Long-term changes in runoff generation mechanisms for two proglacial areas in the Swiss Alps II: subsurface flow

Maier, Fabian; van Meerveld, H J; Weiler, Markus

Abstract: Lateral subsurface stormflow (SSF) is the most important runoff generation mechanism for most hillslopes in temperate climates. It is influenced by pedological, biological, and topographic factors that change during landscape evolution, but so far little is known about how SSF changes over long-time scales. Therefore, we conducted sprinkling experiments on a silicate and carbonate moraine chronosequence in the Swiss Alps. Each chronosequence consisted of four moraines ranging between a couple of decades and 13,500 years in age. On each moraine, we installed three plots and measured shallow SSF in a trench. We added tracers (2H and NaCl) to the sprinkling water to identify mixing and flow pathways in the subsurface. The coarse and drainable sediments on the young moraines provoked more frequent and larger SSF responses than for the old moraines. There was no SSF during the sprinkling experiments on the older moraines at the calcareous study area, but SSF occurred during larger natural rainfall events. The pre-event water fractions in SSF were higher for the old moraines than the young moraines due to the increase in silt, clay, and soil organic matter content, and subsequent increase in the amount of water stored in the soil. The results of this study suggest that soil and vegetation development affect SSF characteristics and help—together with the results for overland flow (companion paper; Maier van Meerveld, 2021, https://doi.org/10.1029/2021WR030221)—to improve hydrological models and our understanding of the changes in near-surface runoff generation processes during the first millennia of landscape evolution in Alpine areas.

DOI: https://doi.org/10.1029/2021wr030223
Long-Term Changes in Runoff Generation Mechanisms for Two Proglacial Areas in the Swiss Alps II: Subsurface Flow

Fabian Maier1, Ilja van Meerveld1, and Markus Weiler2

1Department of Geography, University of Zurich, Zurich, Switzerland, 2Chair of Hydrology, University of Freiburg, Freiburg, Germany

Abstract Lateral subsurface stormflow (SSF) is the most important runoff generation mechanism for most hillslopes in temperate climates. It is influenced by pedological, biological, and topographic factors that change during landscape evolution, but so far little is known about how SSF changes over long-time scales. Therefore, we conducted sprinkling experiments on a silicate and carbonate moraine chronosequence in the Swiss Alps. Each chronosequence consisted of four moraines ranging between a couple of decades and ∼13,500 years in age. On each moraine, we installed three plots and measured shallow SSF in a trench. We added tracers ($\delta$H and NaCl) to the sprinkling water to identify mixing and flow pathways in the subsurface. The coarse and drainable sediments on the young moraines provoked more frequent and larger SSF responses than for the old moraines. There was no SSF during the sprinkling experiments on the older moraines at the calcareous study area, but SSF occurred during larger natural rainfall events. The pre-event water fractions in SSF were higher for the old moraines than the young moraines due to the increase in silt, clay, and soil organic matter content, and subsequent increase in the amount of water stored in the soil. The results of this study suggest that soil and vegetation development affect SSF characteristics and help—together with the results for overland flow (companion paper; Maier & van Meerveld, 2021, https://doi.org/10.1029/2021WR030221)—to improve hydrological models and our understanding of the changes in near-surface runoff generation processes during the first millennia of landscape evolution in Alpine areas.

1. Introduction

Rainfall either infiltrates into the soil or is stored in puddles on the surface and runs off as overland flow (OF). OF pathways on the surface are traceable but the partitioning of the water that infiltrates into soil water storage ($\Delta$SW), lateral subsurface flow (SSF), and deeper percolation (DP) is more difficult to observe. This partitioning is affected by many soil, vegetation, and topographic factors that change during landscape evolution. However, the effects of these changes in near-surface conditions on the partitioning of rainfall and SSF generation are still poorly documented. Better knowledge of this partitioning and lateral SSF is important because it affects the runoff response at the hillslope scale (Bachmair & Weiler, 2011) and catchment scale, and thus affects floods (Hümann et al., 2011; Weingartner et al., 2003), hydropower production (Huss et al., 2008; Romerio, 2008; Schaefl et al., 2007), and water resources availability for agriculture and tourism (Benistion, 2012; Viviroli et al., 2003, 2011). It also affects water residence and transit times and thus transport of labile nutrients into surface water bodies (Li et al., 2017; McGlynn & McDonnell, 2003), weathering rates (Brantley et al., 2013; Xiao et al., 2021), and in steep terrain the risk for landslide initiation (Montgomery et al., 1997), and thus landscape evolution.

Most hillslope hydrological studies have focused on SSF generation on well drained hillslopes in temperate climates (Barthold & Woods, 2015), where lateral flow occurs above a lower permeability layer, such as the bedrock (Hardie et al., 2012; Hewlett & Hibblett, 1967; Kirkby & Chorley, 1967; Scaini et al., 2018; Weiler et al., 2005; Whipkey, 1965), or clay layers (Dahlke et al., 2012; McDaniel et al., 2008; Parlane et al., 1989). However, blue dye staining (Schneiter et al., 2014) and sprinkling experiments (Feyen et al., 1996; Hopp et al., 2011; Kienzler & Naef, 2008; Weiler et al., 1998) have highlighted that significant lateral flow can also occur in the topsoil. The accumulation of clay during soil development decreases the hydraulic conductivity ($K_{sat}$) and leads to shallower and more lateral flow pathways (Lohse & Dietrich, 2005; Maier et al., 2020; cf. arrows #2 and #5 in Figure 1). The conceptual framework of Elsenbeer (2001) describes how the relative importance of vertical and lateral flow pathways varies for different (tropical) soil types, depending on the depth to this lower permeability soil layer. In general, a larger depth to the lower permeability soil layer where ponding occurs and lateral flow is initiated, leads...
to a later onset of SSF and a reduction in the peak flow rate (Hopp & McDonnell, 2009). Deeper soils also have a larger storage capacity and thus dampen the effects of variations in rainfall intensity on the runoff response (Keim et al., 2006).

Soil texture does not only define the permeability of the soil and the pace to which incoming precipitation is translated into subsurface flow (Hopp et al., 2009), but also affects the drainable porosity (i.e., the difference between the porosity and the moisture content at field capacity; cf. arrow #1 in Figure 1). The water table tends to rise higher above the lower permeability layer for soils with a low drainable porosity (Weiler & McDonnell, 2004). The changes in water retention capacity will also affect the mixing of water in the soil and the transit times of SSF. Most studies have shown that SSF mainly consists of old water that was stored in the soil before the rainfall event occurred (e.g., Anderson et al., 1997; McDonnell, 1990; Pearce et al., 1986; Sklash et al., 1986). However, recent tracer experiments on grassland hillslopes underlain by Cambisols in pre-Alpine catchments have suggested that pre-event water fractions in SSF are highly variable (~17%–~98% in Kienzler & Naef, 2008 and ~45%–~85% in Dahlke et al., 2012) and depend on the degree of saturation prior to the event. The pre-event water fraction in SSF generally decreases with rainfall intensity (Elsenbeer et al., 1995; Newman et al., 1998; Turton et al., 1995). Vegetation, in particular roots, also changes the soil characteristics and modifies SSF generation (Figure 1). The establishment of root networks and macropores leads to preferential flow, so that water and solutes move quickly along certain pathways (arrows #3 and #5 in Figure 1), thereby bypassing large fractions of the soil matrix (Beven & Germann, 1982; Weiler, 2017). Vegetation and root networks may also enhance water uptake (#4 in Figure 1) and thereby reduce pore-water pressure and the risk of landslide initiation (Ghestem et al., 2011).

Although soil and vegetation characteristics affect subsurface flow pathways and change during landscape evolution, we still do not understand very well how these processes interact with each other and affect the SSF response (see Figure 1 for a schematic overview of the most important interactions between these processes). Recent reviews on landscape evolution models have stressed the need to improve our understanding of the myriad of interactions and feedbacks between the bedrock, soil, vegetation, and water in the critical zone (Temme et al., 2017; Tucker & Hancock, 2010). Others (e.g., van der Meij et al., 2018) have emphasized that more field data on the evolution of soil hydraulic parameters and hydrologic functioning are needed to improve landscape evolution models.

Only a few studies have looked at how landscape evolution affects soil characteristics and inferred how this affects the partitioning of rainfall and runoff generation. Lohse and Dietrich (2005) found for soils on volcanic bedrock on Hawaii that the accumulation of clay in older well-developed soils led to ponding of water and promoted saturation overland flow, while in younger soils water moved vertical and deep percolation dominated (arrows #2 and #5 in Figure 1). Beal et al. (2016) found that older volcanic soils had a lower hydraulic conductivity than younger soils due to the higher silt, clay and soil organic matter contents (#2 and #3 in Figure 1), and that water retention was also higher for older soils (#1 and #4 in Figure 1). This implied faster infiltration and more shallow lateral water movement for the younger sites. Other studies (e.g., Jefferson et al., 2010; Musiak et al., 1981; Yoshida & Troch, 2016) have shown that catchments on older volcanic bedrock have flashier hydrographs and a smaller base flow component than catchments on younger volcanic rock, and similarly attributed these differences to a change from vertical recharge and groundwater-dominated flow to lateral subsurface flow during landscape evolution. Less is known about the effects of soil development and SSF responses for moraines, even though glacial till soils are common in Alpine regions (Egli et al., 2010; Greinwald et al., 2021).

To improve our understanding of how landscape evolution affects the SSF response of moraine hillslopes in rapidly changing Alpine areas, we conducted sprinkling experiments with three different intensities on two chronosequences of moraines in the Swiss Alps. We measured the OF (companion paper; Maier & van Meerveld, 2021) and SSF responses (this paper) during the sprinkling experiments and natural rainfall events to determine how the near-surface runoff responses change during hillslope evolution and with soil and vegetation development. Sprinkling experiments are particularly useful to study the effects of event size or rainfall intensity on runoff processes, and to study the responses to extreme events (Lange et al., 2003; Scherrer et al., 2007; van Meerveld et al., 2014). So far they have only rarely been coupled with a chronosequence (i.e., space-for-time) approach to identify changes in runoff pathways during landscape development (Bernasconi et al., 2011; Rosengqvist et al., 2010). Even though the chronosequence approach has its limitations (e.g., Johnson & Miyamishii, 2008; Pickett, 1989; Walker et al., 2010), it is one of the few feasible methods to detect long-term changes in soil and vegetation development.
and their impact on runoff generation. More specifically, we tried to answer the following research questions:

1. How do SSF response characteristics (amount, peak flow rate, timing, rainfall threshold, event water fraction) change during the first millennia of landscape evolution on moraines?
2. How are the observed changes in SSF responses related to changes in soil and vegetation characteristics?
3. How does moraine age affect the partitioning of rainfall into overland flow (OF), soil water storage (ΔSW), lateral subsurface flow (SSF), and deeper percolation (DP)?

We hypothesized that the increase in vegetation cover and the related increase in root density and depth (right side of Figure 1), in combination with soil development, particularly the development of clay-rich layers (left side of Figure 1), would increase lateral SSF for the older moraines (e.g., Ghestem et al., 2011; Lohse & Dietrich, 2005). We also expected that, despite the increase in preferential flow, the pre-event water fraction in SSF would be higher for the older moraines due to the increased water retention capacity caused by the accumulation of organic matter and the finer texture of older soils (Beal et al., 2016; Crocker & Dickson, 1957; Evans, 1999; Hartmann, Semenova, et al., 2020; Rasmussen et al., 2017; see Figure 1).

2. Site Description

2.1. The Two Chronosequences

The two moraine chronosequences of this study are located in the Swiss Alps: the forefield of the Steingletscher (47°43′N, 8°25′E), close to the Sustenpass (hereafter called Sustenpass) and the forefield of Griessfirn (46°50′N, 8°49′E), close to the Klausenpass (herefrom on called Klausenpass). The two chronosequences are located at a similar elevation (~2,000 m above sea level) but are underlain by different bedrock. The bedrock at the Sustenpass mainly consists of premesozoic metagranitoids, amphibolites and biotite-plagioclase-gneiss (Lahmert, 1977), whereas the bedrock at the Klausenpass is dominated by calcareous material (Globigerinina limestone and Globigerinina marl), schist (Pectinien schist), and some quartzites (Frey, 1965; Pfiffner, 2014). Within each study area, the geology of the glacier foreland is similar and the moraines thus have a similar mineralogy (Musso et al., 2021).

The type of bedrock affects the rate of soil development (Bochter, 1984) and its permeability can have a significant impact on SSF generation (e.g., Hale & McDonnell, 2016). The dissolution of carbonates is several orders of magnitude faster than for silicates (Binder, 2019; Jacobson et al., 2002; Lasaga, 1984; White & Buss, 2003; Williamson & Rimstidt, 1994); carbonate-rich substrate generally buffers the organic and caronic acids and thus slows pedogenesis (Bochter, 1984). The weathered bedrock may also contain fractures that enhance the permeability and favor deeper percolation (#9 in Figure 1) and thus reduce lateral SSF (Graham et al., 2010; Kosugi et al., 2006; Onda et al., 2001; Scaini et al., 2018; Tromp-van Meerveld et al., 2007).

The study areas are located above the tree line and are characterized by a similar Alpine climate. The mean annual air temperature and the mean annual precipitation at a nearby climate station at a comparable elevation (Grimsel Hospiz) were about 1.9°C and 1,856 mm yr⁻¹, respectively, for the 1981–2010 period. The daily precipitation with a return period of 2.3, 30, and 100 years is 78, 131, and 161 mm day⁻¹, respectively (MeteoSwiss, 2016).

At each study area, we selected four moraines between ~30 and ~13,500 years in age (Table 1; Figure 2 in Maier & van Meerveld, 2021 [companion paper]). Their names reflect their approximate age, that is, the 10-ky moraine is about 10,000-years old, whereas the 160-ky moraine is ~160 years old and was formed during the little ice age (i.e., soil development began in ~1860). The age of the moraines was based on either 10-beryllium dating (10-ky and 3-ky moraine at Sustenpass; Schimmelpfennig et al., 2014), radio-carbon dating (13.5-ky and 4.9-ky at Klausenpass; Musso et al., 2019), glacier extent maps and aerial photographs (160-yr and 30-yr moraines at Sustenpass, and 160-yr moraine at Klausenpass), or ring analyses of Dryas octopetala and Salix retusa (80-y moraine at Klausenpass). We assume that the formation processes, as well as erosive forces and depositional settings, were somewhat similar for the moraines in each study area because all of them are lateral (i.e., side) moraines (e.g., Musso et al., 2020; Schimmelpfennig et al., 2014) of the same glacier. In other words, we assume that the moraines were initially similar and that differences in near-surface characteristics and SSF response between the moraines on a chronosequence are due to the difference in their age. For a discussion of assumptions and limitations of this chronosequence approach, as well as more information on the age dating of the moraines, see Maier and van Meerveld (2021).
2.2. Characteristics for the Studied Moraines

2.2.1. Vegetation Cover

The surface of the young moraines mainly consists of rocks and stones and small patches of pioneer plants. The surface of the oldest moraines can be characterized either as Alpine shrubland, dominated by Alpine rose (Sustenpass), or Alpine grassland (Klausenpass). All moraines are occasionally used for low intensity grazing by sheep or cows. We assume that this did not have a significant effect on the soil hydrological characteristics and runoff responses.

2.2.2. Soil Characteristics

2.2.2.1. Sustenpass

Musso et al. (2019) classified the soils of the chronosequences after the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015). At Sustenpass, the Dystric Cambisol of the oldest moraine (10-ky) is silty-loamy in texture and the soil and litter layers are moderately developed (Figure 2a). Thick roots from the abundant Alpine rose and decomposed organic material dominate the O horizon (0–20 cm below the surface). The A horizon (20–35 cm) contains fine roots and has a dark brown to black color. A clay-rich B horizon is located at 35–50 cm below the surface. The saprolite underneath the B horizon contained many coarse particles and rocks. The soil of the second oldest moraine at Sustenpass (3-ky) has a sandy-loamy texture (Figure 2b) and a thinner organic layer and less developed horizons than the 10-ky moraine. The thin B horizon also had a larger fraction of coarse particles (>2 mm) than the 10-ky moraine. The soil was classified as a Skeletic Cambisol.

The soils of the second youngest (160-y) and youngest (30-y) moraines at Sustenpass were sandy Hyperskeletic Leptosols (Figures 2c and 2d) that consist of coarse gravel fragments, sand and buried stones throughout the profile. The root density and organic matter content on the 160-y moraine was higher than on the 30-y moraine,
especially for the surface layer (0–5 cm), but lower than for the older moraines (Table 1). At the 30-y moraine, a fine rock flour layer was observed at ∼35 cm below the surface. The well-sorted fine-grained material was wet and had a blueish hue, suggesting permanently saturated and anoxic conditions.

2.2.2.2. Klausenpass

The soils of the oldest (13.5-ky) and second oldest (4.9-ky) moraine at Klausenpass were identified as Calcaric Skeletic Cambisols and the soils on the second youngest (160-y) and youngest (80-y) moraine as Hyperskeletic and Orthoskeletic Leptosols, respectively (Musso et al., 2019). The soil of the 13.5-ky moraine (Figure 2e) had a silty-loamy texture and consisted of an A horizon (0–28 cm) with dense roots in the top 5 cm and was more compact below 15 cm. Underneath, some clay had accumulated to form a B horizon (28–32 cm), but this was only rudimentary and much less developed than on the oldest moraines at Sustenpass (Figure 2e). The BC horizon (32–70 cm) contained roots to a depth of 55 cm and included more coarse fragments, gravel and weathered rocks.
than the upper layers. The weathered calcareous bedrock underneath had cracks and fractures (see Figure S1 in Supporting Information S1).

The sandy-loamy Calcaric Skeletic Cambisol on the 4.9-ky moraine at Klausenpass (Figure 2f) was slightly shallower than on the 13.5-ky moraine and was characterized by a root-dominated A horizon (0–15 cm) above a denser B horizon (15–21 cm). Roots were found down to 55 cm depth. The sandy BC horizon (21–55 cm) contained a high amount of gravel and stones. The C horizon was free of roots and located above weathered bedrock.

The soil on the 160-y moraine at Klausenpass (Figure 2g) had a sandy-loamy texture and only a shallow AC horizon (0–10 cm depth). Organic matter accumulation was only observed near the vegetation patches. The substrate consisted of a mixture of sand, gravel, and stones. Only a few thicker roots were found below 30 cm depth. The unweathered C horizon was found at a depth of 45 cm.

There was no visible soil development for the loamy-sandy soil of the 80-y moraine at Klausenpass (Figure 2h), other than a yellowish hue on the surface of the rocks. Roots were only found in the top 25 cm between coarse fragments of rocks and stones. Buried stones and rocks were observed throughout the whole profile. At some locations, a mixture of sand and gravel covered a fine-grained, rock flour layer with a dark hue at 25 cm depth.

2.3. Plot Selection

On each moraine, we installed three 4 × 6 m bounded runoff plots. The location of the plots was determined based on vegetation surveys at 10 1 × 1 m subplots on each moraine, where the structural vegetation complexity (defined by the vegetation cover, number of species and functional diversity described by stem growth form, root type, clonal growth organ, seed mass, Raunkiaer's life form, leaf dry matter content, nitrogen content, and specific leaf area) was measured. From these 10 plots, we selected the plots with the lowest, medium, and highest vegetation complexity to cover as much of the potential variation in surface and near-surface characteristics for each moraine as possible (Garnier et al., 2016; Greinwald et al., 2021). All of the plots were relatively steep (Table 1), planar, and located at a midslope position or higher, except for the low and high complexity plots of the 30-y moraine and the high complexity plot of the 3-ky moraine at the Sustenpass, and the high complexity plot of the 160-y moraine at the Klausenpass, which were located at the bottom of the slope. The maximum distance between the three plots on each moraine was ∼40 m. For more information on the selection of the plots, as well as the surface topography of the moraines, see Maier and van Meerveld (2021). We took the same measurements on all 12 plots of each chronosequence (Sustenpass in summer 2018 and Klausenpass in summer 2019).

3. Methods

3.1. Saturated Hydraulic Conductivity (K_sat)

We determined the vertical saturated hydraulic conductivity K_sat for three different depths (0–5, 5–20, and 20–40 cm below the soil surface) at three locations at each plot based on the steady state infiltration rate. For the surface (0–5 cm), we used a Double-Ring-Infiltrometer with an inner diameter of 20 cm; the constant water level was 15–25 cm (see Maier and van Meerveld [2021] for more details). For the subsurface, we used a Constant Head Permeameter (Amoozometer; Amoozegar, 1992, 1989). The diameter of the borehole was 6 cm; the height of the water level was 15 cm for the measurements at 5–20 cm depth and 20 cm for the measurements at 20–40 cm depth. We report the median, average, and standard deviation of the nine measurements per depth for each moraine. We acknowledge that many more measurements are needed to obtain a robust average value of the K_sat for each moraine (see e.g., Harden & Scruggs, 2003; Zimmermann, 2008) but this was not possible due to time limitations. However, these measurements already indicate some of the expected changes in K_sat with moraine age.

3.2. Subsurface Flow Measurements

3.2.1. Plot Setup and Sprinkling Experiments

The 4 × 6 m plots were bounded using plastic sheeting (see Figure 4 in Maier & van Meerveld, 2021) that was inserted ∼5 cm into the ground to prevent inflow and outflow of OF. Four soil moisture sensors (Trübner SMT100
and Decagon 5TE) were installed along the outside border of each plot at 10 cm below the surface. Two additional sensors were installed at the top and bottom of each plot along the outside border at 30 and at 50 cm depth.

At the bottom of each plot, a trench was excavated (depth between 50 and 70 cm; Figure 3a) down to the first lower permeability layer (clay-rich horizon, rock flour layer, or bedrock), as trenched hillslopes are a common way to study SSF dynamics. The trench installation was similar to that described by Bachmair and Weiler (2014).

A drainage mat was inserted into the trench (covering the whole cross section of the soil profile, except for the top 5 cm) to prevent downslope subsurface flow (Figure 3b). The drainage mat was folded to reduce losses to the bottom of the trench and to channel the SSF into the lateral ditch, where the mat was attached to a gutter, which was stabilized with larger stones and rocks (Figure 3b). The trench was refilled with soil after the installation of the drainage mat to avoid a collapse of the trench face.

During the sprinkling experiments, water flowed from the gutter via a 5 cm diameter hose to an Upwelling Bernoulli Tube (Stewart et al., 2015) with a pressure transducer, Electrical Conductivity (EC), and temperature sensor (DCX-22-CTD, Keller). For the low complexity plots, SSF rates were also measured during natural rainfall events. Reliable SSF data were collected between 25.7.19 and 25.8.19 at the Klausenpass area. Unfortunately, SSF data collected during natural rainfall events at the Sustenpass study area were unreliable.

At each plot, we performed three sprinkling experiments on three consecutive days with a different intensity (average of 20, 44, and 62 mm hr$^{-1}$), which reflect events with a return period of 2.3, 30, and 100 years, respectively. The experiments will be referred to as low intensity (LI), medium intensity (MI), and high intensity (HI) experiments in the remainder of the text. The water for the sprinkling experiments was obtained from nearby streams, stored in two 4 m$^3$ pools, and routed by gravity to the sprinklers (Senninger I-Wob; nozzle number 22). The area to which water was applied by the sprinklers extended at least 0.5 m above the plot and 6 m to the sides (as well as several meters below each plot). The rainfall intensity for the different experiments applied with either one (LI on day 1), two (MI on day 2), or three (HI on day 3) sprinklers varied due to differences in the pressure that was applied to the sprinklers and wind drift. The rainfall intensity was measured using two tipping bucket rain gauges installed in each plot and four funnel gauges installed in and next to the plot. The average for these six rain gauges was used to determine the average rainfall intensity for each experiment. The experiments typically lasted 75,
45, and 30 min, for the LI, MI, and HI experiments, respectively, so that the total amount of water applied to the hillslope was ∼20 mm per experiment.

For each experiment, different amounts of 99.8% Deuteriumoxide were added to the water in the pools to give it a distinct isotopic signature, because tracers are a well-established method to directly infer mixing processes that happen in the subsurface (e.g., Klaus & McDonnell, 2013). For the HI experiment, 2 kg of NaCl was added as well. The water in the pool was thoroughly stirred for at least 10 min to ensure that it was fully mixed. For a more detailed description on the plot setup and additional instrumentation (including overland flow collectors), see Maier and van Meerveld (2021).

3.2.2. Water Sampling and Analyses

Samples of SSF were taken from the outflow of the Upwelling Bernoulli Tubes during and after the sprinkling experiments. The sampling interval was shorter at the start of the events than at the end. Samples were also taken from the rainfall gauges after each experiment. Soil water samples were taken before the first (i.e., LI) experiment using suction lysimeters (SMF-30, UMS) installed at ∼30 and ∼50 cm depth. All samples were filtered using 0.45-μm syringe filters (SimplePure™ Syringe Filter) and stored at 4°C in 20-ml glass vials without any air bubbles. They were analyzed for stable water isotope analysis using a Cavity Ring-Down Spectrometer (L2130-I Picarro Inc.) at the isotope laboratory of the Chairs of Hydrology at the University of Freiburg (Germany). The isotope data are reported using the delta notation relative to Vienna Standard Mean Ocean Water (VSMOW). The precision of the analysis was ±0.05‰ for δ¹⁸O and ±0.35‰ for δ²H.

Soil samples were taken at 10 cm intervals to the depth of the trench prior to the start of the first sprinkling experiment as well. The isotopic composition of the soil water in these samples was analyzed by equilibration with the air in the sample bags (i.e., bag method; e.g., Jiménez-Rodríguez et al., 2019).

3.3. Data Analyses

3.3.1. Subsurface Flow Response Characteristics

For each sprinkling experiment, we determined the time until SSF occurred ($t_{lag}$), the total amount of rainfall applied before SSF occurred ($P_{lag}$), the peak flow rate ($Q_{peak}$), the total SSF volume ($Q_{total}$), the duration of SSF ($t_Q$), and the runoff ratio (total SSF volume divided by the applied rainfall amount, $Q_{total}/P_{total}$). We determined the time of SSF drainage ($t_D$) as the time between the end of the experiment and the time when SSF ended. For each event, we also determined the ratio of the SSF rate and the average rainfall intensity ($P_{int}$, i.e., scaled SSF rate) and the ratio of the EC of SSF and the EC of the applied rainfall (scaled EC) in order to better compare the responses for the different events.

For the 30-y moraine low and high complexity plots, which were installed at the bottom of the hillslope, there was (perched) groundwater flow (∼1.6–2.2 l s⁻¹) above the bedrock/rock flour layer. We subtracted the relatively constant groundwater flow rate before the experiment from the SSF hydrographs to determine the SSF hydrograph characteristics (runoff ratio, SSF volume, flow rates, $t_{lag}$, $P_{lag}$, $t_Q$, $t_D$).

We used the Antecedent Soil-moisture Index (ASI; Haga et al., 2005; Penna et al., 2015) to represent the moisture conditions prior to the start of the sprinkling experiments and also the natural rainfall events at Klausenpass. The ASI was calculated for the top 50 cm of the soil by summing the product of the average volumetric soil water content at 10, 30, or 50 cm below the surface with the depths of the soil layers that they represented (200, 200, and 100 mm, respectively).

3.3.2. Hydrograph Separation

For the LI experiments, we determined the fractions of rainfall (event water fraction, $f_e$) and soil water ($f_{sw}$) in SSF using two-component hydrograph separation with δ²H as the tracer (cf. Sklash et al., 1976). The average δ²H value of the rainfall samples collected during the experiment was used to represent the applied rainfall, and similarly the average δ²H of all soil water samples (from the suction lysimeters and the soil cores) was used to characterize the soil water isotopic composition.

For the MI and HI sprinkling experiments, a three-component hydrograph separation (Gibson et al., 2000) with both δ¹⁸O and δ²H as the tracers was used to determine the fraction of rainfall (from the experiment, $f_e$), the frac-
tion of rainfall from the previous event (i.e., the rainfall of the LI experiment for the MI intensity experiment and the rainfall of the MI experiment for the HI experiment, \( f_{\text{prev}} \)) and the fraction of soil water (\( f_{\text{sw}} \)). For the 30-y moraine at the Sustenpass that had continuous groundwater flow, we did the two-component and three-component hydrograph separation calculations using the composition of the groundwater instead of the soil water because the mixing diagram suggested that soil water did not contribute to SSF (see Figure S2 in Supporting Information S1).

The uncertainty of these different fractions was calculated following the method of Genereux (1998). For the uncertainty of the event water and previous event water compositions, we used the standard deviation of all rainfall samples collected during these experiments. For the uncertainty of the composition of the soil water, we used the standard deviation of all soil water samples collected prior to the first sprinkling experiment at each plot (\( n = 5–12 \)). For the 30-y moraine at Sustenpass, we used the standard deviation of all groundwater samples collected prior to and after the sprinkling experiment at each plot (\( n = 6 \)) as the uncertainty of the composition of the groundwater. For the uncertainty of the composition of the SSF, we used two times the precision of the measurements.

### 3.3.3. Rainfall Partitioning

Because we measured for each experiment the total amount of rainfall and SSF, as well as the total amount of overland flow (OF; see companion paper, Maier & van Meerveld, 2021), and could calculate the change in the amount of soil moisture that was stored in the top 50 cm of the soil between the start and the end of the experiment (\( \Delta S_W = \Delta A_S I \)), we were able to deduce the amount of deeper percolation (DP) for each experiment and plot

\[
DP = P - OF - SSF - \Delta S_W
\]  

(1)

It is important to note that because deep percolation was calculated (rather than measured), it includes also all the measurement errors. Furthermore, some of the water that was stored in the soil may have drained vertically after SSF (and OF) stopped. DP is therefore likely underestimated and differences in DP between plots need to be interpreted with caution.

### 3.3.4. Statistical Analyses

We used the Shapiro-Wilk-test to determine the normality of the \( K_{\text{sat}} \) values and the SSF response characteristics (runoff ratio, SSF volume, flow rates, \( t_{\text{lag}} \), \( P_{\text{lag}} \), \( t_{\text{D}} \)). We used the Kruskal-Wallis tests and Nemenyi tests to determine if the differences in the median \( K_{\text{sat}} \) values for the different moraines were statistically significant.

To determine if the median values of the SSF response characteristics for the two study areas were different, we used the Mann-Whitney test. For this analysis, we grouped the moraines by age class. In other words, we considered the 10-ky, 3-ky, and 30-y moraine at Sustenpass to be comparable to the 13.5-ky and 4.9-ky and 80-y moraines at Klausenpass, respectively. We used a 0.05 level of significance for all analyses. All analyses were completed using the software R (v3.5.1—used with RStudio v1.1.463) and in particular the packages: “stats” and “ggplot2.”

### 4. Results

#### 4.1. Saturated Hydraulic Conductivity (\( K_{\text{sat}} \))

The median vertical \( K_{\text{sat}} \) decreased with depth below the surface and moraine age (Figure 4). At the soil surface (0–5 cm depth), \( K_{\text{sat}} \) increased significantly from the oldest moraines (median of 540 mm hr\(^{-1}\) on Sustenpass and 900 mm hr\(^{-1}\) on Klausenpass) to the youngest moraines (median values of 4,320 mm hr\(^{-1}\) on Sustenpass and 6,140 mm hr\(^{-1}\) on Klausenpass). At 5–20 cm depth, the median \( K_{\text{sat}} \) was also smallest for the oldest moraines (8 and 20 mm hr\(^{-1}\) for the 10-ky and 13.5-ky moraine, respectively) and largest for the youngest moraines (194 and 191 mm hr\(^{-1}\) for the 30-y and 80-y moraine, respectively). At 20–40 cm depth, the median \( K_{\text{sat}} \) values increased from the oldest moraines to the 160-y moraines (from 4 to 75 mm hr\(^{-1}\) at Sustenpass and from 9 to 69 mm hr\(^{-1}\) at Klausenpass) but was lower on the youngest moraines than for the 160-y moraines (27 mm hr\(^{-1}\) for the 30-y moraine at Sustenpass and 60 mm hr\(^{-1}\) for the 80-y moraine at Klausenpass). The median \( K_{\text{sat}} \) values were higher at Klausenpass than Sustenpass but this difference was only significant for the second oldest (i.e., 3-ky versus 4.9-ky) moraines (\( p = 0.03 \)).
4.2. Hydrograph Characteristics for the Sprinkling Experiments

SSF was observed for 13 out of the 36 sprinkling experiments at Sustenpass and only four out of the 36 experiments at Klausenpass. For both study areas, SSF responses were more frequently observed during the sprinkling experiments on the youngest moraines than the oldest moraines (44%, 11%, 22%, and 67% of all experiments on the 10-ky, 3-ky, 160-y, and 30-y moraine at Sustenpass and 0%, 11%, 22%, and 22% of all experiments on the 13.5-ky, 4.9-ky, 160-y, and 80-y moraine at Klausenpass; Table 2). The average runoff ratio for SSF (i.e., average for all experiments) was 42% for the 30-y moraine at the Sustenpass; for all other moraines it was <10%. Average runoff ratios differed markedly between the moraine age classes (3%, 1%, 1%, and 22%; from the oldest to the youngest moraine classes) and were significantly higher at Sustenpass (13% on average) than at Klausenpass (<1%). The differences between the study areas were much smaller if the two plots on the 30-y-old moraine at Sustenpass with constant groundwater flow were excluded (average runoff ratios of 2% for Sustenpass). The peak SSF runoff ratios were also highest for the youngest moraines (92% on the 30-y moraine at Sustenpass and 5% on the 80-y moraine at Klausenpass; Figure 6). The runoff ratios were slightly higher for the HI experiments than the LI experiments (Figures 7j–7l). The topography (slope, aspect, microtopography) and the rainfall intensity did not have a pronounced impact on any of the other SSF characteristics (Figure 7).

The average $Q_{\text{peak}}$ (23 mm hr$^{-1}$), average $t_{\text{f}}$ (132 min) and average $t_{\text{o}}$ (185 min) were much higher for the 30-y moraine at Sustenpass than for the other moraines (average $Q_{\text{peak}} < 14$ mm hr$^{-1}$, average $t_{\text{f}} < 44$ min, and average $t_{\text{o}}$ of 61 min). Scaled peak flow rates on the 30-y moraine were $>0.9$, whereas at Klausenpass none of the scaled peak flow rates were larger than 0.1 (Figures 5a and 5c). Due to the very different response of the two plots on the 30-y moraine, most of the SSF characteristics (i.e., $t_{\text{lag}}$, $P_{\text{lag}}$, $Q_{\text{peak}}$, $t_{\text{o}}$) differed significantly between the moraine age classes and the two study areas. Excluding these two 30-y plots from the analyses still led to significant differences between the two study areas for $Q_{\text{lag}}$ ($p = 0.01$) and $Q_{\text{peak}}$ ($p = 0.05$).
4.3. Hydrograph Separation

For the MI experiments, the event water fractions were highest on the youngest moraines (average: 53 ± 7%; Figure S7 in Supporting Information S1). Previous event water contributed little to SSF for the youngest moraines (average: 6 ± 3% for the two plots on the 30-y moraine and the one plot on the 80-y moraine that produced SSF). The groundwater contributions for the low and high complexity plots on the 30-y moraine was high (40 ± 5% and 58 ± 7%; the experiment on the other plot did not produce any SSF). For the youngest moraine at Klausenpass (i.e., the 80-y moraine), soil water contributed 26 ± 5% to SSF. Soil water was the dominant source of SSF for the older moraines (48 ± 5% for the plot on the 160-y moraine at Sustenpass where SSF was measured, and 42 ± 15% on average for the two plots on the 10-ky moraine). Previous event water contributed less to SSF for these plots (average: 19 ± 8%).

During the HI experiments, the event water fractions were also largest for the youngest moraines (42 ± 17% on average for the plots on the 30-y moraine on Sustenpass and 65 ± 17% for the plot on the 80-y moraine at Klausenpass that generated SSF, i.e., comparable to those of the MI experiments). The event water fraction was again smaller for the older moraines (23 ± 7% on average for the 160-y moraines, 38 ± 10% for the second oldest moraines, and 30 ± 9% for the oldest moraines; Figure 7). The contribution of previous event water to SSF was higher for these older moraines (average: 61 ± 3, 51 ± 7, and 45% ± 6 for the 160-y, 3-ky and 4.9-ky, and the 10-ky moraines, respectively) and higher than for the MI experiments (average of 24 ± 5% and 17 ± 8% for the 160-y and 10-ky moraines at Sustenpass, respectively). Generally, the contribution of soil water and previous event water was larger at the beginning of the event than later during the event (Figure 8).

### Table 2

**Overview of the Rainfall and SSF Characteristics for All Sprinkling Experiments of Sustenpass and Klausenpass for Which SSF Was Observed:**

| Study area | Moraine age (years) | Experiment (intensity) | Veg. complexity | $P_{\text{total}}$ (mm) | $P_{\text{int}}$ (mm h$^{-1}$) | $P_{\text{CV}}$ (%) | $t_{\text{lag}}$ (min) | $P_{\text{lag}}$ (mm) | $Q_{\text{peak}}$ (mm h$^{-1}$) | $Q_{\text{total}}$ (mm) | Runoff ratio (%) | $t_{D}$ (min) | $f_e$ (%) |
|------------|---------------------|------------------------|-----------------|------------------------|-------------------------------|-----------------|-----------------|----------------|-------------------|----------------|----------------|-----------|----------|
| Sustenpass | 10-ky 10,000        | MI L                   | 22              | 24                     | 12                            | 51              | 20              | 5.0              | 2.2               | 10              | 24             | 29 ± 2    |          |
|            | 10-ky 10,000        | MI M                   | 27              | 26                     | 16                            | 37              | 16              | 1.3              | 1.1               | 4               | 75             | 55 ± 12   |          |
|            | 10-ky 10,000        | HI L                   | 24              | 43                     | 34                            | 32              | 23              | 12.5             | 4.5               | 19              | 38             | 21 ± 5    |          |
|            | 10-ky 10,000        | HI M                   | 19              | 33                     | 27                            | 29              | 16              | 6.1              | 3.8               | 20              | 40             | 38 ± 2    |          |
|            | 3-ky 3,000          | HI L                   | 31              | 44                     | 42                            | 23              | 17              | 6.2              | 4.3               | 14              | 16             | 42 ± 6    |          |
|            | 160-y 160           | MI M                   | 52              | 56                     | 52                            | 43              | 40              | 13.9             | 5.2               | 10              | 38             | 28 ± 5    |          |
|            | 160-y 160           | HI M                   | 63              | 90                     | 26                            | 27              | 41              | 14.0             | 5.1               | 8               | 35             | 28 ± 3    |          |
|            | 30-y 30             | LI L                   | 19              | 15                     | 18                            | 13              | 3               | 10.5             | 14.8              | 78              | 174            | 37 ± 11   |          |
|            | 30-y 30             | LI H                   | 18              | 14                     | 16                            | 33              | 8               | 12.9             | 7.9               | 44              | 47             | 6 ± 13    |          |
|            | 30-y 30             | MI L                   | 30              | 37                     | 21                            | 8               | 5               | 16.5             | 9.5               | 32              | 77             | 48 ± 5    |          |
|            | 30-y 30             | MI H                   | 27              | 33                     | 26                            | 10              | 6               | 23.6             | 22                | 81              | 245            | 39 ± 7    |          |
|            | 30-y 30             | HI L                   | 32              | 48                     | 38                            | 7               | 6               | 40.3             | 17.6              | 55              | 62             | 55 ± 13   |          |
|            | 30-y 30             | HI H                   | 27              | 46                     | 61                            | 17              | 13              | 35.9             | 24.7              | 92              | 186            | 28 ± 6    |          |
| Klausenpass| 4.9-ky 4,900        | HI M                   | 51              | 61                     | 57                            | 50              | 51              | 2.7              | 0.4               | 1               | 5              | 33 ± 4    |          |
|            | 160-y 160           | MI M                   | 53              | 70                     | 23                            | 65              | 76              | 2.0              | 0.3               | 1               | 18             | 35 ± 3    |          |
|            | 160-y 160           | HI H                   | 42              | 63                     | 61                            | 32              | 34              | 3.1              | 1.4               | 3               | 28             | 6 ± 2     |          |
|            | 80-y 80             | MI M                   | 34              | 46                     | 22                            | 45              | 35              | 2.8              | 0.4               | 1               | 20             | 71 ± 5    |          |
|            | 80-y 80             | HI M                   | 35              | 60                     | 27                            | 21              | 21              | 3.4              | 1.8               | 5               | 40             | 65 ± 17   |          |

*Note:* $Q_{\text{peak}}$ is the peak SSF rate, $Q_{\text{total}}$ the total amount of SSF, the runoff ratio is $Q_{\text{total}}/P_{\text{total}}$, $t_{\text{lag}}$ and $P_{\text{lag}}$ represent the time and total rainfall between the start of the experiment and the onset of SSF, $f_e$ is the event water contribution to SSF determined using two (LI) or three-component (MI and HI) hydrograph separations with $\delta^2$H and $\delta^{18}$O as the tracers (±the uncertainty).
The scaled EC values did not change notably during the experiments on the 10-ky moraine (Figure 5b) but tended to increase during the experiments on the youngest moraines at both study areas (Figures 5b and 5d), which is in line with the higher event water fractions for the youngest moraines. On the 3-ky moraine, the pronounced increase in scaled EC toward the end of the HI experiment also reflects the increase in the event water contribution at the end of the event (Figures 5b and 8a).

4.4. Subsurface Flow for Natural Rainfall Events at Klausenpass

SSF was measured during natural rainfall events at all four low complexity plots at the Klausenpass (Figure 9). SSF was observed mainly in response to periods of intense rainfall during long duration rainfall events (e.g., the events of August 11–13 and 19–21), except for the 4.9-ky moraine plot for which less SSF was observed than for the other moraines. SSF runoff ratios for the whole period were very small (<1% for each plot) but higher than during the LI and MI sprinkling experiments when almost no SSF occurred for the Klausenpass plots. The SSF runoff ratio was highest during the first event on the oldest (i.e., 13.5-ky) moraine (5%). This was the only plot for which there was more SSF during the measurement period than OF (7.8 mm of SSF versus 7.1 mm of OF for the 13.5-ky, 1.4 mm of SSF versus 9.8 mm of OF for the 4.9-ky, 4.9 mm of SSF versus 15.9 mm OF for the 160-y plot, and 6.3 mm of SSF versus 13.8 mm OF for the 80-y plot; Figure 9). For most of the events, SSF was less pronounced during the first rainfall event and only started during a second burst of higher intensity rainfall. This was generally several hours after the onset of OF (Figure S8 in Supporting Information S1), except for the 80-y plot, where SSF started earlier than OF and the delay between the onset of rainfall and SSF was shorter (between 45 and 240 min for the different events).
For the 13.5-ky, 4.9-ky, and 80-y moraines, SSF occurred when a rainfall plus antecedent soil moisture storage (ASI) threshold was exceeded (Figure 10). These thresholds were ∼137, ∼179, and ∼94 mm, respectively. The difference in these threshold values can be explained by the higher volumetric water content on the 4.9-ky (average of the mean volumetric water contents at 10 cm, 30 cm, and 50 cm depth during the study period for all plots: 0.27; range: 0.22–0.29) compared to the 13.5-ky moraine (0.23; range: 0.20–0.27), 160-y moraine (0.08; range: 0.07–0.10), and 80-y moraine (0.10; range: 0.08–0.11). At Sustenpass, average soil moisture was also higher on the older moraines than on the younger moraines (10-ky moraine: 0.36, range: 0.32–0.38; 3-ky moraine: 0.14, range: 0.11–0.19; 160-y moraine: 0.11, range: 0.11–0.12; and 30-y moraine: 0.10, range: 0.07–0.14). For the two oldest moraines at both study areas, the average volumetric water content during the field season was higher at 10 cm depth (0.29 at Sustenpass and 0.32 at Klausenpass) than deeper in the soil (average of the mean volumetric water contents during the study period at 30 cm and 50 cm depth: 0.20 at Sustenpass and 0.17 at Klausenpass).

4.5. Rainfall Partitioning

The fraction of rainfall that became SSF decreased with moraine age at both study areas. For OF, there was no clear trend observable (Maier & van Meerveld, 2021; Figure 11). At Sustenpass, the fraction of rainfall that became OF or SSF increased with rainfall intensity but at Klausenpass, these two components were negligible, regardless of the intensity. Most of the water applied during the sprinkling experiments at Sustenpass was stored in the soil (ΔSW; average of 65% for Sustenpass versus 36% for the Klausenpass). At Klausenpass, most of the rainfall went to deeper percolation (DP; 62% of the rainfall during all sprinkling experiments). This was much less for Sustenpass (16%, Figure 11). The fraction of rainfall that was stored in the soil was smaller for the higher rainfall intensity experiments (average of 83%, 59%, and 53% for the LI, MI, and HI rainfall intensity experiments at Sustenpass and 46%, 34%, and 27% for Klausenpass, respectively), even though the antecedent soil moisture conditions in the upper 50 cm of the soil were similar.

5. Discussion

5.1. Subsurface Flow Generation

5.1.1. Subsurface Flow on Old Moraines

Most studies have shown that lateral subsurface flow occurs either because of temporary saturation above an impeding layer or because the water table rises into a more permeable layer near the surface (Weiler et al., 2005).
Soil development leads to an increase in fine particles due to physical weathering (He & Tang, 2008; Mavris et al., 2010; Righi et al., 1999) and chemical weathering (i.e., clay formation; Crocker & Dickson, 1957; Román-Sánchez et al., 2021; Schaaf et al., 2017; Young et al., 2004). Illuviation of this fine-textured material leads to a lower permeability layer that promotes ponding and lateral SSF (e.g., Dahlke et al., 2012; Lohse & Dietrich, 2005). Indeed, the silt and clay content were highest for the old moraines at both study areas (Hartmann, Weilar, & Blume, 2020; Maier et al., 2020), and led to a strong decrease in the vertical $K_{sat}$ with moraine age.

Figure 7. Selected subsurface flow (SSF) response characteristics for all low intensity (LI), medium intensity (MI), and high intensity (HI) sprinkling experiments (left, middle, and right panels, respectively) that produced SSF for each moraine age class at the Sustenpass (circles) and Klausenpass (triangles) study areas. The dashed lines represent the average values for each rainfall intensity for all plots for which SSF was measured. Significant differences in the average values between the two study areas are indicated with a gray star and significant differences between the moraine age classes are indicated by a brown star at the right side of the panels. There were no significant differences between the response characteristics for the different rainfall intensities. Figure S4 in Supporting Information S1 shows the same results organized by moraine age class.
However, the clay-rich layer was only pronounced for the 10-ky moraine at Sustenpass (Figure 2a), and was less clear for the 3-ky moraine at Sustenpass and the oldest moraines at Klausenpass. A similar effect of soil development on SSF has been reported by Lohse and Dietrich (2005), who describe the development of a clay layer at 20–50 cm depth and related decreases in $K_{sat}$ for a 4.1 million year-old Oxisol compared to a young (300 years) Andisol ($K_{sat}$ of 0.8 and 140 mm hr$^{-1}$ for the old and the young soil, respectively).

The $K_{sat}$ values at 20–40 cm below the surface for the 10-ky moraine at Sustenpass and the 13.5-ky moraine at Klausenpass are smaller than the 1-hr rainfall intensity with a 2-year return interval (13 mm hr$^{-1}$ at the Grimsel Hospiz climate station; MeteoSwiss, 2019). For the 10-ky moraine, this is even the case at 5–20 cm depth. This suggests that for these old moraines, a perched water table and SSF are likely to occur during intense events. Indeed, for the low and medium complexity plots on the 10-ky moraine, SSF was observed for the MI experiments and the runoff ratios increased to $\sim 20\%$ for the HI experiments (Figure 6).

SSF consisted mainly of previous event water and soil water (Figure 8 and Table 2) and these fractions were higher when antecedent soil water storage was higher ($r_\gamma = 0.71; p = 0.02$). This suggests that the rainfall mixed with the water that was stored in the soil. The high mean volumetric water content for the 10-ky moraine is closely linked to the high organic carbon content and water retention capacity for this moraine (Hartmann, Semenova, et al., 2020; see #4 in Figure 1). High pre-event water fractions for SSF have been observed in many hillslopes (e.g., Anderson et al., 1997; Dahlke et al., 2012; Klaus et al., 2013; Zhao et al., 2013). However, sprinkling
experiments on grassland hillslopes in pre-Alpine catchments of the Swiss Alps showed large variations in the chemical composition of SSF, depending on whether SSF was directly fed by rainfall via preferential flow paths (little mixing and small pre-event water fractions) or if SSF came from saturated parts of the soil (enhanced mixing and larger pre-event water fractions) (Kienzler & Naef, 2008). Dye staining experiments on the 10-ky moraine showed that the pronounced root network (Figure 2a; Hartmann, Semenova, et al., 2020) induced lateral macropore flow (arrows #3 and #5 in Figure 1; Hartmann, Semenova, et al., 2020). SSF likely occurred through these preferential flow pathways, as has been observed for many other hillslopes (e.g., Anderson et al., 2009; McDonnell, 1990; Uchida et al., 2005; Weiler & Naef, 2003). The results from our experiments for the oldest moraines thus suggest that there is significant mixing of rainwater and soil water and quick SSF through preferential flow pathways.

SSF was not observed for the LI experiments on the 10-ky moraine at Sustenpass, even though the rainfall intensity was higher than the $K_{sat}$ in the subsoil, because the soil did not become saturated. Instead, all applied water went into soil water storage (Figure 11). This increased the antecedent soil moisture conditions and helped to trigger SSF for the subsequent experiments (#6 in Figure 1).

The absence of SSF for all sprinkling experiments on the oldest moraines at Klausenpass can be explained by the less developed soils and in particular the thinner clay-rich layer compared to the oldest moraines at Sustenpass (Figure 2; see #2, #3, and #5 in Figure 1). The higher initial pH for the carbonate rock slows down chemical weathering and the development of secondary clay minerals (Bochter, 1984; Pott & Hüppe, 2008). The average porosity for the oldest moraines at Sustenpass and Klausenpass was similar (~30%; Musso et al., 2019); the average antecedent soil moisture storage in the top 50 cm was similar as well (average of 118 mm for the 10-ky moraine at Sustenpass versus 115 mm for the 13.5-ky moraine at Klausenpass during the field season). This suggests that the lack of lateral SSF on the oldest moraines at Klausenpass was due the faster drainage to deeper layers (Figure 11) because the weakly developed clay-rich layer did not impede the drainage as much as on the oldest moraines at the Sustenpass. The fractures in the weathered carbonate bedrock will have further promoted vertical drainage (e.g., Hartmann et al., 2013; White, 2002; Figure S1 in Supporting Information S1). The observations during natural rainfall events show that SSF does occur on
these moraines (Figure 9a) once a soil moisture and precipitation threshold has been exceeded (Figure 10) and the soils become locally saturated.

### 5.1.2. Subsurface Flow on Young Moraines

In contrast to the old moraines, there were no clay-rich layers in the shallow soils of the young moraines (Figure 2). Although the saturated hydraulic conductivity $K_{sat}$ decreased with depth in the young moraines as well, $K_{sat}$ values at 20–40 cm depth were as high or higher than the applied rainfall intensities. Instead, the interfaces where ponding can occur in the young moraines are the boundaries between the coarse sediment and the large boulders (e.g., Mandal et al., 2005), between the coarse sediment and the bedrock (e.g., Renzetti et al., 1992), or above the fine rock flour layers. The soils of the young moraines are highly permeable and drainable. This caused quick SSF reactions and short drainage times for the 160-y moraines and the 80-y moraine (Table 2). Staining experiments (Hartmann, Semenova, et al., 2020) showed that, in contrast to the soils on the old moraines, flow is dominated by matrix flow. The low water retention capacity (Hartmann, Weilar, & Blume, 2020) and thus low soil moisture storage limit mixing with stored soil water, leading to large event water fractions in SSF (Figure 8). These high event water fractions in SSF are not unique. Kienzler and Naef (2008) found even higher average event water fractions in SSF (up to 83%) for hillslopes in Swiss pre-Alpine catchments for which there were no saturated areas in the soil or saturated areas were isolated from the infiltrating rainfall.

The results for the low and high complexity plots on the 30-y moraine at Sustenpass were very different from those of the other young moraines. For the 160-y moraines and also the 80-y moraine at Klausenpass, SSF occurred infrequently (only for 6 of the 27 sprinkling experiments; Table 2) and the runoff ratio was <10%. In contrast, for the two plots at the bottom of the 30-y moraine, SSF was common and the runoff ratios were very high (Figure 6). The average peak flow rates were also almost four times higher than on the other moraines (Figures 7g–7i). The most likely reasons for this difference are the position of the plots, the presence of the rock flour layer, and the depth of the trench. The rock flour layers (Figures 2d and 2h) are created by the glacier grinding over the bedrock and consist of well-sorted fine-grained material. The presence of these fine layers explains the low $K_{sat}$ at 20–40 cm depth for the 30-y moraine at Sustenpass, and to a lesser degree also for the 80-y moraine at Klausenpass (Figures 3c and 3d). The blueish hue of these layers suggests anoxic (saturated) conditions and that these layers limit deeper percolation (#2 and #7 in Figure 1). This promotes SSF above these layers (#5 in Figure 1). The 30-y moraine is located relatively close to the Steinsee (see Figure 2 in Maier & van Meerveld, 2021). The low and high complexity plots on the 30-y moraine were located at the base of the moraine (in contrast the medium complexity plot was located toward the ridge of the moraine) and likely intersected groundwater flow.

---

**Figure 11.** Partitioning of the rainfall applied during the sprinkling experiments with different rainfall intensities at Sustenpass (top) and Klausenpass (bottom) into overland flow (OF), subsurface flow (SSF), change in soil water storage ($\Delta$SW), and deep percolation (DP; see Equation 1). The stacked bars represent average values for the three plots per moraine. Note that part of the $\Delta$SW drained vertically after the end of the event and thus contributed to DP.
through the moraines (Figure 8a; represented by #8 in Figure 1). This groundwater flow is closely linked to the bedrock topography (McClymont et al., 2011). Other studies have also identified talus slopes and moraines as important contributors of groundwater flow and storage in Alpine watersheds (Roy & Hayashi, 2009).

5.2. Effects of Moraine Age and Geology on Runoff Generation

The results of the field campaigns at both study areas suggest that the age of a moraine impacts hillslope runoff generation (Figures 1 and 12). SSF (this study) and OF (companion paper, Maier & van Meerveld, 2021) on the old moraines are both due to saturation and mixing of rainfall with stored water. The accumulation of fine material and clay on the oldest moraine reduces vertical percolation and promotes saturation and lateral flow above this layer (cf. arrows #2–#5 in Figure 1). At the same time, the increase in clay, silt, and organic matter content (indicated by the change in color of the hillslopes), together with some topsoil water-repellency, increased peak OF ratios for the older moraines at Sustenpass, where SSF occurred mainly along root channels and other preferential flow pathways. In contrast, there is a lack of a runoff response on the oldest moraines at Klausenpass during intense rainfall events and most of the water goes to soil water storage and deeper (>50 cm) percolation. Here, OF and SSF only occur in response to large events that cause (local) saturation of the topsoil and near-surface biomat flow. Illustration created with the help of the University of Zurich, Information Technology (MELS/SIVIC) and used with their permission.

Figure 12. Conceptual diagram showing the changes in the main hillslope characteristics and flow pathways along the moraine chronosequences at Sustenpass (top) and Klausenpass (bottom). Rainfall on the youngest moraines is transmitted downslope via subsurface flow (SSF) at the interface of the sediment and the bedrock. Despite the highly porous und permeable substrate, overland flow (OF) is generated frequently over the rocks and stones on and near the surface and hydrophobicity of the sand after long dry periods (cf. companion paper, Maier & van Meerveld, 2021). The increase in clay, silt, and organic matter content (indicated by the change in color of the hillslopes), together with some topsoil water-repellency, increased peak OF ratios for the older moraines at Sustenpass, where SSF occurred mainly along root channels and other preferential flow pathways. In contrast, there is a lack of a runoff response on the oldest moraines at Klausenpass during intense rainfall events and most of the water goes to soil water storage and deeper (>50 cm) percolation. Here, OF and SSF only occur in response to large events that cause (local) saturation of the topsoil and near-surface biomat flow. Illustration created with the help of the University of Zurich, Information Technology (MELS/SIVIC) and used with their permission.
drainable sediments that promote reinfiltration of the OF. SSF from young moraines is mainly caused by local saturation of the top soil. The permeable soils drain quickly and limit water retention, so that event water contributes significantly to both SSF and OF (Figure 10).

The results also show that other factors, like topography and geology, are important and impact the effects of hillslope aging on rainfall partitioning and runoff responses (as indicated by #8 in Figure 1). Topography (and in particular the elevation above the lake or groundwater table) explains the different runoff responses for the three 30-y moraine plots, which all have similar soil and vegetation characteristics. The position of the low and high complexity plots at the base of the moraine resulted in higher antecedent soil moisture conditions that increased the likelihood for saturation and SSF, as well as continuous groundwater flow (Figures 11 and 12; cf. Zhu et al., 2014). However, the effect of the slope itself on the amount of SSF and OF was negligible (cf. Tables 1 and 2), perhaps partly because all plots were very steep.

The more rapid soil development (in particular the accumulation of clay) on siliceous bedrock increases the soil moisture retention capacity (Figure 11; #1 in Figure 1), which promotes vegetation and soil development (Egli et al., 2015). This thus represents a positive feedback. On the other hand, carbonate bedrock in humid climates is much more prone to carbonic acid weathering (Binder, 2019; Blum et al., 1998) and thus the development of conduits with low resistance (White, 2002) that promote deep percolation (Figures 11 and 12; see also #9 in Figure 1). This means that the lower permeability layer that promotes ponding and near-surface lateral flow, develops significantly later in calcareous areas than in silicate areas. This leads to less SSF and OF during the first millennia of landscape development (which is reflected by the lack of SSF during the sprinkler experiments for the old moraines on Klausenpass). However, this can change over longer time scales when soil development proceeds further. Thus, OF and lateral SSF may become more important later during landscape evolution.

5.3. Implications for Models

Despite the high variability within and among the moraines, our study identified specific changes in hillslope properties and flow pathways with moraine age. These results on the changes in soil characteristics and the related hydrological responses can be helpful to simulate soil profile and root network development and the establishment of lateral subsurface flow paths, which are still inadequately represented in existing hydrological models and landscape evolution models (Chifflard et al., 2019; Minasny et al., 2015). Detailed field information on water flow through different flow pathways and the partitioning of water along these flow pathways (cf. bottom part of Figure 1) are crucial to improve the performance of the hydrological aspects of soil and landscape evolution models (van der Meij et al., 2018).

The results of this study show that SSF responses, and in particular the frequency of occurrence and peak flow rates, are different for the young and old moraines. The OF responses and sediment yield are also different (see companion paper, Maier & van Meerveld, 2021). Thus when simulating water and sediment transport for Alpine catchments with different aged moraines, these differences need to be taken into account, and are probably more important than the differences in slope.

Recent reviews have stressed the need to improve our understanding of the myriad of interactions between bedrock, soil, vegetation, and hydrology in the critical zone (cf. Figure 1), and the implementation of these feedbacks in landscape evolution models (Temme et al., 2017; Tucker & Hancock, 2010). This study and the accompanying study on OF (Maier & van Meerveld, 2021) are a step to establish a data basis to test and help to improve landscape evolution models. It provides valuable information on the characteristics of the moraines (see also Hartmann, Semenova, et al., 2020; Maier et al., 2020; cf. top part of Figure 1) and thus the parameters for these models, as well as information on the hydrological responses to evaluate the models.

We provide two recommendations for landscape evolution models based on these results. First, our work has shown that the changes in $K_{sat}$ during the first millennia of landscape evolution are mainly driven by changes in soil texture (see Figure 4). This change can be modeled either by simulating the physical and chemical weathering of the material and development of fine particles and clay-rich horizons, or the change in $K_{sat}$ can be directly parameterized as a function of age, e.g., using an exponential decay with time ($R^2$ of an exponential fit through the median $K_{sat}$ values at 0–5 cm, 5–20 cm, and 20–40 cm soil depth is 0.93, 0.97, and 0.67, respectively). The latter would limit uncertainties that emerge from an indirect approach, such as pedotransfer functions (van der
Our experimental study on two moraine chronosequences in the Swiss Alps revealed that the saturated hydraulic conductivity ($K_{sat}$) decreases not only with depth below the surface but also with moraine age because the combined effects of mechanical weathering and clay accumulation were larger than the effect of the development of the root network and formation of preferential flow pathways. On the youngest moraines, large buried stones and rocks, as well as local layers of fine rock flour, reduced $K_{sat}$ and induced lateral flow, which caused SSF to occur most frequent and runoff ratios to be highest for the young moraines. The fraction of soil water in SSF was smaller for the young moraines than the old moraines because of the limited water retention in the coarse freely draining material. In contrast, the more developed and finer textured soils on the older moraines increased water retention and promoted the mixing of rainfall with soil water.

At the calcareous study area, there was little or no shallow subsurface flow (SSF) during the high intensity sprinkling experiments because the fine-textured clay-rich layer was thinner than at the siliceous study area and because deep percolation into the coarse sediment and carbonate bedrock was stronger. However, during natural rainfall events, SSF was generated on all moraines due to (local) saturation of the soil.

The results of our experiments can be used—together with the results on the changes in overland flow responses (see Maier & van Meerveld, 2021)—to improve landscape evolution models and hydrological models for Alpine areas. The results do not only highlight how soil hydrological characteristics and runoff processes change during landscape evolution but also show that the spatial variability in SSF is high.

**6. Conclusions**

The challenge of decoupling different processes within the soil profile, such as bedrock weathering and overland flow, can be reduced by careful experimental design. The results of our experiments are in line with previous studies on the importance of bedrock weathering and overland flow in shaping landscapes (e.g., Ameli et al., 2017; Anderson et al., 2009). However, our results also highlight the importance of soil properties, such as texture and clay content, in shaping the spatial variability of subsurface flow in alpine landscapes.

**Conflict of Interest**

The authors declare no conflicts of interest relevant to this study.

**Data Availability Statement**

The data described in this article are openly available in the online data repository GFZ Data Services: [https://dataservices.gfz-potsdam.de/panmetaworks/review/5c198b26c936d4a7a5263dbb091db52a8f16b39efb7306f413e79ceee4488/](https://dataservices.gfz-potsdam.de/panmetaworks/review/5c198b26c936d4a7a5263dbb091db52a8f16b39efb7306f413e79ceee4488/).

**References**

Ameli, A. A., Beven, K., Erlandsson, M., Creed, I. F., McDonnell, J. J., & Bishop, K. (2017). Primary weathering rates, water transit times, and concentration-discharge relations: A theoretical analysis for the critical zone. *Water Resources Research, 53*, 942–960. [https://doi.org/10.1002/2016WR019448](https://doi.org/10.1002/2016WR019448)

Amoozegar, A. (1989). A compact constant-head permeameter for measuring saturated hydraulic conductivity of the vadose zone. *Soil Science Society of America Journal, 53*(5), 1356–1361. [https://doi.org/10.2136/sssaj1989.03615995005300050009x](https://doi.org/10.2136/sssaj1989.03615995005300050009x)

Amoozegar, A. (1992). Advances in measurement of soil physical properties: Bringing theory into practice, compact constant head permeameter: A convenient device for measuring hydraulic conductivity, compact constant head permeameter: A convenient device for measuring hydraulic conductivity (pp. 31–42). Soil Science Society of America. [https://doi.org/10.2136/sssaspapub30.c3](https://doi.org/10.2136/sssaspapub30.c3)

Anderson, A. E., Weiler, M., Alila, Y., & Hudson, R. O. (2009). Subsurface flow velocities in a hillslope with lateral preferential flow. *Water Resources Research, 45*, W11407. [https://doi.org/10.1029/2008WR007121](https://doi.org/10.1029/2008WR007121)

Anderson, S. P., Dietrich, W. E., Montgomery, D. R., Torres, R., Conrad, M. E., & Logue, K. (1997). Subsurface flow paths in a steep, unchannelled catchment. *Water Resources Research, 33*, 2637–2653. [https://doi.org/10.1029/97WR02595](https://doi.org/10.1029/97WR02595)
Bachmair, S., & Weiler, M. (2011). New dimensions of hillslope hydrology. In Igarss, (pp. 455–481). Springer. https://doi.org/10.1007/978-94-007-1363-5_23

Bachmair, S., & Weiler, M. (2014). Interactions and connectivity between runoff generation processes of different spatial scales. Hydrological Processes, 28, 1916–1930. https://doi.org/10.1002/hyp.9705

Barthold, F. K., & Woods, R. A. (2015). Stormflow generation: A meta-analysis of field evidence from small, forested catchments. Water Resources Research, 51, 3730–3753. https://doi.org/10.1002/2014WR016221

Beal, L. K., Huber, D. P., Godsey, S. E., Navotnik, S. K., & Lobse, K. A. (2016). Controls on ecohydrologic properties in desert ecosystems: Differences in soil age and volcanic morphology. Geoderma, 271, 32–41. https://doi.org/10.1016/j.geoderma.2016.01.030

Beniston, M. (2012). Impacts of climatic change on water and associated economic activities in the Swiss Alps. Journal of Hydrology, 412–413, 289–296. https://doi.org/10.1016/j.jhydrol.2010.06.046

Bernaconi, S. M., Basuler, A., Bourdón, B., Brunner, I., Bünemann, E., Chris, I., et al. (2011). Chemical and biological gradients along the Damma glacier soil chronosequence, Switzerland. Vadose Zone Journal, 10, 867–883. https://doi.org/10.2136/vzj2010.0129

Beven, K., & Germann, P. (1982). Macropores and water flow in soils. Water Resources Research, 18, 1311–1325. https://doi.org/10.1029/WR018i005p01311

Binder, T. (2019). Entwicklung und Zusammenhang von Abflussreaktion und Wassermenge entlang einer Moränen-Chronosequenz im Gletscherwasserbau der Steingletscher (Master thesis). University of Innsbruck.

Blum, J. D., Gasz, C. A., Jacobson, A. D., & Page Chamberlain, C. (1998). Carbonate versus silicate weathering in the Raikhot watershed within the Southern Siwaliks, India. Geology, 26, 411. https://doi.org/10.1130/0091-7613(1998)026<0411:CVSWTT>2.3.CO;2

Blum, J. D., Gazis, C. A., Jacobson, A. D., & Page Chamberlain, C. (1998). Carbonate versus silicate weathering in the Raikhot watershed within the Southern Siwaliks, India. Geology, 26, 411. https://doi.org/10.1130/0091-7613(1998)026<0411:CVSWTT>2.3.CO;2

Dahlke, H. E., Easton, Z. M., Lyon, S. W., Todd Walter, M., Destouni, G., & Steenhuis, T. S. (2012). Dissecting the variable source area concept—Subsurface flow pathways and water mixing processes in a hillslope. Journal of Hydrology, 400–412, 125–141. https://doi.org/10.1016/j.jhydrol.2011.11.052

D’Amico, M. E., Freppaz, M., Filippa, G., & Zanini, E. (2014). Vegetation influence on soil formation rate in a proglacial chronosequence (Lys Glacier, NW Italian Alps). Catena, 113, 122–137. https://doi.org/10.1016/j.catena.2013.10.001

Egli, M., Mavris, C., Mirabella, A., & Giaccai, D. (2010). Chlorite formation along a chronosequence in the Morteratsch proglacial area (Pontresina, Switzerland): Straight forward or chaotic? Flora-Morphology, Distribution, Functional Ecology of Plants, 205(9), 561–576. https://doi.org/10.1007/s11368-013-0835-7

Egli, M., Lessovaia, S. N., Chistyakov, K., Inozemzev, S., Polekhovsky, Y., & Ganushkin, D. (2015). Microclimate affects soil chemical and mineralogical properties of cold Alpine soils of the Altai Mountains (Russia). Journal of Soils and Sediments, 15, 1420–1436. https://doi.org/10.1007/s11368-013-0838-4

Evans, D. J. A. (1999). A soil chronosequence from neoglacial moraines in western Norway. Geografiska Annaler-Series A: Physical Geography, 81(1), 47–62. https://doi.org/10.1111/j.0043-6736.1999.00048.x

Feyen, H., Leuenberger, J., Papritz, A., Gysi, M., Flühler, H., & Schleppi, P. (1996). Runoff processes in catchments with a small scale topography. Physics and Chemistry of the Earth, 21, 177–181. https://doi.org/10.1016/S0031-9201(96)00079-9

Frey, F. (1965). Geologie der östlich Claridenkette. Fakultät für Biologie, Chemie und Geowissenschaften, Uni- versität Bayreuth, Fakultät für Biologie, Chemie und Geowissenschaften.

Gibson, J. J., Price, J. S., Aravena, R., Fitzgerald, D. F., Maloney, D. (2000). Runoff generation in a hypermaritime bog-forest upland. Hydrological Processes, 14, 2711–2730. https://doi.org/10.1002/1099-1085(20001030)14:27<2711:ADYBP8>2.3.CO;2

Graham, C. B., Woods, R. A., & McDonnell, J. J. (2010). Hillslope threshold response to rainfall: (1) A field based forensic approach. Journal of Hydrology, 383, 65–76. https://doi.org/10.1016/j.jhydrol.2009.12.015

Greinwald, K., Dieckmann, L. A., Schippick, C., Hartmann, A., Scherer-Lorenzen, M., & Gebauer, T. (2021). Vertical root distribution and biomass allocation along proglacial chronosequences in Central Switzerland. Arctic, Antarctic, and Alpine Research, 53, 20–34. https://doi.org/10.1002/1523-0400(2020)1859720

Haga, H., Matsumoto, Y., Matsutani, J., Fujita, M., Nishida, K., & Sakamoto, Y. (2005). Flow paths, rainfall properties, and antecedent soil moisture controlling lags to peak discharge in a granitic unchanneled catchment. Water Resources Research, 41, W12410. https://doi.org/10.1029/2004WR003426
