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Regionalization of a distributed catchment model for highly glacierized Nepalese headwater catchments

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Abstract In this study, the distributed catchment model TAC^D was developed further and applied to three highly glacierized Himalayan catchments (141–360 km^2). Snow and ice melt is regionalized using the calculated potential sunshine duration of each 200 × 200 m^2 raster cell. Hydrological response units (glacier covered areas, non-glacier areas, flat glacier parts, valley bottoms) are simulated with different reservoir concepts. The model runs on a daily time step with daily mean air temperature and daily sums of precipitation as input data. It was calibrated successfully for the Langtang Khola catchment, Nepal, and this parameter set formed the starting point for the application of the model to the Modi Khola and Imja Khola catchments. In the case of the Modi Khola catchment the parameter set was left unchanged and used directly for discharge simulation, and only minor modifications of the parameter values of the snow and glacier routine were necessary for the Imja Khola catchment to obtain reasonable runoff simulations. It was demonstrated that this distributed modelling approach enables the assessment of the temporal and spatial distribution of runoff from high mountain areas where data are limited.

Key words TAC^D model; regionalization; Himalayan headwater; Nepal; distributed modelling; process-oriented runoff simulation; Langtang; Annapurna; Khumbu

INTRODUCTION

In 1987, the German Agency for Technical Cooperation (GTZ) initiated a project with the aim to quantify the hydrological conditions of glacierized Himalayan catchments (Grabs & Pokhrel, 1993). Within this project several climate stations were set up in six headwater catchments across the Nepalese Himalaya. Today the measurement programme is maintained by the Snow and Glacier Hydrology Unit (SGHU) of the Department of Hydrology and Meteorology (DHM), Kathmandu, Nepal.

Earlier modelling studies of daily discharge of the Himalayan headwater catchments revealed problems in simulating the hydrograph of the winter and monsoon season (Braun *et al.*, 1993, 1998). The winter discharge is relatively high although there is neither liquid precipitation or melt water which contributes to the runoff generation. With our TAC^D model we overcome this problem with storage concepts which enable the storage of water during the monsoon season to maintain winter discharge (Konz *et al.*, 2006). In this paper we present the application of the further developed distributed catchment model TAC^D to three remote Himalayan catchments with limited data availability. The model is applied to the Langtang Khola, the Imja Khola and Modi Khola catchments with only minor re-calibration of model parameters. The transfer of rainfall–runoff models to ungauged sites is a topic of wide interest in the scientific community and different approaches to the regionalization of model parameters are suggested (e.g. Gottschalk e*t al.*, 2001). Here, we focus on the regionalization of model parameters based on the delineation of hydrological response units; a detailed description of the model can be found in Konz *et al.* (2006).

METHODS AND DATA

The TAC^D model

The conceptual structure of TAC^D consists of separate modules (snow and glacier-, soil- and runoff-generation routines) that are sequentially linked and represent the main parts of the land phase hydrological cycle (for further details see Uhlenbrook *et al.*, 2004; Ott & Uhlenbrook, 2004; Johst *et al.*, 2006: Konz *et al.*, 2006). The meteorological data input requirement is limited to daily mean air temperature and daily sums of precipitation. The model is fully distributed with rectangular grid cells of 200 × 200 m^2.

The temperature-index method is used to calculate snow- and ice-melt in a distributed way based on potential sunshine duration expressed by a dimensionless factor (R_{expMap}). In grid cells with high potential sunshine duration melt is increased ($R_{expMap} > 1.0$) and *vice versa*. Temperature is regionalized using a fixed gradient. Water retention in the present snow cover is also considered in the snow and glacier routine. If glaciers are present, ice melt starts as soon as the snow cover is melted. The enhanced melt of ice as compared to snow is a result of reduced surface albedo and considered by a multiplicative factor (R_{ice}) applied to the temperature-index method. The reduced melt rate of ice under thick debris-covered parts of the glaciers is accounted for by another multiplicative factor ($R_{debris} < 1.0$ reduced melt) (Braun *et al.*, 1993; Konz *et al.*, 2006):

$$Q_{melt} = CFMAX \cdot (Temp - TT)\, R_{expMap}\, R_{ice}\, R_{debris}$$

where Q_{melt}: melt water (mm day^{-1}), $CFMAX$: degree-day factor (mm day^{-1} °C^{-1}), $Temp$: daily mean air temperature (°C) and TT: threshold value of temperature (°C).

The runoff generation routine is the core of the model which is designed for process-oriented runoff simulation. Units with similar dominating runoff generation behaviour (hydrological response units, HRUs) were delineated using maps of topography and land use, aerial photographs and a digital elevation model (DEM) as well as experiences gained during field visits. Four units were distinguished for which different runoff generation processes are assumed and incorporated into the model as a raster map (200 × 200 m^2):

1. non-glacier area;
2. glacier area;
3. glacier area with an inclination of less than 3° and debris cover;
4. valley bottoms with an inclination of less than 8°.

Sequentially connected or overflowing reservoirs simulate the runoff processes of unit Types 1 and 2. In these units, upper and lower storages exist which are vertically linked via a constant percolation rate. For conceptualization of the runoff generation processes of the third unit type, only a single storage is used. This conceptualization is based on the assumption that the large valley glaciers can store a great amount of water in pools or small sub- and supra-glacial lakes (Jansson *et al.*, 2002). Storage capacity is limited by an upper limit. Runoff of this storage is computed by applying a storage coefficient with additional water if the storage content exceeds the storage capacity. The valley bottom with an inclination of less than 8° is considered to be an aquifer consisting of glacial moraine and gravel beds where water can be stored. The same structure of storage as in Type 3 is used to simulate the hydrological processes but with different parameterization for different flow dynamics.

Catchments and data used in the study

Three highly glacierized Himalayan catchments were investigated: Imja Khola (Khumbu region), Langtang Khola (Langtang region) and Modi Khola (Annapurna region). Catchment characteristics are shown in Table 1. SGHU provided air temperature (T), precipitation (P) and discharge (Q) data sets. There is one climate station in each catchment and gauge height is measured at an undefined cross-section in the river using dilution techniques to derive discharge data. The number of missing data in the observation series varies between the catchments, and for the investigation periods it is in the range of 91–98% for temperature, 71–93% for precipitation and 38–80% for discharge. Statistical methods to fill the missing values had to be applied using meteorological data of DHM stations in the vicinity of the catchments (for further details see Konz *et al.*, 2006). Spatial data sets were derived from digital maps of the Survey Department, Nepal. The glacier covered area was taken from maps published in the glacier inventory of the International Center of Mountain Development (ICIMOD) (UNEP/ICIMOD, 2002).

RESULTS AND DISCUSSION

The model was initially applied to the Langtang Khola catchment (Table 2) for which glaciological data (glacier mass balances) of a glacier within the catchment are available from literature

Table 1 Catchment characteristics.

			Imja Khola	Modi Khola	Langtang Khola
Investigation period			1988–1995	1991–1994	1987–1998
Area	Total	(km²)	141.4	160.6	360.0
	Glacierized	(km²/%)	53.4/37.7	76.6/47.7	166.1/46.1
	Debris-covered glacier	(km²/%)	24.0/45.0[a]	6.96/9.1[a]	32.1/19.3[a]
Altitude	Range	(m a.s.l.)	4355–8501	3470–8091	3800–7234
	Average	(m a.s.l.)	5500	5327	5169
Exposition	North (315°–45°)	(%)	17.9	12.7	21.3
	South (135°–225°)	(%)	37.0	38.0	26.8
	East, west, horizontal [b]	(%)	45.1	49.3	51.9
	Mean slope	(°)	28.6	34.9	26.7
Land cover	Glacier	(km²/%)	53.4/37.7	76.6/47.7	166.1/46.1
	Barren land	(km²/%)	67.8/48.0	66.81/41.6	183.8/51.1
	Forest	(km²/%)	–	0.7/0.4	2.1/0.6
	Grass land	(km²/%)	17.6/12.5	15.0/9.3	3.4/0.9
	Others	(km²/%)	2.6/1.8	1.4/0.9	4.6/1.3

[a] in percent of glacier-covered area
[b] 45°–135° and 225°–315°

(Braun *et al.*, 1993; Fujita *et al.*, 1998). These data were used for calibration and validation of the model beside discharge measurements. The model was calibrated using data from the period 1993–1998 and validated on an independent period, 1987–1993. The model obtained satisfying results for discharge and glacier mass balance simulations for the Langtang Khola catchment (Fig. 1) with objective evaluation criteria (Nash & Sutcliff, 1970) varying from 0.28 to 0.87 (Table 3) (Konz *et al.*, 2006). The parameter values of the soil routine and runoff generation routine were derived from experiences from previous TAC^D-applications to other basins. In particular, the parameter values were defined such that our understanding of the dominant process behaviour is represented. We concentrated on ratios between parameters of the different HRUs

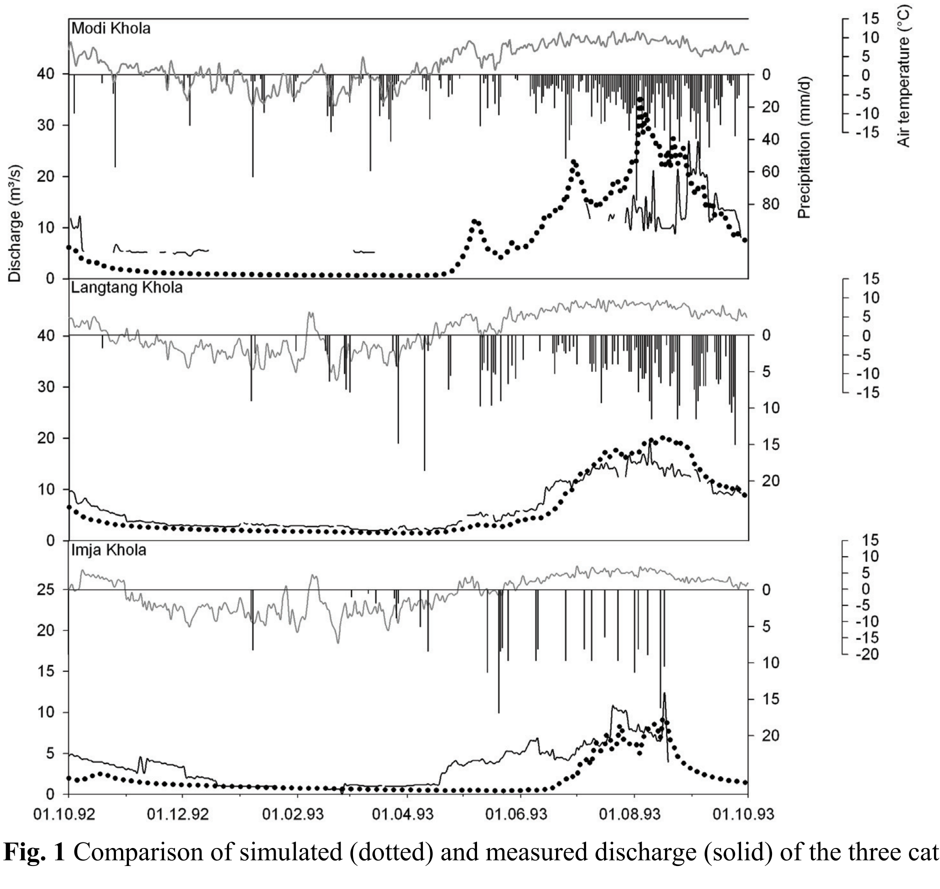

Fig. 1 Comparison of simulated (dotted) and measured discharge (solid) of the three catchments.

Table 2 Optimized parameter set of TAC^{D} for the investigated catchments. Bold, italic numbers are changed compared to the parameter set of the Langtang Khola catchment.

Parameter	Description	Determination	Langtang Khola	Modi Khola	Imja Khola	Unit
Precipitation correction and regionalization						
PCF	"Precipitation correction factor" for rain	Calibration	1.05	1.05	***1.15***	(–)
P_{Grad}	Vertical precipitation gradient	Calibration (externally set from values in literature)	0.04	0.04	0.04	(% 100 m^{-1} 100^{-1})
$P_{HorizGrad}$	Horizontal precipitation gradient	Calibration (set from values in literature)	–0.03	***0.0***	***0.0***	(% 1000 m^{-1} 100^{-1})
SFCF	"Snowfall correction factor"	Calibration	1.2	1.2	1.2	(–)
Temperature regionalization						
T_{Grad}	Vertical temperature gradient	Calibration (set from values in literature)	–0.5	–0.5	–0.5	(°C 100 m^{-1})
Potential evaporation calculation and regionalization						
ET_{max}	Maximum of potential evapotranspiration	Calibration (set from values in literature)	2.2	2.2	2.2	(mm day^{-1})
ETGrad	Vertical evapotranspiration gradient	Calibration (set from values in literature)	–0.01	–0.01	–0.01	(% 100 m^{-1} 100^{-1})
Snow and glacier routine						
TT	Threshold value of temperature for snowfall also general temperature correction	Calibration (set from values in literature)	–0.2	–0.2	***–0.5***	(°C)
CFMAX	Degree-day factor	Calibration	7.0	7.0	***9.0***	(mm °C^{-1} day^{-1})
CWH	Water holding capacity of snow	Literature (Bergström, 1992)	0.1	0.1	0.1	(–)
CFR	Coefficient of refreezing	Literature (Bergström, 1992)	0.05	0.05	0.05	(–)
R_{exp}	Correction factor for cells with maximum potential sunshine duration	Calibration	1.3	1.3	1.3	(–)
R_{ice}	Multiplicative factor to account for accelerated melt over ice cf. snow	Calibration	1.4	1.4	1.4	(–)
R_{debris}	Reduction factor of glacier melt over debris-covered parts of the glacier	Calibration (set from values in literature)	0.3	0.3	***0.6***	(–)
Soil routine						
LP	Reduction parameter of field capacity	Literature (Menzel, 1997)	0.6	0.6	0.6	(–)
Non-glacier area (nRGType 1)						
FC1	Maximum soil moisture storage (field capacity)	Calibration	20	20	20	(mm)
BETA1	Empirical parameter	Calibration	2.0	2.0	2.0	(–)
Glacier area (nRGType 2)						
FC2	Maximum soil moisture storage (field capacity)	Calibration	20	20	20	(mm)
BETA2	Empirical parameter	Calibration	1.5	1.5	1.5	(–)
Glacier area with inclination less 3° and debris cover (nRGType 3)						
FC3	Maximum soil moisture storage (field capacity)	Calibration	40	40	40	(mm)
BETA3	Empirical parameter	Calibration	1.5	1.5	1.5	(–)
Valley bottom with inclination less 8° (nRGType 4)						
FC4	Maximum soil moisture storage (field capacity)	Calibration	120	120	120	(mm)
BETA4	Empirical parameter	Calibration	2.5	2.5	2.5	(–)
Runoff generation routine						
Non-glacier area (nRGType 1)						
US_K1	Storage coefficient of upper storage	Calibration	0.13	0.13	0.13	(day^{-1})
LS_K1	Storage coefficient of lower storage	Calibration	0.005	0.005	0.005	(day^{-1})
US_P1	Percolation capacity	Calibration	1	1	1	(mm day^{-1})
US_H1	Limit of upper storage	Calibration	100	100	100	(mm)
Glacier area (nRGType 2)						
US_K2	Storage coefficient of upper storage	Calibration	0.1	0.1	0.1	(day^{-1})
LS_K2	Storage coefficient of lower storage	Calibration	0.02	0.02	0.02	(day^{-1})
US_P2	Percolation capacity	Calibration	3	3	3	(mm day^{-1})
US_H2	Limit of upper storage	Calibration	200	200	200	(mm)
Glacier area with inclination less 3° and debris cover (nRGType 3)						
GlacierLS_K	Storage coefficient of glacier storage	Calibration	0.01	0.01	0.01	(day^{-1})
GlacierLS_H	Limit of glacier storage	Calibration	3000	3000	3000	(mm)
Valley bottom with inclination less 8° (nRGType 4)						
ValleyLS_K	Storage coefficient of valley storage	Calibration	0.01	0.01	0.01	(day^{-1})
ValleyLS_H	Limit of valley storage	Calibration	1000	1000	1000	(mm)
Routing routine						
MaxBas	Empirical parameter	Set *a priori*	1	1	1	(–)

Table 3 Evaluation criteria of simulation results calculated using TAC^D for the investigated catchments (R_{eff}: Nash-Sutcliff coefficient, R^2: correlation coefficient, VE: volume error).

Hydrological year	R_{eff} (–)	$log\ R_{eff}$ (–)	R^2 (–)	VE (mm year^{-1})
Langtang Khola				
1987–1998	0.20 – 0.87	0.05 – 0.84	0.72 – 0.91	–43 – 97
Modi Khola				
1991–1994	–1.41 – 0.37	–9.21 – 0.12	0.42 – 0.86	–68 – 289
Imja Khola				
1988–1995	0.03 – 0.79	–0.80 – 0.77	0.56 – 0.87	–69 – 323

which are considered to represent the different dynamics of the runoff generation processes. These parameters were not included in the calibration procedure (manual trial and error technique).

Intra-annual distribution of water with spatial distributed storage concepts as described above yielded satisfactory simulation results documented by the objective evaluation criteria if the available input data are of reliable quality (Table 3). This indicates that simple conceptual reservoir approaches to describe the hydrological processes of the Langtang Khola catchment can be considered as sufficient for runoff simulation. With the sequentially linked storages it is possible to simulate water storage mechanisms of glaciers as well as soft and hard rock with different hydraulic behaviour. The high potential of topographic information combined with land-cover data for the delineation of hydrological response units and for the regionalization of runoff generation processes and snow and ice melt, enables a robust runoff simulation in remote areas where additional information (e.g. nested catchments, tracer experiments, etc.) are not available.

In the second phase, the TAC^D model was applied to two catchments in the Khumbu and Annapurna region (Table 1). It is assumed that the hydrological conditions of the three catchments are relatively similar. Therefore, the optimized parameter set of the Langtang Khola catchment was taken for the simulation of the Modi Khola (Annapurna) and Imja Khola (Khumbu) catchments. No evidence was found in the literature for an unequal distribution of basin precipitation as is the case in the Langtang Khola catchment, where a mountain barrier running west–east at the southern side of the valley prevents moisture laden air from penetrating into the northern part of the valley (Konz *et al.*, 2006). Thus, the horizontal precipitation gradient ($P_{HorizGrad}$) was set *a priori* to zero in both catchments (Table 2). The parameters of the runoff generation routine were assumed to be constant for all catchments as the dominant hydrological processes appear similar in the three catchments. In the case of Modi Khola catchment, the data availability is very limited and the measurements are of questionable reliability. Therefore, no re-calibration of the model was conducted in this catchment.

Literature shows that glacier melt rates are higher in the Imja Khola catchment than in the Langtang Khola catchment (Kayastha *et al.*, 2000). This was considered by an increased degree-day factor (*CFMAX*, Table 2). Further parameters which were recalibrated for the application of TAC^D to the Imja Khola catchment are *PCF*, *TT and* R_{debris} (Table 2). Only five calibration runs were computed to adjust the parameter set of the Langtang Khola catchment to the situation of the Imja Khola catchment. Simulation without recalibration underestimated the discharge in all simulated monsoon periods. *CFMAX*, *TT* turned out to be sensitive for the simulation of the monsoon period, when melt water largely contributes to runoff generation.

The visual inspection of the hydrographs and the objective evaluation criteria show that discharge can be reproduced reasonable well if the input data and discharge measurement are of sufficient quality (Fig. 1, Table 3). However, significant deviations from measured discharge can be found in the Imja Khola catchment in the pre-monsoon season 1993 (Fig. 1). The unusually high measured discharge in the pre-monsoon season cannot be explained by the model and might well be an inconsistency (error) in the measurements. Snow and ice at the gauging station could cause too high water levels being recorded.

These results demonstrate that the model TAC^D can be applied satisfactory in highly glacierized catchments if one or more years of input and output measurements are available. The application of the model to the Modi Khola catchment is an example of the way in which a hydrological model can be used in areas with limited data. Regionalization of model parameters was possible in the case of the parameters for the runoff generation routine and soil routine. Glacier mass balance data turned out to be appropriate data for the (re-) calibration of the parameters of the snow- and glacier routine. This enables water resources assessments in remote areas with limited data availability if spatial data (e.g. DEM, land cover data) are available.

CONCLUDING REMARKS AND OUTLOOK

The ability to regionalize the model structure and parameter set of the distributed catchment model TAC^D has been demonstrated based on the parameter set obtained for the relatively well investigated Langtang Khola catchment. As the application of TAC^D to the Imja Khola catchment showed, only the parameters of the snow and glacier routine had to be adjusted, while the parameters of the soil- and runoff generation routine remained unchanged to yield reasonable simulation results. The parameters of the snow and glacier routine could be determined through measured glacier mass balances. The mass balances are integral values of all the ablation and accumulation processes within a specified period, and are relatively simple and inexpensive to measure. Further research should evaluate the potential of targeted short term measurements (e.g. glacier mass balances or equilibrium line altitudes) to regionalize hydrological models.

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