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# Report on the application of a conceptual hydro-meteorological model to selected alpine river basins

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ABSTRACT

A conceptual hydro-meteorological model has been applied to selected alpine river basins to assess the potential impact of climate change, in particular of changing air temperature and precipitation, on the basin runoff. This report summarizes results of 4 master theses that have been performed at the Institute of Meteorology and Geophysics, University of Innsbruck:

- Bacher M. (2008) Modellierung der Wasserhaushaltskomponenten im Einzugsgebiet des Pegels Krössbach für verschiedene Klimaszenarien.
- Meingaßner A. (2008) Modellierung des Wasserhaushalts von vier kalkalpinen Einzugsgebieten für verschiedene Klimaszenarien.
- Rastner L. (2008) Modellierung des Abflusses der Ahr im Tauferer Ahrntal für verschiedene Klimaszenarien.
- Wieser E. (2009) Bestimmung des Wasserhaushaltes der Einzugsgebiete der Passer, des Pfeldererbaches, des Mareiterbaches und des Pflerscherbaches mit dem OEZ Modell 2.1.

## INTRODUCTION

The knowledge of the water cycle in alpine river basins is a fundamental prerequisite for water authorities regarding hydropower production and public water supply. In alpine regions, glaciers often significantly contribute to the runoff in headwaters and determine daily and annual basin hydrographs, depending on the degree of glacierization. Climate change, in particular changes in air temperature and precipitation affects runoff patterns in alpine rivers through changes in the seasonal snow cover and the retreat of glaciers, as has been observed in recent decades. Changes in basin runoff has ecological effects, which include habitat changes in rivers and streams, water level changes in reservoirs, effects on "ecosystem services" such as biodiversity, fish stocks, tourism, water availability to agriculture and other uses.
The Austrian Hydrographic Service, the Central Institute for Meteorology and Geodynamics, Austrian energy suppliers and the Austrian Avalanche Warning Service have established a network of several hundred precipitation and discharge gauges. Long-term hydro-meteorological data are used to calibrate the conceptual OEZ model. Different scenarios of air temperature and precipitation help to evaluate the impact of projected climate change on discharge patterns in alpine river basins.

### The OEZ Model

The conceptual model OEZ (Kuhn and Bartlogg, 1998, 1999; Kuhn 2000) has been developed as an analytical tool to assess the reaction of the water balance in alpine watersheds to changes in climate. The model runs on monthly time steps with an altitudinal resolution of 100 m and uses long-term means of precipitation P, runoff R, evaporation E and storage S. Runoff is the only directly measured component of the water balance. The following assumptions are made:

- In alpine catchments, evaporation is generally small compared to annual precipitation and storage, thus the absolute error by the approximation of E is assumed to be small, too. Average values of E are inferred based on vegetation type and snow cover duration.
- The long-term mean storage term is assumed to be zero for non-glacierized basins, while it is determined by changes in the glacier mass balance for glacierized catchments.
- Annual basin precipitation is derived from the water balance (P = R + E + S), with monthly values calculated according to the relative monthly values of the reference stations.

Based on results of many *evaporation* studies in the alpine region, the following average values have been used to estimate monthly values of evaporation:

| | |
|---|---|
| Snow cover – all year round | 0.5 mm per day |
| Forest snow covered – all year round | 1.0 mm per day |
| Vegetation - October to March | 0.5 mm per day |
| Vegetation – April to September | 2.0 mm per day |
| Areas above 2600 m a.s.l. – all year round | 0.5 mm per day |

The altitudinal gradient of *precipitation* is based on gradients derived from reference stations in the watershed or its surroundings and may increase with elevation. The *temperature* lapse rate is kept constant at all altitudes and is determined with the mean value of reference stations in the watershed and a nearby mountain station.
The fraction of snow in total monthly precipitation (r) depends on the mean monthly air temperature $T_{month}$ and is estimated according to:

$$r = 60 - 55 * T_{month} \quad (\%)$$

Potential snowmelt is determined by the degree-day method. The average monthly degree-day factor generally lies between 4 and 6 mm $deg^{-1}$ $d^{-1}$ with increasing values in spring and early summer due to a reduced snow albedo.
The model is calibrated with long-term hydro-meteorological data. The calibration is considered to be satisfying as soon as the difference between modeled and measured monthly basin runoff is less than ± 20 mm. The model was originally designed in Excel, while the latest version OEZ 2.1 has been transferred into Matlab (Olefs, unpubl.).
A more detailed description of the OEZ model is found in Kuhn and Bartlogg (1999) and Kuhn (2000).

## The catchments

The catchments selected in the 4 master theses differ in size, bedrock and degree of glacierization. They are situated in Tyrol (Austria) and in the north of Italy (Figures 1, 2, 3 and 4).

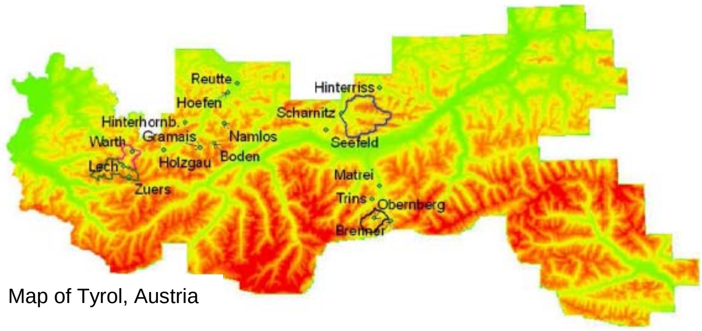



Figure 1. Non-glacierized basins in calcareous bedrock (Austria), marked by green, black, blue and red lines.

| | |
|---|---|
| Elevation | 950 – 2870 m |
| Areas | 60 – 250 km² |
| Forest | 20 – 45 % |

(Meingassner, 2008)

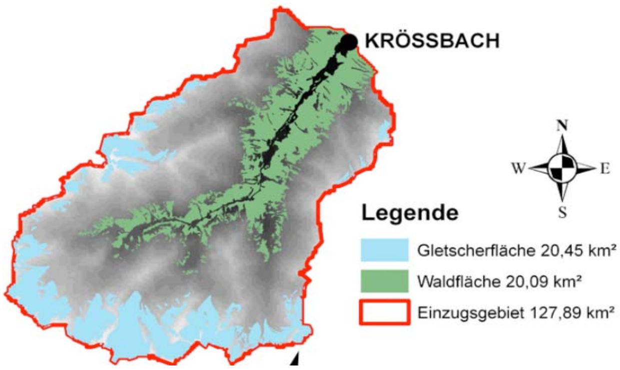



Figure 2. Glacierized basin of Krössbach (Austria)

| | |
|---|---|
| Elevation | 1086 – 3505 m |
| Area | 128 km² |
| Forest | 20 % |
| Glacier | 16 % |

(Bacher, 2008)

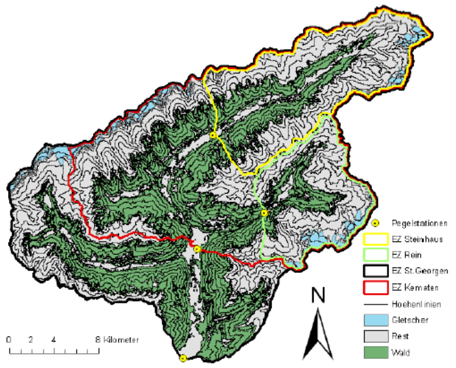



Figure 3. Glacierized basin Tauferer Ahrntal with sub-catchments (Italy) marked by black, red, yellow and green lines.

| | |
|---|---|
| Elevation | 840 – 3500 m |
| Areas | 90 – 610 km² |
| Forest | 18 – 38 % |
| Glacier | 4 – 9 % |

(Rastner, 2008)

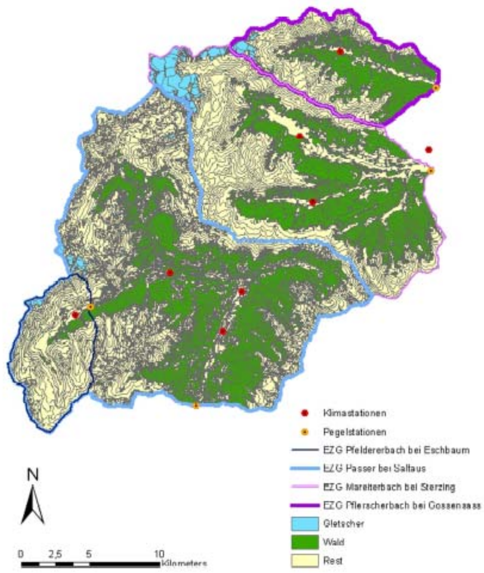



Figure 4. Glacierized basins south of the main divide of the Alps (Italy) marked by dark blue, light blue, rosa and violet lines.

| | |
|---|---|
| Elevation | 450 – 3480 m |
| Areas | 74 – 345 km² |
| Forest | 5 – 34 % |
| Glacier | 1 – 4 % |

(Wieser, 2009)

RESULTS

Global Climate Models give a temperature increase of about 0.2°C per decade over the next two decades for a range of emission scenarios (IPCC, 2007). The projected changes in the climate system during this century would very likely be larger than those observed during the 20$^{th}$ century. The best estimate of the global average surface warming, expressed as the temperature change from 1980-1999 to 2090-2099 is projected to range from 1.8°C for the low scenario B1 to 4.0°C for the high scenario A1F1. Global Climate Models project a likely increase in winter precipitation in Central Europe and a decrease in summer (IPCC, 2007). However, changes in precipitation may vary considerably on horizontal scales, in particular in areas of complex topography like the Alps. A lot of uncertainty is still in the projection of future precipitation.
Model runs simulated basin runoff under different scenarios of temperature (T) and precipitation (P) change such as shifts in air temperature by up to 3°C, increasing and decreasing precipitation up to ± 20% of the current amounts, and combined scenarios with both temperature and precipitation changes. The effect of seasonal shifts in temperature and precipitation on runoff patterns is simulated by changing both variables differently for the winter and summer, for

instance by higher precipitation in winter but less precipitation in summer compared to the long-term mean.
All results are given for the water year, which is defined to run from October to September of the following calendar year.

<u>Non-glacierized river basins</u>

An increase in annual precipitation, i.e. monthly precipitation is assumed to increase by 20% during the entire year, is simulated to raise runoff between April and October and to significantly increase the peak value in June. In winter, basin runoff remains unchanged, as most of the precipitation is accumulated in the seasonal snow pack, but the increased winter precipitation raises runoff with the onset of snow melt in spring (Figure 5).
Less precipitation leaves winter basin runoff unaffected, while runoff between early summer and autumn is reduced compared to the long-term reference hydrograph.

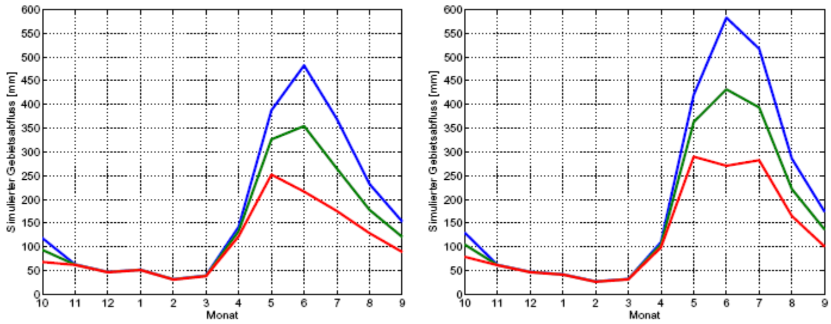



Figure 5. Simulated basin runoff (mm) under varying precipitation scenarios in 2 non-glacierized basins: reference (green), + 20% P (blue), - 20% P (red).

(Meingassner, 2008)

Simulations using scenarios of increased air temperature reveal that the summer peak in basin runoff becomes split into 2 peaks. The first peak is attributed to snowmelt in spring, while the second peak refers to summer precipitation (Figure 6), which is on average highest in summer at these basins.

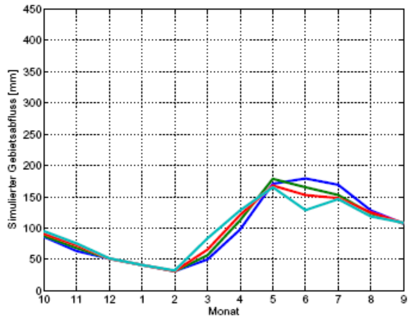



Figure 6. Simulated basin runoff (mm) under varying temperature scenarios: reference (blue), T+1°C (green), T+2°C (red), T+3°C (light blue)

(Meingassner, 2008)

Climate change is not expected to shift air temperature and precipitation uniformly in all months of a year. Therefore, combined scenarios have been used for OEZ model runs, with different changes of temperature and precipitation in summer and in winter. Here, we show simulations of how snow cover and basin runoff are expected to change due to rain and snow melt under the following scenario:

| | |
|---|---|
| Summer (April to September) | T+2°C, -20% P |
| Winter (October to March) | T+1°C, +15% P |

Reference period Scenario

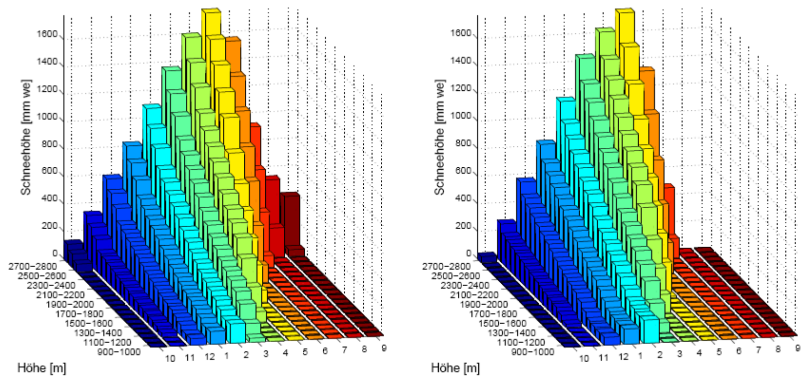
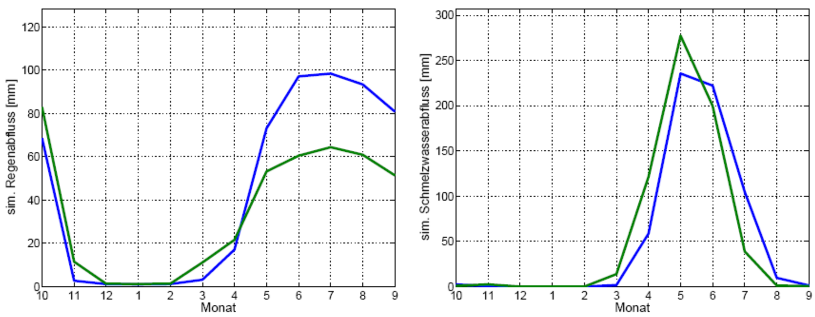



Figure 7. Height of the simulated snow cover (mm water equivalent): reference period (left) and scenario (right) in a non-glacierized basin.

(Meingassner, 2008)




Runoff by rain Runoff by snow melt

Figure 8. Simulated basin runoff (mm) induced by rain (left) and snow melt (right): reference (blue), scenario (green).

(Meingassner, 2008)

Under the selected scenario, snow cover tends to be reduced at lower elevations in autumn and spring. In summer, the 2°C temperature increase causes the snow pack to disappear even at the highest parts of the catchment (Figure 7). In the selected river basin, an earlier onset of snow melt in spring due to higher air temperatures causes the melt induced runoff to be shifted by one month from March to February. The higher peak of melt runoff in May can be attributed to the increased scenario winter precipitation (Figures 8). The hydrograph of the rain induced basin runoff reflects the shift in precipitation, i.e. reduced runoff between May and September due to less summer precipitation, increased runoff between October and April due to more winter precipitation and a higher temperature.

<u>Glacierized river basins</u>

Runoff in alpine basins, particularly in headwater basins is dominated by the intermittent storage of snow and by the seasonal and daily course of snow melt. Glaciers may significantly contribute to runoff in alpine catchments, depending on the degree of glacierization. Winter runoff is generally low, but runoff peaks in summer due to meltwater production may exceed annual average runoff by up to 4 times in highly glacierized catchments (Kuhn, 1998).
Wieser (2009) has simulated runoff in catchments south of the main divide of the Alps under varying scenarios of temperature and precipitation. A typical hydrograph is given in Figure 9. Similar to non-glacierized basins, changes in precipitation do not affect winter baseflow, as long as precipitation is accumulated in the seasonal snow cover. Under the P+20% scenario basin runoff increases in all months except for winter and runoff is reduced except for winter under the scenario with a reduction in precipitation.

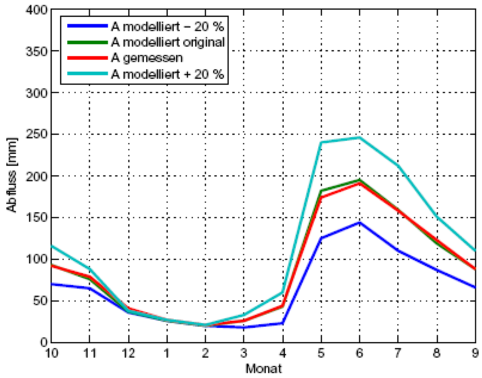



Figure 9. Runoff in a glacierized basin (mm) under varying precipitation scenarios: modelled reference (green), measured reference (red), + 20% P (light blue), - 20% P (blue).

(Wieser, 2009)

The impact of increasing air temperature on basin runoff depends on the degree of glacierization (Figure 10). Runoff in catchments with a small fraction of glaciers tends to react similarly to non-glacierized basins under a warmer climate (Figure 10 left). With increasing glacierization, runoff related to the melting of glacier ice significantly contributes to the total basin runoff in summer and autumn, and this contribution becomes more important with increasing air temperature due the enhanced melting of ice (Figure 10 right).

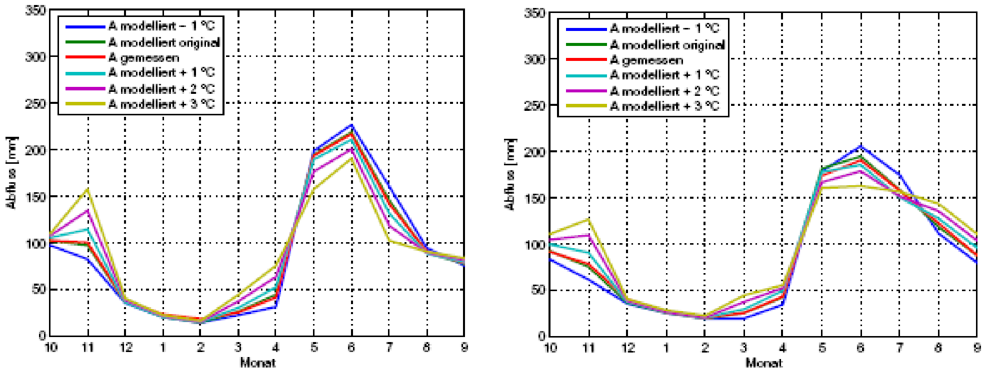



Figure 10. Simulated basin runoff (mm) under varying temperature scenarios: modelled reference (green), measured reference (red), T-1°C (blue), T+1°C (light blue), T+2°C (violet), T+3°C (yellow). The 2 basins differ in their degree of glacierization: 0.7% left, 9% right. (Wieser, 2009)

Bacher (2008) has simulated basin runoff in a catchment with about 16% glacierized area under combined scenarios with different changes of temperature and precipitation in summer and in winter (Figure 11, Table 1). Generally, less precipitation reduces runoff in all months except for winter months. This reduction in annual runoff may be counterbalanced by a concomitant higher air temperature, i.e. here, under the summer/winter scenario T+2°C, -20%P / T+1°C, -15%P. However, increasing air temperature would cause an enhanced melting of glacier ice and would thus shift the specific glacier mass balance to highly negative values, i.e. with about –2600 mm almost 4 times more negative than under current reference conditions.
Both increases in temperature and precipitation are simulated to raise basin runoff by about 20% compared to the reference period, and under a combined scenario annual runoff would range some 35% above current conditions (Table 1).

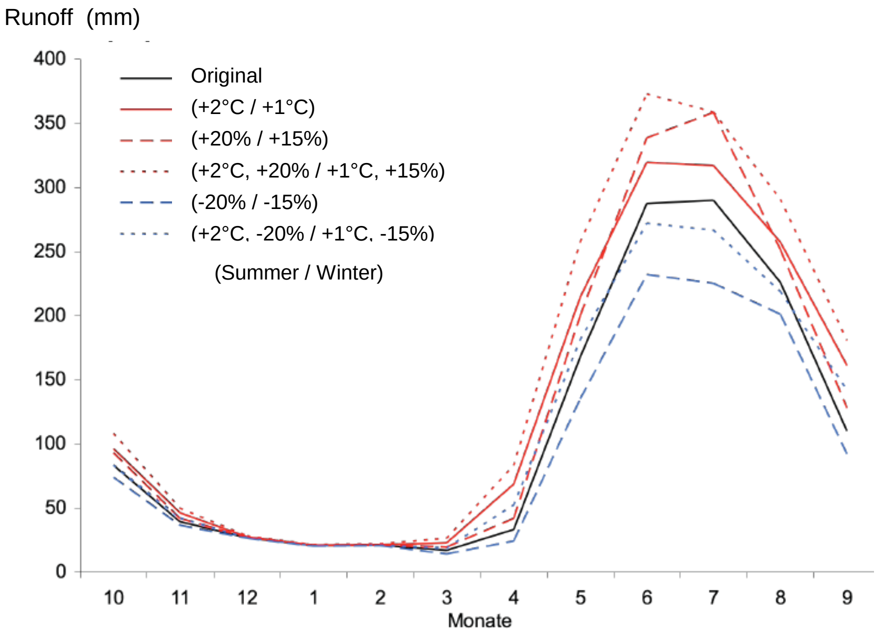



Figure 11. Simulated basin runoff under seasonally (summer / winter) varying scenarios of T and P.

(Modified from Bacher, 2008)

Table 1. Annual precipitation (P), specific glacier mass balance (b) and basin runoff (R) under seasonally (summer/winter) varying scenarios of temperature and precipitation - values refer to the model simulations in Figure 11 (SO summer, WI winter). (Modified from Bacher, 2008)

| | original | SO: +2°C<br>WI: +1°C | SO: +20%<br>WI: +15% | SO: -20%<br>WI: -15% | SO: +2°C -20%<br>WI: +1°C -15% | SO: +2°C +20%<br>WI: +1°C +15% |
|---|---|---|---|---|---|---|
| P (mm) | 1546 | 1546 | 1823 | 1269 | 1269 | 1823 |
| b (mm) | -690 | -2247 | -358 | -1023 | -2556 | -1941 |
| R (mm) | 1321 | 1571 | 1541 | 1100 | 1344 | 1798 |

Climate change, in particular the increase in air temperature, will lead to a further reduction in the degree of glacierization. Rastner (2008) performed model runs with a reduced glacierized area in the studied catchment under a specific “Year 2050 scenario” (Table 2), i.e. he assumed that no glaciers exist below an elevation of 2800 m a.s.l. in the year 2050.

Table 2. “Year 2050 scenario” according to Frei (2007) with monthly changes of temperature and precipitation.

| Month | 10 | 11 | 12 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T change (°C) | 2.2 | 2.2 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 2.8 | 2.8 | 2.8 | 2.2 |
| P change (%) | -4 | -4 | 11 | 11 | 11 | -4 | -4 | -4 | -19 | -19 | -19 | -4 |

Higher air temperatures and less precipitation under the “Year 2050 scenario” caused basin runoff to increase by about 5% and specific glacier mass balance to become about 5 times more negative compared to reference conditions (Table 3). However, less glacierization under the “Year 2050 scenario” (i.e. the fraction of glaciers changed from ~9 % to ~6 %) reduced melt runoff in summer, and the annual amount of basin runoff was even less than reference runoff.
These model results suggest that in highly glacierized basins runoff may increase in the initial phase of climate warming, but summer runoff will gradually be reduced as the mass loss of glaciers continues.

Table 3. Specific glacier mass balance (b), melt runoff ($R_{melt}$) and basin runoff (R) under reference conditions, the year 2050 scenario and the year 2050 scenario with reduced glacier area in a selected catchment (Modified from Rastner, 2008).

| | Reference | Year 2050 | Year 2050 Reduced glaciers |
|---|---|---|---|
| b (mm $yr^{-1}$) | -585 | -2945 | -2399 |
| $R_{melt}$ (mm $yr^{-1}$) | 643 | 764 | 664 |
| R (mm $yr^{-1}$) | 1318 | 1396 | 1296 |

## SUMMARY

The conceptual hydro-meteorological OEZ model has proofed to be a good tool to assess the potential impact of climate change, in particular of changing air temperature and precipitation on basin runoff. The model has been applied to alpine river basins of varying degree of glacierization in the Central Eastern Alps.
As expected, increasing air temperature causes an earlier, snow melt induced runoff peak in spring. A secondary runoff maximum in summer may be attributed to precipitation in those regions, where precipitation typically peaks in summer. In highly glacierized basins, the secondary runoff peak in summer or early autumn is rather due to the enhanced melting of glacier ice. The decrease in the degree of glacierization that is expected to continue under a warmer climate will cause a reduction in basin runoff of highly glacierized catchments as the ice melt induced contribution declines.

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