

Storage-discharge characteristics of an alpine active rock glacier catchment – a multidisciplinary approach applied to the Innere Ölgrube, Austrian Alps

Thomas Wagner¹, Simon Kainz¹, Karl Krainer², and Gerfried Winkler¹

¹University of Graz Faculty of Natural Sciences

²University of Innsbruck

December 23, 2020

Abstract

The active rock glacier “Innere Ölgrube”, and its catchment area (Ötztal Alps, Austria) are assessed using various hydro(geo)logical tools to provide a thorough catchment characterization and to quantify temporal variations in recharge and discharge components. During the period from June 2014 to July 2018, an average contribution derived from snowmelt, ice melt and rainfall of 35,8 %, 27,6 % and 36,6 %, respectively, is modelled for the catchment using a rainfall-runoff model. Discharge components of the rock glacier springs are distinguished using isotopic data as well as other natural and artificial tracer data, when considering the potential sources rainfall, snowmelt, ice melt and groundwater. Seasonal as well as diurnal variations in runoff are quantified and the importance of shallow groundwater within this rock glacier-influenced catchment is emphasized. Water derived from ice melt is suggested to be provided mainly by melting of two small cirque glaciers within the catchment and subordinately by melting of permafrost ice of the rock glacier. The active rock glacier is characterized by a layered internal structure with an unfrozen base layer responsible for groundwater storage and retarded runoff, a main permafrost body contributing little to the discharge (at the moment) by permafrost thaw and an active layer responsible for fast lateral flow on top of the permafrost body. Snowmelt contributes at least 1/3rd of the annual recharge. During droughts, meltwater derived from two cirque glaciers provides runoff with diurnal runoff variations; however, this discharge pattern will change as these cirque glaciers will ultimately disappear in the future. The storage-discharge characteristics of the investigated active rock glacier catchment are an example of a shallow groundwater aquifer in alpine catchments that ought to be considered when analysing (future) river runoff characteristics in alpine catchments as these provide retarded runoff during periods with little or no recharge.

1. INTRODUCTION

Rock glaciers, moraines and talus slopes as the most important alpine coarse-grained sediment deposits may play a critical role in providing groundwater discharge in alpine catchments (besides highly fractured or karstified bedrock aquifers) that sustain baseflow in larger river systems further downstream (Hayashi, 2020). Intact, particularly active rock glaciers on the one hand may store hydrologically valuable ice volumes (Jones et al., 2018) and on the other hand act as shallow groundwater storages or reservoirs in alpine headwaters (Jones et al., 2019; Wagner et al., 2020a; Winkler et al., 2016, 2018). To fully recognize the hydrological cycle in alpine regions, shallow groundwater systems such as rock glaciers need to be better understood in the light of climate change as these water storages / buffers are expected to be more resilient than e.g. ice glaciers (Jones et al., 2019; Wagner et al., 2019). In the last decades, investigations related to the hydro(geo)logy of rock glaciers were thus intensified (e.g. Harrington et al., 2018; Hayashi, 2020; Krainer & Mostler, 2002; Krainer et al., 2007; Winkler et al., 2016) and further research is warranted.

Rock glaciers evolve from active, downslope creeping rock-ice mixtures to inactive (still containing permafrost-ice, but not moving anymore) and further to relict, permafrost ice-free distinct debris accumu-

lations (e.g. Barsch, 1996; Berthling, 2011)). Relict rock glaciers display a complex internal structure (e.g. Zurawek, 2003) and can be characterized as an aquifer with at least a fast and a delayed flow component (Pauritsch et al., 2015, 2017; Winkler et al., 2016). The delayed flow component is related to a fine-grained base layer representing the main shallow groundwater component, whereas lateral flow in the coarser upper layers allows generating a fast flow component.

Geophysical investigations and drillings showed that intact, permafrost-ice containing rock glaciers have an unfrozen base layer underneath the permafrost-ice-debris main body that is up to more than 10 m thick and contains high amounts of fine-grained sediment (Hausmann et al., 2007, 2012; Krainer et al., 2015). This unfrozen base layer is interpreted to be responsible for base flow during longer periods of little to no recharge (e.g. winter; Wagner et al., 2020a). Lateral flow on top of the permafrost body (within the active layer; e.g. Krainer et al., 2007; Winkler et al., 2018) or along channels within the permafrost body (related to talik formation; e.g. Arenson et al., 2010; Zenklusen Mutter & Phillips, 2012) might be responsible for a fast flow component. The actual contribution of potential permafrost ice melt is another component that needs further attention (besides increasing storage capacity due to melting of ice; cf. Rogger et al., 2017). In addition, cirque glaciers or remnants thereof in the upper catchment of a rock glacier provide recharge / melt water which may affect the flow dynamics of rock glacier springs and act as an additional runoff component (e.g. Wagner et al., 2020a) that might decrease when climate warming continues (Shannon et al., 2019).

The aim of this study is to (i) differentiate between various sources of recharge (namely rainfall, snowmelt and ice melt from cirque glaciers within the rock glacier catchment) and (ii) quantify the diurnal and seasonal patterns of the individual contributions in addition to groundwater to the discharge at the rock glacier springs. (iii) The ice melt contribution (from permafrost and cirque glacier) to spring discharge is discussed in the light of climate change and uncertainties of the methods applied. The quantification of individual flow and recharge components is achieved using a multidisciplinary approach and is considered as an important step towards a better understanding of climate change impact in alpine catchments.

2. STUDY AREA

The Innere Ölgrube rock glacier (also known as Ölgrube Süd; “inner” or “southern” as the valley head is towards south) is an active rock glacier located about 1.5 km southeast of the Gepatsch hut in a small, west-facing tributary valley of the Kauner Valley in the western Ötztal Alps of North Tyrol (Austria) at an average elevation of 2582 m a.s.l. with an areal extent of $\sim 0.24 \text{ km}^2$ (Figure 1). The rock glacier catchment area measures $\sim 1.83 \text{ km}^2$ and the bedrock as well as the moraine and talus deposits consist of orthogneiss, paragneiss and mica schists of the Ötztal-Stubai Metamorphic Complex (Hoinkes & Thöni, 1993). Two small cirque glaciers (“western Hintere Ölgruben Ferner” and the “Hintere Ölgruben Ferner”) covering an area of $\sim 0.16 \text{ km}^2$ are (still) present within the catchment (Buckel & Otto, 2018). A small creek evolving from glacier melt water infiltrates a few tens of meters downstream of the lower glacier. Another (very likely the same) creek appears further down below a moraine ridge, which infiltrates at the rooting zone of the rock glacier. The rock glacier is composed of two tongue-shaped lobes with a length of 896 m and a width of 334 m; the northern, larger lobe is composed of orthogneiss debris, the smaller southern lobe of paragneiss and mica schists. Transverse and longitudinal furrows and ridges characterize the distinct surface morphology. The rooting zone is at an elevation of 2727 m and the active front that is up to 70 m high with a steep gradient of $40 - 45^\circ$ is located at an elevation of 2394 m (Berger et al., 2004).

[Insert Figure 1]

At the base of the steep front several springs are developed (Figure 1c; details see Berger et al., 2004; Hausmann et al., 2012; Krainer & Mostler 2002, 2006; Krainer et al., 2007). The rock glacier is active. During the period 2002 – 2005 flow velocities of up to 2.5 m/year were recorded near the front (Krainer & Mostler, 2006). More recent analysis of Groh and Blöthe (2019) based on image tracking are consistent with these observations, indicating a maximum of 1.7 m/year for the period 2003 – 2015. The internal structure of the rock glacier was determined by geophysical methods (ground penetrating radar, seismics and gravimetry; Hausmann et al., 2012). The rock glacier is composed of an active layer with a thickness of 4 – 6 m which is

underlain by the permafrost body (20 – 30 m). Ice-content in the permafrost body ranges from 40 to 60 % (Hausmann et al., 2012). Between the permafrost body and the bedrock an ice-free sediment layer is present, which is 10 – 15 m thick. This unfrozen sediment layer is interpreted to represent a shallow groundwater storage responsible for base flow even during winter (Wagner et al., 2020a).

3. DATA AND METHODS

3.1 Spring hydrograph

Spring discharge data for the time period June 2014 to June 2017 was analysed among other discharge data from active rock glacier springs by Wagner et al. (2020a) using master recession curves based on the approach proposed by Posavec et al. (2017). Fitted recession functions are based on the exponential model of Maillet (1905) and related assumptions are described in more detail in Wagner et al. (2020a). Here we use the same data and add more recent data until July 2018 (Figure 2, to overlap with available natural tracer data). On the one hand, the data are used to calibrate and validate the rainfall-runoff model; on the other hand the data serve as a base for a detailed event water separation in combination with electrical conductivity (EC) and isotopic data.

Water level and EC were measured directly at the gauging station (Figure 1b). The former was converted to discharge by applying a rating curve based on the salt dilution method implemented under a wide range of flow conditions (Heigert, 2018). Several data gaps in the discharge and EC record are due to the harsh alpine environment and related maintenance restrictions (Figure 2). However, the overall dynamics are captured reasonably well and the presented analyses take into account the associated uncertainties. Note that in contrast to the pressure probe, the EC probe fell dry due to low water levels during the winter months as the probe is situated higher than the pressure probe (Figure 2). Precipitation and air temperature were recorded at a measurement interval of 15 min at the meteorological station Weißsee (2464 m a.s.l.; distance ~4 km to the southwest; courtesy of TIWAG). The mean catchment air temperature and precipitation were calculated applying a correction factor of 0.5°C /100 m and 7 % /100 m, respectively, to account for the mean catchment elevation of 2887 m a. s. l. (Kuhn et al., 2013; Wagner et al., 2020a).

[Insert Figure 2]

3.2 Tracers analysis

3.2.1 Artificial tracers

Artificial tracers were applied to infer the connection between glacier input from the meltwater stream and the rock glacier spring. Tracer injection was downstream of the cirque glaciers where the glacier melt water infiltrates into the sediments in the vicinity of the rooting zone of the rock glacier (which is already disconnected from the cirque glaciers; Figure 1b). Two tracer experiments were performed with injection points along the creek that infiltrates into the rooting zone of the rock glacier in two different years (Figure 1b; 2015: distance to the gauging station ~980 m; 2017: distance to the gauging station ~910 m) using fluorescein as a conservative dye tracer. In 2015 25 g of tracer were injected, in 2017 a greater amount of 202,5 g was used. Detection of tracer concentrations was done using a field fluorometer GGUN-FL30 (Abilla Co.; Schnegg, 2002) installed at the gauging station. Linear flow velocities were calculated based on the observed peak tracer concentration as well as on the mean tracer residence time using the method of moments (Kreft & Zuber, 1978).

3.2.1 Natural tracers

Time series of EC available at the gauging station were used in combination with individual samples analysed for EC and stable isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) taken during various field trips between 31.07.2017 and 15.09.2017. These samples include glacial meltwater (4 samples), a cumulative rainfall sample collected during the same period using a funnel connected via a flexible tube to a bottle (placed 1 m deep within the coarse blocky surface to avoid evaporation by direct radiation), as well as 18 samples taken by an automatic sampler between 01.08.2017 and 06.08.2017 (Figure 2; sampling locations indicated in Figure 1b). During field

campaigns no direct access to permafrost ice (below the active layer) was obtained, so the actual signature of permafrost ice in this catchment remains unknown.

Natural tracer data (EC, isotopes) allow to determine variations in event water contributions from the endmembers of rain, snowmelt and ice melt (e.g. Winkler et al., 2016). The restricted rock-water interaction in the alpine catchment composed of metamorphic bedrock allows regarding EC as a conservative tracer (cf. Winkler et al., 2016). Based on this assumption a two component mixing model was applied to identify groundwater and event water components at diurnal and seasonal time scales (Harrington et al., 2018; Williams et al., 2006; Winkler et al., 2016). The event water component is composed of low mineralized rainfall, snowmelt and glacier ice melt, which is distinguishable from the higher mineralized groundwater component.

3.3 Rainfall-Runoff Modelling

For a better understanding of the discharge pattern and to further constrain the contribution of rainfall, snowmelt and ice melt within the rock glacier catchment, a parsimonious lumped parameter rainfall-runoff model was deployed. The model was successfully applied for a relict rock glacier and catchments downstream of relict rock glaciers by Wagner et al. (2016) and was shown to be especially valuable in alpine catchments where input data are usually scarce (e.g. Wagner et al., 2013, 2016). Here, the model was extended by an ice store module (Figure 3) to account for ice melt within the spring catchment. The module is based on a degree-day factor and contributes ice melt as input in the production store if seasonal snow is melted as described in Nepal et al. (2017). This model setup relates ice melt to melt from glaciers and not from permafrost. For simplicity the initial glacier ice water volume is assumed to be large so that over the analysed period of more than 4 years, ice melt is warranted. The actual percentage of runoff contribution within the catchment is related to the areal coverage of the cirque glaciers within the total catchment of $\sim 10\%$ (Figure 1b) and is assumed to remain constant over the time period of 4 years. Input data for the model are daily values of precipitation and average temperature for the catchment.

Discharge data from the gauging station are used to calibrate and validate the model using split sample tests (e.g. Klemes, 1986). The results are compared to the hydrograph analyses and natural and artificial tracer data thereby allowing to differentiate the various input (“recharge”) components over time (in contrast to the other data that indicate discharge variations). Moreover, the model is then used to hypothetically remove/ignore the cirque glacier ice stores and explore potential changes in the runoff characteristics. In addition, the model parameters representing a relict rock glacier (Wagner et al., 2016) can be used to account for a hypothetical decay from an active to a relict rock glacier (a trading space-for-time approach accounting for changing watershed behaviour; Singh et al., 2011) and observe a potential change in storage-discharge characteristics.

[Insert Figure 3]

3.4 Glacier mass loss

The reduction in the areal extents of the two cirque glaciers within the rock glacier catchment was calculated for the time period 2006 to 2015 (Figure 1b) using the glacier inventories GI3 of Fischer et al. (2015) and GI4 of Buckel and Otto (2018)). The corresponding ice volume loss was estimated based on a thickness-area scaling relation (e.g. Chen & Ohmura, 1990; discussed in Azocar & Brenning, 2010). Assuming a linear trend in volume loss for the 9 years between the two glacier extents, an estimated annual average ice loss was computed. Assuming further an ice density of $\sim 900 \text{ kg/m}^3$, the water equivalent lost per year was estimated.

This order of magnitude estimate is used as a plausibility check for the glacier ice melt water contribution of the rainfall-runoff model as no direct information on the runoff from the cirque glaciers is available.

4. RESULTS AND INTERPRETATION

4.1 Discharge components

Figure 4 depicts the updated hydrograph analysis of Wagner et al (2020a), extended by an additional year of data. Master recession curves derived from single recessions to infer a theoretical recession curve over a long period of time indicate at least a fast and a slow flow component. Importantly, runoff at the rock glacier springs is still present in winter (base flow) with a discharge of a few l/s. The additional data strengthen the results of Wagner et al. (2020a), who related this base flow to the unfrozen base layer of the active rock glacier (Hausmann et al., 2012). In general, the variable discharge behaviour ranging from 6,5 l/s up to 718 l/s with a discharge ratio of 110 (Q_{max}/Q_{min}) is similar to the pattern observed at karst springs (e.g. Wagner et al., 2020a; Winkler et al., 2016).

[Insert Figure 4]

The results of the artificial tracer tests indicate a fast flow component exhibiting a mean residence time of around 9 hours (Figure 5; 2015: 9:16 hrs; 2017: 8:41 hrs). When the tracer was injected into the glacial meltwater creek, this locally infiltrating meltwater significantly contributes to the fast flow component. Peak flow velocities during the 2015 (recovery rate 45,8 %) and 2017 (recovery rate 40,0 %) tests were 0,061 and 0,047 m/s, respectively, while the mean flow velocity was 0,029 m/s during both tests.

[Insert Figure 5]

The seasonal variations in discharge components are deciphered using natural tracers. EC measured at the gauging station ranges from 68 to 281 $\mu\text{S}/\text{cm}$, indicating an average event water contribution of 42,6 %. The measured EC of glacial meltwater ranges from 1.2 to 4 $\mu\text{S}/\text{cm}$, while the measured EC of a single precipitation sample within the catchment is 42 $\mu\text{S}/\text{cm}$ (sampling sites indicated in Figure 1b). The event water end member of the two component mixing model is therefore assigned an EC of 20 $\mu\text{S}/\text{cm}$, similar to values used in alpine catchments by Wetzel (2003) and Winkler et al. (2016). The ground water EC is parametrized using the highest measured EC at the gauging station (281 $\mu\text{S}/\text{cm}$, measured at a discharge of 22 l/s on 5.11.2015). Presumably, even higher EC values would have been measured if the EC probe would not have fallen dry during the winter months characterized by very low discharge.

In general EC and discharge are inversely correlated (Figure 6). The overall variation in discharge components reflects the superposition of several regularly repeating patterns, exhibiting periods ranging from one day to one year (Heigert, 2018). Following the onset of snowmelt in spring, the event water contribution increases until discharge reaches its maximum in early summer (Figure 6a). The exact event water contribution is strongly dependent on local weather conditions, reflecting the variable snowmelt intensity in response to air temperature (note variability in both discharge and EC/event water share during May in Figure 6a). Maximum discharge (several hundred l/s) is reached in early summer, indicating also the maximum level of storage within the rock glacier. At this time event water accounts for up to 75 % of the total discharge and is subject to pronounced diurnal variations (Figure 6a,b). As summer progresses the overall discharge decreases and the event water share reduces accordingly, resulting in a mean contribution of ~60 % during the summer months. Prominent peaks after heavy rainfall on melting snow cover (early summer) and intense thunderstorms (late summer) are superimposed on this pattern, while peak magnitude decreases steadily during summer (Figure 6a,b). Dry, warm summer periods induce pronounced diurnal variation in EC mirroring the diurnal discharge variations (Figure 6b,c). Declining air temperatures strongly reduce discharge as well as event water contribution and attenuate diurnal variations - temporarily during the summer months (Figure 6a around 23.6.2017) but persistently at the beginning of autumn (Figure 6b around 1.9.2017). After the onset of snowfall, spring flow steadily declines and groundwater contribution increases towards 100 % until the next snowmelt in early spring, occasionally intermitted by single peaks in response to warm rainfall events (Figures 2, 6b).

[Insert Figure 6]

Figure 6c depicts the periodic variations in discharge and natural tracers during a dry, warm summer period in early August 2017, following a heavy precipitation event in late July. The time lag between the diurnal air temperature maximum and peak discharge equals 16 hours. Since snow was absent in the catchment, the periodicity is caused by ice melt responding to diurnal variations in radiation and air temperature. Note

that EC and $\delta^{18}\text{O}$ are inversely correlated to discharge due to the dilution with ice melt water exhibiting low EC ($\sim 2 \mu\text{S}/\text{cm}$) compared to groundwater ($281 \mu\text{S}/\text{cm}$), confirmed by the corresponding variation in $\delta^{18}\text{O}$. However, differentiating permafrost ice melt from cirque glacier ice melt is not possible due to the lack of data concerning the former.

While the two component mixing model indicates a mean event water contribution of 65 % during the period depicted in Figure 6c, plotting EC against $\delta^{18}\text{O}$ allows a more detailed analysis of the event water component (Fig. 6d). The observable hysteresis clearly indicates a dynamically changing composition of the event water component (Harrington et al., 2018; Williams et al., 2006). The diurnal variation introduced by periodic dilution of groundwater with meltwater is superimposed on a general trend towards lower $\delta^{18}\text{O}$ values (Figure 6c). This trend indicates a progressive shift from rainwater (around -8.05 towards ice meltwater (around -15.3 component. Decreasing rainwater contributions correspond to continued runoff since the last heavy rainfall event on 29.7.2017. A minor rainfall event that occurred during the night from Aug. 4 to Aug. 5, 2017 (Figure 6c) immediately shifts the diurnal cycle towards higher $\delta^{18}\text{O}$ values on Aug. 5, 2017 (Figure 6d). The simple two component mixing model is merely a projection of the actual mixing process involving multiple sources as well as temporary storage within the catchment (see section 4.2).

4.2 Recharge components / Discharge pattern

Applying the lumped-parameter rainfall-runoff model yields satisfactorily results visually (Figure 7) as well as expressed in average Nash-Sutcliffe efficiency (NSE) criteria (89.6%; Nash & Sutcliffe, 1970). NSE values using a split sample test (Klemes, 1986), where the model is calibrated on the first half of the available data set, validated on the second half and vice versa and compared to the complete data set are shown in Table 1 for calibration and validation periods. The model performs in a similar way as for the relict Schöneben rock glacier (NSE of 89.5%; Wagner et al., 2016). An average Nash-Sutcliffe efficiency (NSE) criteria is computed using a combination of the classic Nash-Sutcliffe efficiency criterion (Nash & Sutcliffe, 1970) and the modified Nash-Sutcliffe criteria based on log-transformed and square root-transformed discharges (see Wagner et al., 2013, 2016). Also here, the physical relevance of model parameters is stressed (Mouelhi et al., 2006; Wagner et al., 2013, 2016). Table 2 shows the model parameter set from the best-fit model for the catchment of the active rock glacier Innere Ölgrube as well as the parameter set from the relict Schöneben rock glacier catchment (cf. Wagner et al. 2016). Comparable to the results of the relict Schöneben rock glacier catchment, a relatively large routing store (x3) is needed to achieve acceptable model fits. This is suggested to be related to the unfrozen base layer within the rock glacier, which was shown to exist by Hausmann et al. (2012) and interpreted to be the dominant shallow aquifer within the spring catchment (Wagner et al., 2020a). The production storage (x1; or soil moisture accounting store) is even smaller than that of the Schöneben rock glacier catchment. Again, this relates physically to the fact that the Innere Ölgrube catchment is basically a bare rock / debris field and evapotranspiration is limited. Interestingly, model parameters x1 to x4 are not very different to those of the relict Schöneben rock glacier catchment. These implications will be picked up later in the discussion section.

[Insert Figure 7]

[Insert Table 1]

[Insert Table 2]

The rainfall-runoff model for the Innere Ölgrube rock glacier spring catchment allows a quantification of relative input of rainfall, snow- and ice melt (Figure 7). The input fractions of rainfall, snowmelt and ice melt for the observed period of time are 36,6, 35,8 and 27,6%, respectively. It has to be noted, that ice melt is considered to be derived mainly from the melt of the cirque glaciers as indicated by artificial and natural tracer analyses (see discussion section). Berger et al. (2004) also reported about 30% of the rock glacier spring runoff to be related to the glacier melt water and serves as an independent (admittedly vague) information.

4.3 Glacier mass loss estimates from glacier inventories

Applying the formula provided by Chen and Ohmura (1990) to compute glacier thickness for the area estimates of the two cirque glaciers of the two glacier inventories, a loss of 1135708 m³ over the time period 2006 to 2015 was calculated, which is 126190 m³ on average per year. This is the same order of magnitude and about twice of what is “needed” in the rainfall-runoff model for the years 2015-2018; however the areal extents of the cirque glaciers are even smaller by now and moreover the difference between ablation and actual melt needs to be considered. Sublimation is not considered here and therefore ablation estimates from the area-thickness relation will be higher than the glacier melt water “input” estimated in the rainfall-runoff model. Moreover, the positive exchange term in the rainfall-runoff model allows for additional “inflow” (x2 being positive; Table 2). The data analysis allows an order of magnitude consistency check, but not more. Approximately 30% of the recharge are derived from melt water of the cirque glaciers. When considering this rather significant contribution, a future glacier loss is supposed to have a significant impact on the runoff pattern.

5. DISCUSSION

Despite the obvious difficulty of gathering data in high alpine catchments, the complementary information derived from natural and artificial tracer data and from a rainfall-runoff model (i.e. a water balance) allowed a thorough quantification of recharge and discharge components of the catchment of the active rock glacier Innere Ölgrube at present. Recharge components vary seasonally as well as diurnally reflecting varying contributions from rainfall, snowmelt and ice melt. Discharge components are delayed to a certain extent due to the storage capabilities of the shallow aquifer within the rock glacier catchment (Wagner et al., 2020a), depending on the flow paths and saturation status of the groundwater body (Winkler et al., 2016, 2018).

The tracer velocities are in the range of reported values in active layers (Buchli et al., 2013; Krainer & Mostler, 2002; Tenthorey, 1992). The low recovery rate (< 50 %) likely indicates that some of the tracer is lost to the deeper domains of the rock glacier (potentially the unfrozen base layer). The tracer is presumably stored there for a longer period of time, thereby preventing it from reaching the measurement device at a detectable concentration within the observation period. Yet, the fast recovery of at least 40% of the tracer clearly indicates a fast flow component likely related to lateral flow on top of the permafrost table towards the rock glacier spring. This is also reflected in the hydrograph analysis. Concerning the slow flow component related to the unfrozen sediment layer (subpermafrost flow) at the base of the rock glacier and potentially other fine sediments within the catchment (e.g. till deposits and moraines between the cirque glaciers and the rock glacier) EC and isotopic data was analysed.

Figure 8 depicts the seasonal variations in individual “recharge” and discharge component contributions. “Recharge” is inferred from the rainfall-runoff model (Figure 8a) and does not take the loss due to evapotranspiration into account, as this process is happening in the production store (Figure 3) where the different input components are already mixed and evapotranspiration is dependent on the saturation / water level within that store. Nevertheless, evapotranspiration is limited in such an alpine environment. Discharge is inferred from event water analysis (Figure 8b), where higher mineralized water (higher EC) is related to longer stored water within the groundwater body and low mineralized water is related to event water derived from snowmelt, ice melt or rainfall. The actual differentiation of event water into rainfall, snowmelt and ice melt is not possible for that time frame (see Figure 6c,d for a detailed analysis over a short period of time using isotopic data in addition to EC).

Combining the information of Figure 8a and 8b allows for an interesting interpretation:

The groundwater component (longer stored water within the aquifer) is the most important component during periods of little to no recharge (e.g. winter time; Wagner et al., 2020a). Snowmelt and (subordinately) rainfall are the dominant recharge components during early summer, rapidly increasing the event water contribution to ~60 %. In particular during the summer with little to no rain and after snow has melted, ice (glacier or permafrost ice) runoff and groundwater discharge become the relevant components. Separating groundwater and ice melt water due to the diurnal pattern of melting process (related to variations in air temperature) is possible. The pronounced change in discharge pattern in early autumn observable in

Figure 6b (reduced discharge and attenuated diurnal variations caused by declining air temperatures in early September) indicates the transition from the event-water dominated period (late April - August) to the groundwater dominated period (September until onset of the snowmelt in April-early May). Some caution is required when interpreting relative discharge component contributions during the onset of snowmelt in April (Figure 8), since the only available EC time series during that month starts on April 25, 2018. Thus, the groundwater contribution during (early) April is likely underestimated in Figure 8.

[Insert Figure 8]

To identify and quantify the main source of the ice melt water potentially from permafrost ice melt or from the upper cirque glaciers is more complex. Natural and artificial tracer test results show that event water travels through the rock glacier within several hours. Ice-derived meltwater can be observed with a time lag in the order of ~ 16 hours relative to air temperature indicated by EC and isotopic data (Figure 6c). This time lag in combination with the fast response due to event water suggests some distance of the melt water source to the spring/rock glacier and favour the cirque glaciers as the main melt water source. This is further substantiated by comparing the time lag to the artificial tracer test results: The linear distance between the lowermost point of the cirque glacier and the gauging station is approximately 1500 m, indicating an actual flow distance ~ 1500 m. Typically, runoff from glaciers reaches a maximum a few hours after the peak in meltwater production (Cuffey & Paterson, 2010), thus the runoff peak at the glacier precedes the peak at the gauge by ~ 16 h. Both estimates suggest that the water travels from the front of the glacier to the gauging station at a velocity $\sim 0,026$ m/s. This is in good agreement with the artificial tracer test results yielding slightly higher linear velocities. Note also that melting rates at the cirque glaciers reflect diurnal variations in radiation, heat and vapour content of the adjacent air (Cuffey & Paterson, 2010). The coarse grained active layer covering the permafrost ice within the catchment protects it from radiation and induces a damped and retarded variation in temperatures, decoupling it from external weather and climate conditions (Haeberli, 1985; Jones et al., 2019; Vonder Muhll, 1993; Wagner et al., 2019). Accordingly, melting of permafrost ice is expected to follow changes in atmospheric conditions in a more damped and retarded fashion, suggesting cirque glacier melting to account for the observed diurnal variation in discharge and natural tracers.

The amount of ice melt is in the order of 30% of the annual recharge and will decrease and finally disappear in the future due to glacier melt. Thus, ignoring ice contribution from cirque glacier melt is hypothetical, but interesting at least. This can be assessed by using the calibrated rainfall-runoff model and assuming that ice melt from the cirque glaciers is absent due to potential future complete glacier melt (green line in Figure 9). This was simulated in a simplified manner by actually eliminating the (glacier) ice storage, keeping all the other parameters constant. Increasing runoff during snowmelt periods does not change expectedly; however, the runoff in late summer indicates a certain reduction. Interestingly, base flow during winter months does not change significantly. This is an important finding that further supports that base flow is mainly derived from the unfrozen base layer of the rock glacier (and other fine-grained sediments in the catchment area (e.g. till deposits, moraines); cf. Wagner et al., 2020a). In total, a runoff reduction of almost 30% is expected in this hypothetical scenario due to the disappearance of the cirque glaciers.

Another hypothetical scenario can be constructed by applying the model parameters of a relict rock glacier where the same model was already applied (Table 2; cf. Wagner et al., 2016) for the current setting of the active rock glacier. This trading space-for-time approach accounting for changing watershed behaviour under permafrost-free conditions (Singh et al., 2011) allows to speculate how progressing climate change might influence the discharge pattern, considering the associated uncertainties (purple line in Figure 9).

[Insert Figure 9]

Changes are not great and only a slightly more buffered behavior during storm events or snowmelt periods is visible compared to the scenario where only the ice melt from the glaciers is neglected. Interestingly, slightly slower recessions at the onset of winter periods are observable. This can be explained by a higher routing store $\times 3$ for the relict (Schoneben) rock glacier catchment than the active (Innere Olgrube) rock glacier catchment. This might indicate an increase in storage capacities as permafrost thaw potentially

leads to more available pore space in the shallow aquifer system (cf. Rogger et al., 2017). Nevertheless, in the case of the relict Schoneben rock glacier as well as for the active Innere Olgrube rock glacier, both are known to have a rather fine-grained, unfrozen base layer that is 10-15 meters thick. These similarities might explain their rather similar behavior, although one may speculate about a further increase in storage capacity within the Innere Olgrube catchment as permafrost thaws eventually. This potential change is depicted by computing the master recession curves of the modelled runoff patterns for the “current” data, the hypothetical scenario of vanished cirque glaciers and the other hypothetical scenario of a relict rock glacier (Figure 10). The comparison to the observed data further indicates the good model fit in addition to the efficiency criteria and visual fit of the hydrographs presented before (and shown again in the inset). The similar master recession curves of the “current” data and the hypothetical one without the glacier ice melt is to be expected, as the actual internal (or model) structure did not change, but only a recharge component was “removed”. The discharge pattern and consequently master recession curve of the hypothetically relict rock glacier catchment (using the parameter set of the relict Schoneben rock glacier; Wagner et al., 2016) indicates a slightly slower recession during winter periods as storage capabilities increased.

[Insert Figure 10]

What remains to be identified is the actual contribution of permafrost ice melt at present and future changes in the runoff pattern due to this additional water in the short term and potential increases in the storage capacity in the long term when the permafrost ice will melt completely. The trading space for time approach presented herein does suggest a slight difference in runoff patterns and supports what was suggested by Rogger et al. (2017): Runoff might be dampened slightly and storage capacities might increase to some extent. However, further research addressing this particular case and ideally monitoring rock glacier catchments without the influence of cirque glaciers within their catchment is needed. Colombo et al. (2018) suggest establishing baselines for future monitoring related to downstream water quality (and quantity) as solute export from deteriorating rock glaciers might provide valuable information.

In alpine catchments, rock glaciers should be seen as hydro(geo)logically (and geomorphologically) conservative systems (Giardino et al., 1992) that become increasingly important as ice glaciers will continue to vanish. For a recent assessment of potential changes in the European mountain cryosphere until the end of the 21st century, see Beniston et al. (2018). There, improvements in understanding changes in re- as well as discharge in high-alpine areas are warranted. The here gathered information and developed understanding of a high-alpine spring catchment that drains an active rock glacier and two cirque glaciers is of importance and should be extended by including downstream observations (cf. Wagner et al., 2016). Another open question remains the actual contribution of permafrost ice melt relative to the glacier ice melt and becomes increasingly important with regard to climate change and a likely further warming trend. A recent review about potential ecosystem shifts in alpine streams highlights the importance of a better understanding of permafrost / rock glacier thaw (Brighenti et al., 2019). Therefore, long-term monitoring of such high-alpine catchments (and streams further downstream) are essential.

6. CONCLUSIONS

Applying a number of “standard” hydrogeological tools in a high alpine catchment allows the differentiation of multiple recharge sources for and subsequently delayed discharge from a shallow groundwater aquifer, i.e. an active rock glacier. Faster flow through the system is accomplished by supraperafrost, whereas slower flow by subpermafrost; although intermediate flow paths are to be expected and indicate the complex internal structure of these landforms. Groundwater contribution does play an important role in rock glacier spring discharge, especially during the winter months or periods of little recharge. Ice melt contribution from cirque glaciers within the catchment of the rock glacier spring mask the potential – but likely still negligible – influence of permafrost ice melt during snow-free periods. A future scenario with vanished cirque glaciers, diminishing amounts of permafrost ice within the rock glacier and thereby increasing storage capacity of the shallow groundwater store within the rock glacier might suggest an increasing importance of these (ice-) debris accumulations in shaping the runoff pattern of alpine catchments.

The storage-discharge characteristics of the investigated active rock glacier catchment is an example of a shallow groundwater aquifer in alpine catchments that ought to be considered when analysing (future) river runoff characteristics in alpine catchments as these provide retarded runoff during periods with little to no recharge. The provided steady baseflow and delayed release of water within such an alpine catchment is crucial to understand and critical to sustain ecological diversity in the light of climate change.

ACKNOWLEDGEMENTS

This work was co-funded by the Austrian Federal Ministry of Agriculture, Regions and Tourism (former Federal Ministry of Sustainability and Tourism) and the Federal States of Vorarlberg, Tyrol, Salzburg, Styria and Carinthia within the DaFNE projects RGHeavyMetal (Nr. 101093) and RG-AlpCatch (Nr. 101561). Digital elevation models were provided by the GIS Service of the Federal Government of Tyrol.

REFERENCES

- Arenson, L.U., Hauck, C., Hilbich, C., Seward, L., Yamato, Y., & Springman, S. (2010). Sub-surface Heterogeneities in the Murtel – Corvatsch Rock Glacier, Switzerland. In: Canadian Geotechnical Society (eds.): Proceedings of the joint 63rd Canadian Geotechnical Conference and the 6th Canadian Permafrost Conference. Calgary, Alberta, S. 1494–1500.
- Azocar, G.F., & Brenning, A. (2010). Hydrological and geomorphological significance of rock glaciers in the dry Andes, Chile (27°–33°S). *Permafrost and Periglacial Processes*, 21(1), 42–53. <https://doi.org/10.1002/ppp.669>
- Barsch, D. (1996). *Rockglaciers: Indicators for the Present and Former Geoecology in High Mountain Environments*. Springer Series in Physical Environment, vol. 16. Springer, Berlin (1996).
- Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L. M., Coppola, E., Eckert, N., Fantini, A., Giacona, F., Hauck, C., Huss, M., Huwald, H., Lehning, M., Lopez-Moreno, J.-I., Magnusson, J., Marty, C., Moran-Tejeda, E., Morin, S., Naeim, M., Provenzale, A., Rabatel, A., Six, D., Stotter, J., Strasser, U., Terzago, S., & Vincent, C. (2018). The European mountain cryosphere: a review of its current state, trends, and future challenges. *The Cryosphere*, 12, 759–794. <https://doi.org/10.5194/tc-12-759-2018>
- Berger, J., Krainer, K., & Mostler, W. (2004). Dynamics of an active rock glacier (Oetztal Alps, Austria). *Quaternary Research*, 62(3), 233–242. <https://doi.org/10.1016/j.yqres.2004.07.002>
- Berthling, I. (2011). Beyond confusion: Rock glaciers as cryo-conditioned landforms. *Geomorphology*, 131, 98–106. <https://doi.org/10.1016/j.geomorph.2011.05.002>
- Brighenti, S., Tolotti, M., Bruno M.C., Warthon, G., Pusch, M.T., & Bertoldi, W. (2019). Ecosystem shifts in Alpine streams under glacier retreat and rock glacier thaw: A review. *Science of the Total Environment* 675, 542–559. <https://doi.org/10.1016/j.scitotenv.2019.04.221>
- Buchli, T., Merz, K., Zhou, X., Kinzelbach, W., & Springman, S. (2013). Characterization and Monitoring of the Fuggwanghorn Rock Glacier, Turtmann Valley, Switzerland: Results from 2010 to 2012. *Vadose Zone Journal* 12(1). <https://doi.org/10.2136/vzj2012.0067>
- Buckel, J., & Otto, J.-C. (2018). The Austrian glacier inventory GI 4 (2015) in ArcGis (shapefile) format. *Pangaea*, <https://doi.org/10.1594/PANGAEA.887415>. PANGAEA supplement to: Buckel, Johannes; Otto, Jan-Christoph; Prasicek, Gunther; & Keuschnig, Markus (2018): Glacial lakes in Austria - Distribution and formation since the Little Ice Age. *Global and Planetary Change*, 164, 39–51
- Chen J, & Ohmura, A. (1990). Estimation of Alpine glacier water resources and their change since the 1870s. In *Hydrology in Mountainous Regions, I – Hydrological Measurements; the Water Cycle*, Proceedings of two Lausanne Symposia, August 1990, Lang H, Musy A (eds). IAHS Press: Wallingford, Oxfordshire, UK 193, 127–135.

- Colombo, N., Salerno, F., Gruber, S., Freppaz, M., Williams, M., Fratianni, S., & Giardino, M. (2018). Review: impacts of permafrost degradation on inorganic chemistry of surface fresh water. *Global and Planetary Change*, 162, 69–83. <https://doi.org/10.1016/j.gloplacha.2017.11.017>.
- Cuffey, K. M., & Paterson, W. S. B. (2010). *The Physics of Glaciers*. 4th ed. Elsevier Butterworth Heinemann, Burlington, MA.
- Fischer, A., Seiser, B., Stocker-Waldhuber, M., Mitterer, C., & Abermann, J. (2015). In: Fischer, A. (Ed.), *The Austrian Glacier Inventories GI 1 (1969), GI 2 (1998), GI 3 (2006), and GI LIA in ArcGIS (Shapefile) Format*. PANGAEA; Supplement to: Fischer, Andrea; Seiser, Bernd; Stocker-Waldhuber, Martin; Mitterer, Christian; & Abermann, Jakob (2015): Tracing glacier changes in Austria from the Little Ice Age to the present using a lidar-based high-resolution glacier inventory in Austria. <https://doi.org/10.1594/PANGAEA.844988>.
- Giardino, J.R., Vitek, J.D., & Demorett, J.L. (1992). A model of water movement in rock glaciers and associated water characteristics. In: Dixon, J.C., Abrahams, A.D. (Eds.): *Periglacial Geomorphology*. Wiley, Chichester, pp. 159–184.
- Groh, T., & Blothe, J.H. (2019). Rock glacier kinematics in the Kaunertal, Otztal Alps, Austria. *Geosciences*, 9, 373. <https://doi.org/10.3390/geosciences9090373>
- Haeberli, W. (1985). Creep of mountain permafrost. Internal structure and flow of alpine rock glaciers. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zurich*, 77. Eidgenössische Technische Hochschule, Zurich.
- Harrington, J.S., Mozil, A., Hayashi, M., Bentley, L.R. (2018). Groundwater flow and storage processes in an inactive rock glacier. *Hydrological Processes*, 32, 3070–3088. <https://doi.org/10.1002/hyp.13248>
- Hausmann, H., Krainer, K., Bruckl, E., & Mostler, W. (2007). Internal structure and ice content of Reichenkar Rock Glacier (Stubai Alps, Austria) assessed by geophysical investigations. *Permafrost and Periglacial Processes*, 18, 351–367. <https://doi.org/10.1002/ppp.601>
- Hausmann, H., Krainer, K., Bruckl, E., & Ullrich, C. (2012). Internal structure, ice content and dynamics of Olgrube and Kaiserberg rock glaciers (Otztal Alps, Austria) determined from geophysical surveys. *Austrian Journal of Earth Sciences* 105(2), 12–31.
- Hayashi, M. (2020). Alpine Hydrogeology: The Critical Role of Groundwater in Sourcing the Headwaters of the World. *Groundwater*, 58(4), 498–510. <https://doi.org/10.1111/gwat.12965>
- Heigert, K. (2018). Speicherverhalten und Abflussdynamik aktiver Blockgletscher am Beispiel „Olgrube Sud“, Kaunertal [storage and discharge dynamics of active rock glaciers, example „Olgrube Sud“, Kaunertal valley]. *Beiträge zur Hydrogeologie*, 62, 33–42.
- Hoinkes, G., & Thoni, M. (1993). Evolution of the Otztal-Stubai, Scarl-Campo and Ulten basement units. In: von Raumer, J.F., Neubauer, F. (eds.) *Pre-Mesozoic Geology in the Alps*, pp. 485–494. Springer, Berlin, Heidelberg
- Jones, D.B., Harrison, S., Anderson, K., Selley, H.L., Wood, J.L., & Betts, R.A. (2018). The distribution and hydrological significance of rock glaciers in the Nepalese Himalaya. *Global and Planetary Change*, 160, 123–142. <https://doi.org/10.1016/j.gloplacha.2017.11.005>
- Jones, D. B., Harrison, S., Anderson, K., & Whalley, W. B. (2019). Rock glaciers and mountain hydrology. A review. *Earth-Science Reviews*, 193, 66–90. <https://doi.org/10.1016/j.earscirev.2019.04.001>
- Klemes, V. (1986). Operational testing of hydrological simulation models. *Hydrological Sciences*, 31(1), 13–24. <https://doi.org/10.1080/02626668609491024>
- Krainer, K., & Mostler, W. (2002). Hydrogeology of active rock glaciers: Examples from the Austrian Alps. *Arctic, Antarctic and Alpine Research*, 34(2), 142–149. <https://doi.org/10.1080/15230430.2002.12003478>

- Krainer, K., & Mostler, W. (2006). Flow velocities of active rock glaciers in the Austrian Alps. *Geografiska Annaler: Series A, Physical Geography*, 88, 267–280. <https://doi.org/10.1111/j.0435-3676.2006.00300.x>
- Krainer, K., Mostler, W., & Spotl, C. (2007). Discharge from active rock glaciers, Austrian Alps; a stable isotope approach. *Austrian Journal of Earth Sciences*, 100, 102–112.
- Krainer, K., Bressan, D., Dietre, B., Haas, J. N., Hajdas, I., Lang, K., Mair, V., Nickus, U., Reidl, D., Thies, H., & Tonidandel, D. (2015). A 10,300-year-old permafrost core from the active rock glacier Lazaun, southern Otztal Alps (South Tyrol, northern Italy). *Quaternary Research*, 83(2), 324–335. <https://doi.org/10.1016/j.yqres.2014.12.005>
- Kreft, A., & Zuber, A. (1978). On the physical meaning of the dispersion equation and its solutions for different initial and boundary conditions. *Chemical Engineering Science*, 33(11), 1471–1480. [https://doi.org/10.1016/0009-2509\(78\)85196-3](https://doi.org/10.1016/0009-2509(78)85196-3)
- Kuhn, M., Kuhn M., Dreiseitl E., & Emprechtinger M. (2013). Temperatur und Niederschlag an der Wetterstation Obergurgl, 1953-2011. In Koch, E.M. Erschbamer, B. (eds.): *Klima, Wetter, Gletscher im Wandel*. Innsbruck university press (Alpine Forschungsstelle Obergurgl, 3), ISBN 978-3-902811-89, 9, 11–30.
- Maillet, E. (1905). *Essais d'hydraulique souterraine et fluviale*. Librairie Scientifique A. Hermann, Paris
- Mouelhi, S., Michel, C., Perrin, C., & Andreassian, V. (2006). Stepwise development of a two-parameter monthly water balance model. *Journal of Hydrology*, 318, 200–214. <https://doi.org/10.1016/j.jhydrol.2005.06.014>
- Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I – A discussion of principles. *Journal of Hydrology*, 10(3), 282–290. [https://doi.org/10.1016/0022-1694\(70\)90255-6](https://doi.org/10.1016/0022-1694(70)90255-6)
- Nepal, S., Chen, J., Penton D.J., Neumann, L.E., Zheng, H., & Wahid, S. (2017). Spatial GR4J conceptualization of the Tamor glaciated alpine catchment in Eastern Nepal: evaluation of GR4JSG against streamflow and MODIS snow extent. *Hydrological Processes*, 31, 51–68. <https://doi.org/10.1002/hyp.10962>
- Pauritsch, M., Birk, S., Wagner, T., Hergarten, S. & Winkler, G. (2015). Analytical approximations of discharge recessions for steeply sloping aquifers in alpine catchments. *Water Resources Research*, 51, 8729–8740. <https://doi.org/10.1002/2015WR017749>
- Pauritsch, M., Wagner, T., Winkler, G. & Birk, S. (2017). Investigating groundwater flow components in an Alpine relict rock glacier (Austria) using a numerical model. *Hydrogeology Journal*, 25, 371–383. <https://doi.org/10.1007/s10040-016-1484-x>
- Posavec, K., Giacometti, M., Materazzi, M., & Birk, S. (2017). Method and Excel VBA algorithm for modeling master recession curve using trigonometry approach. *Groundwater*, 55(6), 891–898. <https://doi.org/10.1111/gwat.12549>
- Rogger, M., Chirico, G.B., Hausmann, H., Krainer, K., Bruckl, E., Stadler, P., & Blöschl, G. (2017). Impact of mountain permafrost on flow path and runoff response in a high alpine catchment. *Water Resources Research*, 53, 1288–1308. <https://doi.org/10.1002/2016WR019341>
- Schnegg, P.-A. (2002). An inexpensive field fluorometer for hydrogeological tracer tests with three tracers and turbidity measurement. XXXII IAH & ALHSUD Congress Groundwater and Human Development. Balkema, Mar del Plata, Argentina, pp. 1484–1488.
- Shannon, S., Smith, R., Wiltshire, A., Payne, T., Huss, M., Betts, R., Caesar, J., Koutroulis, A., Jones, D., & Harrison, S. (2019). Global glacier volume projections under high-end climate change scenarios. *Cryosphere*, 13, 325–350. <https://doi.org/10.5194/tc-13-325-2019>
- Singh, R., Wagener, T., van Werkhoven, K., Mann, M.E., & Crane, R. (2011). A trading space-for-time approach to probabilistic continuous streamflow predictions in a changing climate – accounting for changing

- watershed behavior. *Hydrology and Earth System Sciences*, 15, 3591–3603. <https://doi.org/10.5194/hess-15-3591-2011>
- Tenthorey, G. (1992). Perennial neves and the hydrology of rock glaciers. *Permafrost and Periglacial Processes*, 3(3), 247–252. <https://doi.org/10.1002/ppp.3430030313>
- Vonder Muhll, D. S. (1993). Geophysikalische Untersuchungen im Permafrost des Oberengadins [Geophysical investigations of permafrost in the Upper Engadin]. Doctoral Thesis, Eidgenössische Technische Hochschule, Zurich.
- Wagner, T., Mayaud, C., Benischke, R., & Birk, S. (2013). Ein besseres Verständnis des Lurbach-Karstsystems durch ein konzeptionelles Niederschlags-Abfluss-Modell [A better understanding of the Lurbach karst system via a conceptual rainfall-runoff model]. *Grundwasser*, 18, 225–235. <https://doi.org/10.1007/s00767-013-0234-4>
- Wagner, T., Pauritsch, M., & Winkler, G. (2016). Impact of relict rock glaciers on spring and stream flow of alpine watersheds: Examples of the Niedere Tauern Range, Eastern Alps (Austria). *Austrian Journal of Earth Sciences*, 109(1), 84–98. <https://doi.org/10.17738/ajes.2016.0006>
- Wagner, T., Kainz, S., Wedenig, M., Pleschberger, R., Krainer, K., Kellerer-Pirklbauer, A., Ribis, M., Hergarten, S., & Winkler, G. (2019). Wasserwirtschaftliche Aspekte von Blockgletschern in Kristallingebieten der Ostalpen – Speicherverhalten, Abflussdynamik und Hydrochemie mit Schwerpunkt Schwermetallbelastungen (RGHeavyMetal) – Endbericht. Final report, 158 p. <https://www.bmnt.gv.at/wasser/wasserqualitaet/RG-HeavyMetal.html>
- Wagner, T., Pauritsch, M., Mayaud, C., Kellerer-Pirklbauer, A., Thalheim, F., & Winkler, G. (2019). Controlling factors of microclimate in blocky surface layers of two nearby relict rock glaciers (Niedere Tauern Range, Austria). *Geografiska Annaler: Series A, Physical Geography*, 101(4), 310–333. <https://doi.org/10.1080/04353676.2019.1670950>
- Wagner, T., Brodacz, A., Krainer, K., & Winkler, G. (2020a). Active rock glaciers as shallow groundwater reservoirs, Austrian Alps. *Grundwasser*, 25, 215–230. <https://doi.org/10.1007/s00767-020-00455-x>
- Wagner, T., Pleschberger, R., Kainz, S., Ribis, M., Kellerer-Pirklbauer, A., Krainer, K., Philippitsch, R., & Winkler, G. (2020b). The first consistent inventory of rock glaciers and their hydrological catchments of the Austrian Alps. *Austrian Journal of Earth Sciences*, 113(1), 1–23. <https://doi.org/10.17738/ajes.2020.0001>
- Wagner, T., Ribis, M., Kellerer-Pirklbauer, A., Krainer, K., & Winkler, G. (2020c). The Austrian rock glacier inventory RGL1 and the related rock glacier catchment inventory RGCL1 in ArcGis (shapefile) format. PANGAEA, <https://doi.org/10.1594/PANGAEA.921629>
- Wetzel, K.-F. (2003). Runoff production processes in small alpine catchments within the unconsolidated Pleistocene sediments of the Lainbach area (Upper Bavaria). *Hydrological Processes*, 17, 2463–2483. <https://doi.org/10.1002/hyp.1254>
- Williams, M.W., Knauf, M., Caine, N., Liu, F., Verplanck, P.L. (2006). Geochemistry and source waters of rock glacier outflow, Colorado Front Range. *Permafrost and Periglacial Processes*, 17, 13–33. <https://doi.org/10.1002/ppp.535>
- Winkler, G., Wagner, T., Pauritsch, M., Birk, S., Kellerer-Pirklbauer, A., Benischke, R., Leis, A., Morawetz, R., Schreilechner, M.G., & Hergarten, S. (2016). Identification and assessment of groundwater flow and storage components of the relict Schoneben Rock Glacier, Niedere Tauern Range, Eastern Alps (Austria). *Hydrogeology Journal*, 24, 937–953. <https://doi.org/10.1007/s10040-015-1348-9>
- Winkler, G., Wagner, T., Krainer, K., Ribis, M., & Hergarten, S. (2018). Hydrogeology of Rock Glaciers – Storage Capacity and Drainage Dynamics – an Overview. In: Sychev, V.G., & Mueller, L., Novel methods and results of landscape research in Europe, Central Asia and Siberia, Vol II/71, 329–334.

Zenklusen Mutter, E., & Phillips, M. (2012). Thermal evidence of recent talik formation in Ritigraben rock glacier: Swiss Alps. In K. M. Hinkel (Ed.), *Resources and risks of permafrost areas in a changing world*. Proceedings. Vol. 1: international contributions (pp. 479-483). The Northern Publisher.

Zurawek, R. (2002). Internal structure of a relict rock glacier, Sleza Massif, southwest Poland. *Permafrost and Periglacial Processes*, 13, 29–42. <https://doi.org/10.1002/ppp.403>

TABLE LEGENDS

Table 1: Model calibration efficiency criteria NSE [%] using a split sample test.

Table 2: Model parameter sets and model efficiency criteria of the rainfall-runoff model for the active Innere Olgrube and the relict Schoneben rock glacier spring catchments; efficiency criteria are given for the whole time series. For more details on the relict Schoneben rock glacier, refer to Wagner et al. (2016).

FIGURE LEGENDS

Figure 1: Innere Olgrube rock glacier and its catchment area. (a) Location of Innere Olgrube within Austria relative to all 5769 rock glaciers mapped in the Austrian Alps (Wagner et al., 2020b,c). (b) Topographic map of the Innere Olgrube rock glacier and its catchment (red polygon) including the extents of two cirque glaciers for the years 2006 and 2015. Location of the gauging station, of the precipitation and the glacier meltwater samples and the two artificial tracer injection points are depicted. Rock glacier and catchment extents from Wagner et al. (2020b,c); glacier extent from the Austrian glacier inventories GI3 (Fischer et al., 2015) and GI4 (Buckl & Otto, 2018). (c) Field impression of the two tongues of the active Innere Olgrube rock glacier seen from the western side of the Kauner valley viewing towards east. Note the active (unweathered) steep slope of the fronts; the creek (“Schiltibach”) which emerges below is the result of several springs at the base of the rock glacier front.

Figure 2: Data overview. Precipitation and air temperature data (from the Weisssee station (TIWAG) and corrected to the average elevation of the catchment), isotopic data sampled at the gauging station as well as within the spring catchment, electrical conductivity and discharge from the gauging station.

Figure 3: Model structure of the rainfall-runoff model GR4J+ with a daily time step and an additional ice store (modified after Wagner et al., 2016). P = precipitation; T = air temperature; Ts = temperature at which snow starts to fall; Tm = temperature at which snow starts to melt; Cm = melt factor that allows a certain amount of snowmelt per degree temperature increase; Tim = temperature at which ice starts to melt (if snow is absent); Cim = melt factor that allows a certain amount of ice melt per degree temperature increase; Re = extraterrestrial solar radiation; x1 = maximum capacity of the production store; F = groundwater exchange term acting on the fast and slow flow components; x2 = water exchange coefficient; x3 = maximum capacity of the routing store; x4 = time parameter; UH1 and UH2 = unit hydrographs to account for the time lag between rainfall and resulting streamflow that depend on the time parameter x4; Q = runoff simulated by the rainfall-runoff model.

Figure 4: Master recession curve and the interpreted recession coefficients shown as straight lines in a semi-log plot and the spring hydrograph as an inset. Modified after Wagner et al. (2020a) and extended with more recent data (a time period in which also natural tracer data became available).

Figure 5: Artificial tracer breakthrough curve of (a) 2015 and (b) 2017 with a range of tracer recovery reflecting uncertainties in the runoff computation. Note the different scale of the tracer concentration for (a) and (b); tracer recovery and discharge are displayed at the same scale.

Figure 6: Natural tracer data. Runoff separation based on EC related to longer stored / higher mineralized groundwater. (a) Snowmelt period; (b) summer to autumn period with diurnal variations that are shown in more detail in (c) including air temperature, precipitation and isotopic data. (d) Observed hysteresis in EC versus isotopic data indicates dynamic event water composition (ice melt, rainfall, and groundwater).

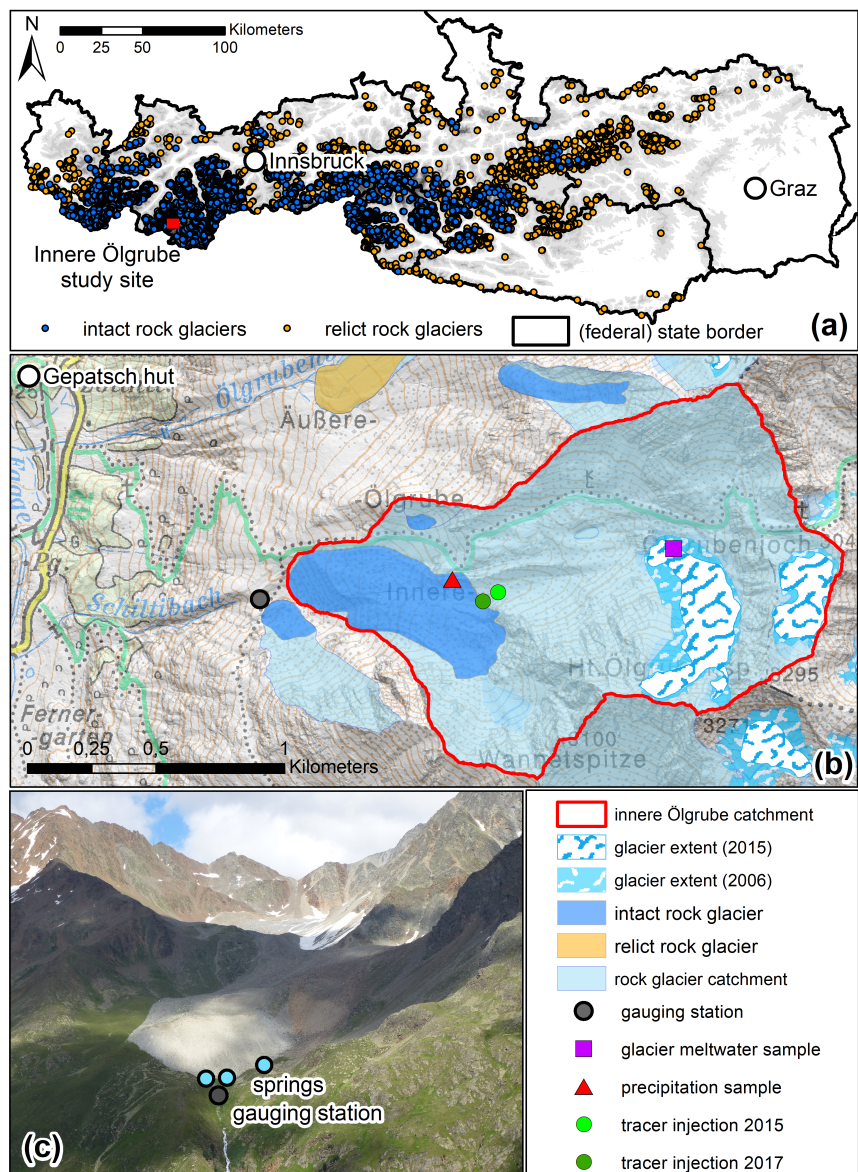
Figure 7: Observed and modelled specific discharge of the Innere Olgrube spring catchment. Visual fit

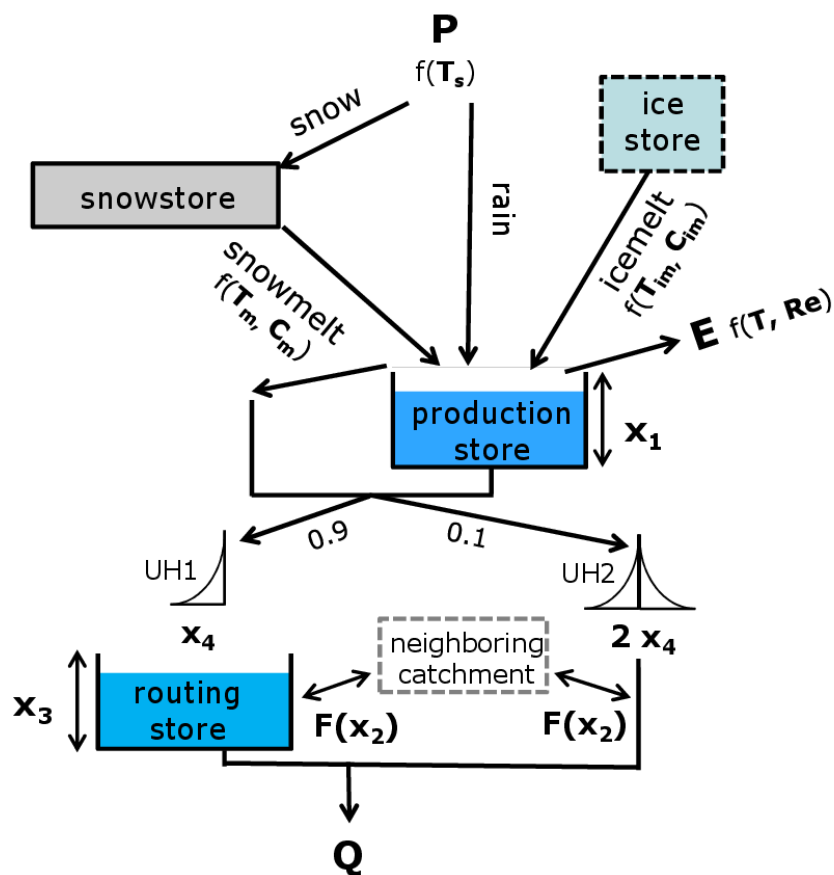
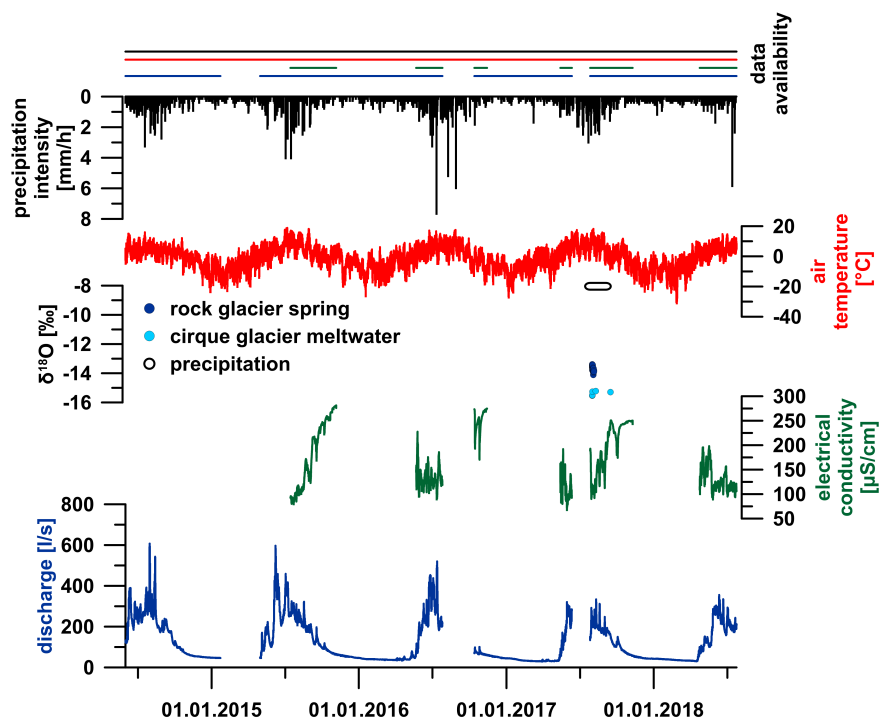
between observed and modelled discharge and related precipitation input data. Differentiation of rainfall, snowmelt and ice melt input as well as snow accumulation over the winter periods.

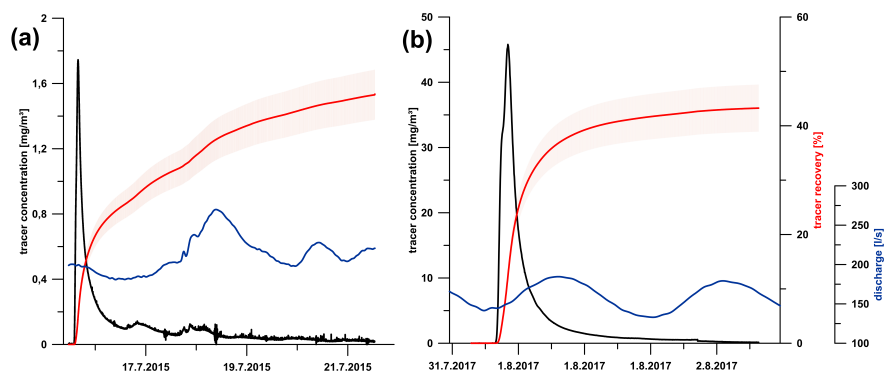
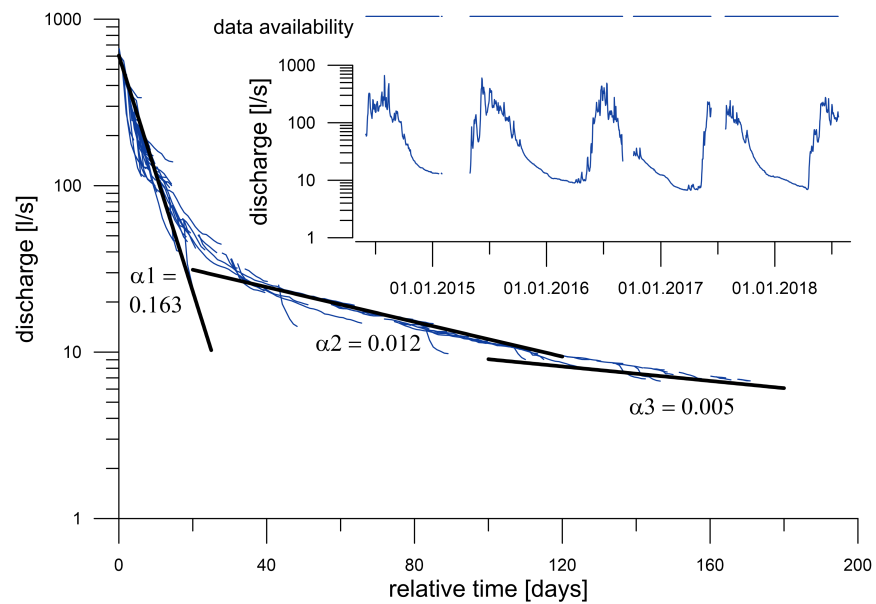
Figure 8: Monthly contribution of “recharge” (input into the rainfall-runoff model without considering potential loss due to evapotranspiration) and discharge components (based on event water analysis); absolute values normalized to catchment area. Shaded area indicates total flux. Dashed lines indicate assumed groundwater/event water contribution during periods of low discharge (no EC record available). Numbers next to bars indicate the number of months analysed (see Figure 2).

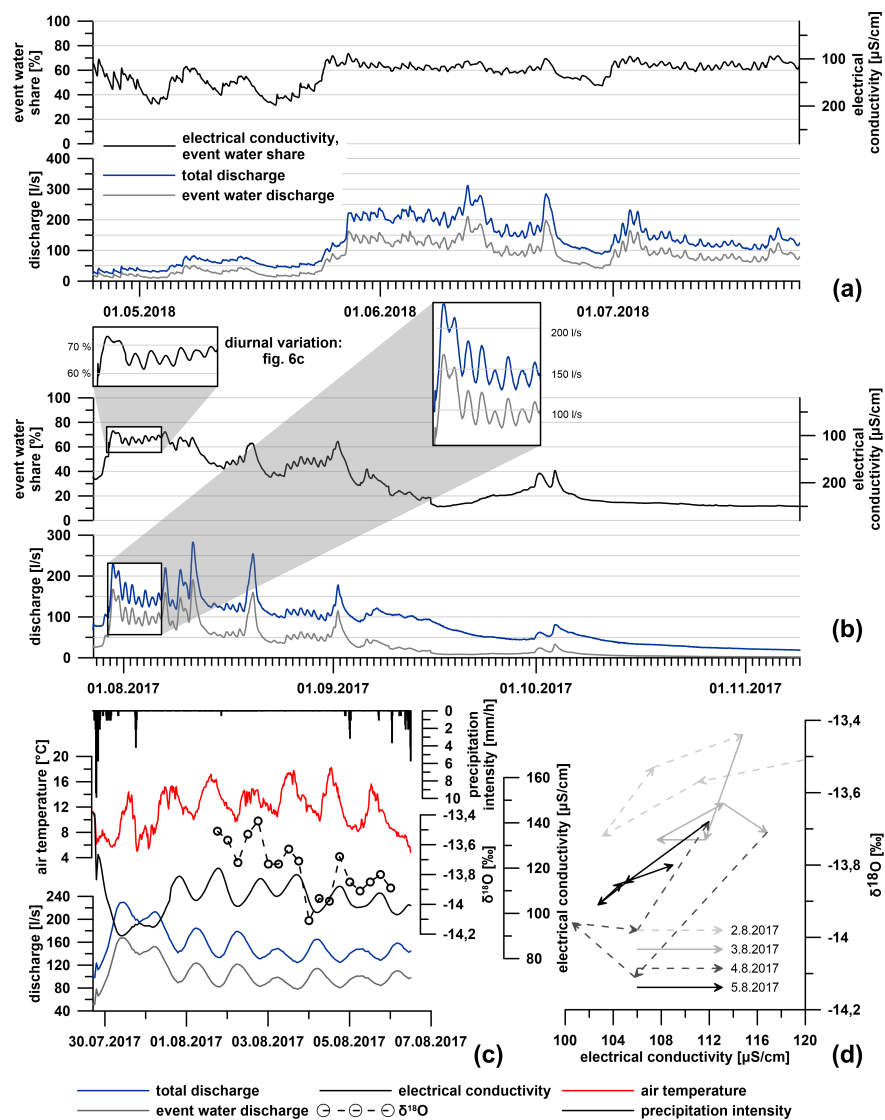
Figure 9: Observed discharge (dark blue line), modelled discharge (green line) without the input from the ice store, assuming cirque glaciers have vanished; and modelled discharge (purple line) without the input from the ice store and applying model parameters from the relict Schoneben rock glacier (Table 2; cf. Wagner et al., 2016); assuming the cirque glaciers as well as all the permafrost ice have vanished. Red line refers to the simulated runoff as in Figure 7.

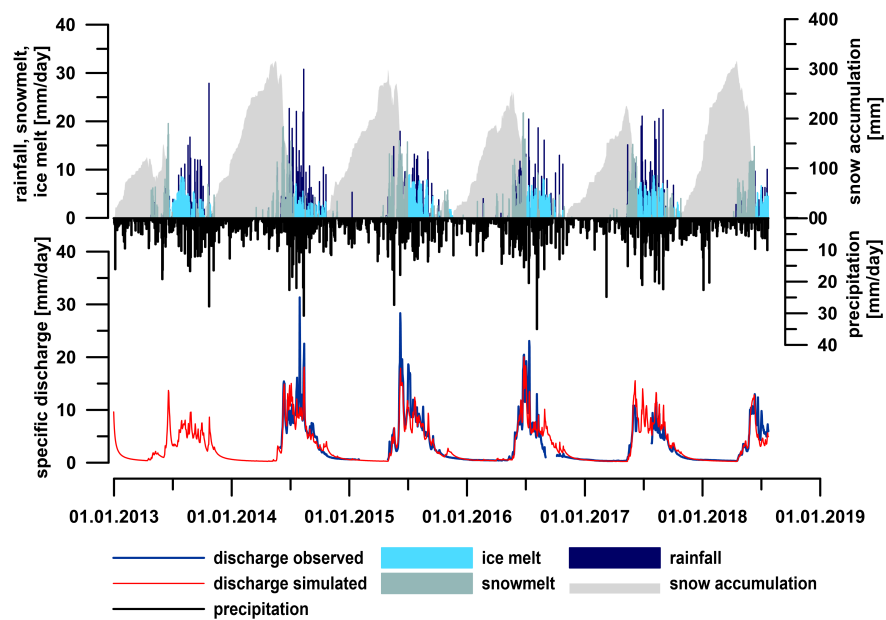
Figure 10: Master recession curves (MRC) of observed as well as simulated runoff; in addition the simulated MRCs without the ice melt and the hypothetical scenario of a relict rock glacier in the (far?) future.

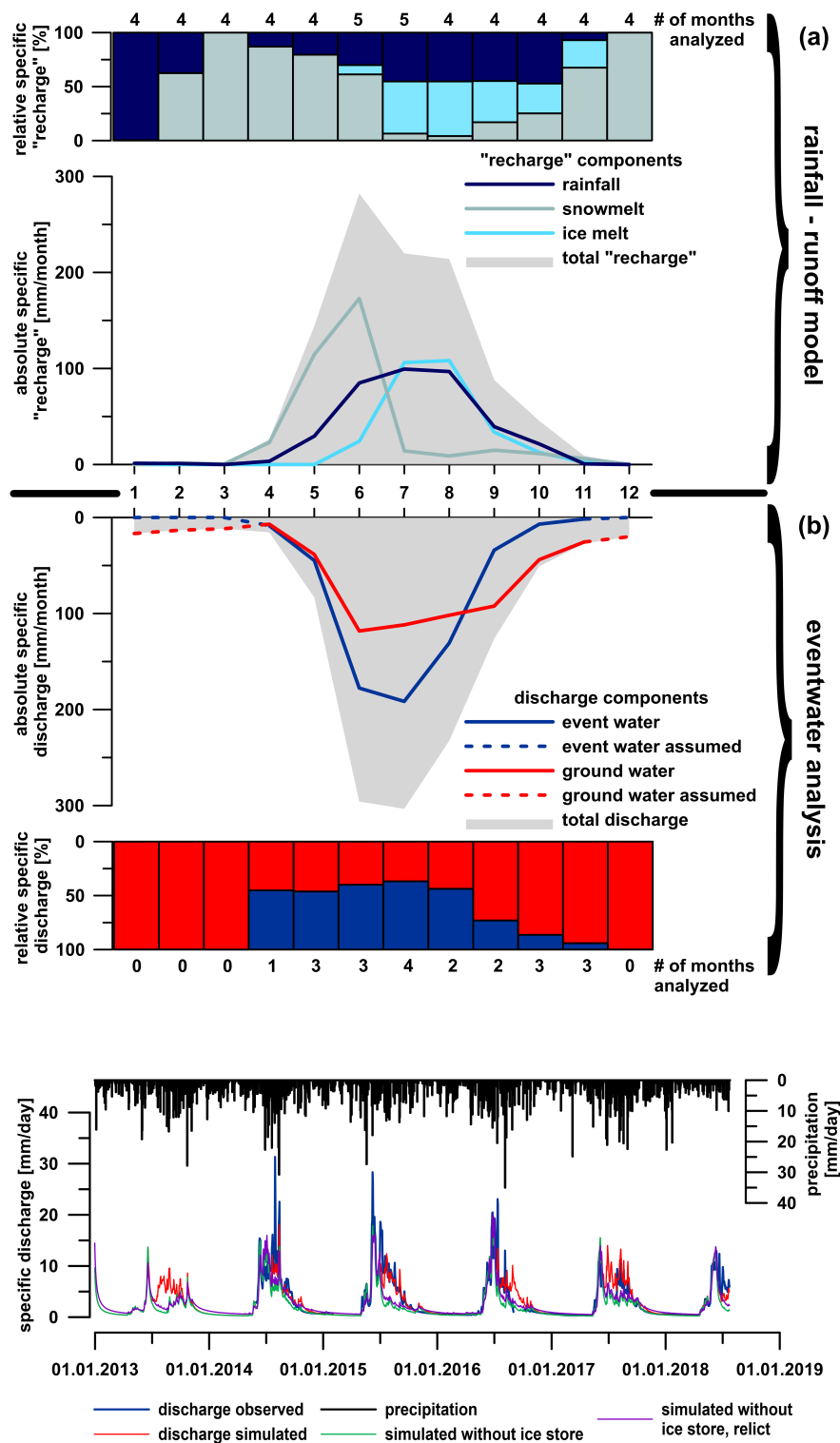


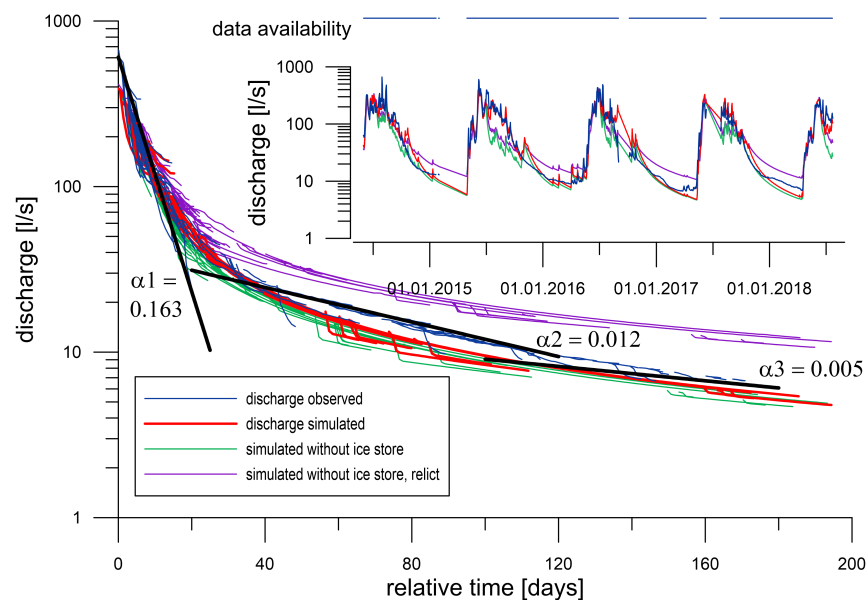












Hosted file

Table1_WagnerEtAl.pdf available at <https://authorea.com/users/384720/articles/500267-storage-discharge-characteristics-of-an-alpine-active-rock-glacier-catchment-a-multidisciplinary-approach-applied-to-the-innere-%C3%B6lgrube-austrian-alps>

Hosted file

Table2_WagnerEtAl.pdf available at <https://authorea.com/users/384720/articles/500267-storage-discharge-characteristics-of-an-alpine-active-rock-glacier-catchment-a-multidisciplinary-approach-applied-to-the-innere-%C3%B6lgrube-austrian-alps>