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Modelling the impact of land use changes on peak discharge in the Urseren Valley, Central Swiss Alps

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ABSTRACT

In alpine regions, global climate change will likely alter rain and snowfall patterns and increase the frequency of extreme meteorological events such as floods. These events, combined with land use changes, may pose an immediate hazard to the life and properties of downslope inhabitants and to water resource structures downstream. The aim of this study is to evaluate the impact of land use changes (e.g., areas covered by grassland, green alder, and dwarf shrubs) on peak discharge for different return periods and different scenarios (past, current, and future) in the Urseren Valley in the Central Swiss Alps. In addition to the entire Urseren Valley, we also considered four microcatchments of various sizes and land covers within the valley. We used the ZEMOKOST model, which considers the impact of a wide range of vegetation and channel characteristics on surface hydrology. Results at the catchment scale show an increase in peak discharge for all return periods from 2 to 300 years. In two microcatchments, simulation results indicate that expected changes in the vegetation cover will drastically decrease peak discharge in the future for all return periods, by up to 41% (for a 100-year return period). At the catchment scale, although the surface area covered by green alder increases by 38% and the area covered by dwarf shrubs decreases by 26% from the current to the future scenario, the peak discharge increases for all return periods except for the 2- and 5-year return periods. It appears that the drastic decrease of grassland area from the current to future (− 52%) scenario is responsible for the slight increase in peak discharge (about 4% for a 100-year period). In addition, surface area covered by dwarf shrub not only decreases from past to current scenario, but also clusters into more continuous zones damping lateral flow and resulting in such moderate increase. The consistency between observed and simulated peak discharge for a 100-year return period attests the reliability of our modelling outcomes. Careful land use planning taking into account the results of our analysis can help to better manage land and water resources in the region.

1. Introduction

Mountainous headwater catchments play an important role for water supply (e.g., drinking water production) to the adjacent lowlands (e.g., Finger et al., 2013; Rice and Hornberger, 1998; Viviroli et al., 2011). In alpine catchments, meteorological, glaciological, periglacial, and hydrological phenomena display very intimate and complex interactions that affect process variability at both small and large spatial and temporal scales (Verbunt et al., 2003). Changes in the global climate will likely alter rain and snowfall patterns and cause an increase in the frequency of extreme meteorological events, such as floods (e.g., Beniston et al., 2011; Birsan et al., 2005; Gobiet et al., 2014). The estimation of extreme floods is crucial to sustainable water resource system management since extreme events may pose an immediate hazard to the life and properties of downstream inhabitants and water resource structures.

The expansion of shrubs is a phenomenon occurring worldwide (Sala and Maestre, 2014; Tape et al., 2006). Shrubs of different types are for example expanding in arctic tundra environments due to climatic changes (Tape et al., 2006). The forested area in Switzerland increased by 1304 km^2, including 174 km^2 shrub woodland, between the observations in 1983/85 and 2009/11 (WSL, 2012, cited in Caviezel et al., 2017). Almost all of the newly forested area (97.5%) lies within the Swiss Alpine region (Brändli, 2010). In the Swiss Alps, green alder (*Alnus viridis (Chaix) DC*), an early successional species, is a major component of the increasing subalpine shrub woodland: 70% of the

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shrub areas consist of green alder, 20% of dwarf mountain pine (*Pinus mugo* subsp. *prostrata*), while the remaining 10% is dominated by hazel (*Corylus avellana*) and various willow species (*Salix sp.*) (Brändli, 2010).

In the Urseren Valley in the Central Swiss Alps, the influence of shrub encroachment on the total water balance (Alaoui et al., 2014) as well as mean water transit times and geochemistry at baseflow conditions (i.e. in the long term) was shown to be of minor importance (Mueller et al., 2013). However, shrub encroachment might affect the generation of surface runoff, since the vegetation cover strongly interacts with runoff components during rainfall events (Bachmair and Weiler, 2011). In the case of the Urseren Valley, it has led to higher soil hydraulic conductivities (Alaoui et al., 2014) and a higher infiltration capacity of the soil (Caviezel et al., 2014), which in turn might decrease surface runoff generation. The dominant land use type in the Alps is grassland, and its degradation is mostly due to the coupled processes of soil erosion and excess surface runoff. Accordingly, information on the magnitude of peak discharge in response to extreme events can help to better manage soil and water resources in the region. The question is: How will a certain specific change in land use affect the hydrology at the catchment scale?

To assess the impact of land use and land cover changes on environmental processes, including surface hydrology, different scenarios have to be implemented in global and regional models of climate change and land-ecological systems. Therefore, modelling studies contributing to a better understanding of interactions in the human–land system (Hovius, 1998) and of the hydrological dynamics in catchments (Huismann et al., 2009) are still at the focus of attention (Rogger et al., 2017).

While the potential effects of changes in land use and climate on freshwater resources and runoff behavior in Urseren Valley catchments were assessed from a long-term perspective (e.g., Alaoui et al., 2014), the literature offers no information about their short-term impacts on surface runoff generation so far. This study aimed to fill this gap by evaluating the impact of land use change, expressed as the expansion of green alder, on peak discharge for different return periods in the Urseren Valley, Switzerland.

2. Material and methods

2.1. Location and geology of the study area

The catchment of the Urseren Valley is located in the Central Swiss Alps (Fig. 1) and covers an area of 191 km^2. The Urseren Valley is a glacially influenced U-shaped valley with steep, rugged slopes and a flat valley bottom, running from west to east. In terms of elevation, the catchment extends from 1400 m a.s.l. at the valley bottom up to almost 3200 m a.s.l. at the highest peaks in the north-west. The southern mountain ridge, the Saint-Gotthard Massif, consists mainly of paragneisses and granites; the northern crests are made up of granites, granitoids, gneisses, and migmatites belonging to the Aar system (Labhart, 1977). The Aar and Saint-Gotthard massifs are separated by the so-called Urseren Zone, which is formed by vertically dipping Permocarbonic and Mesozoic layers along a geological fault line. The latter corresponds to the valley axis.

2.2. Hydrology of the study area

The hydrometeorological conditions in the Urseren Valley are characterized by an alpine climate, with precipitation distributed rather evenly throughout the year. 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 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 with a runoff coefficient of 0.81 (for Switzerland, the mean annual discharge was 991 mm with a runoff coefficient of 0.68 for the same period).

The region's current hydrological regime can be classified as nivo-glacial. Based on average values over the past 100 years, the catchment is snow-covered from 21 November to 30 April, and snowmelt occurs mainly in May and June. The climatic context is complex due to the valley's geographical situation: being open both in the east and west, it is influenced by the southerly foehn wind that brings large amounts of precipitation in summer.

2.3. Soils in the study area

The most widespread soil types in the Urseren Valley are Podsols and Cambisols (Meusburger and Alewell, 2008). Leptosols are common at higher elevations and on steep slopes. Clayey gleyic Cambisols, Histosols, Fluvisols and Gleysols have developed on the valley bottom, on the lower slopes, and on other fairly flat areas. Soil organic carbon contents of up to 34 wt% were observed in places where riparian wetland soils and peat bogs had developed (Schroeder, 2012). Soil pH is between 4 and 5 throughout the Urseren Valley (Lagger, 2012; Mueller et al., 2013).

The texture of most soils in the Urseren Valley can be described as silt loam or sandy loam. Soils are generally high in silt (41 ± 9 wt%) and sand (50 ± 13 wt%) content; the clay fraction plays a minor role (9 ± 5 wt%) (n = 106) (Gysel, 2010; Mueller et al., 2014). Stone fragments of up to 0.3 m length have been observed within several soil profiles in the Urseren Valley (Mueller et al., 2014). Skeleton content in the soils ranged from 1 to 45% dry weight (dw) (n = 100) on a north-facing slope and from 3 to 65% dw (n = 28) on a south-facing slope (Mueller et al., 2014, Konz et al., unpublished data).

2.4. Assessment of land cover and vegetation types

Catchment scale: Vegetation has been altered strongly by centuries of anthropogenic activities such as pasturing (Kägi, 1973). In recent decades, shrubs have been encroaching into formerly open habitats after grazing activities were reduced (Tasser et al., 2005; Wettstein, 1999). Invasion by shrubs, mainly *Alnus viridis (Chaix) DC* (green alder) along with *Sorbus aucuparia* (mountain-ash) and *Salix appendiculata* (large-leaved willow), has been observed on both the north-facing and the south-facing slopes of the Urseren Valley (Kägi, 1973; Küttel, 1990; Wettstein, 1999). The shrub cover in the valley increased by 32% between 1965 and 1994 (Wettstein, 1999) and by 24% between 1994 and 2004 (van den Bergh et al., unpublished data) and is located predominantly on the north-facing slopes. On the south-facing slopes, the vegetation consists of dwarf-shrub communities and diverse herbs and grass species, and has undergone little change (Kägi, 1973; Küttel, 1990).

Green alder grows in humid and nutritious alkaline soils (Oberdorfer, 1994; Ellenberg, 1996) on calcareous, silty or clay material with high soil moisture. The upper limit of the abiotic environment of green alder is situated around 2000 m a.s.l, while its lower limit is below the base limit of the Urseren Valley. In alpine and sub-alpine regions, green alder compete with spruce, larches and other shrubs and stabilizes slopes which are prone to soil erosion and landslides (Aeschimann et al., 2004). Other anthropogenic factors have strongly contributed to the changes in land use in the region of the Urseren Valley. Expansion of agricultural land on the expense of the coniferous forest has favorited the expansion of green alder (Wettstein, 1999). Dwarf shrubs are also the dominant land cover in the region and contain principally rhododendron that exist up to 2000 m a.s.l. (Aeschimann et al., 2004). Their limiting factors, however, are the disturbance by grazing animals and its extensive use as burning material (Kägi, 1973). At elevations above 2000 m a.s.l., blueberries are the most important vegetation constituting the dwarf shrubs. Extensive livestock farming favors the expansion of dwarf shrubs in Central Alps. Coniferous forest was abundant until the middle Ages and disappears