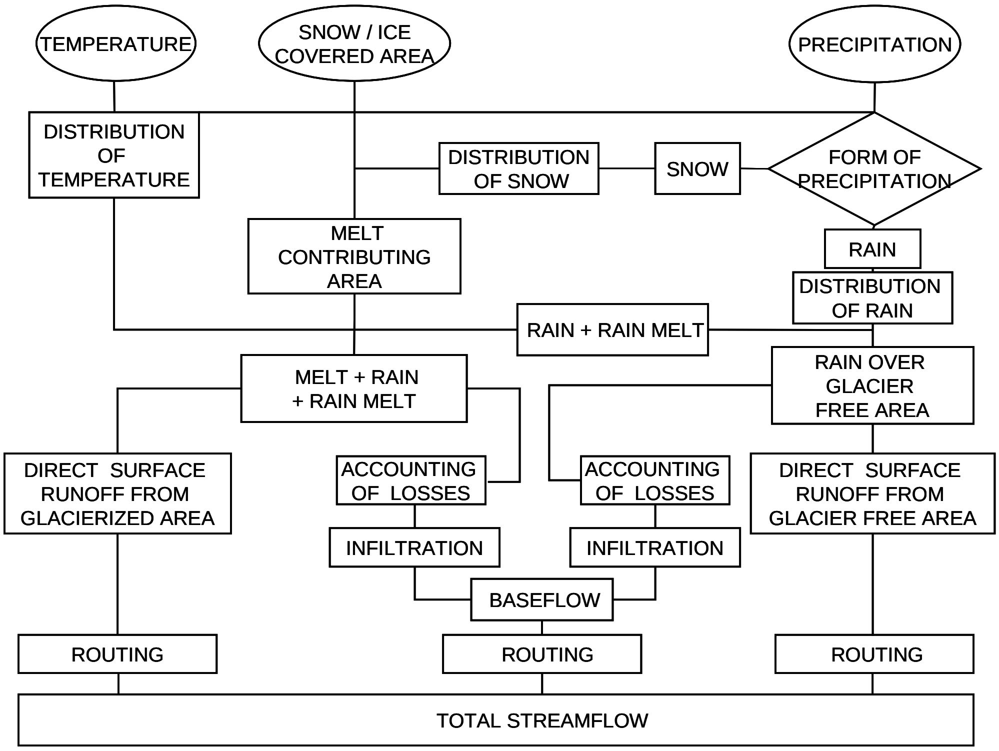

Fig. 2 Flowchart of the snowmelt model (SNOWMOD).

data. There is a very sparse network of measurement stations in the Himalayas and data collected at most of them are restricted to temperature and precipitation values. Therefore, bearing this in mind, SNOWMOD was developed using a temperature index approach. Details of the model may be found in Singh & Jain (2003) and the flow chart of the model structure is shown in Fig. 2. The structure of this model has been kept simple so that all suitable/available data are properly utilized. The model uses practical, yet theoretically sound, methods for subdividing the basin to evaluate the various physical and hydrological processes relevant to melt and its appearance as streamflow at the outlet. The basin is divided vertically into 400-m elevation zones and the glacierized and non-glacierized area of each zone is identified for computing the runoff. The model has the ability to perform computations over any specified time interval according to the availability of input data. Therefore, in the present study, it computes the meltwater and total runoff processes on a daily basis. As well as simulating direct runoff from melting of snout ice and rainfall, the model simulates baseflow and the sum of these three components provides the total streamflow from the basin. A simple cascade reservoir approach is used to route different components of runoff.

The hydrological responses of the glacier-covered area (GCA) and glacier-free area (GFA) are different and depend on their respective areal extents. Moreover, the extent of melting area changes with time because of changes in air temperature over the glacier. Such changes in the course of the melting season influence the hydrological response. These variations in hydrological response were accounted for by routing each component of runoff separately and considering the storage coefficients of melt and rainfall using the Rosenbrock optimization technique (Kuester & Mize, 1973) as a function of effective GCA_e and GFA, respectively. The storage coefficient for the baseflow routing was determined using the streamflow records of the recession period. These parameters and other relevant processes are discussed in detail in the next section, where parameters and corresponding equations are presented. An initial storage of soil moisture was assumed at the beginning of the simulation period. It is to be noted that this model has been used previously for large Himalayan basins, where rainfall-generated runoff dominated melt runoff. This is the first time that the model has been extended to highly glacierized basins where snout ice dominates runoff.

MODELLING OF STREAMFLOW

Temperature and rainfall are the main input to the model. In addition, information on the physical features of the basin, which includes glacierized area, elevation zones and their areas, total area of the basin, altitude of meteorological station, and other watershed characteristics affecting runoff, are used in the model. The processing of these physiographic and meteorological data for the study basin is described below.

Physiographic data

Elevation zones and glacierized area of basin In a mountainous basin, temperature and precipitation vary with elevation. The temperature generally decreases with elevation and is influenced by aspect and topographic shading; precipitation generally increases with elevation, as does the proportion that falls as snow, and is influenced mostly by aspect, slope position and other exposure indices. To distribute the temperature in the study basin, it was divided into nine elevation zones based upon the topographic relief. A digital elevation model (DEM) of the study area was generated in ILWIS software package, using the Survey of India (SOI) topographic map nos 53 M/4, N/1, 2, 5, 6 (scale 1:50 000). The DEM was used for the preparation of an area–elevation curve (Fig. 3). Distribution of cumulative area is shown in this figure. The DEM and area-elevation curve were used for the preparation of zone specific distribution of glacierized and non-glacierized area (Table 1).

Meteorological data

Precipitation The distinction between rain and snow for each elevation zone is important for all the melt runoff models because precipitation falling in the form of rain and snow behaves

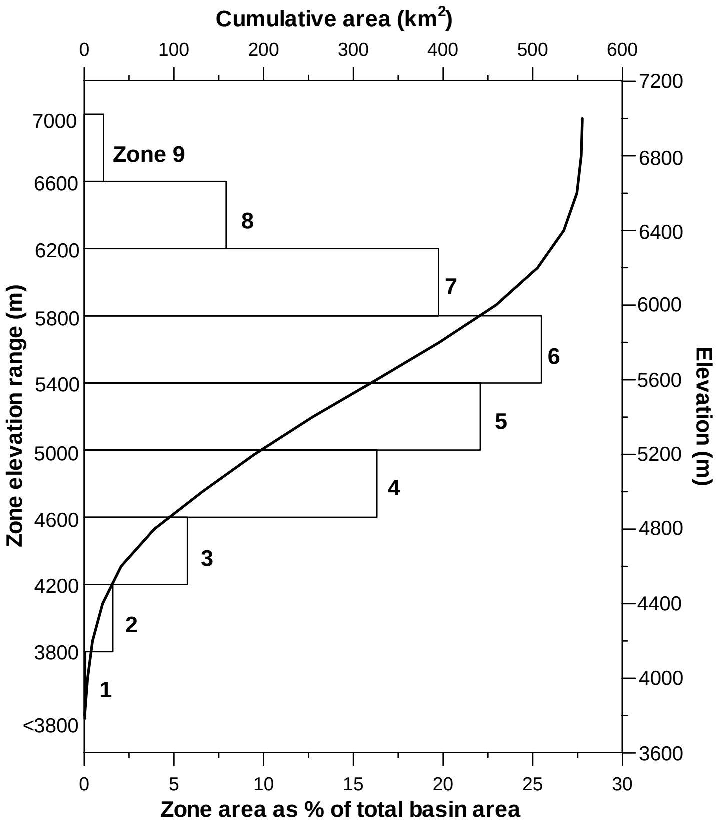

Fig. 3 Area of different elevation zones as percentage of total basin area and area–elevation curve for the Gangotri Glacier basin upstream of the observation site.

Table 1 Glacierized and non-glacierized area covered at different elevation bands.

Zone	Elevation range (m)	Glacierized area (km^2)	Non-glacierized area (km^2)	Total zone area (km^2)
1	<3800	0	0.41	0.41
2	3800–4200	2.38	6.49	8.87
3	4201–4600	14.39	17.66	32.05
4	4601–5000	52.93	37.72	90.65
5	5001–5400	65.17	57.55	122.72
6	5401–5800	72.36	68.43	140.79
7	5801–6200	53.00	56.35	109.35
8	6201–6600	21.37	23.85	45.22
9	6600–7000	4.39	1.78	6.17
Total	3800–7000	285.99	270.24	556.23

differently in terms of contribution to the streamflow. The contribution of rain to the streamflow is faster than that of snow because snow is stored in the basin until it melts, whereas rain contributes to streamflow almost immediately. The temperature in a particular elevation zone determines the form of precipitation and the model handles it accordingly. A critical temperature, T_c, is specified in the model to determine whether the measured precipitation was rain or snow. Therefore, the value of T_c is usually selected slightly above the freezing point (T_c = 2°C in the present study). The model uses the following concept to determine the form of precipitation:

if $T_m \geq T_c$, all precipitation is considered as rain,

if $T_m \leq 0$°C, all precipitation is considered as snow,

where T_m is the daily mean temperature. In the case where $T_m \geq 0$°C and $T_m \leq T_c$, the precipitation is considered as a mixture of rain and snow and their proportion is determined as follows:

$$\text{Rain} = \frac{T_m}{T_c} \times P \tag{1}$$

$$\text{Snow} = P - \text{Rain} \tag{2}$$

where P is total observed precipitation.

The distribution of precipitation with altitude was not considered in the present study, simply because the relevant information was not available. Moreover, in view of the fact that less rain is generally observed in the study area, except for a few heavy rain events, an orographic factor (1.5) was used for the heavy rain events (≥40 mm). Only such high rain events influenced the runoff.

Temperature index and distribution of temperature As discussed above, due to the limitations of data availability, a temperature index or degree-day method was considered to be the most suitable method for melt computation. Air temperature expressed in degree-days is used in melt computations as an index of the complex energy balance. The simplest and most common expression relating daily melt to the temperature index is:

$$M = D(T_i - T_b) \tag{3}$$

where M is the depth of meltwater (mm d^{-1}), D is a degree-day factor (mm $°C^{-1}$ d^{-1}), T_i is the index air temperature (°C) and T_b is the base temperature (usually 0°C).

In general, daily mean temperature is the most commonly used index of temperature for melt computation. Mean temperatures, T_{mean}, or the number of degree-days are computed using maximum, $T_{\max}$, and minimum temperatures, $T_{\min}$, as:

$$T_i = T_{\text{mean}} = \frac{(T_{\max} + T_{\min})}{2} \tag{4}$$

However, in the present study, the use of T_{mean} was found to result in underestimated streamflows, while $T_{\max}$ resulted in overestimated flow. The same trend was found for both years used in calibrating the model. There are several methods of dealing with the index temperatures used in calculating the degree-day value. As reported by Garstka *et al.* (1958), sometimes the degree-days from the daily mean temperature do not represent the actual thermal regime over the basin. Such cases have been reported for mountainous areas in many parts of the western USA. Thus, inclusion of minimum temperature at an equal weight with maximum temperature gives higher emphasis to surface heat deficit effect, while maximum temperature alone excludes this effect. Under such conditions, US Army Corps of Engineers (1956) recommended the use of maximum and minimum temperatures with different weights, and this advice was followed in the present study. Finally, considering the matching of observed and computed streamflow, the weights appropriate for maximum temperature and minimum temperatures were found to be 0.80 and 0.20, respectively. Thus, the following temperature index method was used:

$$T_i = (0.80T_{\max} + 0.20T_{\min}) \quad (5)$$

Moreover, air temperature varies with altitude and melt runoff computations need air temperature data for all the elevation bands of a basin to provide a better representation of temperature distribution. However, in the present study basin, temperature data were available for only one station located near the terminus of the glacier. Therefore, temperatures were extrapolated or interpolated to the mid-elevation of each elevation zone using a predefined temperature lapse rate in the model, given by:

$$T_{i,j} = T_{i,\text{base}} - \delta(h_j - h_{\text{base}}) \quad (6)$$

where $T_{i,j}$ is the daily mean temperature on the *i*th day in the *j*th zone (ºC); $T_{i,\text{base}}$ is the daily mean temperature (ºC) on the *i*th day at the base station, h_j is the zonal hypsometric mean elevation (m), h_{base} is the elevation of the base station (m), and δ is the temperature lapse rate (ºC/100 m). Several other field studies have determined the temperature lapse rates for mountainous regions of the world in the range of 0.5–0.7ºC/100 m (Pielke & Mehring, 1977; Barry, 1992; de Scally, 1997; Singh & Singh, 2001; Singh & Jain, 2002; Singh & Jain, 2003; Thayyen, 2003). For the Himalayan basins, temperatures were lapsed at 0.60ºC/100 m to the mean hypsometric elevation of different elevation zones for melt computation (Singh & Jain, 2002) and such a lapse rate was used in the present study.

Degree-day factor The degree-day factor (*D*) is used to convert the degree-days into melt expressed in depth of water. This factor is influenced by the physical properties of the snow/ice and, because these properties change with time, this factor also changes with time. However, this factor still has practical importance for accurate ablation estimation using limited data (Singh & Singh, 2001; Hock, 2003). It is understood that, while using the temperature index model, a seasonally changing degree-day factor should also be taken into account. In the present study, the degree-day factor varied in the range of 2.5–9.0 mm $°C^{-1}$ d^{-1}, being at a minimum at the start of the melt season, reaching a maximum during the peak melt season, and then starting to decrease because of fresh snowfall. For a study at Qamanârssûp sermia, West Greenland, Braithwaite & Olesen (1993) suggested that the degree-day factor is high in July in comparison to June and August. They reported degree-day factors for, June, July and August in the range of 6.19–8.25, 6.62–9.07, and 5.96–8.49, respectively. Singh & Kumar (1996) and Singh *et al.* (2000) computed the value of *D* for a Himalayan basin for a specific time and compared it with others.

ESTIMATION OF RUNOFF COMPONENTS

Each component of runoff was computed for each elevation zone separately and then output from all the zones was integrated to provide the total runoff from the basin. Details of the methodology adopted for estimating different components of streamflow are discussed below.

Surface runoff from glacierized area

The surface runoff generated from the glacierized part of the basin can be categorized in three parts, namely: (a) melt caused due to prevailing air temperatures; (b) under rainy conditions, melt due to heat transferred to the ice surface from rain; and (c) runoff generated from the rain falling over the glacierized area. Melt runoff for each elevation zone of the basin was computed using the degree-day approach and the extent of glacier-covered area (GCA) in that zone.

$$M_{g,i,j} = C_{g,i,j}\, D_{i,j}\, T_{i,j}\, G_{c,i,j} \tag{7}$$

where $M_{g,i,j}$ represents glacier melt in terms of depth of water (mm d^{-1}), $C_{g,i,j}$ is the runoff coefficient for glacier melt, $D_{i,j}$ is the degree-day factor (mm °C^{-1} d^{-1}), $T_{i,j}$ is the index temperature (°C) and $G_{c,i,j}$ represents the ratio of GCA to the total area of the elevation band. The suffixes *i* and *j* denote day and zone, respectively.

Runoff depth due to melt from rain falling on the glacier

The depth of melt caused by rain in an elevation zone is given by:

$$M_{r,i,j} = \frac{4.2 T_{i,j} P_{i,j} G_{c,i,j}}{325} \tag{8}$$

where $M_{r,i,j}$ is the melt in terms of depth of water due to rain on glacier (mm d^{-1}), $T_{i,j}$ is the temperature of the rain (ºC), $P_{i,j}$ is the depth of the rain (mm d^{-1}), and $G_{i,j}$ is the depth of rainfall on the glacier (mm d^{-1}). Rainfall events occurring at higher temperatures would cause melting due to rain; otherwise this component would not be so significant. In the present study area, by and large, rain events were negligible and heavy rains were concentrated in only a few events (Haritashya *et al.*, 2006a); therefore, the overall impact of rain on melt was insignificant.

The runoff depth from rain falling over the GCA, $R_{g,i,j}$, for each zone is given by:

$$R_{g,i,j} = C_{g,i,j}\, P_{i,j}\, G_{c,i,j} \tag{9}$$

It is to be noted that, for the computation of runoff from rain, the coefficient C_g is used (not C_r, rainfall runoff coefficient), because the runoff from the rainfall falling on the GCA responds in the same way as the runoff from the melting of the glacier.

The daily total discharge from the GCA, Q_{GCA}, is computed by adding contributions from each elevation zone. Thus, discharge from the GCA for all the zones is given by:

$$Q_{\mathrm{GCA}} = \alpha \sum_{j=1}^{n} (M_{g,i,j} + M_{r,i,j} + R_{g,i,j})\, A_{\mathrm{GCA},i,j} \tag{10}$$

where n represents the total number of zones, $A_{\mathrm{GCA},i,j}$ is the glacier-covered area (km^2), and α is a conversion factor (1000/86400) used to convert runoff depth (mm d^{-1}) into discharge (m^3 s^{-1}).

Surface runoff from the glacier-free area

The source of surface runoff from the glacier-free area (GFA) is only rainfall. As for the melt runoff computations, runoff from the GFA, $R_{f,i,j}$ was also computed for each zone using:

$$R_{f,i,j} = C_{r,i,j}\, P_{i,j}\, G_{f,i,j} \tag{11}$$

where $C_{r,i,j}$ is the coefficient of runoff for rain and $G_{f,i,j}$ is ratio of GFA to the total area of *j*th zone on the *i*th day. Because GCA and GFA are complementary, $G_{f,i,j}$ can be directly calculated as $1 - G_{c,i,j}$. The total runoff from the GFA for all the zones is thus given by:

$$Q_{\mathrm{GFA}} \alpha \sum_{j=1}^{n} R_{f,i,j} A_{\mathrm{GFA},i,j} \tag{12}$$

where $A_{\mathrm{GFA},i,j}$ is the glacier-free area in the *j*th zone on the *i*th day.

Estimation of subsurface runoff

The subsurface flow or the baseflow represents the runoff from the saturated zone (subsurface) of the basin to the streamflow. The direct surface runoff having been accounted for from the melt and rainfall, the remaining water contributes to the groundwater storage through infiltration and appears at the outlet of the basin after much delay as subsurface flow or baseflow. The model deals with the hydrological processes separately for the GCA and GFA. No evaporation losses were considered from the GCA, whereas such losses were only considered from the GFA where some moisture is retained when rainfall occurs in this area. The depletion of soil water storage takes place due to evapotranspiration and percolation of water to the deep groundwater zone. It is assumed that 50% of the water retained in the soil percolates down to shallow groundwater and contributes to baseflow, while the remaining 50% accounts for loss from the basin in the form of evapotranspiration and percolation to the deep groundwater aquifer, which may appear further downstream or becomes part of deep inactive groundwater storage. The depth of runoff contributing to baseflow from each zone, $R_{b,i,j}$, is given by:

$$R_{b,i,j} = \beta[(1 - C_{r,i,j})\, R_{f,i,j} + (1 - C_{g,i,j})\, M_{t,i,j}] \tag{13}$$

where $M_{t,i,j} = M_{g,i,j} + M_{r,i,j} + R_{g,i,j}$ represents the total input to a particular zone from different sources and β is a coefficient (=0.50).

The subsurface runoff was computed by multiplying the depth with conversion factor α and area, and given as follows:

$$Q_b = \alpha \sum_{j=1}^{n} R_{b,i,j}\, A_{i,j} \tag{14}$$

where $A_{i,j}$ is total area of zone j on the ith day and represents the sum of $A_{\mathrm{GCA},i,j}$ and $A_{\mathrm{GFA},i,j}$. This component is also routed separately before being added to the other components of discharge from the melt and rainfall.

ROUTING OF DIFFERENT COMPONENTS OF RUNOFF

Routing of runoff from the GCA and GFA was done separately because the hydrological responses from these areas are different. The linear cascade reservoir approach was used for routing. Considering n reservoirs in a series, the outflow from the second reservoir becomes the inflow to the third reservoir, etc. The outflow from the nth reservoir represents the response of the basin in terms of outflow. As mentioned, routing of different components of streamflow has been done separately and then the total outflow from the basin was computed by summing the different routed components of runoff. In the present study, GCA and GFA were represented by one and two linear reservoirs, respectively. Keeping in view the different responses of melt and rain and their variations with time, both components were routed separately considering their respective areas, namely GCA and GFA. Each part of the basin was conceptualized as a cascade of linear reservoirs. The values of storage coefficients for these parts were optimized using the Rosenbrock optimization technique (Kuester & Mize, 1973).

The model routes the subsurface runoff similarly to surface runoff with a given value of subsurface storage coefficient, k_b, which is determined using streamflow records of the recession period. In order to determine the storage coefficient for the baseflow, the streamflow of the recession period was plotted against time on semi-log paper and a straight line was fitted. For this purpose, flow records of the later part of the melt season (i.e. 15 September–20 October 2001) were used. This year was considered as a better representation of recession of flow because the influence of rainfall on runoff was small over the whole melt period (Haritashya *et al.*, 2006b). The slope of the fitted line was used to determine the value of the recession constant, k_b, which in the present study is found to be about 38 days.

Total streamflow

The daily total streamflow emerging from the basin is calculated by adding the different routed components of discharge for each day:

$$Q = Q_{\mathrm{GCA}} + Q_{\mathrm{GFA}} + Q_b \tag{15}$$

As discussed above, the direct surface runoff results from the overland or near surface flow, while the baseflow is regarded as the contribution from the water stored in the groundwater reservoir to the streamflow. In order to consider the soil moisture deficit, soil moisture index, SMI, which represents the soil moisture deficit in the basin at the beginning of simulation, was considered. The contribution to baseflow only starts after saturation of the topsoil. In the present study, the initial value of SMI, determined on the basis of an appropriate match between observed and computed streamflow for the initial period, was 50 mm.

CALIBRATION OF MODEL

The model was calibrated using a daily data set of two melt seasons (2000 and 2001). The calibrated parameter values have been computed considering the overall performance of the model and reproduction of the flow hydrograph for the two melt seasons. The results of daily streamflow

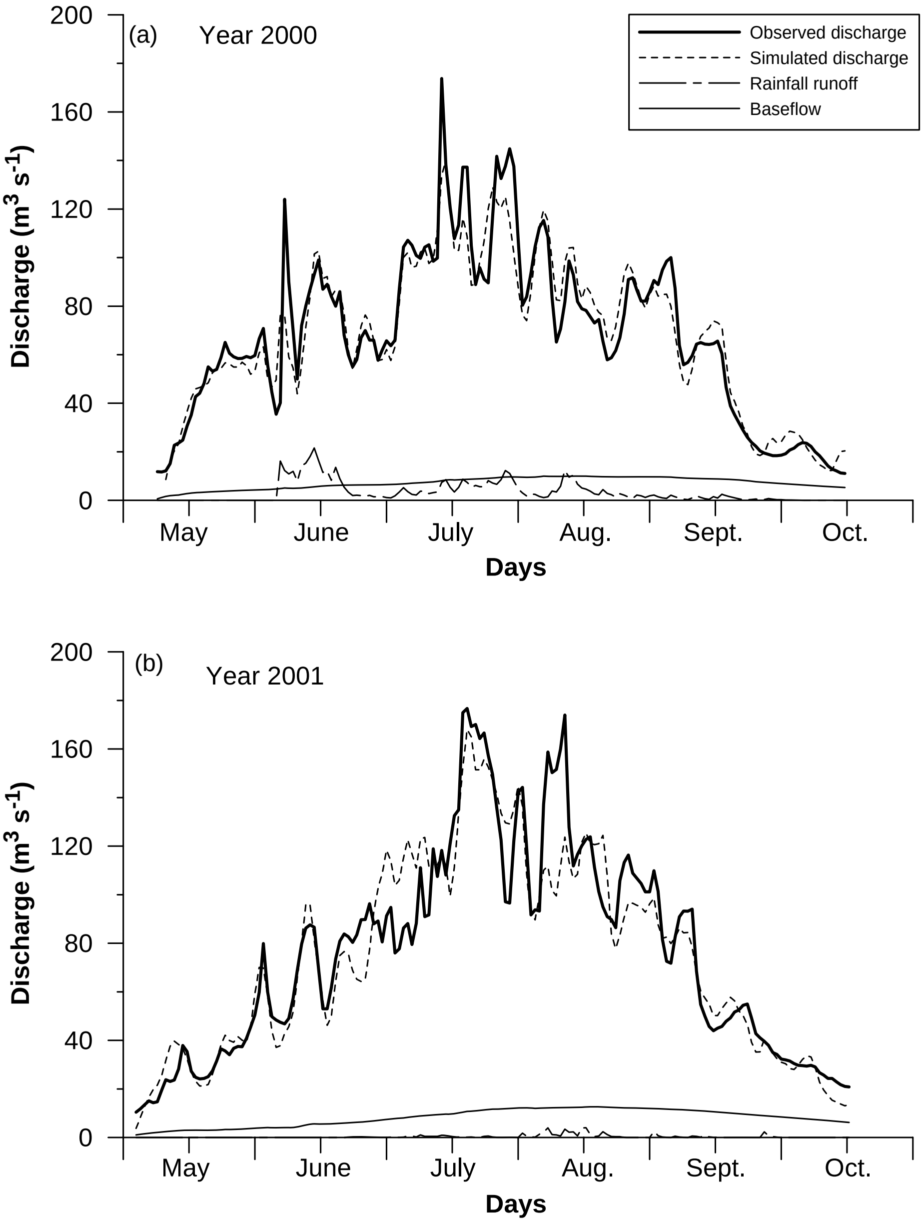

Fig. 4 Comparison of observed and simulated discharge for the calibration years (a) 2000 and (b) 2001.

simulated for two melt seasons are shown in Fig 4. In this figure, observed and estimated streamflow are shown along with the runoff due to rainfall and baseflow. Estimated and observed hydrographs match very well in both years. The efficiency of the model was determined using R^2 (Nash & Sutcliffe, 1970). For the melt seasons 2000 and 2001, R^2 was 0.97 and 0.95, while difference in volume (D_v) was –0.12% and –1.6%, respectively. The root mean square error (RMSE) for these two years was 0.25 and 0.29, respectively. High peaks of runoff for both years were well simulated by the model. The results indicate good performance of the model for both the years.

SIMULATION OF STREAMFLOW

After successful calibration of the model, it was used for simulation for two independent melt seasons, i.e. 2002 and 2003. The parameter estimates obtained in the calibration stage were used in the model for simulation years. The comparison of daily observed and simulated streamflow is shown in Fig 5. The value for R^2 was 0.97 and 0.98 for 2002 and 2003, respectively, while the

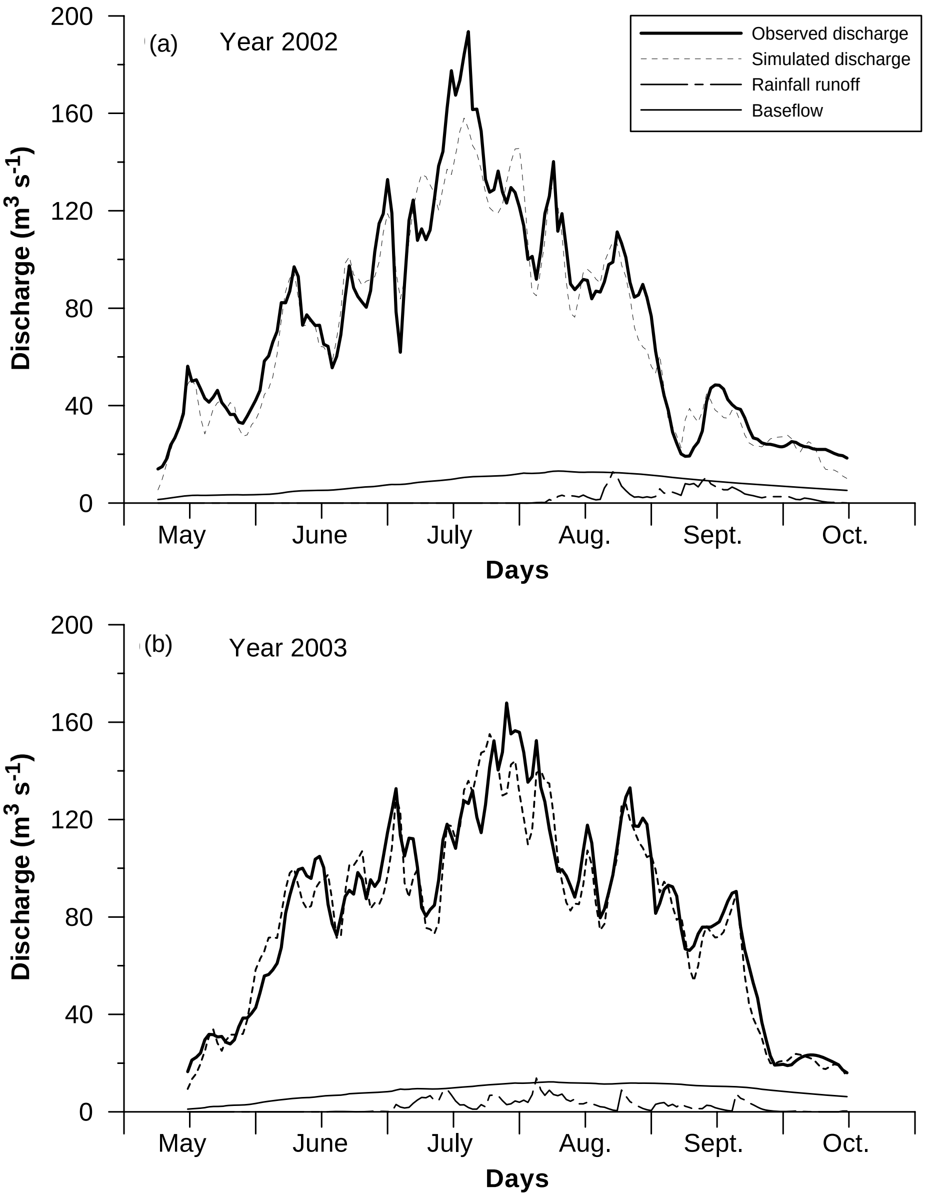

Fig. 5 Comparison of observed and simulated discharge for the simulation years (a) 2002 and (b) 2003.

corresponding value of D_v for these two years was –3.71% and –4.33%, and RMSE was 0.23 and 0.20. The overall efficiency of the model (R^2) over the study period of four years was about 0.96 and the average difference in computed and observed streamflow was only –2.5%. The results indicate that the model performed very well to generate the runoff distribution and volume of total flow.

Figure 5 also shows runoff generated from the melt, rainfall and baseflow. It can be noted that a major contribution in the study basin comes from melting in the glacierized part of the basin. Rainfall has not had much effect on the total runoff during the melt period. Moreover, the contribution of rain varies because of changes in its magnitude and distribution from season to season. Most of the high peaks observed during July and August were generated by glacier melt. However, some of the peaks in runoff were due to high rainfall. For example, in June 2000, the rainfall occurred on six days (5–10 June 2000) and provided total rainfall of 131.5 mm (Haritashya *et al.*, 2006a). This rain event generated a peak in the flow in the early part of the melt season. Similarly, another high-rainfall event sustained for eight days (6–13 September 2002), provided total rainfall of 222.8 mm, and generated a peak in the latter part of the melt season. The simulation of baseflow indicates that the baseflow contribution to the streamflow increases as the melt season advances, being at a maximum during the peak melt period and then starting to decrease.

Overall, the model reproduced the distribution of runoff over the melt season reasonably well for all the years, except for a few peaks in 2001 and 2002. It is assumed that some peaks in the observed runoff are produced by sudden bulk meltwater discharge from the previously stored meltwater in the glacier. One such peak can be seen in August 2001. Identification of such peaks is possible through simulation because neither rainfall nor temperature supports such peaks. Such events need detailed investigation into their formation, development and depletion, including the internal meltwater storage system.

CONTRIBUTION OF MELT AND RAINFALL TO THE TOTAL OUTFLOW

As the model has the capability to compute different components of runoff, it was therefore possible to determine the contribution of rain and melt in the total runoff at the gauging site. On the basis of analysis of four-year discharge simulation (2000–2003), it is found that on the seasonal scale most of the runoff is generated from the glacier melt (97%). The contribution of rain to runoff was very small (3%). Monthly contribution of melt and rainfall to total runoff is shown in Fig. 6. Table 2 shows average percentage contribution of rain and melt to the total streamflow for

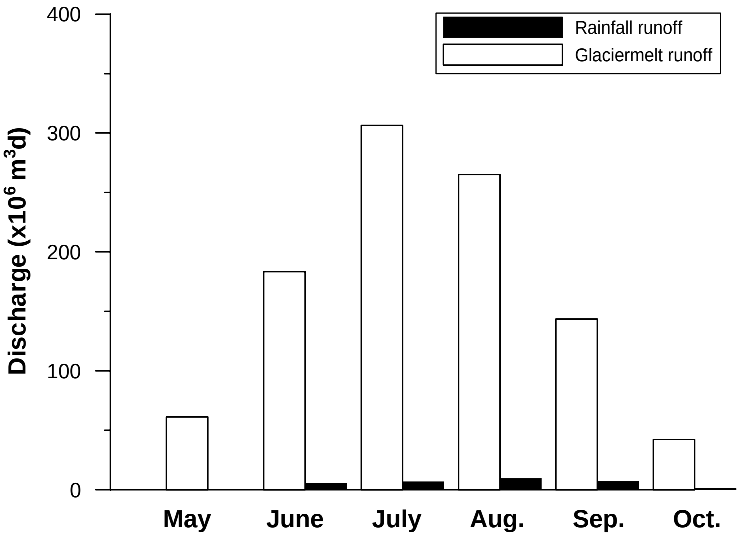

Fig. 6 Monthly contribution of glacier melt and rainfall to total runoff for the summer periods 2000–2003.

Table 2 Average contribution of glacier melt and rainfall to total streamflow for the summer periods 2000–2003.

Month	Melt contribution (%)	Rain contribution (%)
May	100	0.0
June	97.1	2.9
July	97.6	2.4
August	96.4	3.6
September	93.9	6.1
October	97.1	2.9
May–October	97.0	3.0

different months. It can be noted that during May total runoff is derived from melt. There is no contribution from rain. The maximum (6%) contribution of rain is observed in September.

DISCUSSION AND CONCLUDING REMARKS

Most of the large Himalayan basins receive runoff from melt as well as rain. The runoff from the glacierized basins is dominated by the melt because rainfall is much lower in the high-altitude regions of the Himalayas. Limited efforts are made to simulate flows in the glacier-dominated basins of the Himalayan region. The present study deals with simulation of streamflow for the Gangotri Glacier basin along with quantification of melt and rain components in the total runoff. The snowmelt model (SNOWMOD) was used in this study for simulating runoff from the Gangotri Glacier basin. The study shows that the temperature index method, a combination of T_{max} and T_{min}, worked very well for meltwater runoff modelling in the study basin, where availability of data is limited. The meteorological data in the study basin were only available for one station, which is established near the snout of the glacier. Both meteorological and hydrological data were collected for four melt seasons at the same site. Although daily mean temperature is the most commonly used index of temperature for melt computation, in the present study use of mean temperature underestimates the melt computation. Different weights were assigned for maximum and minimum temperature. Finally, 80% of maximum temperature and 20% of minimum temperature were found suitable in terms of reproduction of streamflow. The first two years (i.e. 2000 and 2001) were considered as the calibration period, while the next two years (i.e. 2002 and 2003) were used as the validation period. The model performed well for all four consecutive melt seasons (2000–2003). The R^2 for 2000, 2001, 2002 and 2003 was 0.97, 0.95, 0.97 and 0.98, respectively, while D_v was –0.12%, –1.6%, –3.71% and –4.33%, respectively. The model also determines the contribution of different components of runoff, i.e. glacier and rain. The study basin receives maximum contribution (97%) from glacier melt and only 3% of the total runoff as rainfall runoff.

A few streamflow peaks could not be generated in simulated runoff, which was possibly due to sudden release of stored water at some location in the glacier body. Such events are clearly identified because they are not supported by climatic conditions. Although very difficult, there is a need to carry out detailed investigations on such specific events. Moreover, it is felt that data collection at different altitudes would give a better distribution of climatic conditions over the glacier; therefore, such information should be collected for the glaciers.

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