Hydrol. Earth Syst. Sci. Discuss., 9, 5983–6021, 2012
www.hydrol-earth-syst-sci-discuss.net/9/5983/2012/
doi:10.5194/hessd-9-5983-2012

Hydrology and
Earth System
Sciences
Discussions

The importance of glacier and forest change in hydrological climate-impact studies

N. Köplin[1,2], B. Schädler[1,2], D. Viviroli[1,2], and R. Weingartner[1,2]

[1]Institute of Geography, University of Bern, Bern, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

Received: 26 April 2012 – Accepted: 28 April 2012 – Published: 9 May 2012

Correspondence to: N. Köplin (nina.koeplin@web.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Changes in land cover alter the water balance components of a catchment, due to strong interactions between soils, vegetation and the atmosphere. Therefore, hydrological climate impact studies should also integrate scenarios of associated land cover change. To reflect two severe climate-induced changes in land cover, we applied scenarios of glacier retreat and forest cover increase that were derived from the temperature signals of the climate scenarios used in this study. The climate scenarios consist of ten regional climate models from the ENSEMBLES project; their respective temperature and precipitation deltas are used to run a hydrological model. The relative importance of each of the three types of scenarios (climate, glacier, forest) is assessed through an analysis of variance (ANOVA). Altogether, 15 mountainous catchments in Switzerland are analysed, exhibiting different degrees of glaciation during the control period (0–51 %) and different degrees of forest cover increase under scenarios of change (12–55 % of the catchment area). The results show that even an extreme change in forest cover is negligible with respect to changes in runoff, but it is crucial as soon as evaporation or soil moisture is concerned. For the latter two variables, the relative impact of forest change is proportional to the magnitude of its change. For changes that concern 35 % of the catchment area or more, the effect of forest change on summer evapotranspiration is equally or even more important than the climate signal. For catchment with a glaciation of 10 % or more in the control period, the glacier retreat significantly determines summer and annual runoff. The most important source of uncertainty in hydrological climate impact studies is the climate scenario, though, and it is highly recommended to apply an ensemble of climate scenarios in impact studies. The results presented here are valid for the climatic region they were tested for, i.e. a humid, mid-latitude mountainous environment. They might be different for regions where the evaporation is a major component of the water balance, for example. Nevertheless, a hydrological climate-impact study that assesses the additional impacts of forest and glacier change is new so far and provides insight into the question whether or not it

is necessary to account for land cover changes as part of climate change impacts on hydrological systems.

1 Introduction

Changes in land use and land cover alter the hydrology of a catchment through changes in evapotranspiration (e.g. Cuo et al., 2009; Dunn and Mackay, 1995; Klöcking and Haberlandt, 2002; Lahmer et al., 2001) and altered surface roughness and soil properties, which modify the runoff concentration processes (Hundecha and Bárdossy, 2004).

In addition to anthropogenic land modifications, the vegetation itself responds to changes in climate with species movement or redistribution (Leuzinger, 2009; Schumacher and Bugmann, 2006; Theurillat and Guisan, 2001). In a mountainous environment, for example, increasing temperatures result in an upward movement of the tree line because the tree line is a climatically determined ecotone (Dullinger et al., 2004). Another climate-induced change in land cover is glacier retreat. Glaciers, however, constitute a special case of land cover since they produce runoff themselves from previously stored water.

The rapid and severe global glacier retreat due to the past increase in temperature is very well documented (see e.g. Arendt et al., 2002; Dyurgerov and Meier, 1997; Paul et al., 2004) and easy to comprehend. Concerning the increase in tree line it is often argued that trees are incapable of responding to changed environmental conditions within rather short time periods like, e.g. less than a century (Dullinger et al., 2004; Egli et al., 2008; Theurillat and Guisan, 2001). This is assumed because other environmental conditions than temperature, such as a low soil-moisture in shallow alpine soils, could prevent rapid upslope migration of trees (Henne et al., 2011). On the other hand, paleoecological records provide evidence for a rapid upslope (and downward) movement. Tinner and Theurillat (2003), for instance, who analysed pollen in lake sediment cores from study sites in Southwest Switzerland, concluded that the tree line in this region fluctuated during the past 11 500 yr, and Tinner and Lotter (2001) showed that these fluctuations can be attributed to climatic change, i.e. to increases and decreases in temperature. Moreover, Tinner and Kaltenrieder (2005) demonstrated that, during the Holocene, "[...] vegetation was in dynamic equilibrium with climate, [and] forecasted global warming may trigger rapid upslope movements of the tree line of up to 800 m within a few decades or centuries [...]".

These observed and anticipated changes in forest cover in Switzerland are not only a result of climate change, but also a result of altered land use practices. Gehrig-Fasel et al. (2007), for example, found an increase in forest cover in the Swiss Alps for the very short period from 1985 to 1997. They attributed this increase to both the change in climate and in land use, the latter of which being most important for the observed increases in forest cover, however. They expect climate change to gain in importance for the 21st century, though.

In spite of this documented change in forest cover due to climate and land use change, most studies assessing the impacts of climate change on hydrological systems neglect the effects of accompanied changes in land cover (see e.g. Elsner et al., 2010; Gunawardhana and Kazama, 2012; Laghari et al., 2012). There is a growing consensus, however, that these land cover impacts have to be accounted for, to reliably assess future availability of water resources because of possible feedbacks between land cover and climate (e.g. Bronstert, 2004; Hejazi and Moglen, 2008; Viviroli et al., 2011).

Given that the forest and glacier area in Switzerland will change considerably, the question is, to what extent would this change alter the projected hydrological change? Or more specifically, how does the relative changes that are introduced by an altered glacier runoff and a changed forest cover compare to the relative impact of the climate signal itself? These questions are answered in this study by means of hydrological climate-impact modelling in 15 mesoscale catchments in Switzerland. A study with this focus is new so far and provides insight into the question whether or not it is necessary to account for land cover changes as part of climate change impacts on hydrological systems.

2 Study area and data

We extended an earlier study by Köplin et al. (2012) who modelled and analysed a comprehensive set of 186 mesoscale catchments in Switzerland with respect to hydrological change. They applied ten regional climate models (RCMs) as well as scenarios of glacier retreat that were derived from the projected climate change to determine climate-change sensitive regions in Switzerland. They ran the hydrological modelling system PREVAH (Viviroli et al., 2009a) with this input. Here, we use the same model set up with respect to the RCMs, the glacier retreat and the hydrological model but extend it by applying three different forest change scenarios (cf. Sect. 2.3). Although climate scenario data for two periods (2025–2046 and 2074–2095) in the 21st century are available, we only assess the so called far-future period at the end of the century. This is to account for ecological time lags of a few decades (Harsch et al., 2009) that will likely prevent significant tree growth until the near-future period.

We will analyse the hydrological impacts of climate change together with its accompanying forest increase and glacier retreat in a sample of 15 case study catchments in Switzerland (Fig. 1). The catchments are representative of the different regions in Switzerland that are particularly sensitive to climate change as defined in Köplin et al. (2012): each sensitive region (C2 to C6 in Fig. 1a) is represented by three case study catchments. Moreover, the case study catchments evenly cover an altitudinal range from 1000 to 2500 m a.s.l. (Fig. 1b). Catchments located within this range are specifically sensitive to changes in temperature, which was demonstrated by Köplin et al. (2012). Since the land cover scenarios in this study solely depend on temperature change (cf. Sects. 2.2 and 2.3), the selected catchments constitute a suitable sample for our study.

The study catchments were parameterized through regionalisation of calibrated parameter sets, for details see Köplin et al. (2010, 2012) and Viviroli et al. (2009b,c). A regionalisation procedure was applied because most of the catchments in the high alpine area are used for hydropower production and can therefore not be calibrated on measured natural runoff data. That is, we study the natural runoff behaviour of the catchments under scenarios of climate and land cover change, which should be kept in mind when interpreting the results.

2.1 Climate scenarios

The climate scenarios are part of the Swiss climate change scenarios CH2011 (2011). They are provided for the meteorological variables temperature and precipitation and are based on the Delta Change approach. Bosshard et al. (2011a) applied this downscaling procedure to ten RCMs from the ENSEMBLES-project (van der Linden and Mitchell, 2009), all of them driven by the A1B emission scenario. The novelty introduced to the downscaling procedure by Bosshard et al. (2011a) is a spectral smoothing method to filter the annual cycle of daily deltas. This yielded continuous representations of the annual cycle of climate change signals. The annual cycles of temperature and precipitation were provided for all meteorological stations in Switzerland, i.e. 188 temperature and 565 precipitation stations (CH2011, 2011).

Because the climate scenarios are based on the Delta Change approach that assesses changes in the long-term mean annual cycle of the climate variables, all of the subsequent analyses of hydrological response variables are based on the mean annual cycle, too (i.e. mean monthly, seasonal and annual values, respectively).

The projected climate change for the case study catchments can be summarized as follows: the ensemble mean projects temperature increases during the whole year with the most pronounced increase in summer (4 K) and a smaller increase in spring (2.8 K). The winter precipitation increases by 10 % on average, whereas summer precipitation decreases by 20 % and spring as well as autumn precipitation do not show a distinct change signal.

2.2 Glacier retreat

The glacier scenarios are calculated as a function of the climate scenarios' temperature deltas using a glacier retreat model (Linsbauer et al., 2012; Paul et al., 2007, 2011). The model is based on alterations of the glaciers' equilibrium line altitude (ELA). The ELA is the altitude at which the mass balance of a glacier equals zero or in other words, where accumulation equals ablation (Paul et al., 2007), and it rises with increasing temperature. In the model of glacier retreat, the equilibrium line is defined to rise 100 m per 1 K (Paul et al., 2011).

In the Swiss Alps, the glacier area above the ELA, the accumulation zone of a glacier, comprises 60 % of the total glacier area, on average (MBB, 2005; Paul et al., 2007). An increase of the ELA entails adaptation of the glacier to the altered condition until the ELA divides the glacier at a ratio of 40 to 60 % again. This adaptation occurs delayed over a longer time period whereas the ELA immediately reacts on altered temperatures. The delayed adaptation, i.e. the response time of a glacier, is specific for every glacier and is at 10–40 yr for most glaciers in the Swiss Alps and 50–100 yr for the thickest and largest ones (Paul et al., 2011). In the model applied here, a mean response time of 50 yr is assumed, whereas the shift of the ELA is calculated with scenario-specific temperature changes.

The surface that is revealed when a glacier retreats is defined as rock because it is assumed that soil formation takes much longer than only 100 yr, i.e. it is not completed in the time period from the control to the scenario period. The glacier change (GC), i.e. the retreat per catchment from the control to the scenario period is depicted in Fig. 2. It has to be stated that the glacier retreat assumed in this study is rather conservative because the model does not take into account enhanced input of dust or lake formation, for example, which would accelerate glacier retreat. Based on the latest observed temperature increase and considering positive feedbacks, the glacier retreat would be more severe than calculated with the model, here (Linsbauer et al., 2012).

Nevertheless, these glacier scenarios constitute a unique data basis for our study since they comprehensively assess the glacier retreat for the entire Swiss Alps.

For the analysis of variance (Sect. 3.2), we added an extreme glacier scenario to the setup, where we removed all glaciers from the catchments (G_{NO}). This represents one possibility to assess the relative impact of glacier retreat on the projections if no scenarios were available. Moreover, we thereby cover the whole range of possible glacier extents, from the control period extent to a complete glacier-free state: as mentioned above, the scenarios of glacier retreat have to be considered being rather conservative, and most of the smaller glaciers in our study could possibly have disappeared at the end of the century.

2.3 Forest scenarios

In this study, vegetation change is defined as an increase of forest cover due to both the increase of the tree line and land abandonment. We narrowed down vegetation change to a change in forest cover, because the conversion of any vegetation into forest constitutes a drastic change in land cover and presumably causes the strongest hydrological signal.

Our forest change model comprises different rules that control tree growth: trees can only grow where the former land cover was bush, pasture, sub-alpine meadow, alpine meadow, alpine vegetation, rough pasture or bare soil vegetation, but they cannot grow on rock, urban areas, water and wetlands, for obvious reasons. Areas used for agriculture are excluded from forest expansion, too, because these areas are protected by law in Switzerland since 1992 (Lüscher, 2004). Furthermore, trees can only grow on areas with a slope of less than 40° because steeper slopes unlikely support higher vegetation (Theurillat and Guisan, 2001).

Temperature is the most important factor determining plant growth (Körner, 2007), since it controls, i.e. promotes and limits tree growth (Grace et al., 2002). This is why we calculated potential scenario tree lines based on mean annual temperature increases of the ten climate scenarios in use and without accounting for changes in precipitation.

The increase in tree line was calculated according to the average temperature lapse rate of 0.56 K per 100 m (Körner, 1998; Theurillat and Guisan, 2001). The mean annual temperature deltas of the ten climate scenarios vary between 2.4 K and 4.2 K for the case study catchments. For a climate scenario with a rather low temperature increase, for example, the scenario tree line would be 465 m higher ($2.6\,\mathrm{K}/0.56\,\mathrm{K}\cdot 100\,\mathrm{m}$) than the actual catchment-specific control period's tree line.

Based on the outlined forest scenario constraints, we define three different forest scenarios which we briefly describe in the following. Attention should be paid to the consecutive setup of the scenarios (see Table 1 for a summary): each scenario incorporates the changes of the previously introduced scenario, i.e. the second forest change (FC_2) integrates the changes of the first forest scenario (FC_1) whereas the third (FC_3) inherits the changes from both FC_1 and FC_2. All three forest scenarios, on the other hand, integrate glacier retreat (GC), and all four land cover scenarios are run with the climate scenario input (CC), of course. We decided on this successive structure of the scenarios because this is a common increase of the degree of complexity observed in other impact studies. Thanks to this, the results are comparable to studies that do not account for land cover change at all, to studies that incorporate a glacier retreat and to studies that additionally assess changes in forest cover.

The first forest scenario FC_1 represents *tree line increase*, where deciduous and coniferous forests are treated separately, here, because of their specific natural tree lines. First, the coniferous forest grows beyond its control period tree line on the allowed areas specified above and rises up to the scenario treeline, i.e. it is purely an upwards expansion. Then, the deciduous forest grows above its control period tree line and on the same allowed areas. Deciduous forest, however, can also replace coniferous forest. This first scenario of forest change thereby reflects findings from Leuzinger (2009) who assumes that the tree line in Switzerland will increase significantly and deciduous forest will replace the formerly dominating coniferous forest. It has to be stated, though, that some authors actually anticipate a shift of whole vegetation belts (e.g. Leuzinger, 2009; Theurillat and Guisan, 2001). For our forest scenario, however, existing trees remain in the lower ranges, which we attribute to the Swiss forest law from 1991 (WaG, 2008). This law protects forested areas and aims at preserving the forest in Switzerland in its area and spatial distribution. Therefore, the formerly forested area is not changed, here.

The second forest change FC_2 is an additional *land abandonment*. Please note that only areas formerly used for alpine farming are abandoned in this scenario, e.g. subalpine meadows or pastures, not to be confused with the agricultural areas protected by law from abandonment (see above). Within the control period's range of lower and upper tree line, first the coniferous forest grows on the allowed areas, then deciduous forest grows and again replaces coniferous within the deciduous forest's tree line boundaries. That is, this scenario reflects a sideways forest expansion in addition to the previous upwards expansion. Both FC_1 and FC_2 are based on the results of Gehrig-Fasel et al. (2007) who found that climate change causes upward shifts of the tree line, whereas land abandonment results in forest ingrowth.

The last scenario of forest change (FC_3, *soil genesis*) is not a further increase in forested area but an additional increase in soil depth under forest cover. This increase in soil depth has to be distinguished from the slow soil formation on bare rocks mentioned in Sect. 2.2. Here, it is an increase in depth of existing soils on forested areas because of the high input of organic matter through trees. It is based on results by Mavris et al. (2010) who found a distinct accumulation of soil organic matter within 150 yr of exposure after glacier retreat and re-colonisation of higher plants at the Morteratsch glacier in Eastern Switzerland. We mimic this in our scenarios with a general increase of soil depth by 10 cm in 100 yr on forest covered areas, both new and existing forests.

The scenario tree lines of our study catchments for coniferous forest range from 1910 m a.s.l. where the control period's tree line was low (1490 m a.s.l.), to 2870 m a.s.l. where the calculated shift in tree line due to the high temperature increase was maximal (780 m). The relative area of deciduous and coniferous forest per scenario, as well as the relative increase in soil depth per study catchment can be examined in Fig. 2.

2.4 Land cover in PREVAH

This section is based on the documentation of the hydrological modelling system PREVAH (Precipitation-Runoff-EVAporation-Hydrotope based model, Viviroli et al., 2007, 2009a). The land cover in PREVAH includes water bodies, glaciers, rock, bare soil, urban areas and natural as well as cultivated vegetation. Altogether, 22 land cover types are defined with the following land cover specific variables that are parameterized a priori on a monthly basis: surface roughness, which is represented by average vegetation height, root depth, minimal stomatal resistance, leaf area index (LAI), vegetation density, maximal interception storage and albedo. These vegetation-specific parameters are used, among others, to calculate potential evapotranspiration (ETP) after the Penman-Monteith equation (Monteith, 1975). The actual evapotranspiration (ETA) is then derived from ETP using adjustment factors, dependent on the actual moisture and vegetation as well as soil conditions.

Vegetation therefore has a direct influence on interception (SI and EI; see Fig. 3), depletes the soil moisture storage (SSM) via transpiration (ESM) and thereby alters ETA, which is a basic water balance component. Land cover, however, also modifies the maximum storage capacity of SSM: the storage's limit is defined vegetation-specific using plant-available soil-moisture capacity, root depth and soil depth. That is, in our scenarios SSM is not only increased through the root depth of the increased forest cover but also through the increased soil depth under FC_3, of course. So, an increased forest cover increases ETA and SSM, and thereby acts as a sink for runoff through withdrawal of water from the runoff generation modules (SUZ, SLZ). That is, the forest scenarios have the potential to indirectly reduce runoff, in particular the quick runoff component ($R0$). This indirect influence of vegetation on runoff reflects the commonly recognized effect of afforestation.

In contrast to vegetation, glaciers have a direct influence on runoff as they generate runoff themselves through melt of previously stored water which is added to different runoff components (see Fig. 3, lower left corner). Therefore, glaciers are a source for water in addition to liquid precipitation and snow melt and have to be considered a special case of land cover. The area that is released by the glacier is converted into rock (cf. Sect. 2.2), which constitutes a drastic change: sublimation is reduced and, more important, the composition and amount of direct runoff (RD) is changed leading to an altered total runoff and a changed runoff behaviour.

As set out in this section, the hydrological modelling system PREVAH represents all important components that matter with respect to land cover change and its impact on hydrology, which is a prerequisite in this kind of impact study (Bronstert, 2004).

3 Methods

3.1 Descriptive analysis

We ran the hydrological model for all climate and land cover scenarios and then aggregated the hourly time series to the mean annual cycle of monthly values or seasonal and annual values, respectively. Because we study changes in water balance components, these aggregated values are more meaningful. For ETA and R_{tot} we computed the sum per month (season, year), and for SSM, being a state variable instead of a flux, we calculated the mean for the respective periods. The runoff coefficient RC was calculated as the ratio of direct runoff (RD) to the sum of liquid precipitation (P_{liq}) and snowmelt (SME). RD is the sum of surface runoff ($R0$) and interflow ($R1$) per time step, i.e. per month, season or year, minus the glacier melt (GLAC). So RC is calculated as

$$\text{RC} = \frac{(R0 + R1) - \text{GLAC}}{P_{\text{liq}} + \text{SME}}. \tag{1}$$

We subtracted GLAC from RD because in the model structure of PREVAH the glacier melt is directly added to the surface runoff. To reduce the effect of glacier retreat on RC to its mere alteration of the land cover (conversion of ice to rock), we subtracted GLAC from RD. Moreover, we do not so much aim at assessing the change in glacier runoff than at assessing its effect on the water balance components. The altered glacier runoff is implicitly incorporated analysing changes in the target variable R_{tot}, of course. For all analyses in this study, we used the R version 2.14.1 (R Development Core Team, 2011).

Please note that, for the descriptive analysis and each target variable, we computed the ensemble mean of the climate scenarios per land cover scenario (see Fig. 4, upper half, right side). That is, we aggregated the spread in the target variables that is caused by the different climate models to the mean value, here, to oppose this single CC_{EM} value to the respective values for GC_{EM} and $\text{FC}_{1,\text{EM}}$ – $\text{FC}_{3,\text{EM}}$ as well as to the CTRL. The spread that is caused by the climate scenarios will be analysed in the ANOVA (Sect. 3.2).

3.1.1 Comparison of water balance components

First, we chose two very different catchments (5 and 9, cf. Fig. 2) to study the possible range of changes in the water balance components due to the climate and land cover change. Catchment 5 shows the strongest increase as well as the highest degree of forest cover under FC_2 (CTRL: 32 %; FC_2: 87 %) and is not glaciated. On the other hand, catchment 9 shows the second lowest degree of forest cover under FC_2 (34 %; CTRL: 14 %), the second highest relative glaciation (21.2 %) and the highest absolute glacier extent (117 km^2) of all study catchments. The analyses are based on absolute values to ease the comparison between alterations of different water balance components; the results can be found in Sect. 4.1.

3.1.2 Comparison of net changes between catchments

Then, we analysed the net changes for the target variables actual evapotranspiration and total runoff both for the summer (ETA_{JJA}, $R_{\text{tot,JJA}}$) and the annual time scale (ETA_{a}, $R_{\text{tot,a}}$). The net change is defined as the change in a target variable that is caused by one particular scenario and that is calculated relative to its preceding scenario. That is, the net change of GC_{EM} (cf. Table 1) is calculated relative to the simulation of CC_{EM}, or the net change of $FC_{2,EM}$ is calculated relative to $FC_{1,EM}$. This relative calculation is necessary because every scenario incorporates the changes of its preceding scenarios as explained in Sect. 2.3.

We calculate the net changes per scenario and catchment to compare all 15 catchments and to analyse possible relations between the net change and the glacier retreat as well as the forest increase. For a strong forest increase, for example, one would expect a higher net change due to this forest change and compared to that of the climate and glacier changes. So, the net change allows to assess the relative importance one scenario has for the target variable and differs from the analysed absolute values mentioned in the previous section. The comparison of all catchments facilitates to distinguish systematic relationships between the relative importance and an associated degree of glaciation or forest cover, if at all measurable.

3.2 Analysis of variance (ANOVA)

To analyse the relative impact of the three types of scenarios (climate, glacier, forest) on the target variables, we furthermore conducted an analysis of variance (ANOVA; see e.g. Doncaster and Davie, 2007 for a comprehensive overview, which this section is based on). In the following we explain how this analysis differs from the descriptive analysis above.

Through an ANOVA one can assess causal relationships between explanatory variables (the three types of scenarios) and a response variable (here one of ETA, SSM, R_{tot}, RC). The explanatory variables can be of categorical scale, and in the ANOVA terminology they are referred to as factors, whereas their numbers of categories are called levels. For example, the climate scenarios constitute a factor with ten levels (i.e. ten different scenarios or categories). In contrast to the descriptive analysis above, which is more a qualitative comparison of the scenarios' effects, the ANOVA facilitates to quantify the relative importance the scenarios have for the variation in the target variables. It assesses whether the target variables' responses change for different levels of the factor. That is, an ANOVA decomposes the total variation of a target variable into variance fractions that can be ascribed to changes in the factor variables' levels. The main advantage of this procedure is that the effects of various factors can be assessed simultaneously (and not separated as for the descriptive analysis), and, moreover, the effects of their interactions on the response can be accounted for, too. Interactions are defined as effects of a factor that depend on the effects of one or more other factors. Because of possible feedbacks between the scenarios (cf. Sect. 1), these interactions are an important feature for our analysis.

To account for the interactions, the ANOVA design has to be a so called fully cross factored design, which means that all possible scenario combinations are assessed (see Fig. 4, lower half). The three-factor cross factored model in our study is then written as

$$Y = C + G + F + I \tag{2}$$

with Y being the total variation of the response, C being the variation explained through the climate scenarios, G that explained through glacier change and F that through forest change. The interaction term I is defined as

$$I = C \cdot G + C \cdot F + G \cdot F + C \cdot G \cdot F. \tag{3}$$

Because the ANOVA assesses the impact of various categorical factor variables simultaneously and accounts for their interactions, too, it is an ideal tool for the analysis, here. This might also be the reason why it is increasingly used in hydrological climate-impact studies as a measure of uncertainty (see e.g. Bosshard et al., 2011b; Finger et al., 2012; Rössler et al., 2012).

With the ANOVA, we analysed the annual cycles of monthly change signals of all target variables, separately. Because the additional glacier scenario (G_{NO}, cf. Sect. 2.2) required additional computationally demanding model simulations, we conducted the ANOVA on a subset of six catchments (see Fig. 2) that cover a certain gradient of glacier and forest extents.

4 Results

4.1 Comparison of water balance components

In catchment number 5 (Fig. 5), the increased temperature in the scenario period leads to significantly increased liquid precipitation in winter (November–February) on the expense of solid precipitation and, therefore, on the expense of snow melt. The decreased snow storage in the scenario period also affects the snow melt in spring (March–May), which is considerably reduced at the end of the century, as is the summer precipitation. The increased temperature furthermore leads to increased evapotranspiration which interestingly is most pronounced in autumn, winter and spring instead of the summer. In July and August, even a slight decrease of actual evapotranspiration (ETA) is observed, whereas potential evapotranspiration slightly increases. This indicates a limiting effect of the reduced precipitation in this season. This assumption is supported by the projected changes in soil moisture storage SSM which is significantly depleted during the summer months of the scenario period. For the variables ETA and SSM, the resulting values for forest change are added to the plot. A slight effect of increasing forest cover can be observed for ETA: the monthly values increase with every scenario of forest change ($\mathrm{FC}_{1,\mathrm{EM}}$ – $\mathrm{FC}_{3,\mathrm{EM}}$), and these monthly changes add up over the year. For SSM, the soil genesis scenario ($\mathrm{FC}_{3,\mathrm{EM}}$) leads to a significantly increased soil moisture storage because the maximum storage capacity is, among others, defined via soil depth (cf. Sect. 2.4). Summer ETA, as a result, is significantly increased under this forest scenario, too. For the target variables R_{tot} and RC, the annual cycle is clearly altered through the climate change signal, and the forest change scenarios follow this predefined annual cycle of the scenario period, in general. They lower the projected runoff and runoff coefficients slightly, though, which can be attributed to the increased ETA and SSM that constitute a withdrawal of water. In summary, there is an effect of the extreme change in forest cover in this catchment, especially with respect to changes in SSM. For the other target variables and compared to the changes that can be attributed to the climate scenario alone, however, these changes are rather small.

Catchment number 9, on the contrary, has an entirely different hydrological regime because of the differing mean altitudes of the catchments. The high-alpine catchment 9 has a snow- and ice-fed regime with a typical peak in summer and a low flow season in winter (see Fig. 6). The increase in temperature causes an increase of liquid precipitation, similar to that of catchment 5, but this effect is identifiable during the whole year, except for July and August. Snow melt occurs during the whole year, too, but it is markedly reduced in the summer of the scenario period. Due to the higher temperatures in the scenario period, the potential evapotranspiration is distinctly elevated. Actual evapotranspiration, however, does not change discernible, neither due to the climate scenario nor due to land cover change. Moreover, evapotranspiration as a water balance component has a minor relevance in this catchment compared to catchment 5. The same is true for the soil moisture storage SSM, which varies marginally over the year and for the scenarios, with the exception of $\mathrm{FC}_{3,\mathrm{EM}}$: the deeper soil causes slightly higher values for soil moisture in this scenario. For the target variables R_{tot} and RC, the four symbols of land cover change are exactly superimposed. Because the forest scenarios are added to the glacier change (cf. Sect. 2.3), this means forest change does not add a distinct signal to the projections and this change can be attributed to the glacier change, alone. The glacier retreat in turn has a pronounced effect on summer runoff through the reduced storage for ice melt. Not accounting for glacier retreat would therefore lead to a substantial overestimation of runoff in the melt season (June–September). This is particularly true if one considers that the glacier retreat might actually be more pronounced. The proportionately small forest extent and forest change in this catchment cannot further alter the projections that are strongly determined through climate and glacier change.

Overall, the analysis of these two very different catchments indicates distinct influences of the forest and glacier change on the water balance components in addition to the changes caused by the climate scenarios. This additional influence of forest and glaciers, however, highly depends on the considered target variable and is either substantial or negligible. To study the effects of the degree of forest and glacier cover in more detail, we compared all catchments for the two target variables ETA and R_{tot} in the next section.

4.2 Comparison of net changes between catchments

As set out in the methods section, increasing net changes with increasing changes in forest cover would indicate a causal relationship between the degree of forest cover and its importance for the change in a target variable. Although there is no consistent pattern, this anticipated relationship can be observed for summer evapotranspiration ($\mathrm{ETA}_{\mathrm{JJA}}$; Fig. 7, left column): in the lower part of the column, the net changes due to the three forest scenarios are equally or even more important than the climate and glacier change. Remarkable are catchments 13 and 14, where the net change of ETA due to the climate scenario is negative in summer, but it is converted into a positive signal under forest change. This effect was already observed in the previous section, where the climate signal alone yielded decreasing summer ETA, whereas it increased under forest change. This contrary signal was then attributed to the strong increase in soil moisture storage under forest change and therefore a higher amount of water available for evapotranspiration. Both catchments nevertheless show clear increases of annual ETA due to the climate scenarios. We know from the previous analysis that ETA increases during the whole year due to climate change except for the summer months, where decreasing precipitation limits actual evapotranspiration. In general, the annual ETA shows a similar but less pronounced pattern of higher net changes with higher forest increase. The climate scenarios' net changes are dominating the change in $\mathrm{ETA}_{\mathrm{a}}$, though. For the summer runoff as well as annual runoff ($R_{\mathrm{tot,\,JJA}}$, $R_{\mathrm{tot,\,a}}$; third and fourth column), the forest net change is negligible, which underlines the findings from the previous analyses.

As opposed to the minor impact of forest change on the runoff, the glacier change has a noticeable effect on summer runoff. The net change of the glacier scenario slightly alters the annual runoff, too, but only for catchments where glacier retreat is substantial (e.g. 8, 9, 7, 12). However, the glacier net change never exceeds that of the climate scenario, with the exception of the summer runoff of catchments 9 and 7. Again, it has to be stated that the glacier effect might be more pronounced for extremer scenarios of glacier retreat.

To summarize, the comparison of all catchments shows a discernible effect of forest change on summer evapotranspiration for catchments with a strong forest increase of at least 35 %. To a smaller degree, this additional effect of forest change can be observed for annual ETA, too. Furthermore, the glacier retreat clearly alters summer runoff in addition to the climate scenario. Overall, however, the climate scenario largely dominates the changes in the assessed target variables.

4.3 ANOVA

The ANOVA results for the sample of six catchments (Fig. 8, rows) and all four target variables (columns) can be studied per target variable from top to bottom or per catchment line by line. From top to bottom, the forest extents decrease, whereas the glacier extents increase. If there was a causal relationship between the land cover and the respective variation in the target variable, the variance fractions of the forest scenarios should decrease from top to bottom, whereas the variance fractions of the glacier scenarios should increase in the same direction. For all panels, the interaction term is rather small which indicates independence of the scenarios with respect to the considered target variables.

The abovementioned pattern, decreasing variance fraction for forest and increasing for glacier change from top to bottom, is particularly obvious for ETA: with decreasing forest area and increasing glacier extent, the variance fraction that is attributed to forest change decreases whereas glacier change gains in relative importance. For each catchment, a clear annual cycle of the variance distribution with respect to ETA is observed: the relative importance of forest change, for example, is largest in late summer, which can be attributed to the minor importance of the climate scenario in this season (cf. Sects. 4.1 and 4.2) rather than to the superior importance of the forest scenario. The increasing variance fraction of glacier change with respect to ETA might seem surprising, but evaporation from snow and ice comprises a non-neglectable amount of evaporation. Moreover, the relative importance of the forest scenarios is small in the highly glaciated catchments, which indirectly raises the variance fraction explained through glacier change. The major variance fraction in the less forested catchments arises from the climate scenarios, though.

The forest change does not add a significant variance to the target variables R_{tot} and RC which confirms our findings from the descriptive analyses. The relative importance of glacier change for these two variables, in contrast, increases with glacier extent, which was also indicated by the previous results. As for ETA, the climate scenarios account for the major part of the variance of R_{tot}, too, and the contribution of glacier change is only distinct in summer during melt season. The catchment with the highest range of glaciation (catchment 8, lowest row in Fig. 8) shows a rather balanced variance fraction of around 30 % during the whole year with a small peak during melt season. The relative importance of glacier change for the runoff coefficient RC cannot be attributed to the altered direct runoff because we subtracted glacier melt from direct runoff to calculate RC (cf. Sect. 3.1). Glaciers and especially the snow on glaciers in PREVAH can store a certain amount of water, however. If the land cover glacier is converted to rock, this short-term storage is reduced and this in turn alters RC.

The interpretation of the soil moisture storage SSM is less straightforward. Not only does this target variable lack a clear pattern of glacier and forest change, but also is the interaction term quite large for two of the six catchments. One pattern that recurs in five of six catchments, though, is the significant peak of the climate scenario's variance fraction in summer and the absence of the same during the rest of the year. This clear signal can be attributed to the pronounced temperature increase in summer and the associated depletion of SSM through evapotranspiration, but also to the decreasing summer precipitation and, therefore, a reduced input into the storage. An interesting feature can be observed comparing catchments 15 and 11: their relative forest cover does not vary substantially, but the composition of deciduous and coniferous forest does (cf. Fig. 2). For catchment 15, which has a higher proportion of coniferous forest, the variance fraction that is attributed to forest change is significantly higher, too. The same applies for these two catchments and their ANOVA results for ETA. Obviously, the different parameterizations of deciduous and coniferous forest effect the variance distribution. The seemingly wrong order of catchments 7, 12 and 9 with respect to the variance distribution for SSM cannot be explained.

The ANOVA results suggest that for catchments with a glaciation of 10 % or more in the control period, glacier retreat contributes a considerable amount (40–90 %) of variation to the hydrological projections in summer. Forest cover is always important as long the evapotranspiration is considered, and the variance fraction is proportional to the change in forested area. The variation of forest cover is negligible, however, with respect to total runoff or the monthly runoff coefficient.

5 Discussion

We demonstrated a correlation between the degree of forested area and the variation in projected evapotranspiration. For extreme scenarios with forest increases on more than 35 % of the catchment area, the net effect on ETA caused by the forest change is larger than that caused by the climate scenarios, alone. Regarding total runoff or the monthly runoff coefficient, no effect of forest change was observed. These results are supported by previous studies (e.g. Fohrer et al., 2005; Hundecha and Bárdossy, 2004; Lahmer et al., 2001) who found only minor impacts of a changed land cover on hydrological systems. Those studies analysed catchments in similar mid-latitude climate regions, but only assessed land cover changes without examining climate change. Glacier retreat, in contrast to forest change, has a discernible influence on annual runoff and significantly alters the summer runoff even for catchments that are moderately glaciated (10 %) during the control period. This is supported by a study from Cuo et al. (2009), who found that altered snow- and glacier-melt regimes dominate the hydrological response of a catchment to climate change. Climate change, in turn, proved to be the most important source of uncertainty in this study, by far, and dominates the changes in the target variables to a large extent. This result is supported by numerous studies, for example Arnell (2011), Jasper et al. (2004) and Kay et al. (2009) to name just a few.

In the following we discuss the validity of our results with respect to the forest scenarios. Our forest change scenarios represent a possible future forest extent under perfectly favourable growing conditions. The scenario tree lines in our study are therefore very likely too high, or, in other words, the increase in forest extent is too extreme. As Henne et al. (2011) argued it is unlikely that trees rapidly grow beyond historic tree lines, i.e. above 2550 m a.s.l., where soils are mostly undeveloped. Our maximum projected scenario tree line is at 2870 m a.s.l., though. Besides, several additional changes of environmental factors are expected to determine tree line, such as rising CO_2 concentrations, increasing deposition of nitrogen (Grace et al., 2002) and soil water availability (Henne et al., 2011). Moreover, we neglected natural hazards like avalanches or mudflows which actually play an important role for the distribution of forests in high alpine regions (Theurillat and Guisan, 2001). These factors could be limiting rather than favourable for tree growth. Some authors (see e.g. Theurillat and Guisan, 2001) would furthermore anticipate an altitudinal shift of whole vegetation belts rather than an increase of the upper tree line, only. A shift, however, would lead to decreasing forest areas in the scenarios. For all those reasons, our forest change scenarios are extreme. Considering that, the runoff changes provoked by the forest scenarios are already at the maximum level but nevertheless insignificant.

One could argue, of course, that another hydrological model that is able to represent flexible feedbacks between the plant and the hydrology, i.e. a flexible growing season, for example, would yield different results regarding the impact of forest change. We showed, however, that the influence of forest change can be mainly attributed to its alteration of evapotranspiration. Evapotranspiration, on the other hand, is of minor importance in this region, which is the reason for the minor importance of forest change.

The successive structure of our scenarios (cf. Sect. 2.3 and Table 1) should be critically discussed at this point, too. It is possible that the order of the scenarios (climate change – additional glacier change – additional forest changes) biases the results because of possible interactions of these different types of scenarios (cf. Sect. 3.2). The ANOVA results, however, showed only very small interactions of the scenarios, almost without exception. Certainly, the glacier and forest scenarios depend on the climate scenarios, but their impact on the water balance components does not depend on each other. Therefore, we question the frequently proposed strong interactions of climate and land cover, at least for the studied climate region. Moreover, the small interaction terms thus indicate that the order in the successive setup does not affect the resulting projections.

6 Conclusions

There is a growing consensus that hydrological climate impact studies should integrate scenarios of associated land cover change to reliably assess future water availability. Bronstert (2004), for example, emphasized the necessity to apply coupled climate and land cover scenarios because of their strong interactions. Hejazi and Moglen (2008) concluded that these interactions "[. . .] can result in more significant hydrologic change than either driver alone".

Therefore, we developed different scenarios of land cover change, i.e. changes in forest cover, that are based on the temperature increase of the climate scenarios used in this study. We applied those forest scenarios to extend an earlier climate impact study (Köplin et al., 2012) that incorporated scenarios of glacier retreat, already. The relative influence of forest change on the hydrological projections was assessed and compared to the relative influence of glacier retreat and climate change. Through an ANOVA, the respective variance fractions of the three types of scenarios were analysed with respect to changes in actual evapotranspiration, soil moisture storage, total runoff and the runoff coefficient.

Our findings suggest that, at any rate, it is obligatory to apply an ensemble of climate scenarios because applying a single scenario could result in severely biased hydrological projections. If the runoff of a catchment with a significant glaciation (>10 % in the control period) is analysed in the context of climate change, the accompanying glacier retreat has to be accounted for, too. If no such retreat scenario is available, the relative contribution of glacier melt to the total runoff has to be quantified, at least, for example by removing all glaciers from the catchment and evaluating the resulting changes in runoff. Thus, one can estimate the maximum error that is introduced to the projections by neglecting glacier retreat. The net impact of climate-induced changes in forest cover highly depends on the target variable considered. As long as total runoff or the runoff coefficient is concerned, the forest cover likely has a very minor impact on the projections and can be neglected. If the evapotranspiration or the soil moisture is of interest, the hydrological projections are altered significantly through forest change.

These findings, however, only apply to hydrological projections under mid-latitude, humid climate conditions and in a mountainous environment where precipitation exceeds evapotranspiration by far. Furthermore, they are only valid for the projections of mean flow conditions as analysed here. The net effect of land cover can be different if low or high flow conditions are concerned. This has to be kept in mind analyzing those variables while not accounting for land cover change.

An interesting extension of this study would be to apply the proposed setup but in another climate region, for example a more continental area or to assess the impact of the climate-induced land cover scenarios on the lower and higher quantiles of the projected hydrographs. This would complete the picture we established here.

Acknowledgements. This study is funded by the Swiss Federal Office for the Environment (FOEN) in the framework of the joint research project “Climate Change in Switzerland – Hydrology” (CCHydro). The authors would like to thank the FOEN, the Swiss Federal Statistical Office (SFSO) and the Federal Office for Meteorology and Climatology (MeteoSwiss) for providing the necessary input data. The delta change scenario data were distributed by the Center for Climate Systems Modeling (C2SM). The data were derived from regional climate simulations of the EU FP6 Integrated Project ENSEMBLES (Contract number 505539) whose support is gratefully acknowledged. The dataset has been prepared by Thomas Bosshard at ETH Zurich, partly funded by swisselectric/Swiss Federal Office of Energy (SFOE) and CCHydro/Swiss Federal Office for the Environment (FOEN). The authors would like to thank Frank Paul and

Andreas Linsbauer, Institute of Geography, University of Zurich (GIUZ), for providing the scenarios of glacier retreat.

References

Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S., and Valentine, V. B.: Rapid Wastage of Alaska Glaciers and their contribution to rising sea level, Science, 297, 382–386, doi:10.1126/science.1072497, 2002.

Arnell, N. W.: Uncertainty in the relationship between climate forcing and hydrological response in UK catchments, Hydrol. Earth Syst. Sci., 15, 897–912, doi:10.5194/hess-15-897-2011, 2011.

Bosshard, T., Kotlarski, S., Ewen, T., and Schär, C.: Spectral representation of the annual cycle in the climate change signal, Hydrol. Earth Syst. Sci., 15, 2777–2788, doi:10.5194/hess-15-2777-2011, 2011a.

Bosshard, T., Carambia, M., Görgen, K., Kotlarski, S., Krahe, P., Zappa, M., and Schär, C.: Quantifying uncertainty sources in hydrological climate impact scenarios, Water Resour. Res., submitted, 2011b.

Bronstert, A.: Rainfall-runoff modelling for assessing impacts of climate and land-use change, Hydrol. Process., 18, 567–570, doi:10.1002/hyp.5500, 2004.

CH2011: Swiss Climate Change Scenarios CH2011, C2SM, MeteoSwiss, ETH, NCCR Climate, and OcCC, Zürich, Switzerland, 88 pp., 2011.

Cuo, L., Lettenmaier, D. P., Alberti, M., and Richey, J. E.: Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin, Hydrol. Process., 23, 907–933, doi:10.1002/hyp.7228, 2009.

Doncaster, C. P. and Davey, A. J. H.: Analysis of Variance and Covariance, Cambridge University Press, Cambridge, UK, 2007.

Dullinger, S., Dirnböck, T., and Grabherr, G.: Modelling climate change-driven treeline shifts: relative effects of temperature increase, dispersal and invasibility, J. Ecol., 92, 241–252, 2004.

Dunn, S. and Mackay, R.: Spatial variation in evapotranspiration and the influence of land use on catchment hydrology, J. Hydrol., 171, 49–73, 1995.

Dyurgerov, M. B. and Meier, M. F.: Mass balance of mountain and subpolar glaciers: a new global assessment for 1961–1990, Arctic Alpine Res., 29, 379–391, 1997.

Egli, M., Mirabella, A., and Sartori, G.: The role of climate and vegetation in weathering and clay mineral formation in late Quaternary soils of the Swiss and Italian Alps, Geomorphology, 102, 307–324, doi:10.1016/j.geomorph.2008.04.001, 2008.

Elsner, M. M., Cuo, L., Voisin, N., Deems, J. S., Hamlet, A. F., Vano, J. A., Mickelson, K. E. B., Lee, S.-Y., and Lettenmaier, D. P.: Implications of 21st century climate change for the hydrology of Washington State, Climatic Change, 102, 225–260, doi:10.1007/s10584-010-9855-0, 2010.

Finger, D. C., Heinrich, G., Gobiet, A., and Bauder, A.: Projections of future water resources and their uncertainty in a glacierized catchment in the Swiss Alps and the subsequent effects on hydropower production during the 21st century, Water Resour. Res., 48, W02521, doi:10.1029/2011WR010733, 2012.

Fohrer, N., Haverkamp, S., and Frede, H.-G.: Assessment of the effects of land use patterns on hydrologic landscape functions: development of sustainable land use concepts for low mountain range areas, Hydrol. Process., 19, 659–672, doi:10.1002/hyp.5623, 2005.

Gehrig-Fasel, J., Guisan, A., and Zimmermann, N. E.: Tree line shifts in the Swiss Alps: climate change or land abandonment?, J. Veg. Sci., 18, 571–582, doi:10.1111/j.1654-1103.2007.tb02571.x, 2007.

Grace, J., Berninger, F., and Bagy, L.: Impacts of climate change on the tree line, Ann. Bot.-London, 90, 537–544, doi:10.1093/aob/mcf222, 2002.

Gunawardhana, L. N. and Kazama, S.: A water availability and low-flow analysis of the Tagliamento River discharge in Italy under changing climate conditions, Hydrol. Earth Syst. Sci. Discuss., 9, 139–173, doi:10.5194/hessd-9-139-2012, 2012.

Harsch, M. A., Hulme, P. E., McGlone, M. S., and Duncan, R. P.: Are treelines advancing? A global meta-analysis of treeline response to climate warming, Ecol. Lett., 12, 1040–1049, doi:10.1111/j.1461-0248.2009.01355.x, 2009.

Hejazi, M. I. and Moglen, G. E.: The effect of climate and land use change on flow duration in the Maryland Piedmont region, Hydrol. Process., 22, 4710–4722, doi:10.1002/hyp.7080, 2008.

Henne, P. D., Elkin, C. M., Reineking, B., Bugmann, H., and Tinner, W.: Did soil development limit spruce (*Picea abies*) expansion in the Central Alps during the Holocene? Testing a palaeobotanical hypothesis with a dynamic landscape model, J. Biogeogr., 38, 933–949, doi:10.1111/j.1365-2699.2010.02460.x, 2011.

Hundecha, Y. and Bárdossy, A.: Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model, J. Hydrol., 292, 281–295, doi:10.1016/j.jhydrol.2004.01.002, 2004.

Jasper, K., Calanca, P., Gyalistras, D., and Fuhrer, J.: Differential impacts of climate change on the hydrology of two alpine river basins, Climatic Change, 26, 113–129, 2004.

Kay, A. L., Davies, H. N., Bell, V. A., and Jones, R. G.: Comparison of uncertainty sources for climate change impacts: flood frequency in England, Climatic Change, 92, 41–63, doi:10.1007/s10584-008-9471-4, 2009.

Klöcking, B. and Haberlandt, U.: Impact of land use changes on water dynamics – a case study in temperate meso and macroscale river basins, Phys. Chem. Earth, 27, 619–629, 2002.

Köplin, N., Viviroli, D., Schädler, B., and Weingartner, R.: How does climate change affect mesoscale catchments in Switzerland? – a framework for a comprehensive assessment, Adv. Geosci., 27, 111–119, doi:10.5194/adgeo-27-111-2010, 2010.

Köplin, N., Schädler, B., Viviroli, D., and Weingartner, R.: Relating climate change signals and physiographic catchment properties to clustered hydrological response types, Hydrol. Earth Syst. Sci. Discuss., 9, 3165–3202, doi:10.5194/hessd-9-3165-2012, 2012.

Körner, C.: A re-assessment of high elevation treeline position and their explanation, Oecologia, 115, 445–459, 1998.

Körner, C.: The use of “altitude” in ecological research, Trends Ecol. Evol., 22, 569–574, doi:10.1016/j.tree.2007.09.006, 2007.

Laghari, A. N., Vanham, D., and Rauch, W.: To what extent does climate change result in a shift in Alpine hydrology? A case study in the Austrian Alps, Hydrolog. Sci. J., 57, 103–117, doi:10.1080/02626667.2011.637040, 2012.

Lahmer, W., Pfützner, B., and Becker, A.: Assessment of land use and climate change impacts on the mesoscale, Phys. Chem. Earth, 26, 565–575, 2001.

Leuzinger, S.: Stand der Kenntnisse zu den Auswirkungen des globalen Wandels auf Schweizer Wälder, Bericht im Auftrag des Bundesamtes für Umwelt BAFU, Synthesis Report, available online: http://www.bafu.admin.ch/wald/01198/01209/index.html?lang=de, last access: 26 April 2012, Bern, Switzerland, 56 pp., 2009.

Linsbauer, A., Paul, F., and Haeberli, W.: Comparing different methods to model scenarios of future glacier change for the entire Swiss Alps, Geophys. Res. Abstr., 14, EGU2012-12916, 2012.

Lüscher, C.: 10 Jahre Sachplan Fruchtfolgeflächen (FFF), Erfahrungen der Kantone, Erwartungen an den Bund, Legislative Text, Federal Office for Spatial Development ARE, Bern, Switzerland, 64 pp., 2004.

Mavris, C., Egli, M., Plötze, M., Blum, J. D., Mirabella, A., Giaccai, D., and Haeberli, W.: Initial stages of weathering and soil formation in the Morteratsch proglacial area (Upper Engadine, Switzerland), Geoderma, 155, 359–371, doi:10.1016/j.geoderma.2009.12.019, 2010.

MBB: Glacier Mass Balance Bulletin No. 8, in: World Glacier Monitoring Service on Behalf of IUGG (CCS)/UNEP/UNESCO/WMO, edited by: Haeberli, W., Noetzli, J., Zemp, M., Baumann, S., Frauenfelder, R., and Hoelzle, M., WGMS, Zurich, 100 pp., 2005.

Monteith, J. L.: Vegetation and the Atmosphere, Vol. 1: Principles, Academic Press, London, UK, 298 pp., 1975.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., and Haeberli, W.: Rapid disintegration of Alpine glaciers observed with satellite data, Geophys. Res. Lett., 31, L21402, doi:10.1029/2004GL020816, 2004.

Paul, F., Maisch, M., Rothenbühler, C., Hoelzle, M., and Haeberli, W.: Calculation and visualisation of future glacier extent in the Swiss Alps by means of hypsographic modelling, Global Planet. Change, 55, 343–357, doi:10.1016/j.gloplacha.2006.08.003, 2007.

Paul, F., Linsbauer, A., and Haeberli, W.: Grossräumige Modellierung von Schwundszenarien für alle Schweizer Gletscher, Klimaänderung und Wasserkraft, Sektorielle Studie Wallis, Modul B Gletscherszenarien, Final Report, University of Zurich, Zurich, 29 pp., 2011.

R Development Core Team: R: a language and environment for statistical computing, R version 2.14.1, R Foundation for Statistical Computing, Vienna, Austria, available online: http://www.R-project.org/ (last access: 26 April 2012) 2011.

Rössler, O., Diekkrüger, B., and Löffler, J.: Potential drought stress in a Swiss mountain catchment – ensemble forecasting of high mountain soil moisture reveals a drastic decrease, despite major uncertainties, Water Resour. Res., 48, W04521, doi:10.1029/2011WR011188, 2012.

Schumacher, S. and Bugmann, H.: The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps, Global Change Biol., 12, 1435–1450, doi:10.1111/j.1365-2486.2006.01188.x, 2006.

Theurillat, J.-P. and Guisan, A.: Potential impacts of climate change on vegetation in the European Alps: a review, Climatic Change, 50, 77–109, 2001.

Tinner, W. and Kaltenrieder, P.: Rapid responses of high-mountain vegetation to early Holocene environmental changes in the Swiss Alps, J. Ecol., 93, 936–947, doi:10.1111/j.1365-2745.2005.01023.x, 2005.

Tinner, W. and Lotter, A. F.: Central European vegetation response to abrupt climate change at 8.2 ka, Geology, 29, 551–554, doi:10.1130/0091-7613(2001)029<0551:CEVRTA>2.0.CO;2, 2001.

Tinner, W. and Theurillat, J.-P.: Uppermost limit, extent, and fluctuations of the timberline and treeline ecocline in the Swiss Central Alps during the past 11,500 years, Arct. Antarct. Alp. Res., 35, 158–169, 2003.

van der Linden, P. and Mitchell, J.: ENSEMBLES: Climate Change and its Impacts: Summary of Research and Results from the ENSEMBLES Project, FitzRoy Road, Exeter, UK, 160 pp., 2009.

Viviroli, D., Gurtz, J., and Zappa, M.: The Hydrological Modelling System PREVAH, Part II – Physical Model Description, Geographica Bernensia P40, Institute of Geography, University of Bern, Switzerland, 87 pp., 2007.

Viviroli, D., Zappa, M., Gurtz, J., and Weingartner, R.: An introduction to the hydrological modelling system PREVAH and its pre- and post-processing-tools, Environ. Modell. Softw., 24, 1209–1222, doi:10.1016/j.envsoft.2009.04.001, 2009a.

Viviroli, D., Zappa, M., Schwanbeck, J., Gurtz, J., and Weingartner, R.: Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part I: modelling framework and calibration results, J. Hydrol., 377, 191–207, doi:10.1016/j.jhydrol.2009.08.023, 2009b.

Viviroli, D., Mittelbach, H., Gurtz, J., and Weingartner, R.: Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: parameter regionalisation and flood estimation results, J. Hydrol., 377, 208–225, doi:10.1016/j.jhydrol.2009.08.022, 2009c.

Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor, M. I., López-Moreno, J. I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M., and Woods, R.: Climate change and mountain water resources: overview and recommendations for research, management and policy, Hydrol. Earth Syst. Sci., 15, 471–504, doi:10.5194/hess-15-471-2011, 2011.

WaG: Bundesgesetz über den Wald, 921.0, Legislative Text, Bundesversammlung der Schweizerischen Eidgenossenschaft, 18 pp., available online: http://www.admin.ch/ch/d/sr/9/921.0.de.pdf (last access: 26 April 2012), 2008.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Nomenclature of scenario combinations for the descriptive analysis (cf. also Fig. 4, upper half). CTRL always corresponds to the control period from 1984–2005, each scenario is valid for the scenario period from 2074–2095. Note the successive structure of the scenario combinations: per scenario just one member in the chain is changed.

Name	Climate change	Glacier change	Forest change	Description
CTRL	C_{CTRL}	G_{CTRL}	F_{CTRL}	Baseline scenario with control period climate, glacier and forest extent.
CC_{EM}	CC_1–CC_{10}	G_{CTRL}	F_{CTRL}	Climate change only. Note that for the descriptive analyses the ten simulations (due to ten CCs, i.e. RCMs) are averaged to the ensemble mean (EM).
GC_{EM}	CC_1–CC_{10}	GC	F_{CTRL}	Additional glacier retreat. Again, the ten resulting simulations (due to 10 CCs) are averaged to the EM.
$FC_{1,EM}$	CC_1–CC_{10}	GC	FC_1	Additional *tree line increase*, averaged to EM.
$FC_{2,EM}$	CC_1–CC_{10}	GC	FC_2	Additional *land abandonment* (i.e. in addition to tree line increase), averaged to EM.
$FC_{3,EM}$	CC_1–CC_{10}	GC	FC_3	Additional *soil genesis*, averaged to EM. Soil depth increases on all former and new forest areas.

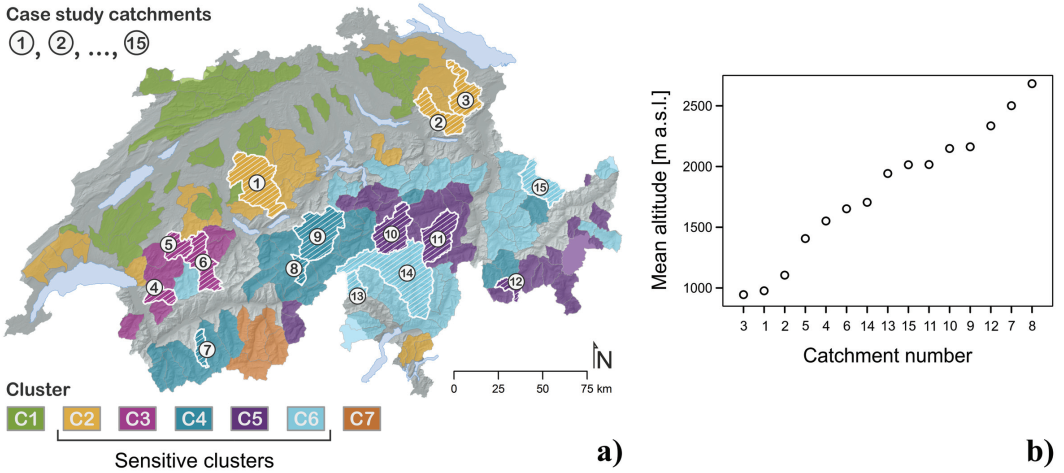

Fig. 1. Spatial **(a)** and altitudinal **(b)** distribution of the case study catchments. The climate-change sensitive clusters according to Köplin et al. (2012) are displayed to demonstrate that the representation of clusters through case study catchments is balanced (three catchments per sensitive cluster).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

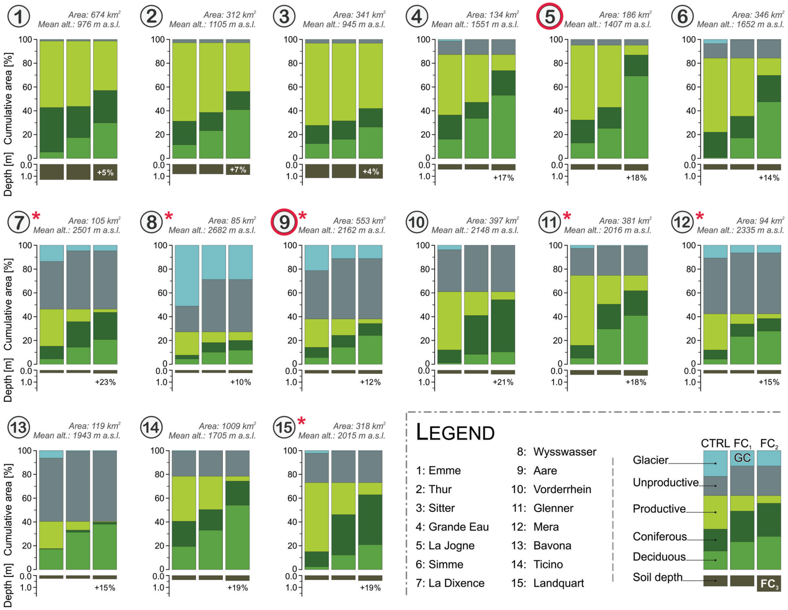

Fig. 2. Relative proportion of glacier, unproductive, productive, and coniferous and deciduous forest area per catchment, as well as proportional increase of the catchments' mean soil depth. Unproductive area subsumes water bodies, urban area and rock; productive area comprises all vegetational land covers except for forest. The left column of each catchment-panel visualizes the control period's proportional land covers (CTRL), the middle column those for both glacier retreat (GC) and tree line increase (FC_1), the right column depicts additional land abandonment (FC_2) and soil genesis (FC_3), the latter shown on the lower right bar. The names of the catchments' main channels are given in the legend, for the respective locations please see Fig. 1. The catchments marked with a red circle are analysed for changes of the water balance components (Sect. 4.1); the catchments marked with a red asterisk are used in the ANOVA (Sect. 4.3).

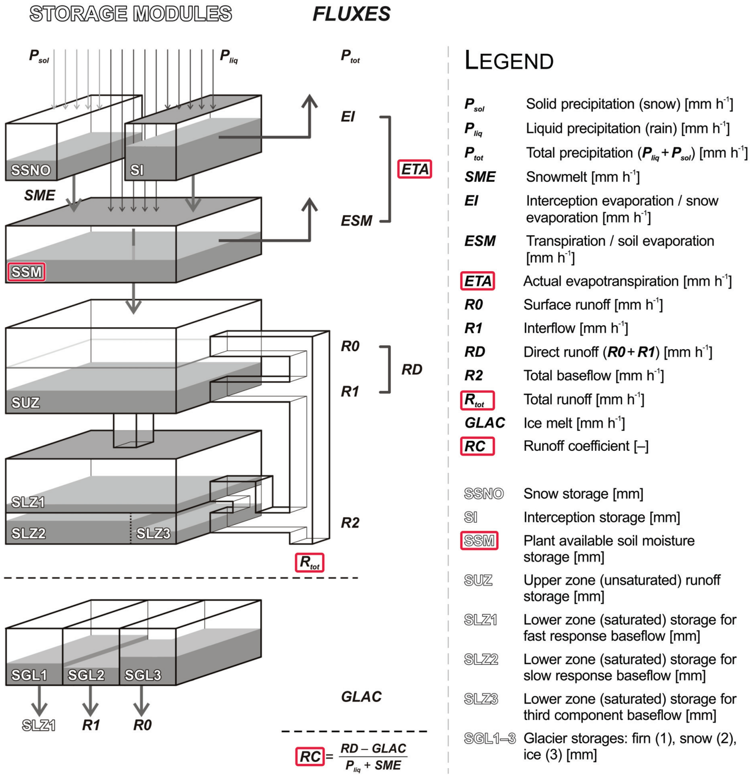

Fig. 3. Schematic of the modular model structure of PREVAH (modified after Viviroli et al., 2009a). The target variables analysed in this study are marked with red rectangles. Note that the model is driven by hourly input and therefore provides output in hourly resolution. For the analyses in this study the data are aggregated (cf. Sect. 3.1).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

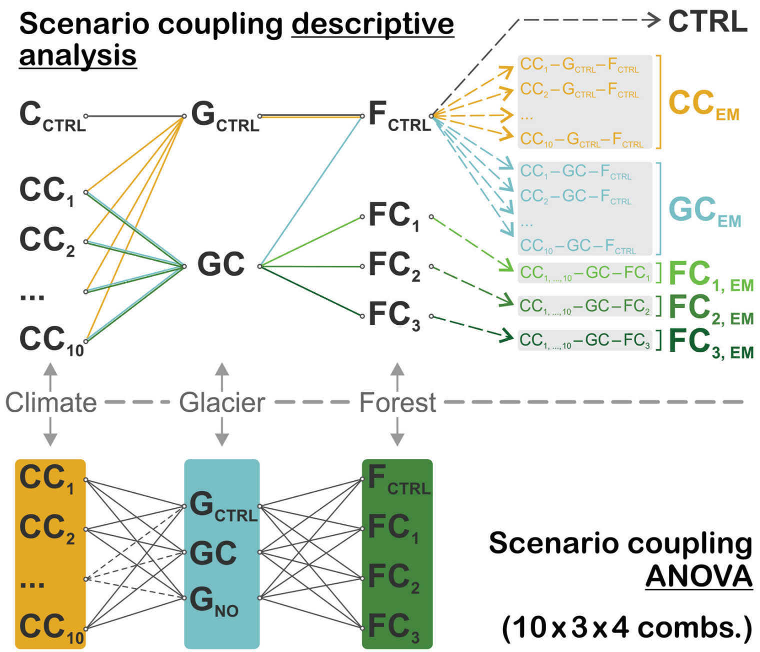

Fig. 4. Schematic of scenario coupling used in the descriptive analyses (upper half) and in the ANOVA (lower half). For the descriptive analyses, the ten climate model realisations for each combination of glacier and forest scenario are averaged computing the ensemble mean (right side, upper half) which results in six simulations to analyse (CTRL, CC_{EM}, GC_{EM}, $FC_{1,EM}$, $FC_{2,EM}$, $FC_{3,EM}$). Please note that the green lines between CC and GC symbolize the combination for all three forest changes (FC_1 – FC_3). For the ANOVA, every possible combination of scenarios is used, resulting in 120 (10 CCs × 3 GCs × 4 FCs) simulations to analyse. The subscript CTRL indicates that the respective conditions during the control period (1984–2005) are considered.

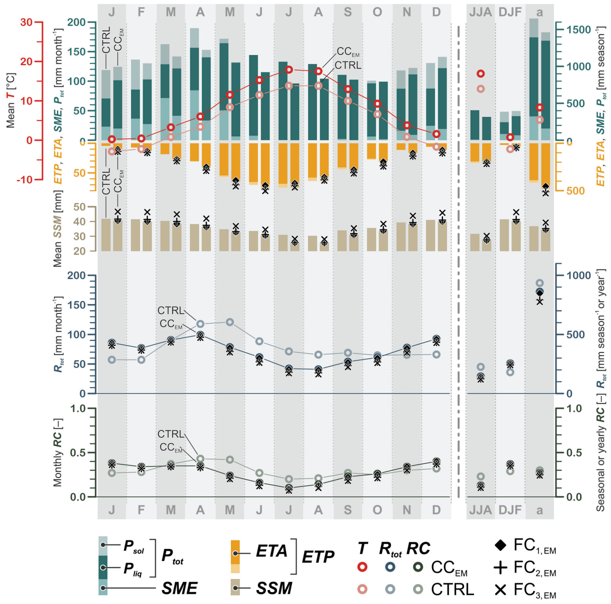

Fig. 5. Comparison of water balance components for the non-glaciated catchment 5 (for catchment characterization see Fig. 2). For every panel, the annual cycle of monthly values is displayed as well as the summer (JJA), winter (DJF) and annual (a) values (separated from the monthly cycle by a dash-dot line). In the top panel, stacked bars show the input into the simulated water balance (SME, P_{liq} and P_{sol}) for the control (CTRL, left bar per month, season, year) and the scenario climate (SCE, respective right bar per month, season, year). Superimposed, one can find the control (light red) and scenario (red) mean temperatures per time step. Below the input into the water balance the corresponding actual and potential evapotranspiration (ETA, ETP) is displayed for CTRL and CC_{EM} (left and right bar per time step). The resulting ETA values for the forest change scenarios ($\text{FC}_{1,\text{EM}} - \text{FC}_{3,\text{EM}}$) are added to the panel. The same applies to the other target variables soil moisture storage (SSM, second-upper panel), total runoff (R_{tot}, second-lower panel) and runoff coefficient (RC, lower panel).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

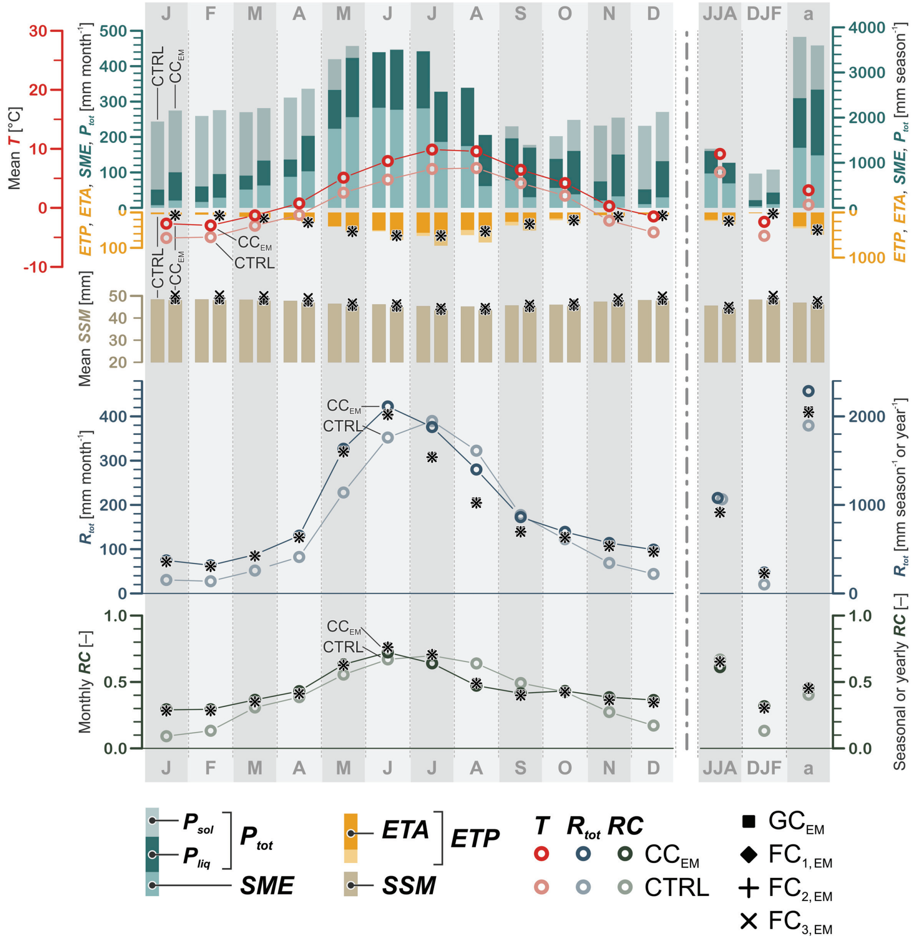

Fig. 6. Same as Fig. 5 but for catchment 9. Please note that this catchment is glaciated and has therefore an additional symbol per target variable (GC_{EM}, black square).

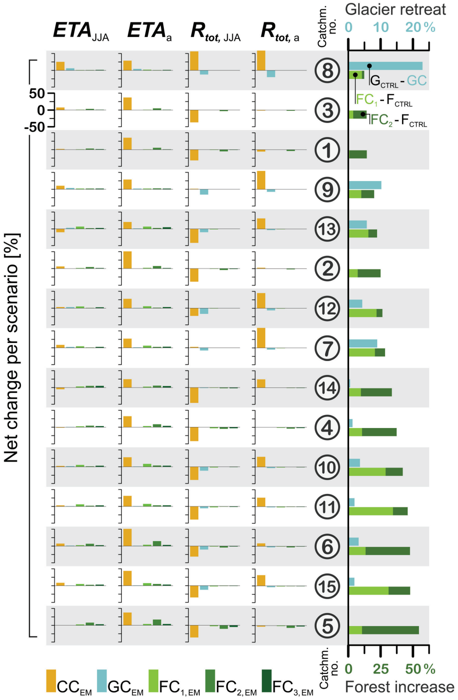

Fig. 7. Comparison of relative net changes per scenario (CC_EM, GC_EM, $\text{FC}_{1,\text{EM}}$ – $\text{FC}_{3,\text{EM}}$) and catchment. The first column (left) displays results for summer evapotranspiration (ETA_JJA), the second those for annual evapotranspiration (ETA_a), the third column depicts summer total runoff ($R_{\text{tot, JJA}}$), the fourth (right) annual total runoff ($R_{\text{tot, a}}$). The scale is the same for each panel, ranging from −50–50 % (indicated for ETA_JJA, catchment 3). The catchments are sorted from top to bottom according to increasing forest change between CTRL and FC_1 (light green bars) as well as FC_2 (dark green bars), see right panel of the figure. The relative glacier retreat in per cent catchment area is added to the right panel, too (light blue bars).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀|
|▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

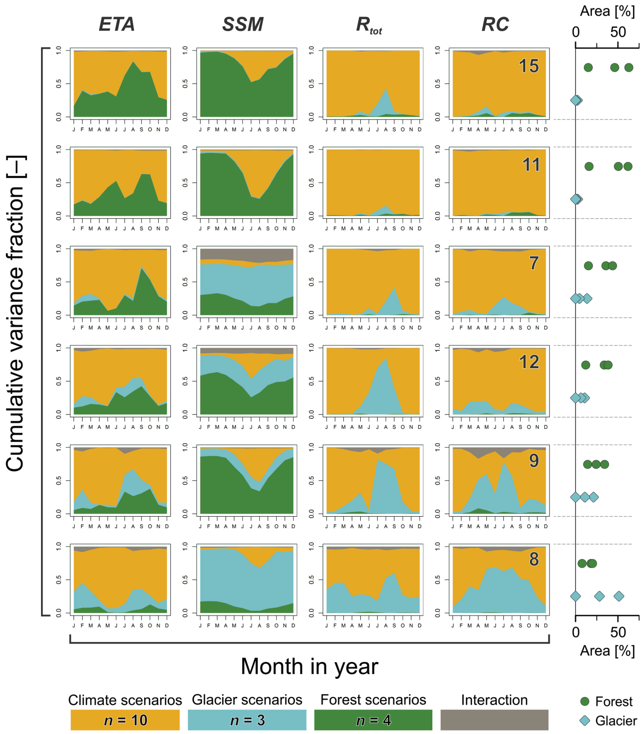

Fig. 8. ANOVA for the annual cycles of monthly change values per target variable ETA, SSM, R_{tot} and RC. Each column shows the ANOVA results for one target variable and each row of four panels represents the results per catchment. The catchment number is indicated in the upper right corner of the respective right panel. The catchments are sorted from top to bottom according to increasing glaciation as well as decreasing forest cover. The respective forest extents (from forest cover during control to forest cover in the scenarios) and glacier extents (from no glaciation to glaciation during control period) in per cent catchment area is given for every catchment (rightmost panel).