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Modelling of hydrological response to climate change in glacierized Central Asian catchments

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Abstract

The arid lowlands of Central Asia are highly dependent on the water supplied by the Tien Shan mountains. Snow and ice storage make large contributions to current runoff, particularly in summer. Two runoff models with different temporal resolutions, HBV-ETH and OEZ, were applied in three glaciated catchments of the Tien Shan mountains. Scenario runs were produced for a climate change caused by the doubling of atmospheric CO_2 as predicted by the GISS global circulation model and assuming a 50% reduction of glaciation extent, as well as a complete loss of glaciation. Agreement of the results was best for runs based on 50% glaciation loss, where both models predict an increase in spring and summer runoff compared to current levels. Scenarios for complete loss of glaciation predict an increase in spring runoff levels, followed by lower runoff levels for July and August. Model predictions differ concerning the degree of reduction of late summer runoff. These scenarios are sensitive to model simulation of basin precipitation, as well as to reduction of glaciation extent.

1. Introduction

Water supply from Central Asian mountains to the surrounding lowlands is favourably influenced by the presence of glaciers, in terms of volume, timing (intra-annual variability), and interannual consistency. Glaciers collect solid precipitation in winter and release it with a seasonal delay in the form of meltwater, just when it is needed most urgently for agriculture and as drinking water. The fact that summer precipitation and ablation complement one another and meltwater production is strongest in hot and dry periods, has a minimizing effect on the year-to-year variation of runoff (Röthlisberger and Lang, 1984). According to Shults (1965), the mean fraction of ice melt in annual runoff in Central Asia is 8-9%, but since it is concentrated on few months it can strongly increase summer runoff. In basins with pronounced glacier cover, Shults (1965) determined portions of ice melt up to 22%, reaching 37% during the ablation period (Jul-Sep). In high mountain river basins of the Northern Tien Shan, glaciermelt contributes 18-28% to annual runoff and 40-70% to summer runoff (Aizen et al., 1996). This corresponds well with calculations in six catchments of Kungey and Terskey mountain ranges, where glacier runoff reaches up to 69% of total runoff in summer (Dikich and Hagg, 2003). A compilation of 36 Central Asian river catchments in Aizen et al. (1995) shows annual percentages of glacier runoff up to 61% (Aksai river).

Glacier retreat can be observed all over Central Asia. In the Zailiskiy range in Kazakhstan, glacier area was reduced by 20% from 1955 to 1979 (Vilesov and Uvarov, 1998), which marks a very strong deglaciation. In other parts of the Central Asian mountain systems, observed glacier retreat in the same period (1957/58/59-1978/79/80) is more moderate and ranges between 10% in the Pamirs and 16% in the Alay range (Shchetinnikov, 1998). From surface and remote sensing data, Aizen et al. (2006) observed a total glacier reduction in Central and Northern Tien Shan by 14.2% from 1943-2003, being 3% higher in Northern Tien Shan (Ala Archa) than in Central Tien Shan (Akshiirak massif). The recession of glacier area is pronounced since the 1970s, which can be correlated to an increase in summer temperatures (Aizen et al. 2006). Narama et al (2006) compared 1971 Corona and 2002 Landsat images of western Terskey Alatoo and noticed an arial shrinkage of 8%, with an overproportional loss on small glaciers (<1 km²). The presently observed retreat of mountain glaciers is expected to continue as a result of predicted warming in southeast Kazakhstan (KazNIIMOSK, 1999) and Kyrgyzstan (UNDP, 2003).

In earlier studies, the runoff model "HBV-ETH" was applied in the Central Asian basins of the glaciers Tuyuksu, Abramov and No. 1 and results have been compared with similar investigation in the Alps (Hagg and Braun, 2005). The extension of modelling efforts to the catchments of Ala Archa and Oigaing (Hagg et al. 2006) showed the limited possibilities for applying the HBV-ETH model due to its requirement of daily meteorological and hydrological data. In order to expand hydrological modelling to a broader range of remote catchments with a sparse data set, the monthly time step model "OEZ" which showed good performance in Alpine glacier basins (Kuhn and Batlogg, 1998), was added to the studies carried out in Central Asia. This paper shows how in a first step both models have been applied simultaneously to compare their results and evaluate their performance. The three test sites "Ala Archa", "Abramov" and "Oigaing" have been chosen for this purpose. The main reason for their selection was data availability. Although the two models are rather conceptual and simple, these were the only basins in Central Asia where all necessary input data for both models could be collected. The aim of the modelling is to estimate how the availability of water from glacierized Central Asian catchments may change under climate conditions predicted by the GISS global circulation model (KazNIIMOSK, 1999) for the doubling of CO_2 in the atmosphere.

2. Description of research areas

2.1 Location, topography and climate

Fig. 1 shows the location of the three catchments studied in the northern Tien Shan (Ala Archa), north-western Tien Shan (Oigaing) and Alay (Abramov).

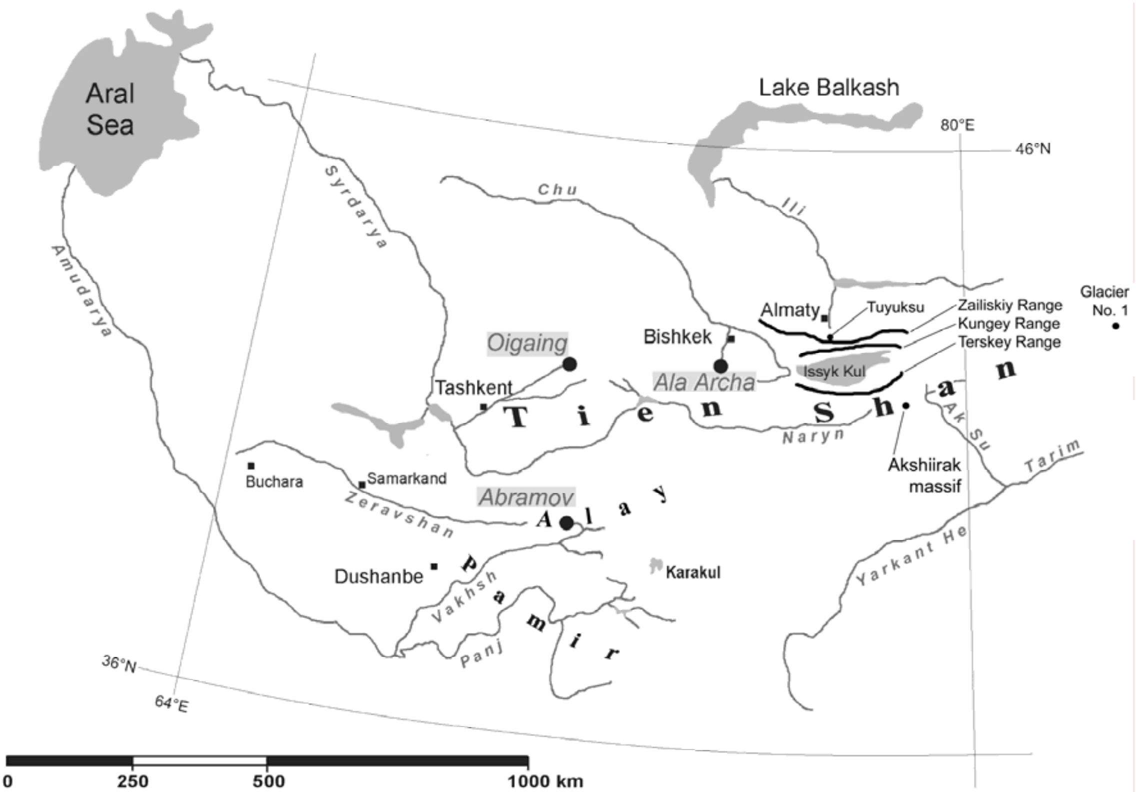

Fig. 1. Location of test sites.

Table 1 gives an overview on the main topographical, climatic and hydrological features. The higher value of runoff in relation to precipitation is due to the fact that precipitation is a point value measured in lower elevations of the catchments and, in case of Ala Archa and Abramov, to the strongly negative glacier mass balances over the years observed.

Table 1
Geographical, topographical and hydrometeorological features of test sites (data from CADB, 2003 and Pertziger, 1996).

	Ala Archa	Oigaing	Abramov
	Location		
National territory	Kyrgyzstan	Uzbekistan	Kyrgyzstan
Mountain Range	Kyrgyz Alatoo	Pskemski	Pamiro-Alay
River system	Chu	Syr Darya	Amu Darya
	Topography		
Elevation range (m a.s.l.)	2945-4400	2140-4300	3500-5000
Catchment size (km²)	31	463	5
Observation years for glacier data	1960	1960	1986
Glacier Area (km²)	11	43	26
Glaciation (%)	36	7	51
Elevation range glaciers (m a.s.l.)	3400-4100	3400-4300	3630-4960
	Climate		
Observation period	1958/59-1973/74	1962/63-1994/95	1967/68-1997/98
Elevation meteorological station (m a.s.l.)	2945	2140	3840
Mean annual precipitation (mm)	700	760	730
Precipitatiom maximum	May-Jun	Dec & Apr	Mar-May
Precipitatiom minimum	Dec-Feb	Jul-Sep	Aug-Sep
	Runoff		
Observation period	1960/61, 1962/63-1963/64, 1974	1963/64, 1971/72-1973/74, 1978/79-1979/80	1968/69-1987/88
Annual total (mm)	900	900	1650
Peak: magnitude (mm), timing	230, Jul	250, Jul	500, Aug

The climate of Central Asia is generally continental and influenced by the Siberian anticyclone in winter, which acts as a block for western air masses and decreases the quantity of winter precipitation (Aizen and Aizen, 1994). In the Tien Shan, this influence is strongest in the northern and eastern parts, and of the three basins studied it has the greatest effect on Ala Archa. This is the reason for the winterly precipitation minimum in this basin.

2.2 Data set

Hydrometeorological data of Abramov was taken from Pertziger (1996), the two other basins were covered by the Central Asian Database (CADB, 2003). This data contains daily means of temperature, precipitation and runoff, and was available for the hydrological years 1968/69-1987/88 (Abramov), 1960/61, 1962/63-1963/64, 1971/72-1972/73 (Ala Archa) and 1971/72-1972/73, 1978/79-1979/80 (Oigaing). Monthly altitudinal gradients of temperature and precipitation were calculated according to the formulae and parameters provided by Aizen et al. (2000) in the cases of Ala Archa and Oigaing. For the HBV model, which assumes a stable gradient throughout the year the annual mean was determined. At Abramov glacier all lapse rates had to be calibrated.

Topographical data (distribution of area by elevation and aspect, for glaciers and total catchment) was derived from maps 1:25'000 (Abramov, Ala Archa) and DTM (Oigaing, taken from CADB, 2003). Grass and forest cover is needed by the OEZ model to estimate evaporation and was also determined from Soviet Military Topographic Maps 1:100000.
Measured glacier mass balances are required by the OEZ model to calculate basin precipitation from the water balance equation; moreover, they can be used for additional validation of HBV-ETH results. Abramov glacier mass balances for the whole modelling period were taken from Kamnyansky (2001). At Ala Archa, mass balance was calculated as a residual of the water balance. Extrapolations from nearby Golubina glacier were not possible, because the mass balance data does not cover the time span of the hydrometeorological data available for Ala Archa basin. Unfortunately, no mass balance measurements were carried out at Oigaing or neighbouring basins. Severtsova glacier in the Oigaing catchment shows front variations from 1976-1980 of -0.9 m (Fluctuations of Glaciers Vol. IV), including two years of glacier advance (+10 m in 1977 and +17.6 m in 1978). This indicates that the glaciers could have been in a stable state during the observed period. From the 1960s to the 1980s, many glaciers in the Alps were advancing due to cool summers in Europe. In Central Asia, this phenomenon was not observed to the same degree (Ciaohai and Tianding, 1992), but it is conceivable that some regions, especially in the more maritime western parts that are more strongly influenced by Atlantic air masses, showed stable glacier behaviour. Due to the lack of better options and the fact that the error will be limited due to the low glaciation of the catchment, glacier mass balance was assumed to be zero. A calculation of glacier mass balance as a residual of the water balance was not executed here due to the large extent of the basin down to low elevations, where vegetation cover would introduce large errors in estimating evapotranspiration.

3. Methods

Two conceptual runoff models have been applied for current and future climate at the three test sites. Both models are semi-distributed with coarse vertical spatial discretization.
HBV-ETH is a linear reservoir model with a daily time-step. The original HBV model was developed at the Swedish Meteorological and Hydrological Institute (Bergström and Forsman, 1973; Bergström, 1992) and expanded at the Swiss Federal Institute of Technology (ETH) in Zurich for the application in glacierized catchments (Braun and Renner, 1992; Hottelet et al., 1993). From here on, the model will be referred to as the "HBV" model.
The second model, the OEZ model, is a water balance equation model which works with longterm means of monthly data. It was developed at the Institute for Meteorology and Geophysics of the University of Innsbruck (Kuhn et al., 1982; Kuhn and Pellett, 1989; Kuhn and Batlogg, 1998, 1999; Kuhn, 2003).
The essential difference between the two models is the temporal resolution. The HBV model can reproduce weather patterns and therefore has a higher prediction power than the OEZ model, which is climatological in nature.

3.1 HBV-ETH model

A short overview on the HBV-ETH model is given below, for more detailed information see Braun and Aellen (1990) and Braun and Renner (1992).

Required input consists of topographical data (total and glaciated area of each elevation belt) and hydrometeorological data (daily values of air temperature and precipitation to drive the model, and runoff for calibration purposes). In order to account for varying energy inputs from solar radiation, the area-elevation data is further differentiated according to aspect in three classes (north, south, east-west-horizontal)

A distinction is made between liquid and solid precipitation using a vertical temperature gradient and a threshold temperature. Basin precipitation is calculated by applying a rainfall/snowfall correction factor to measured precipitation values, and precipitation increase with altitude is calculated using a seasonally stable precipitation gradient. Whenever possible, these gradients are taken from measurements, otherwise they are calibrated. Snow cover depletion and glaciermelt are calculated using the temperature index method. The degree-day factor varies over the year using a sine-wave function. On south-facing slopes, melt rates are multiplied and on north-facing slopes divided by the calibrated factor RMULT to account for different solar radiation inputs. Best model fit was achieved with RMULT values of 1.7, 1.65 and 1.5 for Ala Archa, Abramov and Oigaing, respectively. Enhanced melt of glacier ice compared to snow is also calculated using a multiplicative factor after the disappearance of the snowpack. Meltwater refreezing in the snowpack is accounted for by using a refreezing coefficient, which comes into effect below the threshold temperature for melt. Meltwater retention in the snow cover is calculated as a percentage of the water equivalent of the snow cover.

The sum of rainwater and meltwater from the snow and glacier routine is the input for the soil moisture routine. This routine contains all water losses due to actual evapotranspiration, which is calculated from potential evapotranspiration dependent on the soil moisture content. A coefficient controls the flow of water into the upper storage, a part of the third module, where runoff is generated. The upper storage has two outlets, slow runoff (interflow) and quick runoff (overland flow), which appears only if the filling level of the storage exceeds a certain threshold. A model parameter controls percolation into the lower storage that empties linearly through an outlet, analogous to a groundwater body. The three outflows are summed to form total runoff.

The HBV model produces the following output data (mm): runoff, basin precipitation, evapotranspiration; and storage change for glaciers, snow and groundwater.

Part of the data series is used for calibration, the rest for validation. The adjustment of optimization parameters is done by comparing model output to measured runoff, though glacier mass balance values and snow cover values can be used in addition, if available. Optimization parameters are adjusted manually using numerical and graphical criteria for goodness of fit. The numerical criteria used are the accumulated difference between measured and simulated discharge, and the Nash-Sutcliffe efficiency criterion (Nash and Sutcliffe, 1970).

3.2 OEZ model

All terms of the water balance treated by the model are longterm means of monthly values. A brief summary of the OEZ structure is given below, for a comprehensive model description see Kuhn and Batlogg (1998, 1999). The model uses four iterations, which mark the stages of the modelling procedure:

1. Annual basin precipitation is determined as a residual of the water balance from a first approximation of evaporation, measured runoff, and measured basin storage (equal to glacier mass balance, as groundwater storage change is assumed to be zero in this first approximation). Annual basin precipitation is then distributed over the months proportional to the rainfall pattern as recorded by a representative meteorological station.
2. Precipitation gradients for each month of the year need to be calculated from the precipitation records of two representative meteorological stations. Monthly precipitation values are then recalculated in accordance with the seasonal course of the precipitation gradients.
3. Monthly mean air temperatures are taken from two reference stations and adapted to the proper altitude using calculated altitudinal temperature gradients. Snow cover for each elevation belt is calculated by the snow storage of the previous month, solid precipitation, potential melt, and evaporation. Evaporation is roughly estimated according to the state of the ground (snow, bare ground, grass and forest), time of year and altitude. Below 2600 m a.s.l., evaporation is set according to forest cover in winter (0.5 mm/d in forests, 1 mm/d in grasslands and on bare ground), and snow cover in summer (0.5 mm/d above snow, 2 mm without snow). Above 2600 m, evaporation is assumed to be 0.5 mm/d throughout the year. Total storage changes can then be determined as a residual of the water balance equation. Runoff is considered separately in the form of rain and meltwater.
4. Calculated monthly runoff is compared to and brought into agreement with measured runoff with a difference of less than 20 mm, a number suggested by Kuhn and Batlogg (1998). This is achieved by optimizing several calibration parameters, which are: (i) redistribution factor (improving the model's internal mass balance by allowing more snow accumulation on glaciated areas relative to ice-free areas); (ii) degree-day factor; (iii) inital snow cover factor, describing the proportion of the ice-free area of the catchment covered by snow in each month; (iv) coefficient *a* of the equation determining the fraction of solid precipitation ($P_{solid} = a - 0.055$ * air temperature).

The OEZ outputs are means of monthly runoff, basin precipitation, evaporation, glacier mass balance and vertical specific mass balance and snow accumulation profiles. The model is calibrated using the full length of the available hydrometeorological data series. Total, glaciated, and forested area data are required for each elevation belt of 100 m vertical extent. The model can be successfully validated by applying the calibrated version to subsets of the calibration period of the order of one decade. Validation for single years did not produce reliable results (Kuhn, 2000).

To provide a contrast to earlier applications (e.g. Kuhn and Batlogg, 1998) and in order to produce scenarios comparable to HBV, temperature and precipitation changes were performed simultaneously in one model run, and glaciation was reduced in the same manner in both model applications.

3.3 Future scenarios

Climate Scenario outputs for the doubling of CO_2 were taken from the KazNIIMOSK study (1999), where climate modelling was carried out for the mountain areas of SE-Kazakhstan, which are quite close to the test sites of this study. A baseline climate has been created from monthly data of 10 meteorological stations in the Zailiskiy range. This baseline is a statistical description of the climate from 1951 to 1980 and was used to test the performance of the following Global Circulation Models (GCM´s): GFDL and GFDL-T (Geophysical Fluid Dynamics Laboratory, University of Princeton), UKMO (Meteorological Agency of the UK), CCC (Canadian Climate Center) and GISS (Goddard Institute for Space Studies). All models take into account CO_2 concentration only, but not aerosol variations. Regional climate change scenarios were prepared by linear regression. Three time series of global air temperature anomalies were used to develop relationships with the local climate, which reached correlation coefficients between 0.3 and 0.5 (KazNIIMOSK, 1999). As a next step, linear regression parameters between global temperature anomalies and the mean annual (and seasonal) anomalies at the meteorological stations were calculated. Results of the regional scenarios show a range of possible temperature increases between 3.7°C (GFDL) and 7.1°C (CCC). Precipitation changes are less conclusive, and according to most models a slight increase is expected. Since the GISS model showed the best agreement to measured temperatures in the 1xCO_2 model runs (KazNIIMOSK, 1999), its output (Table 2) was chosen to serve as the model input. Monthly changes in temperature and precipitation are presented below. The temperature increase of 4.2 °C and the precipitation increase by 17% correspond well with the results of the UKTR model and the IS92a emission scenario (moderately high emissions with doubled CO_2 concentration) for the territory of Kyrgyzstan, carried out by UN Framework Convention on Climate Change (UNEP, 2003).

Table 2
Temperature differences and precipitation ratios between 2xCO_2 and 1xCO_2 averaged over the stations Ust-Gorelnik, Mynzylki, Verhniy Gorelnik, Almaty, Big Almatinka Lake and Esik (KazNIIMOSK, 1999).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Summer**	**Winter**	**Year**
ΔT(°C)	+4.2	+5.7	+3.6	+4.6	+3.1	+3.2	+3.4	+4.7	+4.4	+4.5	+3.4	+5.5	3.9	4.5	**4.2**
ΔP(%)	1.42	1.29	1.13	1.25	1.21	1.16	0.94	0.81	1.17	1.20	1.03	1.47	1.08	1.27	**1.17**

Daily meteorological data from the HBV model are modified by adding single hot days with additional convective rainfall or deleting precipitation events until the predicted monthly means are achieved. This procedure reflects future weather patterns more realistically than a general monthly factor. To cover the whole range of possible reactions, two reference years with temperature conditions as different as possible were chosen and one scenario for a reference year with much galcier melt ("HBV hot") and another with little glacier melt ("HBV cool") were produced. These scenarios are meteorological in nature, i.e., weather patterns and associated runoff can be displayed, in contrast to the mean monthly conditions produced by OEZ.

Since both models are not capable of describing deglacierization in an iterative way, scenarios are run for 50% of current glacier extent, which marks a pronounced step of deglaciation and lies within the range of possible reactions for the 2 x CO_2-scenario, which is assumed to come into effect between 2050 and 2075 (KazNIIMOSK, 1999). Moreover, a model run for total loss of glaciation is executed to estimate the full extent of the hydrological response if glacier cover disappears.

4. Results

4.1 Periods with observed climate

To calibrate the models, they were applied for periods with observed climate and runoff. Exact years are given in chapter 2.2 and Table 2. Exemplary model outputs at Oigaing watershed are visualised as hydrographs in Fig. 2.

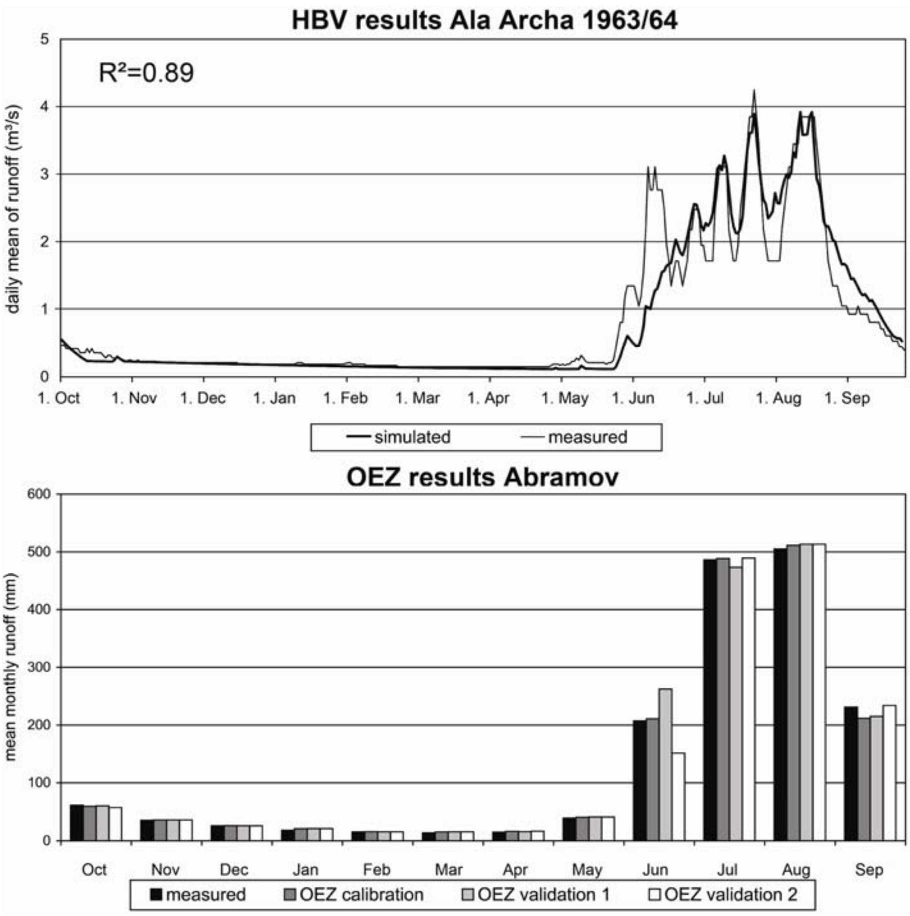

Fig. 2. Example hydrographs generated by HBV and OEZ models in comparison to measured runoff (OEZ calibration period: 1968/69-1987/88, validation 1: 1968/69-1977/78, validation 2: 1978/79-1987/88).

4.1.1 Goodness of fit

Table 3 shows the model efficiency criterion after Nash and Sutcliffe (R^2), and accumulated differences between measured and simulated discharge for the HBV results. Unfortunately, only Abramov had a data series long enough to permit dividing it into a calibration and a validation period. R^2 values for the validation period are only slightly lower than for the calibration period, which indicates a good model performance.

Application of the same model version in the Alps yielded slighty better results (mean R^2 values of 0.87-0.93 for calibration, 0.86-0.90 for validation) in two Austrian and one German catchments (Braun et al. 2000) and a poorer model efficiency (mean R^2 values of 0.66-0.92 for calibration, 0.78-0.96 m for validation) in five Swiss basins (Braun and Renner 1992). From three catchments with discontinous data series in the Nepal Himalayas, HBV/ETH model performances from 0.43 to 0.95 have been reported (Braun et al 1993, 1998). Moore (1992) tested a modified HBV version in the south Coast Mountains of British Columbia and reached mean Nash-Sutcliffe criterions for calibration and validation of 0.84 and 0.81, respectively.

Aizen et al. (2000) have applied a single- and a two-reservoir model and achieved comparable model performances at Ala Archa (mean R^2: 0.82) and Oigaing (mean R^2: 0.78) river basins, with negligible advantages for the two-reservoir approach. Singh and Kumar (1997) achieved an impressing mean model efficiency of 0.86 when applying the UBC watershed model in the western Himalayan region, but their modelling period was only three years, also lacking an independent validation period.

A worldwide comparison of the conceptual Snowmelt-Runoff Model (SRM) by Rango (1992) has revealed model efficiencies in catchments reaching altitudes above 3000 m a.s.l. of 0.63 to 0.93, with a mean of 0.82. This indicates that the results presented here lie well within the usual range.

Table 3

Goodness of fit for HBV simulations (Q_{diff} = accumulated difference between measured and simulated discharge in mm/a [percentage of the measured value], R^2 = Nash-Sutcliffe criterion).

	$Qdiff_{mean}$	$Qdiff_{min}$	$Qdiff_{max}$	R^2_{mean}	R^2_{min}	R^2_{max}
Ala Archa (1960/61, 1962/63-1963/64, 1971/72-1972/73)	127 [13%]	8 [1.0%]	398 [30.2%]	0.88	0.80	0.94
Oigaing (1971/72-1972/73, 1978/79-1979/80)	66 [7.8%]	24 [2.8%]	113 [11.1%]	0.89	0.77	0.96
Abramov (1968/69-1977/78) calibration period	226 [14.5%]	117 [8.3%]	539 [25.0%]	0.85	0.77	0.91
Abramov (1979/80-1987/88) validation period	283 [16.7%]	30 [2.7%]	566 [35.9%]	0.83	0.70	0.91

Since the OEZ model calculates longterm means of monthly runoff, these results consist of 12 values only, which is not enough to apply a statistical criterion for the goodness of fit. However, there is the possibility to check the plausibility of the results during optimization, by evaluating three aspects of the internal mass balance distribution: accumulation / ablation profiles of glaciated and ice-free areas, equilibrium line altitude (ELA), and accumulation area ratio (AAR). The maximum discrepancy between measured and modelled monthly runoff values of less than 20 mm suggested by Kuhn and Batlogg (1998) was reached in all months and test sites, exept for May at Oigaing and June at Abramov (Table 4).

Table 4
Discrepancies between measured monthly mean and monthly mean calculated using the OEZ model (mm).

	Ala Archa	Oigaing	Abramov		
	Calibration 1960/61-1964/65, 1971/72-1973/74	Calibration 1962/63-1964/65, 1971/72-1973/74, 1978/79-1979/80	Calibration 1968/69-1988/89	Validation 1968/69-1977/78	Validation 1978/79-1987/88
Oct	0	2	-2	-1	-4
Nov	0	1	1	1	1
Dec	-1	1	0	0	0
Jan	0	0	3	3	3
Feb	-1	-2	0	0	0
Mar	1	1	2	2	2
Apr	-5	0	2	1	2
May	0	42	2	2	2
Jun	-1	2	-4	55	-56
Jul	0	-2	-3	-13	3
Aug	1	-2	6	8	8
Sep	-2	-1	-7	-16	3
Year	-9	3	0	42	-36

Only Abramov has a data series long enough to permit validation, which showed for both decades that June runoff was not reproduced very well. Simulated runoff deviates from measured values from between 55 mm to 75 mm, which lies well outside the stipulated limit of 20 mm. A look at the mean values of precipitation and temperature for the OEZ calibration and validation periods suggests that the difference in June temperature is the reason for the failure of the OEZ in replicating runoff. The mean monthly temperatures of the first and second validation decades for June differ by 0.9°C, and this is enough to cause significant errors in replicating measured runoff. In the other summer months, temperatures from the validation decades differ only very slightly from those of the calibration period. Differences in precipitation cannot be the cause of failure, because differences for June are comparable to those for other summer months, which are validated successfully.

4.1.2 Annual water balance

Table 5 below presents the values of the water balance produced by the calibrated models, contrasting them with available measured values for the same time period. Evaporation,

runoff, and basin precipitation values produced by the OEZ are consistently higher than those of the HBV. The difference in basin precipitation is small for Oigaing and large for Ala Archa and Abramov. Since all meteorological stations are located at the lowest parts of the test sites, basin precipitation is expected to lie well above measured values. Surprisingly, basin precipitation for Ala Archa produced by the HBV model is lower than the mean recorded by the reference station. HBV basin storage (glacier mass balance) is much more negative than that generated by the OEZ for both Ala Archa and Abramov, and in the case of the latter, available mass balance measurements suggest that the HBV value is too negative. This raises the question of whether basin precipitation calculated by the OEZ model is more realistic. The HBV model possibly underestimates basin precipitation and partly compensates this error by overestimating glacier melt.
The HBV model implies the danger of underestimating basin precipitation and partly compensating this error by overestimating glacier melt.

Table 5
Annual water balance values modelled by the OEZ and HBV model.

	Ala Archa		**Oigaing**		**Abramov**	
	HBV	**OEZ**	**HBV**	**OEZ**	**HBV**	**OEZ**
Time period	1960/61-1964/65, 1971/72-1973/74		1962/63-1964/65, 1971/72-1973/74, 1978/79-1979/80		1968/69-1988/89	
Basin Precipitation (mm)	**636**	**946**	**997**	**1080**	**1146**	**1551**
difference to station precip. (mm)	-26	302	275	358	416	821
difference to station precip. (%)	-4	+46	+38	+50	+57	+112
Evaporation (mm)	**151**	**171**	**148**	**181**	**167**	**183**
Basin glacier mass balance (mm)	**-360**	**-108**	**70**	**13**	**-369**	**-285**
Runoff (mm)	**845**	**901**	**778**	**886**	**1348**	**1653**
difference to measured runoff (mm)	-52	4	-121	-13	-305	0
difference to measured runoff (%)	-6	0	-13	-1	-18	0

4.2 Runoff scenarios for future climate conditions

4.2.1 OEZ scenarios

After the anticipated climate change, melt begins in April instead of May in the case of Oigaing (Fig. 3). With the glaciation of 1960, May and June runoff levels are above the ”old” July peak (current climate), whereas runoff levels for July to September show little change. This curve is not very realistic, since glacier area should have been reduced drastically after such a strong climate change. On the other hand, it shows the expected trend of an earlier and more intense spring snowmelt and it can be regarded in a similar way as an exceptionally hot year under current glaciation conditions, as occurred in Europe in 2003 (Schär and Jendrinsky, 2004).

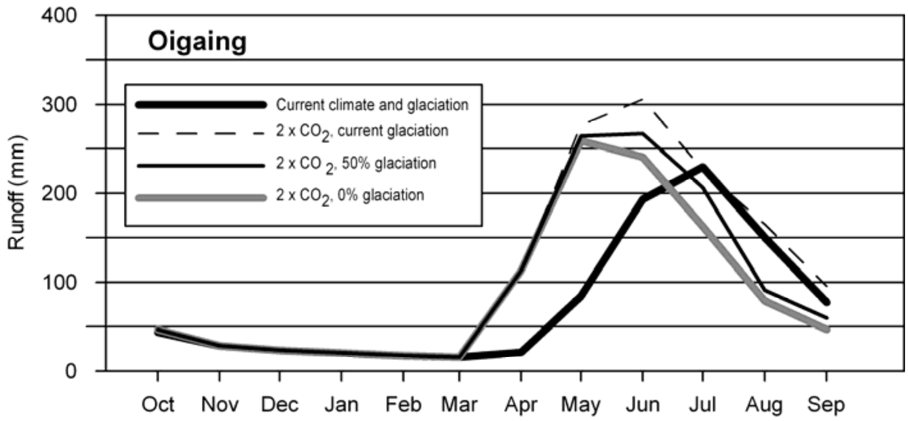

Fig. 3. OEZ model results at Oigaing for current climate and for the doubling of CO2 in combination with two steps of deglaciation as mean values over the simulated period (8 years)

Reducing glaciation area to 50% of the 1960 extent, which means bringing down basin glaciation from 7% to 3.5% has no further effect on runoff for April and May, but lowers June runoff to levels similar to May. Runoff for July to September is reduced to levels below those of the runoff curve for current climate, with the greatest effect occuring in August. The effect of more intense spring snowmelt remains, but the reduction of glaciation extent affects summer runoff negatively. With no glaciation remaining, runoff for June to September is reduced further, showing that even at a basin glaciation of 3-4%, icemelt generated by the OEZ model makes a significant contribution to summer runoff. Without glaciers, runoff peaks in May, and runoff deficit relative to current conditions is greatest in July and August.
Fig. 4 illustrates runoff scenarios in the Ala Archa basin. The 2 x CO_2 scenario with the 1960 glaciation shows significantly higher runoff levels for June to September than the calibration hydrograph. Peak runoff shifts from July to August and is roughly doubled, which is the expected effect of the intensified snow- and icemelt.

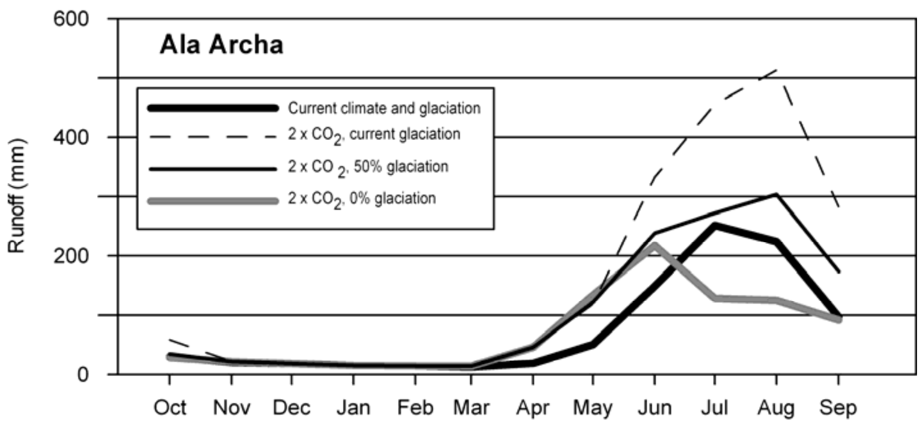

Fig. 4. OEZ model results at Ala Archa for current climate and for the doubling of CO2 in combination with two steps of deglaciation as mean values over the simulated period (8 years)

The stronger glaciation compared to Oigaing explains why the effect of enhanced icemelt is much clearer here and peak runoff is shifted backwards to August and not forward as was the case at Oigaing. Reducing the 1960 glaciation area to 50% does not change runoff for April and May, but lowers June runoff to levels comparable with the July peak of the current

conditions runoff curve. The flattening of the runoff curve means that July runoff is comparable to that of current climate and glaciation, whereas August runoff is still markedly higher and forms the peak. With no glaciation remaining, the runoff curves follows the same shape until June, after which it drops to levels for July, August and September similar to September runoff under current conditions.
The runoff curve for the 1986 glaciation at Abramov (Fig. 5) is similar to the 1960 glaciation curve at Ala Archa.

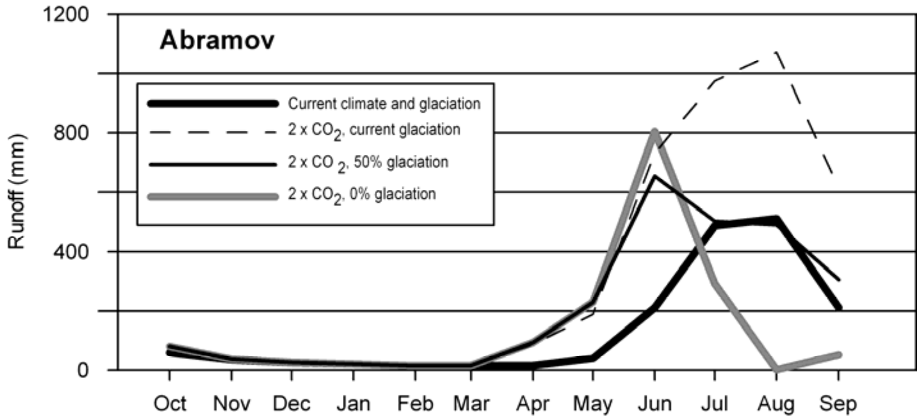

Fig. 5. OEZ model results at Abramov for current climate and for the doubling of CO2 in combination with two steps of deglaciation as mean values over the simulated period (20 years)

Reducing the 1986 glaciation area to 50%, however, produces a runoff curve which is surprising on two accounts: firstly, the level of runoff in June is lowered only slightly, and this remains well above the peak of the runoff curve for current climate. Secondly, runoff drops from June to much lower levels for July and August – similar to the July, August values for current runoff. It seems unlikely that, with the halving of glacier area extent, spring snowmelt would produce runoff of greater intensity than summer icemelt in a catchment with 20% of its area still glaciated. The cause for the unexpected behaviour for Abramov may be found in the high degree-day factor used (8.85 mm w.e. K^{-1} d^{-1}, with no differentiation between snow and ice), causing more intense snowmelt than is realistic. A factor for the enhancement of ice melt relative to snow might significantly improve the OEZ's ability to reflect the hydrological processes of the Abramov catchment.
Reducing glaciation extent to 0% increases June runoff to a level above that of both the 100% and 50% glaciation runs, which cannot be explained. The sharp drop in runoff after June is to be expected, as the low precipitation levels for July, August, and September leave snowmelt and ground water as the sole sources of summer runoff. The high degree-day factor exaggerates the rise, peak, and fall of the runoff curve. Runoff levels for August are close to zero, though values for August and September are very sensitive to the necessary re-adjustment of groundwater movement. It must be concluded that the non-realistic progression of OEZ runoff scenario curves in response to changes in glaciation extent confirms that the model is incapable of replicating measured conditions properly in the Abramov glacier basin.

4.2.2 Comparison of OEZ and HBV runoff scenarios

Here, the two HBV senarios for warm and cold reference years (”HBV hot” and ”HBV cool”) are compared with the mean climate predictions of the OEZ model. Theoretically, the OEZ curve should lie somewhere between the two HBV curves. Since the OEZ model failed in the 0% glaciation scenario at Abramov, this case is not further investigated.

Scenario *”2 x CO_2, 50% glaciation”* at Oigaing: Fig. 6 shows that OEZ runoff levels are very similar to those predicted by the “HBV hot” scenario for all summer months apart from June. The runoff curve for the “HBV cool” scenario rises a month later, but its June peak is 60% higher than that of the OEZ. “HBV cool” scenario runoff values for June to September are not only higher than the “HBV hot” and OEZ scenarios, but also higher than the OEZ simulation of runoff for current climate conditions.

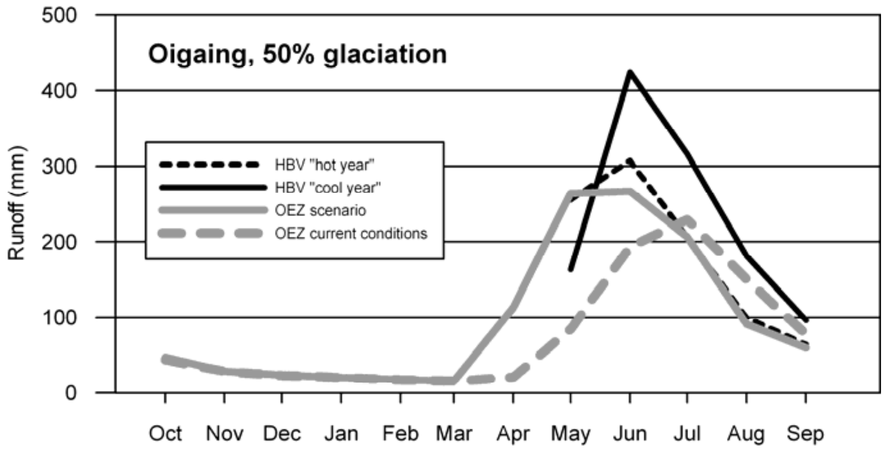

Fig. 6. Runoff scenarios of HBV and OEZ hydrological models for Oigaing catchment after doubling of CO_2, as predicted by the GISS model (KazNIIMOSK 1999) and for 50% of current glaciation. HBV scenarios were produced for a cool and a hot reference year, the OEZ scenario is based on mean climatological conditions of the simulated period (8 years).

Differences between the three scenarios can be adequately explained by differences in the meteorological data upon which they are based. The “HBV hot” reference year’s precipitation sum is very similar to the means which form the input for the OEZ scenario. The “HBV cool” year’s winter precipitation is similar to the mean used by the OEZ, but precipitation from May to September is higher by 55%, in June by as much as 190%. The similarity between the OEZ and the “HBV hot” scenario curves and their reference meteorological data suggests that the “HBV hot” scenario is much more representative of the mean around which future runoff scenarios can be expected to cluster. It is not, therefore, close to representing the one extreme in the possible range of future changes.

Scenario *”2 x CO_2, 50% glaciation”* at Ala Archa: In most months, the OEZ hydrograph lies between the HBV curves (Fig. 7). Differences between the three runoff scenarios can be explained by comparing the meteorological model input. Differences for May appear to be temperature-driven, whereas for June higher precipitation levels of the reference month adequately explain why the “HBV cool” scenario peaks here at a level above that of both the “HBV hot” and OEZ scenarios. Thus it is evident that with 50% glaciation remaining (covering approximately 18% of the catchment), some of the runoff variation is induced by fluctuations in summer precipitation. August runoff for the “HBV cool” scenario is below levels of both the OEZ and “HBV hot” scenarios, and coincides with the cool reference year having the lowest mean temperature for August. September runoff levels reflect the precipitation levels of the reference data.

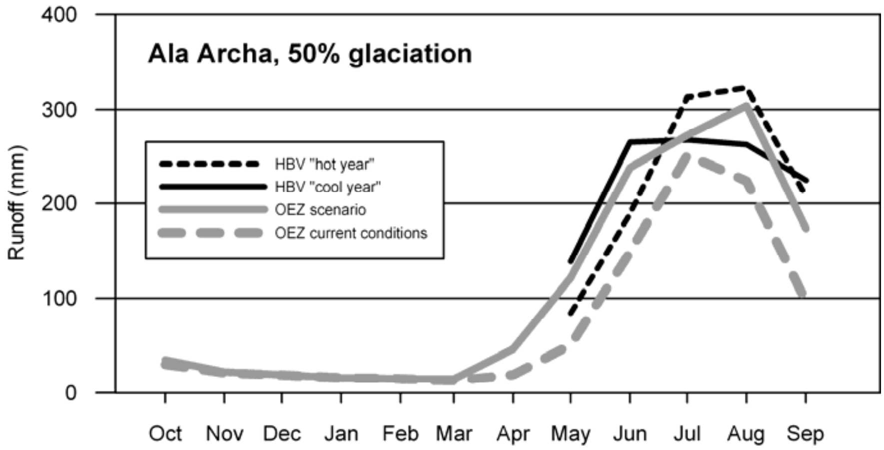

Fig. 7. Runoff scenarios of HBV and OEZ hydrological models for Ala Archa catchment after doubling of CO_2, as predicted by the GISS model (KazNIIMOSK, 1999) and for 50% of current glaciation. HBV scenarios were produced for a cool and a hot reference year, the OEZ scenario is based on mean climatological conditions of the simulated period (8 years).

Both models, therefore, predict a moderate increase in runoff compared to current levels. Spring snowmelt begins approximately a month earlier and runoff for the months of April to September is increased. Runoff changes is much less dramatic than that predicted for Oigaing.

Scenario *”2* x *CO_2, 50% glaciation”* at Abramov: Fig. 8 demonstrates clearly that predictions for spring runoff with a 50% glaciation reduction differ from one another dramatically.

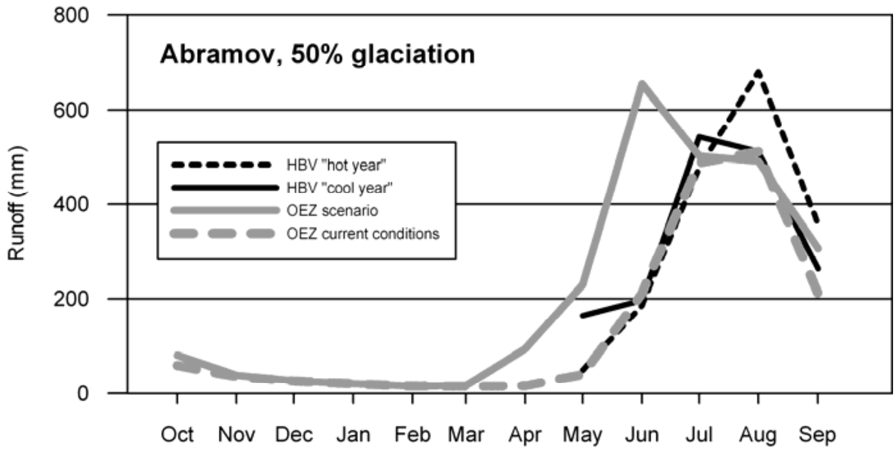

Fig. 8. Runoff scenarios of HBV and OEZ hydrological models for Abramov catchment after doubling of CO_2, as predicted by the GISS model (KazNIIMOSK, 1999) and for 50% of current glaciation. HBV scenarios were produced for a cool and a hot reference year, the OEZ scenario is based on mean climatological conditions of the simulated period (8 years).

Explanations for differences in the HBV and the OEZ runoff scenarios are hard to find. It is the OEZ runoff scenario which seems doubtful, whereas the HBV scenarios appear more plausible. Differences between the “HBV average” and ”cool, wet” scenarios can be adequately explained by differences in their reference meteorological data. The only slight surprise concerning the HBV scenarios is that spring snowmelt does not set in any earlier, despite the predicted increase in mean monthly temperature.

Scenario *”2* x *CO_2, 0% glaciation Oigaing”:* Comparison of the results from Fig. 9 below with Fig. 6 show that the HBV runoff scenarios for Oigaing are virtually identical to those for the 50% glaciation runs. The further reduction in OEZ runoff caused by complete loss of glaciation, therefore, opens a gap between the OEZ runoff scenario and the “HBV hot” scenario. The HBV scenarios for Oigaing imply that whether glaciation extent is reduced by 50%, or whether glaciation is completely lost, is of no relevance for future runoff. The progression of the OEZ runoff curve with a decrease of summer runoff as glaciation is reduced from 50% to 0% seems more plausible.

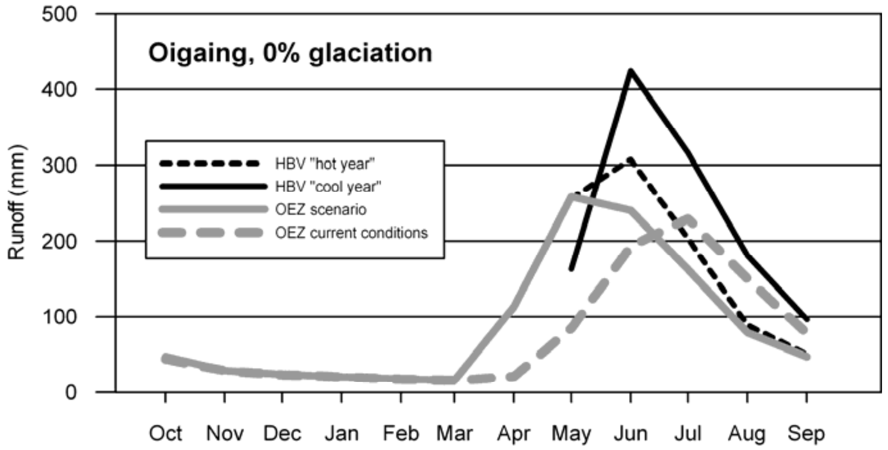

Fig. 9. Runoff scenarios of HBV and OEZ hydrological models for Oigaing catchment after doubling of CO_2, as predicted by the GISS model (KazNIIMOSK, 1999) and for a complete loss of glaciation. HBV scenarios were produced for a cool and a hot reference year, the OEZ scenario is based on mean climatological conditions of the simulated period (8 years).

Scenario *”2* x *CO2, 0% glaciation”* at Ala Archa: As can be seen in Fig. 10 below, all three scenarios for Ala Archa peak in June (of which the OEZ’s is the highest), and display a marked drop to very similar runoff levels for July, after which the runoff for both HBV scenarios continues to fall to levels well below the curve for the OEZ scenario.

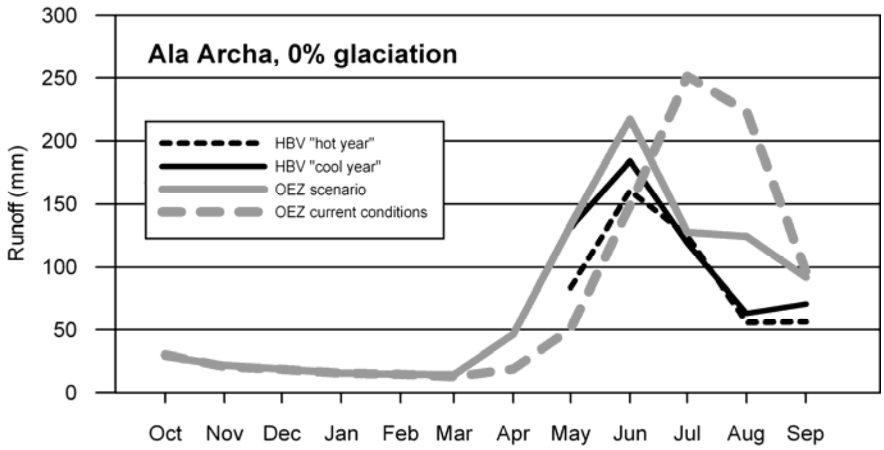

Fig. 10. Runoff scenarios of HBV and OEZ hydrological models for Ala Archa catchment after doubling of CO_2, as predicted by the GISS model (KazNIIMOSK, 1999) and for a complete loss of glaciation. HBV scenarios were produced for a cool and a hot reference year, the OEZ scenario is based on mean climatological conditions of the simulated period (8 years).

In August, for example, the OEZ predicts a reduction in runoff of around 50% compared to that simulated for current climate and glaciation conditions, whereas both HBV scenarios predict a reduction of runoff by approximately 75%. These differences cannot be explained through comparison of reference meteorological data. Rather, it is most likely that the differences in calculated basin precipitation now manifest themselves. The OEZ and HBV scenarios thus span a range within which future runoff can be expected. Uncertainty is greatest for the second half of summer.

5. Discussion

Agreement between HBV and OEZ scenario results was best for the Oigaing and Ala Archa river basins´ 50% glaciation runs.

The greatest differences were caused by discrepancies in simulated basin precipitation. This confirms the necessity of measured mass balance values in order to confine errors. In addition to basin precipitation simulation, runoff scenarios are also very sensitive to the degree of glaciation change. The subjective alteration of glaciation extent can mean the difference between a prediction of higher runoff levels (compared to those under current climate and glaciation conditions) and a drastic reduction in runoff availability.

Both models showed the general picture of enhanced snowmelt during spring and a higher flood risk in summer, which turns into a runoff deficiency after a certain degree of glacier degradation is reached. This pattern was also observed in the Alps (Hagg and Braun 2005) and other mountain systems. It seems that local factors like weather patterns or the degree of glaciation have a far stronger effect on hydrological response than any paramter on a global scale, such as continentality. In larger catchments with a small portion of glaciers like Oigaing, glacier runoff plays only a minor role at least if monthly runoff is considered. This correlates with findings of Singh and Kumar (1997) in the Himalayas, where total runoff showed only very little changes to annual temperature increases of up to 3°C. Moore (1992) modified HBV model inputs according to GCM scenarios in a glaciated basin in Southwest Canada. In contrast to the approach presented in this study, daily temperature and precipitation were changed linearly by annual change predictions that were quite moderate and a glacier retreat has not been taken into account. Hydrological responses depend on the combination of temperature and precipitation changes. In case of the warmer (+1°C) and wetter (+10%) scenario model results showed runoff increases in all months, with a maximum of 34% due to a more rapid snow melt in April and May. August runoff increases by 8% only, which is explained with an earlier release of glacially stored water due to the more intense ice melt (Moore 1992). This does not correspond with our results which predict highest runoff increases in August for the highly glaciated basins of Abramov and Ala Archa and in June for the nival regime of Oigaing.

6. Conclusion

Adding the OEZ model to the hydrological studies in the Tien Shan was successful in two out of the three basins, but in the Abramov catchment the model failed. Incorporating an optimization parameter into the OEZ model to allow differentiation between snow- and icemelt may enhance its ability to reproduce the conditions of the Abramov basin and other catchments with a very large glacier cover. However, the OEZ modelling gives information about the mean around which future runoff can be expected to cluster. On the other hand, the HBV model provides information about runoff variability (amplitude of variation around the new mean) which the OEZ cannot.

Moreover, OEZ runoff scenarios also added insight to HBV predictions. It was important to learn that the “HBV hot” and ”cool” scenarios do not necessarily represent the upper and lower limits of the hydrological response. Runoff is determined mainly by two meteorological factors in high alpine catchments – air temperature and precipitation – and additional HBV scenarios based on reference years with differing precipitation sums may assist in filling in the picture of potential future runoff conditions.

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