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Modelling the effects of land use and climate changes on hydrology in the Ursern Valley, Switzerland

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Abstract:

While many studies have been conducted in mountainous catchments to examine the impact of climate change on hydrology, the interactions between climate changes and land use components have largely unknown impacts on hydrology in alpine regions. They need to be given special attention in order to devise possible strategies concerning general development in these regions. Thus, the main aim was to examine the impact of land use (i.e. bushland expansion) and climate changes (i.e. increase of temperature) on hydrology by model simulations. For this purpose, the physically based WaSiM-ETH model was applied to the catchment of Ursern Valley in the central Alps (191 km^2) over the period of 1983–2005. Modelling results showed that the reduction of the mean monthly discharge during the summer period is due primarily to the retreat of snow discharge in time and secondarily to the reduction in the glacier surface area together with its retreat in time, rather than the increase in the evapotranspiration due to the expansion of the "green alder" on the expense of grassland. The significant decrease in summer discharge during July, August and September shows a change in the regime from b-glacio-nival to nivo-glacial. These changes are confirmed by the modeling results that attest to a temporal shift in snowmelt and glacier discharge towards earlier in the year: March, April and May for snowmelt and May and June for glacier discharge. It is expected that the yearly total discharge due to the land use changes will be reduced by 0.6% in the near future, whereas, it will be reduced by about 5% if climate change is also taken into account. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS land use changes; climate change; surface hydrology

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INTRODUCTION

In the alpine catchments that play an important role in the global water cycle, meteorological, glaciological, periglacial and hydrological phenomena display very intimate and complex interactions on variability at both short and long spacial and temporal scales (Verbunt *et al*., 2003). Strongly depending on altitude, discharge of alpine catchments is influenced by glacier melt, snow accumulation and snowmelt (Gutz *et al*., 1999). Therefore, the quality of hydrological modeling, even of larger catchments, depends on how the model describes those specific processes in mountainous regions (Gutz *et al*., 1997) and how it depicts their changes in space and time scales (Roots and Glen, 1982).

Warming of the climate system is unequivocal (Solomon *et al*., 2007). Recorded temperatures have risen by up to 2 °C since 1900, particularly at high elevations – a rate that is roughly three times the global average for 20th century warming (Beniston, 2004). For the Swiss Alps, a further temperature increase of 1.8 °C in winter and 2.7 °C in summer has been projected until the year 2050 (Frei, 2007). Glaciers in the European Alps are comparatively small, but their disappearance (disintegration) could have considerable economic and societal impacts. For example, the decreasing glacierization could have large influence on hydrologic regime, tourism and natural hazards, as the Alps are the most densely populated high-mountain region in the world (Haeberli and Beniston, 1998).

Snow is an interesting indicator of climate change, as it depends not only on temperature but also on precipitation. Snow cover and duration play a key role in a number of environmental and socio-economic systems in mountain regions. In a country such as Switzerland, where 60% of the electricity is produced by hydropower, energy supply is highly sensitive to changes in the amount and duration of snow cover (Beniston, 1997).

In addition to climate variables, investigating land use and land cover changes may provide the key environmental

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issues in global change by considering different scenarios implemented in global and regional models of climate change and land-ecological systems. Modeling results contribute to understand the interactions in the human–land system (Hovius, 1998) and the hydrological dynamics of catchments (Huisman *et al*., 2009). Different approaches have been used to identify land use change effects: (i) statistics that show the contribution of land use change to hydrological change (e.g. Siriwardena *et al*., 2006), and (ii) paired catchment studies to reveal differences in hydrological behavior (e.g. Brown *et al*., 2005). However, these techniques can only be used to analyse the effects of past land use changes (Bormann and Elfert, 2010). To analyse future land use changes, models must first be validated for current conditions. Therefore, hydrological models are usually set up for current land use in a first step. Then, the models are run with land use scenarios representing future conditions. Finally, the difference is analysed between the simulation results representing past and future hydrological conditions (e.g. Bhaduri *et al*., 2000; Niehoff *et al*., 2002; Ott and Uhlenbrook, 2004; Huismann *et al*., 2009; Bormann and Elfert, 2010).

While changes in land use on the Swiss plateau and their effect on hydrological processes have been investigated earlier (see for instance Alaoui *et al*., 2011), the interactions between climate and land use components have an unknown impact on hydrology in Alpine regions. This requires special attention in order to devise possible strategies concerning general development in these mountain regions.

In the Swiss Alps, the Ursern Valley is considered a key region because of its rich natural resources, due in part to its high mean annual precipitation of 1900 mm per year compared to the mean annual precipitation in Switzerland of 1458 mm (for the period 1961 to 1990) (Schädler and Weingartner, 2002). This results in relatively high mean annual discharge, estimated to be 1540 mm (the mean for Switzerland was 991 mm for the same period); moreover, only one third of this water is diverted to neighboring catchments for hydropower production.

Additionally, almost all forestland was converted to grassland during the medieval period. More recently, large areas of mountain grazing land (1500 – 2200 m) were invaded by local *Alnus viridis* (green alder) shrub with a height of 2−3 m. Between 1965 and 1994, the area covered by this shrub increased by 32% (Wettstein, 1999).

All these factors and their interactions have an unknown effect on hydrology in this region that has not yet been sufficiently investigated.

The main aim of this study was to simulate the influence of land use changes (i.e. expansion of green alder) and climatic components (i.e. snowmelt and glacier discharge) on total discharge for a long time period (1983 – 2005) in order to highlight the dominant variables that significantly affect the hydrology in the region under consideration and to project the effect of these changes in the near future (2006–2028).

MATERIAL AND METHODS

Field description

The catchment of the Ursern Valley is located in the central Swiss Alps (Figure 1), covering an area of 191 km^2. The elevation ranges from 1400 to 3600 m a.s.l. The watershed is primarily covered by grassland (65%). The main water flow, Reuss-Andermatt, runs west to east.

Soil is classified as dystric Fluvisol (FAO)/Fluvents (US-Taxonomy) in the valley (Wallenboden near the Furka-Reuss) to Ranker (FAO)/Lithic Haplumbrepts (US-Taxonomy) (USDA, Soil Survey Staff, 2003) in the steepest locations of the valley where soil is very shallow, which means that there is only a very small capacity to store soil water in this area except in the restricted zones covered by green alder, forest and other bushlands. Soil

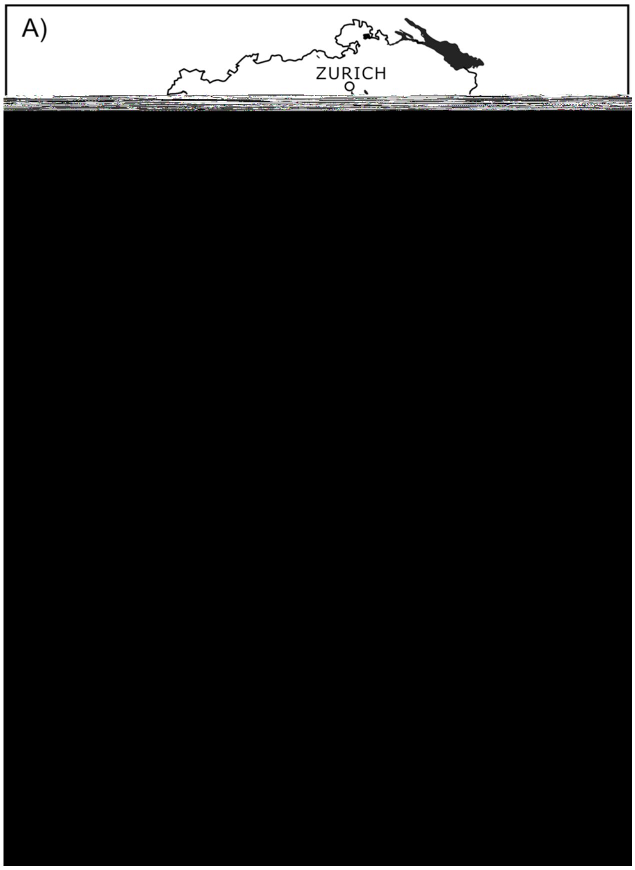

Figure 1. A) Map of Switzerland; B) location of the catchment under consideration with the main inflows of the Reuss−Andermatt river, and four sub-catchments in which basic soil parameters were measured: 1) Laubgädem, 2) Bonegg, 3) Wallenboden and 4) Chämleten

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texture consists mainly of sandy loam. Its pH varies between 4 and 5.

The Ursern Valley lies between two massifs: the Aarmassiv (para- and orthogneiss) in the north and the Gotthardmassiv (granite rocks) in the south (Kägi, 1973). Both massifs have a similar composition consisting of old metamorphic rocks ('Altkristallin') and newer ones (e.g. granite) (Labhart, 2005).

Considering average values over 100 years, a snow cover exists between November, 21 and April, 30. The current regime of the region can be classified as nivo-glacial. The geographical location of the Ursern Valley results in a complex climatic context. The Valley is open on both sides in the east and west and is influenced by climatic input from the south in the form of the 'foehn' wind that results in high precipitation in summer.

Laboratory analysis

Soil texture. The texture of samples (one sample per depth) was determined after H_2O_2 treatment to remove organic material (Konen *et al*., 2002). The sand fraction (2000 − 63 μm) was obtained by wet sieving. The amounts of silt and clay fractions, 63 to 2 μm and < 2 μm, respectively, were measured for pretreated samples by sedimentation with a SediGraph 5100 (Micromeritics, Norcross, USA), using particle sedimentation rates in combination with X-ray absorption. Soil pH was measured at 1:2 (soil: 0.01 M $CaCl_2$) on a mass basis (Soil Survey Staff, 2004). Organic carbon content was determined by the mass loss on ignition. For all sites, only one sample per depth (0 − 0.15 and 0.20 − 0.35 m) was used for the analysis of pH, organic carbon content and texture.

Hydraulic parameters. Soil samples were collected to analyse the differences between soil porosity and saturated hydraulic conductivity (K_{sat}) values between grassland and green alder soil. The samples (100 mm × 42 mm for K_{sat} and 115 mm × 98 mm for total porosity) were taken on different plots representing the two land use types in four sub-catchments (Bonegg, Laubgädem, Chämeleten and Wallenboden). A total of 100 samples were used to define the structure of top- and subsoil in the sub-catchments. K_{sat} was determined with a constant head permeameter (Klute and Dirksen, 1986). Total porosity was then determined directly for each undisturbed sample after drying at 105 °C for 24 h, assuming a particle density of 2.65 g/cm^3. K_{sat} and total porosity were determined for both grassland and green alder soils.

Statistical analysis

A trend analysis on reconstructed discharge (derived from measurements as described below) and measured precipitation was performed to detect any seasonal variations of both water balance terms. We used the nonparametric Mann–Kendall (MK) test for trend, which is a rank-based procedure especially suitable for non-normally distributed data, data containing outliers and nonlinear trends (e.g. Helsel and Hirsch, 1992).

The slope estimator is conducted with the nonparametric Theil–Sen method which is suitable for a nearly linear trend in the variable x and is less affected by non-normal data and outliers (e.g. Helsel and Hirsch, 1992; Birsan *et al*., 2005).

In addition, change in the hydrological regime was investigated using the dimensionless Pardé coefficient that relates the mean monthly discharge of a given month to the total annual discharge.

The WaSiM-ETH model

The WaSiM-ETH model (Schulla, 1997; 2012) was used to simulate water balance in the Ursern Valley. The model was chosen because it is a physically based model that uses the Richards equation to simulate flow within the unsaturated zone. The inverse distance weighting method was used to interpolate the input data. Soil and land use interpolated data were taken from the national databank (Swiss Federal Statistical Office), while the meteorological data are taken from the Swiss meteorological stations. The evapotranspiration was calculated using the Penman–Monteith equation (Monteith, 1975; Brutsaert, 1982). The glacier melt module implemented in WaSiM-ETH makes use of an extended temperature index method including global radiation (Hock, 1999). To calculate the glacier runoff, this temperature index method is coupled to a discharge model, which is based on the concept of linear reservoirs (Backer *et al*., 1982). Basic soil parameters (i.e. K_{sat} and porosities) were taken from the *in-situ* measurements and kept constant while three parameters were calibrated: the recession parameter for baseflow (k_{rec}), the interflow drainage density (d_r) and the empirical parameter expressing change in the relative hydraulic conductivities with depth (c_k). Manual calibration was carried out on the three parameters. Additionally, the snowmelt module parameters were calibrated against independent interpolated measured snow water equivalents (SWE) (see description of interpolation method in 'Observational SWE data'). Measured basic soil parameters (e.g. saturated hydraulic conductivity, total porosity, saturated water content and texture) and their differentiation between green alder and grassland were implemented in the model and kept constant through the simulations. For the simulations, land use maps were adapted according to the distribution of green alder under each scenario, and a corresponding specific soil map was attributed to each land use map based on the premise that green alder changes the basic soil parameters which were set according to the measurements, especially in the topsoil.

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To simulate the temporal dynamics of the various hydrological processes in our mountainous catchment, a time step of 1 day and grid cells of $500 \times 500\,m^2$ were used. The model was calibrated using daily reconstructed discharge (observation-based calculations) for a period of 3 years, 1983–1985.

Land use scenarios

To evaluate the impact of land use changes on total discharge, three scenarios of past climate (PC) were considered in the simulations: PLU_PC, CLU_PC and FLU_PC representing past, current and future land use, respectively. Used meteorological data for PC scenarios were recorded between 1983 and 2005. In addition, three other scenarios (PLU_FC, CLU_FC and FLU_FC) based on same land use situations were used to simulate the impact of future climate (FC) on total discharge (Table I). In the last three scenarios, we used projected temperature for the next 23 years (2006 – 2028) as deduced from a linear regression on daily temperature recorded between 1983 and 2005. The past land use was deduced from the literature and corresponds to the period between 1950 and 1960 (Mürner, 1998; Wettstein, 1999) whereas, the future land use was projected to investigate an eventual or exaggerated expansion of green alder in order to highlight the impact of land use on discharge in the worst case (Mürner, 1998; Wettstein, 1999).

It is worth to note that the glacier covered area representing 3.7% was kept constant for all six scenarios (PC and FC) since an eventual complete disintegration of the glacier in the near future doesn't notably affect total discharge. In fact, the actual mean yearly glacier discharge is already small ($0.5\,m^3\,s^{-1}$) compared to mean yearly discharge ($10\,m^3\,s^{-1}$).

Observational SWE data

Modeling quality was additionally evaluated by comparing simulated SWE with observational data. As direct SWE observations were very scarce, we instead used daily snow depth readings (HS) from 54 stations positioned within a radius of 50 km surrounding the watershed and covering an altitude range from 449 to 2550 m a.s.l. These data were converted to SWE using an algorithm based on the work by Martinec and Rango (1991) and Jonas *et al*. (2009). This conversion model was particularly suited here as it was calibrated using snow profile data from the Swiss Alps. For optimal comparison, the station data were mapped to the model grid using a snow data assimilation scheme specifically developed for snow (c.f. Foppa *et al*. 2007): Variable nonlinear SWE lapse rates allowed adapting the station data to be representative of the grid orography used for the hydrological models. A three-dimensional Gaussian filter weighting approach was used for spatial interpolation of detrended data. The weighting filter was regionally calibrated using available SWE point measurements.

Reconstructed discharge

As the discharge of the upper Reuss-Andermatt is altered by human activities, i.e. diverting water to neighboring catchments for hydropower supply, measured discharge, Q_{meas}, must be converted to potential (reconstructed) discharge, Q_{rec}, since there is a direct relationship between production and diverted discharge, Q_{div}, for the catchment under consideration (Herger, 2011). Thus, Q_{rec} is obtained as follows:

$$Q_{rec} = Q_{meas} + Q_{div} \tag{1}$$

For some periods, the error related to Q_{rec} is estimated to be of about 25%. Based on previous studies (e.g. Menzel, 1997; Gerber, 2008), we hypothesize that a significant change in the input (climatic) variables will strongly influence discharge, masking the effect of land use changes especially over a long time period.

RESULTS

Characterization of grassland and green alder soils

In this section, we discuss the effect of land use changes on soil structure expressed with K_{sat} and total porosity measurements. Results of the laboratory analysis highlighted two important points:

i) Higher K_{sat} on green alder than on grassland, especially in topsoil (0 – 30 cm) of all micro-catchments except Chämleten. The higher porosity in

Table I. Fraction of land cover types relative to watershed area for different scenarios used in the simulations, including the actual glaciarized area

	WaSiM-ETH				
Scenarios	Grassland (%)	Green alder (%)	Bare soil (%)	Other (%)	Ice/glaciers (% / km^2)
PLU_PC / PLU_FC	74	0	22	4	3.7 / 7
CLU_PC / CLU_FC	65	9	22	4	3.7 / 7
FLU_PC / FLU_PC	52	24	22	2	3.7 / 7

green alder soil is due to the more intense root system of green alder that loosens the soil structure and promotes vertical infiltration (also limiting surface runoff generation). Similar results were found by Alaoui *et al*. (2012) when grassland soil was compared to forest soil. The authors showed higher storage capacity in forest soil as compared to grassland soil, caused by the more intense root system having a significant effect on surface runoff (decrease).

ii) In Chämleten, the inverse phenomenon occurred (Figure 2). This may be explained by the permanent soil saturation and the water movement on the soil surface, which also promoted sediment transport and consequently local sedimentation of fine material (i.e. organic material) that helps to loosen soil. This phenomenon may increase K_{sat} of topsoil on grassland in comparison with green alder. In subsoil, no significant difference was observed for all plots.

Similarly, total porosity generally presents higher values in green alder soil compared to grassland soil, except in Chämleten.

The results show that the vegetation type has a notable effect on soil structure at the plot scale. Thus, the question arises: how would a given change in land use affect the hydrology at the entire catchment scale?

Trend analysis of long-term discharge and precipitation records

Trend analysis according to MK test (McLeod *et al*., 1990; Hipel and McLeod, 1994) was carried out on the reconstructed discharge. The long-term seasonal discharge (1910 – 2005) increased significantly during February and March (significance at $p < 0.05$, with a slope of +14.2 and +18.7% for February and March, respectively), whereas it decreased significantly during July, August and September (significance at $p < 0.05$, with a slope of −19.1, −32.0 and −25.2% for July, August and September, respectively) (Table II). The same trend analysis doesn't show any significant changes in precipitation (Flury, 2012) (Table III). Three possible causes may explain the reduction in discharge during peak and late summer: (i) a reduction of the glacier surface area and/or its retreat in time, (ii) more snowmelt occurs earlier in the year and thus less in summer and (iii) a higher evapotranspiration due to the expansion of the green alder on the expense of grassland. These hypothesized causes are discussed in the following.

Modeling results

Modelling current yearly discharge over the entire period (1983–2005) gave satisfactory results when compared to reconstructed discharge (Q_{rec}). The model efficiency (E) (Nash and Sutcliffe, 1970) was obtained by comparing calculated monthly values of discharge (Q_{sim}) against the monthly values of Q_{rec} which were basically derived from the measurements (see Equation (1)). In fact, E was equal to 0.84, reflecting good agreement between Q_{sim} and Q_{rec} (Figure 3B). The discrepancies between modeled and reconstructed discharge consisted mainly of slight underestimation of Q by the WaSiM-ETH model.

When comparing PLU_PC with FLU_PC, change in land use results in a difference in the yearly average discharge of $0.06\,m^3\,s^{-1}$. In comparison, the difference between the yearly discharge of FLU_PC and FLU_FC

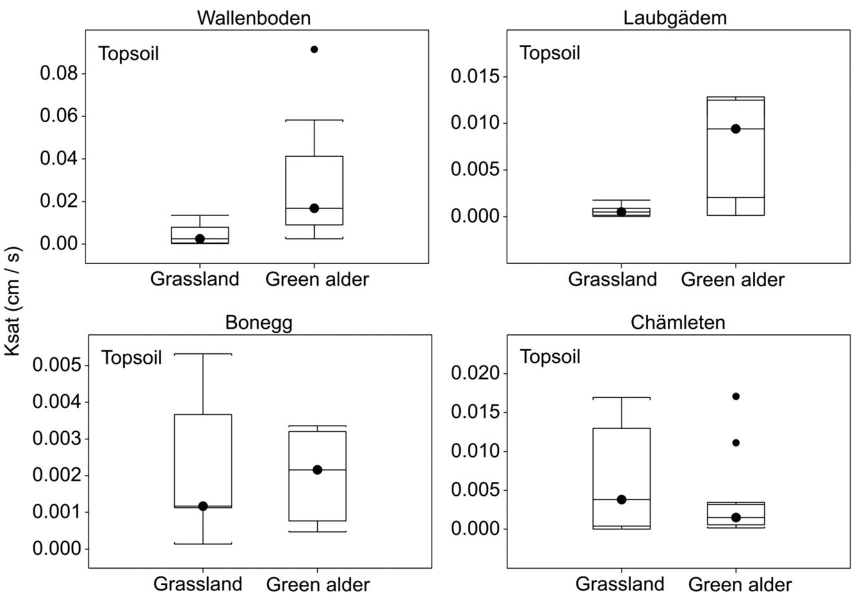

Figure 2. Saturated hydraulic conductivity of topsoil in different sub-catchments; the analysis was made with 100 samples for both top- and subsoil

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Table II. Trend analysis in the discharge for three time periods (Mann–Kendall test); A) monthly average discharge, and B) annual average discharge; only data of significance equal to or greater than 0.95 are shown

A) Mean monthly discharge

Months	1910–2005		1945–2005		1962–2005	
	Sign.	Slope (%)	Sign.	Slope (%)	Sign.	Slope (%)
January			0.95↗	+27.2		
February	0.99↗	+14.2	0.99↗	+35.0	0.99↗	+47.4
March	0.95↗	+18.7	0.95↗	+36.2	0.99↗	+80.4
April						
Mai						
June						
July	0.95↘	−19.1↘				
August	0.99↘	−32.0↘				
September	0.95↘	−25.2↘				
October						
November						
December					0.95↗	+453.

B) Mean annual discharge

Andermatt	Sign.	Slope (%)
	0.98↘	−13.5

Table III. Trend analysis (Mann–Kendall test) for the precipitation; A) monthly, and B) annual cumulated precipitation in two meteorological station: Andernatt (Swiss topo coordinates: 689 000/165 000, altitude: 1442 m a.s.l), and Göschenen (Swiss topo coordinates: 688 000/169 000, altitude: 1099 m a.s.l.)

A) Monthly cumulated precipitation averaged over 5 years running mean

Months	Andermatt		Göschenen	
	Significance	Slope (%)	Significance	Slope (%)
January	0.10	−5.53	0.13	+5.28%
February	0.88↗	+30.92	0.93↗	+27.13%
March	0.02	−0.57	0.07	+2.76%
April	0.05	+1.66	0.29	−7.45%
May	0.68	+20.28	0.66	+23.58%
June	0.85	+16.39	0.17	+2.32%
July	0.50↘	−12.18	0.64↘	−11.34%
August	0.94↘	−22.74	0.54↘	−8.58%
September	0.08	−3.69	0.05	+1.13%
October	0.32	+13.95	0.15	−4.46%
November	0.83↗	+32.74	0.65	+17.48%
December	0.01	−1.52	0.16	+5.19%

B) Annual cumulated precipitation

Andermatt	Sign.	Slope (%)	Göschenen	Sign.	Slope (%)
Averaged over 1 year	0.26	1.96		0.11	2.00

reaches a relatively higher value estimated to be equal to $0.45\ m^3\ s^{-1}$ (Figure 3).

The comparison between the interpolated SWE and the model simulations is shown in Figure 4 and displays good agreement between the two different methods indicating that the hydrological model WaSiM-ETH is able to reproduce the water balance terms including the relevant snow processes in the watershed robustly, especially with respect to time.

Relating the terms of water balance to precipitation over 23 years period clearly shows that snow discharge represents the highest contribution to total discharge, followed by the absolute value of ETP and finally glacier discharge (Figure 5). Thus, the input of the snowmelt is relevant in the water balance and can be considered as a dominant factor in addition to the precipitation. In summary, the catchment of Ursern Valley is controlled

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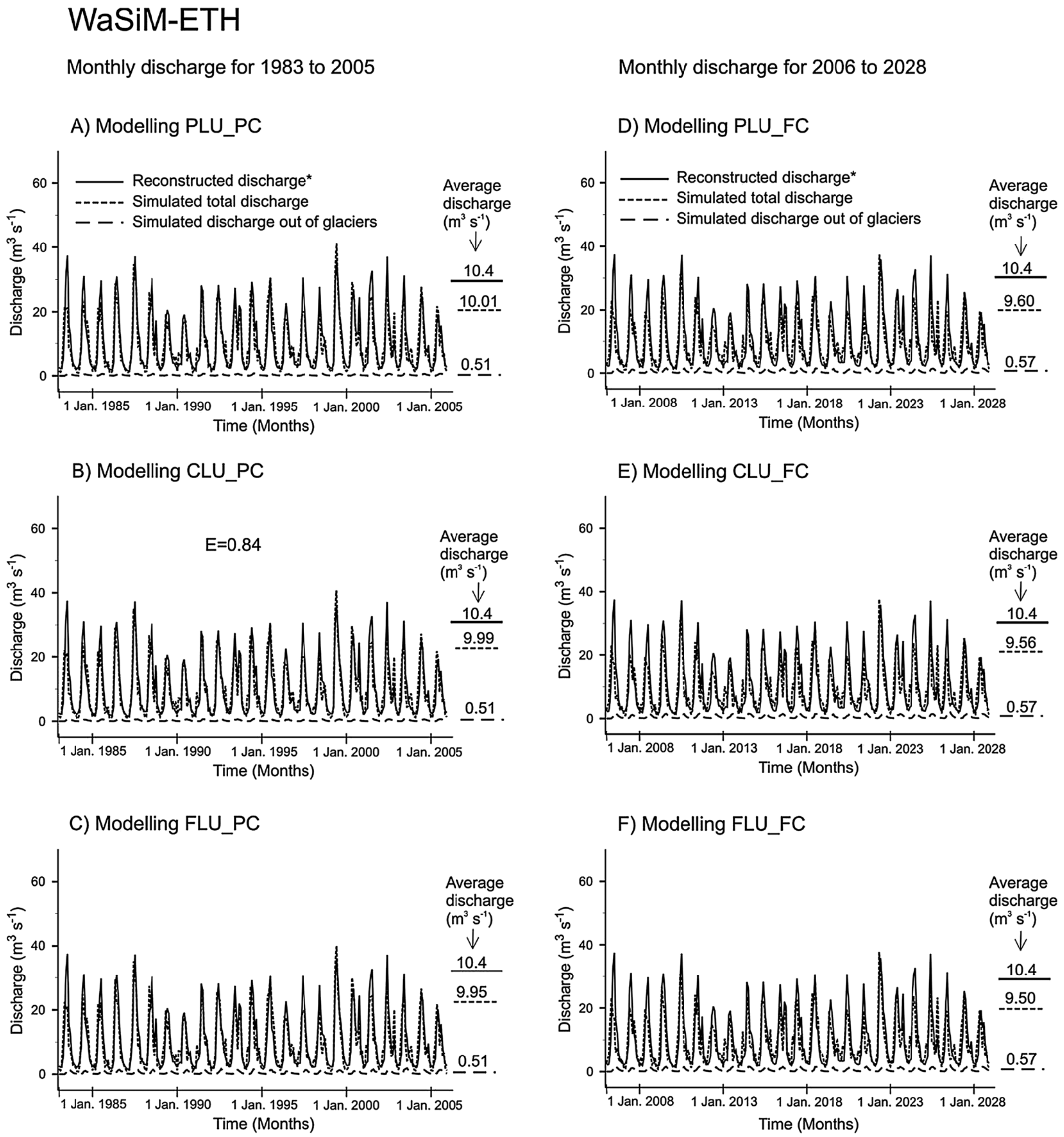

Figure 3. Simulated mean monthly discharge and mean monthly glacier discharge using WaSiM-ETH for different scenarios; *reconstructed discharge is derived from measurements as described by eq. 1

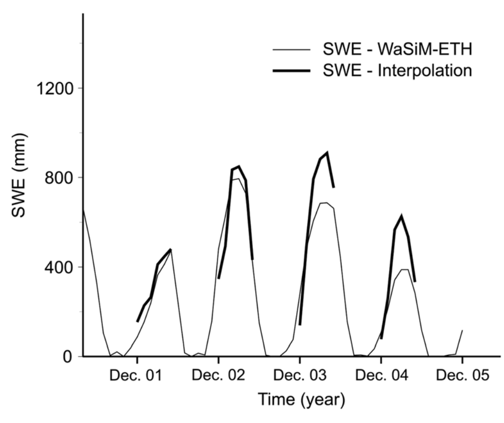

Figure 4. Comparison between SWE calculated with WaSiM-ETH and SWE interpolated from station data (see description in 'Observational SWE data')

by precipitation and snowmelt rather than glacier discharge as in the case of the other catchments located in the central Alps such as Massa and Rhone (Klok *et al.*, 2001; Verbunt *et al.*, 2003).

The comparison between the ETP of PLU_PC and ETP of FLU_PC in terms of mean annual values results in a difference of 1.1 mm (Figure 5A and 5B). In contrast, comparison between ETP of FLU_PC and ETP of FLU_FC results in a higher difference of 4.5 mm confirming also the previous results obtained from the comparison between total yearly discharges of the different scenarios. In addition, modeling results indicate that the increase in the temperature in the near future increases notably yearly snow discharge from 114.8 mm

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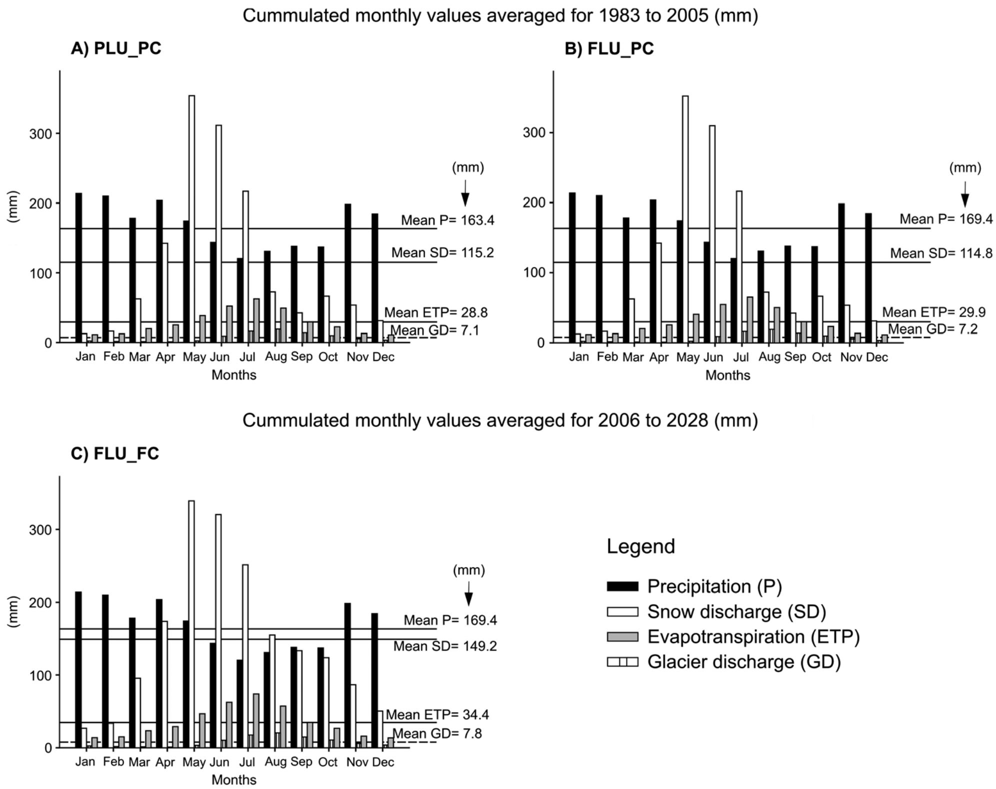

Figure 5. Comparison between the different elements of the water balance as calculated by WaSiM-ETH for different scenarios for 1983 to 2005 (A and B) and for 2006 to 2028 (C)

(FLU_PC) to 149.2 mm (FLU_FC) due to the contribution of the glacier in form of firn melt.

Simulated SWE, snow and glacier discharges for selected months are reported in Figure 6. A notable, however not significant increase in SWE was observed in February and March while the opposite took place already in April (SWE slightly decreased) (Figure 6A). The results show no further increase in the SWE after March, indicating an earlier snowmelt in the recent years compared to the earlier ones. Snow discharge increases also in March and April, while it remains constant in February and May. It exhibits the highest values in April and May compared to total yearly discharge measured during the period between 1983 and 2005 ($10.4\,m^3\,s^{-1}$) (Figure 6B). Therefore, the input of the snowmelt is relevant in the water balance and can be considered as a dominant factor in addition to the precipitation.

Concerning the glacier discharge, Figure 6C shows a notable increase already in April and a significant increase in May and June, attesting to an earlier contribution of glacier melt to discharge for the last years of the study period as compared to the earlier years. The evolution of the glacier discharge then diminished in July.

The early discharge of glaciers, especially in May, is interesting since it confirms the change observed in the hydrological regime when two study periods are compared, 1910−1941 and 1962−2005 (Figure 7). During the first period (1910−1941), the discharge was the highest in June, followed by July and August, while during second period (1962−2005), it was highest in June, followed by July and May rather than August. This change exhibited a transition from the b-glacio-nival to nivo-glacial regime. These findings can be related to a general warming that causes disintegration of the glaciers that no longer feed the rivers during July and August, as projected for the near future by Beniston (2009) and Beniston *et al.* (2011). The authors reported that peak discharge takes place 2–3 months earlier in the year, and maximum flow is reduced because of smaller contributions from the melting of a less voluminous snowpack. Because of the large interannual variability of runoff resulting from the sharply curtailed glacier mass in the mountains and possibly long and dry summers, the volume of summertime glacier melt waters may no longer be sufficient to feed water into river catchments at a time of year when precipitation amounts are low and the snowpack has already melted (Beniston *et al.*, 2011).

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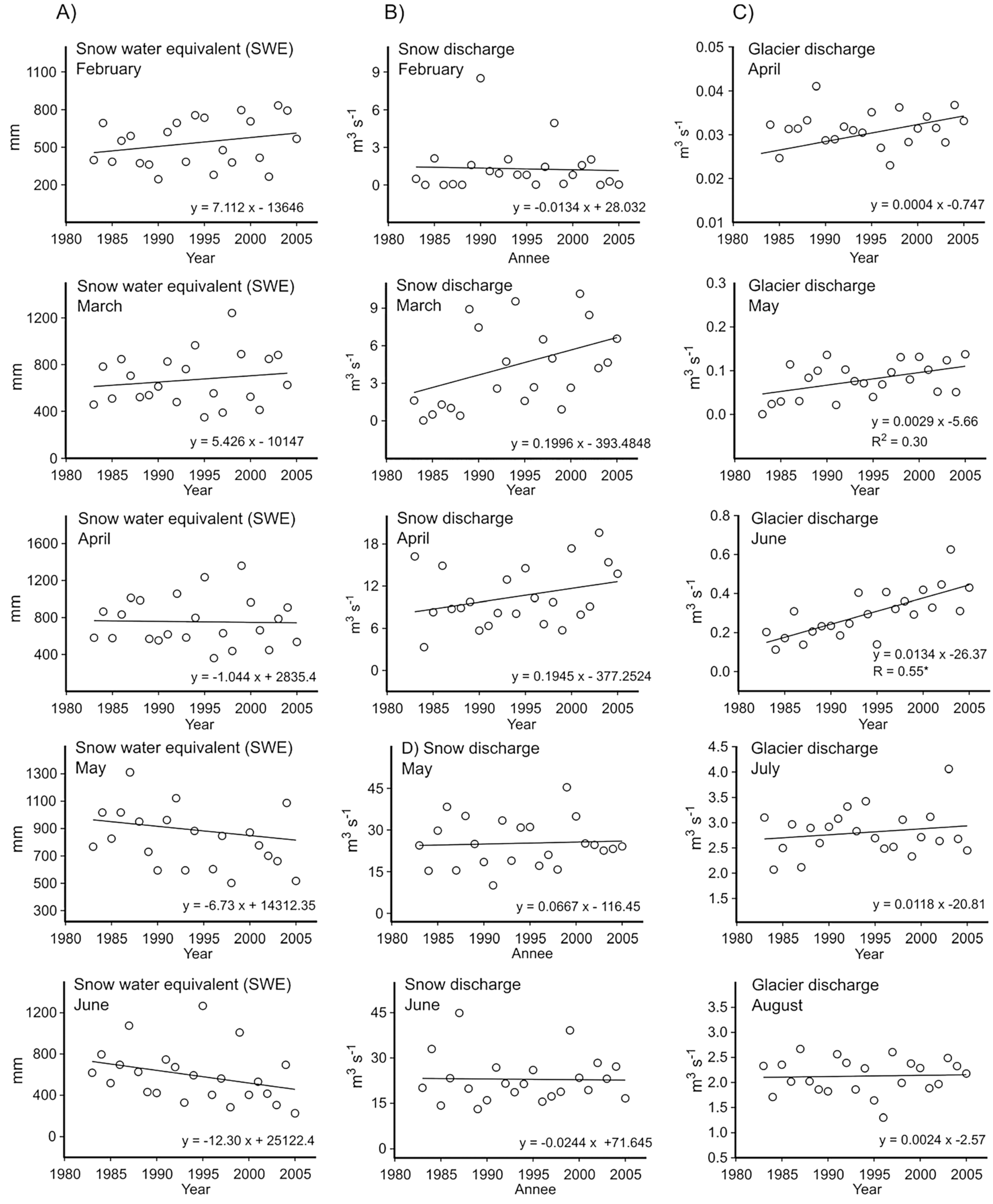

Figure 6. Simulated seasonal changes in A) the snow water equivalent, B) snow discharge and C) glacier discharge using WaSiM-ETH model

Calculated (actual) monthly ETP according to the different scenarios for entire period of 23 years is presented in Figure 8. It shows how ETP will change in future in comparison with current situation (CLU_PC): (i) if land use changes alone; and (ii) if climate changes are also considered.

The largest differences in simulated ETP between PC with current land use situation (CLU_PC) and FC with future land use situation (FLU_FC), varying between 15% and 16%, occur during the months May to September. In contrast and in spite of the large difference in the distribution of green alder between CLU_PC and FLU_PC, the modeled difference in ETP clearly shows a negligible effect of land use changes on the most important elements of the water balance illustrated by the very small difference in ETP that does not exceed 3% even in warm months as June and July.

In summary, three main conclusions can be made with regard to the simulation results:

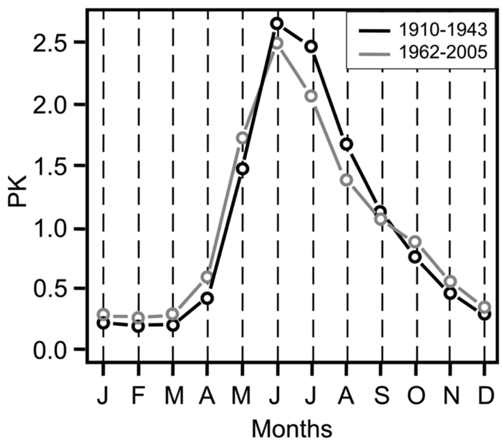

Figure 7. Comparison of flow regimes in terms of discharge for two periods described in terms of the dimensionless Pardé coefficient (PK)

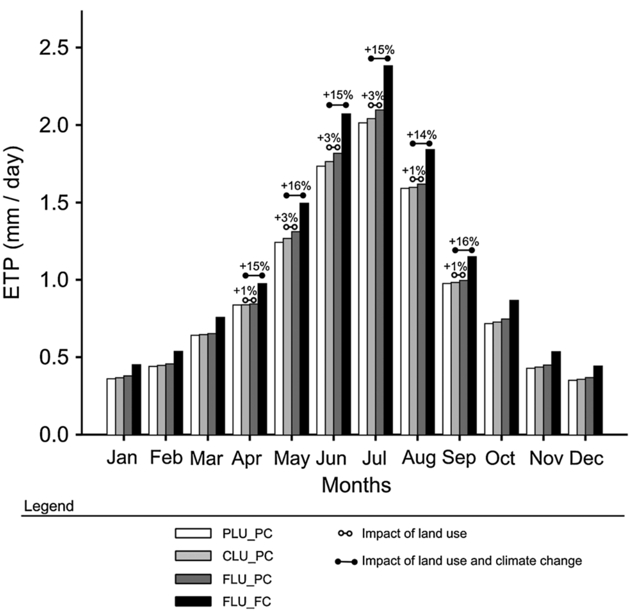

Figure 8. Difference in the mean monthly (actual) ETP between different scenarios as influenced by land use alone and also by climate change (WaSiM-ETH model)

i) Land use changes do not notably influence the simulated discharge, as shown by the differences in modeled discharge for different scenarios that do not exceed 0.6% even if discharge of past situation (PLU_PC) is compared to discharge in the future (FLU_PC) (Figure 3A and 3B, Table IV).

ii) Climate change due to an increase of 1.3 °C expected to occur in near future would reduce mean yearly discharge of approximately 5% attesting of a relatively higher impact if compared to the impact of land use alone (Table IV).

iii) The contribution of glacier melt to runoff is small (about $0.5\,m^3\,s^{-1}$) compared to the measured total yearly discharge ($10.4\,m^3\,s^{-1}$) and an eventual total disintegration in future could not largely affect total discharge.

DISCUSSION

The expansion of green alder has a significant effect on topsoil structure at the plot scale, expressed by a significant increase in the saturated hydraulic conductivity and porosity. For the longer time period under consideration, no significant difference was observed between different scenarios with and without green alder when considering the entire catchment. In this case, the high values of precipitation and snow melt control discharge and mask the small effect of the land cover changes on discharge.

Change in the mean annual ETP due to the vegetation changes does not exceed 1.8% (when the CLU_PC scenario is compared to CLU_FC scenario). In our study catchment situated at high elevation, it is assumed that the impact of land use changes on discharge is less pronounced than for catchments as lower elevation (Menzel, 1997). The snowmelt and precipitation control discharge and also mask the already weak effect of land cover changes. In view of these results, it appears that the reduction of the mean monthly discharge during the summer period is due primarily to the retreat of snow discharge in time and secondarily to the reduction in the glacier surface area together with its retreat in time, rather than the increase in the evapotranspiration due to the expansion of the green alder on the expense of grassland.

Table IV. Evaluation of the effect of land use and climate changes on mean annual discharge in mm and % as simulated by WaSiM-ETH model

Effect of land use on yearly discharge (Q)	Effect of climate change on yearly discharge (Q)	Combined effect on yearly discharge (Q)
$Q_{(FLU\_PC)} - Q_{(PLU\_PC)}$	$Q_{(FLU\_FC)} - Q_{(FLU\_PC)}$	$Q_{(FLU\_FC)} - Q_{(CLU\_FC)}$
−0.027 mm (−0.6%)	−0.203 mm (−1.7%)	−0.221 mm (−5%)

In the Swiss Alps, results of many studies show consistent trends in both temperature and precipitations in the future (e.g. Frei, 2007; Beniston *et al*., 2011). In our case study, the future scenarios are based only on an increase of temperature since no significant changes in precipitation were detected for the study period. The response of precipitation to warmer climatic conditions is more subtle than change in temperature because precipitation trends are more spatially variable and the controls of topography on precipitation are often not adequately represented in regional climate models. Moreover, an average rise of 1 °C is accompanied by a general rise of about 150 m in the altitude of the snowline (Haeberli and Beniston, 1998). As a consequence, warmer conditions associated with enhanced winter precipitation in the Alps are likely to lead to more abundant snowfall in the higher reaches of the mountains, but much reduced snow at lower levels where more precipitation in form of rain is likely to fall (Beniston *et al*., 2003). In addition, based on regional climate models (Christensen and Christensen, 2003; Graham *et al*., 2007), future summers are likely to occasionally favor more frequent extreme events that result in catastrophic flooding, despite a general trend toward drier summer conditions.

Changes in temperature and precipitation will have several consequences on water resources in the Ursern valley in the future: (i) hydrological regime will undergo further changes, (ii) rivers may dry up partially or completely implying important impacts not only for the mountain valley, but also for the populated lowland regions that depend on alpine water resources for an important part of their water supply and (iii) regeneration of groundwater will decline in summer and autumn and average evaporation will increase in summer. These changes together with the expansion of the bushland will also affect the nival flora (Dullinger *et al*., 2004) at the species level. In addition, climate change can have direct impact on tourism in the Alps as the changes in the climatic conditions necessary for specific activities. Our case study has refined these projections by taking into account the impact of both climate and land use changes on the hydrology in a region where the glacier has largely been disintegrated.

CONCLUSIONS

The main aim of this study was to evaluate the impact of land use and climate changes on hydrology (i.e. total discharge) using three different scenarios that represent past, current and future situations.

A physically based model (WaSiM-ETH) was applied in order to highlight the dominant variables that affect the hydrology in the Ursern Valley.

There are two main reasons why no effect of land use changes on hydrology was detected for the study period (1983 – 2005) despite the difference in soil structure (characterized by total porosity and saturated hydraulic conductivity) between the green alder and grassland soils: (i) in the steepest locations of the Valley (majority of the catchment), soil is very shallow, which means that there is only a very small capacity to store soil water over a long time period; (ii) the difference in ETP between grassland and green alder soils at these high elevations is masked by other major factors such as snowmelt and glacier discharge.

Modeling results attest to a retreat in snowmelt and glacier discharge that occur early in the year – March for snowmelt and May for glacier discharge – and imply a change in the hydrological regime from b-glacio-nival to nivo-glacial. These changes explain the major changes occurring in summer discharge, expressed by a significant decrease in July, August and September.

The region of Ursern Valley is controlled by precipitation and snowmelt, in contrast to other regions in the Alps (Massa and Rhone). This is due to the fact that glaciers have largely already disintegrated (now covering 3.7% of total surface area) and their contribution to total discharge is very small: it was estimated to be about $0.5\,m^3\,s^{-1}$, which is negligible compared to the mean annual discharge of approximately $10.4\,m^3\,s^{-1}$.

Modelling results show that the yearly total discharge due to the land use changes will be reduced by 0.6% in the near future whereas, it will be reduced by about 5% if climate change is also taken into account. It was also demonstrated that the reduction of the mean monthly discharge during the summer period is due primarily to the retreat of snow discharge in time and secondarily to the reduction in the glacier surface area together with its retreat in time, rather than the increase in the evapotranspiration due to the expansion of the green alder on the expense of grassland.

About 30% of available discharge is diverted outside of the region, and the remaining 70% of available water can partially supply hydropower in terms of energy. This remaining available water constitutes a potential environmental resource for the near future. Since, seasonal variation in precipitation is expected to occur, emphasis should be placed on better anticipation and management of these water resources.

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