Precipitation-Runoff Simulations for Small Himalayan Basins in Nepal with Important Snow Deposits

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Abstract

Runoff simulations for three experimental basins with a catchment area between 135 and 340sq.km. were carried out by applying the conceptual SACRAMENTO model in connection with Anderson's snow model. A six-year time series (1988-1993) of precipitation, runoff, and air temperature was available for calibration purposes. A sensitivity analysis in which inputs and parameters were altered provided the basis for estimating changes in runoff caused by changed land use and an idea of the possible effects of climatic warming.

Introduction

Areal non-uniformity of snow cover apparently causes obstacles in simulating runoff in snow-covered basins. In high mountain areas like the Himalayas the problem is most obvious and urgent. The vertical redistribution of snow deposits by drift and frequent avalanches and, therefore, the vertical gradients of snow depth and the water equivalent are not unambiguous under such circumstances. Even areal approaches using modern monitoring techniques, such as remote sensing and distribution models, can only provide approximate pictures of reality. This is above all true for the effects of vegetation on snow accumulation and melt.

In areas where changes in land use influence the rainfall-runoff process, it is necessary to take into account also any trends in the affecting phenomena. For the time being, similar situations are developing in many areas of the Himalayas. Analyses and trials have been carried out during the last years which had as their main goal to explain different aspects of the runoff process in these hilly regions (Braun et al. 1993, Fukushima et al. 1991) or in other areas (Braun and Aellen 1990, Rango et al. 1990).

The six-year time series (1988-1993), which are now available for the three small experimental Himalayan basins of the Modi *Khola* (Annapurna massif), Langtang *Khola* and Imja *Khola* (Khumbu Himal) (the latter two are situated in central and eastern Nepal respectively ([Grabs and Pokhrel 1993]), provide more reliable data bases for model evaluation of relevant runoff components by means of the SACRAMENTO model. The results of the hydrological experiments presented here mainly serve to clarify the sensitivity of runoff towards actually occurring and/or assumed environmental changes due to climatic warming. However, since snow deposits are usually affected also by land-use changes, it would be desirable to evaluate both factors for their impact on hydrological regimes simultaneously.

Experiments

Catchment Characteristics

Locations of the three experimental pilot basins are shown in Figure 1, and the main basin characteristics are compiled in Table 1. Information on measuring instruments for the study basins can be found in Grabs and Pokhrel (1993), and on Langtang *Khola*, including warming effects on streamflow, in Fukushima et al. (1991).

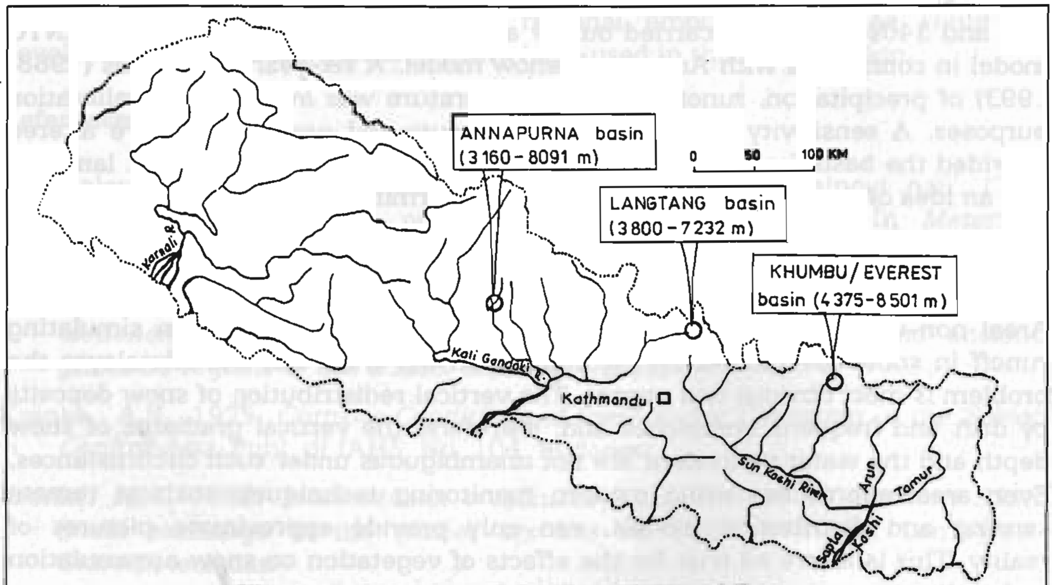

Figure 1: Location of the Experimental Basins

Table 1 Basic Characteristics of the Study Basins

Basin (cf. Figure 1)	Elevation [masl]	Surface area [km^2]	Glaciated area [%]
Imja *Khola* (Khumbu Himal)	4,375 - 8,501	135	27
Langtang *Khola*	3,800 - 7,232	340	38
Modi *Khola* (Annapurna area)	3,160 - 8,091	148	33

Experimental Data

Data Availability

Daily time series of precipitation, discharge, and air temperature over six years (1988-1993) have been used for runoff simulations.

Observed daily time series and monthly averages or sums of precipitation, air temperature, and runoff are shown in Figure 2. A comparison of them provides the basis for estimating tendencies and/or gradients despite the fact that the basins are located in distant regions. Even time series from outside these basins have been partly used for these purposes, i.e., for filling in frequent gaps in the precipitation, temperature, and discharge data. Other data sets have been used for some extrapolations, namely for estimations of the vertical gradients of air temperatures of precipitation.

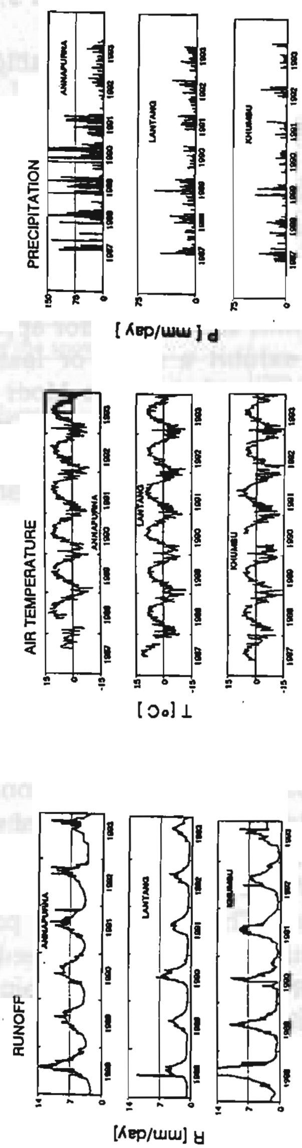

Figure: 2: Observed Precipitation, Air Temperatures and Discharge for the Study Basins

Discussion of Selected Results of Data Evaluation

Similar to the approach taken by Grabs and Pokhrel (1993), different groupings and summations have been arranged in order that the tendencies and/or gradients become apparent. The following phenomena are found there or have been derived from these data sets.

a) Decreasing air temperatures with increasing altitude, as usual; however, Figure 2 provides the basis for further refinement.
   i) Guidelines for quantitative assessments of gradients that distinguish winter and summer periods, as required by the SACRAMENTO model, which is used here for rainfall-runoff simulations;

ii) illustrations of distinct variability of air temperature during winter and summer; and

iii) relatively frequent episodes during the cold dry season with inverse gradients, i.e., with cold air in the bottom part of the (valley) basins which causes the measured air temperature series to be unrepresentative for some time intervals.

b) Orographic effects are different from the usual situation in the hill region at 1,000-2,000masl where precipitation increases with the increasing altitude. Figure 2 suggests that a remarkable decrease in precipitation occurs with rising altitude, at least between 3,500-4,400masl.

Since observations are not available for altitudes higher than 4,400masl, and considerable portions of the study basins extend above this level, simulation inputs can be considered as rough estimates only. Furthermore, extrapolations which made use of the correlations between the three available time series prepared in the initial stage of experiments would be a rather bold approach. In the simulation of water balances, we have tried to correct observed values, i.e. inputs for modelling, by an iterative procedure.

Figure 2 provides also a basis for appraising the constancy of measurements. The observations exhibit a more or less stable course. An important exception is precipitation measured in the Modi *Khola* basin, where a decreasing tendency seems to be quite apparent, thus significantly influencing the accuracy of runoff simulations. A similar but less distinct trend is found in two other precipitation series. Therefore, it would be useful to follow the course over the span of approximately 10-15 years available in the series for the lowland region. Unfortunately, for the time being, these data sets extend only up to 1990.

SAC-SMA Catchment Model

For runoff simulations, the SACRAMENTO soil moisture accounting model (SAC-SMA) has been used (Burnash et al. 1973). Its structure is demonstrated in Figure 3. If it is coupled with Anderson's snow model (Anderson 1968), the model enables one to perform continuous simulations of runoff from snow-covered areas over a span of several years.

The SAC-SMA model is a conceptual water balance model with lumped inputs and parameters. The list of the 16 parameters of its snow sub-model is given in Table 2, in which the values obtained from the calibration for the Langtang basin are given. The parameters of the rainfall-runoff model — altogether 12 values — are given in Table 3.

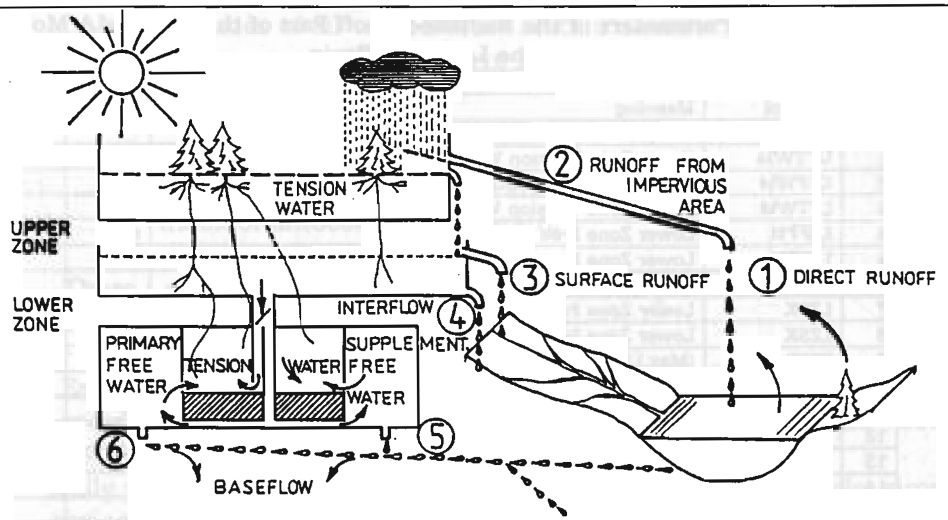

Figure 3: Schematic Structure of the Sacramento Soil Moisture Accounting Model

Table 2. The Parameters of the Snow Sub-model for the Langtang Basin

No.	Symbol	Meaning	Unit	Value
1	MFmax	Maximum/minimum value of the snow-		2.6
2	MFmin	melt factor	mm day^{-1}	2.0
3	SCF	Snow coefficient correction factor		1.15
4	UADJ	Wind function for the given region		0.07
5	SI	Value of SWE above which there is always 100% areal snow cover	mm	300
6	ADC	Areal depletion curve of the snow cover	10 ordinates	
7	NMF	Maximum negative melt factor	Mm/day^{-1}	0.2
8	TIMP	Antecedent temperature index parameter		0.05
9	PXTEMP	The temperature which demarcates rain from snow	°C	1.0
10	MBASE	Base temperature for snowmelt computations	°C	-2.30
11	PLWHC	Per cent liquid water holding capacity		0.05
12	DAYGM	Melt rate of the snow-soil interface	Mm/day^{-1}	0.40

It is worth mentioning that the available software allows one to take explicitly into account: i) correction factors for both solid and liquid precipitation; and ii) vertical gradients of air temperature.

This is a significant advantage under the given conditions, in which snow deposits and snowmelt play a dominant role in runoff simulations. Therefore, the parts describing these processes are treated more fully here, but other processes also need some explanation.

i) There are altogether six runoff components generated by the SAC-SMA model (cf. Fig. 3).

Table 3. The Parameters of the Rainfall-Runoff Part of the SAC-SMA Model for the Langtang Basin

No.	Symbol	Meaning	Unit	Value
1	UZTWM	Upper Zone Tension Water Maximum	mm	100
2	UZFWM	Upper Zone Free Water Maximum	mm	10
3	LZTWM	Lower Zone Tension Water Maximum	mm	250
4	LZFPM	Lower Zone Free Primary Maximum	mm	350
5	LZFSM	Lower Zone Free Supplement Maximum	mm	150
6	UZK	Upper Zone Coefficient		0.5
7	LZPK	Lower Zone Primary Coefficient		0.0045
8	LZSK	Lower Zone Supplement Coefficient		0.055
9	ZPERC	(Max.) PERcolation Rate Coefficient		150
10	REXP	EXPonent of percolation shape curve		2.8
11	RSERV	Portion in LZFPM not available for evapotranspiration	%	10
12	PEREE	Portion of water which goes directly to LZFPM	%	15
13	PCTIM	Portion ConTinuously IMpervious	%	1
14	ADIMP	ADditionally IMPervious area	%	5
15	RIVA	RIparian Vegetation Area	%	0
16	SIDE	The fraction of observed base flow which leaves the basin by non-channel underground routes	%	1

- DIR direct runoff from those parts of the basin which become impervious after saturation
- IMP runoff from those parts of the basin which are permanently impervious
- SUR surface runoff
- INT interflow
- SUP supplementary baseflow (i.e., essentially the seasonal component of outflows from groundwater storages)
- PRM primary base flow, i.e., the long-term proportion of base flow

(The expressions and acronyms used here are the ones proposed and defined by the authors of the model [Burnash et al. 1973]. The first three components represent surface flow, and the last three components sub-surface and groundwater flows, with varying degrees of quick and delayed flow.)

The applications of the model to basins of different size, order, and climatic and geomorphological conditions (Buchtele et al. 1996) indicate that the first two components, which are frequently not included in similar catchment models, contribute significantly to the streamflow during high flow periods. Omission of these phenomena may cause serious distortion in simulations and/or identified parameters in cases of highly urbanised areas, for instance, or basins with sparse vegetation. Figure 4 may serve as an illustration. It compares the simulated runoff components for two different basins: the Lange Bramke in the Harz Mountains, in the Central European highlands of Germany, and the Langtang *Khola*.

Besides the above-mentioned, the following parameters are used.

- geographic and climatic data

TALR .... vertical gradient of the air temperature

WT .... relative weights of the individual zones of the basin

ELEV .... altitudes of air temperature station zones
TALEV .... temperature altitude above sea level.

- initial conditions
SWE .... snow water equivalent
LIQWI .... liquid water volume in the snow
TINDX .... index of antecedent temperature

(ii) There are two alternative forms of inputs in the context of evapotranspiration.

- Estimates of the long-term evapotranspiration demand, representing the requirements of the existing vegetation cover for its seasonal development
- Daily time series of actual evapotranspiration for the whole simulated period

The common problem of data availability forces the first and simpler approach to be applied in our experiments.

Actual evapotranspiration is computed separately for the individual zones (compartments), i.e., UZTW, UZFW, LZTW, and LZFW (cf. Table 3), following the scheme:

$$^{1}E_{akt} = E_{pot} \cdot \frac{UZTWC}{UZTWM},$$

$$^{2}E_{akt} = \min\left[\left(E_{pot} - {}^{1}E\right), UZTWC\right], \quad \text{and}$$

$$^{3}E_{akt} = \left(E_{pot} - {}^{1}E\right)\frac{LZTWC}{UZTWM + LZTWM} \text{ etc.}$$

Initial estimates of evapotranspiration demand are made using the difference E = P - R, where *P* and *R* are long-term annual amounts of precipitation and runoff in mm. Partitioning over individual months is accomplished by adjusting the values to the annual cycle of air temperatures. Corrections of these initial estimates can be obtained by consecutive iterations in which the differences between observed and simulated monthly flows are taken into account.

Of course, two other phenomena which have already been mentioned may affect the monthly water balances: i) the assumed correction factors for precipitation, including snowfall; and ii) the delayed response of the basin to precipitation impulse, i.e., size effects of several soil moisture zones: UZTWM, LZTWM, LZFPM.

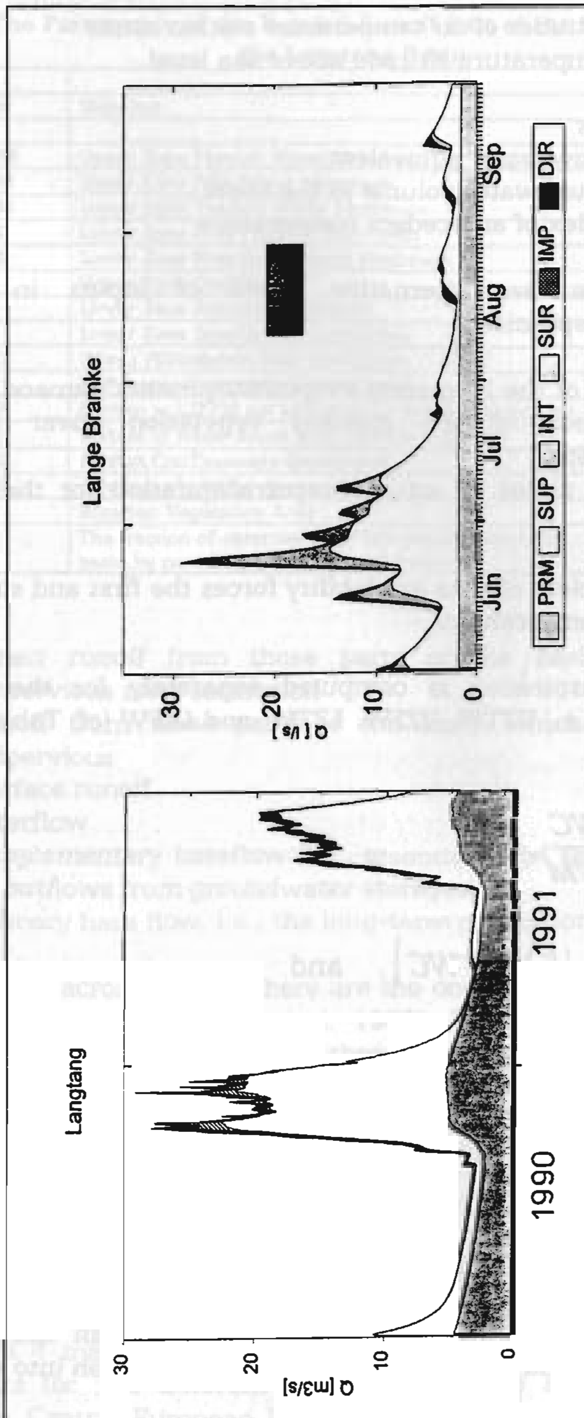

Figure 4: Runoff Components Simulated by SAC-SMA Model

Therefore, it is not possible to ascertain adequate and realistic values of evapotranspiration demand independently, i.e., without considering the two phenomena mentioned above, namely, precipitation correction factors and the parameters UZTWM, ..., LZFPM. All three processes should be analysed simultaneously in an iterative procedure. The evapotranspiration amounts estimated as being appropriate in the initial trials should be corrected in the following iterations in which the sizes of soil moisture zones are to be ascertained.

(iii) Snow Sub-model

In the given region the identification of parameters that characterise the processes of snow accumulation and snowmelt requires greatest attention, as it most seriously affects simulated runoff. Many of the parameters in Table 2 are used also in other models, and their values are more or less compatible. For instance, the following characteristics have often a common meaning and similar structure: snow correction factor, snowmelt factor, ground melt factor, water holding capacity of snow cover, and base air temperature and its vertical gradient. It would be worth comparing values of similar parameters as used, for example, by Braun et al. (1993).

One parameter of the applied model that should be especially mentioned here is the areal depletion curve (ADC), which characterises the areal variability of the snow water equivalent, thus representing, under the given conditions, vertical zoning (changes) of snow storages. The procedure can be considered as the statistically distributed approach for evaluating snow inputs, and it is assumed that the effects of permanent deposits, i.e., glaciers, should be implicitly included. The shape of the ADC curve in the calibrated model for the Langtang basin has been determined using topographic data available from Fukushima et al. (1991). The curve in Figure 8, which is considered optimal, indicates that the relative mean snow water equivalent practically never exceeds about 40 per cent of the area corresponding to the areal extent of glaciers.

Many trials have been made to eliminate existing noise by the re-arrangement of proportions between (computational) average altitude of the basin, air temperature gradients, and other parameters able to affect snow accumulation and snowmelt — namely the bias of observed temperatures, the seasonal shift, the values of the snowmelt factor, and so on.

Simulation Results

The calibration outputs of SAC-SMA model application to the three study basins are shown in Figures 5 and 6. Two alternative linear and semi-logarithmic scales have been used for the Langtang basin in order to allow insight into discrepancies between observed and simulated discharges at low and flood flow conditions.

Relatively good accuracy has been attained for the Langtang basin with the lowest altitudes and the greatest areal extent of glaciers, as shown in Table 4.

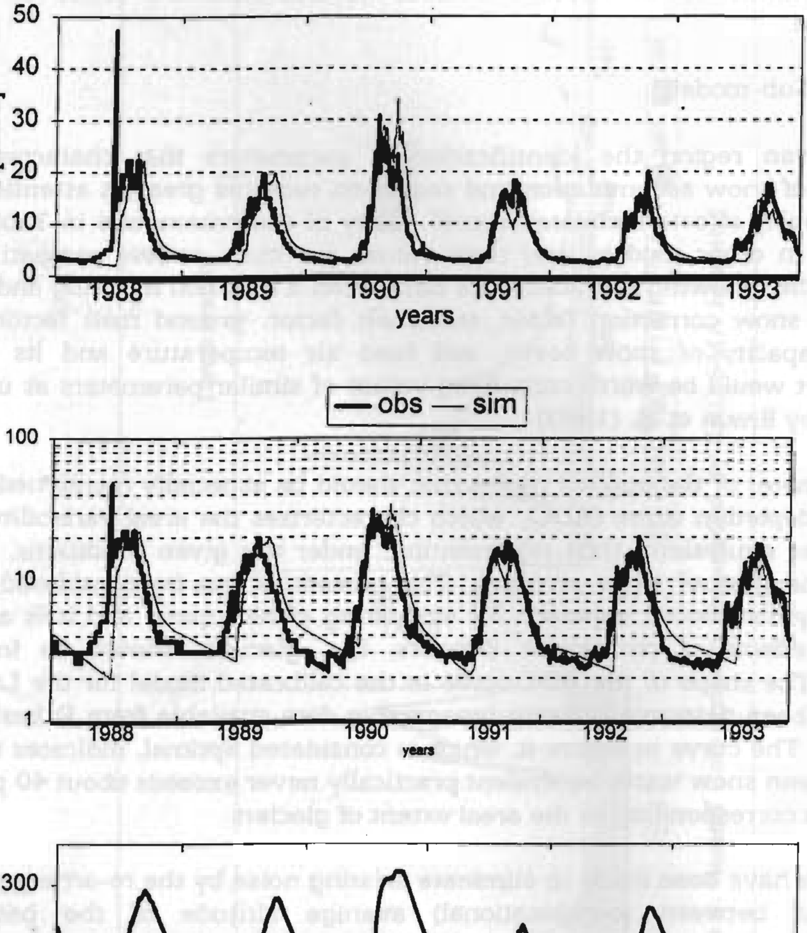

Figure 5: Simulated Discharge (a) and Groundwater Storage (b) for Langtang *Khola* Basin

Table 4. The Statistical Characteristics of Accuracy of Simulated Discharge for the Study Basins

Basin	Surface Area [km²]	Glacier area [km²]	R	|Δ| (%)	σ (%)
Langtang *Khola*	340	129	0.8272	25.6	40.6
Modi *Khola*	148	49	0.7684	24.2	30.7
Imja *Khola*	135	36	0.6034	49.6	98.3

R correlation coefficient of observed and simulated daily discharge
$|\Delta|$ mean absolute error of daily discharge
σ root mean square error of simulated daily discharge

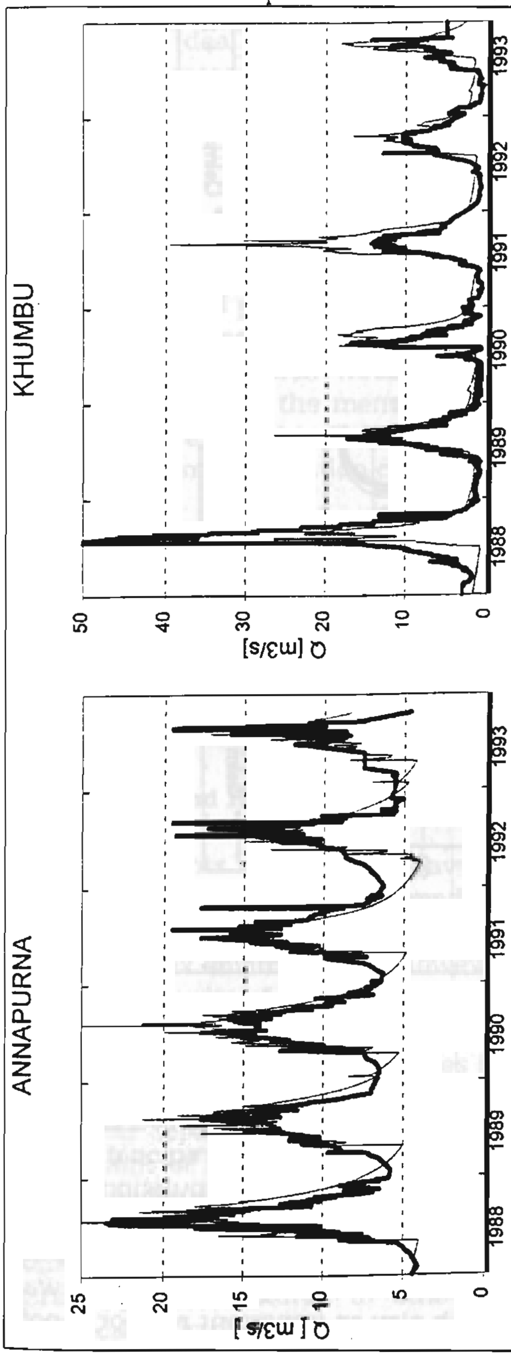

Figure 6: Discharge Simulations for Modi *Khola* (Annapurna) and Imja *Khola* (Khumbu)

Another output of the simulations is basin snow water equivalents. However, there may be doubts concerning whether the lumped values are reasonable, especially since trends are not very similar.

The prevailing situation in all three basins is that the simulated flows are delayed compared to observed discharge. One reason that could be mentioned is inversions during winter months. However, sensitivity analyses, as given in Figure 7, stand partly in contradiction to such a possibility. Another reason could be the non-representative vertical gradients of air temperature and the more complex structure of contributing areas, including the effects of glaciers and the problem of glacier debris, as mentioned by Braun et al. (1993). Such things cannot be expressed in a simple statistical approach, e.g., by the areal depletion curve for snow deposits, which is a relevant snow model parameter.

One main positive aspect of these simulations is that there are no apparent biases in observed and simulated flows. Some amplification and/or dumping is found as the visible effect of different initial conditions at the beginning of a hydrological year, due to the interannual taking over of snow deposits.

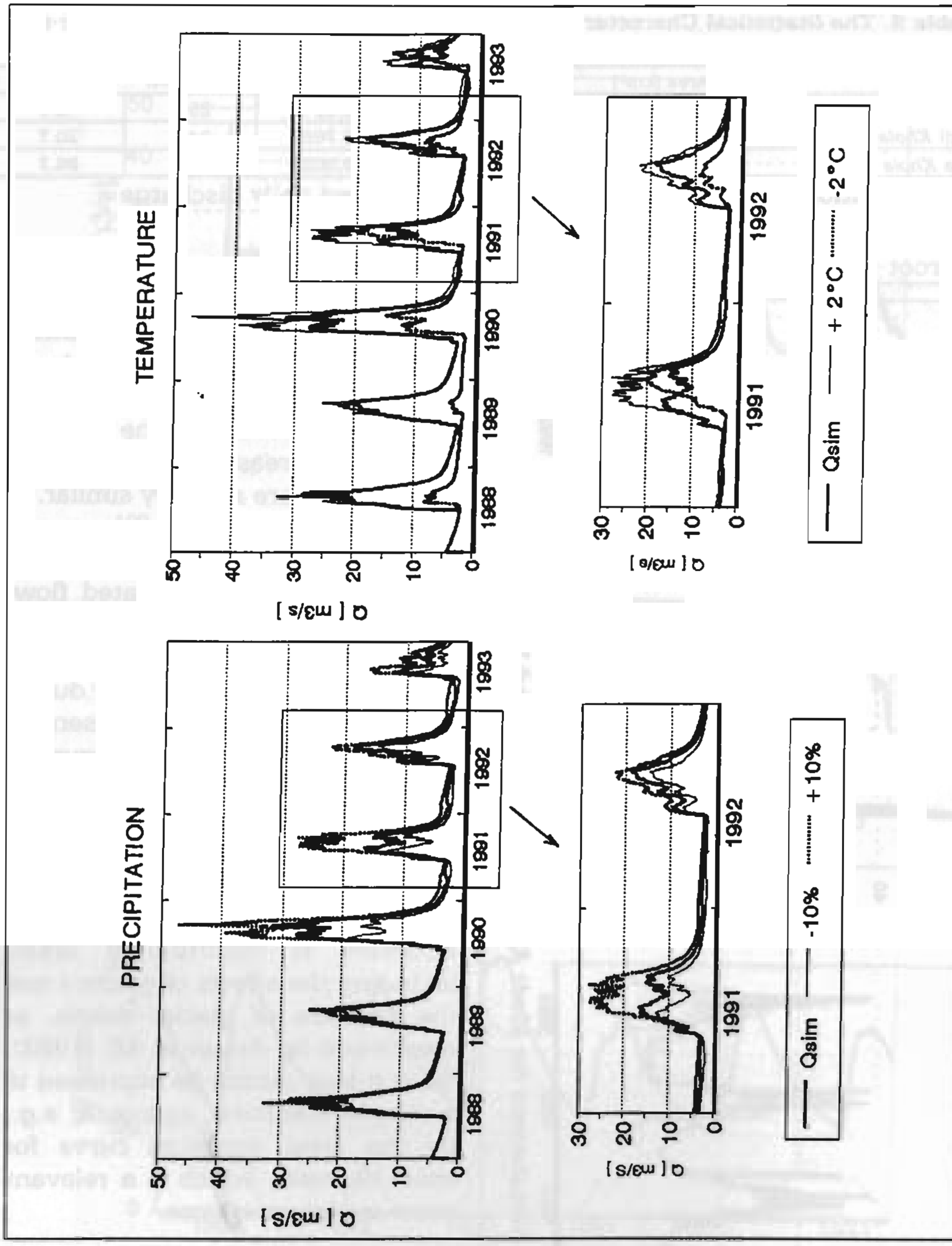

Figure 7: Effects of Increased or Reduced Inputs on Simulated Flow from Langtang Basin

Discussion of Results

One main goal of the described experiments is to contribute to the evaluation of possible runoff changes caused by human activities on local to regional scales, and particularly by the assumed climatic warming. Similar simulations have been carried out for all three basins, whereas the examples presented here concern the Langtang basin only; one main reason why the model calibrations have yielded relatively successful illustrative results there. Special attention was paid to several aspects of snow deposits - which play an important role for runoff have yielded relatively successful illustrative results there. Special attention was paid to several aspects of snow deposits - which play an important role for runoff generation in the region. Precipitational increase or decrease is, of course, most visible in detail, i.e., in the two-year period displayed in the lower part of Figure 7 in which the low flows are more clearly illustrated.

Air temperature change, as presented in Figure 7, causes redistribution of snow deposits over a span of years, as assumed for the conditions of permanent snow deposits in some parts of the basin. The example indicates also that it would be desirable to deal with much longer time series if a new equilibrium stage between increased long-term air temperatures and snow storages is reached. Like the former results attained by, for example, Fukushima et al. (1991), these simulations should be considered as examples representing the transition period only.

As a consequence of climate warming, other parameters and phenomena, too, may simultaneously change: the snowmelt factor, areal depletion curve of snow storages, vertical gradients of air temperature, and so on. Such changes could be caused by the feed-back in underlying processes, that is, due to a change in glacier coverage which would also affect local climatic conditions, including albedo. As a result, the mentioned parameters could be taken on other values than those presented in Table 3. The effects of these changes are illustrated in Figure 8. A similar situation occurs in the shift of snow storages from one year to another.

The preceding figures demonstrate more or less distinct changes in runoff. A similar illustration of, for instance, changes in snow deposits would be possible also. However, such model outputs would be rather doubtful, as Figure 8 suggests, due to the lack of more detailed information about topography and to the relatively short time series. A comparable situation is found for simulated groundwater storages in Figure 5.

Conclusions and Recommendations

The experiments with data sets available for three small mountain basins in the Himalayan region have confirmed the adequacy and ability of the modelling techniques used to simulate runoff and other components of the water cycle in these complex environments. However, gaps in the data in combination with the increased scarcity of data at high altitudes do not make for satisfying evaluations of further system components, such as snow storages, and it is almost impossible to estimate the trends and/or biases in observed and simulated values.

The areal depletion curve of the snow cover is a complex factor figuring into estimations of snow storages. This parameter of Anderson's snow sub-model is an expression of the areal and/or vertical non-uniformity of snow deposits, which may cause simulated fast or slow snow meltwater components and, consequently, quick or delayed runoff. The areal depletion curve is an additional parameter, not featured in other models, which can be interpreted as the statistically distributed characteristic of snow cover.

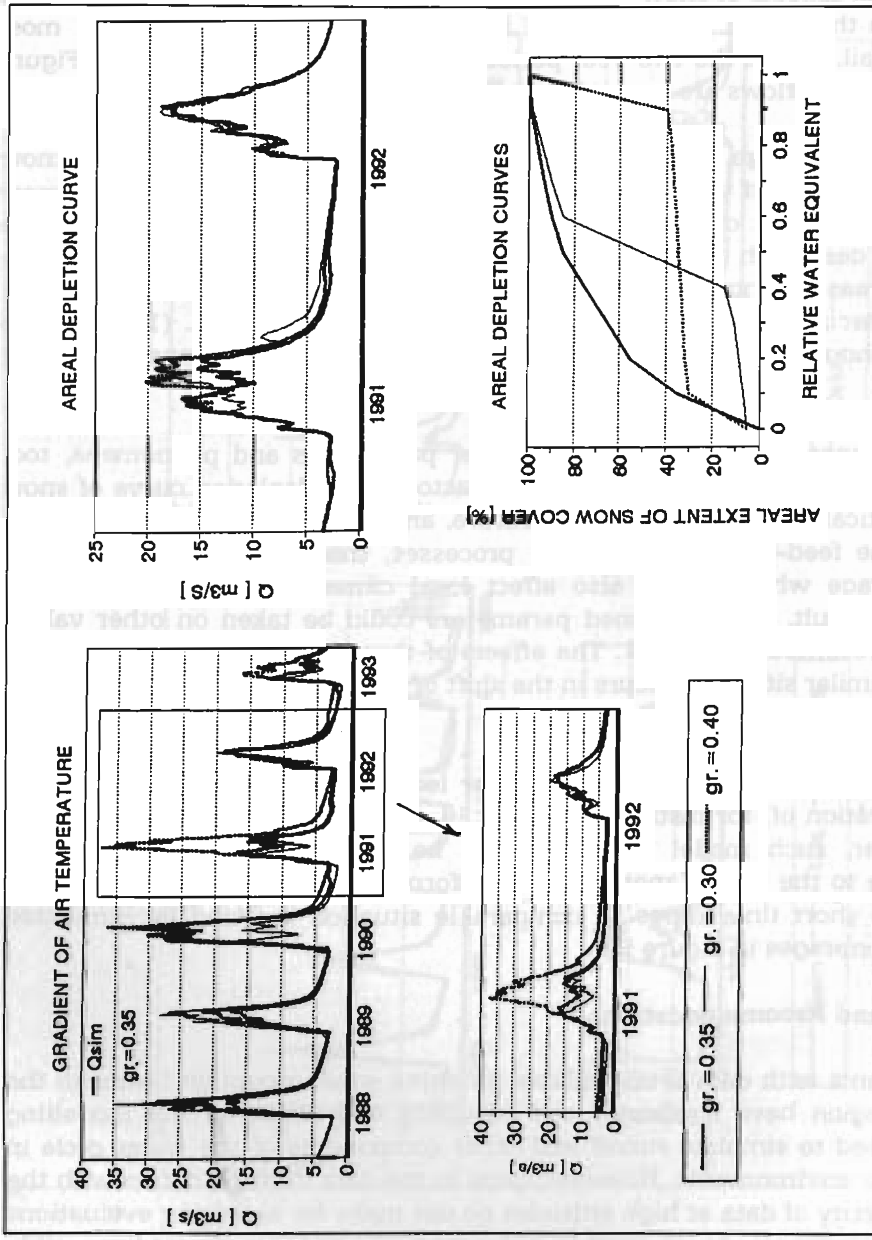

Figure 8: Sensitivity of Discharge of Langtang *Khola* with Regard to:

a) vertical decrease of air temperature [°C/100m]

b) shape of the curve characterising vertical and areal distribution of snow storages

Experiments illustrating the sensitivity of runoff to climate warming are not very conclusive at the present stage of work. However, they should provide at least rough assessments of possible future developments. Of course, more precise evaluation and testing of input data and modelling techniques are still desirable. Some additional observations would also be useful, for instance as pertain to the vertical gradients of air temperature and other orographic effects on the hydrological regime. Data from the application of remote-sensing techniques would also be profitable, as demonstrated by Rango et al. (1990).

Acknowledgement

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