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Modelling observed and future runoff from a glacierized tropical catchment (Cordillera Blanca, Perú)

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Abstract

Monthly runoff from the 34.3% glacierized tropical catchment of Llanganuco in the tropical Cordillera Blanca, Perú, is successfully simulated and compared with a measured 44 year time series. In the investigation area, the climate is characterized by all-year round homogenous temperature conditions and a strong variability in air humidity and moisture content of the atmosphere. Thus, contrary to the mid latitudes, the seasonal variation in glacier melt strongly depends on moisture-related variables, rather than on air temperature. The here presented ITGG-2.0-R model aims for these requirements. The lack of moisture-related input data other than precipitation demands for an intermediate calibration step. Net shortwave radiation, the emissivity of the atmosphere and a sublimation/melt ratio are related to precipitation amounts. Runoff is well simulated and correlates with the measured record with $r^2=0.76$. Seasonally obtained r^2 are only slightly smaller. On a long-term, the cumulative deviation is minor, and the mean annual cycle of runoff is reproduced rather well ($r^2=0.99$). Based on four different IPCC climate change scenarios, future runoff is simulated. All runoff scenarios are modelled for the respective steady-state glacier extent. This leads to a reduction in the glacier size and a decreased amount of glacier melt. On the other hand, direct runoff increases due to larger glacier free areas. Consequently, mean annual runoff remains almost unchanged, but the seasonality intensifies considerably with more runoff during the wet and less runoff during the dry season.

Keywords: runoff model; glacier melt; tropical hydrology; runoff prediction

1. Introduction

Runoff from glacier melt plays a significant role in most parts of the world's high-mountain regions (e.g. McMahon et al., 1987; Chen and Ohmura, 1990; Messerli, 1997). Glacier melt has a strong impact on the seasonal as well as the inter-annual variation of runoff in the respective catchment (Chen and Ohmura, 1990; Kaser et al., 2003). Whereas in the mid latitudes the seasonality of runoff is amplified due to glacier runoff, the effect of glacier melt on seasonality in low-latitude high-mountain areas is a smoothing one, both situations with a favourable effect on agriculture in the respective regions (Kaser et al., 2003).

During the last decades glaciers all over the world have retreated (e.g. Hastenrath and Kruss, 1992; Peterson and Peterson, 1997; Kaser, 1999; Oerlemans, 2000; Ramírez et al., 2001). The reduction in volume and glacier area changes both the intensity of seasons and the inter-annual variation of runoff (e.g. Braun et al., 2000; Jansson et al., 2003). Thus, the influence of a changing climate on glacier runoff is of great importance for regional water supplies all over the world, as

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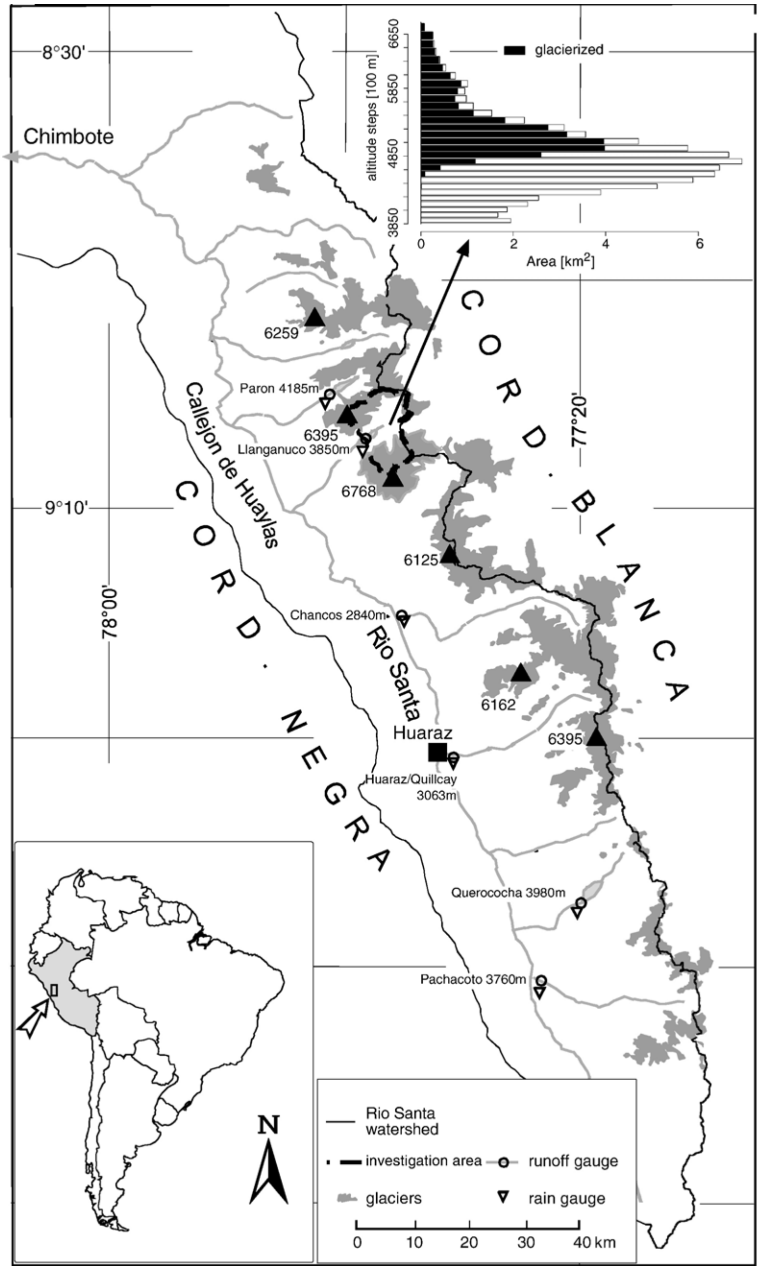

Fig. 1. The Llanganuco catchment in the Cordillera Blanca and its area altitude distribution. Additionally, all locations referred to in the text are shown.

widely discussed for alpine regions (e.g. Collins, 1987; Collins, 1989; Chen and Ohmura, 1990; Braun et al., 2000), as well as on a global scale (e.g. Gleick, 1987; McMahon et al., 1987; Arnell, 1996). In order to understand, analyse and predict glacier runoff, a variety of models has been developed for catchments in the mid and high latitudes (as e.g. summarized in Hock, 1998, 2003). Sophisticated energy balance models (e.g. Arnold et al., 1996; Sicart, 2002) need a considerable amount of measured data with high temporal resolution (e.g. hours), which are usually only available for short experimental periods. Thus, statistical temperature-index-models, with air temperature as only input, are widely used. The high correlation between the sum of positive degree days and melt rates (e.g. Hock, 1998; Braithwaite and Zhang, 2000; Oerlemans and Reichert,

2000) makes these models very successful for the mid and high latitudes (Ohmura, 2001), where temperature governs seasonality.

Contrary to the mid and high latitudes, low-latitude climate is characterized by a pronounced variation in atmospheric moisture content and related variables, whereas thermal variation is minor (Hastenrath, 1991; Kaser, 2001; Kaser and Osmaston, 2002). Especially for the tropical South American Andes, where runoff during the dry season (May–September) can originate 100% from glacier melt (Mark and Seltzer, 2003), the retreat of glaciers can lead to a considerable seasonal water shortage. Nevertheless, knowledge on runoff from glacierized catchments in the tropical Andes is still poor (Fliri, 1968; Francou et al., 1995; Ribstein et al., 1995; Tamayo, 1996; Schuler, 1997; Wagnon et al., 1999; Sicart, 2002; Kaser et al., 2003). Ribstein et al. (1995) found a rather good correlation between runoff from Zongo Glacier (16°S, Bolivia) and the duration of air temperature above 3 °C combined with incident solar radiation, both recorded at a nearby station. Still, energy balance investigations at the same site demonstrate the high importance of sublimation (Wagnon et al., 1999), net longwave radiation, and albedo (Francou et al., 2003) for ablation. They are all directly related to air humidity and atmospheric moisture content. In the tropical Cordillera Blanca (appr. 8–10°S), the correlation between monthly mean air temperature and runoff is very poor ($r^2 < 0.2$) and, thus, temperature-index models are not expected to reproduce the seasonality of runoff.

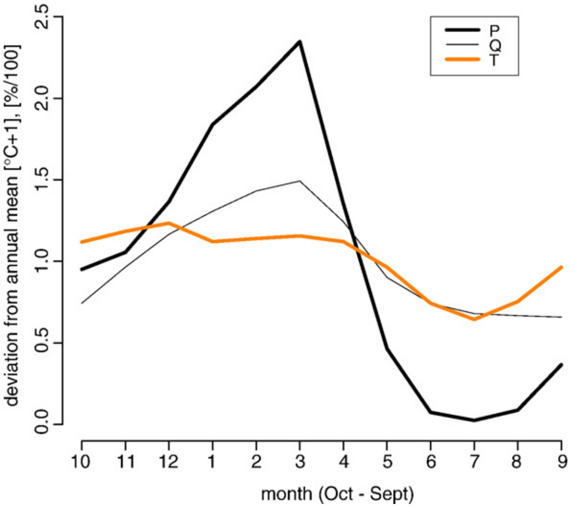

Fig. 2. Mean seasonal deviation from the long-term annual mean of precipitation in the Cordillera Blanca (P), runoff from the Llanganuco catchment (Q) and air temperature at Querococha station (T). The long-term means are depicted in Table 1.

Table 1
Mean, minimum, and maximum of monthly precipitation (P) (calculated as a mean over 6 individual stations at 4000 m a.s.l.), monthly runoff depth (q) and runoff (Q) from the Llanganuco catchment area, and monthly air temperature (T_a) for Querococha station at 3980 m a.s.l. Standard deviations (σ) are also shown

	Mean	Minimum	Maximum	σ
P (mm)	58.9	0	301.1	53
Q(mm)	89.4	33.6	201.6	32.6
Q(m^3/s)	2.98	1.1	6.7	1.08
T_a(°C)	6.48	4.7	8.2	0.6

The runoff model used for this study, referred to as the ITGG-2.0-R model, extracts glacier melt from the ITGG-2.0 mass balance model that was extended from a vertical balance profile (VBP) model (Kaser, 2001). This model not only accounts for ablation terms related to air temperature, but also to those driven by atmospheric moisture content. The aim of this study is to simulate seasonal and inter-annual variations in runoff from a glacierized tropical catchment for a 44 yr time period in order to (1) provide a first validation of the ITGG-2.0 model and to (2) predict mean annual cycles of runoff for different climate change scenarios. Runoff is modelled in monthly time steps.

2. The investigation area

The Perúvian Cordillera Blanca (8°30′–10°10′ S) is a 180 km long mountain range stretching from NNW to SSE with several summits rising above 6000 m a.s.l. (Fig. 1). With more than 600 km^2 glacier covered area (Georges, 2004), it comprises about one quarter of all tropical glaciers (Kaser and Osmaston, 2002). Runoff from these mountains is essential for the intense human activities in the Callejon de Huaylas and the Rio Santa valley as far as the costal area of Chimbote (Fig. 1).

The 34.3% glacierized catchment of Llanganuco situated in the northwest of the Cordillera Blanca (Fig. 1) was chosen for this study. The area altitude distribution of the Llanganuco catchment (86.4 km^2; spanning from 3850 to 6664 m a.s.l.) is shown in Fig. 1. The glacier area (29.6 km^2) and its area altitude distribution were taken from SPOT XS scenes from 1991 (Georges, 2004). The main part of the glacier area terminates at an elevation of 4850 m. a.s.l. negligible parts reach down to 4450 m a.s.l.

Fig. 2 shows the mean seasonal deviation from the long-term mean (%/100) in precipitation, (averaged time series over six individual stations, Kaser et al., 2003) and runoff from the Llanganuco catchment (34.3%

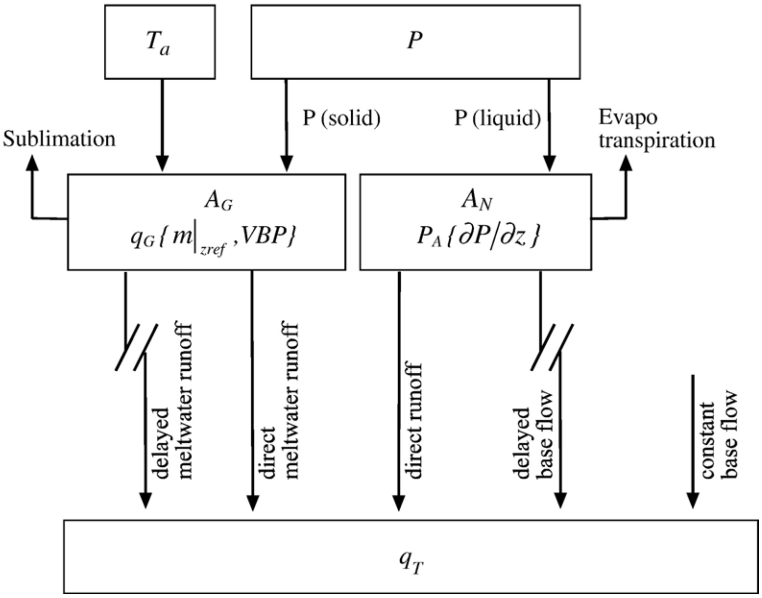

Fig. 3. Schematic structure of the ITGG-2.0-R model. T_a is air temperature, P precipitation, A_G glacier area, A_N glacier-free area, q_G glacier melt, $m|_{zref}$ melt at reference level, VBP vertical balance profile, P_A precipitation volume, ∂P / ∂z vertical gradient of P, and q_T total runoff depth.

glacierized). Precipitation shows a distinct seasonal variation with more than 90% of annual precipitation occurring between October and April. The seasonality of runoff from Llanganuco follows precipitation but with a striking reduced amplitude due to the glacierization. The deviation from long-term mean air temperature as measured at Querococha station is additionally depicted in Fig. 2. The long-term monthly mean air temperature (T_a) is almost constant throughout the year with a standard deviation (σ) of 0.6 (Table 1). Temperature is generally slightly higher during the wet season.

3. The runoff model ITGG-2.0-R

For application of the ITGG-2.0-R model (monthly time steps) the following assumptions are made:

1) Snow cover outside the glacier usually melts within hours or days and, thus, will not cause any delay in runoff on a seasonal scale.
2) Precipitation is assumed to fall as snow over the entire glacier. This is highly probable as indicated by only 3 months out of 528 in which the glacier terminus is below the monthly mean+2 °C level.
3) No albedo feedback is provided. Snow cover usually lasts only a few days on the glacier tongues.
4) The influence of different aspects of the glacier surface is neglected.

In addition, the ITGG-2.0 model is designed and calibrated for all year round melting conditions at all elevations (Kaser, 2001).

The ITGG-2.0-R model calculates the runoff depth in mm for each month $_n$ from i) the glacier q_G, and ii) the glacier-free area q_N (Fig. 3). The runoff depth for the total catchment area for each month q_{Tn} is obtained as

$$q_{Tn} = q_{Gn} + q_{Nn} \tag{1}$$

i) The calculation of glacier melt is based on the ITGG-2.0 glacier mass balance model, which was extended from a vertical mass balance profile VBP model (Kaser, 2001) to a full mass balance model. The absolute vertical balance profile VBP$_a$ is calculated by adding VBP to the specific net mass balance at a reference level, $b|_{zr}$.

$$\mathrm{VBP}_a = b|_{zr} + \mathrm{VBP} \tag{2}$$

Analogous to VBP in Kaser (2001) but with a varying atmospheric emissivity for wet and dry conditions we calculate

$$b|_{zr} = c|_{zr} - \tau F(f)[\mathrm{SW_{in}}(1-\alpha)|_{zr} + \varepsilon_a \sigma T_a^4|_{zr} - \sigma T_s^4|_{zr} + C_s(T_a|_{zr} - T_s|_{zr})] \tag{3}$$

$c|_{zr}$ is the accumulation at the reference level, τ the duration of ablation period, SW$_{\mathrm{in}}$ the incoming shortwave radiation, α the albedo, ϵ_a the emissivity of the atmosphere, σ the Stefan–Boltzmann constant, T_a the air temperature, T_s the glacier surface temperature, and C_s a heat transfer coefficient. The term $F(f)$ describes the contribution of melting and sublimation to ablation under the given availability of respective energy (Kaser, 2001).

The ITGG-2.0-R model extracts glacier melt at each altitude step along the VBP$_a$ with vertical gradients of air temperature $\partial T_a / \partial z$, accumulation $\partial c / \partial z$, and albedo $\partial \alpha / \partial z$. The contribution of glacier melt to the runoff depth of the entire catchment A_T is

$$q_G = \sum (q_{Gi} * A_{Gi}) / A_T \tag{4}$$

with A_G being the glacier area.

Because of a considerable delay in the firn body of the glacier, 30% of total melt water is considered to contribute to the runoff of the next month. The determination of the delay is discussed in Section 4. Following this, total runoff depth derived from glacier melt for each month is

$$q_{Gn} = q_{Gn} * 0.7 + q_{Gn-1} * 0.3 \tag{5}$$

ii) The runoff from the non-glacierized area is calculated from precipitation P and its vertical gradient $\partial P / \partial z$. The precipitation P_i for each altitude step Δz is

$$P_i = P + \partial P / \partial z * \Delta z \tag{6}$$

and total spatial mean P_A for the non-glacierized area A_N is then

$$P_A = \sum (P_i * A_{Ni}) / A_T \tag{7}$$

A portion of $(1-k)$ P_A goes into evaporation, transpiration, and base flow. Due to the lack of further information, a variable base flow is assumed to be 20% of this portion and to contribute to the next month's runoff. The value of k varies from 0.5 to 0.6 with the amount of precipitation, to be discussed in Section 4. The variable part of base flow determined this way is set on top of a constant base flow q_0. The total runoff depth for each month from the non-glacierized area is then calculated as:

$$q_{Nn} = P_{An} * k_n + P_{An-1} * (1 - k_{n-1}) * 0.2 + q_0 \tag{8}$$

4. Input data and model calibration

The ITGG-2.0 model requires values for f, SW$_{\text{in}}$, α, ϵ_a and T_a in order to produce melt water amounts which then contribute to runoff. In practice, at least one moisture-related record and air temperature is needed. In the Cordillera Blanca, monthly precipitation data of different quality are available for several stations from 1953 to 1997. Considering that precipitation is homogeneous in space and in order to minimize errors, an average is calculated from six reliable records (Kaser et al., 2003). Since this is the only moisture-related variable recorded, a relation between precipitation and all other moisture-related variables had to be found. Assuming that maximum values of moisture related parameters coincide in time, a very dry and a very wet scenario can be designed. The reliability of such an assumption increases with the time span over which the values are averaged. In other words, it can be assumed that in months with high precipitation amounts accumulation, albedo and atmospheric emissivity will reach their highest values on average. Sublimation and solar radiation will be lowest. The opposite can be assumed for months with no rain. Obviously, this assumption may be of less validity when looking at much smaller time steps such as days or hours when e.g. a strong shower in the evening cannot characterise the entire day. Even on a monthly basis, one may fail with this approach when simulating particular months within time series such as those described by Francou et al. (2003) when the wet season started with all its attributes except precipitation. Nevertheless, due to the lack of information, a linear relation between the moisture-related variables and precipitation is adopted in order to derive values in between the very wet and very dry situation.

Table 2
Input variables and model parameters for the ITGG-2.0-R model

Input variables			Model parameter derived linearly from precipitation		
	Dry	Wet		Dry	Wet
P (mm month^{-1})	0	300	f	0.85	0.15
Vertical gradients			$SW_{in}\vert_{zref}$ (MJ m^{-2}d^{-1})	23	12
$\partial P / \partial z$ (mm m^{-1}month^{-1})	0.035		$\alpha\vert_{zref}$	0.4	0.85
$\partial \alpha / \partial z$(m^{-1})	0.00066		ϵ_a	0.7	0.86
$\partial T_a / \partial z$ [Km^{-1}]	−0.0065		k	0.5	0.6

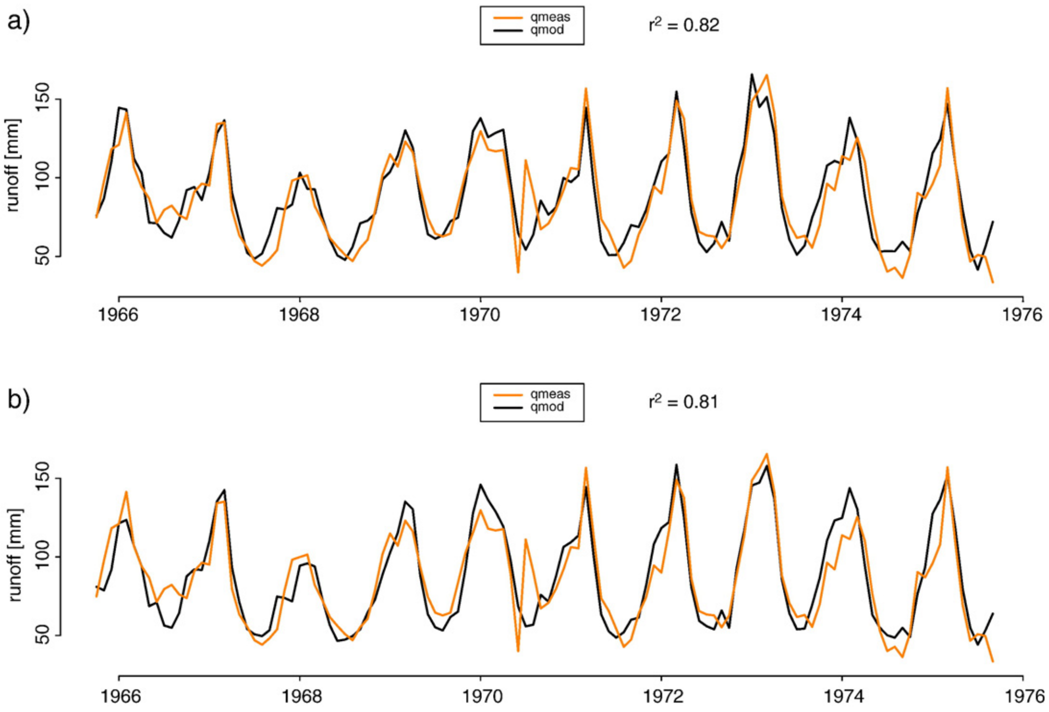

Fig. 4. Modelled (qmod) and measured (qmeas) monthly mean runoff depths for the calibration period 1965 to 1975 with a) measured air temperature at Querococha station and b) air temperature from NCEP–NCAR Reanalysis.

The value ranges of model parameters (Table 2) were obtained from several available data sets in the tropical Andes. Mean monthly global radiation values (SW_{in}) are available from two automatic weather stations operated in the Cordillera Blanca at 4.600 and 5.000 m, respectively, since 1999 (Georges and Kaser, 2002). The ranges of f, α, and ϵ_a are derived from energy balance measurements carried out in the ablation zone of Zongo Glacier in the Cordillera Real, Bolivia, between 1996–1998 (Wagnon et al., 1999) It may be noteworthy that during this experiment several months showed exclusively sublimation, but not a single one exclusively melting. This is quite reasonable since pronounced dry periods may exclude any energy being available for melting whereas each wet period in an environment characterised by convective atmospheric processes has sunny hours with predominant sublimation. The gradient of precipitation $\partial P / \partial z$ is calculated according to Fliri (1968) and Niedertscheider (1990) and by extending the available time series until 1993. The gradients $\partial \alpha / \partial z$ and $\partial T_a / \partial z$ as well as C_s are adopted from Kaser (2001), where they are extensively discussed.

The only long-term record of air temperature in the Cordillera Blanca (1965–1994) is available from Querococha station at 3980 m a.s.l. (Fig. 1). This station is 75 km away from the area of investigation. Its use is justified because of the horizontal thermal homogeneity of the tropical atmosphere. A second model run was performed by using air temperature from NCEP–NCAR Reanalysis data (Kistler et al., 2001). This allows extending the study from 1953 to 1997. Air temperature was determined as an arithmetic mean of values from four grid points surrounding the Cordillera Blanca (280°W, 282.5°W, 7.5°S, 10°S) at the 500 hPa-level. Attempts to derive moisture-related model inputs from gridded data sets have not led to any improvement of runoff simulation so far.

A rather precise evaluation of the glacier extent of 1991 is provided by Georges (2004). There he also thoroughly discusses former glacier extents giving the following picture: From 1950 to 1975 the glacier area was almost constant. After minor advances in the mid 1970s, glaciers lost about 6% of their surface area until 1990. In this study the 1990 glacier extent was used for the whole period. If the glacier area is constantly kept 6% larger for the first decade, the mean difference in modelled runoff is between +3 and −2.5% when looking at individual months.

For the determination of melt water from the firn area contributing to runoff of the subsequent month a simple linear reservoir equation is applied. In the mid- and high-latitudes melt water from the firn area reaches the

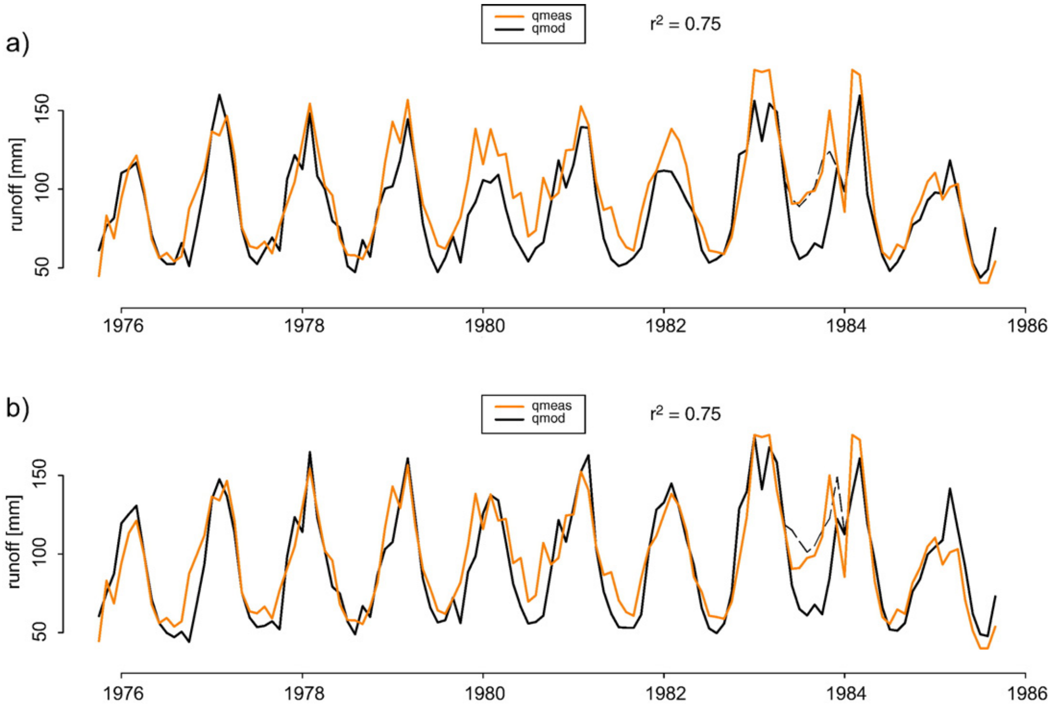

Fig. 5. Modelled (qmod) and measured (qmeas) monthly mean runoff depths for the validation period 1975 to 1985 with a) measured air temperature at Querococha station and b) air temperature from NCEP–NCAR Reanalysis. Additionally, runoff is modelled with a reduced sublimation/melt ratio *f* during the dry period 1983 (dashed line, see text for further explanation).

terminus within 10 to 20 days (Schneider, 1997). Because of the very short glacier tongues in the Cordillera Blanca (Kaser and Osmaston, 2002), and the persistent water saturation of a tropical firn body, a reservoir storage coefficient of 10 days is applied. With this and assuming the amount of precipitation to be the same for each day within a given month, 60% of the entire glacier's melt water production will contribute to the runoff of the next month. In order to obtain the amount of melt water produced in the firn area, its extent has to be defined. Despite further information, the glacier's portion above the long-term mean 0 °C-level (5000 m a.s.l., 1965–1994) is taken as firn area. Although this is 84% of the entire glacierized area, it makes up only 50% of q_G. Consequently, 30% of q_G are delayed into the following month.

The runoff coefficient k is defined as the ratio between direct runoff and precipitation, differing with climate (Ponce and Shetty, 1995) and surface cover (Gottschalk and Weingartner, 1998) within the range 0–1. According to Ponce and Shetty (1995) k is typically less than 0.2 for arid to semiarid regions and often greater than 0.5 in wet tropical regions. In order to derive a suitable value for the non-glacierized portion in the Llanganuco catchment, k is determined for the minimally glacierized (3.2%) catchment of Querococha. To further minimize the influence of the glacier, the calculation was only made for the wet season. The values vary between 0.5 and 0.6, with a clear increase with enhanced precipitation. Accordingly, the value of k changes linearly with precipitation between 60 and 150 mm per month and remains constant below and above this value range. In order to account for a feedback effect Kadioglu and Sen (2001) suggest to calculate k as the arithmetic mean of the preceding and current month's value.

For the constant base flow q_0, the absolute minimum of 8 mm runoff depth per month out of the 44 yr record from Querococha station was again adopted to the Llanganuco catchment.

5. Model results and discussion

All analyses are made for hydrological years starting with October. The calibration period was taken for the hydrological years 1965/1966 to 1974/1975 because (1) this was a period of more or less constant glacier cover (Georges, 2004), and (2) air temperature records at the station Querococha start in 1965. The following ten hydrological years represent the validation period.

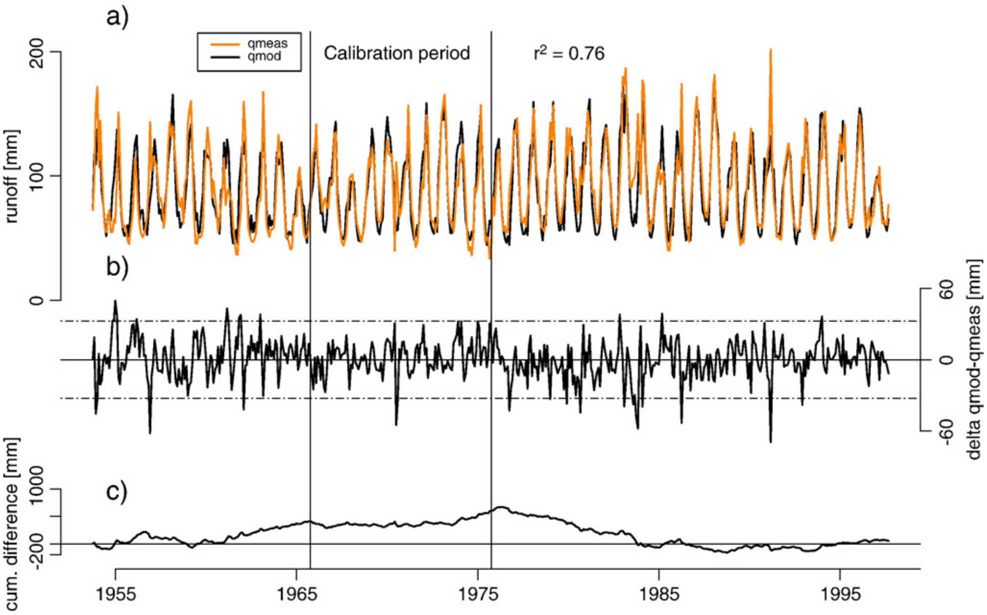

Fig. 6. Results for the 44 yr time series from 1953 to 1997 with air temperature input from NCEP–NCAR Reanalysis: a) modelled (qmod) and measured (qmeas) monthly mean runoff depth, b) difference between modelled and measured runoff with the standard deviation of measured runoff in dashed lines), and c) cumulative monthly difference.

5.1. Calibration period 1965–74 and validation period 1975–84

A first model run (run1) over the calibration period was performed with measured precipitation averaged over six stations, air temperature records from Querococha station, and best fitted model parameters (Fig. 4a). It resulted in a coefficient of determination of $r^2=0.82$ with the above discussed best fit model parameters (Table 2).

For the same period, a second model run was carried out by replacing the Querococha temperature record with respective series from NCEP–NCAR Reanalysis data. The result is shown in Fig. 4b and is almost equal to that of model run1 with $r^2=0.81$.

In both cases the seasonal as well as the inter-annual variations are well represented by the model. When taking a closer look, some particular modelled values deviate from measured ones. The most striking one is the high runoff depth in June 1970 which is not met by the model runs. An amount of more than 110 mm is very unusual for a month in the dry season, where the long-term dry season mean is only about 60 mm month^{-1}. In all available data sets no evidence for this extraordinary high runoff was found. Precipitation in June 1970 is only 9 mm and air temperature is below the long-term mean. Runoff series available from nine other catchments in the Cordillera Blanca (Kaser et al., 2003) do not show any unusual runoff in June 1970. Hence, an underlying climatic reason is not obvious, which precludes modelling this event. One reason for the high runoff in June 1970 can be a recording error. Another explanation could relate to the catastrophic earthquake on May 31, 1970 (Welsch and Kinzl, 1970),

Table 3
Monthly coefficients of determination (r^2) between measured and modelled runoff for the 44 yr period from 1953 to 1997

Wet season: $r^2=0.65$						
October	November	December	January	February	March	April
0.82	0.53	0.85	0.42	0.82	0.88	0.70
Dry season: $r^2=0.72$						
	May	June	July	August	September	
	0.60	0.74	0.80	0.85	0.77	

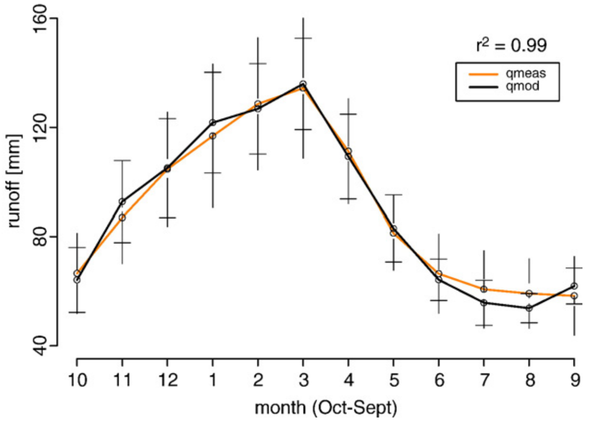

Fig. 7. Long-term mean seasonal variation of modelled (qmod) and measured (qmeas) runoff. Vertical and horizontal bars depict the standard deviation of measured and modelled runoff, respectively.

which might have disturbed the runoff gauge. Excluding the value, the result improves considerably with $r^2=0.86$ for both model runs.

For the validation period the coefficient of determination of modelled versus calculated runoff is $r^2=0.75$ for both model runs (Fig. 5a and b). For the dry seasons 1980 and 1982 air temperature from NCEP–NCAR Reanalysis leads to a much better result than those from Querococha station.

Particularly noticeable is the dry season 1983 when runoff is above 100 mm in each month, which is not met by both model runs. Again, these high observed amounts cannot be explained by precipitation, since this does not deviate from the long-term mean. In addition, both air temperatures at Querococha station and from NCEP–NCAR Reanalysis data are markedly below average. Consequently, the high amount of runoff during the entire dry season of 1983 cannot be explained by the available data. A possible explanation for this high runoff is an influence of the strong 1982/1983 El Niño. Although precipitation is normal, a raise in air humidity could have caused reduced sublimation and, thus, high melting rates (Wagnon et al., 1999). However, this cannot be modelled as long as all humidity-related variables are derived directly from precipitation. A reduction of the sublimation/melt ratio f of 0.15 as independent from precipitation can produce the unusual high runoff during the dry season of 1983 (dashed line in Fig. 5) and improves the over all coefficient of determination ($r^2=0.79$). In a less pronounced way, similar effects may help to explain the underestimation of runoff during several dry seasons. Thus, using an independent time series of air humidity (such as those from NCEP–NCAR Reanalysis data) is expected to improve the model results significantly. Still, the extraction of moisture-related variables from atmospheric reanalysis is not yet developed sufficiently for a glacier mass balance calculation in the tropics.

It has to be mentioned that, the pronounced seasonality of runoff given, these high values of r^2 are not surprising. Monthly analyses, however, are statistically insignificant for the limited number of years. Therefore a seasonally varying r^2 is discussed for the full time series from 1953 to 1997 in the following section.

5.2. *Runoff simulation for the period 1953–1997*

Making use of the entire length of measured precipitation and runoff as well as NCEP–NCAR Reanalysis air temperature, runoff is simulated for the 44 yr period from 1953 to 1997. The result shown in Fig. 6a reaches $r^2=0.76$. The coefficient of determination for each month (Table 3) is worst for November and January with $r^2=0.53$ and $r^2=0.42$, respectively. The highest values are reached for the months December, March and August with values above 0.85. Distinguishing between wet and dry season, the value is higher for the dry season when runoff from glacier melt dominates ($r^2=0.72$) than for the wet season ($r^2=0.65$). This shows that the ITGG-2.0-R model simulated the glacier melt well. The monthly difference between modelled and measured runoff fluctuates between −70 and +50 mm month^{-1} (Fig. 6b). 94.3% are within the standard deviation of ±32.6 mm month^{-1} of measured runoff (Table 1), the mean positive deviation of simulations being +12 mm and the negative one −12.5 mm per month. The accumulated deviation shows a long-term trend (Fig. 6c). Cumulative deviations increase more or less continuously until 1975 and decrease afterwards. Observed glacier area changes cannot account for it since their effect is to small and no other obvious causes for this trend can be retrieved from the available information at this point. Variations in length and

Table 4

Predicted mean annual change in air temperature ΔT_a and precipitation ΔP for four IPCC climate change scenarios with respect to the mean values of 1961–1990 (Hulme and Sheard, 1999). Values are taken as a mean from the four GCM grid points surrounding the Cordillera Blanca

	2050		2080	
	ΔT_a (°C)	ΔP (%)	ΔT_a (°C)	ΔP (%)
b1—low	+1.1	+2.5	+1.45	+3.5
b2—medium	+1.75	+4.2	+2.3	+6.25
a1—medium	+2.1	+5.5	+2.65	+7.0
a2—high	+3.0	+8.5	+4.67	+13.0

intensity of seasons have to be considered the most likely reason. In particular all moisture-related variables being restrictively synchronized so far (Section 4) are thought to stand for the deviations to a certain extend. Over the 528 months of simulation, overestimation and underestimation of runoff nearly balance each other.

The modelled and measured long-term mean seasonal variation of runoff is shown in Fig. 7 ($r^2=0.99$). In each case the monthly standard deviation of modelled runoff is smaller than that of the measured runoff as indicated by the bars in Fig. 7. Again the slight underestimation during the dry season as well as the slight overestimation during the period of increasing precipitation may be related to the missing dissolution of the individual moisture-related variables. Nevertheless the mean annual cycle is simulated rather well, which enables the use of the model for predicting mean seasonal runoff in different climate change scenarios.

6. Runoff scenarios

GCM-computed climate scenarios (Hulme and Sheard, 1999) as based on four different IPCC emission scenarios (IPCC, 2000) for the years 2050 and 2080 are used as input for runoff prediction. The IPCC predicted changes (Table 4) proceed from 1961–1990 means. Changes in glacier extend and runoff are simulated accordingly. The glacier area is simulated for a new steady-state extent by gradually reducing the glacier area until the annual specific mass balance is near zero. Note that this procedure does not include any dynamic response times of the glaciers and therefore excludes prediction in time. The spatial pattern of retreat was adopted from a case study in the Santa Cruz mountain range performed by Georges (2004), where the retreat from 1930 to 1970 and 1990 was analysed in detail.

The mean annual change in glacier melt Δ q_G and direct runoff Δ q_T for the four different scenarios is summarized in Table 5. Additionally, the reduction in glacier area for the new steady state glacier extent Δ A_G is listed. Glacier area is reduced by 38 to 60% for the different scenarios for the 2050 scenario with a decrease in glacier melt of 35 to 53%. For the 2080 scenario the decrease in glacier area is predicted to be 49 to 75% with a corresponding retread in glacier melt of 44 to 69%. Direct runoff from the non glacierized area increases 23 to 40% for 2050 and 31 to 56% for the 2080 scenario. This is due to the higher amount of total precipitation and the increase of A_N. Total annual runoff remains almost unchanged (1–2%) for all model runs due to higher direct runoff which compensates reduced glacier melt.

Table 5
Modelled change of mean annual glacier melt Δ q_G and runoff from the non-glacierized area Δ q_N with respect to the 1961–1990 means (100%). Δ A_G is the change of glacier area (1990=100%) for a new steady-state glacier extent

	2050			2080		
	Δq_G (%)	Δq_N (%)	ΔA_G (%)	Δq_G (%)	Δq_N (%)	ΔA_G (%)
b1—low	−35	+23	−38	−44	+31	−49
b2—medium	−48	+35	−54	−59	+44	−64
a1—medium	−35	+25	−41	−48	+37	−55
a2—high	−53	+40	−60	−69	+56	−75

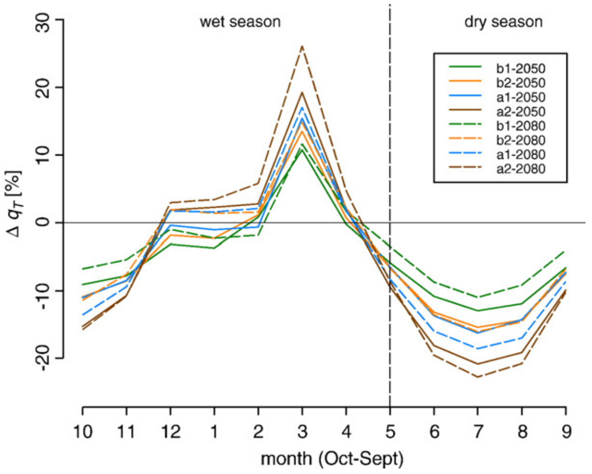

Fig. 8. Changes in seasonal total runoff Δ q_T in four IPCC climate change scenarios with respect to the 1961–1990 mean monthly runoff.

The change in total runoff is, however, crucial when looking at the seasonal cycle (Fig. 8). During the wet season, when runoff is dominated by precipitation, an increase of 10 to 26% is to be expected. The maximum increase is predicted for March when precipitation is highest. The most dramatic changes with crucial impacts on the availability of water in the Rio Santa valley are predicted for the dry season when runoff is dominated by glacier melt. Then, decreases by 11 to 23% of an already low runoff are expected to challenge future water management drastically.

7. Summary and conclusions

For the Perúvian Cordillera Blanca, several long-term series of runoff, precipitation, and air temperature records are available. Annual temperature variations are minor, seasons are driven by precipitation. The extended glaciers of this mountain range have a dominant impact on the availability of water in the Rio Santa valley, particularly during the dry season. In this paper, the 34.3% glacierized Llanganuco sub-catchment is used exemplarily. The runoff model ITGG-2.0-R extracts glacier melt from an extended vertical balance profile model (Kaser, 2001) which was developed for low latitude circumstances. It is principally driven by air temperature as well as several variables related to atmospheric moisture content. Because of the limited availability of data records, incoming shortwave radiation, albedo, atmospheric emissivity, and a sublimation/melt ratio are derived from precipitation in an intermediate calibration step. In addition to the glacier melt the ITGG-2.0-R model calculates runoff from non glacierized areas separately. Different model runs show a high over all correlation with observed runoff ($r^2=0.76$). Seasonally obtained r^2 are only slightly smaller for the wet ($r^2=0.65$) and also for the dry season ($r^2=0.72$). This provides a successful evaluation of the ITGG-2.0-R model.

The measured and modelled mean annual cycles of runoff have a correlation of $r^2=0.99$. Based on this and on four different IPCC climate change scenarios for the years 2050 and 2080 runoff from the Llanganuco catchment is simulated. All runoff scenarios are calculated assuming respective steady-state glacier extents. In each case, the reduced glacier size leads to a decreased amount of glacier melt. This decrease is compensated by an increase in direct runoff and mean annual total runoff remains almost unchanged. However, the seasonality is considerably amplified. During the wet season, when runoff is already high, runoff increases. Dry season runoff, which is dominated by glacier melt, will be reduced up to 23%. This decrease of an already low runoff will challenge future water management considerably.

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