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1   **Hydrologic modeling of a Himalayan mountain basin by using the SWAT model**

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7

8   **ABSTRACT**

9   A large population depends on runoff from Himalayan rivers which have high hydropower
10   potential; floods in these rivers are also frequent. Current understanding of hydrologic response
11   mechanism of these rivers and impact of climate change is inadequate due to limited studies. This
12   paper presents results of modeling to understand the hydrologic response and compute the water
13   balance components of a Himalayan river basin in India viz. Ganga up to Devprayag. Soil and
14   Water Assessment Tool (SWAT) model was applied for simulation of the snow/rainfed catchment.
15   SWAT was calibrated with daily streamflow data for 1992-98 and validated with data for 1999-
16   2005.Manual calibration was carried out to determine model parameters and quantify uncertainty.
17   Results indicate good simulation of streamflow; main contribution to water yield is from lateral and
18   ground water flow. Water yield and ET for the catchments varies between 43-46 % and 57-58% of
19   precipitation, respectively. The contribution of snowmelt to lateral runoff for Ganga River ranged
20   between 13-20%. More attention is needed to strengthen spatial and temporal hydrometeorological
21   database for the study basins for improved modeling.

22   Keywords: Hydrological modeling, SWAT, Western Himalaya, calibration

23

24   **1 INTRODUCTION**

25   Many rivers, springs and lakes in the mountain regions are fed by significant contribution runoff
26   from snow and glacier melt. The headwater catchments of most of the rivers in the Himalayan
27   region such as the Ganga, the Indus and the Brahamaputra, lie in the snow covered areas. Snowfall
28   is temporarily stored in high hills and the melt water reaches the river later in the hot season. Snow
29   and glacier runoff are vital in making big Himalayan Rivers perennial whereas the rainfall
30   contribution during the monsoon season is important for high flow volumes in rivers. Snow
31   accumulates in the Himalayas generally from November to March, while melt season spans the
32   months April to September. Snowmelt is the predominant component of runoff in mountains in
33   April to June months and it forms a significant constituent of streamflows during July - September.

34   High spatial and temporal variability in hydro-meteorological conditions in mountainous
35   environments requires spatial models that are physically realistic and computationally efficient
36   (Liston and Elder, 2006b). Among the models developed to simulate hydrological response of
37   mountainous basins, the most common approach followed for distributed snowmelt modeling in the
38   absence of detailed measured data is to subdivide the basin into zones based upon elevation,
39   allowing the model to discretize the snowmelt process based on watershed topography (Hartman et

40 al., 1999; Li et al., 2013, 2015, 2016). The list of models developed for modeling response of a
41 catchment subject to solid and liquid precipitation includes commercial software such as Mike-SHE
42 (http://mikebydhi.com) and the public domain models such as the SWAT model (Neitsch, 2002), the
43 Xinanjiang Model (Zhao et al., 1995)and the HBV model (Bergstrom, 1992). An obvious advantage
44 of the public-domain models is the saving in cost and ease in sharing model set-ups. SWAT is a
45 public-domain model that has been used extensively. A user-friendly interface to set-up the model
46 in a GIS framework, detailed user's manual and a large user base are the main reasons for a number
47 of applications of the SWAT model.

48   SWAT is a semi-distributed, continuous watershed modelling system, which simulates
49 different hydrologic responses using process based equations. Most of the applications of the
50 SWAT model have used daily or monthly time steps for simulation. Obviously, it has been
51 comparatively easy to obtain higher values of Nash-Sutcliffe Efficiency (NSE) for monthly data
52 than for the daily data. Further, SWAT model has been successfully applied to catchments with size
53 of a few sq. km to thousands of sq. km. For example, Spruill et al., 2000 applied the SWAT model
54 to simulate daily streamflows in a watershed in Kentucky covering an area of 5.5 km^2 whereas
55 Zhang et al., 2008 used it to simulate monthly runoff of a mountainous river basin in China
56 covering area of 114,345 km^2. Some more recent applications of SWAT for rainfall-runoff
57 modeling are those by Jain et al., 2010, Shawul et al., 2013, Kushwaha and Jain, 2013, Khan et al.,
58 2014, Tamm et al., 2016, Awan et al., 2016 and Singh et al., 2016. Tyagi et al., 2014 used it for
59 sediment modelling and Pandey et al., 2014 and Tamm et al., 2016 used results of SWAT to
60 estimate hydropower potential of a catchment.

61   Many studies have attempted to simulate water quality variables by employing the SWAT
62 model. Jha et al., 2006 simulated streamflow, sediment losses, and nutrient loadings in the Raccoon
63 River watershed and assessed impacts of land use and management practice shifts. Hafiz et al.,
64 2012 examined applied the SWAT model to model flow, sediments and water quality parameters in
65 upper Thachin River Basin, Thailand with catchment area of 5,693 km^2. It was reported that the
66 model gave good results. Qiu and Wang, 2014 applied the SWAT model to the Neshanic River
67 watershed to simulate streamflow and water quality parameters including total suspended solids
68 (TSS), total nitrogen (TN), and total phosphorus (TP). An attractive feature of the SWAT model is
69 its ability to model the catchment response due to snow/glacier melt and rainfall. Many studies have
70 harnessed this feature of the model. For instance, Lemonds et al., 2007 calibrated the SWAT model
71 to the Blue River basin (867 km^2) in Colorado (USA) by adjusting the snowmelt, snow formation,
72 and groundwater parameters and obtained good fits to average monthly discharge values (NSE =
73 0.71). As per Stehr et al., 2009, the snow component of SWAT was capable of providing a
74 reasonably good description of the snow-cover extension over a small Chilean Basin (455 km^2).
75 Pradhanang et al., 2011 compared snow survey data for the catchment of Cannonsville reservoir
76 with model simulated snowpack and snowmelt at different elevation bands. When measured and
77 simulated snowpack were compared, correlation coefficients ranging from 0.35 to 0.85 were
78 obtained. Simulations of daily and seasonal streamflow improved when 3 elevation bands were
79 used. Troin and Caya, 2014 demonstrated the ability of SWAT to simulate snowmelt dominated

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80 streamflow in the Outardes Basin, Quebec (Canada). The calibration of SWAT model showed a
81 satisfactory performance at the daily and seasonal time scales.

82   To improve the snow/glacier melt section of SWAT, some authors have attempted to
83 develop and plug-in routines for these processes. For example, Fontaine et al., 2002 developed a
84 snowfall-melt routine for mountainous terrain for the SWAT model which improved the correlation
85 between observed and simulated stream flow.Recently, Luo et al., 2013 proposed a dynamic
86 Hydrological Response Unit approach and incorporated an algorithm of glacier melt,
87 sublimation/evaporation, accumulation, mass balance and retreat into the SWAT model. They
88 simulated the transient glacier retreat and its impacts on streamflow at basin scale. This updated
89 model was applied in the Manas River Basin (MRB) in northwest China and the authors obtained
90 NSE of 0.65 for daily streamflow and small percent bias of 3.7% in water balance. The
91 hydrological community at large can make good use of such innovations if the relevant software
92 and guidelines for data preparation are made easily available.

93   Many other models or frameworks have been used in the recent past for modelling mountain
94 catchments. Shrestha et al. (2013) developed energy budget-based distributed modeling of snow
95 and glacier melt runoff in a multilayer scheme for different types of glaciers within a distributed
96 biosphere hydrological modeling framework. A study of Hunza River Basin (13,733 km^2) in the
97 Karakoram mountains where the SWAT model was used showed good agreement with observations
98 (NSE = 0.93). Likewise, Immerzeel et al. (2013) used results from an ensemble of climate models
99 along with a glacio-hydrological model for assessment of the impact of climate change on
100 hydrologic response of two Himalayan watersheds: the Baltoro (Indus) and Langtang (Ganges).
101 Future runoff was found to increase in both watersheds. A large uncertainty in future runoff arising
102 from variations in projected precipitation between climate models was noted. It is hoped that the
103 numerous attempts to apply the existing models to different geographies and research to develop
104 new modeling theories would lead to significant advances in hydrology of mountain basins across
105 the world.

106   Hydrological modeling of Himalayan river basins is important for many reasons. Nearly 2
107 billion people depend upon the waters of these rivers. Since most of these rivers are perennial and
108 the terrain has steep slopes, they have huge hydropower potential whose exploitation requires a
109 sound understanding of hydrologic response mechanism. Further, water triggered disasters are also
110 frequent in these basins. The region has complex topography and hydrologic data are scarce. In
111 addition, changes in land use/cover and climate are likely to significantly impact snow/glacier
112 accumulation and melt and hydrological response of these river basins. Snow and glacier melt
113 significantly contribute to flow of most Himalayan rivers and their modeling is an important
114 component in streamflow modeling of Himalayan rivers. Global warming is likely to accelerate
115 snow and glacier melt and it is necessary to study its impact for long term water resources planning.
116 However, in spite of well-recognized importance and need of such studies, not many attempts have
117 been made to assess hydrology of these rivers.

118   Clearly, there is a need for better understanding of the hydrologic response of the
119   Himalayan rivers for sustainable water management, developing the ability to forecast floods, and
120   predict the impacts due to changes in climate and land use/cover. To that end, a distributed model is
121   needed whose data requirements match with the availability. Although studies have been carried out
122   in mountainous catchments with a variety of topography, climate, and data availability by using the
123   SWAT model and the results have been quite good, only limited studies have been carried out in the
124   Indian Himalayan region. The hydrological and other data of this region that are needed for
125   modeling are not easily available and considerable efforts are required to collect and process the
126   data and setup a distributed model. Therefore, the objective of this study was to improve our
127   understanding of hydrological regime of the Himalayan rivers and enhance prediction of
128   hydrological processes. The main goal was achieved through carrying out hydrologic modeling of a
129   Himalayan river basin which receives contribution from snow/glacier and rainfall by employing
130   larger amount of observed data. We have also attempted to determine various water balance
131   components for better understanding of hydrologic response of the watershed. Better modeling and
132   hydrologic assessment of these basins will help in improved management of water resources,
133   harness hydropower potential, and partly overcome problems due to data scarcity. Such studies will
134   also help understand the likely impacts of climate change on water resources.

135   Before proceeding further the SWAT model is briefly described in the following.

136   **2 THE SWAT MODEL**

137   The Soil and Water Assessment Tool (SWAT) is a semi-distributed, continuous time watershed
138   modelling system which simulates hydrologic response of a catchment by using process-based
139   equations. It has been developed by the USDA Agricultural Research Service (Arnold et al., 1998).
140   Spatial variability in a catchment are represented in SWAT by dividing the catchment area into sub-
141   watersheds; these are further subdivided into hydrologic response units (HRUs). A HRU possesses
142   unique land use, soil types, slope and management practices (Neitsch et. al., 2002a, 2002b). To
143   computes the water balance, the model simulates a range of hydrologic processes such as
144   evapotranspiration, snow accumulation, snowmelt, infiltration and generation of surface and
145   subsurface flow components.

146   SWAT model allows division of maximum ten elevation zones in each sub-basin to consider
147   orographic effects on precipitation, temperature and solar radiation (Neitsch et al., 2001). Snow
148   accumulation, sublimation and melt are computed in each elevation zone and weighted average is
149   computed subbasin wise. Snowmelt depth in the same elevation band is assumed to be the same in
150   all sub-basins.

151

152   **2.1 Modeling of Snowmelt**

153   A temperature-index approach is used by SWAT model to estimate snow accumulation and
154   melt. Snowmelt is calculated as a linear function of the difference between the average snowpack
155   maximum temperature and threshold temperature for snowmelt. Snowmelt is combined with
156   rainfall while calculating infiltration and runoff. SWAT does not include an explicit module to
157   handle snow melt processes in the frozen soil, but includes a provision for adjusting infiltration and

158 estimating runoff when the soil is frozen (Neitsch et al., 2005). Despite this limitation, SWAT is
159 considered to be an appropriate integrated model for addressing a range of issues. It is noted that
160 many of the existing models do not have the capability to model both snow/glacier melt and
161 rainfall-runoff processes.

162   In the temperature-index approach, temperature is a major factor that controls snowmelt
163 (Hock, 2003). Snowmelt is computed as a linear function of the difference between average
164 snowpack maximum temperature and the threshold temperature for snowmelt, SMTMP:

$$SNO_{mlti} = b_{mlti} \cdot SNO_{covi} \left[\frac{T_{snowi} + T_{maxi}}{2} - SMTMP \right]$$

165   (1)

166 Where SNO_{mlti} is the amount of snowmelt on day i (mm H_2O), T_{maxi} is the maximum air
167 temperature on day i (°C), SMTMP (°C) is snowmelt base temperature above which snow will be
168 allowed to melt and b_{mlti} is the melt factor on day i (mm H_2O-day). Snowmelt is included with
169 rainfall in computation of infiltration and runoff.

170   The classification of precipitation is based on a threshold value of mean air temperature. If
171 the average daily air temperature is below the snowfall temperature, the precipitation in a HRU is
172 considered as solid (or snow) and the liquid water equivalent of the snowfall is added to snowpack.
173 The snowpack is depleted by snowmelt or sublimation. The mass balance for the snowpack for a
174 HRU is:

$$SNO_i = SNO_{i-1} + P_s - E_{subi} - SNO_{mlti}$$

175   (2)

176 where, SNO_i is the water content of the snowpack (mm H_2O), P_s is the water equivalent of snow
177 precipitation (mm H_2O), E_{subi} is the amount of snow sublimation (mm H_2O), and SNO_{mlti} is the
178 water equivalent of snow melt (mm H_2O), all for day i.

179   The spatial non-uniformity of the areal snow coverage over the HRU is taken account
180 through an areal snow depletion curve that describes the seasonal growth and recession of the
181 snowpack (Anderson, 1976). Two addition parameters are defined at the watershed scale,
182 SNOCOVMX and SNO50COV. These control the areal depletion curve by accounting for the
183 variable snow coverage as:

$$SNO_{covi} = \frac{SNO_i}{SNOCOVMX} \left[\frac{SNO_i}{SNOCOVMX} + \exp\left(cov_1 - cov_2 \cdot \frac{SNO_i}{SNOCOVMX} \right) \right]^{-1}$$

184   (3)

185 where SNO_{covi} is the fraction of HRU area covered by snow on the day i, SNO_i is the water content
186 of the snow pack on day i, SNOCOVMX is the minimum snow water content that correspond to
187 100% snow cover (mm H_2O), and cov_1 and cov_2 are coefficients that control the shape of the curve.

188 **2.2 Modeling of Catchment Hydrology**

189 Weather, soil properties, topography, vegetation and land management practices are the most
190 important inputs for the SWAT model. SWAT computes actual soil water evaporation using an
191 exponential function of soil depth and water content. The modified Soil Conservation Service

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192 (SCS) curve number method is used to compute runoff. The influence of plant canopy infiltration
193 and snow cover is incorporated into the runoff calculation. To support soil water processes such as
194 infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers, the soil profile
195 is subdivided into many layers. When field capacity of a soil layer is exceeded downward flow
196 occurs and the layer below is not saturated. Percolation from the bottom of the soil profile recharges
197 the shallow aquifer. Lateral sub-surface flow in the soil profile is calculated simultaneously with
198 percolation. Groundwater flow contribution to total stream flow is simulated by routing the shallow
199 aquifer storage component to the stream. Runoff is routed through the channel network by the
200 variable storage routing method or the Muskingum method (Neitsch et al., 2005).

201   SWAT model simulates hydrologic cycle based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{n} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

202   (4)

203 where, SW_t is the final soil water content (mm H_2O), SW_o is the initial soil water content (mm
204 H_2O), t is time in days, R_{day} is amount of precipitation on day i (mm H_2O), E_a is the amount of
205 evapotranspiration on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O),
206 w_{seep} is the amount of percolation and bypass exiting the soil profile bottom on day i (mm H_2O),
207 and Q_{gw} is the amount of return flow on day i (mm H_2O).

208   Since the model maintains a continuous water balance, the subdivision of the watershed in
209 HRUs enables the model to consider differences in evapotranspiration for different crops and soils.
210 Runoff is predicted separately for each sub area and is routed to compute total runoff for the basin.

211   SWAT model software and documentation are freely available through Internet at
212 http://swat.tamu.edu/software/swat-executables/.

213

214 **2.3 Temperature index with elevation band approach**

215   This method incorporates elevation and temperature which is used to determine the snow
216 pack and snowmelt caused by orographic variation in precipitation and temperature. Many studies,
217 e.g., Zhang et al. (2008), have shown that elevation is an important factor in the variation of
218 temperature and precipitation. Fontaine et al. (2002) introduced a modified snowfall-snowmelt
219 routine for mountainous terrain into SWAT. This modified routine allows the SWAT model to
220 divide each sub-basin into 10 elevation bands and simulates the spatial and temporal variation of
221 snowpack and snowmelt on account of elevation. The temperature and precipitation for each
222 elevation band was adjusted by using:
223

224 $T_B = T + (Z_B - Z) \cdot dT / dZ$ (5)
225 $P_B = P + (Z_B - Z) \cdot dP / dZ$ (6)

226   Where, T_B is the mean temperature (ºC) in the elevation band, T is the temperature measured at the
227   weather station (ºC), Z_B is the midpoint elevation of the band (m), Z is the elevation (m) of the
228   weather station, P is the precipitation measured at the weather station (mm), P_B is the mean
229   precipitation of the band (mm), dP/dZ is the precipitation lapse rate (mm⁄km), and dT/dZ is the
230   temperature lapse rate (ºC⁄km).
231
232   **3   THE STUDY AREA AND DATA USED**

233   In the present study, Ganga River Basin up to Devprayag have been considered. The study area lies
234   in the North- Western Himalayan ranges, between latitudes 30º to 31º 30' North and longitudes 78º
235   7' to 80º 15' East in India and is shown in Figure 1.The size of the catchment is about 18728
236   $km^2$and elevation varies from 427 m to 7785 m. Bhagirathi and Alaknanda Rivers are the two
237   headwater streams that join at Devprayag to form Ganga River. The Bhagirathi River originates
238   from the snout of the Gangotri Glacier at Gomukh (3900 m). It flows for 217 km to reach
239   Devprayag and is joined by Bhilangana and Asiganga Rivers on the way. Asiganga joins Bhagirathi
240   River at 5 km upstream (1120 m) of Uttarkashi from west direction. Bhilangana River originates
241   from Khatling glacier (3950 m) and joins the Bhagirathi River at Tehri from east direction.
242   Alaknanda River rises at the confluence and the foot of the Satopanth and Bhagirath Kharak
243   Glaciers. The Alaknanda River flows for about 224 km before meeting with Bhagirathi River at
244   Devprayag. Its main tributaries are Dhauli Ganga, Pindar, Nandakini and Mandakini. The average
245   rainfall in the study area varies between 1000 to 2500 mm, of which 60-80% falls during the
246   monsoon period between June and September. The rivers experiences strong seasonal climatic
247   variations, which is also reflected in the monthly variation in stream flows. High flow takes place
248   during June-September, when the combined influence of rainfall and snow melt is at the maximum.

249   In this study, a number of maps have been prepared. The sources and resolution of ASTER
250   DEM, land use land cover map and soil map are given in Table 1.

251   Meteorological data for the study area consisted of 16 years of time series (1990-2005) of
252   daily precipitation, minimum and maximum temperature, solar radiation and wind speed for 7
253   stations, namely Badrinath, Joshimath, Karanprayag, Rudraprayag, Uttarkashi, Tehri and
254   Devprayag. The rainfall data obtained for these stations were having many gaps. Therefore,
255   precipitation data from *Asian Precipitation - Highly-Resolved Observational Data Integration*
256   *Towards Evaluation of Water Resources* (APHRODITE's Water Resources) were used. The
257   APHRODITE project develops state-of-the-art daily precipitation datasets with high-resolution
258   grids for Asia. The datasets are created primarily with data obtained from a rain-gauge-observation
259   network. APHRODITE's Water Resources project has been conducted by the Research Institute for
260   Humanity and Nature (RIHN) and the Meteorological Research Institute of Japan Meteorological
261   Agency (MRI/JMA) since 2006. A daily gridded precipitation dataset for 1961-2007 was created by
262   collecting rain gauge observation data across Asia through the activities of the APHRODITE
263   project (http://www.chikyu.ac.jp/precip/).The final data product does not have any gaps.

264   APHRODITE data is available in the form of grid of 0.5°×0.5° and 0.25°×0.25°. The data of
265   0.25°×0.25° was downloaded for the period of 1961-2007 and converted into map form using

266 ArcGIS and exported to ERDAS Imagine. The grids for which data were downloaded and used in
267 this study include Devprayag (altitude 469m), Tehri (608m), Rudraprayag (612m), Karnprayag
268 (784m), Joshimath (1446m) and Badrinath (3136m).

269   Daily stream flow data collected from Central Water Commission (CWC) for gauging
270 station located in the study area were used for model calibration and validation purpose. The
271 discharge gauging station Devprayag-Z9 is located downstream of the confluence of Bhagirathi and
272 Alaknanda rivers at Devprayag. The data measured at Devprayag-Z9 site were used to model the
273 Ganga River Basin up to Devprayag.

274

275 **3.1 Land Use and Soil Data**
276 Land use is one of the most important factors affecting runoff, soil erosion and evapotranspiration
277 in a watershed (Neitsch et al., 2005).

278   In the Ganga basin up to Devprayag, the most dominant land use/ land cover are open forest,
279 dense forest, barren land, snow cover area and range land covering 23.28%, 20.99%, 13.41%,
280 36.4% and 5.9% of the total basin area, respectively (Figure 2). For soils, Orthents (66%),
281 typicudorthents (21%) and typiccryochrepts (12%) are the most dominant soils having 2, 3 and 3
282 layers respectively in the basin (Figure 3).

283

284 **3.2 Model Set Up**
285 In the setup of SWAT model for the study catchment, the first step is identification and delineation
286 of hydrological response units (HRUs). River network for Ganga basin up to Devprayag were
287 delineated from ASTER DEM by using the analytic technique of the ArcSWAT 2009 GIS
288 interface(Figure 4).To obtain a reasonable numbers of HRUs within each subbasin, a unique
289 combination of landuse and soil (thresholds of 10% in land use/land cover and 5% in soil type)
290 were used. In this procedure, the Ganga River Basin was divided into 7 sub-basins and 126 HRUs
291 as shown in Figure 5. These set up ensures a stream network definition that satisfactorily represents
292 the dominant land uses and soils within each subbasin and at the same time, a reasonable number of
293 HRUs are created in each sub-basin.

294   The SWAT model has a large number of parameters that describe the different hydrological
295 taking place in the study basin. During calibration process, model parameters were systematically
296 adjusted to obtain results that best match with the observed values. In the validation process, the
297 catchment response was simulated by using the parameters finally obtained during the calibration
298 process. For evaluating the model performance computed hydrographs was compared with the
299 observed hydrograph. It may be stated here that the streamflow data for the Ganga basin is
300 classified and cannot be disclosed. Hence, we have shown scaled values of the flows in various
301 graphs of Ganga basin.

302   The length of calibration data is an important factor in model calibration. The available data
303 is usually partitioned in two sets: calibration data and validation data. Usually, calibration is carried
304 out by using more years of data; say about 60 – 75 % of the available data. Typical questions that
305 arise in this respect are: how much data are necessary/enough to obtain a good model calibration

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306 and what are the characteristics that the calibration data should have to maximize the chances of
307 obtaining reliable parameter estimates? Ideally, model calibration should result in parameter values
308 that produce the best overall agreement between simulated and observed values (discharge in this
309 case). Yapo et al., 1996 found that for the watersheds similar to their study area, approximately 8
310 years of data may be necessary to obtain a calibration that is relatively insensitive to the period
311 selected and that the benefits of using more than 8 years of calibration data may be marginal.
312 Regarding the characteristics, parameter identifiability significantly improves when the all the
313 hydrologic components are activated during the calibration period.

314   Statistical performance measures of the hydrological models are computed to determine
315 how the values simulated by the model match with those observed. For this study, the statistical
316 criteria that were used to evaluate model performance were the goodness-of-fit (R^2), the Nash-
317 Sutcliffe efficiency index (NSE) and coefficient of regression line multiplied by the coefficient of
318 determination (bR^2). The model performance is considered to be better as the values of R^2 and NSE
319 approach unity.

320   The observed daily stream flow data from year 1990 to 1998 were used to calibrate the
321 SWAT model and the model was validated by using the data from the year 1999 to 2005. Data for
322 the first two years (1990 and 1991) were reserved as "warm-up" period (to overcome the errors due
323 to incorrect initial conditions, the results of model run for a few initial periods are not used in
324 analysis of results. These initial periods are termed as the warm up period). Thus the model
325 calibration statistics was evaluated for the period 1992-1998.

326

327 **4 RESULTS AND DISCUSSIONS**

328   Initially, the SWAT-CUP which uses Sequential Uncertainty Fitting (SUFI2) algorithm
329 developed by Abbaspour et al., 2007 was used in this study.SUFI2 is a multi-site, semi-automated
330 global search procedure for model calibration and uncertainty analysis. The sources of uncertainties
331 which includes temperature and rainfall parameters and measured data are accounted for in SUFI2.
332 SUFI2 uses P-factor, the percentage of measured data bracketed by the 95% prediction uncertainty
333 (95PPU), and the R-factor average width of the 95PPU band divided by the standard deviation of
334 the measured data, to assess uncertainty. Abbaspour et al., 2007 have described SUFI2 algorithm in
335 detail.

336   While studying theSUFI2 calibration results, it was seen that in the table of monthly values
337 of various water balance components produced by SWAT, snowfall had fairly high values in
338 monsoon months whereas the study area does not receive snowfall in monsoon months (June to
339 September). PLAPS and TLAPS were the parameters controlling the temporal distribution of
340 precipitation (whether rain or snow). The calibrated values of PLAPS and TLAPS from the SWAT-
341 CUP were 8.5 and -5.83. To have realistic values of precipitation distribution, TLAPS and PLAPS
342 were changed systematically and TLAPS equal to -4.0 and PLAPS equal to 8.55 yielded
343 precipitation values which were realistic for the study area. However, as a result of this change,

344   there were many significant deviations between observed and simulated hydrographs. In particular,
345   the recession limbs and hydrograph during lean season had poor match as shown in Figure. 6.

346   At this stage, sensitivity analysis of model parameters was performed. Twenty calibrated
347   parameters including seven snowmelt related parameters were used for sensitivity analysis. The
348   sensitivity rank, default value, range of the parameter values and the optimal values for Devprayag
349   sites in the basin are given in Table 2. The remaining parameters were not much sensitive for the
350   model output.A number of SWAT parameters are related to snow but out of these, three parameters,
351   viz. maximum temperature index melt factor SMFMX, the snowmelt base temperature SMTMP and
352   the minimum temperature index melt factor SMFMN were found to be important.

353   The parameters were ranked in terms of their sensitivity to the model calibration. These
354   sensitive parameters were mainly responsible for changes in model output during calibration.
355   Results showed that CN is the most sensitive parameter to changes in discharge. Next to CN, the
356   other parameters that were found to be sensitive are those related to soil and groundwater. Among
357   these, ALPFA_BF is the baseflow recession constant.

358   For proper simulation of the hydrograph during post monsoon and lean season, the changes
359   in hydrograph in response to changes in several key parameters were also studied. It is noted during
360   sensitivity analysis that changes in some model parameters may cause different type of changes in
361   the simulated discharge in different seasons (monsoon and post monsoon). For instance, if the value
362   of CN is increased, the simulated streamflow increased from September to May but decreased from
363   June to August. When the value of ALPHA_BF was reduced, the simulated streamflow was found
364   to increase from October to March and decrease from April to September. When the value of
365   SOL_AWC was decreased, the simulated streamflow increased from September to February and
366   decreased from March to August. When the value of SOL_K was increased, the simulated
367   streamflow increased from February to August but decreased from September to January. When the
368   value of GW_DELAY was increased, the simulated streamflow increased from March to August
369   and decreased from September to February.

370   To improve the match between observed and simulated hydrographs in terms of recession
371   limb and base flow, it was hypothesized that the movement of water through soil and ground water
372   zone is not being properly modeled. Since baseflow was being under-simulated, more water should
373   be allowed to enter the sub-surface zone, stay there for some time, and then emerge as baseflow.
374   Accordingly, several simulations were carried out by changing the soil and ground water related
375   parameters till the simulated hydrographs shows a good match with the observed hydrograph. The
376   parameters that were systematically tuned include ALPHA_BF, SOL_AWC, SOL_K, and
377   GW_DELAY. Two statistical performance measures (coefficient of determination R^2 and NSE) and
378   visual inspection of the plot between observed and computed hydrographs were used to evaluate the
379   performance of the model in simulating streamflows and to decide which parameters to change.

380   The hydrographs of the observed and simulated daily and monthly flows for the calibration
381   period (1992-1998) for the Ganga Basin up to Devprayag are shown in Figure 7a and 9a. It is seen

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382   that the overall shape of the simulated hydrograph is matching well with the observed hydrograph
383   and the recession behaviour is also well simulated now. A few of the observed high peaks have
384   been simulated well while some of the peak values do not match well. The time series of the
385   observed and simulated daily and monthly hydrographs for the validation period are shown in
386   Figure 8a and 10a. It is seen from the graph that the simulated hydrograph correlates significantly
387   well with observed hydrograph. Scatter plot between observed and simulated daily and monthly
388   discharges for the calibration data (Figure 7b and 9b) indicate even distribution of most of the
389   points around the 1:1 line. Of course, a few data points are away from the line. Further, for the
390   validation period, the scatter plot for daily and monthly (Figure 8b and 10b) also shows the points
391   of the simulated flows are close to the 45° line.

392   The statistical performance indicators for calibration and validation for the Ganga basin up
393   to Devprayag are given in Table 3. The coefficient of determination (R^2) was 0.69 and 0.95 for
394   daily and monthly calibration period and 0.57and 0.94 for daily and monthly during validation
395   period. The NSE was computed as 0.64 and 0.80 for daily and monthly calibration period and
396   0.49and 0.85for daily and monthly validation period. Thus one may conclude that the indices for
397   monthly data are excellent and can be termed as very good for the daily data. Figure 11 show the
398   plot of observed and computed hydrograph for one year. It can be seen that some peaks have been
399   properly simulated but some are not. It is highlighted that the density of raingauge network in the
400   study area is grossly inadequate. Due to this many rainfall events that occur in the vicinity
401   contribute large volumes of water in the model even though their spatial coverage may be small. On
402   the other hand, if the event does not occur around the raingauge will be missed even though it may
403   have a large spatial coverage.

404   For calibration and validation, various water balance components are given in Table 4. The
405   water balance components include: the total amount of precipitation, actual evapotranspiration,
406   snowmelt runoff, and water yield. Here, water yield includes surface runoff, lateral flow to stream
407   and water from shallow aquifer that returns to river reach. The results indicate that contribution
408   from direct surface runoff is small in the water yield and the main contribution to water yield is
409   through lateral flow and ground water flow. ET comes out to be 43-46% of precipitation. As
410   catchment of Ganga river up to Devprayag site has comparatively less snow covered area, ET is at
411   higher rate. The snowmelt runoff contribution at Devprayag site comes out to be 20% and 13% of
412   the water yield during calibration and validation respectively. The water yield, i.e. sum of surface
413   runoff, lateral runoff and ground water contribution in stream flow comes out be about 57-58%of
414   the precipitation. In the basin, interflow contributes significantly to the water yield as compared to
415   shallow groundwater.

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417   **5 CONCLUSIONS**

418   This study has attempted to simulate the response of hilly parts of a Himalayan river basin, viz., the
419   Ganga basin up to Devprayag. The values of R^2 and NSE for calibration (1992-1998) and validation
420   (1999-2005) vary between 0.69and 0.64 and can be considered as good (as per Moriasi et al., 2007)

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421 for the basin given the availability of meteorological and pedological data. Overall, the hydrograph
422 shape could be reproduced satisfactorily although all the peaks and the recession limbs could not be
423 reproduced very well. Thus, the SWAT model can be considered to be a good tool to model the
424 discharge hydrograph and various water balance components for a Himalayan basin.

425 Water yield for the basin is ranging between 57-58% of the precipitation. Snow/glacier melt
426 contribution is 13-20% for the Ganga basin. In the Ganga basin, interflow contributes significantly
427 to the water yield. However, these results are required to be buttressed by more detailed hydrologic
428 modeling of some more river basins to investigate their response mechanism. To that end, more
429 attention is needed to strengthen spatial, soil and hydrometeorological database including snowfall
430 for the study basins by installing automatic weather stations to measure precipitation (rain and
431 snow) and other climatic variables at various elevations. Isotope analysis may be carried out to
432 separate the runoff components and compare the results with hydrologic model.

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558   Table 1: Sources and description of the input data for the Ganga Basin up to Devprayag

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Data Type	Source	Spatial/ Temporal Resolution	Description
Topography	http://gdem.ersdac.jspacesystems.or.jp	90 m	Aster Digital Elevation Model
Land use/Land cover	www.iitd.ac.in	90 m	Land-use Classification
Soils	www.iitd.ac.in	90 m	Soil Classification
Weather Data	APHRODITE DATA	1.0 deg 0.25 deg	Temperature, Solar Radiation, Wind Speed, Precipitation, Data
Stream Flow	Central Water Commission, Dehradun	Daily	Daily stream flows measured at the gauging stations

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562   Table 2: Description of 20 calibration parameters: Sensitivity rank, Default value, Range and
563   Optimal value

Parameters	Description	Sensitivity Rank	Default value	Range	Optimal value
CN2	Initial SCS runoff curve number for moisture condition II	1	77-92	35-98	55-92
TLAPS	Temperature Lapse Rate	2	0	-10 to 10	-4.0
SOL_AWC	Available water capacity of the soil layer (mm/mm)	3	0.067 – 0.146	0 - 1	0.024 – 0.053
SOL_K	Saturated hydraulic conductivity of soil (mm/hr)	4	1.95 – 121.12	0 - 2000	3.0 – 186.61

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SOL_Z	Soil depth (mm)	5	60 - 170	0 -3500	30 - 300
ALPHA_BF	Base flow alpha factor (days)	6	0.084	0-1	0.07
GW_DELAY	Groundwater delay (days)	7	31	0-500	35
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	8	1	0-500	499
RCHRG_DP	Deep aquifer percolation fraction	9	0.05	0-1	0.015
GW_REVAP	Groundwater revap coefficeient	10	0.02	0.02 - 0.20	0.162
CH_K2	Effective hydraulic conductivity in main channel alluvium (mm/h)	11	0	-0.01 - 500	20.43
ESCO	Soil evaporation compensation factor	12	0.95	0-1	0.40
PLAPS	Precipitation Lapse Rate	13	0	-1000 to 1000	8.55
SMTMP	Snowmelt base Temperature (^{o}C)	14	0.5	-5 to 5	-3.05
SMFMN	Minimum melt rate for snow during year (mm H_2O/^{o}C -day)	15	4.5	0 - 10	0.80
SMFMX	Maximum melt rate for snow during year (mm H_2O/^{o}C -day)	16	4.5	0 - 10	4.79
SNO50COV	Snow water content corresponding to 50% snow cover	17	0.50	0 - 1	0.48
SFTMP	Snowfall Temperature (^{o}C)	18	1	-5 to 5	-2.79
TIMP	Snow pack temperature lag factor	19	1	0-1	0.394
SNOCOVMX	Minimum snow water content corresponding to 100% snow cover, SNO100 (SNOCOVMX- mm H_2O)	20	1	0 - 500	242.40

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569 Table 3: Statistical performance indicators for calibration and validation for Ganga River Basin up
570 to Devprayag
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Daily/Monthly	Calibration (1992-1998), Validation(1999-2005)	R^2	NSE
Daily	Calibration	0.69	0.64
	Validation	0.57	0.49
Monthly	Calibration	0.95	0.80
	Validation	0.94	0.85

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576 Table 4: Water balance components in mm

	Precipitation	ET	Surface Runoff	Lateral flow	Ground water flow	Water yield	Snow fall	Snow melt
Calibration	1236.1	484.8	96.63	297.30	293.92	686.87	140.74	73.84
Validation	1203.3	512.1	74.24	299.37	290.05	662.81	110.57	48.87

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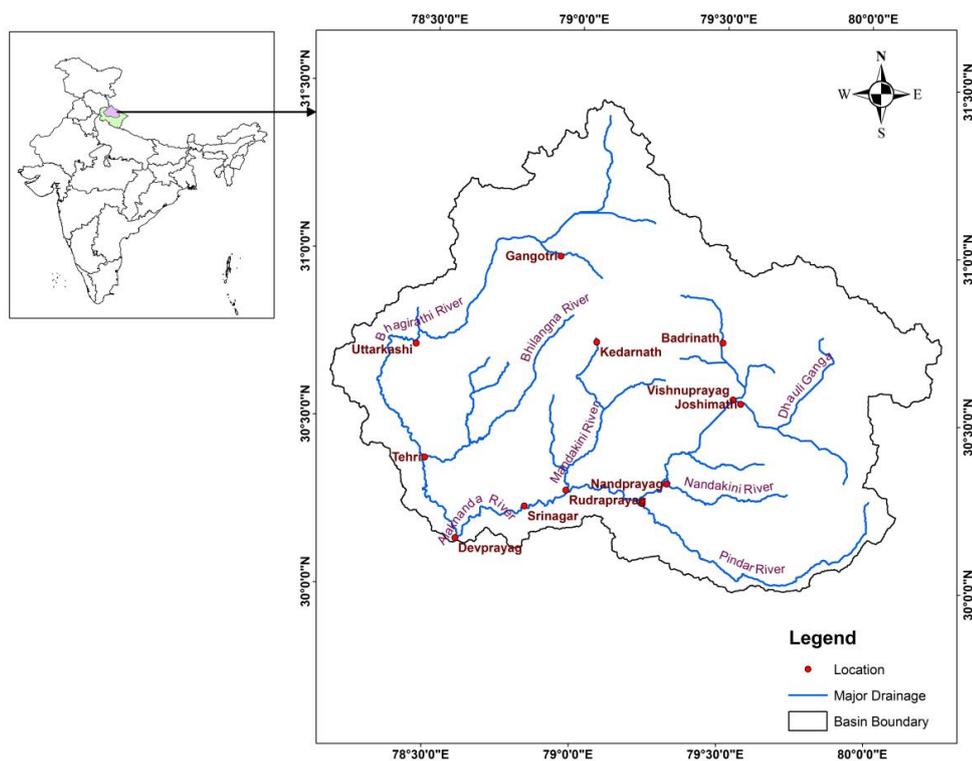
Figure 1: Index map of Ganga basin up to Devprayag

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Figure 2: Land use/cover of Ganga basin up to Devprayag

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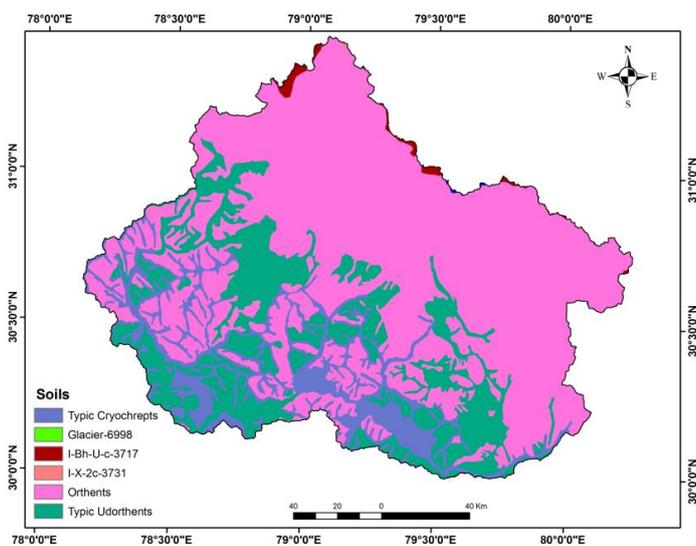
Figure 3: Soil map of Ganga basin up to Devprayag

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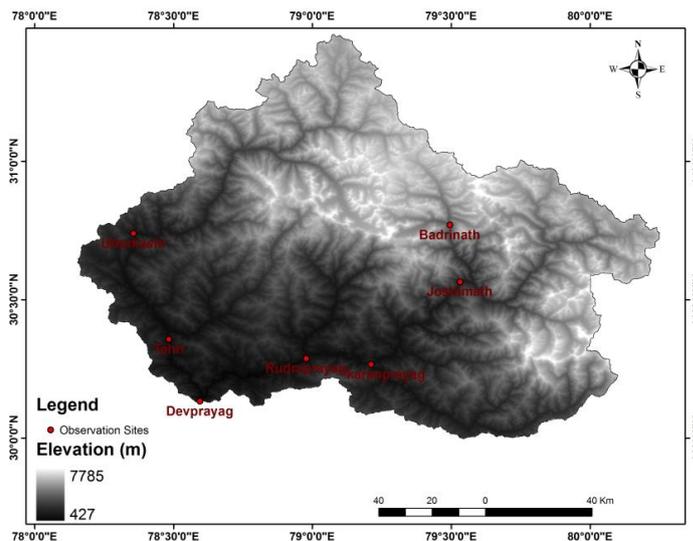
Figure 4: DEM of Ganga basin up to Devprayag
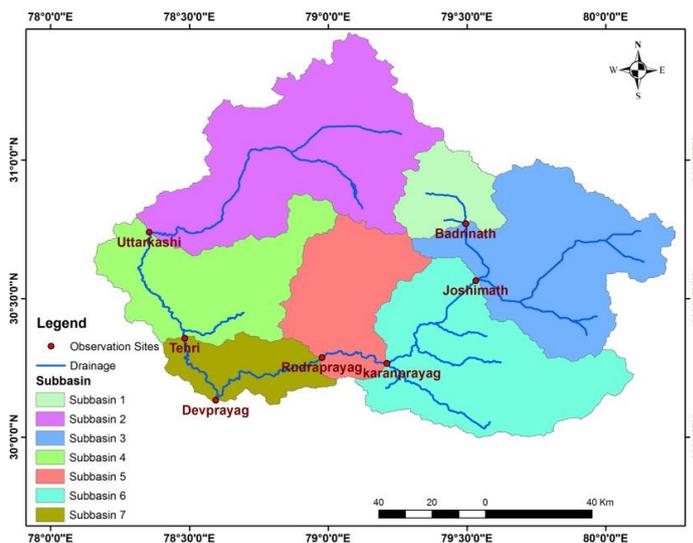
Figure 5: Sub basin map of Ganga basin up to Devprayag

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Figure 6: Comparison of daily observed and simulated stream flow hydrograph of Ganga basin up to Devprayag during calibration period (1992-1998) during iteration process

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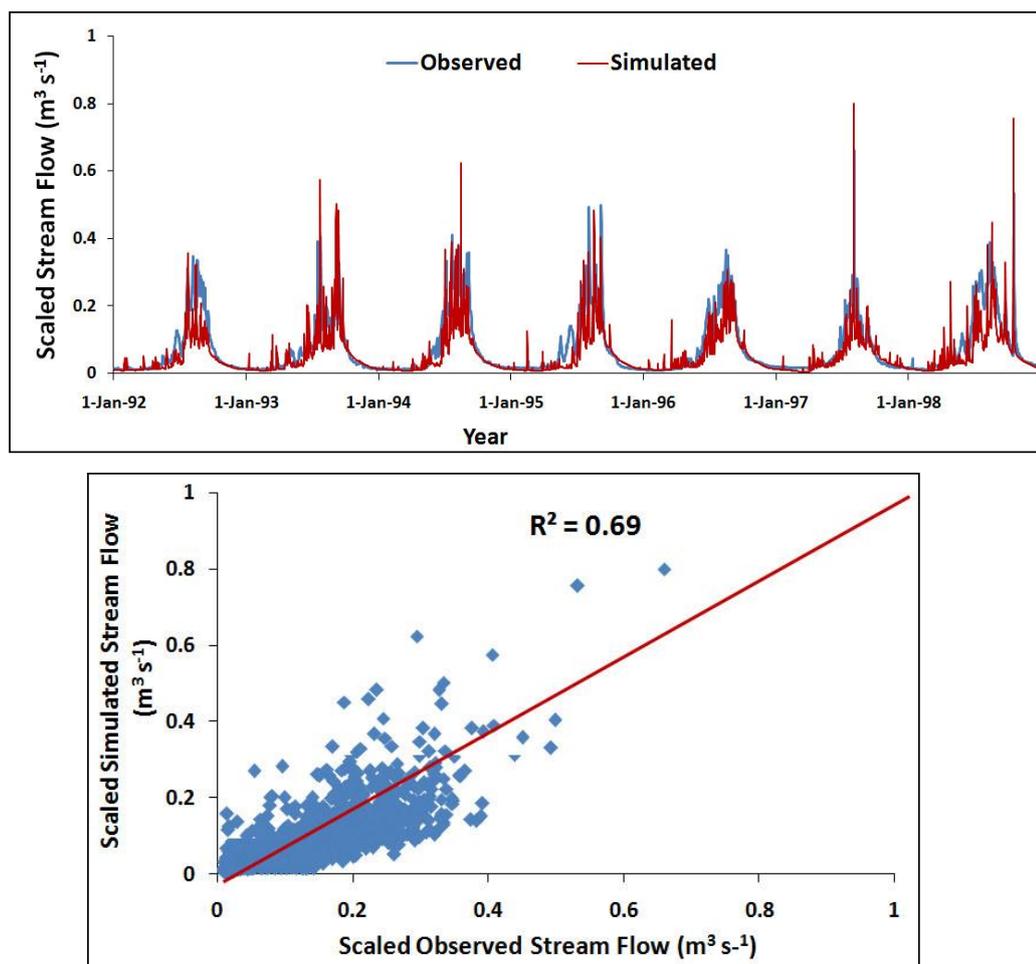
Figure 7: Comparison of a) daily observed and simulated stream flow hydrograph of Ganga basin up to Devprayag during calibration period (1992-1998), and b) scatter plot
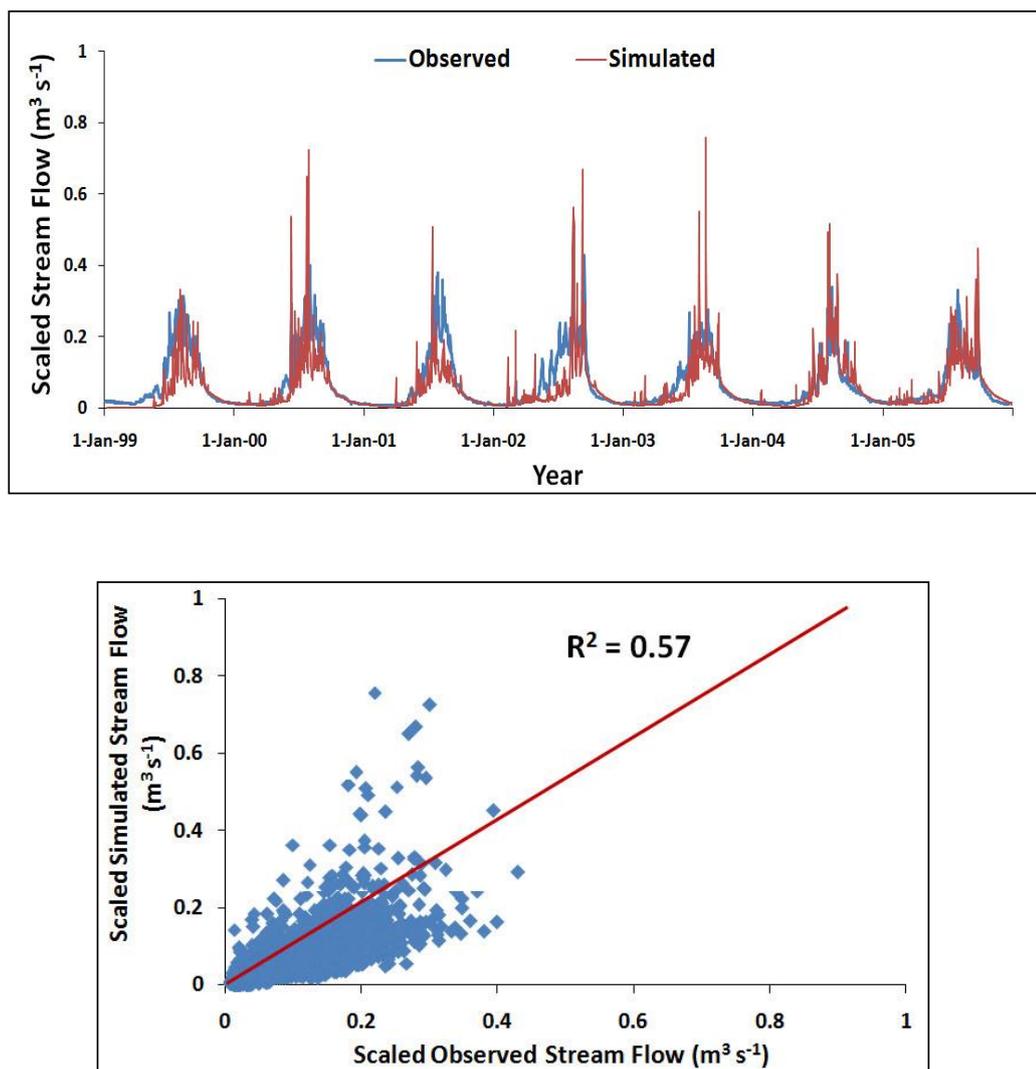
Figure 8: Comparison of a) daily observed and simulated stream flow hydrograph of Ganga basin up to Devprayag during validation period (1999-2005), and b) scatter plot
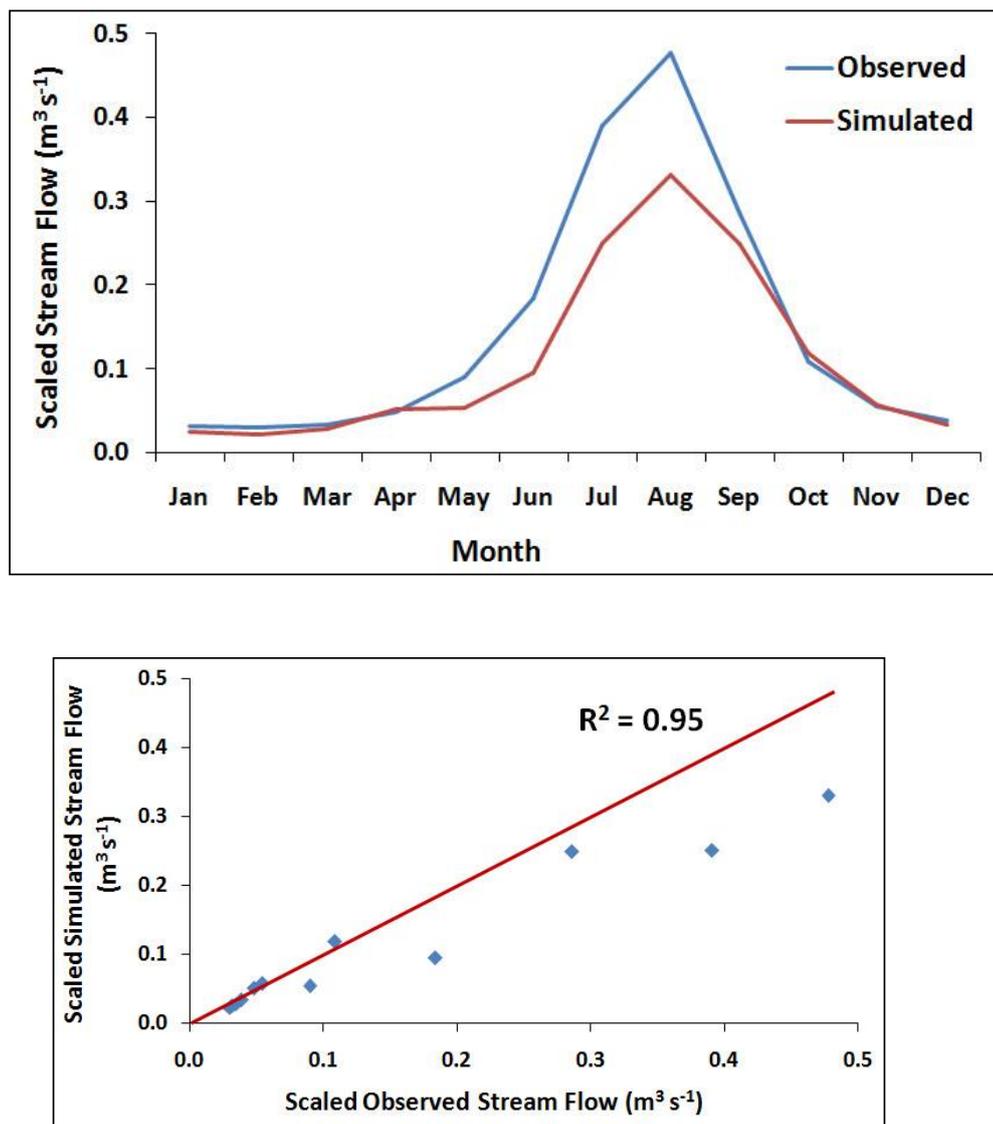
Figure 9: Comparison of a) Monthly observed and simulated stream flow hydrograph of Ganga basin up to Devprayag during calibration period (1992-1998), and b) scatter plot

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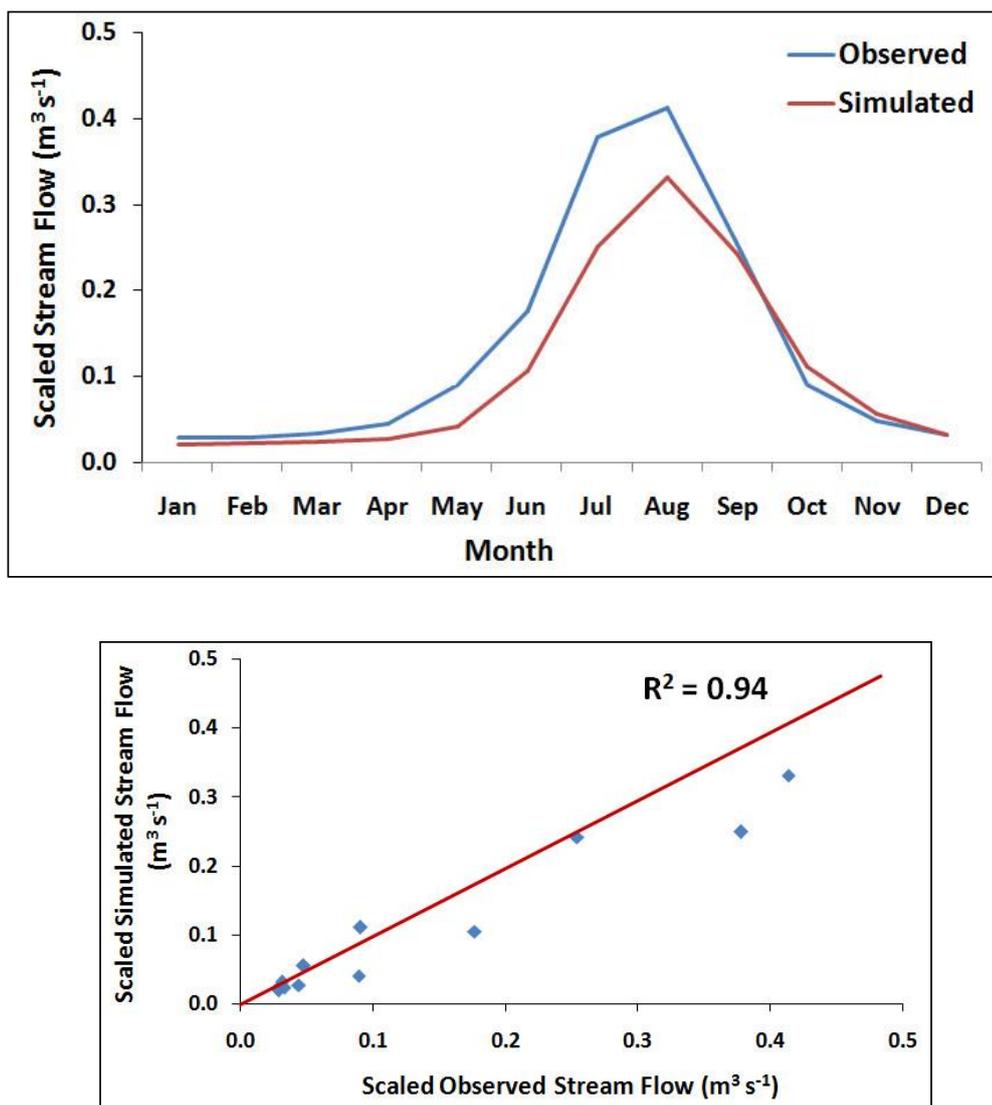
Figure 10: Comparison of a) Monthly observed and simulated stream flow hydrograph of Ganga basin up to Devprayag during Validation period (1999-2005), and b) scatter plot.

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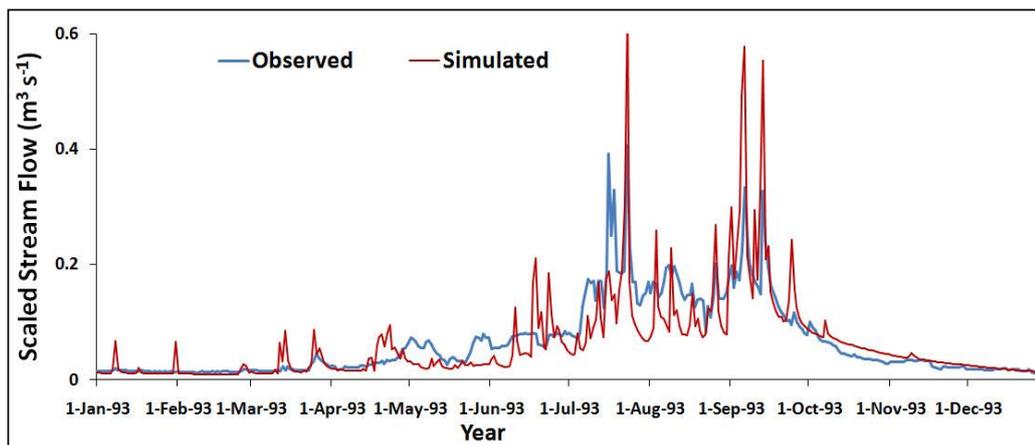
987   Figure 11: Daily observed and simulated stream flow hydrograph of Ganga basin up to Devprayag
988   for the year 1993.

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